Feasible Upper Boundaries of Passive Solar Space Heating Fraction Potentials by Climate Zone

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Abstract

Advances in energy modeling tools and techniques have caused passive solar design guidelines from a previous generation to be superceded by simulation. The ability to model building energy behaviour, heat transfer between multiple zones within a dwelling, and consider the effects of thermal mass and/or phase change materials, along with a variety of shading devices, has shed new light on passive solar energy utilization for space heating. In particular, the ability to accurately model the thermal and optical responses of high performance window technologies has uncovered new possibilities for solar apertures and feasible boundaries of passive solar space heating fraction potentials.

This paper presents a methodology for assessing the feasible upper solar energy utilization boundary for the passive heating of houses, not as a replacement for simulation, but as a helpful guideline to designers, energy code authorities and utilities. For a particular climate zone and building geometry, the methodology can be employed to derive a range of building enclosure characteristics including: opaque component U-values; window and glazing U-values / solar heat gain coefficients, south-facing window-to-wall ratios, thermal mass levels, solar heat gain distribution rates and shading device placement and operating schedules.

It can also inform decision makers involved in housing energy policy, the planning of subdivisions for new communities, and the design of housing typologies. By being able to determine the feasible upper boundary of passive solar space heating potential, the relative utilization of solar energy resources can be assessed for proposed policies, planning guidelines and house designs. This will hopefully promote informed decision making about solar buildings.

Unlike methodologies that involve the optimization of multiple parameters, this paper examines a methodology aimed at establishing feasible upper boundaries for a single parameter - passive solar heating potential - informed, but not constrained, by thermal comfort considerations. This methodology contributes to the design of net-zero energy homes by minimizing the space heating energy use, thereby minimizing the need for supplemental renewable energy sources. It may also contribute to the passive survivability of dwellings.

1 Introduction

Direct gain, passive solar heating of houses is a recognized strategy for cost effectively reducing space heating energy use in houses, and often reducing greenhouse gas emissions. In the conventional housing development context, the planning of subdivisions for optimal solar access is seldom considered, and house designs typically reflect normative conventions corresponding to the architectural vernacular of the marketplace. This paper investigates a methodology for determining the feasible upper boundaries for passive solar heating of houses assuming an ideal solar orientation and variable south-facing window-to-wall ratio. While it is recognized this condition may not be fully achievable in mass market housing, it does afford a means of estimating the level of passive solar heating utilization that may be achieved if the design of housing and subdivision layouts privileged solar energy utilization. It also provides a benchmark against which to assess passive solar utilization in proposed housing projects.

In the past, research into the passive solar performance of housing was conducted in the absence of sophisticated computer simulation tools. Since then, it has been discovered many of the design guidelines derived from the previous generation of research were based on inaccurate and limited energy simulation models. Further, most of the past research was unable to consider the influence of high performance window technology on passive solar heating because low-emissivity films, inert gas fills and low conductivity edge spacers had not been developed. In the absence of robust energy performance modelling software and advanced fenestration technologies (controls), the feasible upper boundaries of passive solar heating potentials were not accurately estimated. Issues related to passive solar energy utilization were often confused by economic optimization objectives. Cost effectiveness models used to generate passive solar potentials typically lacked consideration of externalities and especially greenhouse gas emissions, and did not account for infrastructure system effects, such as reductions in peak energy demand. Intangibles, such as passive survivability and health benefits associated with inhabitant exposure to sunlight, were not evaluated. In summary, up until very recently, the assessment of passive solar heating performance was an incomplete, often incorrect, and highly inconsistent methodology.

This paper does not intend to address all of the limitations identified above. Instead, it seeks to begin a process of addressing passive solar heating performance parameters individually and specifically. This paper proposes a methodology that can provide meaningful answers to the following question:

- What is the feasible upper boundary of passive solar energy utilization for space heating in a house?

It is important to qualify the meaning of feasible upper boundary. In this paper, the annual space heating energy demand[1] is the means of measuring the effectiveness of direct gain, passive solar space heating strategies. Feasibility is determined by taking into account thermal and visual comfort, such that the maximum solar contribution to the reduction of annual space heating energy demand may be acceptably achieved in a particular climatic location. This approach deliberately avoids the architectural style and layout of dwellings, a variable which is determined by personal and cultural preferences influenced by market forces. But it does examine collateral effects such as the need for space cooling energy to offset overheating. Put simply, the focus is on space conditioning energy demand within acceptable levels of inhabitant comfort.

[1] Energy demand is to be differentiated from energy consumption as follows: energy consumption = energy demand/conversion efficiency.

2 General Methodology

The approach taken to energy modeling was to use a base case house and to vary its physical characteristics over a range of values and across a number of climate zones in order to assess the contribution to space heating made by passive solar gains. The corresponding comfort conditions were also estimated in terms of peak temperatures and the number of hours above 25 ^{o}C.

All energy simulation modelling was performed with a base case, square two-storey 300 m^2 (including heated basement) wood-frame house model (see Figure 1) with its physical characteristics input to EnergyPlus software.[2] Aspect ratios for the base case house were not varied since previous research indicated that over a typical range of aspect ratios for houses with highly efficient thermal enclosures, the influence of aspect ratio on passive solar heating contributions was marginal. The focus of the research supporting this paper was to advance a methodology for determining the feasible upper boundaries of solar heating fraction potentials in various climate zones, and interested readers could examine various housing typologies to establish boundaries accordingly.

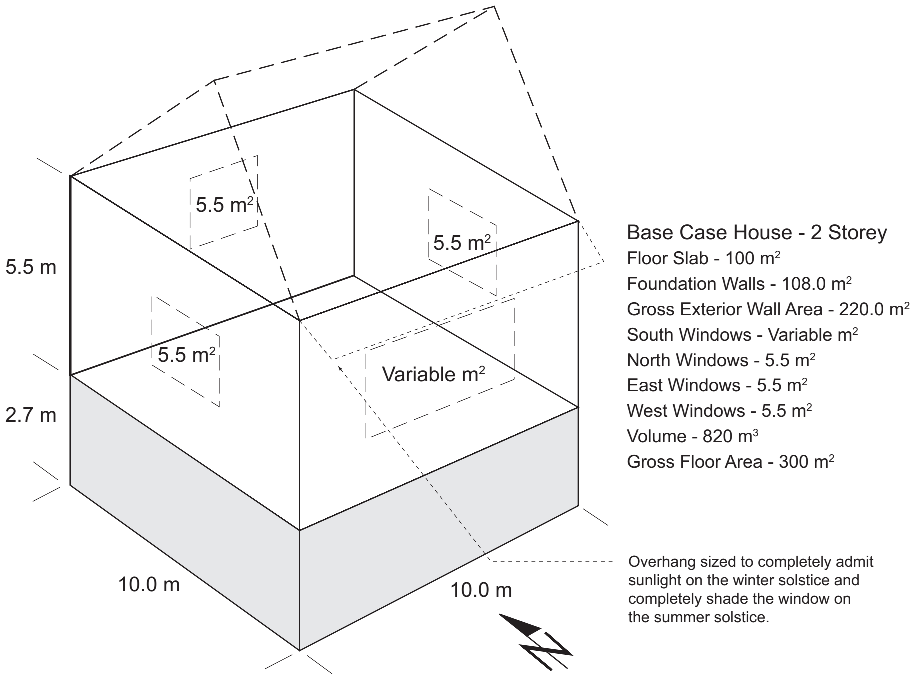

Figure 1. Physical characteristics of the base case house model.

The house energy model was created using EnergyPlus V7.2. The Crank-Nicholson semi-implicit conduction finite difference algorithm, a numerical solution to the one-dimensional Fourier conductive heat transfer equation, was used. Conduction finite difference methods are developed at length by Clarke (2001) and their implementation in EnergyPlus V7.2 is explained in its Engineering Reference (EnergyPlus 2013). A MATLAB (Mathworks Inc. 2013) program was written to create EnergyPlus input files, run the simulations, and analyze the results. Energy modelling was conducted using an approach consistent with the prominent simulation tools (e.g., HEED, HOT2000, and BEopt), except that special attention was paid to ensure that the potential for localized overheating was accurately modeled. Unlike most house energy models that are represented as a single thermal zone, the current model has three zones: a south zone, north zone, and basement zone (see Figure 2). As explained by O'Brien et. al (2011), models with a single fully-mixed zone that simulate the behaviour of

[2] EnergyPlus Version 8.1.0. U.S. Department of Energy, December 31, 2013.

passive solar houses tend to be optimistic in both their predictions of energy performance and thermal comfort because they assume air is perfectly mixed and the solar gains are evenly distributed throughout the house. However, in a typical direct gain passive solar house, the solar gains are mostly admitted into the direct gain zone. The typical representation using a single zone can fail to characterize this phenomenon. While some small, open-concept homes may be properly represented by a single zone, larger homes with fewer openings between rooms or doors which may be closed, should be represented by the more conservative, multi-zone approach.

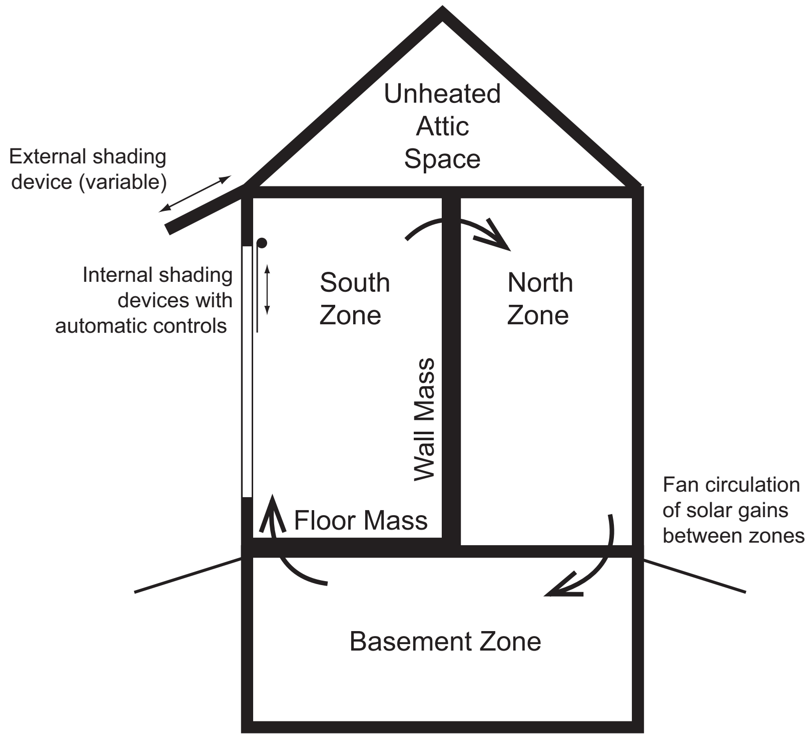

Figure 2. Key characteristics of EnergyPlus energy simulation model.

The occupants are assumed to tolerate operative temperatures between 20 °C and 27 °C. The setpoints are assigned accordingly, though this does not prevent discomfort because only the dry bulb air temperature is controlled; not the operative temperature. The house is assumed to have a typical internal gains level of 850 W, and infiltration is based on an enclosure airtightness of 1.0 air changes per hour at 50 Pa. Mechanical ventilation at a rate of 8 L/s per person is supplied continuously and a heat recovery of efficiency of 60% was assumed.

A total of 4 locations (Chicago, Toronto, Calgary and Yellowknife) corresponding to 4 space heating dominated climate zones as per climatic data set out in acknowledged technical standards (ASHRAE 2007) were investigated. The building enclosure thermal mass levels, opaque component effective thermal resistance values and window effective, overall U-values and solar heat gain coefficients were established based on minimum requirements and these were then varied to achieve higher levels of thermal performance until no significant reductions in annual space heating energy demand were evidenced. The relevant data associated with the variations of base case houses that provided the most effective passive solar heating performance are summarized in Table 1.

Table 1. Building enclosure characteristics corresponding to house variations exhibiting feasible upper boundary passive solar space heating potentials.

ASHRAE 90.2 Climate Zone	Zone 5	Zone 6	Zone 7	Zone 8
City	Chicago	Toronto	Calgary	Yellowknife
Ceiling - RSI (R-value)	11.36 (64.5)	12.94 (73.50)	12.94 (73.50)	13.74 (78.00)
Exterior Walls - RSI (R-value)	7.04 (40.0)	7.04 (40.0)	7.04 (40.0)	7.04 (40.0)
Exposed Floors - RSI (R-value)	6.60 (37.5)	6.60 (37.5)	10.04 (57.00)	10.04 (57.00)
Windows - USI (U-value)	1.13 (.20)	1.13 (.20)	1.13 (.20)	1.13 (.20)
SHGC	0.636	0.636	0.636	0.636
South Facing WWR	0.9	0.9	0.9	0.9
Basement Walls - RSI (R-value)	1.43 (8.10)	2.14 (12.15)	2.85 (16.20)	2.85 (16.20)
Basement Slab - RSI (R-value)	0.88 (5.00)	0.88 (5.00)	0.88 (5.00)	0.88 (5.00)
Thermal Mass (South Zone Floor)	0.1 m concrete	0.1 m concrete	0.1 m concrete	0.1 m concrete

In performing the associated analyses, it was necessary to determine how to appropriately express the solar heating fraction for the base case house variations. There are two established methods for calculation of the solar heating fraction, the first developed by Balcomb (1982) and the second by Duffie and Beckman (2006). These are presented in Figure 3.

Balcomb

$$SHF = \frac{Q_{no\ sun} - Q_{sun}}{Q_{no\ sun}}$$

where:

SHF = solar heating fraction
$Q_{no\ sun}$ = space heating load with windows but no solar gains
Q_{sun} = space heating load with windows admitting solar gains

Duffie and Beckman

$$\mathcal{F}_c = \frac{L_s}{L_o} = \frac{Q_{no\ windows} - Q_{sun}}{Q_{no\ windows}}$$

where:

$\mathcal{F}_c$ = solar fraction
L_s = solar energy supplied
L_o = non-solar building space heating load
$Q_{no\ windows}$ = space heating load with no windows
Q_{sun} = space heating load with windows admitting solar gains

Figure 3. Equations for determining fraction of annual space heating energy demand satisfied by passive solar gains.

Both fractions were calculated in the course of performing the analyses, but it should be noted that in space heating dominated climates, and especially with contemporary minimum requirements for the thermal efficiency of opaque enclosure components, the Balcomb measure will always tend to yield a higher value than the Duffie and Beckman solar fraction. The Balcomb method is advocated in this paper because in reality, housing codes and standards require a minimum amount of fenestration for natural ventilation and emergency egress, and the reference level (denominator) for space heating load should consider these requirements. By switching the sun off and on in an energy model, the true contribution of solar energy gains for space heating may be determined. It is also worth noting that the Balcomb method of calculating the solar heating fraction is the most widely acknowledged in the passive solar energy literature.

3 Analysis of Results

The results obtained from energy simulations were analyzed and summarized in Table 2. It is important to note once the feasible upper boundary candidate variations were identified, additional sensitivity analyses were conducted and the results reported accordingly.

The first set of additional energy simulations examined overheating mitigation measures whereby the thermal mass was increased, automatic shading devices were deployed, and solar gains were circulated between all three zones at a rate of 1,000 L/s.

A second set of additional energy simulations considered enhanced space heating energy conservation measures. The first was providing an RSI 0.88 external shutter that was activated from sunset until sunrise. The second measure increased the effective thermal resistance of the exterior walls to RSI 7.0, and the third was to combine these two measures. The second set of additional energy simulations impacted the solar heating fractions.

Table 2. Performance data for houses with upper boundary passive solar space heating fractions, including variations of selected parameters.

ASHRAE 90.2 Climate Zone	Zone 5	Zone 6	Zone 7	Zone 8
City	Chicago	Toronto	Calgary	Yellowknife
Annual solar gains (kWh)	28,224	22,488	31,341	26,875
Peak solar gains (kW)	29.8	25.6	28.3	27.2
Heating Degree-Days Below 18 ^oC	3,631	4,065	5,108	8,256
Annual Solar Radiation on South-Facing Surface kWh/m^2	1089	1027	1396	1189
Annual Sunshine Hours	2508	2066	2396	2256
Annual Mean Outdoor Temperature ^oC	9.8	7.4	4	-4.6
Design heating load (kW)	5.1	5.3	7.0	10.2
Maximum heating load (kW)*	20.7	20.6	19.1	23.4
Annual space heating energy (kWh)	2,411	4,364	2,882	17,171
Annual space cooling energy @ 25 ^oC (kWh)	1,713	901	1,450	828
Total space conditioning energy (kWh)	4,124	5,265	4,332	17,999
Annual space heating energy use intensity (ekWh/m^2)	8.0	14.5	9.6	57.2
Annual space heating energy - no sun (kWh)	11,524	13,764	16,474	32,470
Annual space heating energy - no windows (kWh)	7,231	9,404	10,523	22,943
Solar heating fraction (Balcomb)	79.1%	68.4%	82.6%	50.0%
Solar heating fraction (Duffie and Beckman)	66.7%	53.7%	72.8%	29.3%
Peak indoor temperature (^oC)	40.7	38.3	42.2	37.5
Hours over 25 ^oC operative temperature	2,902	1,834	3,348	1,078
With Overheating Mitigation Measures				
Peak indoor temperature (^oC)	33.7	33.8	39.3	34.4
Hours over 25 ^oC operative temperature	1,902	1,150	2,257	635
Annual space heating energy (kWh)	2,429	4,379	2,703	17,189
Annual space cooling energy @ 25 ^oC (kWh)	875	356	470	295
Total space conditioning energy (kWh)	3,304	4,735	3,173	17,484
Enhanced Space Heating Energy Conservation Measures				
Annual space heating energy - insulated shutters (kWh)	1,996	3,738	2,391	15,119
Annual space heating energy - RSI 7.0 walls (kWh)	2,036	3,318	2,338	14,797
Annual space heating energy - insulated shutters + RSI 7.0 walls (kWh)	1,624	2,750	1,903	13,753
Annual space heating energy use intensity (ekWh/m^2)	5.4	9.2	6.3	45.8
Solar heating fraction (Balcomb)	85.9%	80.0%	88.4%	57.6%
* indicates maximum heating load across all permutations of house characteristics for a particular climate zone.				

Note that in all four climate zones, as expected, the south-facing window-to-wall ratio of 0.9 provided the highest solar heating fraction. The 0.9 WWR represents a fully-glazed south-facing wall for the upper two storeys, with 10% of the gross wall area assigned to mullions, lintels and floor plate depth between the ground and upper floor.

An examination of the meteorological data indicates that insolation data are not linearly correlated to heating degree-days. Passive solar energy potential is largely dependent on the proportion of time during the heating season when skies are clear, and also on latitude since in the northern hemisphere, lower sun angles during the winter heating season are conducive to passive solar space heating in northerly latitudes. It is also important to appreciate that some perceived irregularities in the results are attributable to the weather file used in energy simulation. Overall, the performance results are consistent with the meteorological data.

The performance parameters reported in Table 2 indicate low energy house performance. For Zones 5, 6 and 7 the annual space heating energy use intensities are well below the Passivhaus (2013) standard of 15 ekWh/m2. It is interesting to note that in the Yellowknife climate, this level of energy use intensity could not be achieved even after the window sizes were reduced to the minimum areas prescribed in the applicable building code for the purposes of natural ventilation and emergency egress.

Solar heating fractions using the Balcomb measure are quite impressive and even in an extremely cold climate like Yellowknife, it is possible to provide 50% of the space heating with direct passive solar gains. However, the results also indicate significant overheating in the initial series of energy simulations. Cooling loads were simulated in this examination of passive solar heating potential, but not compared with a typical house. It is noteworthy that the peak air temperatures are largely a function of the weather file data and are not as meaningful as the number of hours over 25 ^{o}C operative temperature.

In view of the overheating indicators, a series of mitigation measures were invoked, whereby the thermal mass was increased, automatic shading devices were deployed, and solar gains were circulated between all three zones at a rate of 1,000 L/s. The overheating indicators in Table 2 indicate a significant reduction in the number of hours over 25 ^{o}C operative temperature. Results related to overheating mitigation measures are provided in Tables 3, 4 and 5.

Table 3. Indoor operative temperature ranges corresponding to simulation of full set of overheating mitigation measures (increased thermal mass, circulation of solar gains and shading devices).

Operative Temperature Ranges	**Zone 5**	**Zone 6**	**Zone 7**	**Zone 8**
Hours between 25 ^{o}C and 27 ^{o}C operative temperature	1,378.7	822.0	1,232.3	432.3
Hours between 27 ^{o}C and 29 ^{o}C operative temperature	379.0	223.3	532.7	129.3
Hours between 29 ^{o}C and 31 ^{o}C operative temperature	99.7	71.3	284.3	42.3
Hours between 31 ^{o}C and 33 ^{o}C operative temperature	35.0	24.7	112.7	23.3
Hours between 33 ^{o}C and 35 ^{o}C operative temperature	9.7	9.0	56.3	6.7
Hours over 35 ^{o}C operative temperature	0.0	0.0	38.7	0.7
Totals	**1,902**	**1,150**	**2,257**	**635**
Note: Discrepancies between totals in Table 3 and Table 5 are due to rounding.				

Table 4. Indoor peak monthly operative temperatures (^{o}C) corresponding to simulation of full set of overheating mitigation measures (increased thermal mass, circulation of solar gains and shading devices).

Month	Zone 5	Zone 6	Zone 7	Zone 8
January	21.1	20.9	22.8	15.2
February	22.7	21.5	26.2	19.0
March	23.4	24.5	27.0	22.3
April	23.8	20.7	25.3	22.8
May	21.9	21.0	24.7	22.7
June	24.0	23.1	23.6	22.0
July	24.9	24.5	24.2	21.3
August	24.9	24.6	23.2	22.3
September	24.2	26.3	23.4	23.4
October	26.9	26.5	27.8	20.7
November	26.1	25.1	25.2	18.0
December	22.0	20.9	22.4	16.5

Table 5. Number of hours monthly above 25 ^{o}C operative temperature corresponding to simulation of full set of overheating mitigation measures (increased thermal mass, circulation of solar gains and shading devices).

Month	Zone 5	Zone 6	Zone 7	Zone 8
January	41.7	31.7	106.3	0.0
February	69.7	41.3	173.7	26.7
March	118.7	96.3	404.0	100.3
April	45.3	21.7	256.3	109.0
May	36.3	1.0	111.0	115.0
June	217.7	72.7	78.7	92.3
July	319.3	172.7	127.3	38.0
August	218.0	150.0	89.7	56.0
September	101.0	121.0	90.0	92.7
October	541.0	363.3	615.0	6.7
November	164.7	58.0	141.0	0.0
December	30.3	21.7	66.3	0.0
Totals	**1904**	**1151**	**2259**	**637**

An examination of the energy simulation output data indicates most overheating occurs in shoulder months (late spring and early fall) and could be largely mitigated by opening windows and providing effective natural ventilation. Some overheating may occur in winter during entirely clear, sunny days but it is difficult to ascertain if this condition is unacceptable to inhabitants. Seasonal affective disorder (SAD) syndrome is greatly alleviated by visual exposure to bright sunlight, and hundreds of thousands of Canadians take winter vacations in the tropics where they can enjoy elevated temperatures and bright sunshine exposure. When the shoulder season overheating that can be mitigated by natural ventilation of excessive solar gains, and the winter overheating that may actually be a welcome phenomenon, are accounted for, the resulting magnitude of cooling loads is modest - practically non-existent in Yellowknife.

The second set of additional energy simulations to assess enhanced energy conservation measures impacted the solar heating fractions. The results shown are for the case where both RSI 0.88 external shutters and exterior walls with an effective thermal resistance of RSI 7.0 were invoked. In Zones 5, 6 and 7, the annual space heating energy demand was reduced by approximately one-third. In Zone 8, the reduction was in the range of one-sixth. Increasing the opaque building enclosure effective thermal resistance values did not deliver significant reductions in annual space heating energy demand. It should be noted the contribution to energy conservation by the insulated window shutters is significant and this measure also delivers a considerable reduction in peak heating energy demand.

Also worth noting is that beyond this level of passive building system performance, additional space heating energy conservation measures provide diminishing returns (Straube 2009). From a house-as-a-system perspective, potential measures for reducing active systems energy demand (domestic water heating, lighting and plug loads) are more cost effective.

4 Discussion

Energy simulation has now superceded many of the older guidelines for passive solar house design. Figure 4 indicates a practical range of south-facing window-to-wall ratios for contemporary passive solar houses, 0.7 to 0.9, which interestingly corroborates previous work in this area (Kesik and Papp 1998). This range corresponds, approximately and on average, to solar heating fractions of 85% in Calgary, 80% in Chicago and Toronto, and 55% in Yellowknife. These solar heating fractions are much higher than values cited in various guidelines (Balcomb 1982, Sander and Barakat 1984, CMHC 1998, Roscoe and Ward 2009), and represent currently attainable feasible upper boundaries.

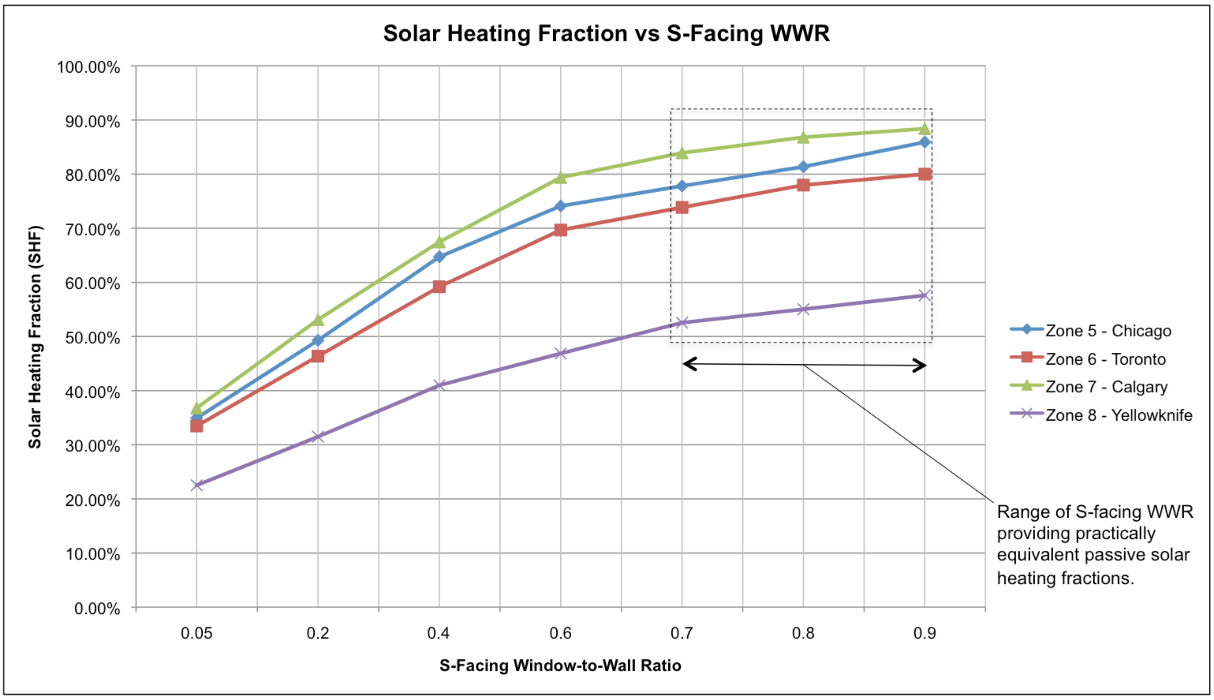

Figure 4. Relationship between south-facing window-to-wall ratio and solar heating fraction in the selected climate zones.

In order to promote a better understanding of the performance of passive solar house design, the authors have proposed a new metric in Figure 5 below, termed the passive solar heating effectiveness.

$$PSHE = \frac{SHF_{design}}{SHF_{max}}$$

where:

PSHE = passive solar heating effectiveness

SHF_{design} = solar heating fraction of proposed design

SHF_{max} = solar heating fraction of feasible upper boundary

Figure 5. Passive Solar Heating Effectiveness - a proposed metric for assessing the effectiveness of passive solar house performance in a given climatic location.

The application of this metric is evaluated in Table 6 below, in reference to an earlier method of sizing passive solar collection area (Balcomb 1983). Using Balcomb's method, the optimal area of south-facing glazing was calculated as 13.5 m^2, much lower than the 49.5 m^2 representing the upper boundary established by this research. The solar apertures are tabulated for convenience, since this was a commonly used metric for passive solar house design.[3] Expressed as a south-facing window-to-wall ratio, the Balcomb method provides roughly one-quarter of the passive solar collection area compared to contemporary simulation methods. When applied to estimating the passive solar heating effectiveness averaged over the 4 climate zones examines in this paper, a value of 55.8% was calculated. This means that reliance on the Balcomb guidelines would forego almost half of the potential passive solar space heating energy attainable by a house.

Parameter	Balcomb	Upper Boundary*
A_p (m^2)	13.5	49.5
Solar Aperture	0.068	0.2475
S-Facing WWR	24.5%	90.0%
* This method for determining the feasible upper boundary of passive solar heating potential is the outcome of research conducted by the authors under the auspices of the Solar Buildings Research Network 2006-11.		
Based on the average for the 4 climatic zones analyzed, the Balcomb method achieves a passive solar heating effectiveness of 55.8% compared to the feasible upper boundary of passive solar heating potential indicated in Figure 4. Almost half of the passive solar heating potential would not been realized by following this method.		

Table 6. Evaluation of Balcomb's *Guidelines for Conservation Levels and for Sizing Passive-Solar Collection Area* with respect to feasible upper boundaries of passive solar heating potentials identified through current energy simulation methods.

[3] The solar aperture is the ratio of south-facing glazing to above grade, conditioned floor space (200 m^2 in Table 3). An established convention is that if the basement level is conditioned and contains south-facing glazing (e.g., walk-out basement), then its conditioned floor area should be included with that of the above grade floor areas.

In practice, the passive solar heating effectiveness would be derived for a particular housing typology (e.g., single detached, semi-detached, row house, etc.) by first establishing the feasible upper boundary and then assessing the passive solar heating performance of proposed designs. Not only would this assess the passive solar energy utilization of a proposed house design, but it would also provide a means of assessing the solar access afforded by various subdivision plans. The work of Ralph L. Knowles (1999) has demonstrated effective means of respecting solar access in housing subdivision design, unfortunately, research and publication by Knowles for the past 4 decades in this area has done little to improve solar access for housing in North America (Kruzner et al. 2013). This does not undermine the relevance of solar access to community design (Scott et al. 2006, van Esch et al. 2012).

Unfortunate community planning practices aside, it is also important to recognize the methodology presented in this paper is not universally applicable to all climate regions without considerable re-formulation. For example, recent research indicates passive solar house design conventions are not conducive to the rainy, cloudy Cascadia corridor of the Pacific Northwest (Rempel et al. 2013). In every climate region, the upper boundary must be established according to the design strategies and measures that maximize passive solar heating potential rather than relying on often outdated guidelines.

5 Summary

The research conducted in this paper is incomplete but has nonetheless begun to shed light on the importance of establishing feasible upper boundaries of passive solar heating potentials. This approach should not be confused with related design techniques (O'Brien et al. 2008) and more comprehensive methodologies for reconciling energy and economic performance (Kesik and O'Brien 2012). The sole purpose of the methodology presented in this paper is to establish a basis for evaluating the effectivness of passive solar heating to the overall energy demand of the house-as-a-system. In view of the research undertaken in support of this paper, the following observations, caveats and recommendations for further research are respectfully submitted:

1. Beginning in 2006, the authors of this paper questioned the concept of optimization as it applied to housing design. Future projection about variables such as energy prices, technological innovation, the changing housing needs and preferences of households, and the dynamics between local economies, demographics and housing markets are simply too complex and chaotic for conventional optimization techniques. In the absence of a meaningful optimization strategy, it was decided to focus on maximizing the utilization of passive solar heat gains and their influence on whole house energy demands.
2. Within the context of net-zero energy and carbon-neutral house concepts, a macro-economic analysis of the cost effectiveness of passive solar heating is needed to identify quasi-optimal solar heating fractions from a societal perspective. In the absence of externalities, avoided infrastructure cost, affordability, resilience, etc., the optimization of solar heating fractions is severely limited by the realm of oversimplified economics. It could be argued that each owner or occupant of a house may choose to privilege non-energy performance parameters, such as aesthetics, acoustics, view, etc., and in a democratic society is free to elect such aspects of housing over energy performance - this phenomenon commonly occurs today.

3. If, on the other hand, the owner or occupant was interested, for whatever reason, all economic and other performative considerations aside, to maximize their utilization of a renewable energy source in the form of passive solar heating, this must be understood as an exercise that takes place after that person has already performed an optimization of sorts within their own system of beliefs, values and preferences. This is the difficult nature of reconciling housing and energy policies in democracies. Therefore, optimization of housing design implies imposing values on present and future occupants and owners by virtue of the selection of parameters, without their explicit consent, or consideration of the needs and desires of future generations. For these reasons, feasibility is a preferred concept over optimization in guiding our research on passive solar housing design.
4. High gain, low U-value windows (Grynning et al. 2013), shading devices, insulated and protective shutters, and passive cooling techniques (natural ventilation and shading by trees) require further research reinforced by demonstration in built projects. The concept of a static housing form that does not respond to changing conditions, unlike so many plant forms, needs to be challenged in contemporary housing research and design.
5. Large window areas have implications for initial costs, resilience under adverse weather events, and may negatively impact peak energy demands. While passive solar heating may enhance the passive survivability of housing, negative repercussions associated with potential damage from wind-borne projectiles and high night time heat losses need to be mitigated. Technologies for protecting windows and providing shading and additional thermal insulation exist and may be deployed to mitigate against the potential adverse impacts of large glazing areas in houses. The serious concerns that continue to be expressed by researchers for overheating and high peak heating and cooling loads associated with large south-facing glazing areas overlook off-the-shelf innovations that are readily available.
6. Regardless, not everyone may want large glazed window areas in their homes and options for achieving reduced carbon footprints and non-renewable energy demands need to be explored so that policy makers, designers and homeowners can make informed decisions about their housing energy demand profiles.
7. Comfort, well being and health are major objectives in housing design and the relationship between these parameters and solar buildings is not well researched, and hence poorly understood. People report enjoying sunny, overheated and plant filled spaces during winter, and find the experience therapeutic and a respite against dreary cold weather, but thermal comfort models predict the opposite reaction. The social and psychological response to solar building environments deserves further study so these may be tailored to suit the desires and preferences of the inhabitants.

As the energy demands of houses diminish over time, the relative contribution of passive solar heating in cold climate housing increases in significance. What was once a very thin slice of a very big pie will become a fat slice of a very small pie. Those interested in promoting more sustainable housing designs and communities should be aware of the passive solar heating effectiveness of their proposed interventions in order to make better informed decisions. This paper advances a simple methodology for beginning to explore this critical perspective on housing energy and solar buildings design.

6 Acknowledgements

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