QC-06-027

Design and Optimization of Net Zero Energy Solar Homes

Rémi Charron

Andreas Athienitis, PhD
Member ASHRAE

ABSTRACT

Homes that utilize solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net zero energy solar homes (ZESHs). Various design guidelines exist that help designers determine form and orientation of buildings along with the best combination of thermal mass and windows. In addition, numerous components are essential to achieve the net zero energy target, including solar thermal collectors, PV, and efficient HVAC systems. Building simulation programs are an essential tool used in the design process to assess different technologies and building configurations. Building simulation and solar system simulation tools and methods have been converging toward modeling environments that consider the full complexities and coupling between thermal processes and solar generation systems. In the future, design optimization tools could assist designers in determining the most cost-effective ZESH design options.

INTRODUCTION

Homes that utilize solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net zero energy solar homes (ZESHs). Bill and Debbie Lord's house in Maine, seen in Figure 1, offers a good example of the possibilities of ZESHs (Lord and Lord 2005). ZESHs are designed to be highly energy efficient and to utilize passive solar building approaches to minimize their loads; the concept is not new. In fact, the first grid-connected ZESH, the Carlisle House, was built in 1980 with 7.5 kW of PV and 14 m^2 (108 ft^2) of solar thermal collectors. In the last 25 years, there have been many one-of-a-kind demonstration projects and international initiatives that have promoted the development of low and net zero energy homes (Hamada et al. 2003; Hoiting et al. 2003). The NRCan CANMET Energy Technology Centre (CETC) in Varennes recently started a multi-year project—research and development on the optimization of low-energy homes in Canada—to study past projects, existing and emerging technologies, and simulation and optimization software in order to learn what is needed to successfully implement low and net zero energy homes under Canadian climatic conditions (Charron and Athienitis 2005). This paper presents existing design guidelines, relevant technologies, and a discussion on building simulation tools. This paper is more heavily weighted for the design in more northern climates. Many of the guidelines are applicable over a wide range of climates; however, readers are encouraged to consult other literature sources for more detail on passive cooling strategies and active solar cooling technologies. Following will be a discussion of a design optimization tool that is being developed based on genetic algorithms (GAs) that will assist designers in creating more cost-effective ZESHs.

Figure 1 *The Lord residence.*

Rémi Charron is a research officer at CANMET Energy Technology Centre, National Research Council Canada, Varennes, Quebec. **Andreas Athienitis** is a professor in the Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada.

DESIGN GUIDELINES

A major requirement in solar-optimized building design is to first select the optimal form and orientation of the building for a given site. Without following this step first, subsequent simulation of design options is often done to justify decisions made on a subjective basis. The design team is faced with numerous parameters with various degrees of freedom. Variables that significantly influence solar energy utilization include window area, window thermal and optical characteristics, PV collector area and orientation, solar thermal collector area and orientation, thermal storage, HVAC system variables, and control strategies. There exist various guidelines and rules of thumb that can be used to help guide the designer in specifying the appropriate parameters. This section will identify some of the existing guidelines. Note that some of the guidelines were not necessarily developed using rigorous analysis and may need to be modified following an in-depth analysis of the problem.

Landscaping

Landscaping is an important element of passive solar design. Trees can help the performance by providing a barrier from the cold incoming wind and by providing shading in the summer. On the other hand, trees can be detrimental in the performance of passive housing design, as they can block the incoming solar radiation required to heat the house. According to the Sustainable Building Industry Council, evergreens should be located at least three times their projected (mature) height away from the south wall of the house (Chiras 2002). When PV is used, shading on the modules should be avoided as even a little shade on one part of the modules can significantly impact the performance of the whole system, since cells are typically connected in series.

Floor Plan and Orientation

As a general rule, a rectangular floor plan works best for passive solar design, with the long (east-west) axis of the house oriented within 10 degrees of true south (Chiras 2002). If the house needs to be off-south orientation, east is better than west, as that will help heat the house in the early morning and avoid direct sunlight in the afternoon. The ideal length-to-width ratio is 1.3 to 1.5 (Chiras 2002). A two-story compact house is better than a single-story house since its exterior building envelope is smaller per unit size of floor space. The layout of the interior space should be done in such a way that daily activities correspond to the sun's predictable path across the sky (Chiras 2002; CMHC 1998). In addition, the internal layout should promote natural ventilation with the use of large open spaces and openings for air to flow between floors and between north and south zones. When partition walls are needed, it is better to orient them in the north-south direction to allow for better north-south ventilation. Finally, lightweight surfaces should be painted lighter colors to allow for more light to be directed to the massive surfaces (CMHC 1998).

Thermal Mass, Windows, and Other Envelope Features

Thermal mass plays an important role in the design of passive solar houses. The mass allows for more heat to be captured, and the heat distribution is modulated allowing for less temperature swings in the house. The optimal amount of thermal mass that is required will depend on the amount of glazing that is used. A typical wood-framed house already has a certain amount of thermal mass associated with the construction materials, particularly gypsum board and ceramic tiles. Additional thermal mass is only required when the south-facing window area is larger than 7% to 8% of the total heated floor space (Chiras 2002; CMHC 1998) and the amount depends on the allowable room temperature swing. In general, using an energy simulation program is essential in understanding the effects that thermal mass has in any particular design (Grumman 2003).

The location of the mass also plays an important role in determining how much mass is required; mass that is heated indirectly by warm air from the living space is reported to require roughly four times more area as the same mass in direct sun to provide the same thermal effect (Chiras 2002). One drawback of thermal mass is that it is generally colder to the touch, which may prompt people to cover it with carpeting or other flooring. However, carpet can reduce effectiveness of thermal mass by up to 70% and vinyl floors can reduce effectiveness by up to 50% (CMHC 1998). The effectiveness of most forms of thermal mass increases proportionately up to 100 mm (Chiras 2002; CMHC 1998). Chiras (2002) offers the following three glass-to-mass ratios to help determine how much 10–15 cm (4–6 in.) thick mass to use:

1. each square meter of south-facing window beyond 7% of floor space requires an additional 5.5 m^2 of uncovered and sunlit floor mass (5.5 ft^2 per additional square foot);
2. for mass not in contact with the sun but in the same room, an additional 40 m^2 of mass is required per additional square meter of south-facing glazing above 7% (40 ft^2 per additional square foot); or
3. 8.3 m^2 of wall mass for each square meter of south-facing glazing above 7% (8.3 ft^2 per additional square foot).

Therefore, the optimal amount of glazing depends on the total heated floor area, total thermal mass, and other design parameters. In general, for direct gain passive solar heating, the solar south-facing glazing should range between 7% and 12% of total floor space. In passive solar homes with two or more solar features (thermal mass, sunspace, etc.), the total allotment of south-facing glass can be increased substantially but generally should not exceed 20% of the heated floor space. Utilization of automatically controlled motorized reflective blinds and possibly active heat storage may enable effective use of south-facing window areas close to 20% of floor area (Athienitis and Santamouris 2002). In direct-gain passive solar houses in most climates, north- and east-facing glass should be minimized, each accounting for no more than 4% of total floor space. Westfacing glass should not exceed 2% of total floor space (Chiras 2002). As a general rule, one large window is preferred to several small windows. To allow for good natural ventilation in the cooling season, 6%–8% operable windows to the conditioned floor area are needed. It is best to locate the operable windows on opposite walls in the direction of prevailing summer winds (CMHC 1998). Enhancing natural cross-ventilation is an important strategy to help reduce the peak cooling loads in the summer and can help reduce or eliminate the need for mechanical ventilation in the summer.

Thermal mass is not the only consideration in passive housing design. Increased insulation is required when houses are built in areas that experience either cold or hot climates. In these areas, it is recommended that the wall insulation be at a minimum of RSI 5 to 7 (R-30 to 40.0) and ceilings at minimum RSI 8.7 to 10.5 (R-50 to 60) (Chiras 2002). Chiras (2002) also provides a number of guidelines pertaining to windows. Low-emissivity windows are essential for optimal energy performance; however, requirements for north, south, east, and west windows may differ. In general, U-factors of smaller than 1.7 $W/m^2 \cdot K$ (0.3 $Btu/h \cdot ft^2 \cdot °F$) and with certified air leakage rates of less than 1.5×10^{-4} $L/s/cm^2$ (0.3 cfm/ft^2) are required for passively conditioned homes. The optimal solar heat gain coefficient (SHGC) is dependent on climate; for hot climates it is recommended to be under 0.4, for intermediate climates between 0.4-0.55, and for cold climates 0.55 or greater (Chiras 2002). If clerestory windows are used, it is suggested that they be placed in front of intended mass walls, usually at a distance of approximately 1 to 1.5 times the height of the wall to ensure maximum contact.

The proper design and placement of shading devices is an important element in passive solar design. When properly designed, overhangs can block out direct solar radiation during the summer and permit direct solar radiation in the winter. As a general rule, overhangs should be used such that they do not shade windows on December 21 but shade 50% to 100% of the windows on June 21 (CMHC 1998). The use of blinds is also important. Blinds placed on the outside of the building will not heat up the indoor environment and will thus help reduce the cooling load. However, these blinds need to be able to withstand the outdoor environmental conditions and blend in with the aesthetics of the house. In addition, the proper control of blinds is important to help regulate the amount of direct solar radiation allowed to penetrate the building envelope. The control of the blinds can be coupled to the control of the heating and cooling equipment to help these systems work together. The use of reflective motorized blinds may allow designers to increase window area for glazings with U-factors less than 1 $W/m^2 \cdot K$ (0.18 $Btu/h \cdot ft^2 \cdot °F$); the blind position may be controlled at four to five positions depending on interior and exterior temperatures as well as solar radiation, as done in the Canadian Solar Decathlon house (Pasini et al. 2005).

There are various other strategies that can be used in solar buildings to capture the sun's energy. CMHC (1998) states that trombe (collector storage) walls are generally not effective in colder climates (e.g., Canada), as they are not insulated, which results in significant heat loss at night. The same reference (CMHC 1998) discourages the use of isolated storage systems, such as rock beds, as the energy required to circulate the heat and the heat losses generated from the systems may make them not as efficient as desirable. However, isolated storage systems, including rock beds, have been successfully applied in both heating and cooling applications. Care should be taken to ensure proper design, construction, and commissioning to minimize the heat losses and ensure the proper operation of such systems.

HVAC Systems

Fewer guidelines are available regarding HVAC systems, as these generally depend on the type of heating, ventilation, and cooling system that is in place. The US Department of Energy (DOE) reports that it is common for heating systems to be two to three times larger than necessary (Chiras 2002); the heating system should be sized according to calculated heating loads. The interactions between the south-facing windows, the thermal mass, and the heating system need to be designed to ensure adequate comfort levels; the temperature in the heating season should only go above 25°C (77°F) for 4% of the heating season (CMHC 1998). In cases where a passive solar house has a south zone that has higher solar gains and reaches higher temperatures than adjacent zones, circulating fans should be turned on when the hot space is 3°C–4°C (5°F–7°F) hotter than the cold space. In the summer, ventilation through mechanical or passive measures should allow roughly 10 air changes per hour, with most exhaust coming from hot spaces (CMHC 1998). Whenever there is a need for exhaust in the heating season, a heat recovery ventilator with effectiveness ranging from 80% to 85% should be used. Proper utilization of thermal mass, window overhangs and blinds, natural ventilation, and other passive design strategies can significantly reduce the cooling load of the building. These factors need to be taken into account when determining the need for and sizing of any cooling equipment.

When installing radiant-floor heating systems, it is important to insulate underneath the floor and around the perimeter of the foundation; 5–10 cm (2–4 in.) of rigid foam insulation is reported to work well (Chiras 2002). Radiant systems can also be utilized for radiant cooling. However, residential applications are not common and are even discouraged by some manufacturers of radiant cooling panels (TWA 2005). The main reason for discouraging this application is the concern of having condensation occur on the cool panels during a hot, humid day. Residential buildings, as opposed to commercial ones, have much higher rates of outdoor air infiltration from open windows and doors, making it more difficult to provide humidity control. If properly designed and controlled, the condensation problem can be overcome as long as radiant panels are maintained at a temperature above the dew-point temperature. If the building envelope is sufficiently designed to minimize daily temperature swings and radiant panel surface areas are sufficient, panels at temperatures above the dew point can sufficiently cool a space (McDonnel 2003).

RELEVANT TECHNOLOGIES

One of the greatest challenges in designing a ZESH for Canada will be to meet the heating loads demanded by its harsh winters. The design of the house will include passive heating techniques in conjunction with an efficient, airtight envelope construction with highly insulated walls to reduce the heating load. However, these strategies alone will generally not be sufficient to meet the heating needs during the coldest days in winter.

Solar Combisystems

An interesting option for heating is to use solar combisystems in conjunction with auxiliary heating using electricity, biomass, or other fuels. A solar combisystem utilizes an active solar thermal collector for space heating and for heating domestic hot water (DHW). Approximately one-quarter of the 1,000,000 m^2 (0.39 mi^2) of solar collectors installed in central Europe in 2001 were used as combisystems (Frei 2003). In Sweden, the share of collector area installed as of 2001 was significantly larger for combisystems than the collector area installed for DHW alone, and it is assumed that in the next ten years a minimum of 20% of collector area installed annually at middle to northern latitudes will be used for solar combisystems (Weiss et al. 2003).

Intrinsic complexity of systems in conjunction with various incentive programs and fuel costs of different countries has led to widely differing system designs. However, the basic principle of promoting stratification of water in the storage tank is found in all designs. What varies are the size and type of collector, the size of thermal storage, the type of auxiliary heating, and the control strategy. Years ago, combisystems had various main components: collector array, space heating storage tank, DHW storage tank, electronic control, and a boiler. The use of a large number of components resulted in problems with the hydronic system and the controller, and the complex design reduced efficiency. The new approach emerging in Europe is to have a single, stratified storage tank that serves as an energy manager. Each energy source (solar and auxiliary) and different draws from the tank are connected at different heights to maintain the temperature layers in the tank, which avoids mixing and maintains stratification. These changes led to lowering the required number of pipes from 17 to 8 and reduced the space requirements from 4.8 to 2.2 m^2 (51.7 to 23.7 ft^2) and lowered the system weight from 250 to 160 kg (551 to 353 lb) (Weiss 2003).

Certain systems utilize large seasonal thermal storage to help increase the fraction of solar energy used throughout the year. Using current technologies and costs, a solar heating system with short-term heat storage that is combined with high standards of thermal building insulation is a more cost-effective system with higher efficiency than using seasonal storage (Weiss et al. 2003). It is possible that future heat storage technologies will be cheaper and more compact, to make having seasonal storage a viable option.

Current systems in Europe vary in size such that the solar contribution of the heating systems ranges from 10% to 100%. In the Netherlands, small systems comprising 4 to 6 m^2 (43.1 to 64.6 ft^2) of collector and 0.3 m^3 (79.3 gal) of storage tank are more typical, whereas in Switzerland, Austria, and Sweden, larger systems using 15 to 30 m^2 (161.5 to 323 ft^2) of collector area and 1 to 3 m^3 (264 to 793 gal) of thermal storage are typical. The larger systems allow for 20% to 60% of the heating demand to be met by solar energy, and for an extremely well-insulated house with low-flow mechanical ventilation, solar contribution can reach 100% (Weiss et al. 2003). In general, the expected range of collector area is 4 to 8 m^2 (43.1 to 86.2 ft^2) for DHW systems and 10 to 30 m^2 (107.6 to 323 ft^2) for combisystems. In IEA task 26 on solar combisystems, TRNSYS was used to optimize the system. The results indicated that for small systems—2 to 5 kW (6.8 to 17 MBH) of heat load—the optimum storage volume is from 50 to 200 L/kW (3.9 to 15.5 gal/MBH), the optimum tilt is 30 to 75 degrees, and orientation is best between 30 degrees east and 45 degrees west (Weiss et al. 2003).

One problem with sizing the collectors to meet both the heating and DHW loads in the winter is that in the summer the collectors will generate too much heat. The heat needs to be discarded in order to avoid overheating in the collector, which can cause damage to the collector and could break down the working fluid (glycol). One option is to use façade-integrated solar collectors. Façade integration is beneficial, as the collector receives a more evenly distributed amount of solar radiation over the year. Summer peak generation is reduced compared to roof systems, but it will still be sufficient to heat DHW and will reduce the potential of overheating. An added benefit of utilizing façade integration is that it results in a higher effective U-factor for the wall during cold days. Simulations have shown that the effective U-factor of a wall with a façade collector is reduced by up to 90% during cold winter days with high irradiation and by up to 45% during days with low irradiation, because the temperature of the outer layer of the wall—the collector—is higher than the ambient temperature outside. Monitoring of test façades confirmed the simulations (Weiss 2003).

Auxiliary Heating Systems

Even if the ZESH utilizes solar energy for both space heating and DHW, there will most likely be a requirement for an auxiliary heating source for extended periods of cold weather and for extended overcast conditions with limited insolation. There are many interesting energy-efficient sources of heat that could be used, such as ground-source heat pumps. What needs to be considered is the total heat load that the auxiliary heater will need to provide. If the house can meet 90% of its heating requirements with solar, it may not make sense to install a $10,000 heating system to provide only $100–$200 worth of heating a year (Chiras 2002). On the other hand, if the net zero energy target is to be met and that electricity is used for back-up heating, then the cost of using an inefficient heating system will result in having to purchase more PV to generate electricity, which would most likely cost more than using the efficient heating system at the current cost of PV. The issue of selecting the most cost-effective heating system for a ZESH is a complicated issue that is currently being investigated by the authors of this paper. Solutions will differ with local climatic conditions, control strategies, and electricity pricing schemes that may vary with time of day.

Domestic Hot Water

Tankless heaters provide users with endless hot water at high appliance energy-efficient performance compared to storage devices; however, they draw large amounts of power in an unpredictable manner (Dennis 2003). This would not be too bad for natural gas systems; however, if electricity is used, this could drive up peak loads and create problems for utilities. There is a way to mimic tankless heaters by using smart tanks that are heated from the top down, providing the ability to control the heated volume and to have faster recovery of usable water. Dennis (2003) suggests using smart tanks with predictive control to heat only the amount of water that would be required by users at a given time. For example, little hot water is consumed at night, whereas large draws can be expected in the mornings when various occupants have showers. In the case of the ZESH, which will depend on solar thermal energy to heat the DHW, a modified approach could be taken that utilizes these principles.

The smart tank principle can be used to increase the solar fraction utilized by a solar DHW system. Furbo et al. (2003) did an analysis that demonstrated the yearly thermal performance of systems with smart solar tanks to be 5%–35% higher than the thermal performance of traditional solar DHW systems depending on hot-water consumption and consumption patterns. As with a traditional system, the smart solar tank can be heated by solar collectors and by an auxiliary energy supply. The tank is designed such that the auxiliary heat to the tank comes from the top. As with a stand-alone smart tank, the energy supply from the electric heating element is controlled in such a way that during all hours the energy content in the top of the tank has a predetermined variable minimum quantity fitted to the hot-water demand, allowing the water volume heated by the auxiliary system to be varied as wanted and reduced to a minimum. The solar collector fluid heats up the DHW by means of the mantel. A side-arm loop draws water from the middle to the bottom of the tank and circulates it back to the top of the tank after it has been heated. A diagram of the smart solar tank investigated in Furbo et al. (2003) is shown in Figure 2. The circulation can either be caused by thermosyphoning or by a pump.

Different configurations of the auxiliary heating system can exist. In Furbo et al. (2003), the side-arm tank and a tank that utilized both a horizontal and a vertical electric heating element at the top of the tank were considered. The investigation revealed that the thermal performance of a system with a smart solar tank with a side-arm was somewhat greater than the performance of a smart tank with two built-in electric heating systems. Other configurations exist that may yield different results. The investigation also revealed that smart solar tanks are suitable for unknown, variable, large, or small hot-water consumption patterns and that risk of oversized solar heating systems and oversized tank volumes is reduced.

Smart solar tanks are most attractive if most hot-water consumption takes place in the evenings and least attractive when consumption is evenly distributed throughout the day. Reduced consumption during the day allows for a greater volume of water available to store the solar energy. The volume of the smart solar tank can be smaller than the volume of a traditional solar tank, the height of mantel for transferring solar heat can be greater for smart solar tanks, and a simple control system for an auxiliary energy supply system based on a few temperature sensors in the top of the tank is almost as good as an advanced control system keeping track of the energy content in the top of the tank. And even though the estimated cost of a small solar DHW with a smart tank is estimated to be 10% higher than traditional solar DHW systems with electric auxiliary heating, the performance/cost ratio is about 25% using the smart tank. A smart solar tank may be suitable for the ZESH. However, if the solar DHW is combined with the heating system through the use of a combisystem or other configuration, modifications to the concept would need to be made.

PV and PV/Thermal Solar Energy Systems

In the past two decades, research and development have improved the efficiency and reliability of photovoltaics and

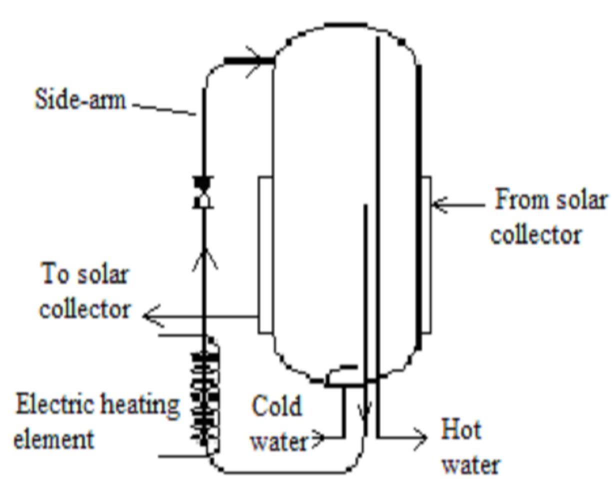

Figure 2 *Smart solar DHW tank (Furbo et al. 2003).*

have reduced the cost of photovoltaic electricity. Because of their overall efficiencies and material stability, the crystalline silicon-based technologies (single, poly, and ribbon) currently occupy over 80% of the market. The historic learning curve for PV modules shows a 20% price reduction for every doubling of the accumulated sales. The invariance of the experience curve for PV modules over this period corresponds to more than 13 doublings of cumulative production. This experience, in conjunction with the expected technological improvements from the R&D labs leading to higher module efficiencies in the range of 15% to 18% by 2010 and the automation of production lines resulting in module price declines to 2.00 US$/Wp by 2010, form reasonable bases for expectation that, with continued investments, a similar progress ratio is likely past 2010. The building of larger crystalline silicon manufacturing plants and the development of "thinner" silicon technologies that use less material will be important factors in reaching future industry cost targets. It has been predicted that the cost of PV electricity decreases to 0.08 US$ per kWh by 2020 without heat recovery. Assuming that twice as much heat is also recovered, the cost could drop to about 0.04 US$ per kWh.

In addition, amorphous silicon solar cells with peak conversion efficiencies between 5% and 13% have gone into continuous production (Uni-Solar 2006). A number of manufacturers are encapsulating PV cells between glass sheets or even depositing amorphous PV onto glass substrates. Modules are now being used in building "curtain-wall" assemblies as energy-producing building cladding or as semi-transparent glazing or are being incorporated into shingles for roof coverings (Ayoub et al. 2001).

Thermal solar energy systems can convert solar energy into heat at a rate greater than 80%. The integration of PV and solar thermal technologies could result in a combined PV/T system that could convert up to 80% of the available solar energy and benefit from the shared packaging, mounting, and installation costs. It is expected that the equivalent energy costs for the combined system would be under $2.50 per peak watt (electrical/thermal) and could approach $1.50 per peak watt in the future. When compared to conventional PV-generated energy at $8 per peak watt, the combined system significantly improves the cost-effectiveness of delivering high-grade solar energy. Although both PV and solar thermal technologies are relatively well developed, their integration into a single combined unit presents a number of technical challenges. In particular, silicon-based PV cells operate most effectively at cooler temperatures; however, conventional solar-thermal collection relies on achieving relatively high temperatures in the solar collector. Certain new PV technologies are less sensitive to increased temperatures but tend to be expensive.

A number of key issues involved in the integration of these two technologies relate to the solar receiver itself. Photovoltaics are electrical devices and therefore must be electrically insulated from each other and their substrate. Solar energy absorbed in the surface of the solar cells will be converted into electricity and heat. A requirement for the integrated solar receiver is that it effectively remove heat from the absorbing (PV) surface. This will require the design of an efficient heat removal mechanism in the solar receiver. PV cells are also fragile and subject to breakage during handling and if subjected to thermal shocks or extreme temperatures. The combined PV/T receiver must maintain its performance over the life of the system while being exposed to extreme temperature, moisture, and UV levels. There have been a few attempts to merge PV and solar thermal technology, with two recent efforts worth noting.

The first is related to the development of a combined PV/T solar collector. Based on the "MaReCo" (Karlsson and Wilson 1999) nontracking, low-concentrating thermal collector, it is best suited for high-latitude locations where integration into the building façade is possible. An absorber is positioned in an east-west orientation and a compound parabolic concentrator is used to direct sunlight onto its surface. Concentration ratios are typically low (i.e., 3×) but will result in higher PV temperatures (an undesirable situation) if not actively cooled. To remedy this situation, excess heat is transferred to a fluid circulating in channels below the cells. The authors claim that heat at 50°C (122°F) can be produced from this system and that about 300 kWh/m^2 (27.9 kWh/ft^2) of heat and 100 kWh/m^2 (9.3 kWh/ft^2) of electricity will be produced annually in Sweden, compared to a conventional (selective surface) thermal system that delivers approximately 400 kWh/m^2 (37.2 kWh/ft^2) of heat annually (Brogren and Karlsson 2002). The authors note that the major benefits of the system are the relative reduction in PV area required when using the reflectors and the ability to provide both electricity and heat energy such as is done in cogeneration applications. This concept, while having considerable merit, is hindered by its high-temperature limitation imposed by the PV cell's temperature dependence.

Another concept that has been commercialized is referred to as "SolarRoof" (CE 2005). This product utilizes the company's perforated-plate air-preheater as an underlay for conventional PV modules. It is a cost-effective system applied to opaque walls in commercial and residential buildings to preheat fresh air; its perforated absorber plate also serves as inexpensive cladding material that can be architecturally integrated in façades. In the system, air is drawn through gaps around and behind individual PV modules.

Other Important Components

There is not enough room in a single paper to mention all the important guidelines and technologies that are utilized to create low and net zero energy buildings. Therefore, this section will briefly mention some of the important parameters that were not formally included in the previous sections. There are various lighting technologies and strategies that can be used to lower the lighting energy consumption, such as using low ambient lighting levels, task lights at workstations, occupancy sensors, etc. The proper use of daylighting not only can help to reduce electricity consumption but also has been shown to improve productivity in schools and increase sales in retail stores (Grumman 2003). Using energy-efficient appliances in residential buildings is an essential way of reducing consumption. The Energy Star program has been developed to assist consumers in selecting energy-efficient appliances, lighting, heating and cooling equipment, and more (EPA 2005). Another important element of energy-efficient designs is the controls. Controls can wield a lot of leverage in affecting how efficiently a building operates, often with little incremental up-front effort or cost (Grumman 2003). Basically, any element of the design needs to be scrutinized to determine the role it can play in affecting the energy performance of the building.

BUILDING SIMULATION TOOLS

Since one of the most important tools in designing a ZESH is the building and solar system simulation tool, this section will provide a quick background on the development of these tools. There is an important distinction between building performance simulation and building energy analysis. Building energy analysis, using such approaches as the degree-day method, the equivalent full-load-hour method, or the more detailed "bin" method, was possible before computers became available and affordable (Sowell and Hittle 1995). True building simulation programs, on the other hand, could not be practically applied without computers; the attempt to imitate physical conditions by treating time as the independent variable results in a complex series of calculations. This is accomplished by re-forming and re-solving equation sets in discrete timesteps (usually a few minutes up to one hour). True simulation methods require significant computational resources. Millions of equations must be formed and solved to model even the most simple of buildings. It is not surprising, therefore, that the evolution of building simulation methods and software has closely paralleled developments in computer hardware.

In parallel to these developments, simulation methods and tools were developed for the modeling of solar hot water and solar-PV systems (Beckman 2000; Orgill and Hollands 1977; Thevenard et al. 1992). These solar-focused tools either decoupled the building's thermal and electric systems from the treatment of the solar conversion systems, as was the case in WATSUN (Orgill and Hollands 1977), or treated the building in a rudimentary manner, as in the case of earlier versions of TRNSYS (Klein el al. 1976). The building simulation and solar system simulation tools and methods have been converging toward modeling environments that consider the full complexities and coupling between thermal processes and solar generation systems. In addition to improving upon its modeling of active solar, water storage tanks, and solar PV components, recent versions of TRNSYS (Klein et al. 2004) include more rigorous treatment of building thermal processes and HVAC components (Welfonder et al. 2003). Models for active solar components (McLean 1982) and PV systems (Kelly 1998) have been incorporated into the ESP-r (Clarke 1985) building simulation program. EnergyPlus (Crawley et al. 2004), first released in 2001, has had two releases of updates every year upgrading the program with enhanced capabilities in modeling HVAC, solar technologies, design analysis, etc. Despite these efforts, much work remains to merge the high-resolution treatment of solar systems with a rigorous treatment of building thermal processes.

The development of building and solar system simulation tools for building designers and energy analysis is a complex and expensive endeavor. Modern simulation programs such as ESP-r, TRNSYS, and EnergyPlus have evolved over decades under the authorship of dozens of researchers and developers and contain many hundreds of thousands of lines of source code. Given the high costs of development and the relatively small potential user basis, there is little incentive for private sector investment in this field. Consequently, most developments are publicly funded and occur either in university settings or government research institutes. The major developer in Canada in terms of the production of building simulation tools for building designers and energy analysts is CETC.

Two different types of building simulation tools are used in practice, namely, open architecture tools (also known as *white box tools*) and black box tools. Open architecture tools allow the user to examine and modify the source code to meet specific modeling needs, and these include TRNSYS, ESP-r, EnergyPlus, etc. These tools generally take longer to learn and have less friendly graphical user interfaces. Black box tools, on the other hand, tend to have more intuitive and streamlined interfaces, where the user enters the required inputs and the program calculates the output without ever seeing the source code involved. These tools include HOT2000 (CANMET 1991), Energy10 (PSIC 1996), and EE4 (NRCan 2005), to name a few. Oftentimes, black box tools interact with open architecture tools such that the inputs are entered in the former and calculations are done in the latter. The multitude of tools available can seem overwhelming to users. When CETC was evaluating which program to use as a starting point for HOT3000 (NRCan 2005), it considered 31 different energy analysis programs. As with any simulation situation, a structured approach is required to determine what tool best addresses the needs.

A preliminary review of the tools' modeling methods, including how they deal with transient heat transfer, if they utilize the heat balance method, how they deal with long-wave radiation heat transfer, etc., helped eliminate 23 tools. Of the eight programs left, six had been developed at universities, HVAC Sim+ (Clark 1985) at the National Institute of Standards and Technology (US), and House II/ASHRAE (Crisafulli et al. 1989) at Energy Systems Group (US). Looking at issues related to obtaining rights to the program and source code helped eliminate another two tools. As people who have worked with simulation tools know, how the programs are documented and structured is critical. Looking at that left only TRNSYS, ESP-r, and EnergyPlus. A more detailed review of the modeling methods was done to try to find which simulation program would provide the best platform for the tasks at hand. All three programs had their disadvantages and advantages when compared with the requirements of HOT3000. In the end, CETC selected ESP-r; however, the other two tools would have also been appropriate. When determining which software to use to model ZESHs, one needs to consider what level of complexity is required and which tools could best model the coupled simulation of the building and its active solar technologies. A good place to start would be to look at a recently released review that contrasts the capabilities of 20 of the most popular building energy performance simulation programs (Crawley et al. 2005).

DISCUSSION

Using General Guidelines

This paper has presented various design guidelines for the design of low and net zero energy solar homes. It is important to understand the limitations of using general guidelines when making a design. General guidelines provide a range of possible solutions that have been known to work well. However, they are not necessarily the most optimal values to use for a particular design. Only detailed simulation can help determine situation-specific optimal values. For example, Chiras (2002) suggests the use of 10–15 cm (4–6 in.) of mass thickness. However, the optimal mass thickness will change depending on wall composition and material properties. In order to verify the validity of this rule of thumb, the magnitude and phase angle of a wall's important transfer functions, such as the self-admittance (Y_s) and transfer admittance (Y_t), need to be examined (Athienitis and Santamouris 2002). The self-admittance relates the effect that a heat source acting on a surface has on that surface's temperature, whereas the transfer admittance relates the effect of an outside temperature variation to the resulting heat flow at the inside surface.

Figures 3a–3d show the magnitude of the self-admittance for different thicknesses using a fundamental frequency of one cycle per day, representing the effect a dominant diurnal harmonic such as outdoor temperature and solar radiation would have, which are important in passive solar design. The wall is composed of an interior massive layer of concrete and an exterior insulating layer of negligible thermal capacity (4 RSI). Different concrete mixes generate different material properties. Figures 3a–3d show the results with four different concrete properties as summarized in Table 1. The maximum admittance occurs at thicknesses ranging from 13–24 cm (5.1–9.4 in.), which correspond to the thickness that would reduce the room temperature fluctuations the most. Varying the RSI value (R-value) of the exterior insulation does not make an appreciable difference in the optimal thickness. However, varying the specific heat of the concrete from the assumed value of 840 J/kg·°C (0.2 Btu/lb·°F) would have an impact. Other factors would also come into play when determining what thickness of concrete to use in a house. For exam-

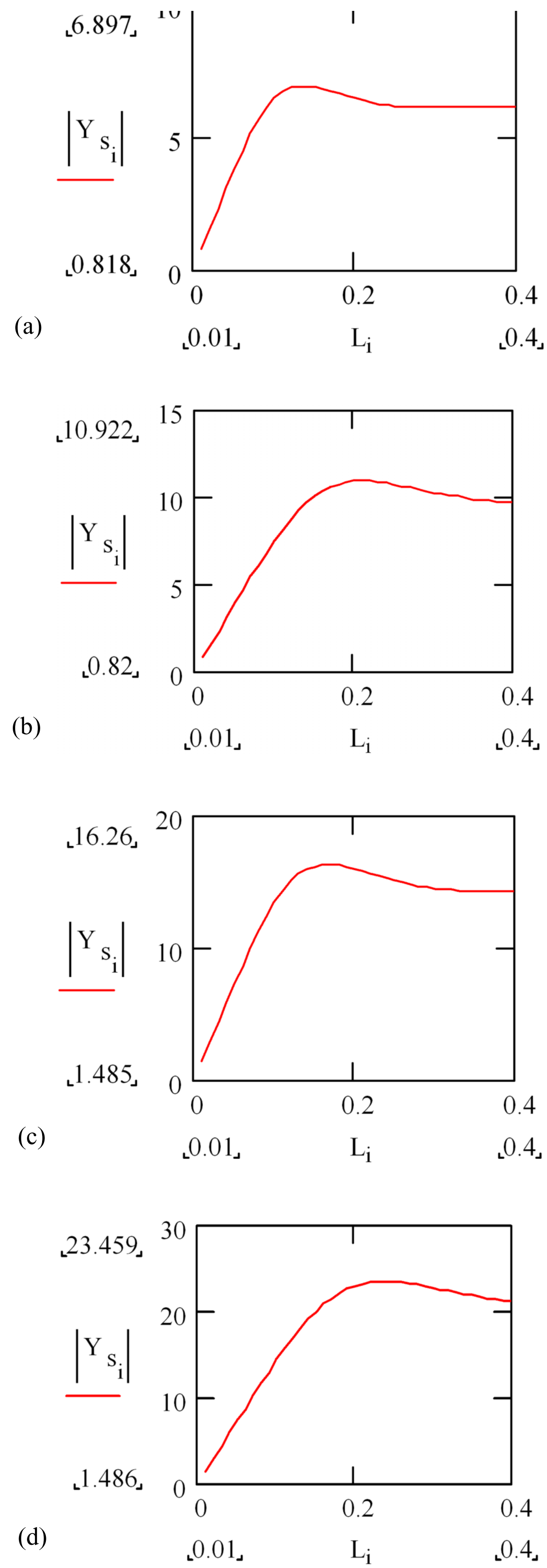

Figure 3 *(a) Peak* Y_s *at 13 cm, (b) peak* Y_s *at 21 cm, (c) peak* Y_s *at 17 cm, and (d) peak* Y_s *at 24 cm.*

Table 1. Various Properties of Concrete Used in Figures 3a–3d (McQuiston et al. 2005)

Figure	Density, kg/m^3 (lb/ft^3)	Thermal Conductivity, W/m·°C (Btu/h·ft·°F)	Specific Heat, J/kg·°C (Btu/lb·°F)
3a	1280 (80)	0.48 (0.28)	840 (0.2)
3b	1280 (80)	1.19 (0.69)	
3c	2400 (150)	1.4 (0.81)	
3d	2400 (150)	2.9 (1.68)	

ple, using 24 cm (9.4 in.) of concrete for the floor of a wood-framed house would result in serious structural challenges.

This one example shows that design guidelines are not necessarily the most optimum. The use of building simulation tools can help the designer determine when that is the case.

Other Design Strategies

As we have seen, designing a ZESH involves the coupling of many different systems to achieve an energy-efficient design that also generates on-site energy using renewable energy technologies to satisfy its yearly energy needs. The design involves the use of various types of systems, which can vary depending on the specific design objectives, the project location, the knowledge of the designer, etc.—all of which leads to many different configurations of ZESHs. This can be observed by examining the various net zero and low-energy building demonstration projects from around the world (Charron and Athienitis 2005). Current design methods depend on trial-and-error optimization using dynamic energy simulation tools coupled with the knowledge of the designers. Simulations are normally used in a scenario-by-scenario basis, with the designer generating one solution and subsequently having the computer evaluate it. This can be a slow and tedious process, and typically only a few scenarios are evaluated from a large range of possible choices (Caldas and Norford 2002).

Although a reduction in the energy use of residential buildings can be achieved by relatively simple individual measures, very high levels of performance require the coherent application of measures, which together optimize the performance of the complete building system. This multi-component optimization problem can lead designers to feel ill-equipped to tackle such a task. The application of computerized optimization techniques to the design of low and zero energy buildings would provide architects and engineers with a powerful design tool (Coley and Schukat 2002). Another drawback of the traditional trial-and-error method is that optimum designs are climate dependent; even if an excellent design was created by a group of expert designers, its functionality would vary in different climates. A design using an air-to-air heat pump might work well in a moderate climate but would most likely fail in very cold climates.

Coupling optimization algorithms to conventional simulation tools would assist designers in finding more optimal ways of reaching the net zero energy target. Various optimization algorithms are available to perform this task (Wetter and Wright 2004). The use of genetic algorithms (GA) for this type of application is emerging, as GAs have many natural advantages in the modeling and simulation of the built environment. They can handle nonlinear, ill-defined problems of many dimensions in search spaces with many local minima and are capable of processing large quantities of noisy data efficiently (Coley and Schukat 2002). The GA searches for optimum solutions by using the principle of natural selection. The GA represents parameters as a series of substrings, which are then concatenated to form a genotype. A random number generator produces a population of these genotypes during the first iteration. The fitness of each individual in the population is evaluated by using the parametric values forming the genotype in a simulation model of the system it represents. The best, or fittest, strings are then allowed to mate and produce progeny by combining substrings (of random length) from genotypes. Mutation is allowed for by occasionally randomly changing the values of a string position of a newly created progeny. After many generations of this process, the parameter values represented by the genotype are found to migrate toward optimized values.

GAs have been used to optimize different building systems, including solar collector and storage tank size (Kalogirou 2004); a low-energy community hall including shape of perimeter, roof pitch, constructional details of envelope, window types, locations and shading, and building orientation (Coley and Schukat 2002); window size and orientation (Caldas and Norford 2002); conceptual designs of office buildings (Grierson and Khajehpour 2002); and HVAC sizing, control, and room thermal mass (Wright et al. 2002).

Another advantage of using a GA is that it provides a population of optimum designs. Figure 4 shows the results of the use of GA in optimizing the construction of a low-energy community hall in the UK (Coley and Schukat 2002). As can be seen, there are countless possible design solutions that would use less energy compared to the average energy intensity for similar buildings in the UK (137 kWh/m^2, or 12.7 kWh/ft^2). What is even more useful is that the optimum designs can be very different, giving a lot of choice to the designer and/or building owner. For example, two of the more optimal designs that evolved in this study had very similar energy use but were very different. One used high levels of insulation to reduce losses with minimal window area, while the other focused more on maximizing passive solar utilization by having more windows and more thermal mass.

CONCLUSION

The growing concern regarding global warming, the continual development of energy-efficient appliances and HVAC systems, the expected drop in PV and solar thermal collector prices, and other driving factors should lead to the

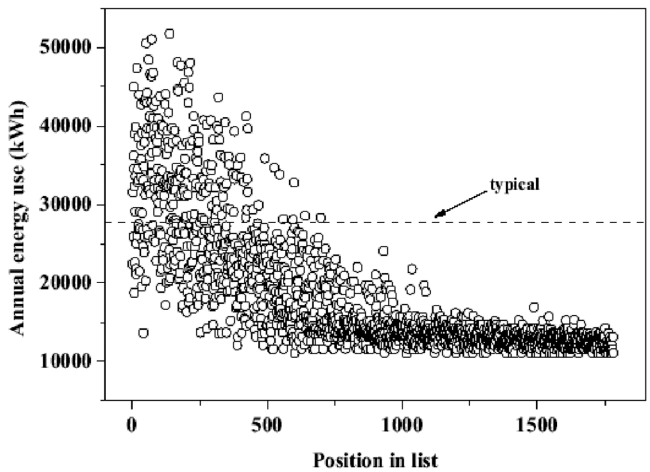

Figure 4 *GA results for the designing of a community hall (Coley and Schukat 2002).*

eventual mainstreaming of solar homes that either consume zero net energy or in fact generate a surplus of energy. Design guidelines and technologies currently exist to generate ZESHs. Advances in computing power and costs have helped facilitate the task of designing net zero and low-energy solar homes. They have helped improve the accuracy and capabilities of building energy performance simulation tools and can soon help in the emergence of a different type of tool altogether—the building optimization tool. In order to help accelerate the uptake of ZESHs, new design tools need to emerge that will help the designers determine the most cost-effective mix of technologies that needs to be introduced to achieve the net zero target, such as a GA-based optimization tool.

ACKNOWLEDGMENTS

Financial support for this collaborative research project was provided in part by Natural Resources Canada through the Technology and Innovation Program as part of the climate change plan for Canada.

REFERENCES

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

Ayoub, J., L. Dignard, and A. Filion. 2001. *Photovoltaic for Buildings: Opportunities for Canada*. Natural Resources Canada.

Beckman, W.A. 2000. TRNSYS: A transient system simulation program. *TRNSYS Manual*, Version 5. University of Wisconsin, Madison, USA: Solar Energy Laboratory.

Brogren, M., and B. Karlsson. 2002. Low-concentrating water-cooled PV-thermal hybrid systems for high latitudes. *Photovoltaic Specialists Conference,* Conference Record of the Twenty-Ninth IEEE, May 19–24, pp. 1733–36.

Caldas, L., and L. Norford. 2002. A design optimization tool based on a genetic algorithm. *Automation in Construction* 11:173–84.

CANMET. 1991. *HOT2000 Version 6.0. Technical Manual*. Ottawa: Natural Resources Canada.

CE. 2005. *SolarRoof—How it works*. Conserval Engineering, www.solarwall.com/roof/roofHow.html.

Charron, R., and A.K. Athienitis. 2005. An international review of low and zero energy homes. *ISES Solar World Congress 2005,* Orlando, FL, USA.

Chiras, D. 2002. *The Solar House: Passive Heating and Cooling*. White River Junction, VT: Chelsea Green Publishing.

CMHC. 1998. *Tap the Sun: Passive Solar Techniques and Home Designs.* Ottawa: Canada Mortgage and Housing Corporation.

Clark, D.R. 1985. *HVAC Sim+ Building Systems and Equipment Simulation Program Reference Manual,* NBSIR 84-2996. Washington, D.C.: National Bureau of Standards.

Clarke, J.A. 1985. The ESP system towards a new generation of building energy analysis program. *Proceedings of the Building Energy Simulation Conference, Seattle, WA*, pp. 215–27.

Coley, D., and S. Schukat. 2002. Low-energy design: Combining computer-based optimisation and human judgment. *Building and Environment* 37:1241–47.

Crawley, D., L. Lawrie, C. Pedersen, F. Winkelmann, M. Witte, R. Strand, R. Liesen, W. Buhl, Y. Huang, R. Henninger, J. Glazer, D. Fisher, D. Shirey, B. Griffith, P. Ellis, and L. Gu. 2004. Energy Plus: New capable and linked. *Proceedings of the SimBuild 2004 Conference, August 2004, Boulder, Colorado,* IBPSA-USA.

Crawley, D., J. Hand, M. Kummert, and B. Griffith. 2005. *Contrasting the Performance of Building Energy Performance Simulation Program.* University of Strathclyde, University of Wisconsin: United States Department of Energy, www.eere.energy.gov/buildings/tools_directory/.

Crisafulli, J.J., R.A. Cudnik, and L.R. Brand. 1989. Investigation of regional differences in residential HVAC system performance using the SP43 simulation model. *ASHRAE Transactions* 95(1):915–29.

Dennis, M. 2003. Optimising energy balance for systems with storage. *ISES Solar World Congress 2003, Gothenburg, Sweden*.

EPA. 2005. Energy Star. www.energystar.gov . Washington, DC: US Environmental Protection Agency.

Frei, U. 2003. Solar thermal collectors, state of the art and further development. *ISES Solar World Congress 2003*, *Gothenburg, Sweden.*

Furbo, S., E. Anderson, S. Knudsen, N. Vejen, and L. Shah. 2003. Smart solar tanks for small solar domestic hot water systems. *ISES Solar World Congress 2003, Gothenburg, Sweden.*

Grierson, D.E., and S. Khajehpour. 2002. Method for conceptual design applied to office buildings. *Journal of Computing in Civil Engineering* 16:83–103.

Grumman, P. 2003. *ASHRAE GreenGuide*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.

Hamada, Y., M. Nakamura, K. Ochifuji, S. Yokoyama, and K. Nagano. 2003. Development of a database of low energy homes around the world and analyses of their trends. *Renewable Energy* 28:321–28.

Hoiting, H., G. Donze, and L. Verhoef. 2003. 10 different zero energy projects in the Netherlands. *ISES Solar World Congress, Gothenburg, Sweden.*

Kalogirou S. 2004. Optimization of solar systems using artificial neural-networks and genetic algorithms. *Applied Energy* 77:383–405.

Karlsson, B., and G. Wilson. 1999. MaReCo—A large asymmetric CPC for high latitudes. *ISES Solar World Congress 1999.*

Kelly, N.J. 1998. Towards a design environment for building-integrated energy systems: The integration of electrical power flow modeling with building simulation. PhD thesis, University of Strathclyde, Glasgow, UK.

Klein, S.A., J. Duffie, and W. Beckman. 1976. TRNSYS—A transient simulation program. *ASHRAE Trans*. 82:623.

Klein, S.A., J. Duffie, J. Mitchell, J. Kummer, J. Thornton, W. Beckman, N. Duffie, J. Braun, R. Urban, N. Blair, D. Bradley, J. Mitchell, T. Freeman, B. Evans, A. Fiksel, and P. Williams. 2004. *TRNSYS 16—A TRaNsient SYstem Simulation program, User Manual*. Madison: University of Wisconsin-Madison, Solar Energy Laboratory.

Lord, D., and B. Lord. 2005. *Maine Solar House.* www.solarhouse.com.

McDonnel, G. 2003. Radiant solutions. *Canadian Architect*, www.omicronaec.com/resources/Radiant_Solutions.pdf.

McLean, D.J. 1982. The simulation of solar energy systems. PhD thesis, University of Strathclyde, Glasgow, UK.

McQuiston., F., J. Parker, and J. Spitler. 2005. *Heating, Ventilating, and Air Conditioning Analysis and Design.* 6th ed. Hoboken, NJ: John Wiley & Sons.

NRCan. 2005. EE4. www.ee4.com. Ottawa: National Resources Canada.

NRCan. 2005. *HOT3000,* www.buildingsgroup.nrcan.gc.ca/software/hot3000_e.html.

Orgill, J.F., and K.G.T. Hollands. 1977. *WATSUN, a Solar Heating Simulation and Economic Evaluation Program: Version 3.0: User's Manual.*Waterloo, Canada: University of Waterloo.

Pasini, M., Y. Chen, R. Moussa, K.W. Park, and A. Athienitis. 2005. Solar energy utilization in the 2005 Canadian solar decathlon home. *30th Annual Conference of SESCI, August 2005, Burnaby, British-Columbia, Canada*.

PSIC. 1996. *Designing Low-Energy Buildings: Passive Solar Strategies & ENERGY-10 Software 1.0*. Washington, DC: Passive Solar Industries Council.

Sowell, E.F., and D.C. Hittle. 1995. Evolution of building energy simulation methodology. *ASHRAE Trans.* 101(1):850–55.

Thevenard, D., S. Dixon, K. Rueb, and M. Chandrashekar. 1992. The current-voltage model for PV modules in the WATSUN-PV simulation software. *Proceedings of the 18th Annual Conf. SESCI, July 4–8, Edmonton, Alberta, Canada,* pp. 39–42.

TWA. 2005. www.twapanels.co.uk/cooling.htm. TWA Panels UK Ltd.

Weiss, W. 2003. Solar heating systems—Status and recent developments. *ISES Solar World Congress 2003, Gothenburg, Sweden.*

Weiss, W., J.-M. Suter, and T. Letz. 2003. Comparison of system designs of solar combisystems. *ISES Solar World Congress 2003, Gothenburg, Sweden.*

Welfonder, T., M. Hiller, S. Holst, and A. Knirsch. 2003. Improvements on the capabilities of TRNSYS 15. *Proceedings of Building Simulation '03*, pp. 1377–84. Eindhoven, Netherlands: International Building Performance Simulation Association.

Wetter, M., and J. Wright. 2004. A comparison of deterministic and probilistic optimization algorithms for nonsmooth simulation-based optimization. *Building and Environment* 39:989–99.

Wright, J., H. Loosemore, and R. Farmani. 2002. Optimization of building thermal design and control by multi-criterion genetic algorithm. *Energy and Buildings* 34:959–72.