# RESIDENTIAL PASSIVE SOLAR DESIGN FOR CANADIAN CITIES: ASSESSING THE POTENTIAL

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## 1. Introduction

In Canada, space heating accounts for over 60% of residential energy consumption (NRCan, 2010). It has been suggested that one of the most effective means to reduce space-heating requirements in Canada is passive solar design design, when used in conjunction with insulation levels equivalent to the requirements of Canada's R-2000 standard (Athienitis, 2007). The Canadian Mortgage and Housing Corporation (CMHC) (1998) has suggested that savings of 30 to 50% are achievable in Canadian climates using passive solar design design. Canada's potential to reduce fossil fuel consumption and associated GHG emissions, with passive solar design design, ranks high relative to other countries, due to its predominantly cold and sunny climate (CMHC, 1998). Most of the research on passive solar design in North America was conducted in mid 1970's to mid 1980's (for overviews refer to: Barakat, 1982 (Canada NRC); Balcomb, 1992 (US DOE)). Research in the US showed that large energy savings could be achieved with little or no additional capital cost (Balcomb, 1992). However, only a few studies have quantified this potential in Canada (eg. Energy, Mines and Resources Canada, 1984). O'Brien et al. (2008) state that most passive solar design literature for cold climates is out of date, as much of the research was carried out several decades ago. They point out that most of the analysis was limited to statistically-based calculations, rather than hourly or sub hourly time step based computation that is common now. Given this, there is a need to produce current, accurate estimates of the potential energy savings for passive solar design. Understanding the potential of passive solar design has significance to policy and planning decisions for cities, regarding density and shading. Also, having typical values for energy savings from passive solar design will useful for informing house designers, and programs which support the adoption of low energy buildings. The purpose of the study is to evaluate the technical potential of passive solar design as a means to save energy in the residential sector, and to produce accurate estimates of typical passive solar design energy savings for a common new home, throughout a range of Canadian climates with major population centers.

## 2. Methodology

### *2.1 Objective & Scope*

Vancouver, Edmonton, Winnipeg, Toronto, Ottawa and Halifax were selected for modelling, as each of these cities represents a unique climate and a significant population centre. Prince George and Yellowknife were selected to assess the potential of passive solar design in Canada's northern cities; although these cities have much smaller populations. The study focused on single-family dwellings, as they are the most common dwelling type in Canada (NRCan, 2010). The direct gain approach was chosen for the analysis. Direct gain is reported to be the simplest and most-cost effective passive solar design strategy (CMHC, 1998). An analysis of a monitoring project of 48 passive solar design buildings in the US by Balcomb (1983), found that energy savings between different passive solar design approaches (eg. direct gain, sunspaces, etc) were very similar, in all cases where the passive solar design buildings were designed properly. The analysis in this study is limited to space heating energy consumption. Overheating issues are not considered because south-facing windows can be shaded during the summer with overhangs or shading devices (CCHT 1998). Furthermore, space cooling represents only 1.6% of residential energy consumption in Canada (based on 2008 data, from NRCan, 2010).

### *2.2 Reference Case*

The analysis was based on the Twin Houses at the Canadian Centre for Housing Technology (CCHT) site, which are architecturally representative of typical tract-built houses in Canada (CCHT, 2010). One of the Twin Houses, referred to as the Reference House, remains unchanged and is used as a baseline for experiments carried out in the other house. The Twin Houses are built to the R-2000 construction standard, a voluntary performance standard that requires approximately 30% less energy than a conventional new home in Canada (NRCan, 2009). The CCHT Reference House has insulation levels slightly higher than most provincial building codes. In addition, the building has a high air tightness rating (1.5 ACH@50) and uses a heat recovery ventilator. In order to ensure the houses are as identical as possible, the houses include simulated occupants. A building automation system turns on and off appliances, hot water fixtures and lights according to a schedule, which represents a typical family of four. Light bulbs are used to simulate the heat released from occupants. The automated internal gains were based on a target electricity consumption of 20 kWh/day, which is a generally accepted value for modelling (Swinton et al., 2001). The detailed schedule of the internal gains can be found in Swinton et al., 2001. For this study, a detailed model of the CCHT Reference House was created and used as a reference case for passive solar design options considered. This model was based on the "As Built" plans for the CCHT Twin Houses, and information provided by the CCHT (M. Armstrong, personal communication). Important features of the CCHT houses are summarized below in Table 1.

**Table 1: Key Features of the CCHT Houses**

| Feature | Value |
|---|---|
| Floor Area (Living Space) | 210 $m^2$ |
| Total Window Area | 35 $m^2$ |
| South Facing Window Area | 16.2 $m^2$ |
| Window Type | double glazed, low-e, argon filled, insulated spacer |
| Window Properties (average) | SHGC = 0.52, U = 1.76 $W/m^2K$ |
| Attic R Insulation R Value | 8.6 $W/m^2K$ |
| Above Grade Wall Insulation R Value | 2.84 $W/m^2K$ (with thermal bridging) |
| Basement Interior Insulation R Value | 1.86 $W/m^2K$ (with thermal bridging) |
| Basement Slab | 75 mm concrete, un-insulated |
| Air tightness rating (at 50 Pa) | 1.5 ACH |
| Gas Furnace Efficiency | 80.2% |
| Heat Recovery Ventilator Efficiency | 84% |
| Internal Gains | 19.35 kWh/day |

The architecture of the CCHT houses is shown below in Figure 1. It includes a double car garage, and a habitable basement. The design includes many jogs and a complex roofline – features that are common in new construction in North America, but not ideal for low energy design. Minor geometric simplifications were made to reduce the number of surfaces modelled without reducing the building's surface area, such as shifting inset wall elements outwards to combine with the surrounding walls.

**Figure 1: Geometry Output of CCHT House as Modelled – Isometric View from South East**

A reference case space heating gas consumption value for each location was determined and used as a baseline to compare the passive solar design savings to. The reference case chosen was the CCHT Reference House, with complete shading on the southern aspect – this scenario allowed for the energy savings due to southern exposure to be quantified. Quantifying the passive solar design energy savings relative to this baseline is similar to that used for the solar heating fraction (SHF). The solar heating fraction, for a passive solar design building, is the fraction of the heating energy, which is supplied by solar gain through the glazing (Jones, 1992). The SHF can also be conceptualized as the savings relative to a scenario where all of the building's glazing is shaded. The authors felt that only including southern shading would serve as a more realistic baseline than that used for the SHF, as the reference case chosen represents a possible scenario where the house is shaded by nearby buildings, forest or hills. It is also similar to a scenario where the building is not oriented towards the south.

Based on the calibrated model, described in the subsequent sections, the CCHT Reference House has a space heating demand of approximately 65.2 GJ/yr (86.2 kwh/m$^2$) which is approximately half of the average Canadian space heating consumption of 136.5 GJ/yr (161.0 kwh/m$^2$) for single family dwellings (2008 data from NRCan, 2010).

### 2.3 Modelling

EnergyPlus, the US Department of Energy's dynamic building energy simulation software, was used to model the energy savings. EnergyPlus is one of the most advance building energy simulation programs, and contains detailed models of solar gains and transient heat flow (DOE, 2010), which are essential to capturing the behavior of passive solar design buildings.

Two main assumptions regarding windows were made:

1. Average values for the windows overall heat transfer coefficients (U values) and solar heat gain coefficients (SHGC) were used rather than the actual individual values for each window (which were unavailable for reference case), for the simulated passive solar design cases with "best glass" the U and SHGCs for a low profile fixed window (Serious 925 9H from Serious Windows) for the NFRC standard size.

2. The Simple Window Model in EnergyPlus was used – this model estimates a set of angular properties based on the SHGC and U value and creates an equivalent single layer window (DOE, 2010).

Thermal bridging through the wall studs was accounted for by calculating a one dimensional area-weighted equivalent thermal resistance (R value) by combining the thermal resistance of the studs with the insulation in parallel according to the formula: 1/Rtotal = 1/Rstud + 1/Rinsulation.

The distribution of solar radiation was modelling using the FullExterior model in EnergyPlus. In all EnergyPlus solar distribution models, direct beam solar radiation is assumed to fall on the floor only, where a fraction of it is absorbed by the floor (according to the solar absortance of the floor), and the remaining fraction is added to the diffuse radiation. The FullExterior model distributes all of the diffuse radiation evenly among all interior surfaces (DOE, 2010). This is a reasonable approximation, as houses typically have light coloured walls and ceilings, which distribute solar gain more evenly amongst surfaces (Johnson, 1992). All interior partition walls were accounted for using the InternalMass object in EnergyPlus. InternalMass assemblies (in this case interior walls and floors) receive an even share of the diffuse radiation.

During initial modelling it was found that ground temperature assumptions have a large influence on energy consumption, this has also been observed by Purdy and Beausoleil-Morrison (2001). Because of this, and the significant variability in ground temperatures across Canadian climates, the EnergyPlus Basement auxiliary program was used to calculate 3D ground contact heat transfer. The default soil conditions were used for all locations.

With exception to the calibration case, explained in section 2.3, all simulations were carried out using Canadian Weather for Energy Calculations (CWEC) weather data, which is based on data from 1953 – 1935 and represents a "typical" weather year (Numerical Logics, 1999).

### *2.3 Model Calibration*

The literature on calibrating building simulations to match measured data, focuses on the commercial sector (for a review refer to Reddy, 2006). Calibration of commercial building models often involves "fine tuning" the parameters which have a high level of uncertainty, until a sufficient match is achieved between recorded and simulated energy consumption. As the CCHT houses undergo extensive research, adequate data was available to define all major modelling parameters, thus the typical "tuning" stage of calibration was not required. Calibration consisted of systematically identifying and fixing errors in the model, and verifying the output results.

The reference case model was calibrated using measured daily gas consumption data from the CCHT Reference House for the 2002/2003 heating season, and a validated weather file from Weather Analytics, which is based on real data from nearby weather stations and climate model data (Keller and Khuen, 2011). The first step in calibration was to reduce the uncertainty of ground heat transfer. Because of the significant effect of ground heat transfer, the model was first calibrated with onsite ground temperature data. Armstrong et al. (2011) recorded seven years of temperature data for the exterior of the foundation wall for the CCHT Reference House, at five depths. These values were averaged to produce monthly values, which were used for the building surface ground temperature input in EnergyPlus. The heat transfer from the foundation walls was modelled using these temperatures, and the basement floor was assumed to be adiabatic due to its depth below the surface and the much longer heat transfer path. After this step, each major component of the model was reviewed, and various simulation outputs (such as mass flow rates, basement temperature set point, heat transfer through windows, walls etc) were examined. This allowed for the detection of several minor errors and fine adjustments required. For example, the ducts were resized based on trial and error to ensure the basement temperature matched with recorded data from (Armstrong et al., 2011); this reduced the energy consumption by 7%. After a good match was achieved with the measured gas consumption, the EnergyPlus's Basement auxiliary program was added – as it is required for the other locations examined. A good match was achieved with Basement coupled to EnergyPlus, after a few data entry errors were detected and eliminated.

After calibration, annual gas consumption matched within 0.6% of measured data, with a coefficient of variation of the root mean square error (CV RSME) of 23% and a normalized mean bias error (NMBE) of -0.58%. ASHRAE Guideline 14 (2002) stipulates that in order to declare a model calibrated, the CV RSME should be within +/- 30% using hourly data, or +/- 15% using monthly data and that the NMBE should be within +/-10% (hourly) or +/-5% (monthly). However, ASHRAE does not provide guidance on calibrating with daily values.

### *2.4 Passive solar design Measures Evaluated*

Four levels of passive solar design were considered, as outlined below:

1. *Sun Tempered* – the house is oriented such that the aspect of the house with the largest area of glazing faces south, and the other design variables remain unchanged.

2. *High Mass, High South Facing Window to Wall Ratio (WWR)* – south facing windows are large, and the building contains high thermal mass, modelled as 100mm concrete floors and partition walls. In this case the south facing window area is doubled, achieved a south glazing to floor area ratio of 30%.

3. *Best Glass* – the effect of high performance glazing was assessed. The glazing used for this scenario has a U value of 0.68 W/m$^2$K and a SHGC of 0.41. These specifications are based on Serious Windows' 925 H, which was the highest performing window in North America that could be found at the time of this study.

4. *Best Glass, High Mass*, *High South Facing Window to Wall Ratio (WWR)* – this combination was used to assess the combined potential of typical passive solar design and high performance glazing.

## 3. Results

In all scenarios and cities the south facing windows had a net energy gain over the heating season. Key results are summarized below in Table 1, which provides the energy savings relative to the reference case, where the south aspect of the house is shaded. These values are similar to the solar heating fraction achieved.

**Table 2: Summary of Passive Solar Design Energy Savings**

| Scenario | Average | Min | Max |
|---|---|---|---|
| Sun Tempered | 18.1% | 13.1% | 20.7% |
| High Mass, High WWR | 25.0% | 14.2% | 30.0% |
| Best Glass | 33.9% | 28.8% | 36.7% |
| Best Glass, High Mass, High WWR | 43.4% | 34.3% | 47.8% |

Figure 2, below, shows the detailed simulated space heating energy consumption for each city considered. The locations are arranged in order of increasing heating degree days (HDD).

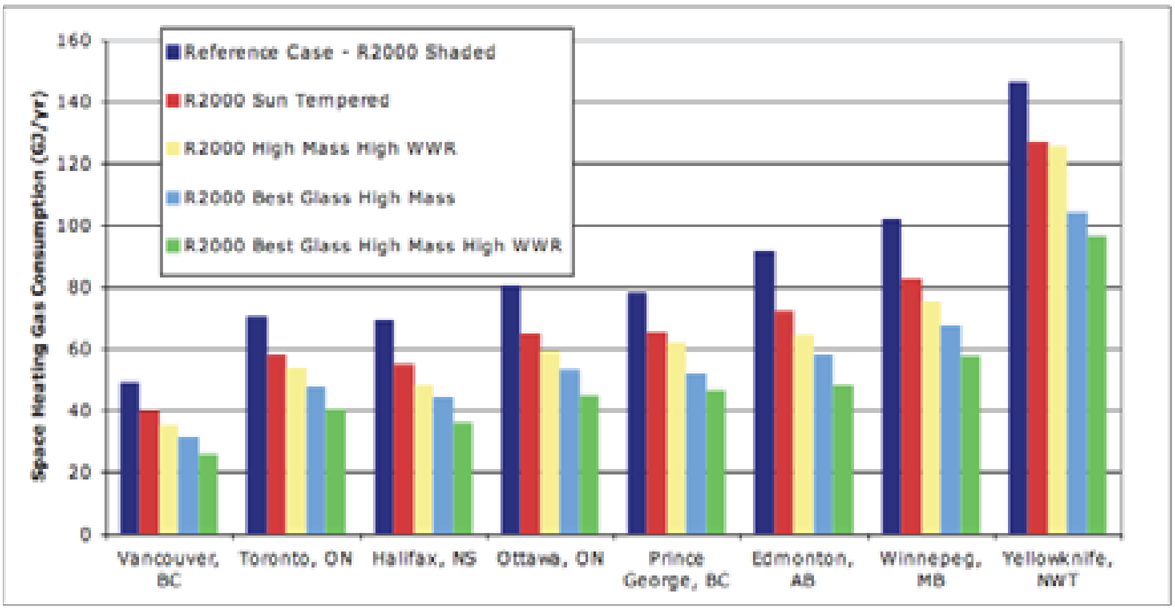

**Figure 2: Simulation Results for Space Heating Energy Consumption**

These results are also presented in Appendix A, which includes heating degree days (HDD) and latitude for each location. The solar heating fraction for the Sun Tempered; High Mass, High WWR; and the Best Glass, High Mass, High WWR cases are shown below in Figure 3 and in Appendix A.

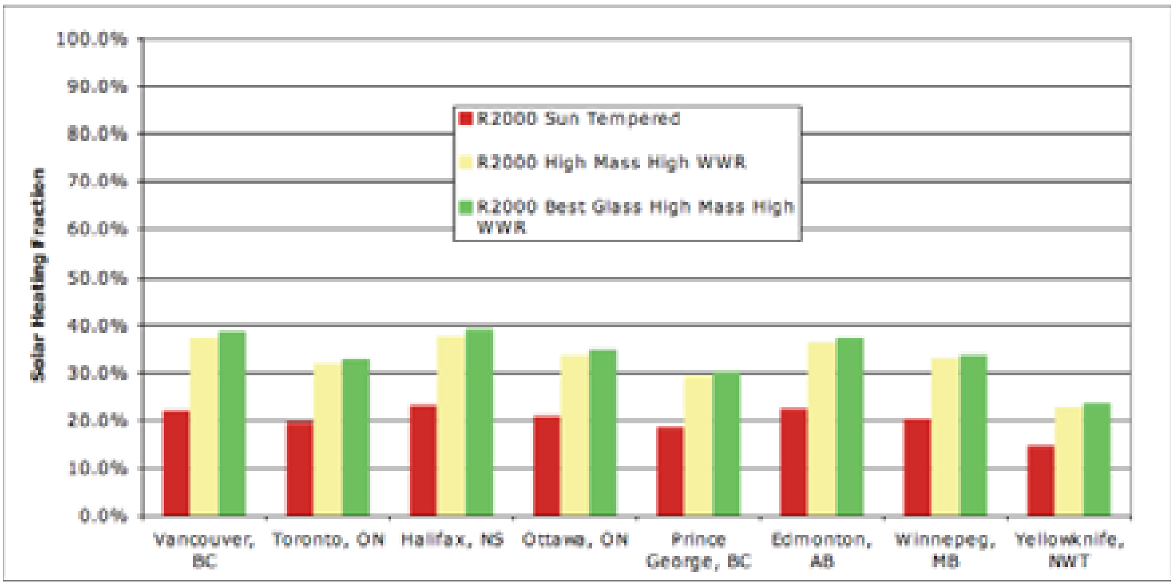

**Figure 3: Solar Heating Fraction by Location**

A sensitivity analysis was carried out for Ottawa. The following observations were made:

- Savings are not highly influenced by thermal mass (5% reduction in savings for the best glass high mass high WWR case when the additional mass is not included)
- Window to Wall Ratio has a considerable effect on savings; in all cases it was found that maximizing south facing window area, maximizes space heating energy savings.
- The glazing properties have a large effect on energy savings, for the reference case upgrading the windows to the best available can result in larger energy savings than increasing the window to wall ratio.
- Solar gains on the non-south aspects of the CCHT Reference house are very small (2 GJ or 2% contribution to space heating)

## 4. Discussion

The results indicate that even without any major passive solar design measures, solar gains contribute a considerable fraction of a typical home's heating requirements in cold climates such as Canada. This highlights the importance of solar access for buildings in heating dominated climates. The results from this study could be used to support policies that encourage passive solar design, and policies such as the Right to Light law in the UK, which protects the solar exposure of existing buildings (Waltham Forest Council, 2011).

The highest solar heating fraction achieved is in Halifax, NS. This can be explained by the high ratio of solar gain to envelope losses (CMHC, 1998). Yellowknife achieves the highest absolute energy savings from passive solar design (High Mass High WWR Case), which can be explained by the very high energy consumption of the reference case in Yellowknife. It should also be noted that the smallest solar heating fraction is achieved in Yellowknife. The solar heating fraction values for the High Mass, High WWR and the Best Glass, High Mass, High WWR cases are very similar, although in each case a slightly higher SHF is achieved with the Best Glass. This can be explained by the lower envelope losses.

The results for solar heating fraction are fairly consistent with other studies. For example, Balcomb (1983) carried out a computer analysis of monitored data from 48 passive solar design houses across the US. Balcomb found an average passive solar design contribution of 37% to the total space heating load. The slightly higher solar heating fraction observed by Balcomb (1983) can likely be attributed to the lower heating demand due to the warmer climate of the US.

Although the design of the CCHT Twin Houses employ basic passive solar design strategies (south orientation, higher glazing area on the south aspect), these houses have not been optimized for passive solar design collection as they are intended to represent typical North American tract-built housing. For example, optimal aspect ratios (south wall length / depth) should be between 1.2 to 1.3 (Athienitis, 2007). It is likely that designs that are optimized for passive solar design collection would achieve higher solar heating fractions. This is evidenced by the solar heating fractions of 0.34 to 0.53 observed by Barakat (1984) for simple one-zone test units, with only south facing glazing. A more recent example, the Alstonvale Net Zero Energy House (NZEH), near Montreal (Canada), achieves a solar heating fraction of approximately 60% (Candanedo and Athienitis, 2009). The high solar heating fraction can also be attributed to the higher level of thermal performance. The Alstonvale NZEH has much higher thermal resistance values than the CCHT Twin houses, with R values of 5.6, 12, 4.6 $m^2K/W$ in the walls, roof and floor, respectively (Candanedo et al., n.d.).

## 5. Conclusion

Estimates of the potential energy savings from passive solar design in Canada were produced, based on a calibrated EnergyPlus model of the CCHT Reference House, a representative sample of new North American single-family dwellings. The results show that considerable energy savings can be achieved by applying basic passive solar design to typical new single-family dwellings in locations throughout Canada, including the far north. By providing full solar access to a home such as the CCHT house, a reduction in space heating of up to 21% can be achieved. Basic passive solar design measures, such as doubling the south facing window area and adding thermal mass can result in savings up to 30%, relative to a shaded case, can be achieved. When these measures are combined with available high performance glazing, savings are up to 48%. The results indicate that the highest energy savings are achieved in the coldest climates, where space heating energy consumption is the highest and that the highest solar heating fractions occur in areas where solar radiation is high relative to envelope losses. It is expected that even larger savings could be achieved if the architecture is optimized for passive solar design collection. Future work is required to quantify the potential for passive solar design applied to more advanced houses. These results may also be useful for planning decisions regarding density. Although the scope of this study is limited to single family dwellings, it is expected that similar savings could be achieved for other building types with comparable thermal performance.

## 6. Acknowledgements

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## 8. Appendix: Detailed Results

**Table 3: Detailed Simulation Results**

| **Location** | **Scenario** | **Heating Energy Consumption (GJ)** | **Energy Savings (GJ)** | **% Reduction from Reference** |
|---|---|---|---|---|
| Toronto, ON<br>43.7°N<br>3570 HDD | Shaded (Reference) | 70.8 | | |
| | Sun Tempered | 58.5 | 12.3 | 17.4% |
| | High Mass, High WWR | 53.8 | 17 | 24.0% |
| | Best Glass, High Mass | 47.6 | 23.2 | 32.8% |
| | Best Glass, High Mass, High WWR | 40.8 | 30 | 42.4% |
| Halifax, NS<br>44.9°N<br>4370 HDD | Shaded (Reference) | 69.3 | | |
| | Sun Tempered | 55.1 | 14.2 | 20.5% |
| | High Mass, High WWR | 48.4 | 20.9 | 30.2% |
| | Best Glass, High Mass | 44.5 | 24.8 | 35.8% |
| | Best Glass, High Mass, High WWR | 36.2 | 33.1 | 47.8% |
| Ottawa, ON<br>45.4°N<br>4520 HDD | Shaded (Reference) | 80.7 | | |
| | Sun Tempered | 65.2 | 15.5 | 19.2% |
| | High Mass, High WWR | 59.2 | 21.5 | 26.6% |
| | Best Glass, High Mass | 53.2 | 27.5 | 34.1% |
| | Best Glass, High Mass, High WWR | 44.9 | 35.8 | 44.4% |
| Vancouver, BC<br>49.3°N<br>2630 HDD | Shaded (Reference) | 49.6 | | |
| | Sun Tempered | 40.1 | 9.5 | 19.2% |
| | High Mass, High WWR | 35.5 | 14.1 | 28.4% |
| | Best Glass, High Mass | 31.4 | 18.2 | 36.7% |
| | Best Glass, High Mass, High WWR | 26.2 | 23.4 | 47.2% |
| Winnipeg, MB<br>49.9°N<br>5780 HDD | Shaded (Reference) | 102 | | |
| | Sun Tempered | 83 | 19 | 18.6% |
| | High Mass, High WWR | 75.7 | 26.3 | 25.8% |
| | Best Glass, High Mass | 67.9 | 34.1 | 33.4% |
| | Best Glass, High Mass, High WWR | 57.8 | 44.2 | 43.3% |
| Edmonton, AB<br>53.3°N<br>5700 HDD | Shaded (Reference) | 91.4 | | |
| | Sun Tempered | 72.5 | 18.9 | 20.7% |
| | High Mass, High WWR | 64.7 | 26.7 | 29.2% |
| | Best Glass, High Mass | 58.2 | 33.2 | 36.3% |
| | Best Glass, High Mass, High WWR | 48.6 | 42.8 | 46.8% |
| Prince George, BC<br>53.9°N<br>5130 HDD | Shaded (Reference) | 78.6 | | |
| | Sun Tempered | 65.6 | 13 | 16.5% |
| | High Mass, High WWR | 62 | 16.6 | 21.1% |
| | Best Glass, High Mass | 52.4 | 26.2 | 33.3% |
| | Best Glass, High Mass, High WWR | 46.5 | 32.1 | 40.8% |
| Yellowknife, NWT<br>62.5°N<br>8260 HDD | Shaded (Reference) | 146.7 | | |
| | Sun Tempered | 127.5 | 19.2 | 13.1% |
| | High Mass, High WWR | 125.8 | 20.9 | 14.2% |
| | Best Glass, High Mass | 104.5 | 42.2 | 28.8% |
| | Best Glass, High Mass, High WWR | 96.4 | 50.3 | 34.3% |

**Table 4: Solar Heating Fractions**

| Location | Scenario | Solar Heating Fraction |
|---|---|---|
| Vancouver, BC | Sun Tempered | 22.0% |
| | High Mass, High WWR | 37.4% |
| | Best Glass, High Mass, High WWR | 38.9% |
| Toronto, ON | Sun Tempered | 19.4% |
| | High Mass, High WWR | 31.9% |
| | Best Glass, High Mass, High WWR | 32.8% |
| Halifax, NS | Sun Tempered | 23.0% |
| | High Mass, High WWR | 37.9% |
| | Best Glass, High Mass, High WWR | 39.1% |
| Ottawa, ON | Sun Tempered | 21.1% |
| | High Mass, High WWR | 33.9% |
| | Best Glass, High Mass, High WWR | 34.9% |
| Prince George, BC | Sun Tempered | 18.6% |
| | High Mass, High WWR | 29.5% |
| | Best Glass, High Mass, High WWR | 30.4% |
| Edmonton, AB | Sun Tempered | 22.5% |
| | High Mass, High WWR | 36.2% |
| | Best Glass, High Mass, High WWR | 37.5% |
| Winnipeg, MB | Sun Tempered | 20.3% |
| | High Mass, High WWR | 32.9% |
| | Best Glass, High Mass, High WWR | 33.9% |
| Yellowknife, NWT | Sun Tempered | 14.5% |
| | High Mass, High WWR | 22.9% |
| | Best Glass, High Mass, High WWR | 23.5% |