DEVELOPMENT AND IMPLEMENTATION OF A GROUND REFLECTIVITY MODEL FOR ESP-R

FINAL REPORT

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TABLE OF CONTENTS

TABLE OF FIGURES

1 INTRODUCTION

1.1 Background

The reflectivity to solar radiation of the ground surface is an important parameter in the prediction of heating and cooling loads using building energy analysis software such as ESP-r. A portion of the solar radiation that impinges on the ground surface is reflected toward the building exterior envelope. Part of this radiation is absorbed by the envelope and then finds its way inside the space. The other part is transmitted directly inside the conditioned space. The solar radiation reflected off the ground also affects the performance of solar collectors and PV facades.

Currently the ESP-r building energy analysis program assumes a constant ground reflectivity entered by the user. This reflectivity is then used to predict the solar radiation reaching the outside of the building for the whole simulation period regardless of the condition of the ground surface and the prevailing weather conditions. This project then deals with the development of a ground surface short wave reflectivity model, for implementation in ESP-r, to improve the prediction of ground reflectivity on space heating and cooling loads and on the performance of solar collectors and PV systems. The model will predict the short wave reflectivity of the ground as a function of the type of ground cover and weather conditions and, subsequently, will be implemented into the building energy simulation engine ESP-r.

1.2 Terminology

Terms such as ground reflectivity, ground reflectance, and albedo can be found in the literature. The first two are most often encountered in the context of building simulation, whereas the last one is often found in solar radiation processing and remote sensing (as well as astronomy, e.g. the albedo of a planet). The terms all refer to the capability of the ground to reflect solar radiation, and will be used interchangeably in the rest of this document. Technically the albedo is calculated as the ratio of reflected solar radiation to incoming horizontal reflected radiation. It can be measured, for example, by using two horizontal pyranometers, one facing down and the other facing up, and taking the ratio of the measurements. Albedo is generally calculated either on an hourly or a daily basis.

1.3 Methodology

The approach taken in this study is as follows:

- The first part of the study focuses on how albedo is used in the calculation of radiation on surfaces of various orientations. This is done by analyzing the equations used in the ESP-r model (section 2.1). The sensitivity of the calculation to variations in albedo is studied with a simple numerical experiment (section 2.2). The variation of energy requirements for a simple house simulated with ESP-r is then reviewed(section 2.3).

- A bibliographic search was then conducted (section 3) to characterize the albedo of various surfaces. The search identified variations of albedo with parameters such as solar elevation, cloud cover, presence of snow, etc.

- Finally the results of the first two parts of the study are used to propose a new albedo model for ESP-r (section 4).

2 REVIEW OF GROUND REFLECTIVITY CALCULATION IN ESP-R

2.1 Theory

There are several models in ESP-r for calculating solar radiation on surfaces of various orientations, from solar radiation on a horizontal surface as provided in the ESP-r weather files. These models can be chosen from the 'Simulation toggles' menu and include the isotropic model, the Klucher model, the Muneer model, and the Perez model[1]. These models sum the direct beam, sky diffuse, and ground reflected components of irradiance. They differ in the way they calculate the anisotropic sky diffuse irradiance (see Clarke, 2001), however, all the models share the same algorithms for the beam and ground-reflected components. The calculation of the beam component is simply a geometric transformation of the direct normal beam irradiance. For the ground-reflected component, the ground is considered to be a *diffuse reflector*; a view factor takes into account how the ground is viewed from the surface. The ground-reflected component of irradiance is therefore calculated as:

$$I_r = \frac{(1 - \cos\beta)}{2} \rho I_g \quad (1)$$

where:

I_r = ground-reflected total radiation incident on the sloped surface

β = slope of the surface

ρ = ground reflectivity

I_g = global irradiance on the horizontal

The ground-reflected component of incident irradiance is therefore highest for vertical surfaces[2], and varies proportionally to ground reflectivity. Ground reflectivity is a constant value entered by the user (menu 'browse/edit/simulate', 'model context', 'ground reflectance').

2.2 Influence of ground reflectivity on the calculation of radiation incident on sloped surfaces

Before going any further it will be useful to provide a quick quantification of the impact of ground reflectivity on the monthly radiation striking surfaces of various orientations, for Ottawa, ON. Let G_h be the monthly radiation on the horizontal, and $G_t(\rho)$ the monthly radiation on a tilted surface, calculated with a ground reflectance ρ. As a base case, let us

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[1] The implementation of the Perez model is based on an early version of the model and is in the process of being replaced by the latest version.

[2] It is actually highest for surfaces facing the ground with an unobstructed view of their surroundings, but those are rarely seen in buildings.

consider a ground reflectivity ρ_1 equal to 0.2. If the ground reflectance is increased, because of the presence of snow, to a value ρ_2, G_t will be increased, according to eq. (1), by:

$$\left(\rho_2 - \rho_1\right)\left(\frac{1-\cos\beta}{2}\right)G_h \qquad (2)$$

Dividing this quantity by G_t give the expected *relative* increment in incident monthly radiation. This value[3] is shown in Table 1, where ground reflectivity is increased from 0.2 (the standard value) to 0.5 (a reasonable value to consider with old snow). In Ottawa, only the months from November to April experience snowfalls of more than 5 cm (Environment Canada, 2005). During these months it can be seen that, according to the model, the increased ground reflectivity will have:

- A very limited relative effect on renewable energy systems, such as solar collectors, placed on roofs (slope ranging from 30 to 60°, azimuth south). It is actually possible that the presence of snow on the collectors themselves will wipe out some of the gains due to the increase in ground reflectivity.
- A somewhat limited relative effect (+12%) on south-facing vertical surfaces such as windows or building-integrated photovoltaics;
- A substantial relative effect (+22%) on radiation striking east and west vertical surfaces;
- An important relative effect (+46%) on radiation striking north vertical surfaces.

Table 1 - Relative increment (in percent) in incident monthly radiation when ground reflectivity is increased from 0.2 to 0.5.

Azimuth	South			East or West			North		
Slope	30°	60°	90°		60°	90°	30°	60°	90°
January	1	4	8	2	9	22	5	20	48
February	1	4	10	2	9	21	5	23	54
March	2	6	15	2	9	23	4	21	50
April	2	8	22	2	9	24	3	19	45
…									
November	1	5	10	2	9	22	4	16	40
December	1	4	9	2	9	22	4	17	41

2.3 Influence of ground reflectivity on heating load calculations in ESP-r

De Wit (1997) studied the influence of uncertainties of various parameters and variables on building simulation. The focus of the study was thermal comfort (rather than energy use). The case studied concern the thermal comfort (number of hours with temperature greater

[3] In the derivation of this table, monthly horizontal and tilted irradiance values were obtained from RETScreen (2002). The method of calculation of G_t is of little consequence on the results of Table 1, the use of the ESP-r tilted radiation algorithms would have lead to similar results.

than 25 °C) of a single room in the top floor of a three storey office building in a suburban/urban environment in the Netherlands. Since the simulation was run for the summer, albedo was varied in the range 0.15 to 0.30. According to the study, albedo ranked 7th among the parameters responsible for the greatest modeling uncertainty.

Purdy and Beausoleil-Morrison (2001) studied the sensitivity of simulation results to input parameter changes. The base case model for the study was a typical R-2000 two-storey house with basement; the focus of the study was the heating load. They found that increasing ground reflectivity from 0.2 to 0.5 reduced the heating load by 6.5%, and they concluded that a model to more accurately determine the ground reflectivity as a function of snow cover was warranted in Hot3000.

A quick series of simulations was run to get a better understanding of the influence of ground reflectivity on heating load in ESP-r, as well as to prepare validations of the future reflectivity algorithm. The house modeled (ccht_detailed) is shown in Figure 1. The simulations were run for Ottawa, ON, with ground reflectivities ranging from 0.2 to 0.7. Total yearly sensible load for the house is shown in Figure 2. Increasing ground reflectivity from 0.2 to 0.5 reduces the load by 5.9%, a value close to that found by Purdy and Beausoleil-Morrison (2001). This value would likely be higher if the house had more passive solar features.

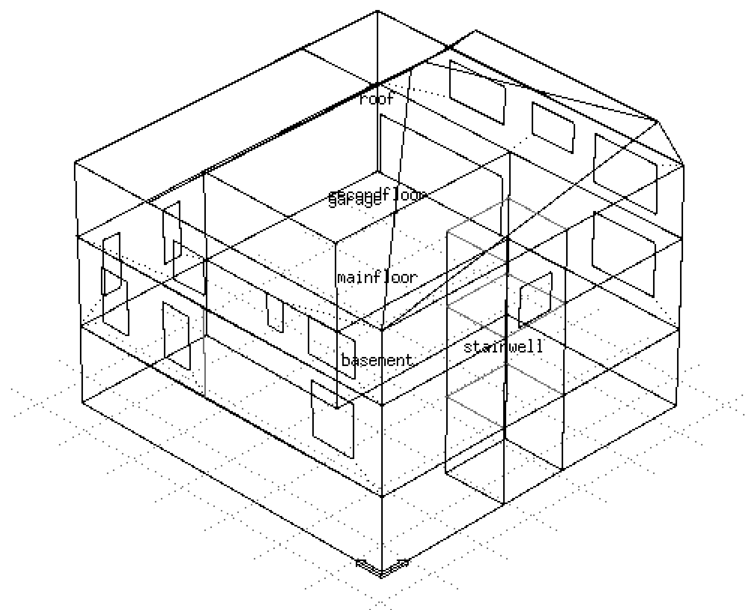


Figure 1 – House model used in ESP-r simulation.

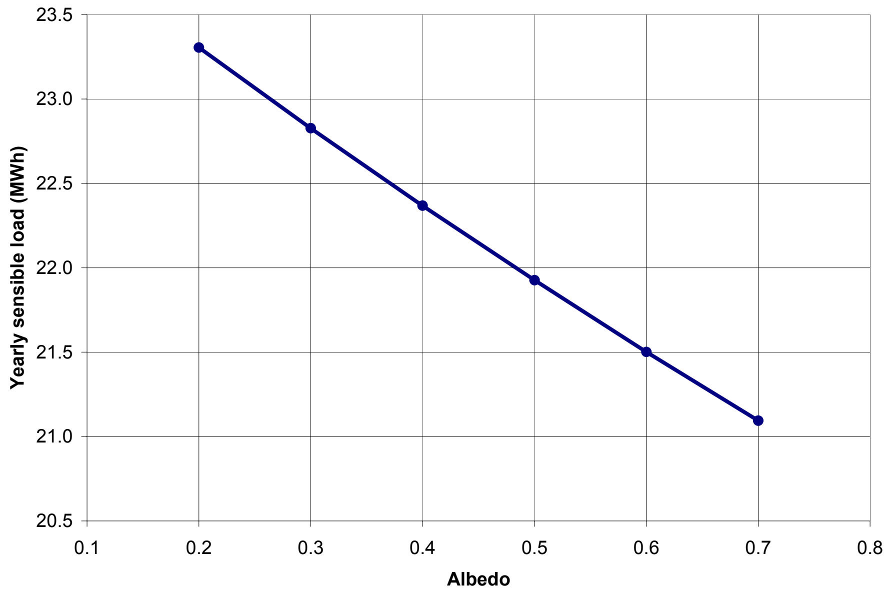


Figure 2 – Heating load as a function of albedo.

3 LITERATURE REVIEW ON GROUND REFLECTIVITY

Estimation of albedo is of importance to a number of fields. Albedo is used to estimate incident solar radiation from earth-sun geometry and cloud cover in locations where it is not measured; albedo permits the calculation of multiple reflections between the ground and the atmosphere / cloud cover. For example the models used to develop the Canadian Weather Energy and Engineering Data Sets (CWEEDS) and the Canadian Weather for Energy Calculation (CWEC) files use estimates of albedo; so does the model used in the US to develop the National Solar Radiation Data Base (NSRDB). There is also a wide body of literature dealing with ground reflectivity (particularly in the presence of snow) in the context of remote sensing and climatology; this is used for example in the development of atmospheric circulation models or to estimate the global energy balance of the earth.

Albedo is known to vary with a number of factors, such as:

- Nature of the surface considered,
- Solar elevation,
- Cloud cover,
- In the case of snow, age and accumulated temperature,
- And for some surfaces, position with respect to the sun.

A fairly complete and concise reference on ground reflectivity in the context of building energy simulation is Chapter 6 of Muneer (1997). The chapter contains tables of ground reflectivity for a wide variety of surfaces, and provides example of variation of ground reflectivity with solar elevation, cloud cover, and snow. It also provides maps of albedo for the UK.

3.1 Default values of albedo

The literature contains an abundance of estimates of default ground reflectivity, depending on the surface. Table 2 gives a summary of the most frequent values found. The values in the table should be considered as ‘average’ values over the course of a day. Estimates may also vary from one author to the next.

Table 2 – Estimates of average ground reflectivity

Ground cover	*Reflectivity*	**References**
Water (large incidence angles)	0.07	b
Coniferous forest (winter)	0.07	b
Bituminous and gravel roof	0.13	b
Dry bare ground	0.2	a
Weathered concrete	0.22	b
Green grass	0.26	b
Dry grassland	0.2 - 0.3	a,b
Desert sand	0.4	a
Light building surfaces	0.6	b

(a) Markvart, 2000
(b) Hunn and Calafell, 1977

3.2 Dependence upon solar altitude and time of day

Some authors find a dependence of ground reflectivity upon solar altitude. Nkemdirim (1972) showed a weak dependency of ground reflectivity upon solar altitude in the morning (particularly for bare soil), and a stronger dependency in the afternoon. He conjectures that the difference between morning and afternoon may be attributable to differences in the spectral composition of incident light, and to changes of optical properties in the vegetation during the day (because the metabolism of leaves changes during the course of the day). Both Nkemdirim (1972) and Arnfield (1975) propose a simple exponential function to represent the dependence; the strength of the dependence of albedo upon the zenith angle increases with the roughness of the surface. This can be explained by the fact that a rough surface will 'trap' light more efficiently than a smooth surface at low elevation angles. On the other hand, Baker *et al.* (1991) found that the dependence of ground reflectivity upon solar altitude is negligible.

3.3 Albedo in the presence of snow

As noted by many authors, ground reflectivity increases dramatically in the presence of snow. Fresh snow has a very high reflectivity (listed, depending on the sources, between 0.75 and 0.95; see Muneer, 1997; Baker *et al.*, 1990, 1991). The reflectivity then diminishes with time, to values between 0.7 and 0.5 or less. This diminution is a function of (Klein et al., 2000):

- surface grain size. Coalescence of snow grains with melting leads to a decrease in albedo;
- deposition of light-absorbing particulates (dust and soot); and
- for thin snow, snow depth.

Liu and Jordan (1963, cited in Hunn and Calaffell, 1977) provided the first, and still widely used, estimate of average ground reflectance in the presence of snow. They assumed a reflectance of 0.2 when there is less than 2.5 cm (1 in) of snow on the ground, and 0.7 otherwise. The average reflectance for any given month is calculated as an average of the two values, weighted by the factional time during the month when more than 2.5 cm of snow is present.

Hunn and Calaffell (1977) have estimated the albedo of snow-covered surfaces from photographs for typical landscapes. They used the photographs to calculate a weighted average of the albedo, according to the relative view factor of the various surfaces visible to the camera. They found that an average ground reflectivity of 0.6-0.7 is accurate for most rural landscapes were a large snow cover is visible without obstruction; the only exception is for locations adjacent to open bodies of water, for which the ground reflectivity is considerably lower. For urban areas, they concluded that no characteristic ground reflectivity in winter could be specified, due to the wide range of possible landscapes details. They suggested values ranging from 0.16 to 0.49. For all landscapes, their conclusion is that ground reflectivity is very sensitive to the fraction of field of view in snow cover – for example in an urban environment, the building may not 'see' much snow because of other buildings, trees, or parking lots and roads cleared of their snow.

3.4 Influence of snow depth

Snow depth plays a role because solar radiation is able to penetrate thin layers of snow. Depending on the kind of snow and which definition of extinction is used, penetration depths range from a few centimeters to as much as one meter. Baker *et al.* (1991) establish the amount of snow required to effectively mask the underlying surface. They found values of 5, 7.5 cm and 15 cm of snow are required over bare soil, sod and alfalfa, respectively. However their definition of 'snow depth' included the height of the vegetative cover itself (5 cm for sod, 7 to 15 for alfalfa), so once this is deducted the actual snow depth is somewhat smaller.

3.5 Influence of time since last snow fall

Variation of now albedo with time is documented in Dirmhirn and Eaton (1975) as a quasi-exponential curve. The rate of decay varies according to the season and to the air temperature. In particular the albedo decay is larger in the snowmelt season than in the snow accumulation season.

In one of the most complete papers on the subject, Baker *et al.* (1990) studied the influence of several variables on the albedo decay of prairie snows. The variables studied were:

- number of days after last snowfall,
- solar altitude,
- average daily air temperature,
- heat sums (sum of daily maximum temperatures greater than 0 °C), and
- cloudiness.

They found that albedo of fresh snow is independent of solar altitude (a result consistent with Dirmhirn and Eaton, 1975). They also found a strong relationship between mean albedo and heat sums. They simplified the relationship by considering only days after last snowfall (instead of heat sums) since the two are well correlated. They found that albedo decreases linearly with time, at a rate of 1% per day or less on average between December-February and between 2.4% and 3.3% per day in November, March and April (the study was limited to snow depths greater than 10.2 cm and albedos greater than 50%).

The study of Baker *et al.* (1990) could be somewhat criticized for not including other factors (for example albedo decay could possibly be related to a combination of daily maximum temperature and incident radiation). One can also wonder whether the different rate of albedo decay in December-February vs. the shoulder months of November, March and April could be better accounted for by the use of heat sums. Nevertheless the study is interesting since it provides a concrete estimate of albedo decay.

3.6 Specularity

Ground reflection of natural surfaces includes diffuse and specular components (specular reflection refers to a sharply defined beam resulting from reflection off a smooth surface). For most ordinary surfaces such as plants and soil, ground reflectivity is almost entirely diffuse. For snow and water, the reflectivity contains a non-negligible specular component. A good discussion of this can be found in Dirmhirn and Eaton (1975). The degree of specularity depends on a variety of factors, such as the smoothness of the surface. Specularity can include forward-augmented reflection or backward-augmented reflection, as shown in Figure

3. The specularity of snow is in the forward direction. Some crops are known to show a high degree of backward specularity (Gueymard, 1987).

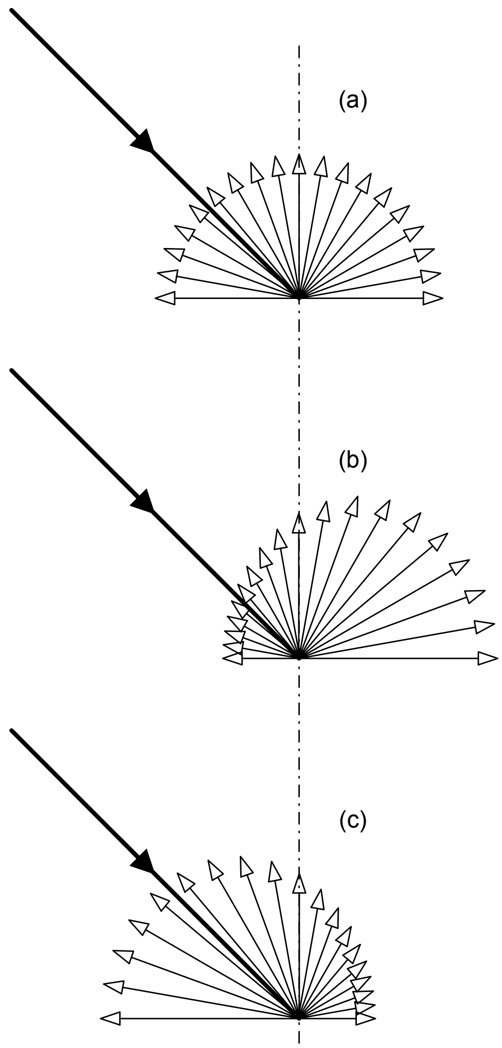


Figure 3 – Specularity:
(a) isotropic reflection
(b) forward-augmented reflection
(c) backward augmented reflection

Reflectivity of fresh fallen snow is almost isotropic (that is, it is the same in all directions, or, equivalently, it is uniformly diffuse). The specular component increases with the age of the snow cover, particularly because of daytime melting and nighttime refreezing cycles (Dirmhirn and Eaton, 1975) which change the shape of the snow grains and harden the snow surface. This last reference contains plots of snow reflectance at different solar angles, which show that forward scattering does occur, particularly at low solar elevation angles. This specularity is of course of concern for building simulation. The main consequence would be an increase of reflected radiation coming from the azimuth of the sun (particularly on South, East and West surfaces) and a diminution of reflected radiation coming from the North, which would in turn change the numbers in Table 1.

It is difficult to properly account for specularity. A model worth mentioning is that of Gueymard (1987). In his model, diffuse and specular components are treated separately and ground-reflected radiation is expressed as:

$$I_r = \frac{(1-\cos\beta)}{2}\left[f_b \rho_b I_b + \rho_d I_d\right] \quad (3)$$

where:

I_r	=	ground-reflected total radiation incident on the sloped surface
β	=	slope of the surface
f_b	=	shading factor
ρ_b	=	ground reflectivity for beam irradiance
ρ_d	=	ground reflectivity for diffuse irradiance
I_b	=	beam irradiance on the horizontal
I_d	=	diffuse irradiance on the horizontal

The shading factor accounts for times when part of the ground in front of the surface is shadowed. The ground reflectivity for beam irradiance is calculated using a semi-isotropic assumption (i.e. reflection is isotropic in each of the forward and backward half hemispheres) and written in the form:

$$\rho_b = \rho_n + f \cdot |\cos\alpha| \cdot H(h) \quad (4)$$

where:

ρ_n	=	albedo for normal incidence
f	=	anisotropy coefficient
α	=	difference of azimuth between normal to surface and sun
h	=	solar elevation
H	=	function describing albedo variation with solar elevation.

f can assume two values, f_f or f_b, depending on the sign of $\cos(\alpha)$. Gueymard provides typical values of f_f and f_b; for example f_f = f_b = 1 for green grass (identical forward and backward anisotropy), f_f = 2 and f_b = 0 for snow (forward anisotropy), and f_f = 2 and f_b = 0 for a plowed field (backward anisotropy). $H(h)$ is fitted to experimental values for green grass and snow. Ground reflectivity for diffuse irradiance is given (after some mathematical developments) by:

$$\rho_d = \rho_n + 0.023 \cdot \left(f_f + f_b\right) \quad (5)$$

This last equation enables to calculate ρ_n from published values of albedo (such as those in Table 2) which can be assumed equal to ρ_d .

This is a clever model which simplifies the problem using reasonable assumptions. Its main drawbacks are that the model includes several functions that appear to have been fitted to some specific surfaces and may not be applicable to others; and that it has not been properly tested against experimental data, so it is not known whether is does indeed improve the calculation of ground-reflected radiation on calculated surfaces. Furthermore, a quick calculation using Gueymard's formulae with a mean daily albedo of 0.7 and a solar elevation angle of 30° (values which would be typical of a winter day) leads to:

ρ_d = 0.7

ρ_n = 0.654

ρ_b = ranging from 0.654 for a surface facing away from the sun to 0.81 for a sun-facing surface.

This means that ground-reflected radiation calculated by Gueymard's formula will be close to the one calculated by the simple isotropic case. The additional computational expense does not seem justified, given the uncertainties attached to albedo estimations on one hand, and to Gueymard's model on the other.

More complex treatment of specularity could be envisioned. For example Reilly *et al.* (1994) calculate solar heat gain reflected from neighboring structures and buildings, using a ray-tracing technique. The same algorithm could be used to calculate radiation reflected by a snow-covered ground. However I believe ESP-r at this moment does not handle reflection from neighbouring buildings; the use of a ray-tracing technique could also be useful to study complex shading devices and their interaction with ground-reflected irradiance (Janák, 2003).

Other approaches of anisotropy, mostly used in remote sending, include the calculation of the bidirectional reflectance distribution function (BRDF). An example can be found in Klein *et al.* (2000). However such algorithms are probably beyond the scope of ESP-r; it is not even clear whether they would be applicable to building simulation since the reflectivity of snow viewed from space over very large areas may be different from that experienced by buildings.

It seems that the treatment of anisotropy is not justifiable at this stage. Ineichen *et al.* (1990) document extensively the importance of albedo on the calculation of ground-reflected radiation. Although they recognize that albedo depends on parameters such as altitude, solar elevation, season, nature of the incident radiation (beam or diffuse), orientation of the receiving surface (S, E, W or N), etc., they conclude from a comparison with experimental data that a good enough accuracy is obtained assuming isotropic ground-reflected albedo. Even is some anisotropy exists, they conclude that "such phenomena depend strongly on the site, its environment and its peculiar characteristics. Consequently, they cannot be fed into the models in a coherent and general way… Site specific gains in performance [from using advanced albedo models] were not found to be substantial… The isotropic model with an albedo known for the site under consideration, is the model to be used and other complications which we could introduce are not justified in most cases[4]".

3.7 Albedo in other building simulation software

In this section the way albedo is used in EnergyPlus and TRNSYS is briefly reviewed.

3.7.1 EnergyPlus

Monthly values of ground reflectance are entered by the user. The user also specifies snow ground reflectance modifiers which allow the user to modify the basic monthly ground reflectance when snow is on the ground (from design day input or weather data values). By default ground reflected radiation is isotropic.

EnergyPlus also includes an optional calculation of ground-reflected radiation using a ray-tracing algorithm (EnergyPlus, 2004). The model takes into account shading by the building itself.

3.7.2 TRNSYS

TRNSYS allows any value of ground reflectance to be used, but does not provide any particular method. Values of 0.2 in the absence of snow, and 0.7 when snow is present, are suggested in the user's manual. Ground-reflected radiation is assumed to be isotropic.

[4] A shortcoming of their study, however, is that it eliminated days with snow on the ground.

4 PROPOSITIONS TO IMPROVE THE ALBEDO ALGORITHM IN ESP-R

In light of the results of the two previous sections, it is clear that a better albedo algorithm is needed in ESP-r, particularly in the presence of snow. However the added complexity of the algorithm has to be balanced with the uncertainties inherent to the estimation of albedo. An added difficulty is that, depending on the kind of weather data used, snow amount may not be known.

It was therefore suggested to implement *two* albedo models:

- A simple model using monthly values of albedo provided by the user. This model would typically be chosen when Typical Meteorological Year (TMY) weather files are used[5].
- A more progressive model which uses actual snow depth values. This other model would typically be chosen when real weather data is used; it may require a modification of the format of some of the weather files used by ESP-r (note, however, that snow depth is available from the common weather format proposed for ESP-r and EnergyPlus; see Crawley *et al.*, 1999). For the moment, snow depth will be read from a separate ASCII file.

As stated earlier, the implementation of a specular ground albedo model does not seem warranted at this stage (however is a specular model has to be implemented, Gueymard's is a reasonable choice; an alternative is to wait until ESP-r incorporates an algorithm to handle reflection from neighbouring buildings and structures).

4.1 Simple model

The user enters twelve values of ground reflectance. Typical values are suggested in the on-line help, as per Table 2.

The use also enters the number of days per month with snow on the ground[6]. Ground reflectance for month i is then calculated as:

$$\rho_i = \rho_{nosnow}\left(1 - \frac{N_{snow,i}}{N_i}\right) + \rho_{snow}\frac{N_{snow,i}}{N_i} \qquad (6)$$

where:

ρ_i = albedo of ground for month i

[5] Even if the TMY contains snow information, it should not be used. TMYs are designed to be representative of the climate of a particular location in terms of temperature and irradiance, but there is no guarantee that the snow information is 'typical'.
[6] For example the Canadian Normals (Environment Canada, 2005) provide the number of days with snow depth greater than 1, 5, 10 and 20 cm. According to the results presented in Baker *et al.* (1991) and the discussion in section 3.4, the 5-cm value should be used.

ρ_{nosnow} = snow-free albedo of ground

$N_{snow,i}$ = number of days with snow on the ground in month i

N_i = number of days in month i

ρ_{snow} = albedo of snow-covered ground. This could be determined according to the site exposure entered by the user (in browse/edit/simulate, model context, exposure), using average values proposed in Hunn and Calafell (1977). The following table of values is suggested:

Table 3 – Suggested reflectivity in the presence of snow

Site exposure	Snow-covered ground reflectivity
Typical city centre	0.2
Typical urban site	0.4
Typical rural site	0.5
Isolated rural site	0.7

it would be a good idea to augment Table 2 with the values of Table 3. Note that the user will not need to enter values of albedo in the presence of snow; but it would still be a good idea to let the user know which values will be used.

4.2 Advanced model

The advanced model assumes that a real historical record of snow depths is available. Hourly snow depth is therefore read from a separate text file. Albedo is calculated through the following algorithms:

When snow depth is greater than 5 cm:

If snow depth increases from the previous time step, albedo is reset to a high value (see later for details).

Otherwise, albedo decreases by a certain amount per day (see later). The decrease is limited in time to that make sure that snow reflectivity does not fall below that of the underlying ground, for example.

When snow depth is less than 5 cm

Albedo is calculated as:

$$\rho = \rho_{nosnow,i}\left(1 - \frac{d}{d_0}\right) + \rho_{snow}\,\frac{d}{d_0} \qquad (7)$$

where d is the snow depth, d_0 is equal to 5 cm, $\rho_{nosnow,i}$ is the no-snow albedo for the month (entered by the user) and ρ_{snow} is the albedo value calculated as if the snow depth was greater than 5 cm.

Albedo after a snow fall should be made dependent upon site exposure, as per Table 3. It is suggested to add 0.05 to the values in Table 3 to account for the fact that albedo will peak higher than what is reported in Hunn and Calafell (1977) right after a snowfall.

The rate of albedo decrease per day should be 1% in the colder months and between 2.4% and 3.3% in the shoulder months, according to the results of Baker *et al.* (1990). One of the possible reasons is that the snow melt increases the concentration at the snow's surface of pollutants deposited with the snow. In our model, the rate of decay is made dependent upon whether or not there is potential snow melt. Snow melt is determined through a simple energy balance at the surface of the snow:

$$\left(1-\rho_g\right)I_g + \varepsilon\sigma\left(T_{sky}^4 - T_s^4\right) + h_c\left(T_a - T_s\right) = \frac{k_s}{L_s}\left(T_s - T_g\right) \qquad (8)$$

where ε is the surface emissivity of snow, σ is the Stefan-Boltzmann constant, T_{sky} is the sky temperature, T_s is the snow surface temperature, h_c is a convection coefficient, T_a is the ambient temperature, T_g is the ground surface temperature, k_s is the thermal conductivity of snow, and L_s is the depth of snow. T_{sky}, T_a, T_g are usually available from the simulation program itself. The emissivity of snow ε is estimated between 0.82 and 0.90 (Incropera and DeWitt, 1995). The convection coefficient h_c is set to 10 W/m^2/K, which corresponds to forced convection with a moderate wind speed (Clarke, 2001). The thermal conductivity of snow ranges from 0.049 to 0.190 (Incropera and DeWitt, 1995). This is a huge range, the former value corresponding to light snow powder (110 kg/m^3) and the latter to heavy, damp snow (at 500 kg/m^3). A value of 0.12 can be used as the snow will probably be most often in an intermediate state.

Equation (10) needs to be simplified so that the snow temperature T_s can be calculated. The radiative term can be approximated by:

$$\left(T_{sky}^4 - T_s^4\right) \approx 4 \cdot T_{sky}^3\left(T_{sky} - T_s\right) \qquad (9)$$

After this simplification, snow surface temperature can be calculated as:

$$T_s = \frac{(1-\rho_g)I_g + 4\varepsilon\sigma T_{sky}^4 + h_c T_a + (k_s/L_s)T_g}{4\varepsilon\sigma T_{sky}^3 + h_c + (k_s/L_s)} \tag{10}$$

T_s greater than 0 °C is indicative of snow melt, and in that case the albedo decay is set to 3% per day. Otherwise, a decay of 1% per day is used. It should be noted that, in equation (10), h_c is often the dominant term; so in most cases, consideration of the ambient temperature would be sufficient to determine the rate of decay of ground albedo, except in periods of very high solar irradiance where the energy balance method is recommended.

5 SUMMARY OF CHANGES TO THE ESP-R SOURCE CODE

5.1 Changes to the code

This section details the modifications made to the ESP-r source code to implement the two models described above.

About fifteen ESP-r source code files were modified. There seems to be a fair amount of code duplication in ESP-r, so I elected to do the same – for example, there is duplication between esrucom/emkcfg.F and esrucnv/ecnv.F, or between esrucom/scsys.F and esrucom/esystem.F. The actual albedo pre-processing and calculation takes place in three subroutines all grouped in esrubld/solar.F. The rest of the changes are mostly for menus and initializations. Here is a summary of the files modified and why:

esrubld/bmatsv.F	The call to MZGREF takes place here
esrubld/input.F	Call pre-processing of snow depth file for advanced albedo model
esrubld/solar.F	The calculation of ground reflectivity in the presence of snow takes place here, in three different subroutines. Note: the call to MZGREF should be here (after the call to MZSANG, at line 423) if specular albedo is considered. Otherwise the call is better placed in bmatsv.f
esrubld/subsys.F	Simply a change of contents for common C5
esrubps/bmatsv.F	The call to MZGREF takes place here
esrubps/input.F	Call pre-processing of snow depth file for advanced albedo model
esrucnv/ecnv.F	Initialize albedo variables, and write albedo information to configuration file
esrucom/emkcfg.F	Write albedo information to configuration file
esrucom/esru_misc.F	Initialization of albedo variables
esrucom/esystem.F	Documentation of variables in common C5 Read albedo information from configuration file Display summary of albedo information to user when model is read
esrucom/scsys.F	Read albedo information from configuration file
esrue2r/e2r.F	Simply a change of contents for common C5

esruprj/context.F	Display menu to choose albedo model
esruprj/folders.F	Simply a change of contents for common C5
esrures/res.F	Document use of IFIL+40 for snow depth ASCII file and IFIL+41 for snow depth binary file

5.2 Suggestions

Apart from removing code duplication by putting the duplicated code in separate subroutines, there could potentially be other improvements that could be made to the ESP-r code. Three are suggested here; had they been implemented, my own work would have been much easier:

- Use INCLUDE to include commons. For example there could be a file C5.CMN that would contain common C5, and each file that needs the common could use:

  INCLUDE C5.CMN

  The advantage of that method are twofold. First, the meaning of the variables of C5 can be properly documented in C5.CMN itself, which makes navigating the code easier. Second, modifications to C5 do not require changes to all the files that use C5, but only to C5.CMN.

- Use IMPLICIT NONE. I am aware that this would require a large rewriting of the code as it would enforce type declaration for all variables; however it would make the code much safer.

- Write a function to automatically affect unit numbers for files. For example instead of using IFIL+40 for the snow depth file, I could have called a function GETFILEUNIT which would have returned a non-used unit number. Then I would not have had to worry whether IFIL+40 is used somewhere else in the code (this would also require either to rewrite OPEN and CLOSE to keep track of which numbers are used, or to add a function to 'free' numbers when a file is closed).

5.3 Tests

The modified program was tested using numerous configurations (for example running the program with 12 identical values of monthly albedo, or with the current constant albedo model, and checking that one gets the same results). Most of these tests were trivial and are not summarized here.

To quantify the influence of the improved snow albedo models, two sets of simulations were run with ESP-r: a passive solar house and a photovoltaic system. Both the simple and the advanced snow albedo models were tested.

Simulation of passive solar house – simple snow albedo model

The passive solar house tested is shown in Figure 4. The house is an energy-efficient two-storey Canadian house with basement, and features a Trombe wall on the south side. Simulations were run for a number of Canadian locations with significant amounts of snow during the winter (see Table 4). The house is assumed to be located in a fairly open, semi-rural setting, so the albedo of the surroundings is set to 0.2 in the absence of snow and to 0.7 in the presence of snow. Canadian Weather for Energy Calculations (CWEC) typical meteorological weather files (Environment Canada, 1999) were used. Number of days with snow depths greater than 5 cm were obtained from the Canadian Normals (Environment Canada, 2005); whenever possible airport locations were used, since they are more representative (climatically speaking) of the semi-rural setting considered. It should be noted that the same house model was used regardless of the location considered; in practice, properly designed houses would be somewhat different in terms of insulation, etc., depending on the climate zone in which they are located.

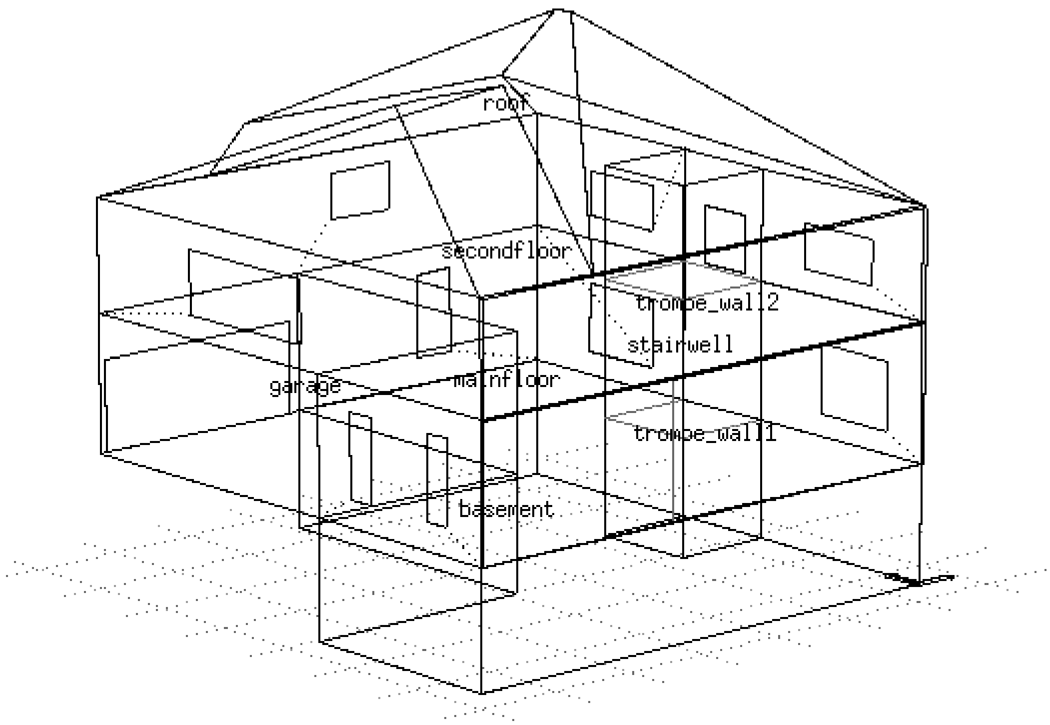


Figure 4 – Model of test house

Table 4 summarizes the results. The sensible load calculated by ESP-r is reduced by between 2.5% and 10.1% on an annual basis, if a snow-dependent albedo is considered instead of a constant albedo equal to 0.2. The reduction is not necessarily proportional to the number of days with snow, though, because the increased albedo of snow reduces the load appreciably only for those months with significant solar radiation. This is illustrated in Figure 5 with data for Montreal and Fort McMurray. For both sites the reduction is higher in

February and March, when the sun shines longer and is higher on the horizon, than in December and January. For Fort McMurray, for example, the improved albedo algorithm results in a load reduction of only 0.12 MWh (or 2.8% of the load) in January, despite 31 days of snow. By contrast, Ottawa experiences load reductions of 0.26 MWh (7.4%) in January and 0.31 MWh (23.3%) in March, despite a lower number of days with snow, because of the lower latitude of the location which results in a longer day length and a higher availability of sunshine.

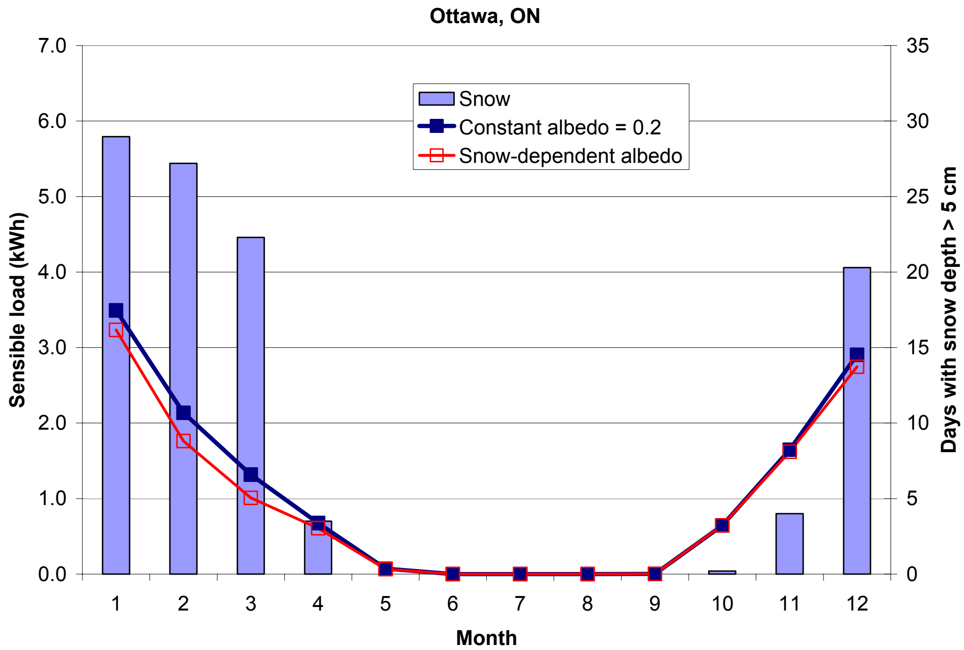
Table 4 - Reduction in annual sensible heating load predicted with the improved albedo algorithm.

Location	Latitude (°N)	Annual # of days with snow depth > 5cm	Annual sensible load (MWh)		
			With constant albedo = 0.2	With variable albedo (simple model)	Difference (%)
Ottawa, ON	45.32	106	12.9	11.7	-9.3
Montreal, QC	45.67	114	13.4	12.1	-10.1
Fredericton, NB	45.87	98	12.6	11.6	-8.9
Winnipeg, MB	49.92	108	16.7	15.6	-7.0
Calgary, AB	51.10	47	13.3	12.9	-3.2
Fort McMurray, AB	56.65	146	19.0	18.0	-5.5
Yellowknife, YT	62.45	177	27.3	26.1	-4.3

It should be noted that the numbers reported here are somewhat extreme: the house is supposed to be located in a rural setting, hence the snow albedo takes a high value (0.7). The effect would have been much less significant, had the house been located in a city centre. Also, the passive design of the house increases the chances that it can make use of the solar reflected radiation. For an ordinary house, the magnitude of the effect would probably have been half as much.

Simulation of passive solar house – advanced snow albedo model

The advanced snow albedo algorithm will be illustrated with yearly simulations for Ottawa, ON. The CWEC weather file (Environment Canada, 1999) for that city was used. CWEC weather files are a catenation of real 'typical' months chosen for their similarity with long-term averages of temperature and solar radiation. It is therefore possible to go back to obtain historical daily snow depths for the months in question, and feed them into the advanced snow albedo model. However Table 5 illustrates that, for this specific example, a typical weather file is not necessarily typical in terms of snow depth. The total number of days with snow depth greater than 5 cm is 106 according to the Canadian Normals (Environment Canada, 2005), but only 68 according to the meteorological records corresponding to the CWEC file.



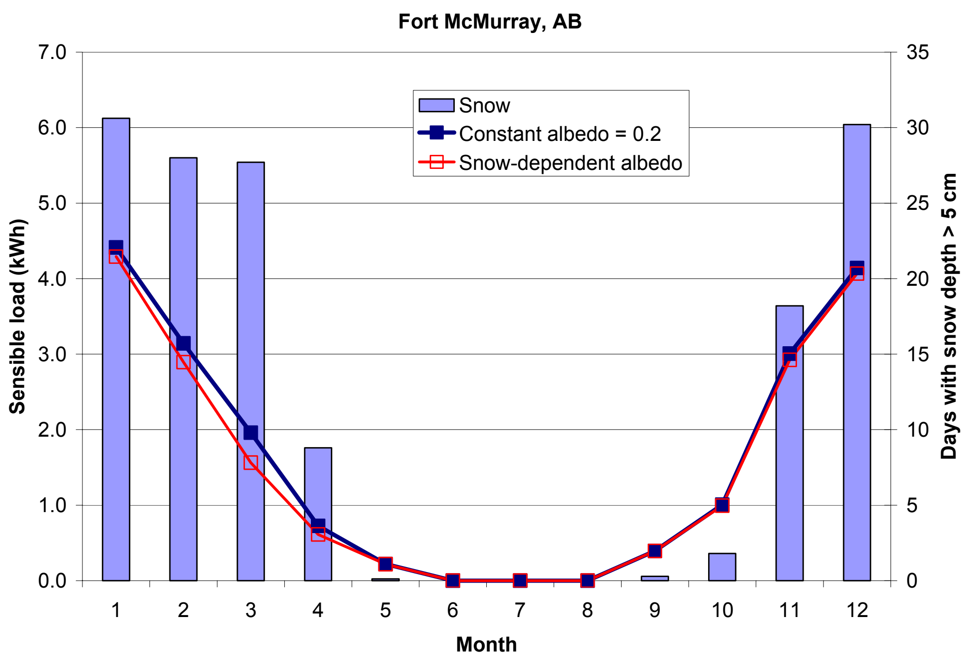


Figure 5 – Reduction of sensible load as modeled with ESP-r with the snow-dependent albedo algorithm

Table 5 – Number of days with snow depth greater than 5 cm, in the Canadian Normals and in the months corresponding to the CWEC typical meteorological file for Ottawa, ON.

Month	Canadian Normals	Months corresponding to CWEC file
January	29	19
February	27	24
March	22	8
April	4	0
May	0	0
June	0	0
July	0	0
August	0	0
September	0	0
October	0	0
November	4	3
December	20	14
Year	**106**	**68**

Figure 6 illustrates the relationship between snow depth and albedo for the January-March period. Albedo is reset to 0.7 at every snow fall, then diminishes at a rate of 1% per day, except when higher ambient temperature and irradiance induce snow melt (one should note, however, that the model does not always correctly predict snow melt). The albedo is also significantly reduced whenever the snow depth falls below 5 cm. The advanced model and the simple model predict about the same reduction in sensible load, if one assumes the same number of days with snow depth greater than 5 cm in the two methods (see Table 6).

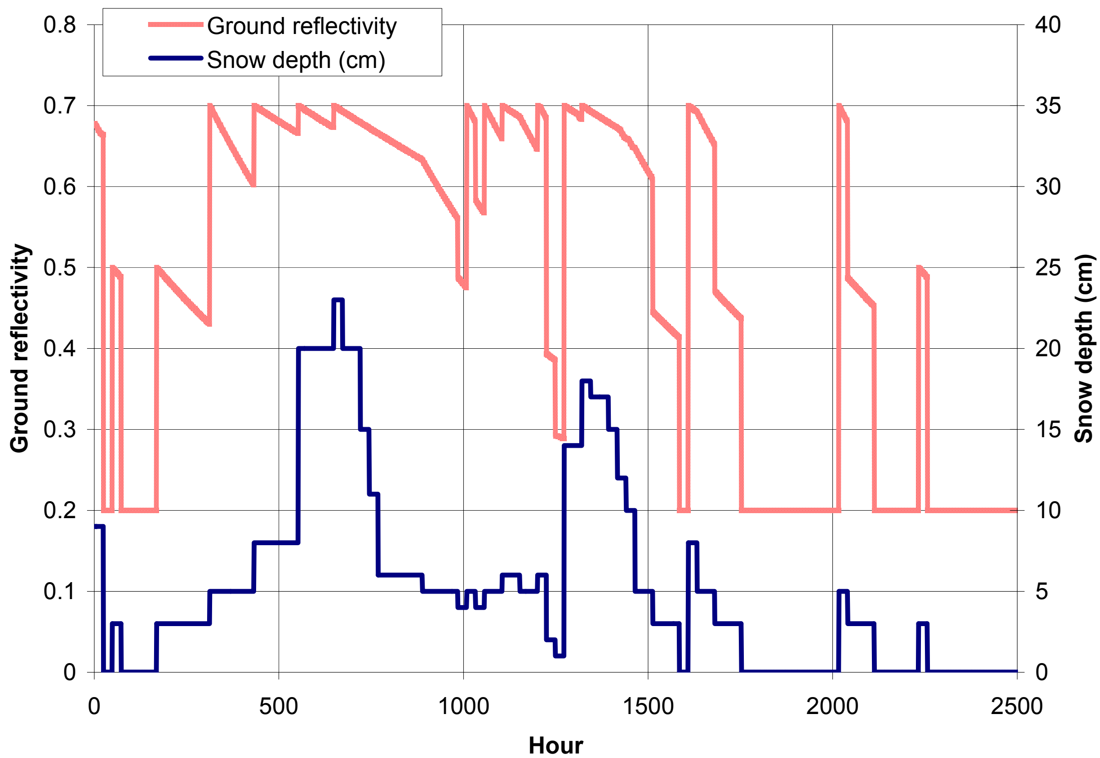


Figure 6 – Simulation of ground reflectivity from January to March for the Ottawa CWEC file.

Table 6 – Sensible heating loads (MJ) predicted by the simple and advanced models for Ottawa, ON.

Month	Simple model	Advanced model
January	3.32	3.28
February	1.80	1.79
March	1.18	1.14
April	0.66	0.66
May	0.07	0.07
June	0.00	0.00
July	0.00	0.00
August	0.00	0.00
September	0.00	0.00
October	0.64	0.64
November	1.63	1.60
December	2.79	2.76
Year	12.10	11.95

Simulation of photovoltaic system

Finally, ESP-r was used to simulate the energy production of a photovoltaic system, using both a constant ground reflectivity (= 0.2) and a snow-dependent reflectivity calculated with the simple model. The locations used were the same as previously. The PV array is a 1.3 kW crystalline-Si array, facing south with a 60° tilt. This tilt angle is recommended to increase the chance that the snow accumulated on the array will slide off by gravity (Ross and Royer, 1999), although it is not necessarily optimal in terms of energy production (note however that with lower tilt angles, the presence of snow on the array during the winter would probably wipe out most of the gains due to the increase in ground reflectivity). Simulation results are summarized in Table 7. It is apparent that the new snow algorithm has much less influence on the PV system than in does on the whole house, with gains ranging from +0.68% to +2.63%. This is of course explained in part by the slope of the PV array, and in part by the different physical behaviour of the system under consideration.

Table 7 – Increase in annual PV energy production predicted with the improved albedo algorithm.

Location	Latitude (°N)	Annual # of days with snow depth > 5cm	Annual energy production (MWh)		
			With constant albedo = 0.2	With variable albedo (simple model)	Difference (%)
Ottawa, ON	45.32	106	1.682	1.718	+2.16
Montreal, QC	45.67	114	1.583	1.622	+2.47
Fredericton, NB	45.87	98	1.597	1.632	+2.20
Winnipeg, MB	49.92	108	1.815	1.848	+1.84
Calgary, AB	51.10	47	1.878	1.891	+0.68
Fort McMurray, AB	56.65	146	1.546	1.579	+2.13
Yellowknife, YT	62.45	177	1.550	1.591	+2.63

6 CONCLUSIONS

Using appropriate values of ground albedo is essential to properly simulate energy use in buildings. This is particularly true during the winter season in cold climates, when the building's energy use is greatest but can be significantly offset by reflection of solar radiation off the snow surrounding the building. In this paper appropriate values of ground albedo to use in the absence of snow are documented; values can range from 0.07 to 0.6 depending on the surface. There is also a wide range of estimates of ground reflectivity in the presence of snow; depending on the type of environment considered, values range from 0.2 to 0.7. Two algorithms for prediction ground reflectivity in the presence of snow were developed. The first, simple algorithm uses the monthly average number of days with snow depth greater than 5 cm, and is appropriate when simulating buildings with 'typical' meteorological years. The second, more advanced algorithm, makes use of actual daily or hourly records of snow depth, and is to be used when 'real' meteorological data is used.

The use of more advance algorithms was considered, for example to model the specular reflectivity of snow; but it was found that the models were somewhat unproven and, in any case, the additional computational expense did not seem justified, given the uncertainties attached to albedo estimations in the first place.

The new algorithms were tested by simulating a passive solar house located in a rural setting, for half a dozen locations in Canada. The reduction in sensible load over the year ranges from 3.2 to 10.1% on a yearly basis, and can be as high as 23% on a monthly basis for the house type considered in this study. The gains from ground-reflected radiation vary over the months and tend to be highest for February or March, when there is both a significant snow cover and relatively more sun to reflect than in December or January. The new algorithms were also tested by simulating a photovoltaic system for the same locations. The gains were more modest and in the order of 0.7% to 2.6% on a yearly basis.

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