PDHonline Course E507 (3 PDH)

Passive Solar Heating Project Analysis

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1. Passive Solar Heating Project Analysis

This course covers the analysis of potential passive solar heating projects, including a technology background and a detailed description of the calculation methods.

2. Passive Solar Heating Background

Passive solar heating (PSH) is the heating of buildings with the solar gains available through windows. The annual heating demand can be significantly reduced by selecting high-performance windows (low heat loss and high solar transmission) and by orienting the bulk of the window area to face towards the equator (south-facing in the Northern Hemisphere). Studies have shown that houses designed using passive solar principles can require less than half the heating energy of the same house using conventional windows with random window orientation. Passive solar designs can also provide a better use of natural daylight for lighting purposes, not to mention a pleasant living environment, and the proper selection of shading devices can result in reduced cooling loads. Typically, the most cost-effective implementation of passive solar designs occurs in new construction since the designer has the freedom to adjust window orientation and add shading devices at very little extra cost. In new construction the designer can take advantage of the lower peak heating load to reduce the size of the heating (and possibly cooling) equipment and distribution systems. Passive solar heating is also cost-effective in retrofits when there are plans to either repair or upgrade the building envelope.

The replacement of conventional windows with high-performance windows can significantly reduce annual heating requirements.

Passive solar heating is best applied to buildings where the heating demand is high relative to the cooling demand. Low-rise residential buildings in moderate to cold climates are the best application. Passive solar heating is more difficult to apply to office and other commercial or industrial buildings where there are high

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internal heat gains especially during the day. However, even in these commercial or industrial applications passive solar design principles have been implemented successfully.

3. Description of Passive Solar Heating Systems

The primary elements in passive solar heating systems are windows. Glass has the beneficial property of transmitting solar radiation allowing energy from the sun to enter the building and warm the interior spaces. Glass is, however, opaque to thermal (or long-wave) radiation, thus heat is not as easily transmitted back outdoors. This phenomenon, known as the "greenhouse effect" is particularly useful for supplying heating energy in the winter.

Clearly, the larger the windows, the more sunlight that will enter the building. Unfortunately, windows are not as thermally insulating as the building walls. A passive solar design will optimize window surface area, orientation and thermal properties to increase the energy input from the sun and minimise heat losses to the outside, while ensuring occupant comfort.

Figure 1 shows the floor plan for a house designed with passive solar principles.

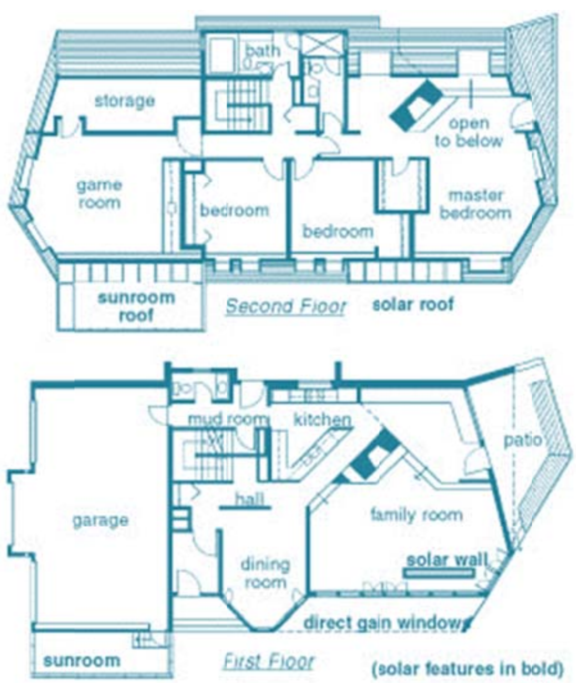

Figure 1. Floor plans for a passive solar house

Sixty percent of the window area is on the south-facing façade. This light mass building has a south-facing window area equal to seven percent of the house floor area. If larger window area were used, additional thermal mass would be required. The windows are triple glazed with 2 low-e coatings, argon gas fills, and insulating edge spacer in an insulated fibreglass frame. The casement and fixed windows have U-values of 1.11 and 1.05 W/(m^2-°C) and solar heat gain coefficients (SHGC) of 0.38 and 0.45 respectively.

Because the sun shines for only part of the day, its heating energy is not always available. A good passive solar design will include some sort of heat storage method. For buildings with modest window area (less than 10% window area to above-grade floor area), traditional North American lightweight construction of wood or steel frame walls with gypsum board offers sufficient thermal mass to store solar gains and prevent overheating on cold sunny days. Heavy materials such as stone or concrete can be used to store heat inside the building during the day releasing it slowly overnight. The thermal mass of the building construction is important for passive solar heating systems with large window area.
The basic principle of operation of a passive solar design, as compared with a conventional building design, is depicted in Figure 2.

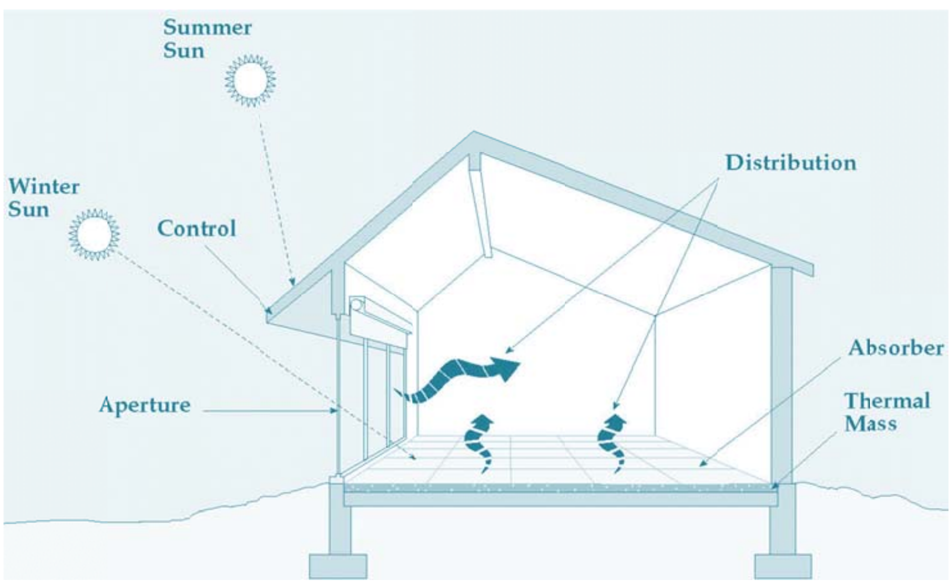

Figure 2. Principles of operation of passive solar heating

Passive solar heating systems do have some disadvantages, particularly during the cooling season. The additional heat provided by the sun can add to air-conditioning loads or make a building uncomfortably warm in the summer. However, this problem can be alleviated by the use of shading elements. Shading a window from direct sunlight is a good way to reduce the solar gains. There are many ways to shade a window: trees in the surrounding yard, awnings or overhangs overhead, or even drapes or blinds. Good passive solar designs will incorporate shading elements to help ensure occupant comfort and to reduce the summer cooling loads that are typically increased by the use of more windows. Another way to help reduce overheating is to minimise the window area on the west side of the building. This passive solar design concept is used because the building will typically be warmer at the end of the day (e.g. daytime temperatures are normally higher than night-time temperatures, the building has been in the sun all day, etc.) and therefore will likely need less solar energy for heating in the afternoon.

In conclusion, passive solar heating involves the proper orientation of buildings and proper location and surface area for windows (most easily implemented in the case of new construction), as well as the correct use of energy efficient windows, shading and thermal mass to reduce both heating and cooling energy demand. A minimal additional investment in passive solar design principles (e.g. energy efficient windows) can greatly improve the performance of the building envelope with positive financial and environmental benefits.

4. Passive Solar Heating Modelling

Passive solar heating project model can be used to evaluate the energy production (or savings) and financial performance associated with energy efficient window use. The model is intended for low-rise residential applications, although it can be used for small commercial buildings, and it applies anywhere in the world where there is a significant heating load. Basically, the model can be used to determine how efficient window use can affect building energy use in four ways:

- Increased solar heat gains to the building through larger and better-oriented windows
- Reduced heat loss through more insulating windows
- Increased or reduced solar gains through the use of appropriate glazing
- Reduced cooling energy demand due to improved shading

A passive solar heating system can incorporate high-performance windows, modified window areas and orientations, and shading elements.

The calculation of solar gains to a building, and the amount of heat lost by conduction is relatively complex. It is dependent upon the solar radiation and outdoor temperature, as well as the thermal properties of the window. The most accurate analysis is to compute these heat transfer on an hourly basis based on detailed characteristics of the building. However, hourly data is rarely available for performing a detailed analysis.

Presented calculations do not predict the building total heating or cooling energy consumption, rather they determine the difference in heating and cooling energy consumption between the proposed passive solar building and an identical building but without the passive solar design features (referred to as the “base case”). In retrofit situations, the base case building would be the existing building before any passive solar alterations. In new construction, the base case would be a building constructed according to standard practices in that region.

The basic premise of the presented calculations is as follows. The base case configuration consists of a building with standard windows (e.g. in North America, double-glazed with a wood or vinyl frame) with varying window area in each of the cardinal directions. The proposed case allows for redistribution of the window area in order to collect more incoming solar radiation and allow for an improvement in window properties so as to increase solar heat gains and/or reduce conductive heat losses. The comparison is performed in terms of the benefit of a reduced heating demand and, in cases where a cooling system is incorporated, the potential penalty of increased cooling demand.

Simplifying assumptions include calculating heat loss and gain based on monthly average solar radiation levels and outdoor temperature, as opposed to hour-by-hour data. The utilisation (or usefulness) of the solar heat gains in reducing heating demand is based on a method developed by Barakat and Sander. It is understood that some margin of error will be introduced by simplifying these calculations.

The net heating and cooling demands are calculated on a monthly basis and summed for the year. The passive solar savings are the difference between the results for the base case and the proposed case buildings. For each month, an energy balance is performed between internal and solar heat gains and conduction losses through the building envelope. The difference between the gains and losses is the net energy saved by the passive solar design; a positive change indicates that the design has contributed to a reduction in the building's energy demand. The model refers to this as renewable energy delivered although it may simply represent a reduction in conventional energy use due to more efficient design. A schematic diagram of the energy model is shown in Figure 3.

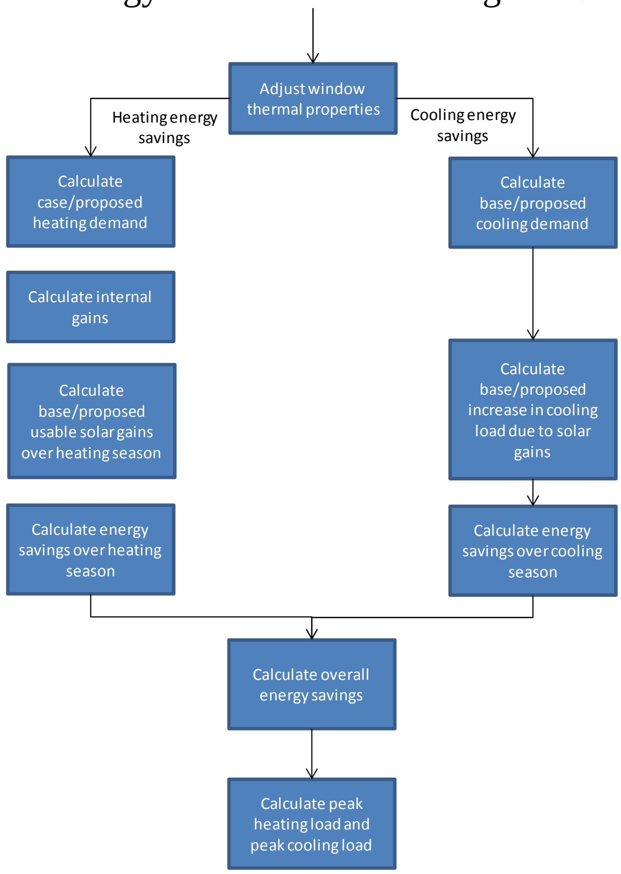

Figure 3. Passive solar heating energy calculation model

Sections below describe how window thermal properties are adjusted to account for actual window size. Also, calculation of heating and cooling energy savings is detailed. Finally, procedure that sums these contributions to calculate the yearly renewable energy delivered is presented.

The traditional definition of "passive solar heating" usually encompasses both the collection of solar energy, for example through windows, and its storage, for example in concrete floors or walls. Presented calculations deal exclusively with the "window" aspect of passive solar heating. For the majority of applications, this is without consequence. Other limitations of the calculations include the fact that:

- The model should only be used for low-rise residential and small commercial buildings (under 600 m^2 of floor area) in heating-dominated climates.
- Window distribution is limited to four orientations, with a 90° difference in azimuth (the building can be rotated to face any azimuth angle);
- Shading effects are calculated using average shading factors that are intended to be representative of seasonal mean values. Because shading factors are time-dependent parameters that change with sun position and time of day, the shading impact should only be viewed as a rough estimate.

These limitations, however, are acceptable at the conceptual design stage to ensure ease-of-use in preparing pre-feasibility studies, especially given the fact that detailed hourly data for a building is not usually available anyhow.

5. Adjustment of Window Thermal Properties

The first step in the calculation process, is to adjust window thermal properties for the actual window sizes (not the tested or rated window size) using a method recommended by Baker and Henry (1997).

Dimensions of samples used to rate windows, with respect to their U-values and solar heat gain coefficients (SHGC), are given in Table 1 for some window types. The SHGC is a dimensionless quantity that is the fraction of the solar energy incident on the window that ends up as heat inside the building. In the model it is assumed that all windows of the same orientation have the same SHGC. If there is more than one type of window used in the building, the individual window SHGC values can be averaged in accordance with their respective window areas.

Window Type	Width (mm)	Height (mm)
Fixed	1,220	1,220
Casement	600	1,220
Sliding	1,550	920
Patio Door	1,830	2,085

Table 1. Standard dimensions of rated windows

To calculate the U-value and SHGC for a window other than the rated size, following parameters can be used:

U_t	= Total window U-value from rating procedure	[W/(m2-°C)]
U_{cg}	= Centre of glass U-value from rating procedure	[W/(m2-°C)]
$SHGC_t$	= Total window solar heat gain coefficient from rating procedure	[-]
$SHGC_{cg}$	= Centre of glass solar heat gain coefficient from rating procedure	[-]
W	= Width of rated product from rating procedure	[m]
H	= Height of rated product from rating procedure	[m]

The calculation assumes that frame dimensions are fixed, frame solar heat gain coefficient is zero, and edge-of-glass U-value can be approximated from the centre-of-glass and total window U-values. For a rectangular window, the fraction frame, defined as the fraction of total-window area covered by the frame, is given by the simple geometrical relationship:

$$F_{fr} = \frac{(WH)-(W-2\overline{H_{fr}})(H-2\overline{H_{fr}})}{(WH)} \quad (1)$$

where $\overline{H_{fr}}$ is the average frame height. Assuming that the frame does not contribute to the solar gain, the fraction frame is also equal to:

$$F_{fr} = 1 - \frac{SHGC_t}{SHGC_{cg}} \quad (2)$$

Solving (1) for the average frame height $\overline{H_{fr}}$ gives:

$$\overline{H_{fr}} = \frac{(W+H)-\sqrt{(W+H)^2-4F_{fr}(WH)}}{4} \quad (3)$$

The estimated frame/edge U-value U_{fr}^* is determined by solving:

$$U_t = \frac{U_{cg}A_g+U_{fr}^*A_{fr}}{A_t} \quad (4)$$

where, A_t, A_g and A_{fr} are the total, glass and frame areas, calculated from window W width and height H and from average frame height $\overline{H_{fr}}$ through:

$$A_t = (WH) \quad (5)$$
$$A_g = (W - 2\,\overline{H_{fr}})\,(H - 2\,\overline{H_{fr}}) \quad (6)$$
$$A_{fr} = A_t - A_g \quad (7)$$

Solving equation (4) leads to:

$$U_{fr}^* = \frac{U_t A_t - U_{cg} A_g}{A_{fr}} \quad (8)$$

Size-specific U-value and solar heat gain coefficient can then be determined from:

$$U_t^* = \frac{U_{cg} A_g^* + U_{fr}^* A_{fr}^*}{A_t^*} \quad (9)$$
$$SHGC_t^* = \frac{SHGC_{cg} A_g^*}{A_t^*} \quad (10)$$

Where U_t^* is the approximate size-specific U-value, $SHGC_t^*$ is the approximate size-specific solar heat gain coefficient, and size-specific areas A_t^*, A_g^* and A_{fr}^* are calculated from actual window dimensions through equations (5) to (7).

Calculations are performed for horizontal-sliding windows and vertical-sliding windows, using different equations to describe the window geometry. Windows can be facing four orientations, with a 90° difference in azimuth (the building can be rotated to face any azimuth angle). For each orientation, values from equations (9) and (10) are summed to obtain the global U-value and solar heat gain coefficient for all windows at that orientation:

$$U_n = \frac{\sum_{j=1}^{k} U_{t,j}^* A_j}{\sum_{j=1}^{k} A_j} \quad (11)$$
$$SHGC_n = \frac{\sum_{j=1}^{k} SHGC_{t,j}^* A_j}{\sum_{j=1}^{k} A_j} \quad (12)$$

where U_n and $SHGC_n$ are the global U-value and solar heat gain coefficient for all windows at orientation n, $U_{t,j}^*$ and $SHGC_{t,j}^*$ are the total-window U-value and solar heat gain coefficient for the j^{th} window at orientation n, A_j is the area of the j^{th} window at orientation n, and k is the number of windows at orientation n.

6. Heating Energy Savings

Two terms are evaluated each month to determine the net heating demand: heating demand (gross) and usable solar heat gains. A third term, internal gains, although part of each monthly evaluation, is assumed constant throughout the year. As noted earlier, calculation determines the difference in energy consumption between the proposed passive solar building and an identical building but without the passive solar features (i.e. the “base case”). The monthly heating demand and usable solar gains will be different between the base case and proposed buildings because of differences in window properties and orientation. The internal heat gains are the same for the two buildings. The following sections describe the determination of these three terms.

7. Monthly heating demand

The building monthly heating demand is assumed to vary linearly with outdoor temperature and is based on typical house heat loss coefficients (UA value in W/°C) and indoor heating set point temperature ($T_{set,heat}$ = 21°C). The heating demand for the base case building for month i, $HL_{base,i}$, expressed in Wh, is:

$$HL_{base,i} = UA_{base}\left(T_{set,heat} - T_{avg,i}\right)N_{h,i} \qquad (13)$$

Where $T_{avg,i}$ is the average outdoor temperature for month i, $N_{h,i}$ is the number of hours in the month, and UA_{base} is the overall heat loss coefficient for the base case building.

The UA value for the base case house is the product of the insulation level and the floor area:

$$UA_{base} = U^{*}A_{floor} \qquad (14)$$

where U^{*} is the insulation level coefficient, and A_{floor} is the total floor area of the building. The value of U^{*} is determined from Table 2, according to a qualitative description of the level of insulation entered by the user.

Insulation Level	U_{wall} $(W/m^2-°C)$	U^* $(W/m^2-°C)$
Low	0.46	3.0
Medium	0.30	2.0
High	0.22	1.0

Table 2. Insulation properties of base case building

The proposed building has a slightly different heat loss coefficient because of changes in the size and U-value of the windows. The building heat loss coefficient for the proposed case, is simply:

$$UA_{prop} = UA_{base} - \left[\sum_{n=1}^{4}(U_n - U_{wall})(A_n)\right]_{base} + \left[\sum_{n=1}^{4}(U_n - U_{wall})(A_n)\right]_{prop} \qquad (15)$$

Where U_{wall} is the assumed wall U-value based on insulation level (see Table 2), U_n is the global U-value for all windows at orientation n (see equation 11), and A_n is the total window area for orientation n.

Finally, the monthly heating demand for the proposed case, $HL_{prop,i}$, is evaluated with an equation similar to equation (13):

$$HL_{prop,i} = UA_{prop}(T_{set,heat} - T_{avg,i})N_{h,i} \qquad (16)$$

where the overall heat loss coefficient UA_{prop} is given by equation (15).

8. Monthly internal heat gain

The monthly internal heat gain is the same for both buildings. The daily internal heat gain IG_{daily} is assumed constant throughout the year and is entered by the user. The internal heat gain IG_i for month i is therefore:

$$IG_i = IG_{daily}\, N_{h,i}/24$$

where $N_{h,i}$ is the number of hours in the month.

9. Monthly usable solar gains over the heating season

Solar radiation transmitted into the building through the windows helps offset the heating demand of the building. However, only some of the solar gains are useful in reducing the heating demand. This section describes the calculation of solar gains and the estimation of the utilisation factor determining what part of the solar gain is usable.

10. Solar gains

The increase in solar heat gains obtained in the proposed case configuration is the sum of two terms: first, the associated increase in solar gains due to higher transmission of short-wave radiation through the glazing, and second, the re-distribution of window area that changes the total amount of solar energy captured by the windows due to their orientations. The solar gains for the ith month for the base case $S_{base,i}$, and for the proposed case $S_{prop,i}$, are determined as follows:

$$S_{base,i} = \sum_{n=1}^{4}\left[S_{inc,n,i}\left(1 - D_{base,n,i}\right)SHGC_{base,n}A_{base,n}\right] 0.93\ N_{h,i} \quad (18)$$

$$S_{prop,i} = \sum_{n=1}^{4}\left[S_{inc,n,i}\left(1 - D_{prop,n,i}\right)SHGC_{prop,n}A_{prop,n}\right] 0.93\ N_{h,i} \quad (19)$$

Where $S_{inc,n,i}$ is the total daily solar radiation incident on a vertical surface of orientation n for month i, $D_{n,i}$ is the seasonal shading factor for windows at orientation n for month i, $SHGC_n$ is the global solar heat gain coefficient for all windows of orientation n (see equation 12), A_n is the global window area for orientation n and is the number of hours in month i. 0.93 is an off-angle incidence correction factor.

The incident solar radiation, $S_{inc,n,i}$, is calculated using the methods described by Duffie and Beckman. The window shading factor ($D_{n,i}$) is selected between two values (both user-defined) according to the season (summer or winter). The seasons are considered six-month periods corresponding to the sun's movement. Regardless of hemisphere, the summer is considered to be the months where the sun is highest in the sky and winter corresponds to the months where the sun is lowest.

11. Utilisation factor for solar gains during the heating season

The utilisation factor, f_i, is calculated according to methods originally developed by Barakat and Sander (1982). The factor, which varies by month, is determined from the equation:

$$f_i = \frac{a+(b\ GLR_i)}{1+(c\ GLR_i)+(d\ GLR_i^2)} \qquad (20)$$

The coefficients (a, b, c and d) are a function of the mass level of building and the acceptable indoor air temperature swing. Values for a 5.5°C temperature swing are used in the software program (this is likely the maximum swing that could be tolerated in a passive solar house). The variation with mass level is given in Table 3. The mass level is user-defined.

Mass Level	a	b	c	d
Low	1.156	-0.3479	1.117	-0.4476
Medium	1.000	4.8380	4.533	3.6320
High	1.000	0.2792	0.245	0.4230

Table 3. Coefficients used in utilisation function

The gain load ratio (GLR) is determined as follows:

$$GLR_i = \frac{S_i}{HL_i - IG_i} \qquad (21)$$

Where S_i is the monthly solar gain (equations 18 and 19), HL_i is the monthly heating load (equations 13 and 16), and IG_i is the monthly internal gain (equation 17).

The resulting utilisation factor indicates the proportion of the transmitted solar gains that are utilised to offset heating load. Because the solar gains are likely different between the base case and the proposed case, distinct utilisation factors and must be computed for each case.

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12. Annual heating energy savings

Heating energy savings are calculated for each month as the difference between the energy required to heat the building in the base case and in the proposed case:

$$\Delta q_{heat,i} = \left(HL_{base,i} - IG_i - f_{base,i}S_{base,i}\right)^{+} - \left(HL_{prop,i} - IG_i - f_{prop,i}S_{prop,i}\right)^{+} \quad (22)$$

The + exponent means that if either value within the parenthesis is negative, the value within the parenthesis becomes zero, because if internal and solar gains are greater than the demand then there is no need for heating. The various quantities appearing in equation (22) were derived in equations (13) and (16) to (20).
The energy savings over the heating season, Δq_{heat}, are the sum of the monthly energy savings:

$$\Delta q_{heat} = \sum_{i=1}^{12} \left[\left(HL_{base,i} - IG_i - f_{base,i}S_{base,i}\right)^{+} - \left(HL_{prop,i} - IG_i - f_{prop,i}S_{prop,i}\right)^{+}\right] \quad (23)$$

13. Cooling Energy Savings

One of the tradeoffs associated with increased solar gains is the additional heat that may contribute to cooling energy demand in the summer months. To determine annual energy savings, the detrimental effects of increased solar heat gain must be assessed. For heating-dominated climates, the conductive heat gain through windows in the summer is very small relative to the solar gains and can be ignored Therefore the additional cooling requirement is determined only from the increased solar gain.

Although the utilisation function was developed for heating, it can be extended to obtain a modified utilisation factor, $(1 - f_i')$, that represents the monthly proportion of non-usable, or undesirable solar gains received during the cooling season. If the heating and cooling thermostat settings were set at the same temperature, the building would always be in either heating or cooling mode (with no fluctuation in building air temperature). In this scenario, solar gains would either be useful in reducing the heating demand or contribute to overheating and a cooling demand. Thus, the contribution to cooling demand would be one minus the utilisation factor.

However, the heating and cooling thermostat settings are not identical. There is a dead band, i.e. a range of temperatures where neither cooling nor heating is required. The modified utilisation factor therefore has to be calculated with the cooling, rather than heating, set point temperature.

The concept of heating and cooling utilisation factors is depicted by example in Figure 4. The lower curve represents the utilisation factor for heating, for a climate in the Northern Hemisphere. During the winter months the heating utilisation approaches 100%, meaning that almost all solar gains are useful towards reducing the heating energy demand. During the summer, this value tapers down to 0% as the need for heating is eliminated.

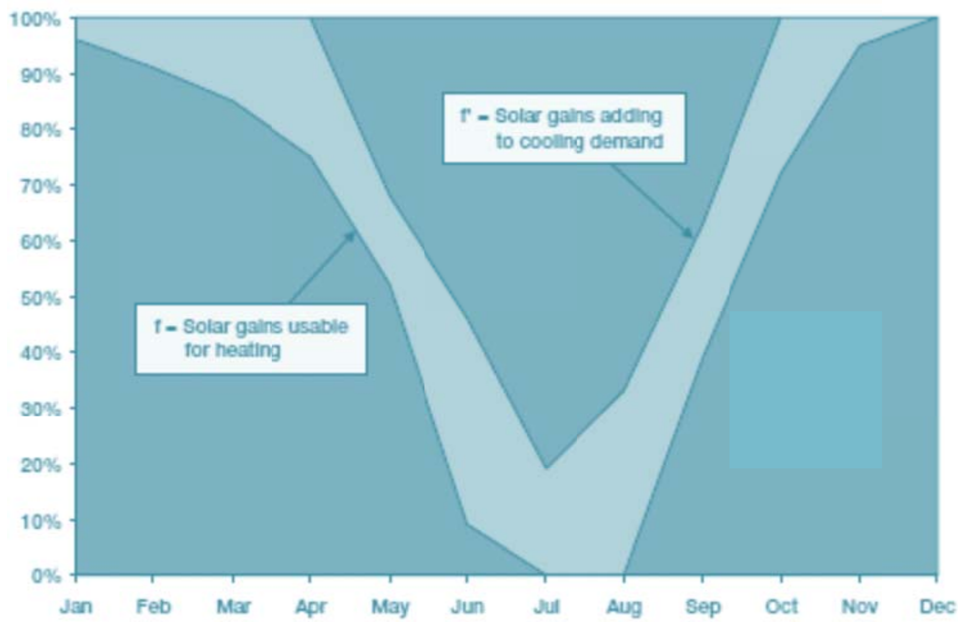

Figure 4. Example of heating and cooling utilisation factors

During the winter months the utilisation factor for cooling, f', is 100% meaning that the contribution of solar gains to the cooling demand, $(1 - f_i')$, is 0%. As the cooling utilisation factor drops in the summer, its conjugate increases, approaching 100%. Thus in the summer, almost all solar gains are detrimental to the cooling demand.

The space between the two curves represents the dead band. The model ignores the percentage of solar gains that neither reduce the heating demand nor increase the cooling demand, as they do not contribute to energy savings.

The procedure followed to calculate the cooling energy savings is therefore similar to previous sections, and the energy savings over the cooling seasons, Δq_{cool}, are expressed through an equation similar to equation (23), but with no heating demand term and with f_i replaced by $(1 - f_i')$:

$$\Delta q_{cool} = \sum_{i=1}^{12}\left[\left(1 - f'_{base,i}\right)S_{base,i} - \left(1 - f'_{prop,i}\right)S_{prop,i}\right] \qquad (24)$$

The modified utilisation factor, f_i', is calculated through equation (20). However, the gain load ratio GLR appearing in that equation has to use the heating demand calculated using the cooling set point temperature $T_{set,cool}$ rather than heating set point temperature $T_{set,heat}$ equations (13) and (16) are therefore replaced with:

$$HL_{base,i} = UA_{base}(T_{set,cool} - T_{avg,i})N_{h,i} \qquad (25)$$
$$HL_{prop,i} = UA_{prop}(T_{set,cool} - T_{avg,i})N_{h,i} \qquad (26)$$

In the equivalent models, the cooling set point temperature is set to $T_{set,cool} = 25°C$. As before, because of the differences between cases, separate modified utilisation factors are needed for both the proposed case and the base case.

14. Annual Energy Savings

Annual energy savings, referred to in the model as renewable energy delivered, Δq_{del}, are obtained by simply summing heating and cooling energy savings (equations 23 and 24):

$$\Delta q_{del} = \Delta q_{heat} + \Delta q_{cool} \qquad (27)$$

Finally, the model also calculates the peak heating or cooling load (power) reductions, which indicate to the user opportunities to reduce the capacity of the conventional heating system or that of the air-conditioning system. Peak heating load reduction ΔP_{heat} is calculated using the following equation:

$$\Delta P_{heat} = (UA_{base} - UA_{prop})(T_{set,heat} - T_{des,heat}) \qquad (28)$$

Where UA_{base} and UA_{prop} were calculated through equations (14) and (15),

$T_{set,heat}$ is the heating set point temperature (21°C), $T_{des,heat}$ and is the heating design temperature. The calculation of the peak cooling load reduction ΔP_{cool} is only slightly more complicated:

$$\Delta P_{cool} = \left(UA_{base} - UA_{prop}\right)\left(T_{des,cool} - T_{set,cool}\right) + S_{max} \tag{29}$$

Where $T_{des,cool}$ is the design cooling temperature, $T_{set,cool}$ is the cooling set point temperature (25°C), and S_{max} is the maximum solar gain. This latter value is calculated assuming that the peak cooling load occurs on a sunny summer day (normal irradiance equal to 1,100 W/m2); solar angles are calculated to estimate the values on north, south, east and west facing windows.

15.Checklist for Good Design

1. Building orientation: A number of innovative techniques can be used for obtaining good solar access on less-than-ideal sites. No matter what the house's design, and no matter what the site, some options for orientation will be more energy-efficient than others, and even a very simple review of the site will probably help you choose the best option available.

2. Upgraded levels of insulation: It is possible, of course, to achieve very high energy-efficiency with a "super-insulated" design. But in many cases, one advantage of passive solar design is that energy-efficiency can be achieved with more modest increases in insulation. On the other hand, if very high energy performance is a priority - for example, in areas where the cost of fuel is high - the most cost-effective way to achieve it is generally through a combination of high levels of insulation and passive solar features.

3. Reduced air infiltration: Air tightness is not only critical to energy performance, but it also makes the house more comfortable. Indoor air quality is an important issue, and too complex for a complete discussion here, but in general, the suntempered and passive solar houses built according to the guidelines provide an alternative approach to achieving improved energy efficiency without requiring air quality controls such as air to air heat exchangers, which would be needed if the house were made extremely airtight.

4. Proper window sizing and location: Even if the total amount of glazing is not changed, rearranging the location alone can often lead to significant energy savings at little or no added cost. Some energy-conserving designs minimize window area on all sides of the house - tut it's a fact of human nature that people like windows, and windows can be energy producers if located correctly.

5. Selection of glazing: Low-emissivity (low-e) glazing types went from revolutionary to commonplace in a very short time, and they can be highly energy-efficient choices. But the range of glazing possibilities is broader than that, and the choice will have a significant impact on energy performance. Using different types of glazing for windows with different orientations is worth considering for maximum energy performance; for example, using heat-rejecting glazing on west windows, high R-value glazing for north and east windows, and clear double-glazing on solar glazing.

6. Proper shading of windows: If windows are not properly shaded in summer - either with shading devices or by high-performance glazing with a low shading coefficient -the air conditioner will have to work overtime and the energy savings of the winter may be cancelled out. Even more important, unwanted solar gain is uncomfortable.

7. Interior design for easy air distribution: If the rooms in the house are planned carefully, the flow of heat in the winter will make the passive solar features more effective, and the air movement will also enhance ventilation and comfort during the summer. Often this means the kind of open floor plan which is highly marketable in most areas. Planning the rooms with attention to use patterns and energy needs can save energy in other ways, too - for instance, using less-lived-in areas like storage rooms as buffers on the north side.

8. Addition of thermal mass: Adding effective thermal mass - for example, tiled or paved concrete slab, masonry walls, brick fireplaces, tile floors, etc. - can greatly improve the comfort in the house, holding heat better in winter and keeping rooms cooler in summer. In a passive solar system, of course, properly sized and located thermal mass is essential.

9. Selection and proper sizing of mechanical systems, and selection of energy-efficient appliances: High-performance heating, cooling and hot water systems are extremely energy-efficient, and almost always a good investment.

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Mechanical equipment should have at least a 0.80 Annual Fuel Utilization Efficiency (AFUE). Well-insulated passive solar homes will have much lower energy loads than conventional homes, and should be sized accordingly. Oversized systems will cost more and reduce the house's performance.

16.Summary

Described mathematical model calculates changes in heating demand and solar gains that result from the adoption of energy efficient window technologies. Changes in heating demand between the base case and the new proposed design are calculated by evaluating the variation in heat loss coefficient related to the proposed changes in the size and U-value of the windows. Changes in solar gain are evaluated by calculating solar gains in both the base and the proposed design, and estimating what part of the solar gain is usable for heating purposes. The same methodology is applied to calculate the associated penalty in cooling demand during the summer months.

Despite the simplifications introduced, the predictions of the passive solar heating project equations prove adequate at the pre-feasibility stage.