NY-14-009

Solar Design Days:
A Tool for Passive Solar House Design

William O'Brien, PhD
Associate Member ASHRAE

Ted Kesik, PhD, PEng
Member ASHRAE

Andreas Athienitis, PhD, PEng
Member ASHRAE

ABSTRACT

Passive solar heating of homes is a dynamic process for which solar energy is transmitted through glazing and then absorbed by the interior building components and released to the indoor air over time. This paper presents solar design days as a useful method for understanding passive solar buildings' dynamic behavior for the purpose of increasing energy performance and thermal comfort through interactive design at the conceptual design stage. Rather than relying on rules of thumb or assessing whole-year performance from building energy simulations to optimize passive solar measures, solar design days can be used to compare different design options by diagnosing potential problems such as excessive heat loss, peak loads, and overheating. Solar design days consist of representative cold sunny, cold cloudy, warm sunny, and mild sunny days. This paper provides a background on recent advances in passive solar design, a methodology for selecting and applying solar design days, a modeling approach for passive solar houses in EnergyPlus, and finally, an example.

INTRODUCTION

Passive solar heating techniques for houses—a combination of strategically-oriented glazing, fixed solar shading, thermally massive interior building components, and a well-insulated and airtight enclosure—are among the most cost-effective and technically simple approaches towards achieving low and net-zero energy design in cold and temperate climates (Balcomb 1992). Passive solar houses use thermally massive building components to moderate indoor temperature swings that often result from high periodic solar gains admitted through large south-facing windows. A key design goal in passive solar house design is to minimize purchased heating and the peak heating load, while ensuring that the indoor spaces do not overheat from excessive solar gains and also do not feel too cold from large windows. Numerous house standards and design approaches suggest that passive solar design be among the first approaches to reducing energy use relative to a standard home, including net-zero energy, PassiveHouse, and R-2000 (Hastings et al. 2006; Marszal et al. 2010; Natural Resources Canada [NRCan] 2008).

The majority of the literature on passive solar houses is several decades old (e.g., Balcomb 1992; CMHC 1998). Passive solar techniques gained considerable momentum during the oil crises of the 1970s and early 1980s (Sander et al. 1985). Recent technological advances in building enclosure components and energy recovery systems have enabled lower heat loss, thus enabling significantly less purchased heating when combined with passive solar strategies. However, the traditional design approach of passive solar homes using rules of thumb is static and cannot adapt to these advances. Such rules of thumb typically suggest appropriate values of, or ratios between, a small subset of major design parameters (e.g., CMHC 1998). For instance, the south-facing wall should be within 15 degrees of south and if the south-facing glazing area is greater than 7% of the floor area, addition thermal mass should be included.

This paper explores a concept called solar design days—a passive solar house design approach that is interactive and can incorporate views, aesthetics, and other desirable architectural considerations. It argues that providing simulation data for a few 24-hour periods for key house performance metrics (purchased heating rate, solar heat gains, air temperature) can be very revealing about a house design's strengths and weaknesses. But first, a brief review of key technological developments related to passive solar homes is presented.

William O'Brien is an assistant professor in the Department of Civil and Environmental Engineering at Carleton University, Ottawa, Ontario, Canada. **Ted Kesik** is an associate professor in the Daniels Faculty for Architecture, Landscape, and Design at the University of Toronto in Toronto, Ontario, Canada. **Andreas Athienitis** is a professor in the Department of Building, Civil, and Environmental Engineering at Concordia University in Montreal, Quebec, Canada.

The overarching strategy to passive solar house design is maximizing solar utilization while minimizing heat loss. To do so, well-insulated, airtight enclosures are fundamental. Residential building energy codes and standards (e.g., ASHRAE 2010) continue to escalate enclosure requirements. For the temperate North American climate zones, effective wall and ceiling insulation values of RSI-2.3 to 9.2 (R-13 to 52) are required, while Passivhaus projects often have insulation levels of RSI-7 to 10 (R-40 to 57). Airtightness in higher performance houses typically approaches as low as 0.5 air changes per hour (at 50 Pa [0.2 in. water]) (Hastings et al. 2006) from 4 to 50 air changes per hour for existing houses (ASHRAE 2009).

Passive solar houses are normally characterized by large south-facing windows. However, windows are usually one of the major sources of heat loss in houses, with even high-performance windows (e.g., USI-0.5 [U-0.09]) being at least three to five times more conductive than insulated walls. Windows can also cause discomfort by affecting the mean radiant temperature, drafts, and direct solar gains (Lyons et al. 1999), and impose upper limits on humidity levels to prevent condensation. Solar heat gain coefficients (SHGC)—the fraction of incident solar radiation that is directly transmitted, convected or radiated inward—typically decrease with lower U-factors. While high SHGCs (>0.5) were originally sought for south-facing windows of passive solar houses, a more balanced approach (SHGC of about 0.3 to 0.4) may be more appropriate if large windows for good views and daylighting are desired or possibly a mix of the two choices depending on the zone of the house; for example, in the Athienitis house (Athienitis 2007) windows with hard low-e coatings (SHGC about 0.5) are used on the ground floor (family room, kitchen) south facing windows and soft low-e coatings (SHGC 0.4) in all other windows. The net heat gain through high-performance windows has become well above positive in many cold and temperate climates (Arasteh et al. 2006), thus reducing the need for nighttime insulating shutters or Trombe walls. Key technological improvements include multiple glazing layers, low emissivity coatings, non-air gas-fills, and insulated spacers and frames (Carmody et al. 2004).

The added thermal mass that is common in passive solar houses, typically made of concrete or masonry, or multi-layered gypsum board, often requires additional structural support, an increase in house volume, and can contribute significantly to embodied energy (Keoleian et al. 2000; Thormark 2002). 10 to 20 cm (4 to 8 in.) of concrete or similar masonry materials is normally optimal for minimizing temperature swings and maximizing diurnal thermal storage (Athienitis and Santamouris 2002). Ideally, thermal mass is placed in the direct path of transmitted solar radiation—either on the floor or south-facing interior walls—but another somewhat less effective strategy is to combine reflective floors with massive surfaces that receive reflected solar radiation (Balcomb 1992). Phase change materials (PCMs), a class of materials that stores latent energy by changing state at a comfortable indoor temperature, can be used to achieve similar performance but with surfaces of much less mass or volume (Athienitis et al. 1997; Khudhair and Farid 2004).

Due to the seasonal lag between daytime solar altitudes and mean outdoor temperatures, autumn can be problematic for overheating in passive solar houses because solar gains can significantly exceed thermal losses. Fixed shading devices (e.g., overhangs and side fins) are not effective at sufficiently reducing solar gains at this time of year because of low midday solar altitudes. Furthermore, attempts to obstruct solar radiation in the shoulder seasons can negatively impact winter heating performance. Dynamic shading systems offer passive solar homes the ability to adapt to seasonal and daily variability of solar radiation. Exterior blinds are much more effective at reflecting solar radiation than interior blinds, but may be subject to severe weather conditions (Laouadi et al. 2008). Blinds can be controlled manually, but, ideally, automatically and with a predictive element (e.g., Intille [2002]) to reduce the reliance on occupant intervention.

Since solar gains in passive solar houses mostly occur in their south-facing zones where the majority of the glazing is positioned, there can be significant imbalances in heat gains and losses. O'Brien et al. (2011) showed that temperature differences of 5°C to 10°C (9°F to 18°F) were possible if the spaces were isolated (i.e., closed doors and smaller rooms). Aside from discomfort, this presents a controls challenge because of the sensitivity of thermostat location in houses with a single control zone. If the thermostat is positioned in the direct gain zone, the mechanical heating may remain off, causing the northern spaces to become cold. If it is positioned in the northern part of the house, the whole house may be mechanically heated even as the direct gain zone has ample solar gains to offset its heat losses. To mitigate this condition, the strategy of implementing a continuous air loop using hallways and openings has showed some success. Alternatively, electronically commutated motor (ECM) fans, which are about 60% more efficient than permanent split capacitor (PSC) fans, can be set to run at a low speed continually or controlled based on thermostat readings to help distribute the heated air from the solar gains (Gusdorf et al. 2010). O'Brien et al. (2011) demonstrated that the potential heating and cooling energy savings is substantially more than the fan operating energy in passive solar houses.

Substantially lower heat losses in passive solar houses can allows for significantly smaller heating and cooling systems. However, it should be noted that to achieve this, the large glazing areas should be compensated for with a high-performance envelope, including a low U-factor for the windows themselves. If the peak heating loss remains below about 10 W/m^2 (3.17 Btu/h·ft^2), fresh air supply can also be used to also deliver space heating; thus, eliminating the need for a separate heating distribution system (Hastings et al. 2006). With outdoor air exchange representing a relatively high source of heat loss in passive solar houses, heat or energy recovery ventilators with effectiveness ratings of 60% to 80% are commonplace. Use of solar thermal collectors can be paired with passive solar energy to supplement heating during cloudy winter days. These systems necessarily require active thermal storage because the collected energy should not be released into the house at the same time it is collected, since passive solar gains normally offset most instantaneous heat losses. Active solar heating systems can be air (e.g., Chen et al. 2010) or water-based (e.g., Wallin et al. 2012). For instance, in the EcoTerra house, the thermal energy from a building-integrated hybrid photovoltaic/thermal solar collector is transferred to and stored in a ventilated slab in the basement for passive release (Chen et al. 2010).

Several tools have been developed specifically to calculate the energy and comfort performance of houses, including HEED, HOT2000/HOT3000, and BEOpt (HEED 2009; National Renewable Energy Laboratory [NREL] 2013; Natural Resources Canada [NRCan] 2010; Natural Resources Canada [NRCan] 2011). These tools primarily focus on monthly or annual performance and are not specifically aimed at passive solar design. Generally, these tools do not display short-term dynamic performance data—that which is critical to passive solar performance (either because the underlying simulation/calculation engine is incapable of doing so or because it is simply not an output option). Several of the aforementioned tools use simplified algorithms (e.g., bin method [Al-Homoud 2001]) that are inadequate for assessing the dynamic performance of buildings with high levels of thermal mass and solar gains. For the tools that are based on accurate analytical or numerical solutions to dynamic building modelling and do provide detailed outputs, there are often overwhelming amounts of data (Prazeres and Clarke 2003) that do not easily facilitate decision-making with respect to passive solar design.

Early simulation methods were often limited to statistically-based calculations, compared to the sub-hourly time-step simulations that are routine today. While hourly timestep simulations could be performed on mainframe computers (Balcomb 1992), the use of such methods was not readily available to most designers. Sander et al. (1985) presented a graphical design approach for passive solar houses which was adopted by HOT2000—a commonly used Canadian tool for evaluating building energy retrofit incentive eligibility for houses (NRCan 2010). However, most of the literature has emphasized accurately predicting annual or seasonal performance using metrics such as solar fraction, seasonal solar utilization (Sander et al. 1985), and annual purchased heating energy. In contrast, the proposed methodology that follows suggests that focusing on lower level metrics (e.g., instantaneous air temperature) during design ultimately leads to strong annual performance. The purpose of this paper is to present an efficient means for simulation-aided design of passive solar houses: solar design days. The above introduction has summarized the key elements, technologies, and design methodologies and tools of passive solar houses. The following sections include a description of the proposed solar design day tool; a methodology that includes selection of solar design days, the modelling approach, and procedures for applying solar design days; and finally, a design example is presented.

SOLAR DESIGN DAYS

In order to provide better guidance for passive solar building design, this paper proposes the use of solar design days (SDDs) to enable designers to make key design decisions early in the design process. Instead of aggregated performance data, SDDs are a tool for exploring the short-term dynamic behavior of passive solar houses and for understanding the cause and effect relationships of weather phenomena and the thermal response of the house. Solar design days are used to visualize key passive solar house performance metrics (instantaneous weather, indoor temperatures, comfort, heating loads, etc.) during a 24 hour period. The use of SDDs has two main advantages over whole-year simulations. First, presenting the designer with only a few carefully selected days' (explained later) worth of performance data allows them to make direct and real connections between the design decisions and the corresponding performance. For example, they can observe how increasing the level of thermal mass can reduce the peak temperature and reduce nighttime heating loads.

A second benefit to SDDs is that computational time is reduced by several orders of magnitude versus whole-year simulations. While computing time is not a problem for single simulations, it becomes cumbersome if many designs are explored. Degelman (1998) showed that using a typical week of weather data for each month of the year reduced simulation times by at least 50% while only introducing an error of 10%. Design day analysis is commonplace for daylight simulations (e.g., SPOT [Architectural Energy Corporation 2012]) for which computation time can be prohibitively slow if it is to influence design and provide high-quality renderings.

While the SDD concept is expected to be effective for many aspects of solar house design (e.g., active thermal, electricity production), passive solar design is the focus of this paper because it is a cost-effective means to harness solar energy (Athienitis 2007), and it is most critically affected by decisions made during the initial stages of the conceptual design process.

It should be noted that solar design days are complementary to HVAC design days. HVAC design days are primarily used to size equipment to ensure that loads are met and comfort is maintained for some prescribed fraction of occupied hours. In contrast, the purpose of solar design days is to support early stage design decisions such as south-facing window-to-wall ratio, house form, and effective enclosure properties. It follows that it is more important to capture typical combinations of weather phenomena for SDDs than extreme conditions that are typical of HVAC design days. That is, basing passive solar design on infrequent conditions could skew the design away from one that would perform well during typical conditions.

METHODOLOGY

The approach to using solar design days for passive solar house design is to identify particular performance profiles and then identify weather characteristics that can be used to evaluate performance. Most passive solar buildings in cold and temperate climates cannot completely rely on solar gains alone. Normally, solar gains can only be passively stored for a single day—long enough to bridge consecutive sunny days—but not long enough to completely eliminate the need for mechanical heating during extended cold cloudy periods (Balcomb 1983). The storage limit of about a day for passive thermal mass stems from the strong coupling between the mass and the surrounding surfaces and air. Thus, the stored energy from solar gains has a limited storage duration. Therefore, the purpose of solar design days is to help reduce a building's mechanical heating and cooling, not necessarily eliminate it. The typical duration of passive energy storage also justifies the 24-hour window used for SDDs. For the standard passive house design approaches for cold climates—*light and tigh*t and *mass and glass* (Sander et al. 1985)—outdoor temperature and solar radiation patterns are of the greatest interest and hence the focus of this paper. However, for buildings that rely on natural ventilation, wind speed and direction would also be of great interest. For humid climates, relative humidity would also play a role in design.

This paper is focused on direct solar gains strategies (i.e., the solar gains are admitted directly into a thermally-massive living space within the house, rather than sunspace or Trombe wall systems). Within this context, the purpose of the four types of SDDs is explained in detail. Cold sunny (CS) days represent the weather during which passive solar design is targeted to be most effective. Solar gains are maximized while reducing heat loss and potential discomfort associated with large glazed areas. Thermal mass can be used to reduce indoor air temperatures swings and store heat to be released at nighttime. Overheating on cold sunny days is to be avoided because it indicates that warmer sunny days could face even more severe overheating.

Cold cloudy (CC) days represents the weather conditions that cause the maximum heat loss expected due to the cold temperatures and minimal solar gains. This design day allows the designer to balance the advantage of a large glazed area with the associated heat loss. Large cold windows can have the indirect effect on energy use whereby the mean radiant temperature of the space is decreased and may trigger occupants to increase the indoor air temperature to compensate.

Warm sunny (WS) days exhibit peak summer outdoor temperatures and moderately high levels of direct solar radiation on glazing, depending on the solar shading present. Some houses may be sensitive to high dry-bulb temperatures if they are not well-insulated. A distinguishing feature of WS days versus mild sunny days, presented next, is that WS days occur during the cooling season (if air conditioning is present). Thus, WS days can be used to assess the need for mechanical cooling, more effective shading and the potential to even remove the air conditioner.

Mild sunny (WS) days represent the weather during a shoulder season day when overheating is the most problematic. For this day, the temperature is warm, but the midday solar altitude is relatively low, allowing for significant solar gains through equator-facing windows. A typical passive solar house with large windows will suffer more from overheating in the fall when solar angles are low and temperatures are mild, than in the summer when solar angles are high but temperatures are very warm. At this time of year, fixed solar shading is largely ineffective at protecting from relatively low sun angle solar gains. Since this type of day normally occurs outside of the mechanical cooling period, it can be used to assess the thermal comfort under such conditions.

SELECTION OF SDDS

As previously mentioned, solar design day selection is not as critical as HVAC design days. However, some rigor should be applied to identify the most appropriate days by visually inspecting the weather data. For the current work, EPW (EnergyPlus Weather) climate files were used. A detailed description of weather files for building performance simulation was written by Crawley et al. (1999). EPW files contain about 20 weather metrics for which there are 8760 hourly values. The metrics of interest for the current work include dry-bulb temperature, direct solar radiation, and horizontal diffuse radiation. EPW data can be visualized using spreadsheet software or several weather visualization tools such as Climate Consultant software (Milne 2013). Climate Consultant is particularly useful for visually grasping the nature of a climate, although it does not provide temporal resolution finer than monthly. Using hourly climate data (e.g., from the EPW file), the solar design days should be selected as follows:

1. Cold sunny day: Select the day that is the clearest, if not perfectly clear (smooth, semi-sinusoidal direct solar radiation profile), and also among the coldest.
2. Cold cloudy day: Select the coldest day with no, or minimal, direct solar radiation (i.e., completely overcast).
3. Warm sunny day: Select the warmest day in the summer that is clear for all or most of the day. Like for the cold sunny day, this can be identified by a sinusoidal direct solar radiation profile. If the house design is expected to have air conditioning, the warm sunny day should occur during the conventional cooling season.
4. Mild sunny day: Select a warm day in the autumn or spring that is very clear all day. Ideally, this day should be chosen to be within about two months of winter solstice since it is intended to identify overheating in the shoulder season when the midday solar altitude is relatively low.

An example for SDD selection for Toronto, Canada is provided later in this paper.

DESIGN USING SOLAR DESIGN DAYS

Prior to in-depth passive solar design, suitability for passive solar should be quickly tested, as follows. If the mean daily outdoor temperature in the heating season is above the balance point temperature for the house, then there would be little benefit to using passive solar gains to offset heating. The balance point for heating (i.e., the outdoor temperature above which no heating is required) is traditionally set as 18.3°C (65°F) (Al-Homoud 2001). However, as the overall building loss coefficient (BLC) (i.e., the total rate of heat loss through the enclosure per unit of temperature) decreases with better enclosures and the internal gains remain fairly constant, this should be re-evaluated (reduced to 10°C to 15°C [50 °F to 59°F]) (Thormark 2002). The BLC, including the infiltration and ventilation, can be calculated as follows.

$$\mathrm{BLC} = \sum_{i=1}^{N_{surfaces}} U_i A_i + [\dot{m}_{inf} + \dot{m}_{vent}(1 - \eta_{HRV})]c_{p,\,air} \tag{1}$$

where $N_{surfaces}$ is the number of surfaces of the house, U and A are the effective thermal conductance and area of those surfaces, $\dot{m}_{inf}$ and $\dot{m}_{vent}$ are the infiltration and ventilation mass flow rates for the house, η_{HRV} is the sensible heat recovery effectiveness for the house, and $c_{p,air}$ is the specific heat capacity of air. The balance point temperature T_{bp}, neglecting solar gains, can be approximated using a steady-state approach as follows.

$$T_{bp} = T_{in} - \frac{Q_{int.gains}}{\mathrm{BLC}} \tag{2}$$

where T_{in} is the indoor air temperature and $Q_{int.gains}$ is the estimated rate of internal heat gains. This formulation does not explicitly consider foundation heat transfer, which requires more detailed methods (e.g., Beausoleil-Morrison 1996).

The second condition that should be checked to determine if passive solar strategies are appropriate is that the net heat gain through windows is positive during the heating season. The net heat gain of windows in the winter is the solar heat gain minus the heat loss. Instantaneous net heat gain through a window can be approximated as follows.

$$\begin{aligned} Q_{gain,window} = A_{window}[&I_{solar,window}\mathrm{SHGC}_{window}(\theta) \\ &- U_{window}(T_{in} - T_{out})] \end{aligned} \tag{3}$$

where $Q_{gain,window}$ is the net instantaneous heat gain from the window, A_{window} is the total window area (frame and glazing), $\mathrm{SHGC}_{window}(\theta)$ is the total area-weighted solar heat gain coefficient for the window (which is dependent on solar incidence angle θ), U_{window} is the area-weighted thermal conductance of the window, and T_{in} and T_{out} are the indoor and outdoor air temperatures, respectively. These window properties can be obtained by Lawrence Berkeley National Laboratory (LBNL) Window software (LBNL 2010) or from *ASHRAE Handbook—Fundamentals* (2009). The net heat gain through a window during winter can be estimated by integrating $Q_{gain,window}$ over the heating season. However, caution must be taken because this represents an upper bound since not all solar gains are necessarily useful. In general, as the south-facing window area increases, less of the solar gains will be useful—particularly at the beginning and end of the heating season when daily solar gains could exceed heat loss. Solar gain effectiveness η, as defined by Thormark (2002) can be quantified using transient simulations and has been historically provided in charts (e.g., Sander et al. 1985). Even a marginal seasonal net solar heat gain (e.g., in cloudy cold climates) is not very suitable for passive solar heating because solar gains can be diminished by dust accumulation on windows, shading from vegetation, and off-south orientations. However, extending considerations to include daylighting, views, and architectural considerations could shift this purely energy-related balance.

Assuming passive solar strategies are deemed suitable for the climate and building type, the following procedures are proposed for application of solar design days to improve passive solar performance. But first, the model on which the procedure is based is described.

PASSIVE SOLAR HOUSE MODEL

To demonstrate the use of SDDs, a house energy model was created using EnergyPlus V7.2 (Department of Energy [DOE] 2012). 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 lengths by Clarke (2001) and the implementation in EnergyPlus V7.2 is explained 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. The model is typical of models in the prominent tools (e.g., HEED, HOT2000, and BEopt), except that effort was made to ensure that the potential for localized overheating was 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 1). As explained by O'Brien et al. (2011), models with a single fully-mixed zone that represent 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. The strategic use of an air-handling unit in circulation mode can greatly assist in the distribution of

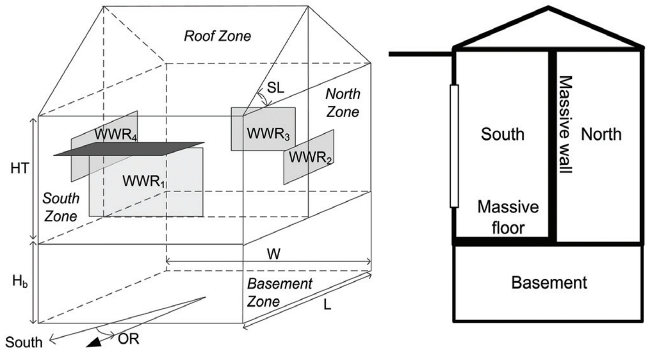


Figure 1 *(Left) Isometric view of parametric house model showing key geometrical parameters. (Right) East elevation cross section of parametric house model, showing zonal configuration.*

the energy from solar gains, but this is something that should be designed for and can be readily characterized using SDDs.

The model is defined by numerous parameters related to geometry, enclosure, and controls and operations. The parameters are explained in detail in O'Brien et al. (2011) and defined in Figure 1. They are meant to be approximately standard minimum as per ASHRAE Standard 90.2-2010 (ASHRAE, 2010) for Climate Zone 6, where applicable. The main geometrical parameters of the model are shown in Figure 1.

Since SDDs are intended for the early design when heating and cooling loads are being minimized and specific HVAC equipment has not yet been selected, the current model uses idealized equipment with infinite heating and cooling capacity. However, if the designer is aware of a particular product or a fixed heating or cooling output capacity, this information can be incorporated into the solar design day-based approach.

Instead of reporting air temperature as a comfort metric, the current approach uses operative temperature T_{op}. The operative temperature is approximated as the average of the zone air temperature and the mean radiant temperature (ASHRAE 2009). The mean radiant temperature is defined as the angle factor-weighted enclosing surface temperatures. For lack of more detailed knowledge, the occupant is assumed to be at the center of the room. The mean radiant temperature of a zone T_{MRT} is approximated in EnergyPlus as follows, assuming that the surface emissivities are equal.

$$T_{MRT} = F_1 T_1 + F_2 T_2 + \cdots + F_n T_n \tag{4}$$

where F_i is the view factor between the occupant and surface i and T_i is the temperature of surface i. Detailed view factors between seated and standing occupants and the surrounding surfaces can be obtained from ASHRAE Standard 55-2010 (ASHRAE 2010).

For effective passive solar heating using sensible storage, a fluctuation in air and surface temperatures is necessary for passive thermal storage. Normally, a greater occupant tolerance to fluctuations can improve energy performance because it enables solar heat gains to be stored for longer. However, care must be taken to prevent overheating. Chronic overheating may prompt occupants to adapt by opening windows in the heating season and other energy-intensive actions. Recent research has suggested that the range of comfort temperatures in residential buildings is wider than conventional models, which are primarily aimed at conditioned workplaces (Charron and Athienitis 2006; Karjalainen 2009). This is largely because there are more adaptive opportunities: clothing and bedding level, activity level, food and beverages, operable windows, and location within the building. Furthermore, simpler HVAC systems and individualized control increase perceived comfort (Karjalainen 2009).

APPLICATION OF SDDS

An iterative procedure, presented in the form of a series of flow charts, is proposed for using SDDs to design a passive solar house. The high-level methodology is to start with solar neutral fenestration (i.e., equally-distributed windows) on a house with a standard-minimum thermal enclosure. The four SDDs are sequentially used to strive for greater performance while testing for undesirable performance (discomfort, high peak loads, and high energy use). The cold sunny day is used to maximize passive solar performance (i.e., reduce purchased heating) while the other three days are used to diagnose performance issues. If any of those are detected, the simplest, most effective, and lowest cost solutions are prioritized. The procedure begins by setting some of the non-design parameters—those which are expected to be fixed at the beginning of the design process. These include floor area, setpoints, and internal gains level (i.e., expected heat gains from appliances, lighting, and people).

The flow charts that follow (Figures 2 to 5) include a high-level methodology, a methodology for use of each of the four SDDs, and, on the lowest level, methodologies for design of certain elements (named with numbers). It should be noted that use of SDDs is flexible, and some knowledge of the function of various building components with common sense can result in successful design progress.

EXAMPLE

This section presents an example of a passive solar house in Toronto, Canada (43.65°N, 79.40°W). The first step in the solar design day process is to identify them from the climate file. For the Toronto EPW file, these were fairly indisputable as per the SDD selection heuristics described above. The SDDs are shown in Figure 6 and labeled with their calendar date in the EPW file.

The example house has a total conditioned floor area of 300 m^2 (3228 ft^2) distributed over the basement and two above-grade stories. It is sited square on a south-facing lot. The occupants are assumed to tolerate operative temperatures between 20°C and 27°C (68°F and 81°F). The setpoints are set accordingly, though this does not prevent discomfort because

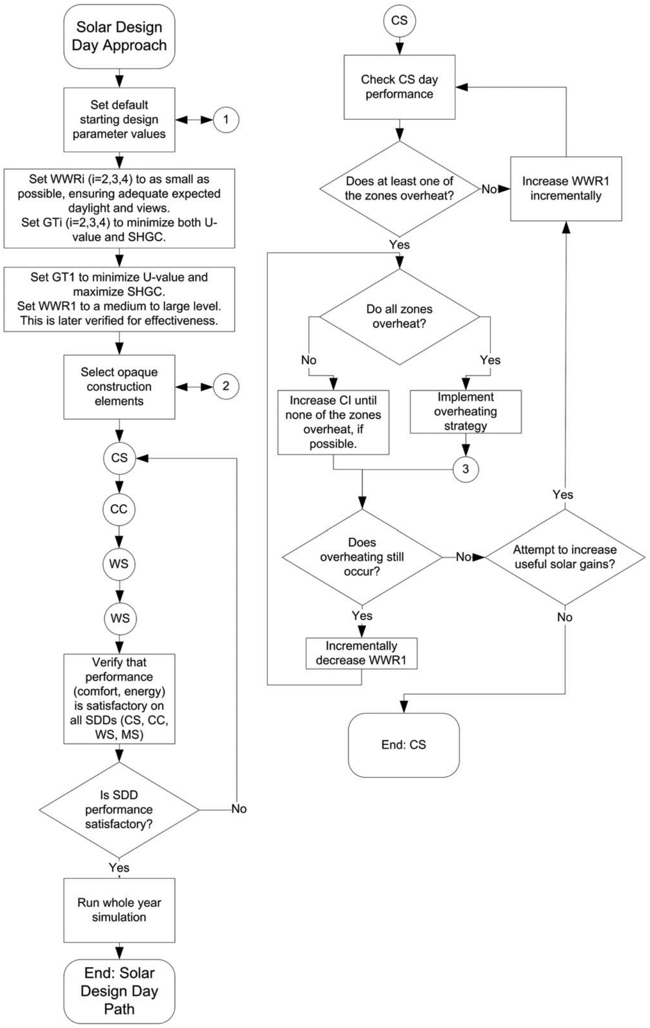


Figure 2 *(Left) High-level solar design day procedure and (right) cold sunny day procedure.*

only the dry bulb air temperature is controlled; not the operative temperature. The cooling season is set to May 1 to September 15, while heating is allowed at any time of year. The house is assumed to have a typical internal gains level and infiltration is set to be relatively airtight at 1.0 air changes per hour at 50 Pa (0.2 in. water). As a starting point, all enclosure components are set to their standard minimum values (ASHRAE 2010), no additional thermal mass is added, and no fixed or dynamic shading is used. Window-to-wall area ratios of 10% for all orientations are set—the minimum level assumed to be necessary for views and daylighting. The predicted energy use for this starting point is 7,980 kWh (27.2 MBtu) for heating and 94 kWh (321 kBtu) for cooling. The example approximately follows the procedure proposed in the previous section and major steps are reported.

The first step taken was to improve the wall insulation to RSI-11 (R-60) and the ceiling insulation to RSI-7 (R-40). The resulting cold sunny day performance is shown in Figure 1(a).

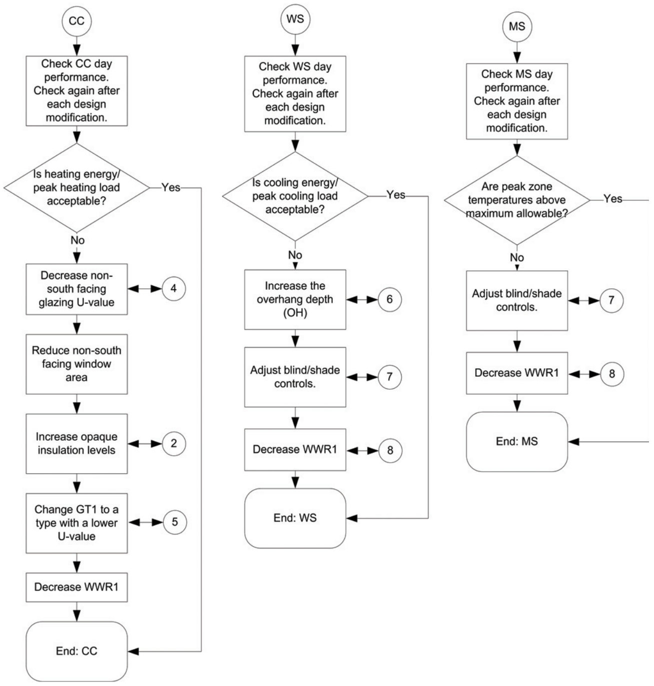
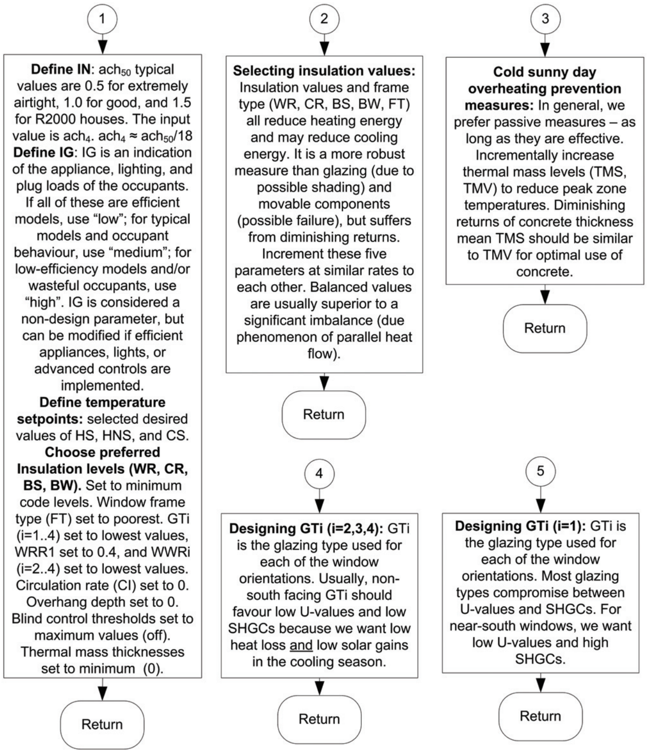


Figure 3 *(Left) Cold cloudy, (middle) warm sunny, and (right) mild sunny day design procedures.*



Define IN: ach_{50} typical values are 0.5 for extremely airtight, 1.0 for good, and 1.5 for R2000 houses. The input value is ach_4. $ach_4 \approx ach_{50}/18$ **Define IG**: IG is an indication of the appliance, lighting, and plug loads of the occupants. If all of these are efficient models, use "low"; for typical models and occupant behaviour, use "medium"; for low-efficiency models and/or wasteful occupants, use "high". IG is considered a non-design parameter, but can be modified if efficient appliances, lights, or advanced controls are implemented. **Define temperature setpoints:** selected desired values of HS, HNS, and CS. **Choose preferred Insulation levels (WR, CR, BS, BW).** Set to minimum code levels. Window frame type (FT) set to poorest. GTi (i=1..4) set to lowest values, WRR1 set to 0.4, and WWRi (i=2..4) set to lowest values. Circulation rate (CI) set to 0. Overhang depth set to 0. Blind control thresholds set to maximum values (off). Thermal mass thicknesses set to minimum (0).

Selecting insulation values: Insulation values and frame type (WR, CR, BS, BW, FT) all reduce heating energy and may reduce cooling energy. It is a more robust measure than glazing (due to possible shading) and movable components (possible failure), but suffers from diminishing returns. Increment these five parameters at similar rates to each other. Balanced values are usually superior to a significant imbalance (due phenomenon of parallel heat flow).

Cold sunny day overheating prevention measures: In general, we prefer passive measures – as long as they are effective. Incrementally increase thermal mass levels (TMS, TMV) to reduce peak zone temperatures. Diminishing returns of concrete thickness mean TMS should be similar to TMV for optimal use of concrete.

Designing GTi (i=2,3,4): GTi is the glazing type used for each of the window orientations. Usually, non-south facing GTi should favour low U-values and low SHGCs because we want low heat loss and low solar gains in the cooling season.

Designing GTi (i=1): GTi is the glazing type used for each of the window orientations. Most glazing types compromise between U-values and SHGCs. For near-south windows, we want low U-values and high SHGCs.

Figure 4 *House parameter design procedures.*

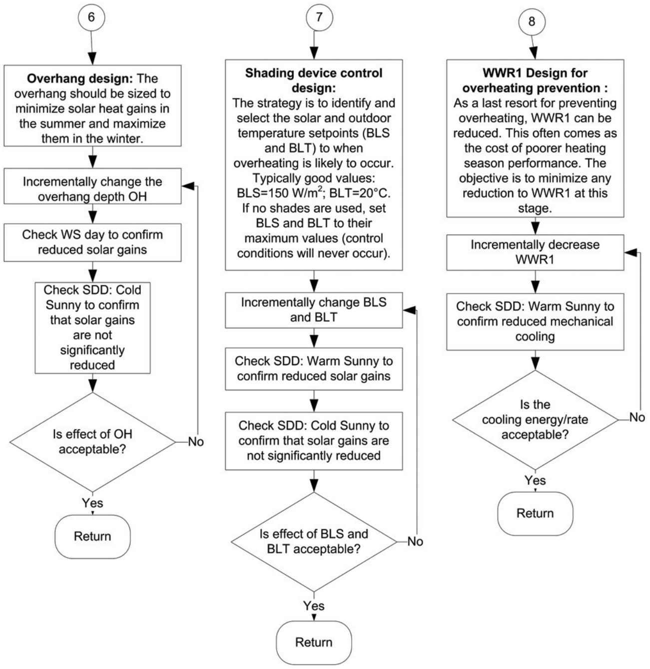
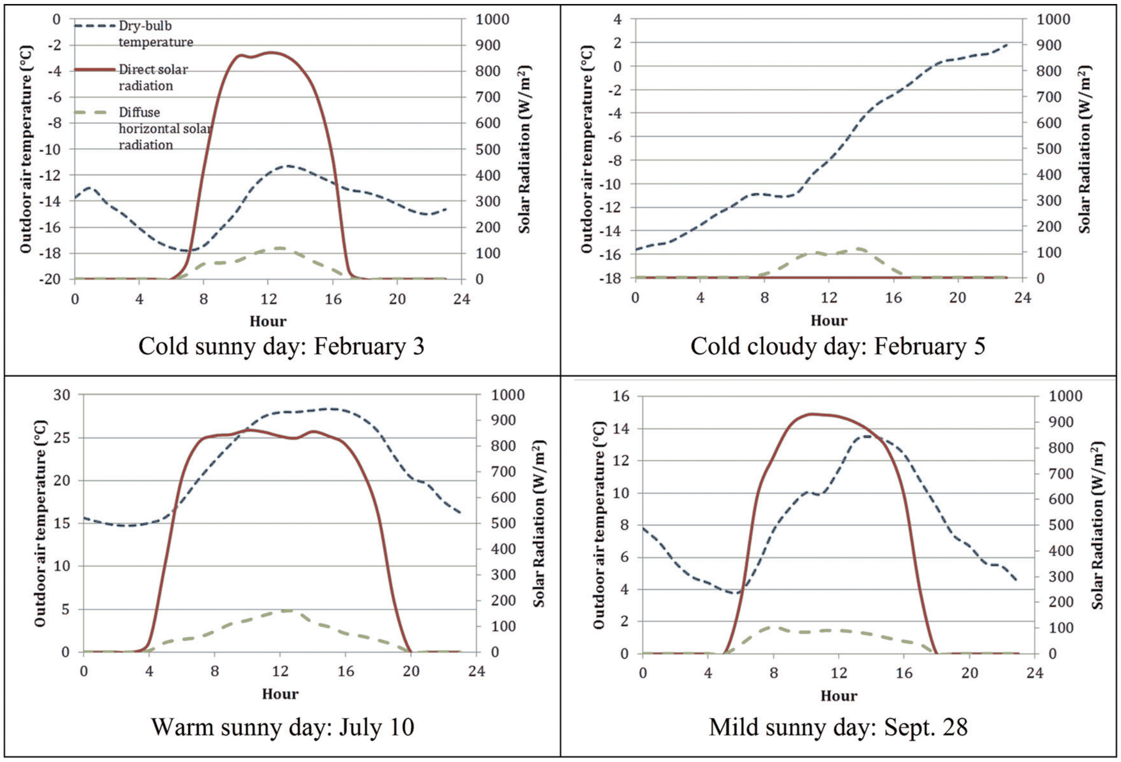


Figure 5 *House parameter design procedures (continued).*

The total heating energy for this cold sunny day is predicted to be 53.8 kWh (184 kBtu). Following that, the upper limit for south-facing glazing area was sought such that none of the spaces exceeded an operative temperature of 27°C (81°F). Meanwhile, the thermal mass on the floor and wall was increased to 10 cm (4 in.) of concrete and air circulation rate was increased to 500 L/s (1060 cfm). This was done to reduce temperature swings and better distribute solar gains (as can be seen by the significant differences in zone temperatures). These design changes resulted in less than half the heating energy on the cold sunny day, 25.2 kWh (86.0 kBtu) (see Figure 7[b]). A last step while still using the cold sunny day was to improve the thermal performance of the glazing to triple-glazed, low-e, argon-filled (not shown). Doing so for the non-south facing windows reduced heating energy by about 10%. However, the same upgrade for the south-facing window actually increased heating energy because the reduced heat loss was not exceeded by the reduced solar heat gains.

Using the cold cloudy day, the peak expected heating load is determined to be approximately 4 kW (13.6 kBtu/hr) (shown in Figure 8[a]). Experimentation showed that the total heating energy use for the cold sunny day cold be reduced from 79 to 69 kWh (270 to 235 kBtu) by increasing the basement insulation to the maximum of the range (see Table 1).Next, the warm sunny day was checked for cooling loads and discomfort [see Figure 8(b)]. While the cooling load is negligible, the operative temperature in the



Cold sunny day: February 3

Cold cloudy day: February 5

Warm sunny day: July 10

Mild sunny day: Sept. 28

Figure 6 *Key weather metrics for the four solar design days selected from the Toronto EPW file.*

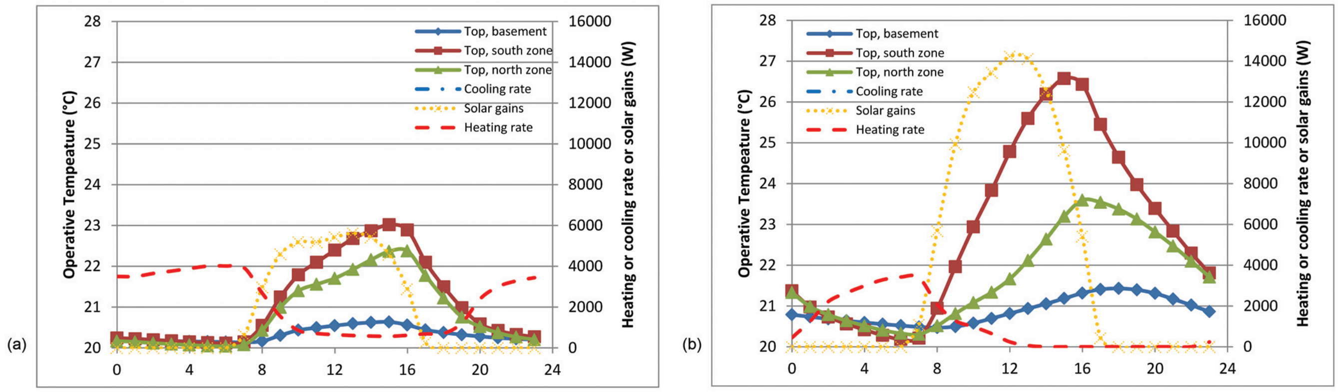


Figure 7 (a) Initial cold sunny day performance and (b) cold sunny day performance with passive solar features.

Table 1. Parameters of the Passive Solar House Model

Abr.	Name	Definition	Minimum	Maximum	Unit
WR	Wall Resistance	Thermal resistance of all above-grade (opaque) walls from surface to surface	3.7 (21)	12 (68.1)	m^2·K/W (h·ft^2·°F/Btu)
CR	Ceiling Resistance	Thermal resistance of the ceiling from surface to surface	8.8 (49)	15 (85.2)	m^2·K/W (h·ft^2·°F/Btu)
BS	Basement Slab Resistance	Thermal resistance of all basement slab (or slab on grade) from surface to surface	1.6 (9.1)	3 (17.0)	m^2·K/W (h·ft^2·°F/Btu)
BW	Basement Wall Resistance	Thermal resistance of all basement wall from surface to surface	3.1 (17.6)	6 (34.1)	m^2·K/W (h·ft^2·°F/Btu)
WT1	Window Type 1	Type of window for South-most window(s)	1	5	Class number[2]
WT2	Window Type 2	Type of window for East-most window(s)	1	5	Class number[2]
WT3	Window Type 3	Type of window for North-most window(s)	1	5	Class number[2]
WT4	Window Type 4	Type of window for West-most window(s)	1	5	Class number[2]
FT	Frame Type	Frame type for all windows on house	1	3	Class number[3]
WWR1	Window-to-Wall Ratio 1	Window-to-wall ratio for South-most window(s)	0.05	0.8	1
WWR2	Window-to-Wall Ratio 2	Window-to-wall ratio for East-most window(s)	0.05	0.5	1
WWR3	Window-to-Wall Ratio 3	Window-to-wall ratio for North-most window(s)	0.05	0.5	1
WWR4	Window-to-Wall Ratio 4	Window-to-wall ratio for West-most window(s)	0.05	0.5	1
CI	Air circulation rate	Air circulation rate between zones (assumed constant while on); turned on if $\Delta T > 3$°C	0	400 (847)	L/s (CFM)
OH	Overhang Depth	Overhang depth to window height ratio	0.001	0.5	1
BLS	Shades close solar threshold	Blinds/shades are closed if both of these conditions are exceeded	0	1000 (317)	W/m^2 (Btu/h·ft^2)
BLT	Shades close temperature threshold		15 (59)	40 (104)	°C (°F)
TMS	Thermal Mass on South zone floor	Thickness of concrete on on South zone floor	0.001 (0.0030)	0.2 (0.61)	m (ft)
TMV	Thermal mass on vertical wall	Thickness of concrete on interior vertical surface	0.001 (0.0030)	0.2 (0.61)	m (ft)

[1] Low, medium, or high internal gains scheme, averaging 550, 850, and 1250 Watts (1877, 2900, 4265 Btu/h).

[2] Double-glazed, clear, air-filled; double-glazed, clear, argon-filled; double-glazed, low-e, argon-filled; triple-glazed, clear, argon-filled; triple-glazed, low-e, argon-filled.

[3] Vinyl, wood, or aluminum with a thermal break.

space remains warmer than 27°C (81°F) for much of the later afternoon. It is critical to note that while the air temperature in the house is controlled to this upper limit, the operative temperature can exceed it when surface temperatures are warmed above 27°C (81°F) by incident solar radiation. To reduce peak temperatures, an overhang was implemented. Its depth is 30% of the window height and it is positioned high enough to not shade the glazing on winter solstice. The overhang reduced the peak operative temperature to 27°C (81°F) (Figure 9[a]). Using the cold sunny

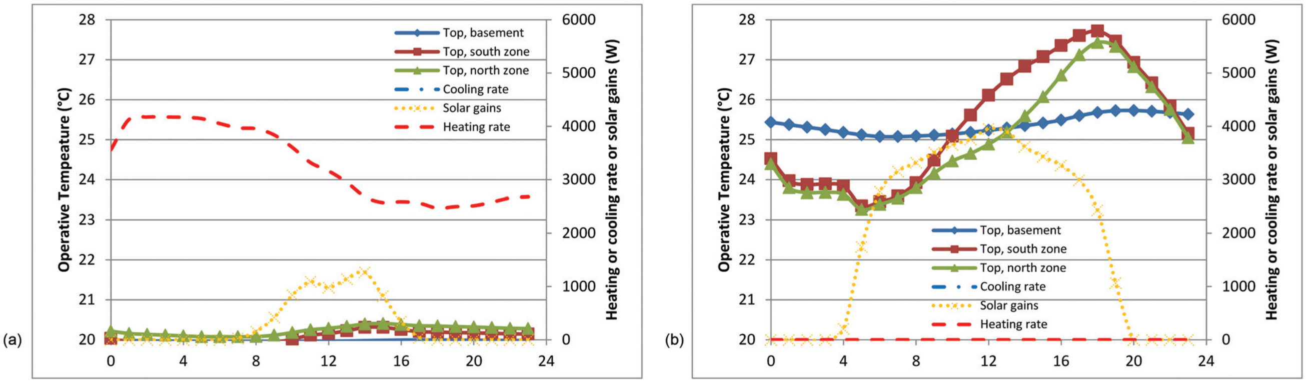


Figure 8 *(a) Cold cloudy day performance and (b) warm sunny day performance.*

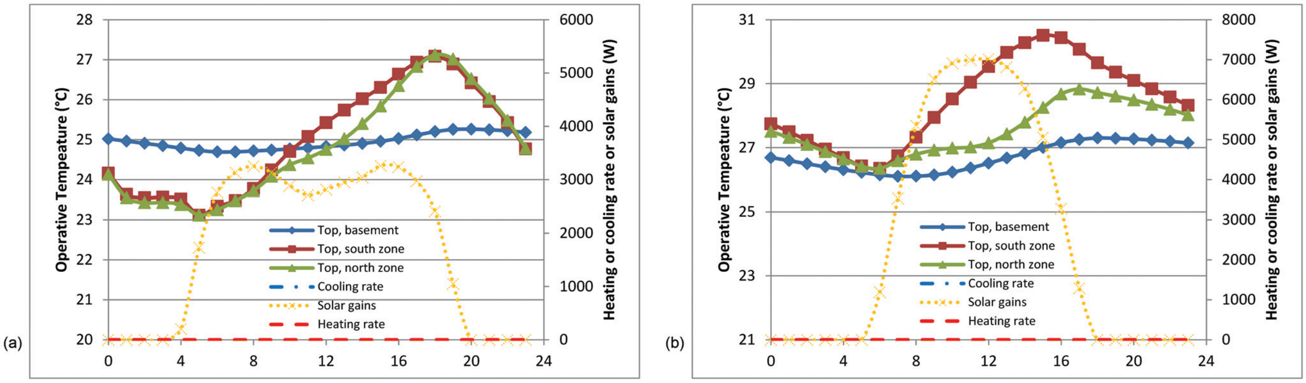


Figure 9 *(a) Warm sunny day performance with overhang and (b) mild sunny day performance.*

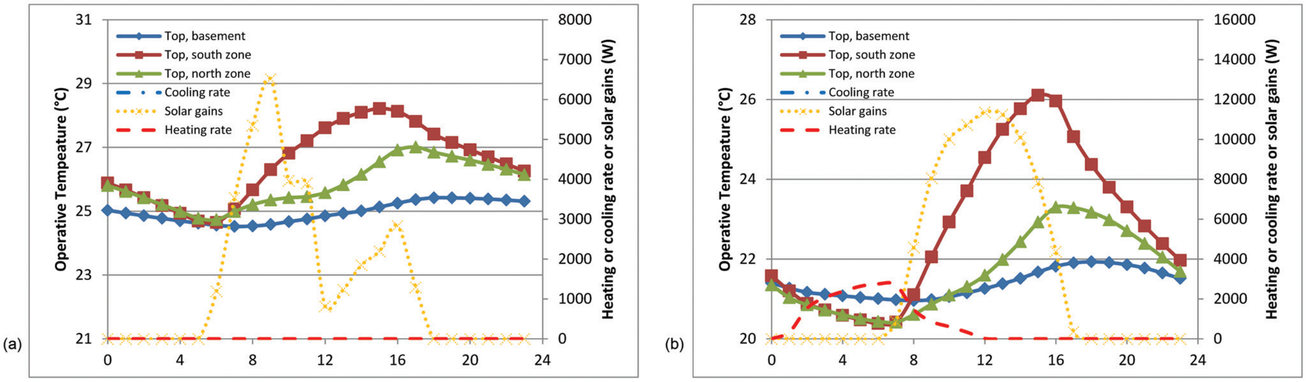


Figure 10 *(a) Warm sunny day performance with overhang and (b) mild sunny day performance.*

day, momentarily, this was found to have a minimal impact on heating energy use.

The mild sunny day is used to ensure comfort after the cooling season. The results (Figure 9[b]) show significant overheating (approaching 31°C [88°F]). The strategy to reduce this is to prioritize passive measures that reduce the peak temperature, while minimizing the effect on heating performance. Increasing the thermal mass thickness to 20 cm (8 in.) yielded only modest operative temperature reductions. Using automated shades that close if both the outdoor temperature and incident solar radiation exceed 10°C (50°F) and 300 W/m^2 (95 Btu/hr·ft^2), respectively, yielded a reduction of peak operative temperature by about 2.5°C (Figure 10[a]). Alternatively, given that the mild sunny day has outdoor temperatures between 4°C and 14°C (39°F to 57°F) (see Figure 6), operable windows could be controlled manually or automatically to alleviate discomfort during the late afternoon.

Finally, the other solar design days were checked to verify that design measures that were intended to prevent overheating did not adversely affect whole-year performance. The cold sunny day performance is actually slightly improved from the initial performance because of the window upgrade (Figure 10[b]).

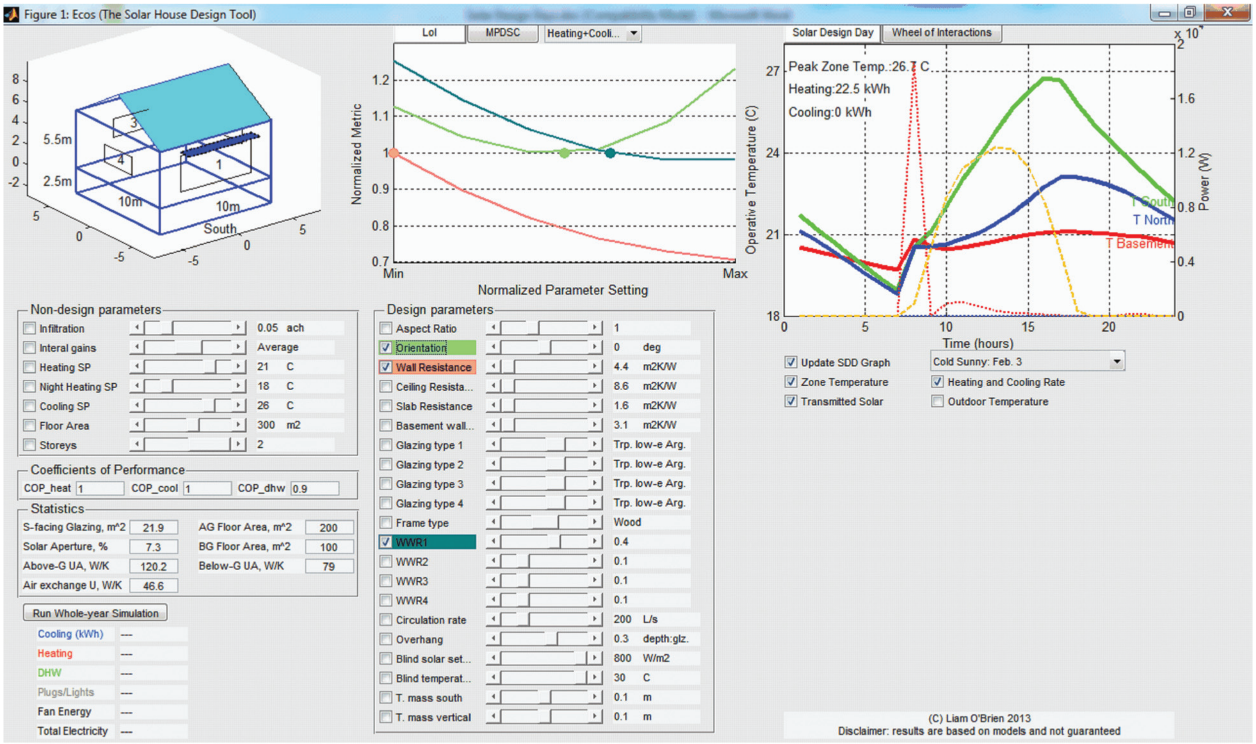
The resulting house design is predicted to use 4345 kWh (14.8 MBtu) per year for heating and 121 kWh (413 kBtu) per year for cooling. To remind the reader, this compares to original performance values of 7980 kWh (27.2 MBtu) for heating and 94 kWh (321 kBtu) for cooling.

CONCLUSIONS

This paper has explored the concept of solar design days and how they can be used to help design a house for near-optimal performance. Rather than attempt to decipher the effect of design changes through whole-year simulations, solar design days provide an insightful and educational experience by increasing the transparency of simulation and revealing cause and effect relationships while facilitating comparison of design options on a relative basis. Assuming the climate is deemed suitable for passive solar techniques, solar design days are intended to assist the designer to iterate a house design from a standard minimum, solar neutral house to a high-performance passive solar house. The cold sunny day is intended to be used to support the specification of south-facing windows and thermal mass. Meanwhile, the cold cloudy day can be used to verify that peak heating loads are not too high and to ensure thermal comfort from the potentially large and cold south-facing window areas is not compromised. The warm sunny day is used to ensure that cooling loads are minimal, while the mild sunny day is used to diagnose and resolve overheating in the shoulder season. As was shown in the example, passive solar houses are typically more prone to overheating in the autumn than in the summer because low midday solar altitudes cause high levels of solar gains.

To test the concept of solar design days, the methodology was implemented into a MATLAB graphical user interface. The interface allows the aforementioned parameters to be varied (bottom half of Figure 11) and the impact to be visualized as a 24-hour time series plot (top right of Figure 11). The one-day simulation takes approximately one second to run on a standard desktop computer, thus making this method very efficient for comparison of design options on a relative basis.

Future work shall be focused on three main areas: (1) visualization of simulation data, (2) increased resolution of thermal comfort modeling, and (3) increased occupant behavior models. Solar design days offer more performance data at a higher temporal resolution than is typically available from building simulation tools (interfaces, not engines). However, such information about individual surface temperatures, and a higher resolution about energy flow paths would be beneficial for targeting building upgrades. The current model used operative temperature to quantify thermal comfort. However, there are numerous other factors that should be considered in the thermal comfort of passive solar houses, including



Peak Zone Temp.:26.7 C
Heating:22.5 kWh
Cooling:0 kWh

Non-design parameters

☐ Infiltration	0.05	ach
☐ Interal gains	Average	
☐ Heating SP	21	C
☐ Night Heating SP	18	C
☐ Cooling SP	26	C
☐ Floor Area	300	m2
☐ Storeys	2	

Coefficients of Performance

COP_heat 1
COP_cool 1
COP_dhw 0.9

Statistics

S-facing Glazing, m^2	21.9	AG Floor Area, m^2	200
Solar Aperture, %	7.3	BG Floor Area, m^2	100
Above-G UA, W/K	120.2	Below-G UA, W/K	79
Air exchange U, W/K	46.6		

Cooling (kWh)	---
Heating	---
DHW	---
Plugs/Lights	---
Fan Energy	---
Total Electricity	---

Design parameters

☐ Aspect Ratio	1	
☑ Orientation	0	deg
☑ Wall Resistance	4.4	m2K/W
☐ Ceiling Resista...	8.6	m2K/W
☐ Slab Resistance	1.6	m2K/W
☐ Basement wall...	3.1	m2K/W
☐ Glazing type 1	Trp. low-e Arg.	
☐ Glazing type 2	Trp. low-e Arg.	
☐ Glazing type 3	Trp. low-e Arg.	
☐ Glazing type 4	Trp. low-e Arg.	
☐ Frame type	Wood	
☑ WWR1	0.4	
☐ WWR2	0.1	
☐ WWR3	0.1	
☐ WWR4	0.1	
☐ Circulation rate	200	L/s
☐ Overhang	0.3	depth:glz.
☐ Blind solar set...	800	W/m2
☐ Blind temperat...	30	C
☐ T. mass south	0.1	m
☐ T. mass vertical	0.1	m

☑ Update SDD Graph
Cold Sunny: Feb. 3
☑ Zone Temperature
☑ Heating and Cooling Rate
☑ Transmitted Solar
☐ Outdoor Temperature

(C) Liam O'Brien 2013
Disclaimer: results are based on models and not guaranteed

Figure 11 *Screenshot of one application of solar design days, where the performance for the four SDDs is updated in real-time as various design parameters are adjusted.*

glare, cold or warm floors, mean radiant temperature asymmetry, incident solar radiation on occupants, and daylight glare. As demonstrated by Doiron et al. (2011), discomfort can cause occupants to adapt a house in ways that cause it to behave thermally in contradiction of the designer's intentions. Finally, a more detailed model of occupant behavior (appliance and lighting use, adaptive measures [e.g., window opening, blind operation, clothing level adjustment], and physical presence), is increasingly important as building enclosures improve in thermal efficiency. The heat generated in well-insulated houses can exceed heat losses in the winter—similar to what commonly occurs in internal-load dominated commercial buildings. While all of these unknown modeling parameters can combine to propagate significant uncertainty about actual energy use, the bigger risk is that in the absence of the solar design days approach, designers will fail to optimize potential passive solar house performance.

ACKNOWLEDGMENTS

Funding by the NSERC Solar Buildings Research Network and the Jeffrey Cook Trust to support this work is graciously acknowledged.

REFERENCES

Al-Homoud, M.S. 2001. Computer-aided building energy analysis techniques. *Building and Environment* 36(4): 421–433.

ASHRAE. 2009. *ASHRAE Handbook—Fundamentals*: SI Edition. Atlanta, GA.

ASHRAE. 2010. ASHRAE Standard 90.2, *Energy-Efficient Design of Low-Rise Residential Buildings*. Atlanta, GA.

ASHRAE. 2010. ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA.

Arasteh, D., S. Selkowitz, J. Apte, and M. LaFrance. 2006. Zero energy windows. ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA.

Architectural Energy Corporation. 2012. SPOTTM: Sensor Position Optimization Tool. http://www.daylightinginnovations.com/spot-home.

Athienitis, A., and M. Santamouris. 2002. *Thermal Analysis and Design of Passive Solar Buildings*. London, James & James.

Athienitis, A. K., C. Liu, D. Hawes, D. Banu, and D. Feldman. 1997. Investigation of the thermal performance of a passive solar test-room with wall latent heat storage. *Building and Environment* 32(5):405–410.

Athienitis, A.K. 2007. Design of a Solar Home with BIPV-Thermal System and Ground Source Heat Pump. 2nd SBRN and SESCI 32nd Joint Conference, Calgary, AB.

Balcomb, J.D. 1983. Heat storage and distribution inside passive-solar buildings, Los Alamos National Lab., NM (USA).

Balcomb, J.D. 1992. *Passive Solar Buildings*. Cambridge, MA, The MIT Press.

Beausoleil-Morrison, I. 1996. *BASECALC™: A Software Tool for Modelling Residential-Foundation Heat Losses*. Third Canadian Conference in Computing in Building and Civil Engineering, Concordia University, Montreal Canada.

Canada Mortgage and Housing Corporation (CMHC). 1998. Tap the Sun passive solar techniques and home designs, CHMC.

Carmody, J., S. Selkowitz, E. Lee, D. Arasteh, and T. Willmert. 2004. *Window Systems for High-Performance Buildings*. New York, WW Norton and Company.

Charron, R., and A. Athienitis. 2006. Design and optimization of net zero energy solar homes. *ASHRAE Transactions* 112(2):285.

Chen, Y., A.K. Athienitis, and K. Galal. 2010. Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept. *Solar Energy* 84(11):1892–1907.

Chen, Y., K. Galal, and A.K. Athienitis. 2010. Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 2, ventilated concrete slab. *Solar Energy* 84(11):1908–1919.

Clarke, J. 2001. *Energy Simulation in Building Design*. Oxford, Butterworth-Heinemann.

Crawley, D.B., J.W. Hand, and L.K. Lawrie. 1999. Improving the weather information available to simulation programs. Building Simulation '99, Kyoto, Japan.

Department of Energy (DOE). 2012. EnergyPlus V7.2.from http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm.

Doiron, M., W. O'Brien, and A. Athienitis. 2011. Energy Performance, Comfort and Lessons Learned From a Near Net-Zero Energy Solar House. *ASHRAE Transactions* 117(2):1–13.

EnergyPlus. 2013. EnergyPlus Engineering Reference.from apps1.eere.energy.gov/buildings/energyplus/pdfs/engineeringreference.pdf.

Gusdorf, J., M.C. Swinton, E. Entchev, C. Simpson, and B. Castellan. 2010. The Impact of ECM furnace motors on natural gas use and overall energy use during the heating season at CCHT research facility. National Research Council Canada: 1-18. http://canmetenergy.nrcan.gc.ca/sites/canmetenergy.nrcan.gc.ca/files/files/pubs/ECM.pdf.

Hastings, R., M. Wall, and S.R. Hastings. 2006. *Sustainable Solar Housing: Two Volume Set*. Routledge.

HEED. 2009. HEED: Home Energy Efficient Design. Retrieved December 5, 2009, from http://www.energy-design-tools.aud.ucla.edu/heed/.

Intille, S.S. 2002. Designing a home of the future. IEEE Pervasive Computing, 1(2):76–82.

Karjalainen, S. 2009. Thermal comfort and use of thermostats in Finnish homes and offices. *Building and Environment* 44(6):1237–1245.

Keoleian, G.A., S. Blanchard, and P. Reppe. 2000. Life-cycle energy, costs, and strategies for improving a single-family house. *Journal of Industrial Ecology* 4(2):135–156.

Khudhair, A.M., and M.M. Farid. 2004. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energy Conversion and Management* 45(2):263–275.

Laouadi, A., A. Galasiu, M. Swinton, M. Manning, R. Marchand, C. Arsenault, and F. Szadkowski. 2008. Field performance of exterior solar shadings for residential windows: winter results. eSim. Quebec City, QC, May 20–22:1–8.

Lawrence Berkeley National Laboratory (LBNL). 2010. *Window 6.3 Software*. Berkeley, CA.

Lyons, P., D. Arasteh, and C. Huizenga. 1999. Window performance for human thermal comfort. *ASHRAE Transactions* 73(2):4.0–4.20.

Marszal, A., P. Heiselberg, J. Bourrelle, E. Musall, K. Voss, I. Sartori, and A. Napolitano. 2010. Zero Energy Building—A Review of definitions and calculation methodologies. *Energy and Buildings.*

Mathworks Inc. 2013. MATLAB 2013a. Natick, MA. from www.mathworks.com.

Milne, M. 2013. *Climate Consultant V5.4*. University of California Los Angeles.

National Renewable Energy Laboratory (NREL). 2013. BEopt 2.0. Golden, Colorado. http://beopt.nrel.gov/.

Natural Resources Canada (NRCan). 2008. About R-2000.

Natural Resources Canada (NRCan). 2010. HOT2000. Ottawa, Canada. http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/software_tools/hot2000.html.

Natural Resources Canada (NRCan). 2011. HOT3000: BETA V1.0, NRCan.

O'Brien, W., A. Athienitis, and T. Kesik. 2011. Thermal zoning and interzonal airflow in design of solar houses: a sensitivity analysis. *Journal of Building Performance Simulation* 4(3):239–256.

O'Brien, W., A. Athienitis, and T. Kesik. 2011. Parametric Analysis to support the integrated design and performance modeling of net-zero energy houses. *ASHRAE Transactions* 117(1):1–13.

Prazeres, L., and J.A. Clarke. 2003. Communicating building simulation outputs to users. Augenbroe and Hensen, ed. *Building Simulation* 3:11–14.

Sander, D.M., S.A. Barakat, National Research Council, C., and Division of Building, R. 1985. Mass & Glass: How Much? how Little?, National Research Council Canada, Division of Building Research.

Thormark, C. 2002. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment* 37(4):429–435.

Wallin, J., D. Bastien, and J. Claesson. 2012. The Influence of Energy Conservation on the Performance of Solar Thermal Systems—A Cold Country Case Study. *Energy Procedia* 30(0):1069–1078.