Solar Strategies for net-zero energy housing in Canadian North

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Abstract. The North imports most of its energy for fuel and cost of fuel is much higher than the national average, consequently, cost for space heating relying on fuel is very high. The North has an abundance of solar energy available. With the growing concerns on climate change, the region desires to be less dependent on fossil fuels. Significant energy savings for little added cost in housing could be achieved by building high performing envelope systems and integrating solar design strategies. The objective of this paper is to investigate the potential of integrating solar design strategies in improving energy efficiency of housing suitable for the Canadian Northern climates through modelling by optimizing passive solar design and optimal use of thermal and electrical energy from Building Integrated Photovoltaic/Thermal system (BIPV/T) to achieve net-zero energy housing. A reference home with typical construction built in Northern region is modelled using EnergyPlus. The key solar design strategies and building envelope parameters are optimized to minimize energy consumption and maximize the energy production for the reference home. The parameters investigated include thermal resistance of building envelope components, window-wall ratios, thermal mass, night window shutters, shading schedules, and ventilation rates. The optimal use of thermal energy produced by BIPV/T system by integration with Heat Recovery Ventilation (HRV) and air-source Heat Pump (ASHP) is evaluated. Modelling results show that 43% energy saving can be achieved by optimizing the passive solar design and overheating can be eliminated by proper solar shading and natural ventilation. The integration of BIPV/T with HRV can reduce the frost cycle by 10.4%. These preliminary findings demonstrate the potential of integrating solar design strategies to reduce energy consumption and develop net-zero energy housing for the Canadian North.

1. Introduction

Housing is central in shaping our lives, yet it remains inaccessible for some northern Canadians. Several geographical, climatic, social and economic factors create challenges to the affordability of northern homes [1-4]. First, the climate, temperatures drop to -50°C for extended periods of time, requiring homes to have high performing windows and well-insulated building envelope while minimizing air leakages [5-6]. Second, the North is remote – it holds 0.2% of Canada’s populations in 40% of the country’s landmass [1]. There is a lack of skilled labour, a market for private housing, or products tailored for the region, and practical knowledge addressing specific technical issues to the North [4]. The North is unable to support important infrastructures for delivery of housing such as road connections to the South [1]. Fuel prices are ten times higher than the national average [7]. Technical issues needing more research include ventilated and unventilated roofs in the North [5, 8-11] and appropriate heat recovery ventilators technology [12-16]. Reducing carbon emission is an important priority for northern governments. There lies the potential for renewable energy to offset fossil fuel usages. Northern Canada receives similar solar radiation as communities in the South [17]. However, there is a mismatch between the abundance of solar radiations available in the summer months and little to no solar energy available in the winter months when it is most needed [18]. Builders can achieve significant energy savings for
little added cost by integrating solar design strategies, while the Northern Canadian design process for homes do not consider solar design strategies [19].

The objective of this paper is to investigate the potential of integrating solar design strategies in improving energy efficiency of housing suitable for the Canadian Northern climates through optimizing passive solar design and optimal use of electrical and thermal energy generated by BIPV/T system. A typical home built in Yellowknife is used as reference for the analysis.

2. Methodology

The passive solar design parameters are chosen based on their potential influence on the energy demand through parametric study. A multi-objective optimization is carried out to determine the optimal values of the passive design parameters by considering the initial construction cost and life-cycle energy cost. The optimized energy efficient house is fitted with BIPV/T system. The optimal use of the electrical and thermal energy is investigated by integrating BIPV/T with HRV and ASHP. EnergyPlus is used for the whole building energy simulation and the optimization toolbox in MATLAB is used for the optimization.

![Plan and elevation view of the reference house](image)

**Figure 1.** Plan and elevation view of the reference house.

2.1. Reference house

The reference home is a single-story detached, rectangular shaped house without basement, representing a newly built home in the city of Yellowknife in compliance with the National Building Code of Canada (NBCC) [20]. It has 4 occupants with a total floor area of 130 m² (figure 1). The reference house has a vented attic and a slab on grade. The floor has a 6 mm wood flooring – act as thermal mass and will be varied for the optimization. The ranges of thermal resistance studied for the wall, roof and floor assemblies are listed in table 1. The reference house has 20% window-wall-ratio on its south façade with triple glazed low-E, argon-filled windows. The indoor condition was set at 21°C for the heating season and 26.5°C for the cooling season. There was a night-set back temperature of 18°C between 10 pm and 8 am during the heating season.

2.2. Optimization

A multi-objective optimization considering the initial construction cost and life-cycle energy cost is carried out. The optimization algorithm in MATLAB assembles input parameters and calls for EnergyPlus to model the energy performance of the reference house, and provide optimal solutions after evaluating all the energy performance data according to set criteria. The optimization parameters and
their ranges are listed in Table 1. The objective functions of optimization are the construction cost and operation cost. The construction cost is calculated based on RSmeans Residential Cost Data [21] according to the construction detail set in EnergyPlus and operation cost is based on the energy price from Northwest Territories Power Corporation [22]. A life cycle of 25 years is used. All the operational costs in the future years are converted back to the present value by using an interest rate of 3.5% while the energy price is kept constant [23].

| Parameters                        | Unit       | Range       | Reference Value | Optimal value |
|-----------------------------------|------------|-------------|-----------------|---------------|
| Thermal resistance for walls      | m²·K/W     | 5.6-20      | 4.26            | 8.20          |
| Thermal resistance for ceiling    | m²·K/W     | 8.75-20     | 5.57            | 15.68         |
| Thermal resistance for floor      | m²·K/W     | 7-20        | 6               | 9.90          |
| Thermal mass on floor             | m          | 0.05-0.2    | 0.006 - wood tile | 0.19 - concrete |
| Thermal mass on walls             | layers     | 1-3         | 1 - Gypsum      | 1 - Gypsum    |
| WWR                               | %          | (0,90)      | 20              | 48            |
| Window type                       | ---        | ---         | Triple glazed   | Triple glazed |
| Shading                           | ---        | ---         | None            | Block 90% solar radiation if cooling |
| Ventilation rate                  | ACH        | ---         | 0.3             | 0.3 & change to 2 if cooling |
| Energy demand                     | kWh/m²     | 132.32      | 76.04           |
| Construction cost                 | $          | 70,172.89   | 84,258.35       |

Note: the lower boundary for optimization is refer to the NWT standard [24]

2.3. BIPV/T integration with HVAC systems

The optimized house is used for the BIPV/T integration study. The HVAC system includes an air-source HP for cooling and heating, and when HP cannot provide sufficient heat or HP compressor stops working during the very cold outdoor temperature (below -15°C), furnace would work as a supplemental heating source. Also an economizer is set to fully use the free cooling by increasing the air flow rate of outdoor air when the outdoor air temperature is below 26.5°C during the cooling season, otherwise no fresh air is introduced by HVAC system. The required fresh air of the house to meet the proper indoor air quality requirement is by the HRV system with a constant inlet air flow rate at 0.3 ACH [24].

EnergyPlus, version 8.9.0, provides only a simple BIPV/T model, which needs to connect to the HVAC air loop [25]. Two approaches are used in modeling BIPV/T in this study. A Matlab code using one-dimensional thermal network and finite difference method is developed to model the electrical and thermal energy output and the outlet air temperature of the BIPV/T system. For the case of BIPV/T with HVAC system, the BIPV/T is modeled in EnergyPlus using the electrical and thermal efficiency calculated using the Matlab code. For the case of BIPV/T integrated with HRV and HP outdoor unit, the output air temperature from BIPV/T modeled using Matlab code is applied to the system inlet node. When modeling BIPV/T in Matlab, all the input data, especially the outdoor temperature, the incident solar radiation on south-facing roof, the surface air convection coefficient and attic air temperature, are taken from EnergyPlus output file.
2.3.1 BIPV/T combined with HVAC (Case: BIPV/T + HVAC). The warmed air from BIPV/T is introduced into the conditioned space when it can make a contribution in decreasing the heating load. Under this configuration, a simple BIPV/T model is set up and connected to the HVAC air loop. The controller for Outdoor Air Mixer will adjust the airflow rate from PV section based on the temperature of the mixed air, as the air from the PV section mixed with the return air can increase the mixed air temperature above heating set point (21°C and 18°C as a setback during the night) but not exceed the cooling set point (26.5°C).

2.3.2 BIPV/T combined with HRV (Case: BIPV/T + HRV). The thermal energy from BIPV/T can be used to preheat the incoming air of HRV to reduce its frost risk time, typically when the HRV inlet air temperature is below -5°C. In this case, the BIPV/T is modeled in Matlab and the hourly outlet air temperature is applied to the HRV inlet air node during the heating season to model the situation of connecting BIPV/T with the HRV system to preheat the inlet air during winter.

BIPV/T combined with HP outdoor unit (Case: BIPV/T + HP). The thermal energy from BIPV/T system can also be used to extend the working hours and efficiency of ASHP under cold conditions by introducing the pre-heated air from BIPV/T to outdoor unit of HP. In this case, the BIPV/T is also modeled in Matlab and the hourly outlet air temperature is applied to the HP evaporator (outdoor unit) inlet air node during the heating season to model the situation of connecting BIPV/T with the HP outdoor unit to raise the ambient air temperature of HP outdoor unit during the winter.

3. Results and discussion

3.1 Optimization

Figure 2 shows all the simulated cases in optimization and the cases show on the Pareto front are the optimal results in considering initial construction cost and annual operation cost. The optimized house could save about 43% energy compared with the reference one. If considering a longer life span of the house, the energy saving could be even higher. The optimal values are listed in table 1.

![Figure 2. Pareto front of optimized results.](image)

3.2 BIPV/T integration with HVAC systems

Table 2 shows the results of energy consumption under each BIPV/T integration case. By integrating the BIPV/T with HVAC system, the total energy consumption of the house can be reduced by 9.4%, while the heating energy consumption can be reduced by 40% for HP and 25% for furnace, respectively. By integrating BIPV/T with HRV system, i.e. preheating the inlet air for HRV system, the frost risk time, which the HR inlet air temperature is below -5°C, is reduced by about 10.4% and the defrost time, which is the actual defrost process when HR is frosted, is reduced about 12.3% (table 3). The energy saving for this configuration, however, is only 1.4% (table 2). As shown in table 3, by integrating the BIPV/T with HP outdoor unit, the HP working period during which the air temperature at HP outdoor
unit is above -15°C, is extended by about 182 hours. The actual working time of HP under heating mode is increased by about 36 hours. As shown in figure 3, by integrating BIPV/T with HP outdoor unit, the COP of the HP is increased by a maximum of 44%. Overall the average COP for heating is increased about 1.1%. For the energy consumption, however, the BIPV/T doesn’t provide any energy saving benefit as shown in table 2. The electricity generated by the BIPV/T (cover 99% of south-facing roof area) is estimated at 7999.6 kWh (61.54 kWh/m²) for a whole year, which could potentially cover the energy demand of the house in simulation on an annual basis. To achieve net-zero house, however, needs to consider the mismatch between electricity and thermal generation and the demand through on-site battery and structure storage, sharing among the community or local area, interaction with the grid if available, etc.

### Table 2. Energy consumption in BIPV/T cases.

| Case          | Total kWh/m² | Heating-HP kWh | Furnace kWh | Improvement |
|---------------|--------------|----------------|-------------|-------------|
| HVAC+HRV      | 58.36        | 816.70         | 2933.09     | ---         |
| BIPV/T + HVAC | 52.86        | 489.33         | 2209.82     | 9.4%        |
| BIPV/T + HRV  | 57.53        | 804.06         | 2854.40     | 1.4%        |
| BIPV/T+HP     | 58.51        | 883.54         | 2911.16     | -0.3%       |

* Total consumption contains the consumption of heat pump, furnace, fans, heat recovery ventilator, lighting and appliance.

### Table 3. HRV frost hours & HP working hours.

| Case          | Defrost Time (hr) | Frost risk time (hr) | Hours of Temperature over -15°C at HP outdoor unit | HP heating hours | Average COP |
|---------------|-------------------|----------------------|---------------------------------------------------|-----------------|-------------|
| HVAC+HRV      | 696.64            | 3938                 | 6013                                              | 891             | 1.91        |
| BIPV/T + HRV  | 611.07            | 3527                 | ---                                               | ---             | ---         |
| BIPV/T+HP     | ---               | ---                  | 6195                                              | 927             | 1.93        |

![Figure 3. HP annual COP](image)

### 4. Conclusion

By optimizing these major passive design parameters, the energy demand of a typical house in Yellowknife can be reduced by 43% from 132.32 kWh/m² to 76.04 kWh/m². Based on this optimized house, the integration of BIPV/T with HVAC system can reduce the total energy consumption by about 9.4%. Also the combination of BIPV/T with HRV could reduce 10.4% of the frost risk time and 12.3% of the actual defrost cycle. Combine the BIPV/T to the HP outdoor unit do have some benefits in bring up HP efficiency in extend 182 hours of its working period and increase the actual COP by 1.1%. The electricity generated by the BIPV/T is 7999.6 kWh (61.54 kWh/m²) for a whole year, which could meet the requirements of the house energy consumption in simulation on an annual basis.
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