# SOLAR ARCHITECTURE AND ENERGY ENGINEERING

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*Anyone who believes exponential growth can go on forever*
*in a finite world is either a madman or an economist.*
—Kenneth Boulding, Economist

## INTRODUCTION

*The modern built environment has been developed in a context of readily-available, low-cost energy from highly concentrated fossil fuels. Today's global energy landscape has dramatically changed; energy costs have become significant in the operation of buildings, and the sector uses a major portion of the global resources of fossil fuels.*

*In recent years a major focus of green building development in North America and internationally has been on setting up sustainable energy practices for the built environment. This focus has advanced energy conservation and efficiency measures for buildings; on-site clean energy generation is now positioned as a critical next step in meeting increasing energy demands while enhancing the functionality and comfort of buildings.*

*"Solar Architecture" as a green building concept addresses sustainable energy practices and the needs of the three major tiers of the built environment: community planning, existing buildings, and new construction.*

*This article uses a case study of integrating renewable energy engineering into university campus energy planning to demonstrate some of the roles energy engineering plays in our built environment. As part of a master planning process for Dalhousie University, solar energy generation potential mapping and the SolarStarRating™ system were used to facilitate the integration of solar technologies into the community energy mix. The process identified the buildings most suited to retrofitting with solar technologies, and enabled the best opportunities to be investigated.*

## KEYWORDS

renewable energy, solar architecture, master-plan, GIS, solar air heating

## SOLAR MAPPING FOR CAMPUS ENERGY PLANNING

Dalhousie University was founded in 1818. It is the largest post-secondary educational institution in the Maritime Provinces, and a member of G13, a group of leading research-intensive universities in Canada. The University supports, as a cornerstone of its sustainability policy, approaches and decisions that improve the campus and local community ecology, economy, and health. To advance its sustainability vision, the University initiated the development of its 10-year comprehensive Campus Master Plan in 2008. The major objectives of the master planning process were to guide improvements in space utilization and development, capital budgeting, and project implementation (renovations and expansions, acquisition and new construction).

A comprehensive Solar Study of the three University campuses was an integral part of Dalhousie's master planning process. The objectives of this Solar Study were to determine the suitability of the University facilities and open areas to solar energy, and to develop recommendations for applying solar energy technologies in the University's energy mix.

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## *Solar Resource Assessment*

Users of solar energy technologies need high-quality solar radiation data to maximize the output of the energy systems and the return on investment.

Solar gain at the earth's surface is the sum of direct and diffuse radiation. When sunlight passes through the earth's atmosphere, a portion is scattered or absorbed by haze, particles, or clouds, and only some of this portion reaches the earth's surface as diffuse radiation. On an overcast day, essentially all radiation that reaches the ground is diffuse, while on a clear day most radiation is direct. Radiation levels are also affected by the position of the sun above the horizon; this angle—and the nature of the air mass through which the sunlight travels—changes during the day and through the year.

For solar energy resource assessments we use the total annual radiation based on calculations of monthly average solar gain on a horizontal surface. This value is typically referred to as global horizontal radiation, expressed as a daily average in units of kWh/m2/day.

Historically, ground measurements have been used to determine surface-level radiation and other weather parameters for renewable energy projects. Although ground measurement data have been used successfully in the past, there are inherent problems and limitations in using them for resource assessment. For this project we also accessed solar energy information from NASA Earth Science Enterprise (ESE) program's satellite and reanalysis research data (http://science.nasa.gov/earth-science/). In contrast to ground measurements, the Surface meteorology and Solar Energy (SSE) data set is a continuous and consistent global climatology of solar gain and other weather data over a period of 10 years or more. The data are provided on a 1° × 1° grid system.

The monthly dynamics of average solar radiation on a horizontal surface in Halifax Region, as estimated by long-term NASA solar climatology and ground site measurements (1964–1988) are plotted in Figure 1. The monthly average values are shown to vary between 1.5 and 5.6 kW/sq.m./day between December and June.

The intent for this project was to provide solar resource information for Halifax Peninsula to enable us to make decisions concerning suitability of a particular building for solar applications. The SSE estimate was considered to have the required precision for preliminary feasibility studies of new renewable energy projects and for application to this project. However, in solar energy prospecting, spatial patterns and variability of data may be more valuable than precise average values; a more advanced solar resource mapping technology, which uses high resolution satellite data and quality ground measurement, is available to address this objective.

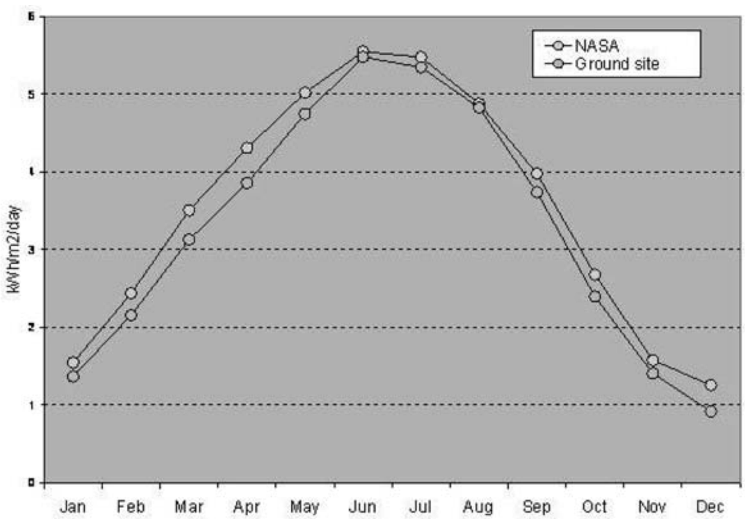



**FIGURE 1.** Monthly Average Solar Radiation on Horizontal Surface, Halifax Region (kWh/m2/day).

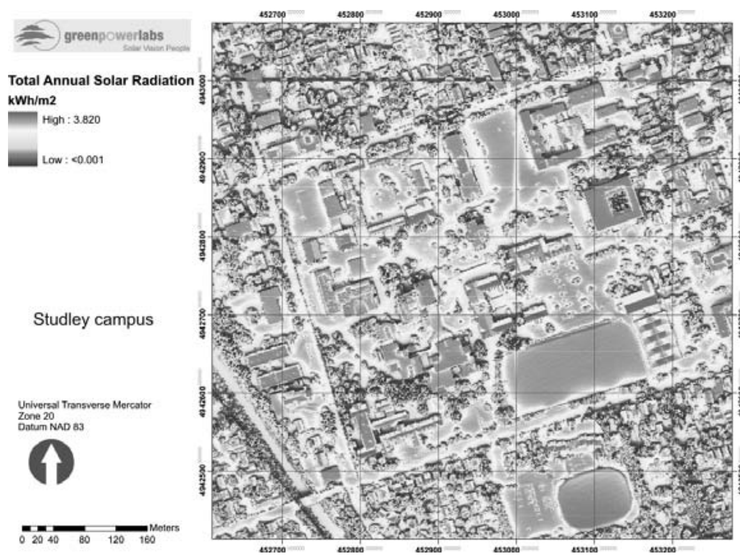



**FIGURE 2.** Total Annual Solar Gain, Studley Campus.

### *Campus-Wide Solar Gain*

The implications of shading in the built environment were studied using geographic information systems (GIS). A three-dimensional model of the campus was developed using LiDAR (Light Detection and Ranging) data obtained from Halifax Regional Municipality. The information was mapped and a "virtual fisheye" analysis then computed the shading characteristics and solar gain on a 20 cm grid for each of the three University campuses.

An example of the resulting solar resource mapping is shown in Figure 2. As shown in this area of 700 m square, the average total solar gain on building and ground surfaces reaches 3.8 kW/sq.m./day on exposed south-sloping roof segments.

The solar mapping identifies the solar resource as a community energy asset. The mapping provides a solid foundation for quantifying the energy output of applicable solar technologies at existing buildings.

The mapping has been used to identify potential sites for developing buildings able to take advantage of the solar resource; it also provides a decision tool in planning the landscaping of the campus by showing areas of high and low solar gain throughout the year. The model may be used as a design tool, for example, by adding proposed building or landscaping options to identify their impact at specific times, seasons, or throughout the year.

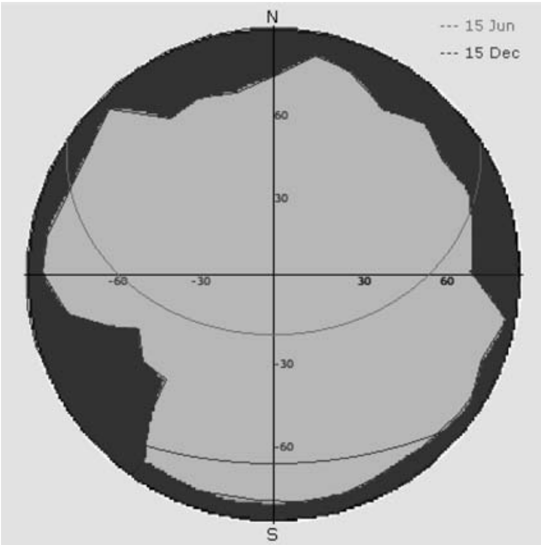
To describe the analysis in more detail, the LiDAR technology measures properties of scattered light to find range and other information of a distant target. Airborne laser scanning delivers the detailed surface information. This study used data for the Halifax area provided by PHB Technologies/LaserMap Image Plus under contract to Halifax Regional Municipality in May 2007, which provided three-dimensional data at density of 10 points/m$^2$.

The data was captured in ArcGIS software (ESRI Canada) and then processed in a 0.2 m grid covering the three campuses to obtain the solar radiation intensity. At each grid point, proprietary software was used to create a "virtual fisheye" image of the surrounding topography, as illustrated in Figure 3, and to perform an obstructions analysis to determine the effect of the topography on the solar radiation at the point.

The virtual fisheye image in Figure 3 is the calculated upward view of the sky hemisphere from a point on the roof of one of the buildings on campus, similar to a photograph from the location using a 180° wide-angle lens. The upper curve shown is the calculated path of the sun on June 15th; the lower curve represents December 15th. Obstructions to direct sunlight are shown in silhouette.

For each grid point, the effects of shading from obstructions were calculated at hourly intervals at the

**FIGURE 3.** Virtual Fisheye Image—Roof of Nu-Tech Building.




middle of each month. The results were presented as average annual global horizontal radiation, but may also be calculated for specific days or seasons.

## SOLAR ENERGY POTENTIAL, TECHNOLOGIES, AND APPLICATIONS

The value of a renewable energy system is a function of the renewable energy resource, the technology for energy harvesting and transfer, and demand for energy.

Typically, the Dalhousie University buildings use significant quantities of energy in the form of electricity from the grid for equipment loads and lighting, and steam or pressurized hot water generated from heavy fuel oil at the University Central Services Building for space heating and domestic hot water. Each building uses more electrical energy than may be generated by available solar technology at the site, and less domestic hot water than may be generated by solar water heating.

The solar resource available at a building is determined by a number of natural and architectural factors, including topography, landscape, building aesthetic criteria, roof configuration, and façade characteristics. These factors are considered to estimate the areas of roof, wall, and/or site surfaces that can be used and the solar radiation that can be harvested. A SolarStarRating™ system was used to provide an initial indication of solar suitability, as a first step in selecting candidate buildings for solar technology applications.

The study considered the energy harvesting technologies for solar air heating, solar water heating, and solar electrical generation. Solar water heating and electrical generation are most commonly applied to roof surfaces, while solar air heating technologies are typically wall-mounted to favour heat gains in the fall and winter. The generation potential for these technologies was calculated for each building.

### *SolarStarRating™: Identifying the Solar Suitability of the University Facilities*

A SolarStarRating™ system was used to measure the suitability of each campus facility to generate solar energy, based on the quality of the solar resource and the architectural features of the facility.

As shown in Figure 4, the potential for solar applications is shown by shading or colour.

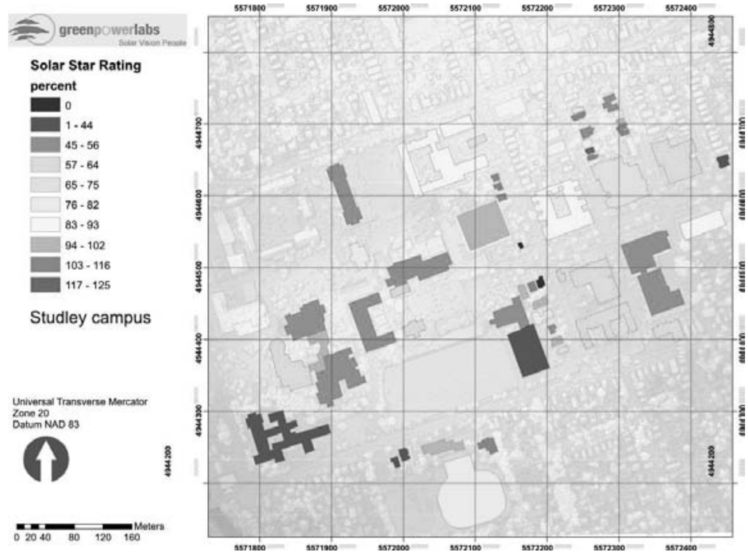
For the 95 buildings included in the analysis, the SolarStar rating varied between zero and 121%, with an average value of 71%. Upper and lower quartile values were 90% and 52%, respectively.

The solar generation potential maps prioritized the campus facilities and identified the best candidates for solar energy applications.

Originally developed for the residential construction sector, the SolarStarRating™ system provides a quick reference and comparison tool on the solar resource potential of each building. The rating compares the amount of useable solar energy yield of each building with the yield of a reference building design optimized for active solar applications.

For residential buildings, the reference building is defined by footprint area, number of floors, and floor-to-floor height. The reference design is considered to have a roof in which half of the area faces due south and has an optimum slope for solar gain, and all of this area is available for solar equipment; walls are configured based on a rectangular floor plan in proportion to the "golden ratio" (from Renaissance architecture) of 1.618, with longer wall surfaces facing south, and 50% of wall surfaces being available

FIGURE 4. SolarStar Rating, Studley Campus.




for solar applications. For commercial buildings, 60% of wall surfaces are considered, and, for flat roofs, 80% of the total roof surface is used. All surfaces are considered unobstructed. The solar gain on these surfaces is based on the local climate.

The solar resource potential of each building was evaluated and presented as a percentage of this reference design value. For this assessment, solar suitable surfaces were considered to include south-facing roof or wall surfaces or flat roofs with a minimum dimension of 3.0 m (10 ft) to accommodate solar equipment.

### Solar Resource Potential of Campus Buildings

The University buildings are orientated with the most southerly facing walls having an azimuth of between 18° and 22° east of south, the majority being at 18°. The larger buildings are predominantly flat-roofed: approximately 3/4 of the overall roof area is nominally flat, 1/8 is sloped and planar, and 1/8 is curved. The slopes typically vary between 20° (nominally 4:12) and 45° (12:12).

At Dalhousie's geographic location, a flat surface has an average annual radiation rate of 3.52 kWh/m2/d. A maximum radiation rate of 4.10 kWh/m2/d is achieved for fixed surfaces sloped at an angle of 35° to the horizontal, and orientated due south.

The Insolation Index is used to identify the relative suitability of surfaces for solar applications. It is defined as a ratio of the annual solar gain of a surface to the maximum possible at the site.

The insolation indices of the typical roof and wall elements are described in Table 1.

As shown in Table 1, the south faces of walls and sloped roofs are significantly more valuable than west- or east-facing slopes. West walls are more valuable than east walls. Also, the insolation indices for the north-facing slopes demonstrate the significant contribution of diffuse and reflected radiation to the total solar gain.

The 95 buildings included in the assessment have a total roof area of 88,000 m2, of which 45,000 m2 was considered suitable for solar applications. The buildings have a total wall area of 128,000 m2 of which 15,000 m2 south-facing and 9,000 m2 west-facing walls were considered suitable for solar applications.

The solar gain on the suitable surfaces, net of obstructions, is summarized in Table 2.

### Solar Technology Applications

The solar energy generation potential for water heating, air heating, and solar power generation was determined and mapped for every campus facility, based on the suitable area of walls, in the case of solar air heating, and roofs for water heating and electrical generation.

**TABLE 1.** Solar Suitability Rates, Unobstructed—Dalhousie University.

| Slope (deg) | Azimuth: (deg) | | | |
|---|---|---|---|---|
| | 'North' +162 | 'East' –108 | 'South' –18 | 'West' +72 |
| 0 | 88.0% | 88.0% | 88.0% | 88.0% |
| 20 | 72.8% | 81.9% | 97.2% | 89.6% |
| 45 | 53.7% | 71.4% | 98.1% | 85.2% |
| 90 | 35.1% | 50.2% | 71.2% | 61.9% |

**TABLE 2.** Total Annual Radiation on Solar Suitable Surfaces.

| | Area (m2) After Obstructions | Total Annual Radiation (MWh) After Obstructions |
|---|---|---|
| Solar Suitable Roof Surface: | 44,142 | 57,116 |
| Solar Suitable Wall Surface: | 23,182 | 22,903 |
| TOTAL | | 80,019 |

Solar Water Heating (SWH) systems are used to preheat water for various applications. Most commonly, SWH systems are combined with a conventional heat source to provide domestic hot water. Typically, the systems include water storage tanks that store the solar energy to provide preheating at times of no solar gain. The most efficient SWH systems currently have an energy conversion efficiency of 40–45% in typical applications; collectors are orientated for optimal solar gain and are spaced out to prevent mutual shading.

Solar Air Heating (SAH) technology is most widely used to heat ventilation air in buildings. The system may also be used to increase the volume of filtered fresh air in buildings while reducing heating costs. Commercially-available solar air heating systems include wall-mounted transpired panel collectors, wall-mounted back-pass panel collectors, and roof-mounted collectors. A wall-mounted transpired panel with a target system efficiency of 68% was used as the reference SAH technology.

A flat-plate polycrystalline photovoltaic (PV) system was used as the reference solar electrical generation technology. The current PV module efficiency is in the range of 15% to 18%, with spacing as described above for solar water heating.

The solar energy generating potential of the campus buildings is summarized in Table 3.

## SOLAR ARCHITECTURE AND EXISTING BUILDINGS

New buildings provide opportunities to integrate solar technologies into the architectural concept of the facility. For existing buildings, however, the renewable energy systems have to fit with the facility's operating objectives (financial, environmental, functional, aesthetic, etc.), and must work within and around the existing infrastructure and use.

Assessments were carried out for selected buildings at Dalhousie to determine the feasibility of solar energy applications. The assessments evaluated the system engineering, projected energy output, cost, and return on investment. Two of the assessments are:

- solar air heating of the Sir Charles Tupper Building, where existing air intake grilles are located along the height of the existing south wall; and
- solar air heating of the Killam Memorial Library, in which solar-heated air could be used to de-stratify air in a large atrium space and provide additional fresh air for the building.

**TABLE 3.** Total Annual Solar Energy Generation Potential.

| | Total Annual Radiation (MWh) | Solar Thermal Generating Potential (MWh thermal) | Solar Electric Generating Potential (MWhe) |
|---|---|---|---|
| Suitable Roof Surfaces: | 57,115 | 9,400 (SWH) or: | 3,700 |
| Suitable Wall Surfaces: | 22,903 | 12,600 (SAH) | — |
| TOTAL | 80,018 | 22,000 | |

These buildings have strong potential for solar applications for different reasons. The examples illustrate how the value of retrofitting solar applications is predicated on the layout and function of existing buildings.

The assessments identified a number of technical considerations here summarized:

### *Air Heating Potential—Sir Charles Tupper Building*

Built in the late 1970s, the Sir Charles Tupper Building includes a tower with 17 floors used for laboratories, research, and teaching. Each of these floors includes a Mechanical Room with an air intake grille on the south face of the building. The intake grilles are 1.2 m wide and 2.4 m high; they align directly above each other in the centre of a precast wall. Air is exhausted by ducts led to the top of the building.

A solar air heating panel 5.5 m (18 ft) wide was considered, located continuously over the height of the building directly over the intake grilles, as illustrated in Figure 5 below.

RETScreen4® software, available from Natural Resources Canada, was used as a screening tool to model the renewable energy systems for the project. For the Tupper Building, our energy modelling used a design fresh air supply flow rate of 0.566 m3/s (1,200 CFM) for each of 17 floors.

**FIGURE 5.** Potential Solar Air Heating Collector, Sir Charles Tupper Building.

The energy required to heat the fresh air was estimated to be 417 MWh annually.

The width of the solar collector was selected to provide a design inflow rate to 0.025 m/s (5 ft/min). The system was estimated to provide 125 MWh of energy annually, or 30% of the building's heating load; it would displace 17,000 L of fuel oil and reduce carbon dioxide emissions by 51 tonnes annually.

Preliminary cost estimates for the system indicated a capital recovery in 6–7 years. However, the life-cycle cost of the building's precast wall system may be an integral issue: construction of the solar collector could be carried out in conjunction with other repairs to the precast concrete facade, or the entire section of precast panels could be covered by a metal wall system.

A related planning consideration is to improve the efficiency of the heating system by adding heat exchangers at each level of the tower.

### *Air Heating Potential—Killam Library*

The Killam Memorial Library is a five-storey structure used for offices, study areas, computer access, reference, and archives. Built in the mid-1960s, it has an interior courtyard that was enclosed by a translucent roof in the late 1990s to form a five-storey atrium. Most of the natural light in the building is from the atrium; precast concrete panels predominate on the exterior walls.

The existing mechanical heating, ventilating, and air conditioning (HVAC) system includes air intakes at ground level in the courtyard and near the roof on the west wall of the building. The design fresh air supply flow rate to the building's two mechanical rooms was estimated to be 5.66–8.49 m3/s (12,000–18,000 CFM).

A wall-mounted solar collector was proposed for the upper level of the building's south wall, together with ducting, fans, and controls, to deliver an additional 2.83 m3/s (6,000 CFM) of fresh air to the building's atrium near the roof level.

The energy provided by the solar air heating system was estimated to be 90.2 MWh annually, or 39% of the estimated heating requirement for fresh air to the building.

In this case, the existing fresh air supply to the building is operated at its maximum capacity; the additional fresh air was a design objective. The solar-heated air would be used to de-stratify air in the atrium, thereby providing additional heat to the building's HVAC system.

The system of solar air heating, fresh air supply, and de-stratification was estimated to have a capital recovery period of 5–6 years.

### *Technical Considerations— Solar Water Heating*

A number of solar water heating projects were initiated in the early 1980s in response to a short-term spike in energy prices. At the time the technology was relatively unproven. Projects were a mixed success; the successful ones have been in service 25 years and have at least 15 years of remaining useful life.

Since then, the technology has matured. Systems are available that combine heat exchangers, pumps, and controls in a modular unit for simpler installation; the heat conversion efficiency of collectors has improved; and more reliable, higher quality products are available.

Solar water heating is most cost-effective where there is a significant and relatively constant demand for domestic hot water, e.g., laundries, health care facilities, apartments, and condominiums with central water heating systems. In these situations, the technology may be cost-effective as a capital improvement. Significant rebates and incentives are currently provided by various Federal, Provincial, and other agencies.

Typical systems in Canada provide 35%–50% of the building's domestic hot water heating requirement. The size of the system is limited by the variations in solar heat gain and hot water demand, and by the allowable operating temperature of the heat transfer fluid. The system is most efficient and cost-effective in situations where excess heat can be redirected, e.g., to heat a swimming pool.

Technical considerations include structural loading, impacts on the roofing membrane, pipe routing, and space for equipment. The structural loading of collectors on existing roofs may be a significant consideration, particularly where collectors are tilted to maximize solar gain. Wind and snow load effects, and possible changes to the design snow loading since construction of the building, may limit the use of solar collectors or require reinforcement of the roof structure. The collectors may be supported on or through the roofing membrane. The detail may depend on wind load effects, which are related to the slope of the panel, and the type, age, and estimated remaining useful life of the roofing membrane. The design solution must include the collectors, support framing, anchorage, roofing membrane, and roof structure as an integrated system.

Typically, the heat transfer unit and water storage is installed close to the existing hot water heater; space and structural support are required for this equipment.

### *Technical Considerations— Solar Electrical Generation*

Solar photovoltaic (PV) technology for electricity generation has been increasingly utilized in building-integrated applications in North America. At the end of 2008 5.2 MW of grid-connected PV power capacity used for distributed applications had been installed in Canada, and 735 MW in the U.S. (Trends in Photovoltaic Applications, IEA, 2009). Most installations are mounted on buildings and parking structures, and a few are integrated into roof or wall surfaces.

The systems include solar panels, inverters, transformers, and controls for connection to the grid, or panels, batteries, and controllers for off-grid applications.

Roof-mounted PV panels may be mounted to optimize the output of individual panels (e.g., sloped at 35° at Dalhousie), or parallel to the roof surface, or at some angle in between. Mounting parallel to the roof surface maximizes the output from the available roof surface but reduces the output of individual panels (e.g., 88% of optimum at Dalhousie).

Snow and wind loads are considerations, as for solar water heating collectors. Snow retention on panels installed close to the horizontal position may reduce overall annual performance significantly; the issue deserves research and publication.

### *Technical Considerations—Solar Air Heating*

Passive solar air heating came to the forefront of residential architecture in the mid 1900s; houses in cold climates were designed, where possible, to direct sunlight to "heat sinks" inside homes. Trombe wall modifications, ceiling fans, and air recirculation in ducts through slabs have since been added to provide more active forms of solar air heating and storage.

More recently, active solar air heating systems have been developed and used in facilities run with mechanical ventilation and heating. For transpired panel applications, fresh air for the building is drawn through a transpired surface into the mechanical heating and ventilating system and/or is ducted into high ceiling areas to de-stratify the air. The transpired surface is typically a dark-coloured, profiled, sheet steel panel with small holes spaced in a grid to enable air to be heated by the panel as it passes through. The collectors may be mounted on walls or steeply sloped roofs with a southern exposure, or in modules on flat roofs.

Optimal conditions occur where buildings need heat and fresh air in winter and there is some radiant heat in the fall and winter sun. In southern Canada and the northern United States the financial return on investment may be 2–5 years for new construction and 3–7 years for retrofits, provided the building's configuration is well suited to the technology. If the configuration is unsuitable, however, solar air heating may be impractical.

With applications for existing buildings, the major considerations may include locating suitable surface, the architectural impact, the ducting and physical connection to the existing heating and ventilating system, and integrating the new and existing systems.

## CONCLUSIONS

There are opportunities for applying solar energy technologies in both new and existing buildings. For new buildings, solar architecture includes the involvement of energy engineers in the project team, from concept to commissioning and beyond. The full potential value of solar energy systems may be realized by developing an energy plan and strategy at the conceptual design phase. Building energy planning examines the building function, energy conservation, and energy efficiency measures, together with options for building-integrated renewable energy systems; energy modeling is an essential part of the process from the conceptual phase.

For existing buildings, a number of characteristics determine whether solar technologies can be incorporated effectively. The solar technology may be as cost-effective as for new construction if the building's configuration, physical condition, and operation are well suited; if not, the technology may be impractical. Buildings have to be assessed individually to determine whether solar or other energy-related measures are applicable. In our experience, a phased approach is appropriate to identify and screen opportunities, assess them, then implement the best.

Renewable energy technologies are at various stages of commercial realization, with some technologies viable and others emerging. The technological advances are frequent, and the marketplace continues to grow steadily, resulting in a gradual change in our cityscapes. As discussed, solar air heating is uniquely effective in the latitudes and climate of southern Canada and the northern United States. Solar water heating is most effective when there is a routine consumption of domestic hot water or a summertime demand, such as swimming pools. PV electrical generation technology is advancing rapidly toward parity with power from the grid; in new designs and major renovations there may be value in providing for the future addition of the technology if it is not included from the outset.

This article presents processes for identifying and mapping the solar energy generation potential of a community or campus, and for screening facilities to prospect the potential for solar technologies in the energy mix.