THE RETSCREEN MODEL FOR SIMULATING THE PERFORMANCE OF SOLAR AIR HEATING SYSTEMS

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ABSTRACT

Solar heating of outdoor air to meet ventilation or process air heating loads is one of the most cost effective solar applications. These systems offer high solar collection efficiencies and low construction cost. An easy-to-use screening tool, a SAH module of RETScreen, was developed to assess the feasibility of solar ventilation air heating systems. RETScreen predicts the annual energy savings, capital cost, financial performance and greenhouse gas savings of renewable energy technologies.

INTRODUCTION

Solar heating of outdoor air to meet ventilation or process air heating loads is one of the most cost effective solar applications. These systems offer high solar collection efficiencies and low construction cost. Heating of ventilation air is a seven-to-nine-month load in cold climates and a 12-month load in industrial processes and tropical crop drying. Because the inlet air temperature is equal to the ambient air temperature, heat losses are low and efficiency is high. The most common design achieves high efficiencies using a perforated plate absorber without a glazing. In many applications, the collector (i.e., perforated plate) is mounted on the south side of the building. The collector serves as the building cladding and reduces heat loss from the building wall. The system can also save energy in high ceiling industrial buildings by destratifying the building indoor air.

The cost effectiveness of the system varies widely depending on the cost of energy displaced, design of the system (in particular flow rate), the length of the heating season, installed cost and the value of equipment displaced by the system (e.g., make-up air system). Because of the uncertainty of the system cost effectiveness, many potentially cost effective applications of this renewable energy technology go unexploited. To address this issue, a Solar Air Heating (SAH) module was added to the RETScreen software. RETScreen is an easy to use screening tool that assesses the cost, performance, economics and greenhouse gas savings of renewable energy technologies. The software can be downloaded from the Internet at no charge at www.retscreen.gc.ca.

This paper covers three areas. First, the current designs of solar air heating systems are described. Second, the models used in the RETScreen program to calculate the energy savings from solar heating, reduction in wall heat loss and destratification of building indoor air are presented. Finally, recent examples of cost effective applications of this technology are discussed.

SOLAR AIR HEATING APPLICATIONS

There are three common applications of solar air heating:

- Industrial ventilation air heating - where a solar ventilation air heating system supplies and distributes solar heated air,
- Commercial ventilation air heating - where the solar collector is used as a pre-heater to a make-up air heater or conventional HVAC system,
- Process air heating- where the solar air heating system is used as either a stand alone system or as a pre-heater in applications such as agricultural crop drying or process air heating.

In all these applications, outdoor air is the inlet to the collector, thus ensuring high solar collection efficiency. The most common collector type is a perforated-plate design. A fan draws outdoor air through small perforations in the absorber into a channel behind the absorber. With this arrangement a glazed cover is not required to reduce heat loss. A summer bypass damper is included to allow outdoor air to enter the building directly and avoid overheating the ventilation air on warm days. In northern applications, the collectors are typically mounted on the south-facing wall as the building cladding, thereby offsetting the cost of conventional building cladding. For tropical applications, the collectors are mounted as part of the roof.

These types of systems save energy in three ways. First, of course, is that when the sun is shining the air is heated as it flows over and through the warm perforated plate. One advantage of this application is that the solar collection efficiency is always high even on cold or cloudy days. The collection efficiency typically varies from 40 to 80% depending on the flow rate through the collector.

The second savings occurs in industrial buildings. Building make-up air from the solar heating system enters the building at ceiling level. This air is mixed with ceiling air to achieve a constant delivered air temperature, thereby replacing the need for a make-up air heater. The amount of outdoor and mixing (or recirculated) air is continuously varied to achieve the desired temperature. Because this mixed air is typically cooler than the ceiling air temperature, it falls to floor level, destratifying the air as it goes.

The third mode of energy savings, referred to as "building heat recapture savings", is the reduction in building heating due to the extra insulating value provided by wall-mounted collectors. The extra insulating value comes from the combination of two effects. The first effect reduces heat loss through building wall behind the collector by providing an air cavity between it and the building wall that is at a warmer temperature than the outdoors. The second effect comes from the recapture of heat loss out the building walI into the ventilation air flowing through the cavity being blown back into the building.

RETSCREEN PROGRAM ALGORITHMS

The heat transfer in solar air heating systems is relatively complex. It is dependent upon the solar radiation, temperature and wind speed surrounding the system. Most solar air heating analyses operate on an hourly basis to follow the changing solar and weather conditions. The RETScreen approach is to evaluate the performance on a monthly basis in order to provide results quickly with a minimum of input information. This approach is deemed suitable at the feasibility stage in project development.

The RETScreen solar air heating model uses average monthly values for solar radiation, temperatures and wind speeds to predict performance. The basis of the calculations is an empirically derived collector efficiency curve. By combining the average monthly weather data and the collector efficiency curve the solar utilization factor and energy savings are determined.

Solar Heat Collected

RETScreen includes weather data for over 1000 locations and a link to the NASA web site so that weather data can be estimated for any location in the world. Horizontal values of monthly solar radiation are converted to values on a tilted surface using methods described in Duffie & Beckman (1991).
The efficiency of a perforated plate solar collector depends on a number of variables. The more dominant of these are collector airflow and wind speed on the surface of the collector. Collector efficiency is calculated using the following equation:

$$\eta = \frac{\alpha}{\left(1 + \dfrac{\left(\dfrac{20 \cdot v'_{wind}}{\dot{Q}_{coll}}\right) + 7}{\dot{Q}_{coll} \cdot \rho c_p (1 - 0.005 \cdot \dot{Q}_{coll})}\right)}$$

where:

η	Solar collector efficiency	[-]
α	Solar absorptivity (of collector material)	[-]
$\dot{Q}_{coll}$	Flow rate of air through the collector	[m³/s]
v'_{wind}	Corrected wind speed	[m/s]
ρ	Density of the air (assumed value $\rho = 1.223$)	[kg/m³]
c_p	Specific heat capacity of the air (assumed value $c_p = 1.005$	[kJ/kg-°C]

These values of ρ and c_p will be used throughout this paper. For the purposes of RETScreen analysis, a corrected wind speed (accounting for sheltering) is used which is different from the free stream wind velocity as follows:

$$v'_{wind} = 0.35 v_{wind}$$

where:

v_{wind}	Average free stream wind speed	[m/s]

The development of the collector efficiency curve is described in detail in "Solar Air Heating Systems", International Energy Agency Solar Heating and Cooling Programme (1999).

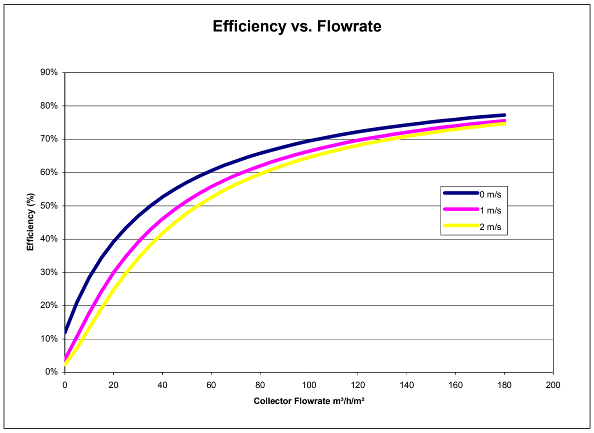

Figure 1 – Relationship Between Collector Efficiency and Collector Airflow at Various Wind Speeds

Solar Utilization

Since solar energy in a SAH system is used to displace heating loads, there will likely be times when energy is collected but cannot be used to offset heating loads. Only energy that can contribute to reducing the heating load can be considered *useable*. Collection of non-useable solar energy is avoided in most SAH systems by using a summer bypass damper that pulls some or al of the air directly from the outside instead of through the collector to limit the delivered air temperature.

To simulate this, a utilization factor $f_{util,i}$ is introduced to determine the quantity of collected solar energy that would only contribute to heating savings. In order to calculate the utilization factor, both the average actual temperature rise through the collector (ΔT_{act}) and the maximum available temperature rise (ΔT_{avl}), are determined. The maximum available temperature rise represents the increase in air temperature as it flows through the collector with no limits on the desired outlet temperature. The actual temperature rise is the increase in temperature after the control system has limited the delivered air temperature to the prescribed maximum, $T_{del,max}$. The utilization factor $f_{util,i}$ is then given by:

$$f_{util,i} = \frac{\Delta T_{act}}{\Delta T_{avl}}$$

Available temperature rise is found using the collector efficiency and the collector air flow rate, $\dot{Q}_{coll}$. For month *i*:

$$\Delta T_{avl} = \frac{\eta \cdot G_{tilt,i}}{\dot{Q}_{coll} \cdot \rho C_p \cdot h_{sunlight,i}}$$

where , ρ and C_p are the density of air and the specific heat capacity of air.

The actual temperature rise is limited by conditions imposed on the temperature of the air exiting the collector, also called *delivered temperature*. The actual delivered temperature $T_{del,act}$ is constrained so as not to exceed the maximum delivered air temperature, $T_{del,max}$, entered by the user. The equations below demonstrate how ΔT_{act} is determined:

$$T_{del,avl} = \left(T_{amb} + \Delta T_{offset}\right) + \Delta T_{avl}$$

$$T_{del,act} = \min\left(T_{del,max}, T_{del,avl}\right)$$

$$\Delta T_{act} = T_{del,act} - \left(T_{amb} + \Delta T_{offset}\right)$$

where $T_{del,avl}$ is the available delivered temperature. ΔT_{offset} is a temperature offset of 3ºC added to the ambient temperature on the assumption that the daytime temperature is higher than the average temperature.

A negative result is not allowed and if necessary, the actual temperature rise is forced to zero.

For commercial buildings and crop drying systems, the airflow rate through the collector is constant and it operates at a fixed condition. The case of heating systems for industrial buildings is slightly more complicated. In industrial buildings, a recirculation damper system incorporated into the fan compartment mixes warm indoor air with cooler solar collector air to maintain a constant delivered air temperature. The ratio of indoor (recirculated) air to solar air heating system (outdoor) air varies continuously with changes in the solar collector outlet air temperature. As a consequence, the flow rate of air through the collector varies, and so does the collector efficiency and the temperature rise through the collector. Since it is impossible to calculate one of the quantities without knowing and the other, an iterative algorithm becomes necessary to find the operating point on Figure 1.

For simplicity the program iterates three times. First an educated guess is made for the starting collector flow rate $\dot{Q}_{coll}^{(1)}$. The following equation provides a suitable estimate:

$$\dot{Q}_{coll}^{(1)} = \min\left(1, \frac{7.5}{\max\left(0, \left(T_{del} - T_{amb}\right)\right)}\right) \cdot \dot{Q}_{design}$$

where $\dot{Q}_{design}$ is the design air flow rate through the collector, T_{del} is the desired delivered air temperature for the supply air, and T_{amb} is the outdoor ambient air temperature for the given month. An initial efficiency $\eta^{(1)}$ is then determined from the efficiency equation using $\dot{Q}_{coll} = \dot{Q}_{coll}^{(1)}$. The first iteration collector temperature rise is then determined using the T_{avl} equation. The corresponding delivered air temperature is then determined based on the limitations discussed earlier. Using the new actual temperature rise, a second estimate of collector flow rate is obtained:

$$\dot{Q}_{coll}^{(2)} = \left(\frac{T_{recirc} - T_{del}}{T_{recirc} - T_{rise1,actual}}\right) \cdot \dot{Q}_{design}$$

where T_{recirc} is the recirculation temperature, taken as the average of the setpoint temperature and the stratified ceiling air temperature. Three iterations provide a converged solution..

Finally the solar energy delivered over the year, Q_{sol}, is obtained by summing monthly contributions:

$$Q_{sol} = \sum_{i=1}^{12} \left[\eta_i \cdot G_{coll,i} \cdot f_{util,i}\right]$$

where η_i is the monthly collector efficiency, $G_{coll,i}$ is the amount of solar energy available to the collectors and $f_{util,i}$ is the monthly utilization factor

<u>Building Heat Recapture Savings</u>

When a SAH collector is installed on a building, there is added benefit due to the return of lost building heat through the collector. If the collector is not running, there is a small benefit associated with a slightly increased R-value of the building wall. The model estimates building heat recapture savings under three different modes: daytime operating, nighttime operating, and during shutdown times. The net savings are found by simply summing these three quantities. The three modes are calculated as follows.

A detailed analysis of the collector [Enermodal, 1997] showed that the effective temperature for determining building heat loss is much warmer than the outdoor temperature (one third outdoor air temperature and two thirds collector temperature).

$$\dot{q}_{recap,daytimeop,i} = \frac{d_{op}}{7} \cdot n_{days,i} \cdot h_{op,daytime,i} \cdot \left[\frac{A_{wall}}{R_{wall}}\left(21 - \left(T_{eff}\right)\right)\right]$$

$$\dot{q}_{recap,nighttimeop,i} = \frac{d_{op}}{7} \cdot n_{days,i} \cdot h_{op,nighttime,i} \cdot \left[\frac{A_{wall}}{R_{wall}}\left(21 - T_{amb,i}\right)\right]$$

The air channel behind the absorber plate is assumed to add an additional RSI 0.33 to the thermal resistance of the wall

$$\dot{q}_{recap,shutdown,i} = \frac{d_{op}}{7} \cdot n_{days,i} \cdot \left(24 - h_{op}\right) \cdot \left[\left(\frac{A_{wall}}{R_{wall}} - \frac{A_{wall}}{R_{wall} + 0.33}\right)\left(21 - T_{amb,i}\right)\right]$$

where:

d_{op}	Operating days per week	[-]
$n_{days,I}$	Number of day in month *i*	[days]
$h_{op,daytime,I}$	Hours of operation during sunlight hours for month *I*	[h/day]
$h_{op,nightime,I}$	Hours of operation during night-time hours for month *i*	[h/day]
h_{op}	Operating hours per day	[h]
A_{wall}	Solar collector area	[m²]
R_{wall}	Insulating value of the wall	[m²-°C/W]
$T_{coll,I}$	Collector air temperature rise for month *I*	[°C]
$T_{amb,i}$	Monthly average temperature	[°C]

Finally $T_{eff,i}$ represents an 'effective temperature' that the building wall loses heat to. Results from monitoring suggest that heat exchanges through the building wall are for two-thirds attributable to collector temperature and for one-third to ambient temperature, thus: (Enermodal, 1994)

$$T_{eff,i} = \frac{2}{3} T_{coll,i} + \frac{1}{3} T_{amb,i}$$

<u>Destratification Savings</u>

Destratification savings are only found in industrial systems. The high ceiling in most industrial buildings allows warm air to rise and settle near the ceiling. Cooler air flowing from the ventilation system near the ceiling mixes with this warm air to reduce the temperature difference between the floor and the ceiling. Accordingly, there is less heat loss through the roof and through rooftop exhaust vents.

$$\dot{q}_{destrat} = \sum_{i=1}^{12} \left[\frac{d_{op}}{7} \cdot n_{days,i} \cdot f_{sys,i} \cdot h_{op} \cdot \left(T_{strat} - T_{strat} \right) \cdot \left(\dot{Q}_{design} \cdot \rho c_p + \frac{A_{wall}}{R_{roof}} \right) \right]$$

where:

d_{op}	Operating days per week	[days]
$n_{days,i}$	Number of days in month *i*	[days]
$f_{sys,i}$	Fraction of the month (*i*) used for system operation	[-]
h_{op}	Operating hours per day	[h]
T_{strat}	Stratified ceiling air temperature after SAH installed	[°C]
T'_{strat}	Stratified ceiling air temperature before SAH installed	[°C]
$\dot{Q}_{design}$	Design air flow rate through the collector*	[m³/s]
ρ	Density of the air	[kg/m³]
c_p	Specific heat capacity of the air	[kJ/kg-°C]
A_{wall}	Area of the collector surface	[m²]
R_{wall}	Insulating value of the wall	[m²-°C/W]

*The exhaust airflow is expected to be equivalent to the SAH design flow and is assumed to run at the same schedule as the SAH system.

The amount of ceiling temperature destratification (T'_{strat} - T_{strat}), is entered by the user. Results from SAH system monitoring have indicated that after the SAH installation, stratification is reduced by at least 25% and not to exceed 5°C (see Figure 2)(Enermodal, 1994).

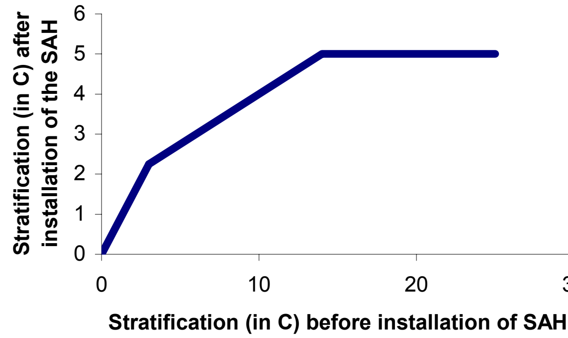

Figure 2 – Effect of SAH installation on building air stratification.

<u>Validation</u>

The RETScreen Solar Air Heating Model uses system design parameters along with monthly weather data to determine annual energy savings. The concept is similar to that used in the SWift™ program developed by Natural Resource Canada's Canmet Energy Technology Centre group in 1999 (Carpenter *et al.*, 1999; Enermodal, 1999). The SWift program is a detailed simulation program used to analyse solar air heating systems. SWift calculates system performance on an hourly basis with equations derived from basic thermodynamic principles such as Fourier's Law. The monthly analysis performed in RETScreen is based more on empirical correlation and is therefore more approximate by definition.

SWift is currently the most sophisticated modelling tool available for analysis of perforated collector systems and therefore serves as an appropriate benchmark for RETScreen. Validation of the RETScreen model was done by comparison to SWift results for two solar air-heating projects. Two Canadian cities were chosen for the comparisons: Toronto, Ontario, Canada, for its warmer, more southern climate and Winnipeg, Manitoba, Canada for its colder northern climate. Both cities have existing solar air heating installations for which monitored data is available.

For each location, three design configurations were tested and compared on an annual basis to the SWift program. A process air heating configuration was not tested because of the direct similarity to commercial systems. Hourly weather data used by SWift was converted to monthly data to be used by RETScreen to avoid any differences in source data. The main parameters of the simulation were:

Building. Floor area 1,200 m^2, walls and ceiling insulation (RSI): 1.0 m² ºC/W; hours of operation: 7 days/week, 10 hours/day;

Collector. Color: black; area: 100 m^2; air flow: 4000 L/s.

The comparison results for Toronto are as shown in Table 1. The agreement between Swift and the RETScreen model in each case is acceptable. The greatest difference was by 9% in the high efficiency case. There appeared to be no systematic over-prediction or under-prediction by the model.

	SAH 2000 [kWh/(m² d)]	**SWift [kWh/(m² d)]**	**SWift Difference**
Industrial (High Temp Rise)	1.23	1.21	2%
Industrial (High Eff)	1.64	1.79	-9%
Commercial (High Eff.)	1.39	1.28	8%

Table 1 – Simulation comparison using Toronto weather data.

Monitored data for a high-temperature rise solar air heating installation in Toronto shows that the average energy savings for the months of January through April were 2.03 kWh/(m² d). The RETScreen model predicted for these four months an average of 2.14 kWh/m²/day, 5% higher than the monitored value. It should be noted however, that the actual weather conditions were not identical to the standard weather data used by RETScreen.

Industrial (High Temp Rise)	1.40	1.64	-15%
Industrial (High Eff.)	2.00	2.20	-9%
Commercial (High Eff.)	2.03	1.93	5%

Table 2 – Simulation comparison using Winnipeg weather data.

Results of simulations using Winnipeg weather data are shown in Table 2. Again the results are within the expected range. The savings of the high temperature rise (low-flow rate) system were somewhat lower than predicted by SWift. A possible reason for this is that the flow rate vs. efficiency curve upon which the RETscreen model is based, drops sharply at lower flow rates. A high temperature rise system operating in a cold climate would be expected to provide poor efficiency due to low average collector flow rates.

The monitored data showed average annual savings of 1.50 kWh/m²/day whereas RETScreen predicted 2.00 kWh/m²/day. This represents an over prediction of 33%. Again, the use of standard rather than monitored weather data makes the comparison slightly less valid.

In the RETScreen Solar Air Heating model the *Solar Resource* worksheet has hidden columns that contain the monthly energy savings values. There are columns corresponding to each mode of energy savings. The SWift program also reports monthly energy savings by each mode. For a detailed comparison, the monthly values as determined by each of the programs are plotted. A monthly comparison of total savings appears in Figure 3. The figure shows that there is a relatively good month-by-month agreement between SWift and RETScreen in the model of heating system for industrial buildings. During the heating season, the energy savings appear to be slightly lower according to the RETScreen analysis but are then bolstered by slightly higher savings in the transitional period.

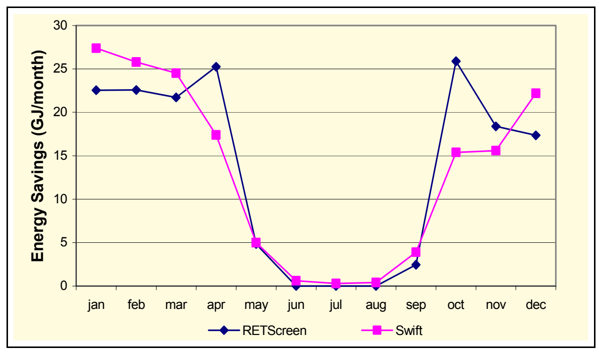

Figure 3 – RETScreen™ vs. SWift™ Total Savings (high temp-rise heating system for industrial building, Toronto).

Figure 4 shows that there is better agreement with the commercial/residential model. The monthly profiles do not deviate significantly between the SWift and RETScreen analyses.

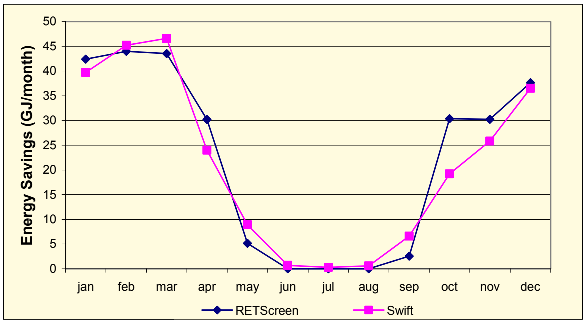

Figure 4 – RETScreen™ vs. SWift™ Total Savings (high-efficiency commercial system, Winnipeg)

Although the RETScreen model does not match exactly with the more accurate SWift model, it does not deviate unacceptably from it and can therefore be considered a good tool for assessing the economical feasibility and energy savings for a Solar Air Heating system.

RECENT SAH APPLICATIONS

Natural Resources Canada is currently sponsoring the design, installation and performance monitoring of solar crop drying systems in several warm climate countries. RETScreen has played an important role in assessing the feasibility of these applications. The first system is a coffee drying operation in Panama (see Figure 5). Other projects under development include jujube and briquette drying in China, and spice drying in India.

Figure 5 – Solar Drying Coffee Beans in Panama

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