PERFORMANCE ASSESSMENT OF ENERGY POSITIVE ROOFS

Sudhakar Molleti, Dominique Lefebvre, Michal Bartko, Pascal Beaulieu and David van Reenen

National Research Council, 1200 Montreal Road, Ottawa, ON, Canada, K1A 0R6

ABSTRACT

As concerns of the worldwide energy consumption continue to grow, the development of alternative technologies and systems is needed to reduce the consumption of energy from both a sustainability and an environmental perspective. Over 30% of Canada's national energy use is expended on energy requirements for buildings. Therefore, advancements in building envelope technologies provide a significant means of improving the overall efficiency and reducing energy use. The current study examines the concept of energy positive roofs, which surpass net zero energy technologies, to obtain energy positive buildings. The energy positive aspect is achieved using high performance insulation, vacuum insulation panels (VIPs), incorporated with energy generating photovoltaics. A roof mock-up was constructed at the National Research Council Canada to assess the field performance of the technology. The thermal insulation used consisted of a composite system to reduce heat losses and gains of VIPs sandwiched between polyisocyanurate (polyiso) insulation. Photovoltaic laminates were added to the roof membrane to allow for energy generation of the system, and the power consumption of the conditioned spaces was monitored. It was found that when the composite insulation systems, such as VIPs with conventional materials, are incorporated with energy generating technologies, such as photovoltaics, the resulting building envelope transitions towards sustainability. Through the implementation of high performance building materials, Canada has the potential to both reduce its overall energy use, and utilize the renewable energy sources available to harness additional energy.

INTRODUCTION

The Department of Energy's (DOE) 2011 Buildings Energy Data Book states that the building sector accounted for 41% of energy consumption in 2010 [1]. In Canada, according to Natural Resources Canada's (NRCan) report of the Survey of Commercial and Institutional Energy Use, the total energy consumption of commercial and institutional buildings represents approximately 12% of the overall energy consumption [2]. NRCan's report states that the commercial and institutional building energy consumption represents 482,266 buildings with an energy use of 842.2PJ (Petajoules). Over 70% of the energy use is consumed for space heating, water heating and space cooling. These significant energy consumptions indicate that energy efficient building envelopes are of paramount importance to prevent undesired energy losses and gains, and thus prevent the consumption of unnecessary energy. Efficient building envelopes reduce both the expenses incurred by the building owner and the resulting negative impacts on the environment.

There are various sources which provide recommendations of the thermal requirements for Canadian climatic zones including the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)

and the National Energy Code of Canada for Buildings (NECB) [3, 4]. The NECB provides recommended effective R-values of 25 to 40 for Canadian regions, as shown in Table 1. In order to achieve the specified R-values with conventional insulation, larger thicknesses are required to provide an increased energy barrier. The increased insulation thickness requirements can present major obstacles when performing a building retrofit where the amount of useable space is already allocated. From a roofing perspective, an increase in the insulation thickness can result in increased movement between the roofing components which can reduce the overall durability of the roof. An alternative to providing additional layers of the conventional insulation is to compliment the current systems with a material that has a superior thermal performance to achieve an increased R-value while maintaining a desirable thickness of insulation. Vacuum insulation panels (VIPs) are a high-performance thermal insulation which can be integrated into current systems in order to achieve the increased R-value requirements. VIPs have a thermal resistance of five to ten times that of typical insulations, and therefore, have the potential to be used as a next-generation material to meet increased R-value requirements.

Table 1: Thermal Transmittance and Corresponding Effective Thermal Resistance for Roofs as Specified in the National Energy Code of Canada for Buildings.

Zone	**4**	**5**	**6**	**7A**	**7B**	**8**
Maximum Overall Thermal Transmittance ($W/(m^2K)$)	0.227	0.183	0.183	0.162	0.162	0.142
Effective Thermal Resistance ($(m^2K)/W$)	4.41	5.46	5.46	6.17	6.17	7.04
Effective Thermal Resistance ($ft^2hr°F/BTU$)	25	31	31	35	35	40

With the goal of obtaining high performance energy efficient building envelopes to minimize undesired energy transfer, the recent trend includes the accommodation of renewable energy sources. Renewable energy technologies, combined with high performance insulation systems, such as VIPs, can reduce or even eliminate a building's energy demand, achieving the status of an energy positive building. Among many types of renewable technologies, harvesting solar energy by photovoltaic (PV) systems is quickly gaining popularity for roofing applications. Many studies worldwide have evaluated the performance of PV rooftop systems and have found that they can effectively harness a significant amount of energy [5, 6, 7, 8, 9, 10, 11]. In order to harvest solar energy efficiently on a building's rooftop, the following considerations and benefits are evaluated.

- Placement above shade line, such as buildings and trees, to allow easy access for sunlight.
- Both steep slope and low slope roofs have higher energy harvest potential compared to walls and other building structures.
- Rooftop PV arrays provide additional value to otherwise unused areas of commercial roofs if properly installed and maintained.
- Installation in an area with limited access to unauthorized individuals.
- Energy is generated at the consumption site, eliminating transportation losses.
- Energy is harvested in proximity to the grid, with no new infrastructure requirements.

For the present study, self-adhesive PV laminates manufactured using the amorphous silicon technology were used. The shape and electrical properties of the PV laminate are shown in Figure 1.

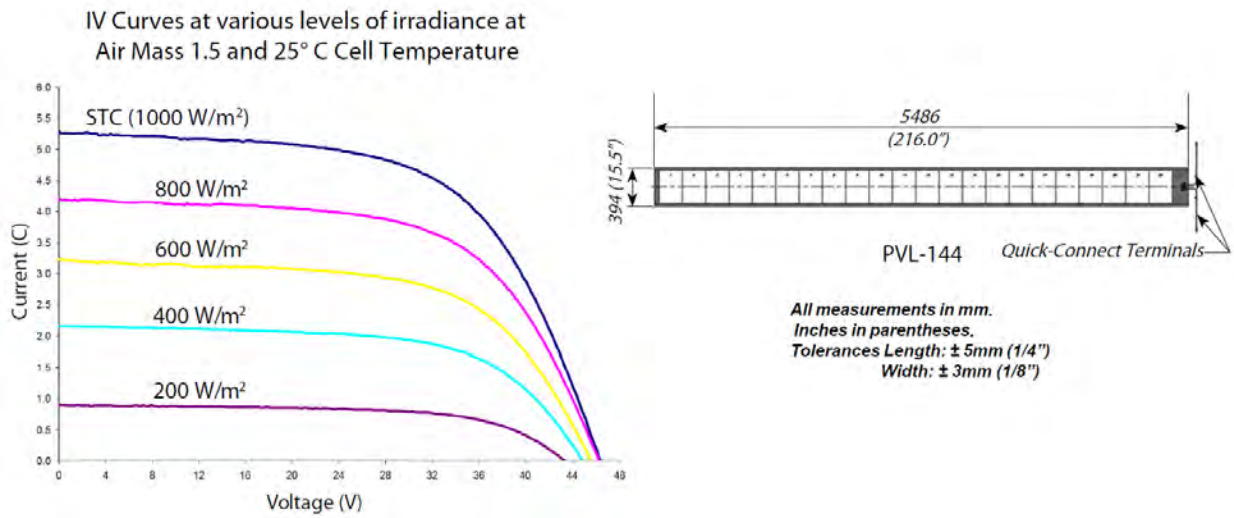

Figure 1: PV laminate schematic and electrical properties.

FIELD-MONITORING SYSTEM SET-UP

In the initial stage of this project in 2010, a roof mock-up of 3.7 m x 3.7 m was constructed with VIPs sandwiched between polyisocyanurate (polyiso) insulation, which were assembled at the NRC. The details of the construction of the mock-up and the roof assembly are discussed in length in Report B1253.2 [12]. The mock-up had a thermoset membrane, i.e. black EPDM membrane, with a 22 Ga steel deck and a self-adhered film vapor barrier. The insulation consisted of 50 mm thick composite VIPs which was adhered to the vapor barrier on the steel deck with a low-rise two part urethane adhesive. The insulation boards were instrumented with thermocouples and heat flux sensors. The VIP composite insulation layout included two layers of 12.5 mm thick polyiso [1.2 m x 2.4 m- 2 boards and 1.2 m x 1.2 m - 2 boards] with a dual layer of 12.5 mm thick VIP panels, to give an overall thickness of 50 mm for the composite VIPs. The thermoset black EPDM membrane was used as the waterproofing membrane and was installed using a solvent based membrane adhesive. The overhang membrane along the mock-up perimeter was mechanically fastened to the sides, and was overlaid with vinyl siding to prevent water ingress into the system. All the instrumentation was connected to a data acquisition system for monitoring. Figure 2 shows the schematics of the mock-up. At a later stage, a heating unit was installed inside the mock-up. The thermostat of the unit was set to control the air temperature inside the mock-up to a constant value of 20°C. The power consumption of the unit was monitored and logged by a data acquisition system.

In order to test the concept of energy positive roofs, PV laminates were added to the roof membrane in August 2015. The self-adhesive photovoltaic laminates PVL-144 were adhered to the EPDM membrane giving a system power of 1.3 kW. Separate arrays of laminates were integrated onto the mock-up, were wired, and were connected to the data acquisition to monitor the energy harvesting. The PV array layout is shown in Figure 3.

Figure 2: Mock-up system construction.

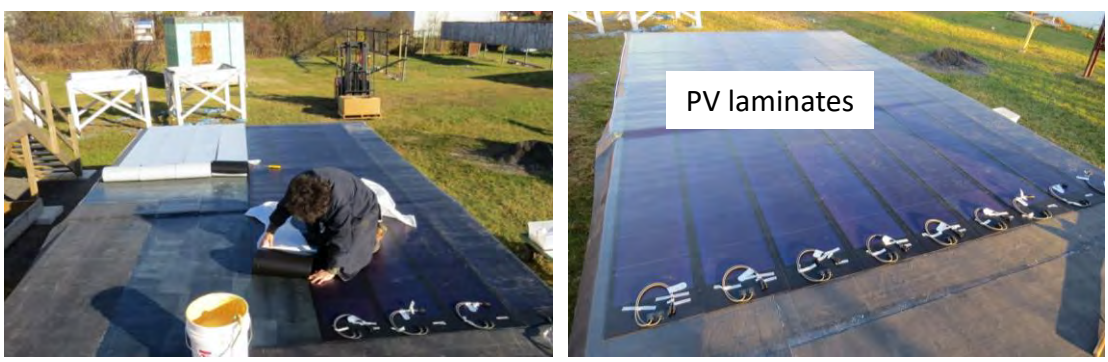

Figure 3: Layout of PV arrays adhered to the mock-up membranes.

RESULTS AND ANALYSIS

The roofing insulation panels have been monitored and analyzed for five years at the NRC facility. The parameters evaluated included the heat fluxes, the thermal resistances, the energy generation and the energy consumption. Emphasis was placed on the winter months to assess the insulation performance in cold weather. Also, the preliminary data for the comparison of the energy generation and energy consumption is presented for the conditioned mock-up to evaluate the energy positive roof concept.

Heat Flux

The average daily heat fluxes were determined for the VIP composite system, and are shown in Figure 4 for a typical winter week in 2016, when the mock-up was conditioned. The average monthly heat flux through the roof of the mock-up for January 2016 was 9.73 W/m2. When compared to an identical system with 2 in. of conventional polyiso, the heat flux was reduced by 52.4% for the system with the polyiso and VIP composite. The significant increase in the resistance to heat flow that the VIP produces demonstrates its suitability for inclusion in composite insulation systems.

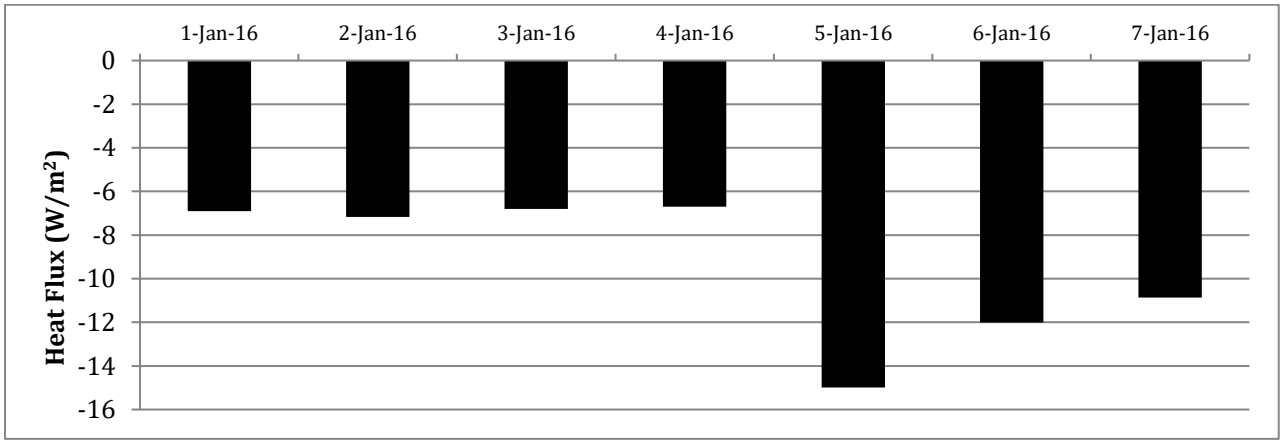

Figure 4: Daily heat flux data for the VIP composite for a typical winter week in January 2016.

Thermal Resistance

The average daily calculations of the dynamic R-value are presented in Figure 5 for the VIP composite during a typical winter week in 2016. The average monthly R-values were also determined for the winter months in 2016 were the mock-up internal environment was conditioned. The average monthly R-value for January 2016 was 3.57 m^2K/W for the 2 in. VIP polyiso composite. Therefore, the inclusion of VIPs within the conventional polyiso insulation was shown to significantly increase the resulting thermal resistance of the system.

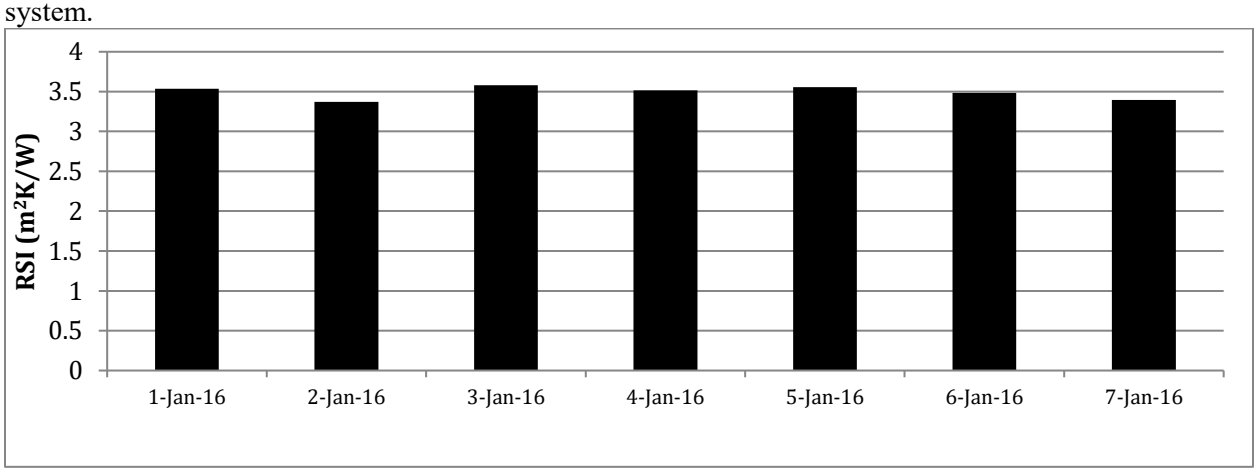

Figure 5: Thermal resistances for a typical winter week for the VIP composite system.

Energy Consumption

The total daily energy consumption for a typical winter week in March 2016 is presented in Figure 6 for the VIP polyiso composite system. The daily fluctuations of the energy consumption data can be attributed to the daily fluctuations of the temperature gradient on both sides of the assembly. It is important to note that the walls of the mock-up were constructed of regular polyiso insulation, providing less thermal resistance and therefore, redirecting the heat transfer from vertical (through the roof assemblies) to the horizontal direction via the walls. The concept of performing experiments on specimens with highly insulated walls has been expressed for the next stage of the project.

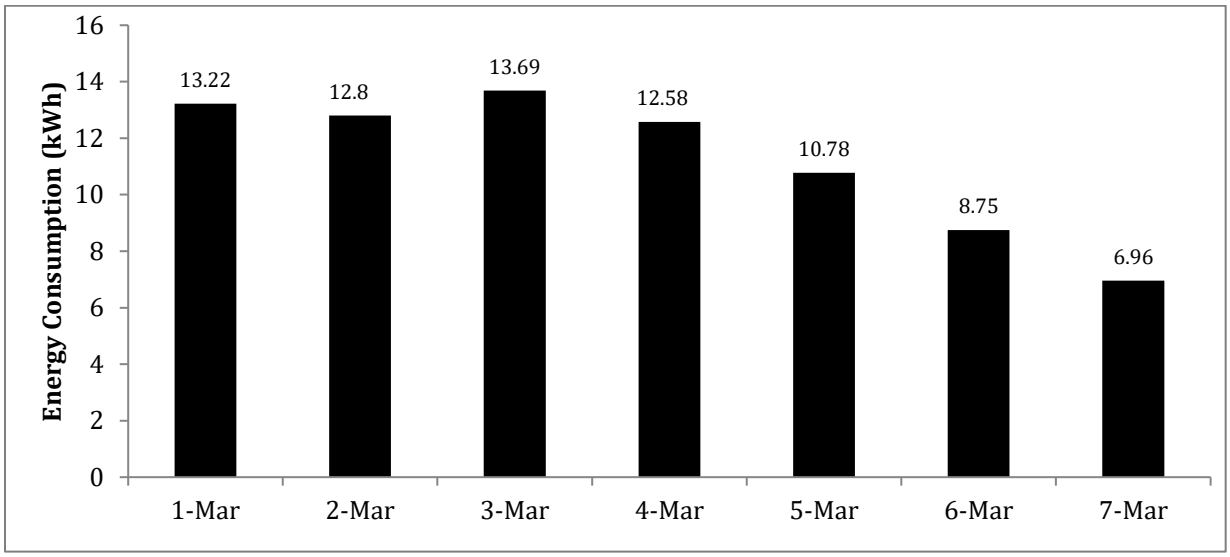

Figure 6: Daily energy consumption of the VIP polyiso composite system for a typical winter week in March 2016.

Energy Generation

The energy generation results of the PV arrays for the month of January 2016 are presented in Figure 7. The amount of generated energy observed is low for several reasons. In the month of January, there were several days with snowfall, which covered the PV laminates and prevented them from generating energy. When the snow was removed from the surface, which is not always the case in the field, the laminates generated a small amount of energy. Due to frequent clouds, the level of solar radiation for Ottawa in January is low. Also the PV arrays exposure time in the proximity to winter solstice prohibits them from producing higher energy generations. An example of the PV array exposure time in one day and the corresponding solar irradiation is shown in Figure 8. The direct dependence of energy harvest on solar irradiation can be observed. During the winter, the power generation duration is limited to approximately 8 hours. In Figure 8, both the irradiation and the power generation begin after 8:00 am and end before 4:00 pm. Much longer active times and higher harvests are expected in the summer months. The summer data is analyzed in the following section together with the energy consumption.

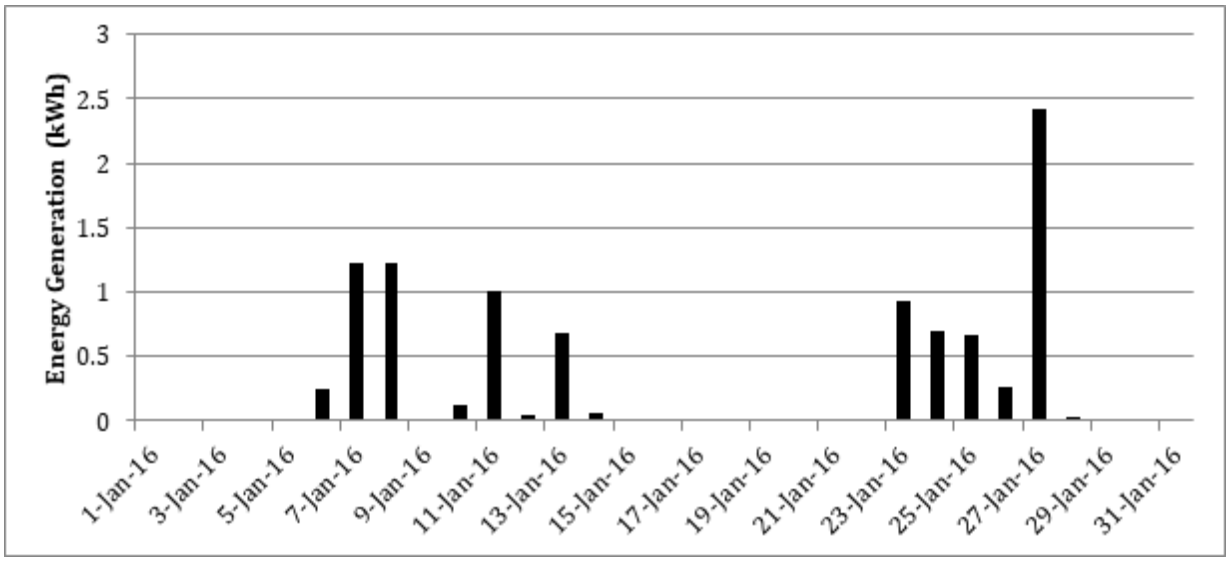

Figure 7: Energy generation by PV arrays of the VIP composite mock-up for a typical winter month.

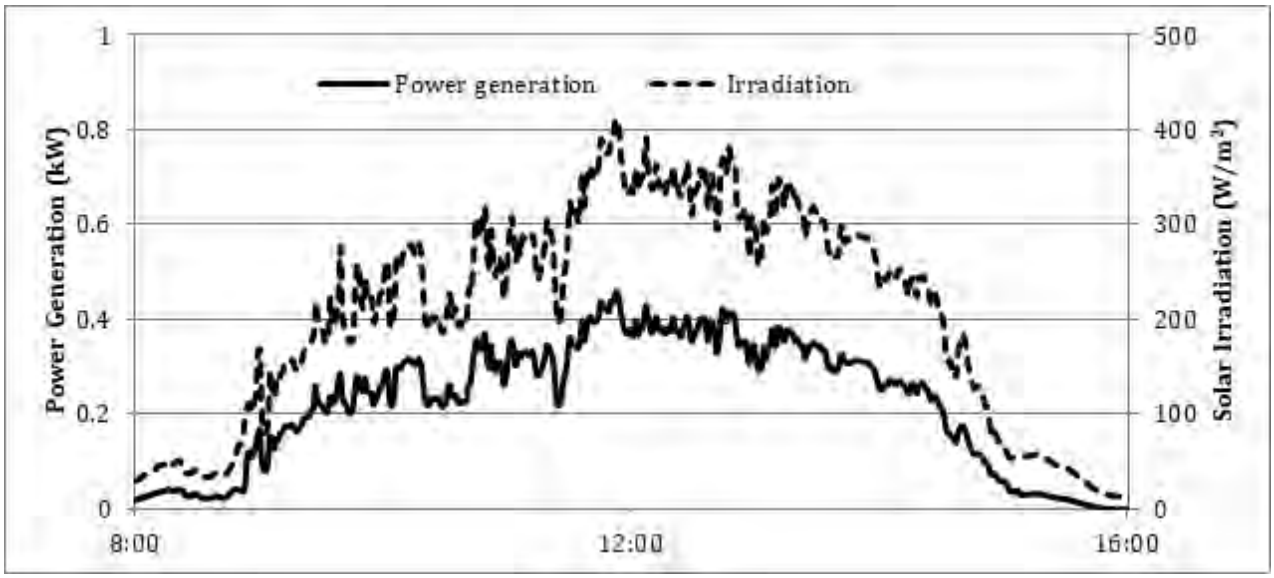

Figure 8: PV power generation vs. solar irradiation for January 2016.

Energy Generation vs. Energy Consumption

The energy generation was compared to the energy consumption in order to determine whether the concept of net energy positive roofs was achieved. The energy consumption and generation was determined for a typical week in January, February, and March 2016 for the VIP composite, and is shown in Figure 9. For the three winter months, the overall consumption was much larger than the generation, and therefore, the energy positive concept was not achieved, which is to be expected given the climate.

A typical summer week was also analyzed to assess the concept of the net energy positive roof. The energy consumption and generation was determined for a typical summer week in July, August, and September 2016 for the VIP composite system, and is shown in Figure 10. The energy generation was significantly higher than the energy consumption, demonstrating that the concept of net energy positive roofs can successfully be achieved during the summer months.

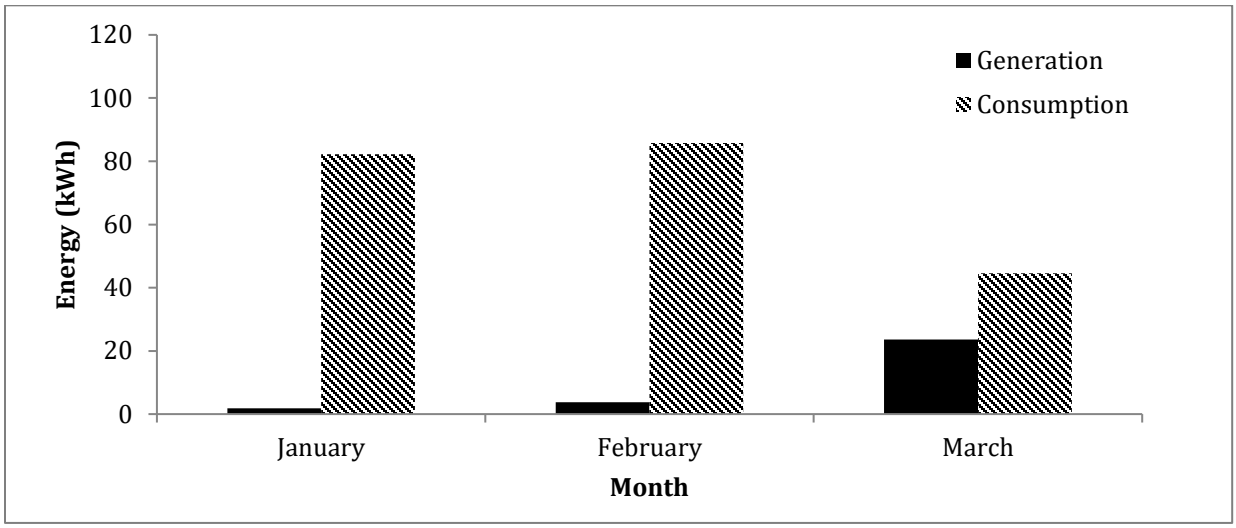

Figure 9: Energy consumption and generation for winter 2016 for the VIP composite system.

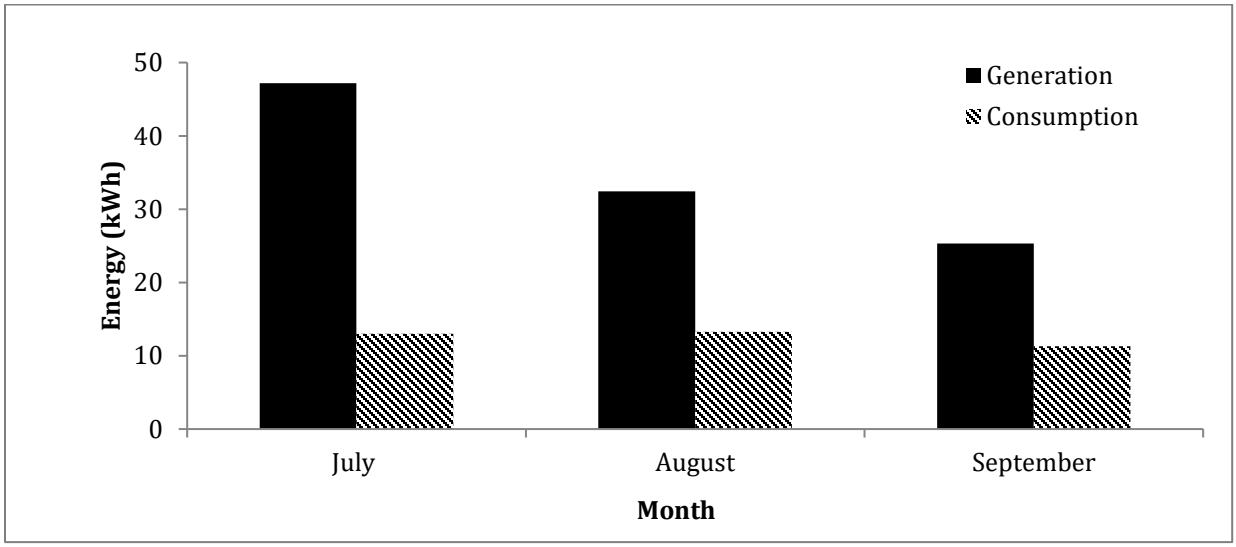

Figure 10: Energy consumption and generation for summer 2016 for the VIP composite system.

CONCLUSION

The concept of energy positive roofs was investigated using high performance insulation, vacuum insulation panels (VIPs), incorporated with energy generating photovoltaics. VIPs were assessed as a complementary insulation component for integration into current roofing insulation, namely polyiso systems. The assessment was completed through in-situ monitoring of the performance of VIP composite insulation systems. Through inclusion of PV panels on the rooftops, the concept of net energy positive roofs was investigated.

The concept of net energy positive roofs was proven through the current study. Although the energy consumption was larger than the energy generation during the winter months of 2016, this was expected due to the high variability of the Canadian climate. However, during the summer months, the energy generation was significantly higher than the energy consumption, proving the concept of net energy positive roofs.

These results indicate that VIPs are a high-performance material that can significantly improve the thermal performance of the construction industry in general and the roofing community in particular. The incorporation of PV panels to obtain energy positive roofs is a significant modification of the roofing system that moves towards sustainability. Although VIPs have several limitations regarding the maintenance of the vacuum environment, they cannot be modified or cut on site and they are sensitive to puncture, research is ongoing to develop strategies for their implementation. Further studies of the energy positive roofs are also ongoing to obtain additional data. System modifications, including the proposal of highly insulated walls, have been considered for the next phase of the project.

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