Chapter 2
Evaluation of Sustainable Energy Options for Non-residential Buildings

Behnaz Rezaie, Ibrahim Dincer, and Ebrahim Esmailzadeh

Abstract The building sector, as the major energy consumers, demands most of the energy research to assess different energy suppliers from various aspects. In this study, two non-residential buildings, one being commercial and the other industrial, are chosen as case studies. For these case studies, two different renewable energy technologies and one hybrid system are considered for a specified size. The environmental impact indices, renewable energy indices, and the renewable exergy indices have been evaluated for every energy options. The results obtained indicate that the hybrid system (without considering the economics factors) is superior since having top indices. The importance of the energy consumption patterns in buildings were proven by the indices. Utilization of the non-fossil fuels is one part of the solution to environmental hazards while energy conservation being the other. It is shown that the re-design of the energy resources would be achievable for buildings.

Keywords Sustainability • Exergy • Renewable energy • Energy • Industrial building • Environmental impact

2.1 Introduction

Population growth, as well as, modern life style increases the energy demand. Energy supply and environmental impact are major issues of increasing energy consumption. Therefore, other sources of energy, which are sustainable, are favorable energy resources in our era and due to this reason renewable energy is receiving much attention. Meanwhile, smart use of energy improves the overall situation. Knowing the energy consumption of each sector is beneficial to tackle the sector with highest energy consumption. Global energy consumption in 2010 is depicted in Fig. 2.1, which shows that building sector allocated the highest energy consumption. Therefore, an insight to the energy consumption in building sector is

B. Rezaie • I. Dincer (✉) • E. Esmailzadeh
Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, ON, Canada L1H 7K4
e-mail: Behnaz.Rezaie@uoit.ca; Ibrahim.Dincer@uoit.ca; ezadeh@uoit.ca

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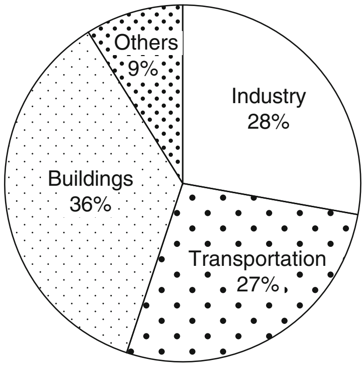


Fig. 2.1 Global energy consumption in 2010 (Data from IEA)

beneficial to unravel the energy issue. Many researches were performed on the subject of energy consumption in buildings [1–3].

A trigeneration system with the goal of improving energy utilization efficiency of buildings was suggested by Huang et al. [4]. Sustainable operations as well as efficient design were reported as important strategies for buildings [5]. Three factors to have the environmental friendly buildings, namely, energy efficiency, energy conservation, and renewable energy were stated by Zaki et al. [6].

Energy efficient buildings also make use of conventional energy sources and rely mostly on fossil fuels. Over and above the major savings in the energy usage, and also cutting down on the greenhouse gases GHG, one can say that much attention has recently been paid on the measurement of energy consumption of buildings. In this regard, Balta et al. [3] have stated that the energy consumption of a building is a function of many variables, such as, the building type, construction materials, occupancy behavior, climatologic conditions, heating and cooling equipment, domestic hot water, and the lighting. As for buildings, Vivancos et al. [7] presented the research results for the thermal characterization of brick, and Drochytka [8] illustrated the role of design for the building envelope to enhance the energy efficiency. Also, Wan et al. [9] showed the trends of energy consumption for future buildings under different climates. Balta et al. [10] stated that exergy analysis is essential for energy system improvement and should be used as a potential tool for sustainable buildings design. The flows of energy in the building systems are more tangible if exergy analysis is considered [11, 12]. Thus, exergy analysis shows possibility of more efficient design by dropping inefficiencies in the system [13]. Environmental advantages and economics of energy can be detected easier by an exergy analysis [10]. Furthermore, energy and exergy ratios are defined and utilized in building sectors for recognizing the building's energy option benefits [14–18].

The present study is based on a previous research, which sizing various energy options for different buildings [19]. The focus is placed on the non-residential buildings while the thermodynamic analysis could be extended to the exergy investigation. Moreover, the energy considerations and the exergy aspects with various energy options for several case studies will be analyzed beyond the efficiency analysis. The study covers the environmental aspects of different possibilities of energy. Parallel with the present study, another study is performed with emphasis on residential buildings [20]. Two non-residential buildings are selected, one a commercial building and the other an industrial building. For every case study the energy, exergy and the environmental impacts of these renewable energy options have been assessed. Some indices are proposed in this work as a useful tool for comparing several energy options from different aspects, including the energy, exergy, and the environmental impact in a peek period.

2.2 Methodology

Different methods of sizing various energy options, namely, environmental impact, energy, and exergy aspects will be defined in this section. Furthermore, these methods will be applied to the previously mentioned case studies.

2.2.1 Sizing Methods

The sizing methods were discussed in detail in the previous study performed by Rezaie et al. [19]. Here, the proposed methodologies for sizing the solar electricity and solar thermal system are used respectively.

2.2.2 Environmental Impact Assessment Method

One of the major reasons to use the non-fossil fuel energy supplier is to protect the environment against the undesirable greenhouse gases (GHGs). To show the performance of each technology, initially, the emitted CO_2 by the conventional fuel for each case study has been estimated. Then the "environmental impact index" is calculated for each design. The environmental impact index is expressed as

$$I_E = 100\,(R_{CO2})/E_{CO2} \tag{2.1}$$

where I_E represents the environmental impact index, R_{CO2} stands for the reduced CO_2 by the design, and E_{CO2} is the emitted CO_2 by the conventional design, respectively. Note that I_E is a dimensionless factor.

It is worth mentioning that the method of estimation of CO_2 for electricity generation should be explained prior to the calculation of the environmental impact index. Electricity is generated in different plants through using different fuels. In Canada, these resources are namely, the hydro, thermal, nuclear, combustion engine, and very limited renewable energies. The resulting pollution due to the electricity generation varies depending on the fuel resources. In a report titled "Power Generation in Canada", published by the Canadian Electricity Association, the electricity generation configuration in the Province of Ontario was [21]:

- 37 TWh from hydro,
- 45 TWh from thermal (mainly coal-based power plants),
- 63 TWh from nuclear and
- 6.7 TWh from combustion engine sources.

When visiting the website "Plug into Green Canada" [22] it offers a calculator, which considers the combination of the above-mentioned sources and presents the total generated amount of CO_2. Alternatively, this calculator can be utilized to estimate the amount of CO_2 from the electricity generation.

To obtain the amount of CO_2 from the burning of natural gas, one has to refer to the report published by the Natural Gas Association [23]. It clearly states that to obtain 1 GJ of energy by burning natural gas, one would generate the unwanted amount of 50.3 kg of CO_2.

2.2.3 Energy Method

The energy demand for each case is important enough to be measured by having the index of the estimated renewable energy. The index of renewable energy is defines as:

$$I_{RE} = 100\,(RE)/TE \tag{2.2}$$

where, I_{RE} represents the renewable energy index, RE refers to the renewable energy, and TE stands for the total energy demand. One should note that I_{RE} is a dimensionless parameter.

2.2.4 Exergy Method

Exergy is defined as a tool to appraise and develop energy systems, by giving more meaningful and valuable information than the more conventional energy analysis [24]. Exergy analysis particularly recognizes the actual thermodynamic losses and efficiencies. Hence, exergy analysis can help in reducing the thermodynamic losses in thermal systems. Exergy with the definition of the *available energy* can be computed for the two case studies. The exergy for commercial case study and industrial case study consists of the exergy from the natural gas and the exergy form the electricity, respectively. Hence, the exergy for electricity determines as [25]:

$$\mathrm{Ex} = \mathrm{E} \times \mathrm{R} \tag{2.3}$$

where Ex stands for the exergy, E is for the energy, and R stands for the energy grade function. It can be said that R has different values for various kinds of energy, e.g., for the electricity R = 1.0, and for the natural gas R = 0.913.

The exergy of the solar energy is calculated by:

$$\mathrm{Ex} = \left(1 - \frac{T_0}{T_s}\right)\mathrm{E}$$

where $T_0 = 20°\mathrm{C}$ (environment temperature) and $T_s = 5{,}000\ °\mathrm{C}$.

Then, the renewable exergy index can be calculated and the index of the renewable exergy can be defines as

$$\mathrm{I_{REx}} = 100\ (\mathrm{REx})/\mathrm{TEx} \tag{2.4}$$

where $\mathrm{I_{REx}}$ represents the renewable exergy index, REx is the renewable exergy, and TEx stands for the total exergy demand. Also, note that $\mathrm{I_{REx}}$ is a dimensionless factor.

2.3 Energy Options Considered

Different energy options for non-residential buildings are tested in this study. Here, the commercial and industrial buildings are categorized as non-residential buildings. In the following, one institutional building and one industrial building have been considered as case studies to assess their energy options.

Ground source energy system, as a source of renewable energy with high performance (the average coefficient of performance (COP) of a ground source energy system is 4), is an interesting source of renewable energy. Geothermal system cost effectively provides energy for heating and cooling of a building. This system can be a reasonable source of energy for heating and cooling of a commercial building due to case studies circumstances.

2.3.1 Commercial Building

The commercial case study here is the central public library in Brampton (in Ontario), having latitude 43.536, and longitude −79.556. In the commercial buildings, there is a demand for electricity to run several computers, lights and appliances, and also furnaces to activate the heating systems as well as providing hot water, and running the air-conditioning system to generate cool air in the summer. Typically, natural gas is used for heating space and providing hot water

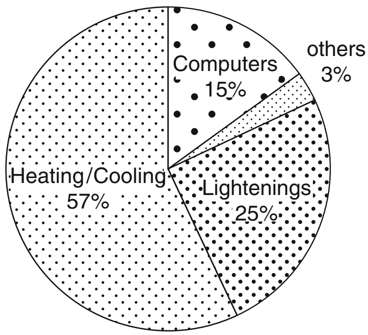


Fig. 2.2 Electricity usage distribution in commercial building case study (Brampton Library)

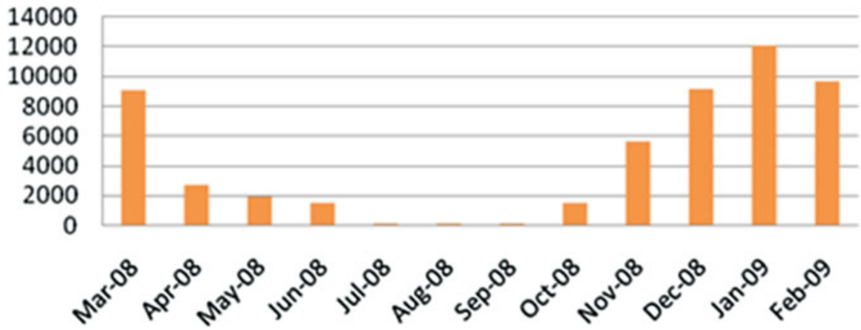


Fig. 2.3 Natural gas Consumption (m^3) in Brampton Library, commercial building case study

in commercial buildings. This library is a two-storey building with the residential area being approximately 1,352 m^2, in both stories. There are many lights in the library, and computers for the use of public and staff. In this case, lightening and computers consume a considerable portion of energy. Figure 2.2 shows the distribution of energy consumption in the commercial case study and illustrates the electricity consumption percentage in the central library. The annual natural gas consumption in this library is 72,748 m^3, and the average monthly consumption is 6,062.3 m^3. Figure 2.3 illustrates the distribution of the natural gas consumption in the central library. Electricity consumption in this library is 765,765.00 kWh (765.8 MWh) per year, and the daily consumption is 2,098.00 kWh for this commercial building.

2.3.1.1 Option 1

Solar water heaters can be employed for this building to heat the space as well as provide hot water. The main demand is for heating the space rather than heating the water, since it is a commercial building. Moreover, there is a large space at the back of the building and wide roof available for installing the solar collectors' panels.

Fig. 2.4 Layout of energy resources for commercial case study when using solar thermal energy

Fig. 2.5 Layout of energy resources for commercial case study when using solar electricity

Figure 2.4 shows the layout of the energy resources for commercial case study. Solar thermal is the renewable source of energy together with two conventional sources of energy—a) grid electricity and b) natural gas. Using the solar thermal energy will reduce the natural gas consumption considerably.

Energy is calculated by using the calculator available in the WSE technology [26]; the engine of this calculation is based on deducting the heat loss of the building by considering the isolation rate as well as the desired temperature, from the heat resulting from the solar collectors. According to this calculator, for the desired temperature of 22 °C throughout the heating space of 1,352 m^2, there is a need of 58 solar collectors WSE58, which should be installed.

The energy generated by 58 solar collectors WSE58 is $58 \times 2{,}741{,}310 = 156$ MJ/h. By considering 7 h of sun per day as the average for all days in the year, the energy produced by these solar panels is: $156 \times 7 = 1{,}092$ MJ/day

Assuming that there are 300 days of sun per year in Ontario, Canada; the energy produced by the solar collectors is 327600 MJ per year. This energy can be released from the use of 8,798.4 m^3 natural gas (201,600 MJ /37,233,949 J = 8798.4). In other words, the gas consumption is reduced by 8,798.4 m^3 every year. In the 25 years life-span of the solar panels, this saving would become as 219,960.5 m^3 natural gas.

2.3.1.2 Option 2

The PV panels are the best technology for the commercial case study in order to generate electricity because this building is located in an urban area, downtown Brampton.

Figure 2.5 illustrates the layout of resources of energy for the commercial case study. Solar electricity through PV panels will generate electricity, which reduces the grid electricity consumption. Grid electricity in smaller amounts and natural gas

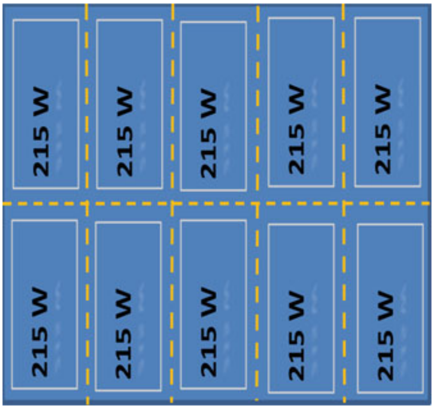


Fig. 2.6 Placing 10 modules in one mount

are both conventional sources of energy for the commercial case study in this design.

The average daily electricity consumption in the commercial case study is 2,098 kWh, and the average insulation coefficient 3.53 kWh/m^2/d in Toronto area, the electricity consumption by the sun hours per day would be 2,098/ 3.53 = 594 kW = 594,000 W (AC).

Hence, 594,000/(CEC = 194) = 3061 W, and 3,061/(CEC = 0.94) = 3257, hence, 3257 is the number of PV panels; PV panels are 210 W each. Before going further for the arrangement of the array, the availability of the installation space should be assessed.

The area of each panel is $0.9 \times 1.7 = 1.53$ m^3. Roof of the building is the installation area and the available area on the roof is $13 \times 22 = 286$ m^3. For the ease of maintenance, every 10 panels in the form of 2×5 places on one mount. Figure 2.5 shows the configuration of 10 modules in one mount.

Then the area of each mount, which contains 10 PV modules, would be $5 \times 3.4 = 17$ m^2. From each side 0.2 m will be added for maintenance purposes, and then the area of each mount comes to $5.4 \times 3.8 = 20.52$ m^2. Figure 2.6 illustrates a mount dimension and surrounded area.

On the roof with the dimensions of 13 m by 22 m, 10 mounts can be installed, and each mount contain 10 PV panels. Then $10 \times 10 = 100$ PV modules 215 W will generate electricity for the library. The layout for the roof design is depicted in Fig. 2.7.

2.3.1.3 Option 3

The “hybrid system” can be considered by the solar technologies through combining the PV panels for generating electricity and the solar water heaters for heating the space. In hybrid system electricity and natural gas consumption will be reduced and the reduction will be calculated in the following paragraphs. This hybrid system

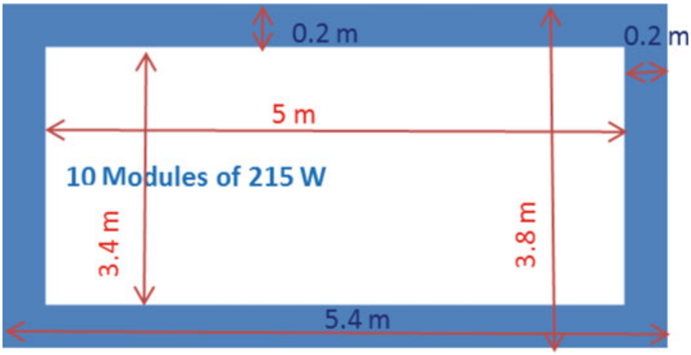


Fig. 2.7 Dimensions on a mount. Blue area is considered for maintenance needs

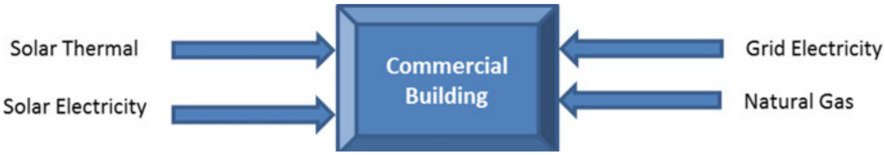


Fig. 2.8 Layout of energy resources for commercial building case study, when using hybrid system

would be directly dependent on the solar energy. In hybrid system, still grid electricity and natural gas are in the system as a backup system for the time there is not quite enough sun in the sky. Figure 2.8 depicts the layout of energy sources in the commercial building case study.

Hybrid system consists of the solar water heaters (Solar Thermal) and PV panels (Solar Electricity). Solar water heaters and PV modules were computed in earlier sections. Based on the previous assessment, the hybrid system is including 58 panels of WSE58 as solar thermal energy for converting the solar energy to 156 MJ/h, plus 100 panels of PV modules 215 W to generate 68.3 kW per day. The configuration of PV modules and the angles of panels are described in the previous section.

2.3.2 *Industrial Building*

Industrial building case study is a plastic injection company in Mississauga, having latitude 43.640 and longitude −79.622. This building can be categorized as an industrial building and one of the specifications of industrial buildings is having high energy consumption. Industrial buildings are high in using electricity over running the machines and production equipment. These machines produce some heat as well. There is not a great demand for having hot water running; however there is great need for heating the building and working space.

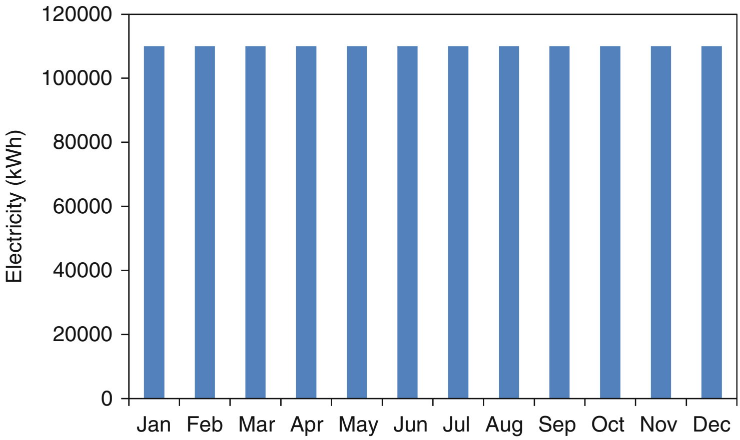
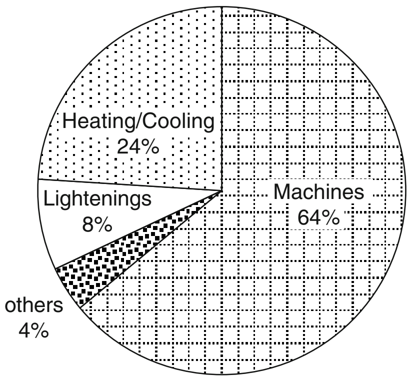


Fig. 2.9 Electricity consumption (kWh) in injection plastic company, Industrial building case study (from the actual monthly bills)

Fig. 2.10 Electricity usage distribution for industrial building case study (Industrial building case study information)



The area of this industrial unit is 1,900 m^2 (30×63.3); there are 100 employees, some working on shop-floor and some are in office space, they are working 5 days per week and each day for 16 h. 24 computers are running all the time, and average load of each computer is 200 W. Lighting load is 10 W/m^2, for 100 h/W. For the 12 months electricity usage was 1320 MWh, and then the monthly average electricity consumption comes down to 110 MWh. Figure 2.9 shows the electricity usage in this company in each month of year. Since the major electricity users are machines and the company runs with the same schedule, the electricity consumption would almost be the same in each month.

As the industrial company case study is an industrial building, the energy consumption pattern is totally different from the prior cases. In this case machines including computers have the highest portion of electricity consumption. Figure 2.10 illustrates energy distribution in the industrial building case study. Also, the natural gas consumption in the last 12 months was 43,000 m^3. The information for monthly usage of natural gas is not available.

Fig. 2.11 Layout of energy resources for industrial building case study, when using solar thermal energy

2.3.2.1 Option 1

Solar water heater can be used for this industrial building to heat the space as well as providing hot water. There is a big space on the back of the building and also big roof available for installing the solar collectors' panels. Figure 2.11 shows the layout of the energy resources for industrial building case study. Solar thermal is the renewable source of energy beside two conventional sources of energy, i.e., the grid electricity and the natural gas. Solar thermal caused reduction of the natural gas consumption.

By using the calculator available in the WSE technology website; for heating the spaces of this company with the area of 1,900 m^2 and for the desired temperature of 22 °C, one would know that 75 solar collectors WSE58 are needed.

The Energy generated by 75 solar collectors WSE58 is $75 \times 2{,}741{,}310 = 205.6$ MJ/h. By considering 7 h of sun per day as average for all days in the year, the energy produced by these solar panels would be: $205.6 \times 7 = 1{,}439.2$ MJ/day.

The assumption is that there are 300 days of sun per year in Ontario, Canada. Then, the energy produced by the solar collectors is 431,760 MJ per year. This energy can be released from 11,606 m^3 natural gas (431,760 MJ / 37,233,949 J = 11606.4), in other word the gas consumption is reduced by 11,606 m^3 every year. In 25 years life-span of the solar panels this saving is 290,161 m^3 natural gas.

2.3.2.2 Option 2

For the PV the average electricity consumption in industrial building case study is 110,000 kWh, generating this much electricity with the average insulation coefficient of 3.53 kWh/m^2/d for Toronto area resulted in having thousands of PV modules, which is not a reasonable decision. Because, that many PV panels demand huge area to stand, this area is not suitable for the injection company. Moreover, the maintenance of so many PV panels is very costly. Maintenance of the PV modules includes adjusting the angle of incident towards sun four times per year, plus cleaning the snow of the panels during the long Canadian winter, though PV modules will be chosen based on the available space on the roof of the building.

Fig. 2.12 Layout of energy resources for industrial building case study, when using solar electricity energy

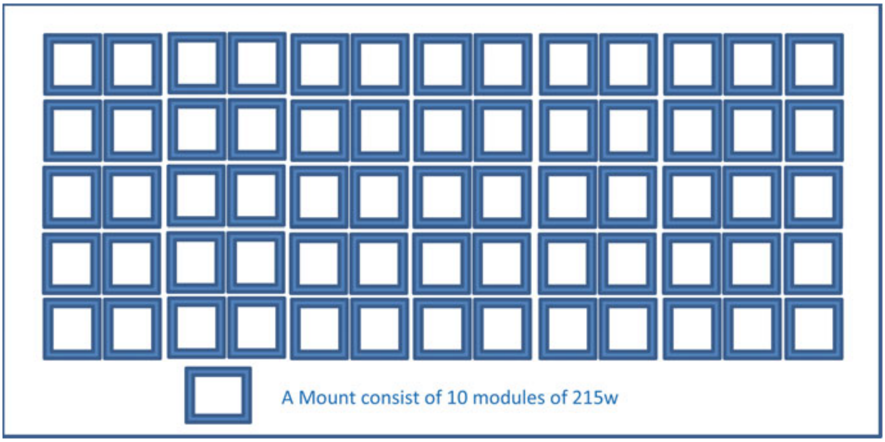


Fig. 2.13 Configuration of PV modules on the roof of injection plastic company, industrial building case study

Figure 2.12 illustrates the layout of resources of energy for the industrial building case study. Solar electricity through PV panels generates electricity, which reduces the grid electricity consumption. Grid electricity in a smaller amount and natural gas are the conventional sources of energy for the industrial building case study in this design.

The area on the roof of this injection company is 30 m × 63.3 m. The actual available area for PV panels is $30 \times 50 = 1{,}500\ \text{m}^2$. In this scenario, the sizing of the PV panels is based on the vacant space on the roof.

Every 10 PV panels are placed together on a mount with a dimension of 5 m × 3.8 m; considering 0.2 m from each side for maintenance, the actual space for each mount is 5.4 m × 3.8 m. Figure 2.13 depicts a sketch of a mount containing 10 PV panels. The best arrangement of the mounts on the roof is 5 × 13, which results into a total of 65 mounts, with each mount containing 10 panels. The total 650 PV panels would then generate electricity for the injection company. The electricity generating from 650 modules 215 W is roughly $215 \times 650 \times 90\ \% \times 3.53 = 443{,}985.8$ W/day = 444 kW/day. Figure 2.13 depicts the configuration of 650 modules on the roof of the injection plastic company.

Fig. 2.14 Layout of energy resources for industrial building case study when using hybrid system

The photovoltaic panels should have the right angle towards sun for getting the maximum amount of solar energy. The angle for each season is then:

Fall/Spring: Angle = Latitude = 43.6°
Summer: Angle = Latitude − 15 = 43.6 −15 = 28.6°
Winter: Angle = Latitude + 15 = 43.6 + 15 = 58.6°

As the seasons change, it is strongly recommended that the angle of PV modules be changed in order to obtain maximum energy from the sun.

2.3.2.3 Option 3

The second hybrid system is defined by the solar technologies through combining PV panels for generating the electricity and solar water heaters for heating the space. In the hybrid system, electricity and natural gas consumption is reduced. The reduction is calculated in the following paragraphs. This hybrid system is directly dependent on the solar energy. In hybrid system, the grid electricity and natural gas are still in the system as a backup for the time that there would not be enough sunshine. Figure 2.14 depicts the layout of energy sources in the industrial building case study. The hybrid system consists of the solar water heaters (solar thermal) and PV panels (solar electricity). Solar water heaters and PV modules are discussed in previous sections. Based on the previous assessments, hybrid system includes 72 panels of WSE58 as the solar thermal energy source to convert the solar energy to 205.6 MJ/h, plus 650 panels of PV modules of 215 W to generate 444 kW per day. The configuration of the PV modules and the angles of the panels are described in earlier section.

2.4 Analysis

The energy options are sized technologically in the previous section. Different aspects of each option have been assessed in this section. When considering the importance of environment, one major aspect of the analysis is the environmental impact of energy as the main purpose of the options. Different design proposals will be measured individually for each option within every case study. Also, energy analysis for each technology options will be performed to show the share of the renewable energy in the proposed design. Following that exergy, as the quality of energy for each energy technology will be examined. It can be another tool to measure capability of different design proposals. The overall analysis of energy options provides insight for the designers and researchers.

2.4.1 Environmental Impact

It has been explained in the introduction that environment issues are very serious matters for human being. The main aspect of any design should be the consideration of the environmental effects of the new design/product/system on the society. To quantify the environment impact, two case studies as explained in Sect. 2.3, with varieties of technology options are chosen. As mentioned, one case study is a commercial building and the other one is an industrial building. The impacts of the environmental issues on every single energy technology, proposed in the previous section, for both case studies are examined in the following paragraphs.

2.4.1.1 Commercial Case Study

When the residential building of commercial case study is running with the conventional energy, say the natural gas and electricity, the volume of the emitted CO_2 is the sum of the emitted CO_2 to generate 765,765 kWh of electricity and the burning of 72,748 m^3 of natural gas. By using the available calculator given in reference [12], one could find that 2,688.7 tons of CO_2 has been emitted to the environment when 765,765 kWh of electricity has been generated. According to the report published in reference [27], the energy contained in every cubic meter of natural gas is 36,116.7 kJ. Therefore, the total energy resulted from the natural gas for the commercial case study is:

$$\begin{aligned} 72,748\ \left(\mathrm{m^3/year}\right) \times 36,116.7\ (\mathrm{kJ}) &= 2,627,417,691.6\ \mathrm{kJ/year} \\ &= 2,627.4\ \mathrm{GJ/year}. \end{aligned}$$

It has been mentioned before that the energy of 1 GJ from burning of the natural gas is equivalent to the generating of 50.3 kg of CO_2, hence:

$$\begin{aligned} 2,627.4\ (\mathrm{GJ/year}) \times 50.3\ (\mathrm{kg\ of\ CO_2}) &= 132,159.1\,\mathrm{kg\ of\ CO_2 per\ year} \\ &= 132.2\ \mathrm{ton/year}. \end{aligned}$$

Therefore, the total amount of CO_2 emitted to the environment, when for the commercial case study the conventional fuel was used, is:

$$2,688.7 \text{ (ton of } CO_2/\text{year)} + 132.2 \text{ (ton of } CO_2/\text{year)} \\ = 2,820.9 \text{ ton of } CO_2 \text{ per year.}$$

Option 1

As mentioned before, by releasing energy of 1,054,350 kJ from natural gas, the mass of 58 kg CO_2 emits into the atmosphere. Therefore, by releasing 327,600 MJ of natural gas, 16.5 Ton of CO_2 is emitted into the atmosphere. In other words, 58 panels prevent emitting 16.5 tons of CO_2 into the air each year; this is 412.5 tons of CO_2 in the 25 years of the panels' life. Figure 2.14 shows the environmental impact index.

Option 2

Following the previous section the PV panels will generate 2,083 kWh per month in accordance with the calculator available in the "Plug into Green Canada" website. In order to generate 2,083 kWh electricity per month, the mass of 7,312 kg CO_2 per year will be emitted into the atmosphere in Ontario. Figure 2.14 depicts the environmental impact index for Option 2 energy.

Option 3

With a similar logic, the emission reduction for hybrid system is equal to the emission reduction by 58 panels of WSE58 which was calculated along with the emission reduction by 100 PV modules. Then, the quantity of emission reduction by hybrid system is defined as

$$16.5 + 7.3 = 23.8 \text{ tons of } CO_2/\text{year}$$

The environmental impact index has been demonstrated in Fig. 2.15.

2.4.1.2 Industrial Case Study

For every day of running of the house, for industrial case study with the conventional energy system being the natural gas and electricity, the volume of the emitted CO_2 can be estimated as the total emitted CO_2 for generating 1,320 MWh of electricity plus the burning of 43,000 m^3 of the natural gas. In order to generate 1.320 MWh of electricity it would produce 4,634,664.8 kg of CO_2 annually according to the reports published [26].

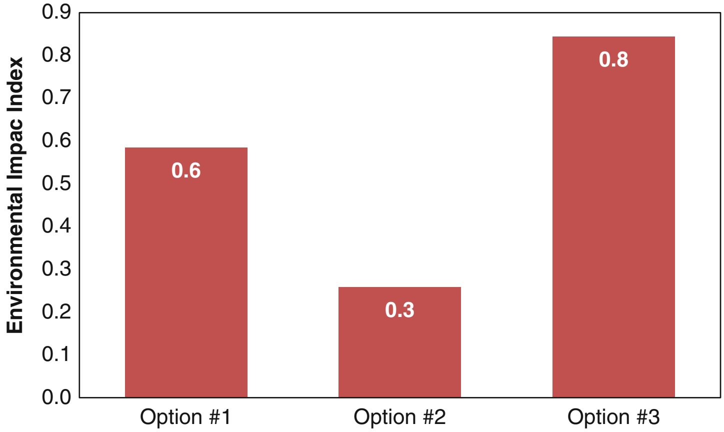


Fig. 2.15 Environmental impact index for commercial building case study

Therefore, the consumed natural gas would contain [27]:

$$43,000\ \left(\mathrm{m}^3/\mathrm{year}\right) \times 36,116.7\ (\mathrm{kJ}) = 1,553,018,100\ \mathrm{kJ/year}$$
$$= 1,553\ \mathrm{GJ\ per\ year}$$

$$1,553\ (\mathrm{GJ/year}) \times 50.3\ (\mathrm{kg\ of\ CO_2}) = 78,116.8\ \mathrm{kg\ of\ CO_2\ per\ year}$$

And the total amount of CO_2 emitted for the Industrial case study with the conventional fuel is:

$$4,634,664.8\ (\mathrm{kg\ of\ CO_2/year}) + 78,116.8\ (\mathrm{kg\ of\ CO_2/year})$$
$$= 4,712,781.6\ \mathrm{kg\ of\ CO_2\ per\ year} = 4,712.8\ \mathrm{ton/year}$$

Option 1

As mentioned earlier, by releasing 1,054,350 kJ of energy from natural gas, the mass of 53 kg CO_2 emits into the atmosphere. Then, by receiving 431,760 MJ of energy from the natural gas, the mass of 21.7 tons of CO_2 emits into the atmosphere. Figure 2.15 depicts the environmental impact index for Option 1 energy.

Option 2

The energy generated by 650 modules is 13.5 MW/month. This means that the injection company uses the amount of 13.5 MW less electricity in each month. These PV modules save the environment from 47,391 kg of CO_2 per year, in accordance with the calculator in the website of "Plug into Green Canada". Figure 2.15 depicts the environmental impact index for Option 2 energy.

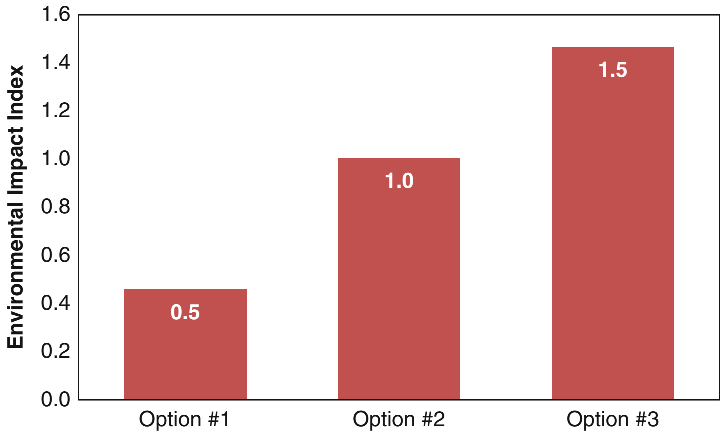


Fig. 2.16 Environmental impact index for energy options of industrial building case study

Option 3

Emission reduction for the hybrid system is equal to the emission reduction by 72 panels of WSE58, plus emission reduction by 650 PV modules. Hence, the quantity of emission reduction by the hybrid system is:

$$21.7 + 47.4 = 69.1 \text{ Ton } CO_2/\text{year}$$

Figure 2.16 depicts the environmental impact index for Option 3 energy.

2.4.2 Energy Aspect

2.4.2.1 Commercial Case Study: Energy Demand

The annual energy requirement of commercial case study is the sum of the natural gas and the electricity consumptions. The energy value of the natural gas used by the commercial case study (72,748 m^3) was calculated for 2,627.4 GJ per year. Also, the energy value of 765,765 kWh per year can be estimated as:

$$\begin{aligned} 765,765 \text{ (kWh/year)} \times 3.6 \text{ (MJ/kWh)} &= 2,756,754 \text{ MJ/year} \\ &= 2,756.8 \text{ GJ per year} \end{aligned}$$

Then the total energy demand for commercial case study is calculated as

$$2,627.4 \text{ (GJ/year)} + 2,756.8 \text{ (GJ/year)} = 5,384.2 \text{ GJ per year}$$

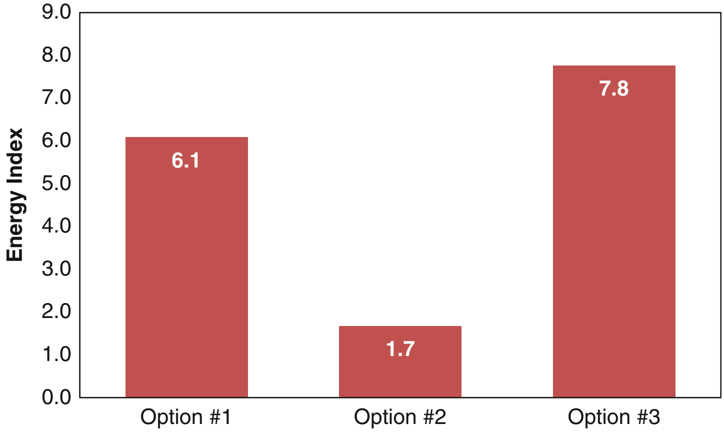


Fig. 2.17 Energy impact index for commercial building case study

The energy value of each technology is already defined in the design of Sect. 2.5. The summary of the energy index are in illustrated in Fig. 2.17. The energy of each design is presented in Table 2.1.

2.4.2.2 Industrial Case Study: Energy demand

The energy demand for the industrial case study is the total sum of the natural gas and the electricity consumptions. The energy value of the natural gas, used by industrial case study (43,000 m^3), was determined in Sect. 2.4 as 1,553 GJ per year. The energy value of 1,320 MWh per year can be computed from:

$$\begin{aligned} &1,320 \times 10^3 (\mathrm{kWh/year}) \times 3.6\ (\mathrm{MJ/kWh}) = 4,752\ \mathrm{X}\, 10^3 \mathrm{MJ\ per\ year} \\ &\quad = 4,752\ \mathrm{GJ\ per\ year} \end{aligned}$$

Therefore, the total energy demand for Industrial case study would be:

$$1,553\ (\mathrm{GJ/year}) + 4,752\ (\mathrm{GJ/year}) = 6,305\ \mathrm{GJ\ per\ year}$$

Initially, the different technology options were examined and then the energy value of every technology has been adapted. Hence, the renewable energy index of every design option is calculated accordingly. The results of the energy for the industrial case study are summarized in Fig. 2.18. The energy of each design is listed in Table 2.1.

Table 2.1 Summary of energy, exergy and CO_2 reduction of each energy options for both cases

		Commercial building case study				Industrial building case study			
		Renewable technology	Energy (MJ)	Energy (MJ)	CO_2 Reduction (tons)	Renewable technology	Energy (MJ)	Energy (MJ)	CO_2 Reduction (tons)
Option 1	Solar Thermal	58 WSE58	327.6	307.9	16.5	75 WSE58	431.8	405.9	21.7
Option 2	Solar Elec.	100 × 215 W	90	84.6	7.3	650 × 215 W	583.2	548.2	47.4
Option 3	Hybrid	58 WSE58 + 100 × 215 W	417.6	392.5	23.8	75 WSE58 + 650 × 215 W	1015	954.1	69.1

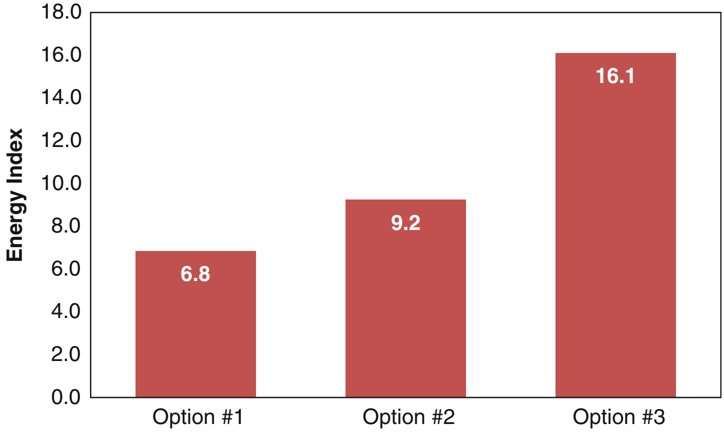


Fig. 2.18 Energy impact index for energy options of industrial building case study

2.4.3 Exergy Aspect

2.4.3.1 Commercial Case Study

The exergy for the commercial case study can be estimated by using Eq. (2.3). Hence, the exergy for electricity can be determined as:

$$\text{Exergy of electricity} = 2,756.8\ (\text{GJ}) \times 1 = 2,756.8\ \text{GJ per year}$$

and the exergy of the natural gas can be calculated as:

$$\text{Exergy of natural gas} = 2,627\ (\text{GJ}) \times 0.913 = 2,398.5\ \text{GJ per year}$$

Then the total exergy for the commercial case study would be:

$$2,756.8\ (\text{GJ}) + 2,398.5\ (\text{GJ}) = 5,155.3\ \text{GJ per year}$$

The renewable exergy index for various technology options considered for the commercial case study can be calculated by using Eq. (2.4). The calculated results are presented in Fig. 2.19 and Table 2.1.

2.4.3.2 Industrial Case Study

The exergy for the industrial case study can be estimated using Eq. (2.3). Hence, the exergy for the electricity can be evaluated as:

$$\text{Exergy of electricity} = 6,305\ (\text{GJ}) \times 1 = 6,305\ \text{GJ per year}$$

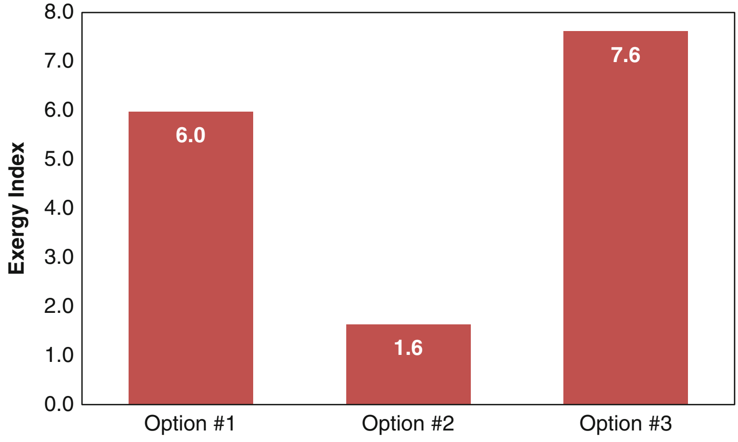


Fig. 2.19 Exergy impact index for commercial building case study

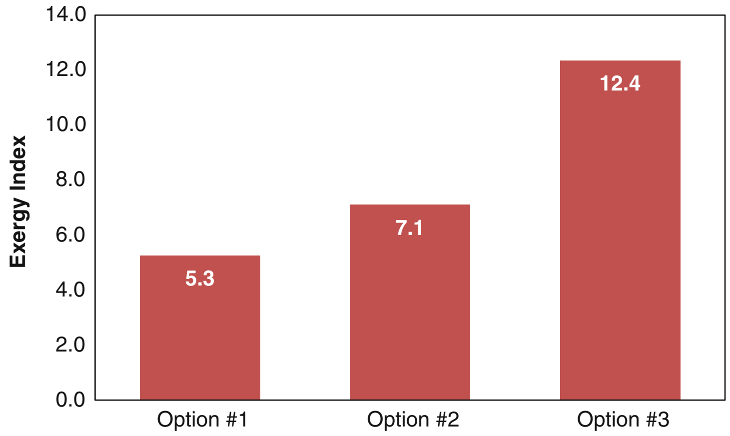


Fig. 2.20 Exergy impact index for energy options of industrial building case study

and the exergy of the natural gas can be calculated as:

$$\text{Exergy of natural gas} = 1,553\ (\text{GJ}) \times 0.913 = 1,417.9\ \text{GJ per year}$$

Then the total exergy for the industrial case study would be the sum of them as:

$$6,305\ (\text{GJ}) + 1,417.9\ (\text{GJ}) = 7,722.9\ \text{GJ per year}$$

Equation (2.4) is the renewable exergy index for different technology options, which has been used to compute for the industrial case study. The computed results of exergy calculations for the industrial case study have been summarized in Fig. 2.20 and Table 2.1.

2.5 Results and Discussion

In comparing different renewable energy design options for the commercial and industrial buildings, the environmental impact, energy, and the exergy, as well as, the environmental impact indices, renewable energy and the exergy indices have been computed. Results of those calculations are presented in Figs. 2.14, through 2.19 for the case studies. Comparisons of various options in this study are based on the environmental impact, energy and the exergy approaches. For the final choice decision, these various options must be considered depending on the management priority cost factor.

In analyzing the commercial case study, the hybrid system has the highest environmental index as illustrated in Fig. 2.14. Since the hybrid systems are formed as the combination of two renewable technologies, the ranking of the hybrid systems as the top priority is a sensible choice. Following the hybrid system, solar heater and PV panels are ranked second and third choices by considering the environmental index, energy and exergy indices. This prioritization is for this particular case study (Brampton library). Depending on the project and its specific situations the design of different energy sources will vary; apparently prioritizations would vary too.

For assessing the industrial case study, the hybrid system has the highest environmental index as depicted in Fig. 2.15. For this case study the PV panels stand as the second choice and the solar heater is the last choice, based on the environmental, energy and exergy indices. As explained earlier, this prioritization is only for this specific building with its own stand-alone situation.

The study of proportions shows the importance of energy resources available in buildings. Using the non-fossil fuels is one part of the solution to the environmental issues and the energy conservation is another part of the resolution. Re-design of energy resources model is effective and achievable for buildings. Whenever equipment is available to use the non-fossil fuel in a building, then the change of energy resources would greatly beneficial in reducing the environmental impact of the building.

2.6 Conclusions

Two non-residential buildings were chosen to consider different energy options. Each building was treated as an independent case study, and various renewable energy and hybrids systems were designed and sized for every one of them. The environmental impact and the energy and exergy aspects of each design were fully assessed through the analysis of the environmental impact index, the renewable energy index and the exergy index. The following important results are obtained from the computer simulation runs and by evaluating the results for both cases:

- The highest environmental impact index belongs to the hybrid system, being 0.8 for the commercial case study and 1.5 for the industrial case study, respectively. Therefore, it indicates that the hybrid system is a far better option.

- The renewable energy indices demonstrate that the hybrid system has a superior technology by achieving the highest energy index of 7.8 for the commercial case study and 16.1 for the industrial case study.
- The upmost renewable exergy index fits well into the hybrid system, being 7.6 for the commercial case study and 12.4 for the industrial case study. This reiterates that the hybrid system is an outstanding design choice.
- Hybrid systems are ranked as top choices with higher indices since they are made with the combination of two technologies and hence, exhibit the advantages of both technologies.

The results presented here are only based on the environmental, energy and the exergy aspects without considering any economic factors. For having a thorough prioritization, it is recommended that one should also consider carefully the initial capital costs, annual maintenance fees, and other financial aspects of every design in order to arrive at an optimum decision. However, if the financial factors taken into consideration then one could say that hybrid systems would be the most expensive technologies since they are made of the combination of two renewable technologies.

Nomenclature

CEC	California Energy Commission
COP	Coefficient of Performance
E	Energy
I_E	Environmental Impact Indices
R_{CO2}	Reduced CO_2
E_{CO2}	Emitted CO_2
Ex	Exergy
R	Energy grade function
RE	Renewable Energy
I_{RE}	Renewable Energy Index
REx	Renewable Exergy
I_{REx}	Renewable Exergy Index
TE	Total Energy
TEx	Total Exergy demand.

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