ROOFS AS EXTENDED SURFACE SOLAR COLLECTORS: PRACTICAL ISSUES AND DESIGN METHODOLOGY

William O'Brien[1], Andreas Athienitis[1], Ted Kesik[2]
[1]Department of Building, Civil and Environmental Engineering, Concordia University
[2]Faculty of Architecture, Landscape, and Design, University of Toronto

ABSTRACT
For most typical houses, roof surfaces represent the major opportunity for solar energy collection. Their nature provides a high level of design flexibility since their slope can be adjusted to a great extent without compromising the shape of the living area. However, in reality many constraints and practical considerations come into play, including snow accumulation, differential pricing, structural costs, construction methods, and solar collector types and their available sizes. Thus, roof design for solar energy collection is complex and presents itself as a time-consuming step in house design. In order to minimize design time, a design tool is being developed to allow for an integrated design procedure. While this paper focuses on building-integrated photovoltaic (PV) panels, the methodology is intended to be applied to other types of solar collectors including solar thermal and combined photovoltaic/thermal collectors. The first part of this paper presents an algorithm for efficient whole-year performance predictions accompanied by validation and a sensitivity analysis. The second part of the paper addresses a comprehensive list of practical roof-integrated PV array issues and how they can be implemented into a new design tool, such that roofs can be efficiently designed. Finally, a high-level methodology for roof design is presented.

INTRODUCTION
The design and optimization of solar houses using existing software is time-consuming and inefficient. Current software only allows unguided design and analysis of houses, thus requiring the designer to have considerable experience. In order for these tools to be used in an iterative manner, a certain amount of guess work is involved. Furthermore, practical issues are largely ignored, thus requiring the designer to perform many menial tasks while the software is being used. This research examines major aspects of the design process of roofs with integrated solar collectors in the context of a new design tool that is being developed to be integrated into HOT3000 (Purdy, 2004). HOT3000 is an ESP-r based home energy performance program. The design tool will provide a prediction of performance while restricting the design options to only those that are practical. It will also enable aesthetic considerations – an issue that was traditionally limited to architectural software. Instead of merely presenting the user with performance metrics, the design tool will provide guidance, enabling them to balance performance with these constraints and soft requirements.

While there are a number of existing solar home energy analysis tools that use hourly time step calculations, including ESP-r, TRNSYS and others, they are not usually properly geared at the typical designer (Fiksel et al., 1995). They generally require significant knowledge and experience designing solar systems. For example, HOT3000, require about twenty inputs for a solar domestic hot water system; many of which would not be readily available to the average designer. Thus, they would be forced to select a particular product early in the design process. Furthermore, the software gives little guidance for selecting proper slope and azimuth of the roof. Also, since the collectors are largely decoupled from the roof, an inexperienced user may select collector angle that cannot be integrated with the house for practical purposes. If a designer wishes to find the optimal size and orientation of a solar collector using energy simulation software, they would have little choice but to use a trial and error approach. For detailed simulation programs, this can be a matter of changing the coordinates that define the location of a collector and other time-consuming processes. This can be a tedious process, given that whole-year simulations can take several minutes. Therefore, it is concluded that a comprehensive design tool for solar homes is needed.

While the focus of this paper is on integration of photovoltaic (PV) systems, the methodology will be applied to other types of solar collectors, including solar thermal and combined PV/thermal panels. Many of the considerations discussed in this paper are common for all types of solar collectors.

It is widely accepted that passive solar design should be the first step in designing a solar house, while active solar design should be used to supplement it. This is because passive solar heating is the most cost-effective, has the greatest impact on major house geometry, and is the simplest (Athienitis, 2007). Also, the nature of the elements of passive solar heating (fenestration and thermal storage) is such that they are often fixed for the life of the house. O'Brien et al. (2008) showed that designing a passive solar house based on good relative performance translates to good absolute performance. Since passive solar collectors (windows) are likely to lead to thermal discomfort well before they reach their maximum possible size, a relative measure of performance is adequate. In contrast, it is possible to oversize active solar collectors. Therefore, it is desirable to predict their absolute magnitude of annual generation. The comparatively higher cost of active solar collectors means that over-sizing should be avoided.

This paper is divided into three sections. The first summarizes and validates a simplified method of calculating annual performance of a building-integrated PV array. The second examines a comprehensive list of practical issues related to roof design and how they can be incorporated into the design tool. The third section presents a methodology to incorporate the two.

THE DESIGN TOOL

The design tool will have two stages – conceptual and detailed. The conceptual design stage is for establishing major geometrical decisions and to allow the user to explore the effect of a wide variety of design issues. This form of feedback in the early design stages and before too many design aspects are fixed is critical (Hong et al., 2000). The process requires a simple interface and real-time feedback and is intended to reduce the design space by an order of magnitude. The detailed design stage is for establishing particular technologies and configurations. While the two stages may seem separate, it is conceivable that the user would choose to use them iteratively.

CALCULATION OF ANNUAL PV ARRAY PERFORMANCE

A number of methods have been established in the literature to predict useful energy output of active solar systems (Duffie and Beckman, 2006). While many of the methods are about 30 years old and their original motivation may have strictly been to shorten computation times (or allow hand calculations), they are very suitable for the conceptual design stage. During conceptual design, performing simulations with hourly (or sub-hourly) time steps can be time-consuming and produce an overwhelming amount of data at an unnecessarily high level of complexity.

The solar house design tool is primarily intended for grid-tied homes, for which electrical demand is supplemented by the grid when demand is higher than generation, and excess electricity generation is sold to the grid. This type of situation is simpler to analyze than off-grid applications because issues related to storage capacity and storage losses are avoided.

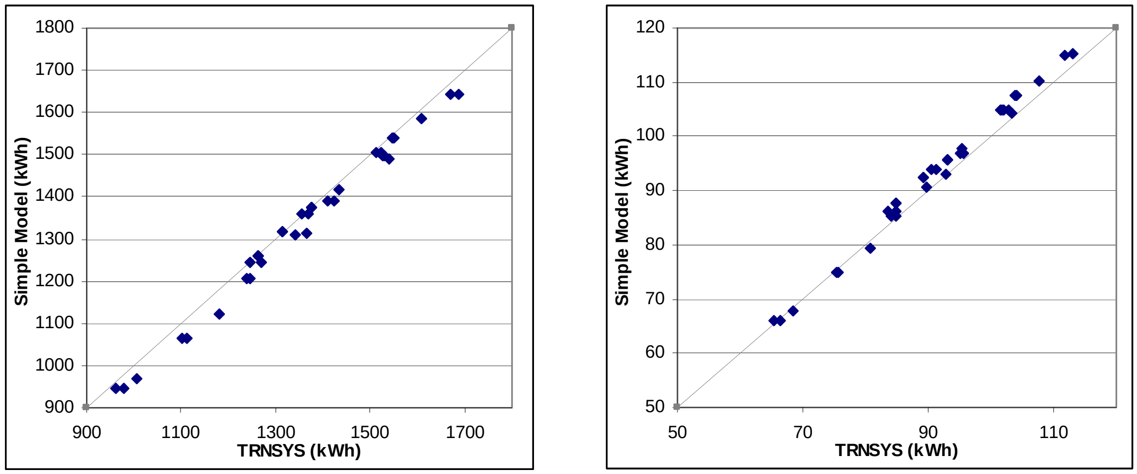
Typically, detailed modeling of PV performance is accomplished using hourly time steps, since both ambient temperature and incident solar radiation are dependent on time. To assess the solar radiation on the surface, diffuse, beam, and ground-reflected components are summed, and depend on surface orientation – surface slope and azimuth – as well as the site coordinates and climate. Cell temperature and electricity production are solved simultaneously since they are dependent on each other. Thus, a system of equations must be solved about 5000 time steps (between sunrise and sunset, only); typically taking several seconds to process. However, to vastly reduce computational intensity, RETScreen (2005) presents a method in which solar angles and daily distribution can be calculated for an average day each month – thus reducing computations by about 30 fold. This is permissible because for a given hour of the day, the sun is at roughly the same position in the sky for a given month. This approach is highly favourable because it is still based on first principles; allowing virtually any PV configuration or effect (e.g., shading, solar tracking, time-of-day electricity pricing) to be explored. Duffie and Beckman (2006) suggest which day should be used to represent the month, although it falls on roughly the 15^{th} day of the month.

A clearness index for each month is defined as the actual amount of horizontal solar radiation as a fraction of the extraterrestrial solar radiation. This value is typically 0.3 to 0.6 for Canadian locations. The Erbs et al. correlation is used to determine the ratio of diffuse to total solar radiation based on the monthly clearness index only (Duffie and Beckman, 2006). Collares-Pereira and Rabl developed daily distributions of solar radiation that are suitable for the average day, as reported by RETScreen International (2005). From this, hourly levels of diffuse and beam radiation are determined for the average day of each month. Since the incidence angle of solar beam radiation can be determined using geometrical relationships, the total amount of incident solar radiation on the PV panel for each hour of the average day of each month can be derived. Evans (1981) established an equation to determine average solar cell temperature from local monthly ambient temperature and clearness index only, meaning that simultaneous equations do not have to be solved. To model the effect of snow, ground reflectance (denoted "ρ") is assumed to be 0.2 for months with average ambient temperatures of above 0°C, 0.7 for below -5°C, and interpolated for months in between. The interested reader is pointed towards the RETScreen Textbook for a thorough development of the algorithm (RETScreen International, 2005).

For this research, the algorithm was implemented in a Matlab program. This allowed batch runs, sensitivity analysis, optimization, and a quantification of runtime to be performed. The total runtime was found to be about three milliseconds for a whole-year performance prediction. This is expected to be suitable for the implementation for conceptual design, where real-time feedback is desired. The equivalent runtime in TRNSYS was about two seconds. The approach was extensively validated for cases that are specific to the design tool being developed. Thirty-six cases were examined and are outlined in Table 1. The results were compared to an equivalent TRNSYS model and are plotted in Figure 1. The validation model was a 1 m^2 panel with a nominal efficiency of 7% and a temperature coefficient (β) of 0.2%/K; typical of amorphous silicon panels. Although only annual results are plotted, monthly results were found to be equally consistent.

TABLE 1: MODEL VALIDATION PARAMETERS

Variable	Explored Values
Location	Ottawa, Edmonton, Vancouver
Roof Slope (degrees)	0,30,60,90
Surface Azimuth (degrees)	-45, 0, 45



(A) (B)

FIGURE 1: VALIDATION OF SIMPLE MODEL SHOWING (A) PREDICTED ANNUAL INCIDENT SOLAR RADIATION ON THE PV PANEL AND (B) PREDICTED ANNUAL ELECTRICITY GENERATION

The error statistics are summarized in Table 2, with TRNSYS used as the reference. The simple model tends to over-predict electrical output slightly. This can be explained by the fact that the model was not necessarily intended for building-integrated PV, whereas the TRNSYS model was created for roof-mounted systems. The difference is that free-standing PV panels tend to shed heat faster since both sides – front and back – are exposed to ambient conditions. While the model is considered amply accurate for design, it would be possible to implement a coefficient that is dependent on the way the PV panels are mounted.

TABLE 2: SUMMARY OF ERRORS

	Incident Solar Radiation	Electricity Generation
Average Error	-1.57%	1.94%
Minimum Error	-5.06%	-1.85%
Maximum Error	0.34%	3.73%

A sensitivity analysis was performed to examine the effects of some of the critical model assumptions including ground reflectance, cell temperature, and the temperature coefficient. Two metrics were explored: optimal panel orientation and predicted electricity output. Of the two, the optimal panel orientation is considered to be much more critical. For grid-tied systems, slightly under or over-predicted performance will lead to a difference of a few tens of dollars in annual utility bills – a value that is trivial relative the system's capital cost. However, a sub-optimal orientation cannot be rectified after construction and will lead to a system that can never perform at its full potential.

For the sensitivity analysis, the model used to predict performance for roof slopes of 0 to 90° and azimuths from -90 to 90° in 1° increments in Ottawa. As expected, the model showed that a south-facing roof is optimal for all sloped roofs, and is thus, not shown. The results are shown in Table 3. The last column represents the consequence of making incorrect assumptions (assuming the nominal assumptions are correct) and using the optimal slope. For example, if the ground reflectance is assumed 0.7 year-round, the optimal slope is 50 degrees. However, if this assumption is found to be incorrect (and the nominal assumptions correct), the optimal slope is 39 degrees. Under nominal conditions, the 50 degree slope performs 1.2% worse than the optimal slope.

Higher ground reflectance assumptions lead to a higher optimal slope because this captures more reflected solar radiation (i.e., the view factor between the roof and ground is higher).

The sensitivity analysis shows that performance is relatively insensitive to the assumptions explored, with a maximum variation of about 8%. The performance is very insensitive to roof slope in the near-optimal range. Even the more extreme assumptions do not misguide the designer significantly. This suggests that designers need only ensure the slope is within 10 to 15 degrees of optimal while ensuring architectural constraints are met. The same can be said for roof azimuth.

TABLE 3: SUMMARY OF SENSITIVITY ANALYSIS

	Average Annual Output (kWh)	Change in Average Output	Optimal Slope (degrees)	Potential Consequence of assumption (%)
Nominal	96.76	-	39	-
ρ = 0.2 year-round	95.26	-1.6%	37	-0.036%
ρ = 0.5 year-round	100.5	3.9%	44	-0.171%
ρ = 0.7 year-round	104.0	7.5%	50	-1.234%
ρ_{no_snow} = 0.2; ρ_{snow} = 0.9	97.07	0.3%	40	-0.018%
Cell temp.: + 10°C	94.43	-2.4%	39	0.000%
Cell temp.: + 20°C	92.89	-4.0%	38	-0.009%
Cell temp.: + 20°C and β = 0.4%/K	88.68	-8.4%	39	0.000%

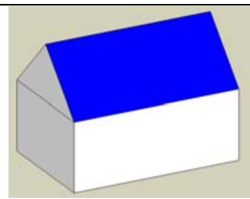
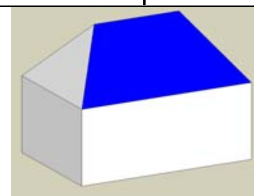
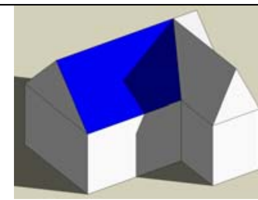
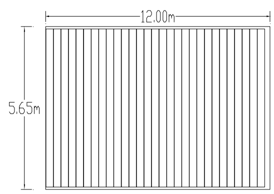
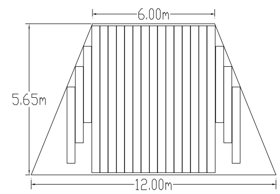
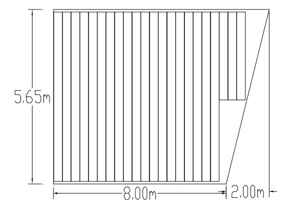
PRACTICAL CONSIDERATIONS OF PV ROOF DESIGN

While reporting energy and thermal performance based on system design is standard for all building simulation software, informing the user of practical issues is uncommon. Among all of the aspects, some can merely be included in numerical performance results, while it may be more appropriate for others to be displayed as warnings. The following is a list of the practical roof design issues.

GEOMETRICAL CONSIDERATIONS

In many PV modeling programs, the annual electricity production is based on collector area only. However, this is not an accurate representation of the system, since the number of PV panels used is discrete. Also, most PV panels have a frame, meaning that not all of this area should be counted. Finally, for non-rectangular roof surfaces, a certain amount of area is wasted from geometric incompatibilities. Electrical constraint can further restrict panel geometry. For the design tool, it is appropriate at the conceptual design stage to assume some conservative percentage of the roof (about 30%) does not have generating capacity. This is illustrated in Table 4. During detailed design, it is necessary to specify the panel size such that the optimal arrangement can be determined and, if necessary, the roof geometry or panel type can be changed. For building-integrated PV, in which the PV panels serve the function of weather protection in addition to electricity production, it may be necessary to match the two exactly. For panels that are merely mounted to an existing roof, this is less critical – functionally. The design tool will allow hip and gable roofs (which can be considered a special case of the former).

TABLE 4: THREE COMMON ROOF TYPES AND THEIR GEOMETRICAL AND SOLAR IMPLICATIONS. THE PANEL LAYOUT IS BASED ON TWO STANDARD SIZES OF UNI-SOLAR PANELS. CLIMATE DATA IS BASED ON TORONTO CONDITIONS. ALL SLOPES ARE 45 DEGREES (12/12) AND SOUTH-FACING.

	Gable	Hip	Cross-Gable
Visualization			
Average Annual Solar Radiation on Roof (kWh/m^2)	1481	1481	1214
% Shaded Annually	0	0	18 %
Optimal Panel Layout			
% Area Covered by Cells	80 %	66 %	76 %

ELECTRICAL CONSIDERATIONS

The electrical layout of the panels must be properly designed to ensure that they are compatible with the inverter. During the design process of the EcoTerra house, the designers realized that the width of the roof would only accommodate 20 of the selected PV panels, whereas, strings of 7 panels were optimal for the selected inverter. Therefore, the roof had to be widened by about 5% to accommodate an additional panel and allow 3 strings of 7 panels. A string is a group of PV panels that are connected in series. Strings are connected in parallel to the inverter.

There are a few guidelines that should be used in selecting an appropriate number of panels per string and the number of strings for a given inverter. First, the inverter's maximum capacity should exceed – though minimally – the maximum possible output of the array. Also, each string's voltage range stay within the inverter's operating voltage range and that the maximum current of the not exceed the inverter capacity. Since voltage is largely dependent on cell operating temperature, the design voltage range should be based on extreme temperatures. James and James suggest -10°C and 70°C. Finally, the number of strings is limited to the maximum current of the inverter. Symbolically, these restrictions are as follows (GSES, 2004).

$$0.8P_{PV} < P_{inv,DC} < 1.2P_{PV} \tag{1}$$

$$\frac{V_{inv,\min}}{V_{MPP,module}\big|_{T=70°C}} < n_{modules/string} < \frac{V_{inv,\max}}{V_{OC,module}\big|_{T=-10°C}} \tag{2}$$

$$N_{strings} \le \frac{I_{inv,\max}}{I_{string}} \tag{3}$$

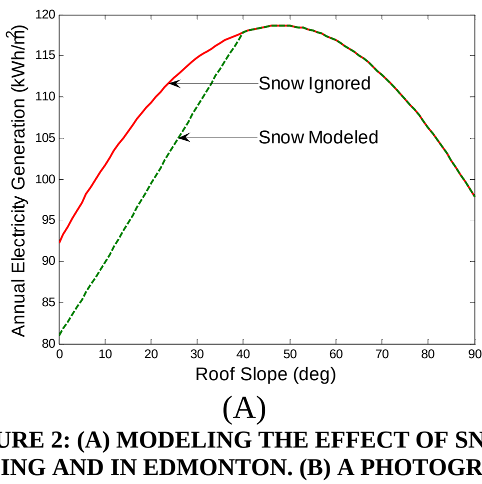
Where P_{PV} is the maximum output of the array, $P_{inv,DC}$ and $I_{inv,max}$ is the maximum power and current of the inverter, respectively, $V_{inv,min}$ and $V_{inv,max}$ is the minimum and maximum operating voltage of the inverter, respectively, $V_{OC,\ panel}$ is the open circuit panel voltage, V_{MPP} is the maximum power point panel voltage, $n_{modules/string}$ is the number of panels per string, and $N_{strings}$ is the number of strings of panels in the array. Because the properties of PV panels and inverters are dependent on the particular product, the design tool will incorporate them by having a product database and allow custom inputs. The selection of specific hardware is part of the detailed design process and should follow conceptual design.

VARIABLE ELECTRICITY RATES

For grid-connected houses that are situated in municipalities in which the retail price of electricity is not constant on an hourly or seasonal basis, it may be favourable to orient the array in a direction that does not yield the highest electricity production. For example, if afternoon rates were considerably higher than morning rates, it could be optimal to have a roof the faces west of south. The benefits of orienting the azimuth of the roof must also be balanced with passive solar heating performance (i.e. the roof orientation relative to the wall orientation is fixed). This feature should only be examined during advanced design stages.

SNOW

The accumulation of snow on solar collectors can have a detrimental effect on performance; affecting more than the covered area alone because the panel's current tends to be based on the worst-performing cell (GSES, 2004). Snow shedding can be promoted by increasing the roof slope and using smooth materials. For the Montreal climate, experience has shown that slopes of at least 30° and preferably 40° are desirable. It may be most effective to issue a warning to the designer if they select a slope below 40° (for regions that experience substantial snowfall), since no generalized relationships have been established. If the designer chooses a shallower slope than this, annual performance can be estimated by assuming electricity generation varies linearly from zero if the roof is flat to nominal if the roof is sloped at 40°, for months when the average ambient temperature is below -5°C. The effect is shown in Figure 2A.



(A)

(B)

FIGURE 2: (A) MODELING THE EFFECT OF SNOW ON ANNUAL PERFORMANCE. THE ROOF IS SOUTH-FACING AND IN EDMONTON. (B) A PHOTOGRAPH OF THE ECOTERRA HOUSE AFTER SNOWFALL.

SELF-SHADING

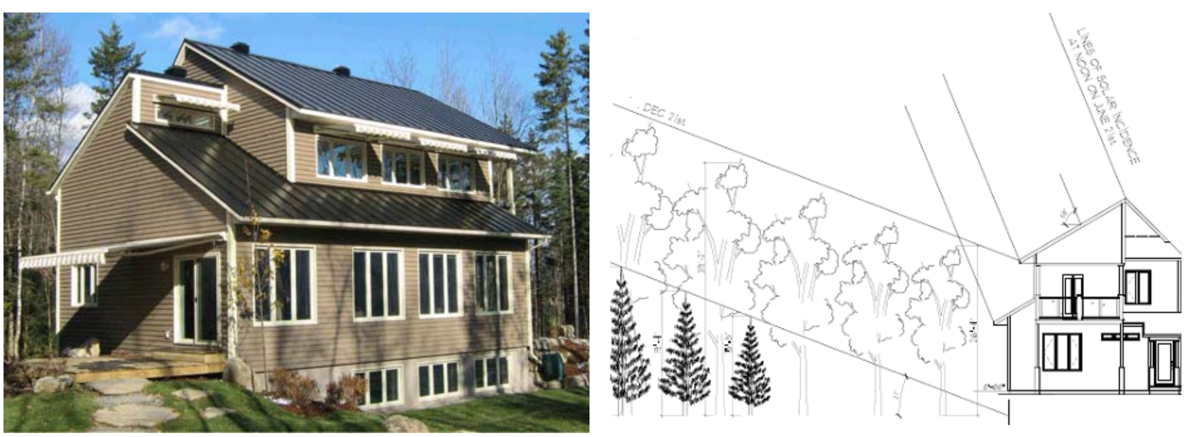
Self-shading includes shading of the PV array from architectural elements, including dormers, chimneys, antennas, or other roof sections. Like the effect of snow, the effect of a small shadow on a PV panel can have an effect which is much greater than its size would suggest. Furthermore, the shadow can sweep out an area that is several orders of magnitude larger than the footprint of the obstruction itself. Therefore, PV shading should be avoided first by eliminating sources of shading, and secondly by not placing panels in the vicinity of the obstruction. Since the design tool and HOT3000 will not allow the input of small obstructions, it will be up to the designer to avoid these elements. Shading from other roof sections can be avoided by excluding valleys, such that self-shading only occurs when the sun goes behind the surface. For example, gable and hip roofs are preferable to cross-gable roofs, simply because the former two do not experience self-shading. Table 4 provides examples of these roofs and their implications.

SHADING FROM EXTERNAL OBSTRUCTIONS

Designing around or avoiding external obstructions is often considerably more challenging than for self-shading for three reasons, as follows.

1. First, the owner of the house of interest may not have control over the obstructions on neighbouring properties.
2. Second, the obstructions may change in shape over the long term, in the case of vegetation (primarily trees).
3. Third, vegetation – in the case of deciduous shrubs and trees – varies seasonally. Thus, a tree can transform from having little effect on PV performance to being nearly opaque and allowing only some diffuse solar radiation to reach the panel.

For the EcoTerra house (shown in Figure 3A), the builder created a west-facing elevation drawing of the house and surrounding vegetation. Lines were drawn to represent summer and winter solstices such that the entire range of solar altitudes at noon were illustrated (as shown in Figure 3B). While this is limited to mid-day conditions, it is a good example of how shading should be considered for detailed site planning and roof design. It is also important to assess the projected growth of the trees to determine their maximum expected canopy, as this may eventually shade the solar panels to result in a significant reduction in electricity generating potential.



(A) (B)

FIGURE 3: (A) A PHOTOGRAPH OF THE ECOTERRA HOUSE, FEATURING A BUILDING-INTEGRATED PV/THERMAL (BIPV/T) SOLAR COLLECTOR COVERING THE ENTIRE UPPER ROOF. 21 LONG FLEXIBLE AMORPHOUS SILICON PANELS ARE FIXED TO THE METAL ROOF. (B) ARCHITECTURAL DRAWINGS OF SOLAR ALTITUDE ON DECEMBER 21 AND JUNE 21 AT SOLAR NOON.

While the simple model presented in this paper is capable of shading analysis, the limitation is that the measuring and input of obstructions is a very imprecise and time-consuming process; easily surpassing the time required to perform the conceptual design for the entire house. Therefore, it is concluded that the designer should input a qualitative description of the site that corresponds to a numerical value, for calculation purposes. The proposed scale is shown below. While this scale is clearly subjective, the purpose at the conceptual design stage is to steer the designer clear of poor design choices. Where losses from shading are greater than 25%, the designer would be wise to eliminate the obstructions, reposition the house on the lot, or select a different site. An analogous system is used in ESP-r, where the user is asked to specify whether the site is urban, suburban or rural to determine localized wind exposure (Energy Systems Research Unit (ESRU), 2007). Naturally, these descriptions are associated with numerical equivalents.

TABLE 5: RATING SYSTEM OF SHADING CONDITIONS

Rating	Equivalent Performance Loss
Clear of obstructions – very exposed site	0 %
Isolated trees that are at least 10 m from house	25 %
1-5 Mature trees with large limbs within 10 m of house	50 %
Many (>5) large mature trees near the house	75 %
Fully shaded with obstructions that extend over the roof	100 %

ROOF CONSTRUCTION

There are a number of roof construction issues that can constrain the design of the PV array, as follows:

- For houses with a large span, a high roof slope necessarily is associated with a high roof. This increases the amount of construction materials and, consequently, costs. The design tool will incorporate a sense of construction costs (though it may be on a relative basis only).
- Overhangs provide some flexibility in slightly extending the roof surface. This is particularly useful in situations where extending the roof by a small amount can allow an additional row of panels. However, overhangs are also tied to passive solar heating performance. During passive design, overhangs are specified to provide shading in summer months. Therefore, the impact of modifying overhang geometry on both active and passive solar performance must be explored on an iterative basis.
- To minimize costs, designers may wish to consider only standard slopes so that manufactured roof trusses can be used, as is standard in wood-frame construction. During conceptual design, the user will be allowed to select any geometry, to suit performance. During detailed design, this will be refined to allow the user to select a standard roof. Likewise, for manufactured/pre-fabricated roofs, the height is limited by transportation restrictions, as was the case for the EcoTerra house. This restricts the design space to shallower slopes and depends on the run of the roof.
- For live-in attics or cathedral ceilings, the slope of the roof impacts the living space. In this case, higher slopes tend to be preferred to increase living space. This can be quantified in the design tool as the living space volume.
- For installations where the PV panels provide weatherproofing, there is a minimum slope allowed, as specified by the manufacturer. Below this, the panels are not considered rainproof, so a watertight sub-roof must be installed under the panels (GSES, 2004).
- A wire connecting each panel to a junction box (or inverter) must be in place. A successful technique used in the EcoTerra house, among others, is to have long slender panels that extend along the entire slope of the roof such that the connection points for all panels are

inline. Furthermore, the wires are concealed by the roof cap such that no holes are drilled into the exposed roof. This improves water tightness of the roof and minimizes wire lengths.

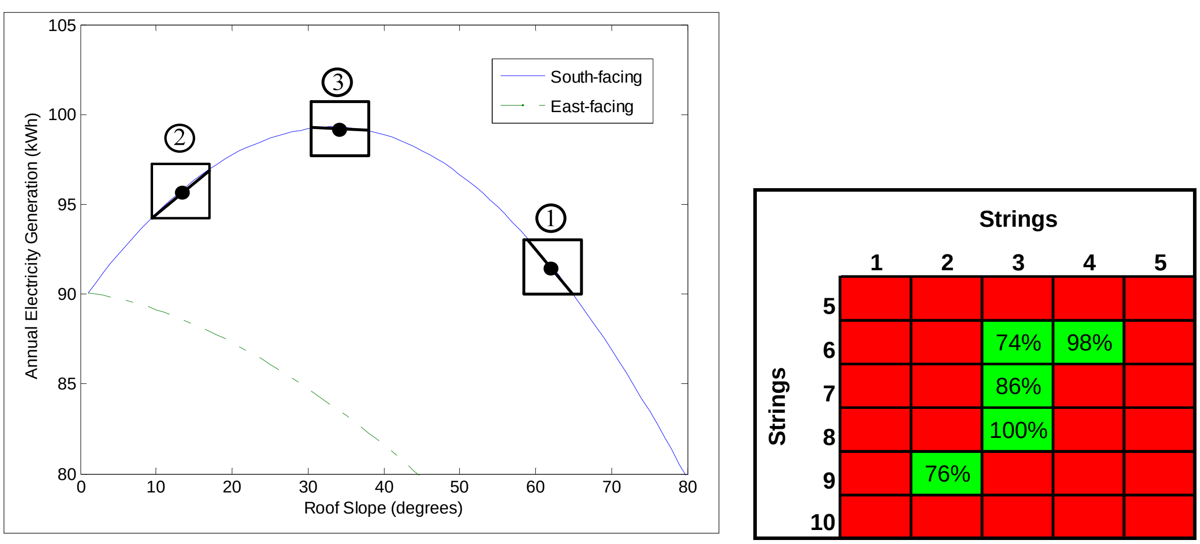
AESTHETICS

A recent extensive survey among architects and engineers by Probst et al (2007) found that the integration of solar collectors on a building is very important to aesthetics. For example, an existing roof on which several PV panels were mounted ranked extremely low. In contrast, buildings with integrated solar collectors that covered entire roofs or facades ranked very high. Probst even suggests that installing non-functional “dummy panels” is worthwhile to ensure consistency in colour and texture on a roof or façade. Athienitis (2007) found that using laminate PV panels that resembled the metal roof in colour enabled seamless integration. The design tool will feature basic panel layout schematics. Thus, the designer can size the panel and roof dimensions simultaneously, in an iterative manner. This has the equally important function of ensuring geometrical feasibility.

DESIGN METHODOLOGY

In order to tie the performance and practical considerations together, a procedure with roof-integrated roofs is presented in Figure 5. The approach is to leave as many specific details as possible to the latter stages. Also, guidance towards the optimal solution is provided in one of two ways:

1. Lines of Influence (termed by Kesik et Stern (2008)) guide the designer toward the optimum solution(s). They present sensitivity of the major design parameters, allowing the designer to gauge the relative effectiveness of incrementing a certain parameter and quickly converge to the optimal solution. Figure 4A shows an example in which the designer quickly converges on a near-optimal design based on three short steps. At step 1, the designer observes that reducing the slope has significant potential. At step 3, there is little potential for improvement. The east-facing curve shows that the slope of the line of influence is not only a function of the value of the current parameter, but also the others. Since there is a single global maximum, it is not necessary to compute (and display) the performance of the entire design space each time the designer changes a parameter value. That is, the lines of influence point to the global maximum.



(A) (B)

FIGURE 4: (A) EXAMPLE OF LINES OF INFLUENCE. (B) EXAMPLE OF REDUCING DESIGN SPACE TO FEASIBLE DESIGNS AND IMPLICATIONS

2. Reduce the design space to a short list of options accompanied by performance indicators for each. For example, Figure 4B shows a table of possible electrical configurations for a given panel and inverter types. Only the configurations with numerical values shown do not violate the electrical restrictions (as specified equations 1 through 3). The values shown represent the predicted annual electricity generation relative to the best performing configuration.

To accelerate the process, the user can opt to not specify detailed information (e.g. electricity, materials, and construction costs). Like any design process, the proposed procedure has several iterative elements. However, real-time feedback is expected to allow the designer to quickly explore the design space and converge on a good solution.

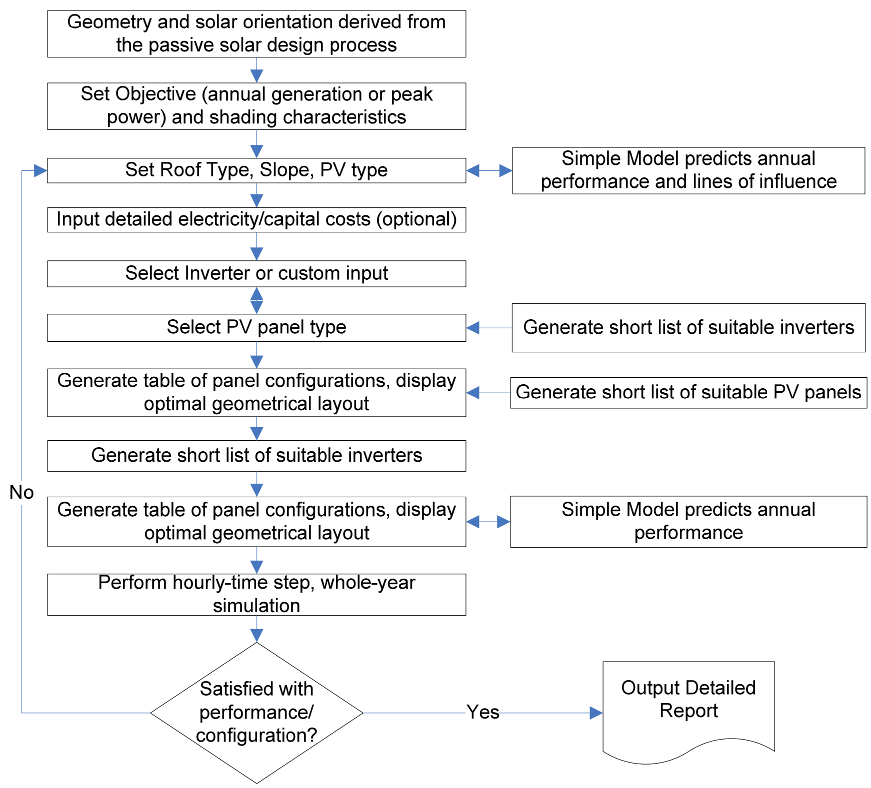


FIGURE 5: HIGH-LEVEL ROOF DESIGN PROCEDURE

DISCUSSION

It was shown that a simple PV model based on a representative day for each month could accurately predict annual performance. A comprehensive list of practical design issues was explored, followed by a methodology for the design of roof-integrated PV arrays. Finally, two methods of displaying information and aiding the designer will be used including: lines of influence and limiting the design space to the best options accompanied by performance implications.

There are a number of issues that still need further exploration. One of these is to limit the list of thousands of available product to the most suitable. Once a prototype for the roof design module of the design tool is created, the exact method of input and display of performance is expected to be more obvious. Also, the design methodology presented must be integrated with the passive solar design methodology, since they are related as a given floor plan limits the number of possible practical roof configurations. Similar work must be performed so that the inclusion of solar thermal and PV/thermal collectors on the roof can be properly explored.

CONCLUSIONS

The paper presented how an existing simple PV model predicts electrical output with a reasonably high accuracy that is suitably efficient for building-integrated photovoltaic system design. A validation of the model showed that it is accurate within about 5% for a wide range of panel orientations and Canadian locations. A sensitivity analysis showed that the model is relatively insensitive to individual assumptions such as ground reflectance and the effect of temperature. Only when these assumptions were combined did the model show significant changes in predicted performance. The second part of the paper examined a number of practical issues of roof-integrated PV design including shading, electrical considerations, roof construction, and electricity pricing. The focus was on the implementation of the restrictions into the design tool, such that the designer can design a roof that is both optimal and practical. Finally, a high-level methodology for roof design was presented that is suitable for advanced as well as simplified analysis.

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