RETScreen® International
Clean Energy Decision Support Centre

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CLEAN ENERGY PROJECT ANALYSIS:
RETSCREEN® ENGINEERING & CASES TEXTBOOK

SOLAR WATER HEATING PROJECT ANALYSIS
CHAPTER

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In collaboration with:
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SOLAR WATER HEATING PROJECT ANALYSIS CHAPTER

Clean Energy Project Analysis: RETScreen® Engineering & Cases is an electronic textbook for professionals and university students. This chapter covers the analysis of potential solar water heating projects using the RETScreen® International Clean Energy Project Analysis Software, including a technology background and a detailed description of the algorithms found in the RETScreen® Software. A collection of project case studies, with assignments, worked-out solutions and information about how the projects fared in the real world, is available at the RETScreen® International Clean Energy Decision Support Centre Website www.retscreen.net.

1 SOLAR WATER HEATING BACKGROUND[1]

Using the sun's energy to heat water is not a new idea. More than one hundred years ago, black painted water tanks were used as simple solar water heaters in a number of countries. Solar water heating (SWH) technology has greatly improved during the past century. Today there are more than 30 million m² of solar collectors installed around the globe. Hundreds of thousands of modern solar water heaters, such as the one shown in ***Figure 1***, are in use in countries such as China, India, Germany, Japan, Australia and Greece. In fact, in some countries the law actually requires that solar water heaters be installed with any new residential construction project (Israel for example).

Figure 1:
Evacuated Tube Solar Collector in Tibet, China.

Photo Credit:
Alexandre Monarque

1. Some of the text in this "Background" description comes from the following reference: Marbek Resources Consultants, ***Solar Water Heaters: A Buyer's Guide***, Report prepared for Energy, Mines and Resources Canada, 1986.

In addition to the energy cost savings on water heating, there are several other benefits derived from using the sun's energy to heat water. Most solar water heaters come with an additional water tank, which feeds the conventional hot water tank. Users benefit from the larger hot water storage capacity and the reduced likelihood of running out of hot water. Some solar water heaters do not require electricity to operate. For these systems, hot water supply is secure from power outages, as long as there is sufficient sunlight to operate the system. Solar water heating systems can also be used to directly heat swimming pool water, with the added benefit of extending the swimming season for outdoor pool applications.

1.1 Solar Water Heating Application Markets

Solar water heating markets can be classified based upon the end-use application of the technology. The most common solar water heating application markets are service hot water and swimming pools.

1.1.1 Service hot water

There are a number of service hot water applications. The most common application is the use of domestic hot water systems (DHWS), generally sold as "off-the-shelf" or standard kits as depicted in ***Figure 2***.

Figure 2:
Solar Domestic Hot Water (Thermosiphon) System in Australia.

Photo Credit:
The Australian Greenhouse Office

Other common uses include providing process hot water for commercial and institutional applications, including multi-unit houses and apartment buildings, as depicted in ***Figure 3***, housing developments as shown in ***Figure 4***, and in schools, health centres, hospitals, office buildings, restaurants and hotels.

Small commercial and industrial applications such as car washes, laundries and fish farms are other typical examples of service hot water. ***Figure 5*** shows a solar water heating system at the Rosewall Creek Salmon Hatchery in British Columbia, Canada. 260 m^2 unglazed solar collectors heat make-up water and help increase fingerlings production at the aquaculture facility. Storage tanks help regulate temperature of make-up water. This particular project had a five-year simple payback period.

Solar water heating systems can also be used for large industrial loads and for providing energy to district heating networks. A number of large systems have been installed in northern Europe and other locations.

Figure 3:

Glazed Flat-Plate Solar Collectors Integrated into Multi-Unit Housing.

Photo Credit:
Chromagen

Figure 4:

Housing Development, Küngsbacka, Sweden.

Photo Credit:
Alpo Winberg/Solar Energy Association of Sweden

Figure 5:
Solar Water Heating Project at a Salmon Hatchery, Canada.

Photo Credit:
Natural Resources Canada

1.1.2 Swimming pools

The water temperature in swimming pools can also be regulated using solar water heating systems, extending the swimming pool season and saving on the conventional energy costs. The basic principle of these systems is the same as with solar service hot water systems, with the difference that the pool itself acts as the thermal storage. For outdoor pools, a properly sized solar water heater can replace a conventional heater; the pool water is directly pumped through the solar collectors by the existing filtration system.

Swimming pool applications can range in size from small summer only outdoor pools, such as the one shown at a home in ***Figure 6***, to large Olympic size indoor swimming pools that operate 12 months a year.

Figure 6:
Unglazed Solar Collector Pool Heating System in the United States.

Photo Credit:
Aquatherm Industries/ NREL Pix

There is a strong demand for solar pool heating systems. In the United States, for example, the majority of solar collector sales are for unglazed panels for pool heating applications.

When considering solar service hot water and swimming pool application markets, there are a number of factors that can help determine if a particular project has a reasonable market potential and chance for successful implementation. These factors include a large demand for hot water to reduce the relative importance of project fixed costs; high local energy costs; unreliable conventional energy supply; and/or a strong environmental interest by potential customers and other project stakeholders.

RETScreen® International Solar Water Heating Project Model

The RETScreen® International Solar Water Heating Project Model can be used world-wide to easily evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction for three basic applications: domestic hot water, industrial process heat and swimming pools (indoor and outdoor), ranging in size from small residential systems to large scale commercial, institutional and industrial systems.

1.2 Description of Solar Water Heating Systems

Solar water heating systems use solar collectors and a liquid handling unit to transfer heat to the load, generally via a storage tank. The liquid handling unit includes the pump(s) (used to circulate the working fluid from the collectors to the storage tank) and control and safety equipment. When properly designed, solar water heaters can work when the outside temperature is well below freezing and they are also protected from overheating on hot, sunny days. Many systems also have a back-up heater to ensure that all of a consumer's hot water needs are met even when there is insufficient sunshine. Solar water heaters perform three basic operations as shown in ***Figure 7***:

- **Collection:** Solar radiation is "captured" by a solar collector;
- **Transfer:** Circulating fluids transfer this energy to a storage tank; circulation can be natural (thermosiphon systems) or forced, using a circulator (low-head pump); and
- **Storage:** Hot water is stored until it is needed at a later time in a mechanical room, or on the roof in the case of a thermosiphon system.

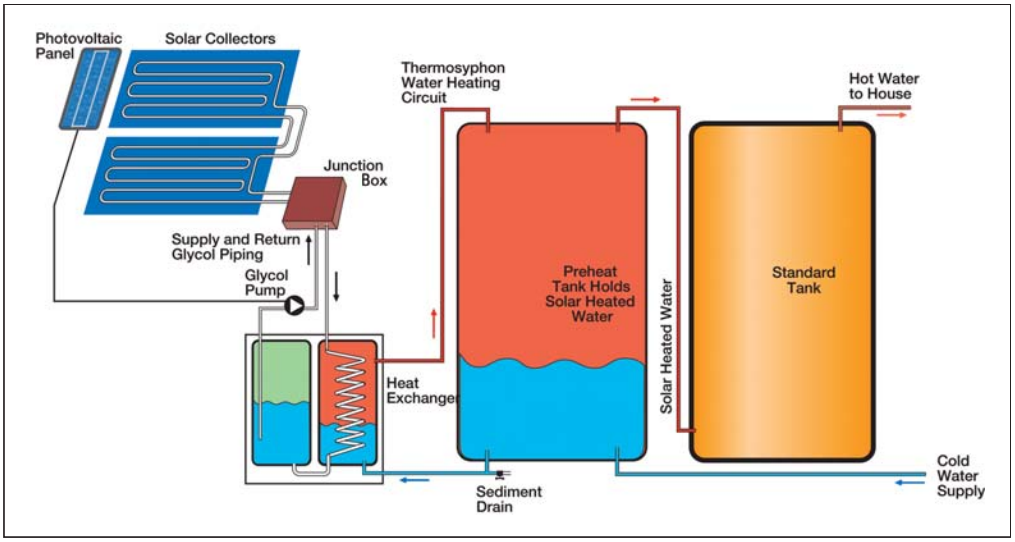


Figure 7:
System Schematic for Typical Solar Domestic Water Heater.

1.2.1 Solar collectors

Solar energy (solar radiation) is collected by the solar collector's absorber plates. Selective coatings are often applied to the absorber plates to improve the overall collection efficiency. A thermal fluid absorbs the energy collected.

There are several types of solar collectors to heat liquids. Selection of a solar collector type will depend on the temperature of the application being considered and the intended season of use (or climate). The most common solar collector types are: unglazed liquid flat-plate collectors; glazed liquid flat-plate collectors; and evacuated tube solar collectors.

Unglazed liquid flat-plate collectors

Unglazed liquid flat-plate collectors, as depicted in ***Figure 8***, are usually made of a black polymer. They do not normally have a selective coating and do not include a frame and insulation at the back; they are usually simply laid on a roof or on a wooden support. These low-cost collectors are good at capturing the energy from the sun, but thermal losses to the environment increase rapidly with water temperature particularly in windy locations. As a result, unglazed collectors are commonly used for applications requiring energy delivery at low temperatures (pool heating, make-up water in fish farms, process heating applications, etc.); in colder climates they are typically only operated in the summer season due to the high thermal losses of the collector.

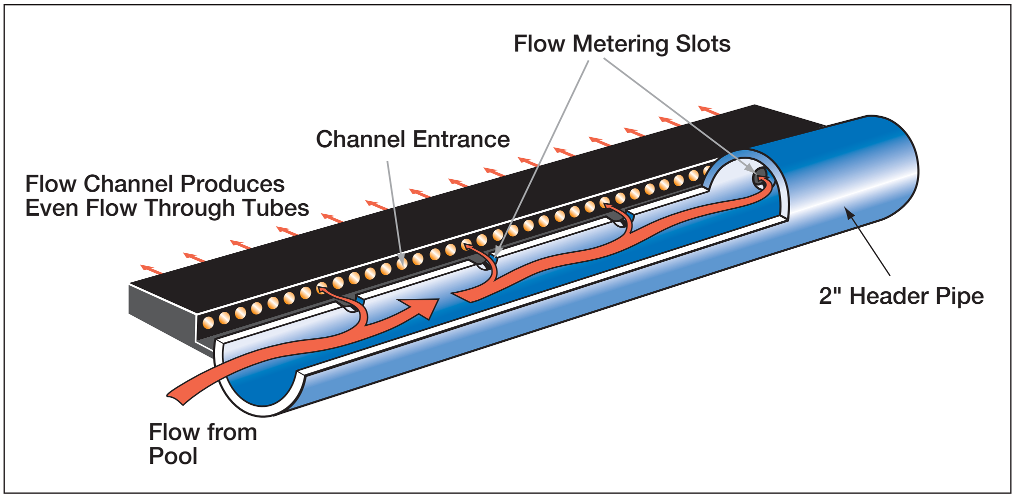


Figure 8:

System Schematic for Unglazed Flat-Plate Solar Collector.

Glazed liquid flat-plate collectors

In glazed liquid flat-plate collectors, as depicted in ***Figure 9***, a flat-plate absorber (which often has a selective coating) is fixed in a frame between a single or double layer of glass and an insulation panel at the back. Much of the sunlight (solar energy) is prevented from escaping due to the glazing (the "greenhouse effect"). These collectors are commonly used in moderate temperature applications (e.g. domestic hot water, space heating, year-round indoor pools and process heating applications).

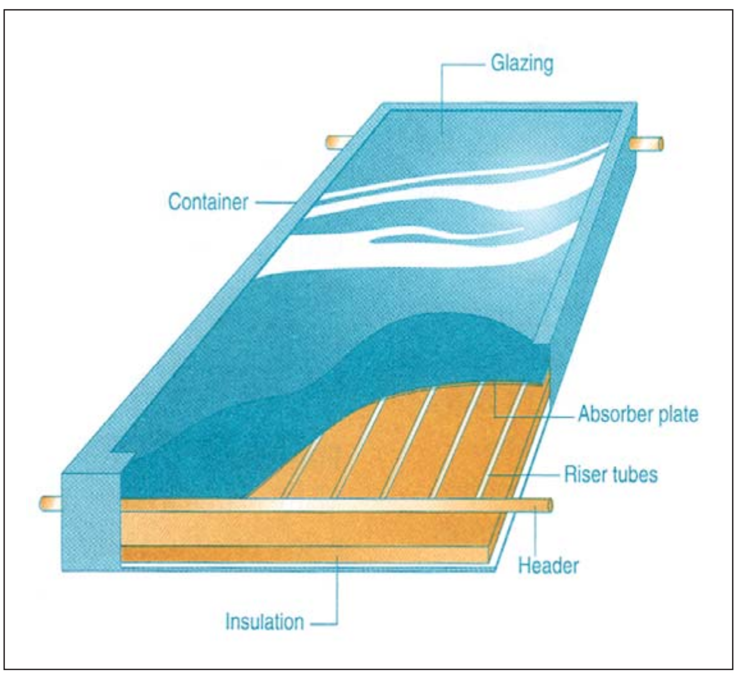


Figure 9:

System Schematic for Glazed Flat-Plate Solar Collector.

Evacuated tube solar collectors

Evacuated tube solar collectors, as depicted in ***Figure 10***, have an absorber with a selective coating enclosed in a sealed glass vacuum tube. They are good at capturing the energy from the sun; their thermal losses to the environment are extremely low. Systems presently on the market use a sealed heat-pipe on each tube to extract heat from the absorber (a liquid is vaporised while in contact with the heated absorber, heat is recovered at the top of the tube while the vapour condenses, and condensate returns by gravity to the absorber). Evacuated collectors are good for applications requiring energy delivery at moderate to high temperatures (domestic hot water, space heating and process heating applications typically at 60°C to 80°C depending on outside temperature), particularly in cold climates.

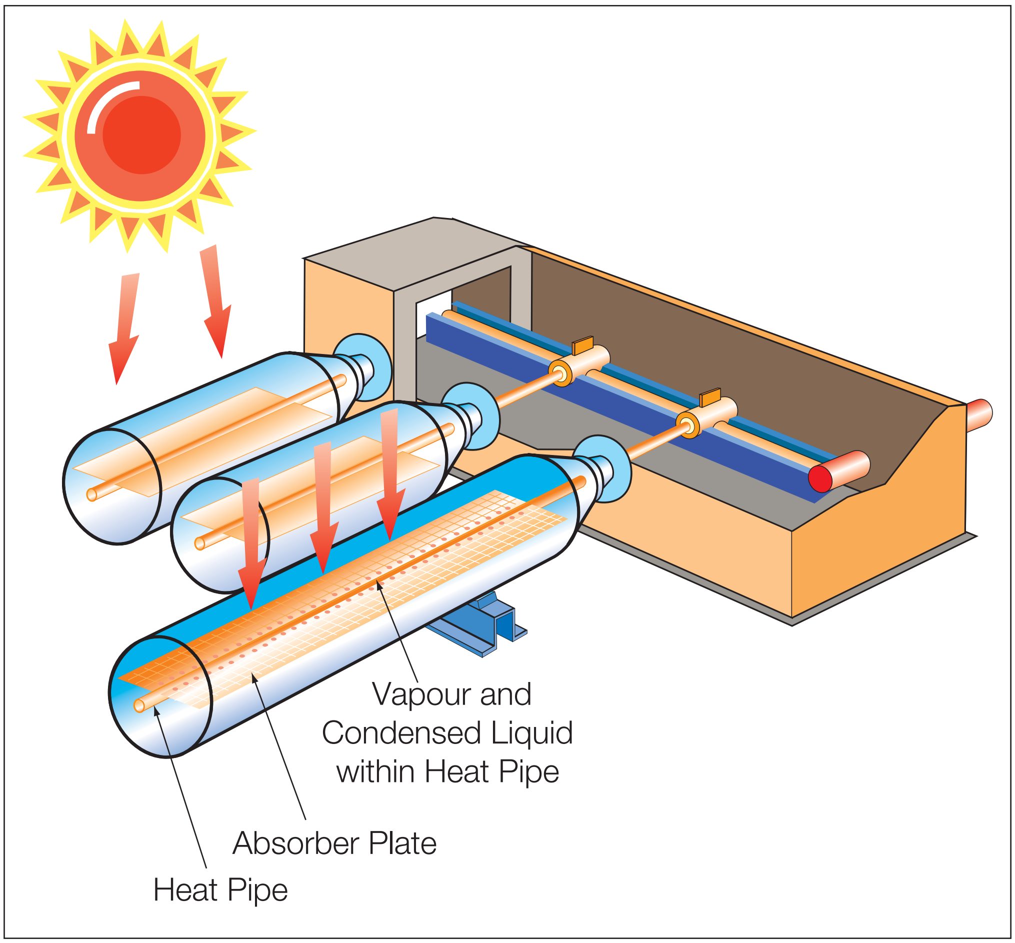


Figure 10:

System Schematic for Evacuated Tube Solar Collector.

1.2.2 Balance of systems

In addition to the solar collector, a solar water heating system typically includes the following "balance of system" components:

1. Solar collector array **support structure**, as depicted in the ***Figure 11***;

Figure 11:
Solar Array Support Structure.

Photo Credit:
Ducey Roch A./NREL Pix

2. Hot water **storage tank** (not required in swimming pool applications and in some large commercial or industrial applications when there is a continuous service hot water flow);

3. **Liquid handling unit**, which includes a pump required to transfer the fluid from the solar collector to the hot water storage tank (except in thermosiphon systems where circulation is natural, and outdoor swimming pool applications where the existing filtration system pump is generally used); it also includes valves, strainers, and a thermal expansion tank;

4. **Controller**, which activates the circulator only when useable heat is available from the solar collectors (not required for thermosiphon systems or if a photovoltaic-powered circulator is used);

5. **Freeze protection**, required for use during cold weather operation, typically through the use in the solar loop of a special antifreeze heat transfer fluid with a low-toxicity. The solar collector fluid is separated from the hot water in the storage tank by a heat exchanger; and

6. Other features, mainly relating to safety, such as overheating protection, seasonal systems freeze protection or prevention against restart of a large system after a stagnation period.

Typically, an existing conventional water heating system is used for back-up to the solar water heating system, with the exception that a back-up system is normally not required for most outdoor swimming pool applications.

2 RETSCREEN SOLAR WATER HEATING PROJECT MODEL

The RETScreen Solar Water Heating Project Model can be used to evaluate solar water heating projects, from small-scale domestic hot water applications and swimming pools, to large-scale industrial process hot water systems, anywhere in the world. There are three basic applications that can be evaluated with the RETScreen software:

- Domestic hot water;
- Industrial process heat; and
- Swimming pools (indoor and outdoor).

Six worksheets (*Energy Model, Solar Resource and Heating Load Calculation (SR&HLC), Cost Analysis, Greenhouse Gas Emission Reduction Analysis (GHG Analysis), Financial Summary* and *Sensitivity and Risk Analysis (Sensitivity)*) are provided in the Solar Water Heating Project Workbook file. The *SR&HLC* worksheet is used to calculate the monthly energy load required to heat water to the desired temperature. This worksheet also calculates the annual solar radiation on the tilted collector array for any array orientation, using monthly values of solar radiation on a horizontal surface.

The annual performance of a solar water heating system with a storage tank is dependent on system characteristics, solar radiation available, ambient air temperature and on heating load characteristics. The RETScreen SWH Project Model has been designed to help the user define the hot water needs, integrating a Water Heating Load Calculation section in the *SR&HLC* worksheet. This section is based on data readily available to building owners or managers. The suggested values of daily hot water usage are based on ASHRAE (1995).

To help the user characterize a SWH system before evaluating its cost and energy performance, some values are suggested for component sizing (e.g. number of collectors). Suggested or estimated values are based on input parameters and can be used as a first step in the analysis and are not necessarily the optimum values.

The ***Energy Model*** worksheet and ***SR&HLC*** worksheet are completed first. The ***Cost Analysis*** worksheet should then be completed, followed by the ***Financial Summary*** worksheet. The ***GHG Analysis*** and ***Sensitivity*** worksheets are an optional analysis. The *GHG Analysis* worksheet is provided to help the user estimate the greenhouse gas (GHG) mitigation potential of the proposed project. The *Sensitivity* worksheet is provided to help the user estimate the sensitivity of important financial indicators in relation to key technical and financial parameters. In general, the user works from top-down for each of the worksheets. This process can be repeated several times in order to help optimize the design of the solar water heating project from an energy use and cost standpoint.

This section describes the various algorithms used to calculate, on a month-by-month basis, the energy savings of solar water heating systems in RETScreen. A flowchart of the algorithms is shown in ***Figure 12***. The behaviour of thermal systems is quite complex and changes from one instant to the next depending on available solar radiation, other meteorological variables such as ambient temperature, wind speed and relative humidity, and load. RETScreen does not do a detailed simulation of the system's behaviour. Instead, it uses simplified models which enable the calculation of average energy savings on a monthly basis. There are essentially three models, which cover the basic applications considered by RETScreen:

- *Service water heating with storage*, calculated with the f-Chart method;
- *Service water heating without storage*, calculated with the utilisability method; and
- *Swimming pools*, calculated by an ad-hoc method. There are two variants of the last model, addressing indoor and outdoor pools.

All of the models share a number of common methods, for example to calculate cold water temperature, sky temperature, or the radiation incident upon the solar collector. These are described in *Section 2.1*. Another common feature of all models is that they need to calculate solar collector efficiency; this is dealt with in *Section 2.2*. Then, three sections which deal with the specifics of each application are described: *Section 2.3* covers the f-Chart method, *Section 2.4* the utilisability method, and *Section 2.5* swimming pool calculations. *Section 2.6* deals with auxiliary calculations (pumping power, solar fraction). A validation of the RETScreen Solar Water Heating Project Model is presented in *Section 2.7*.

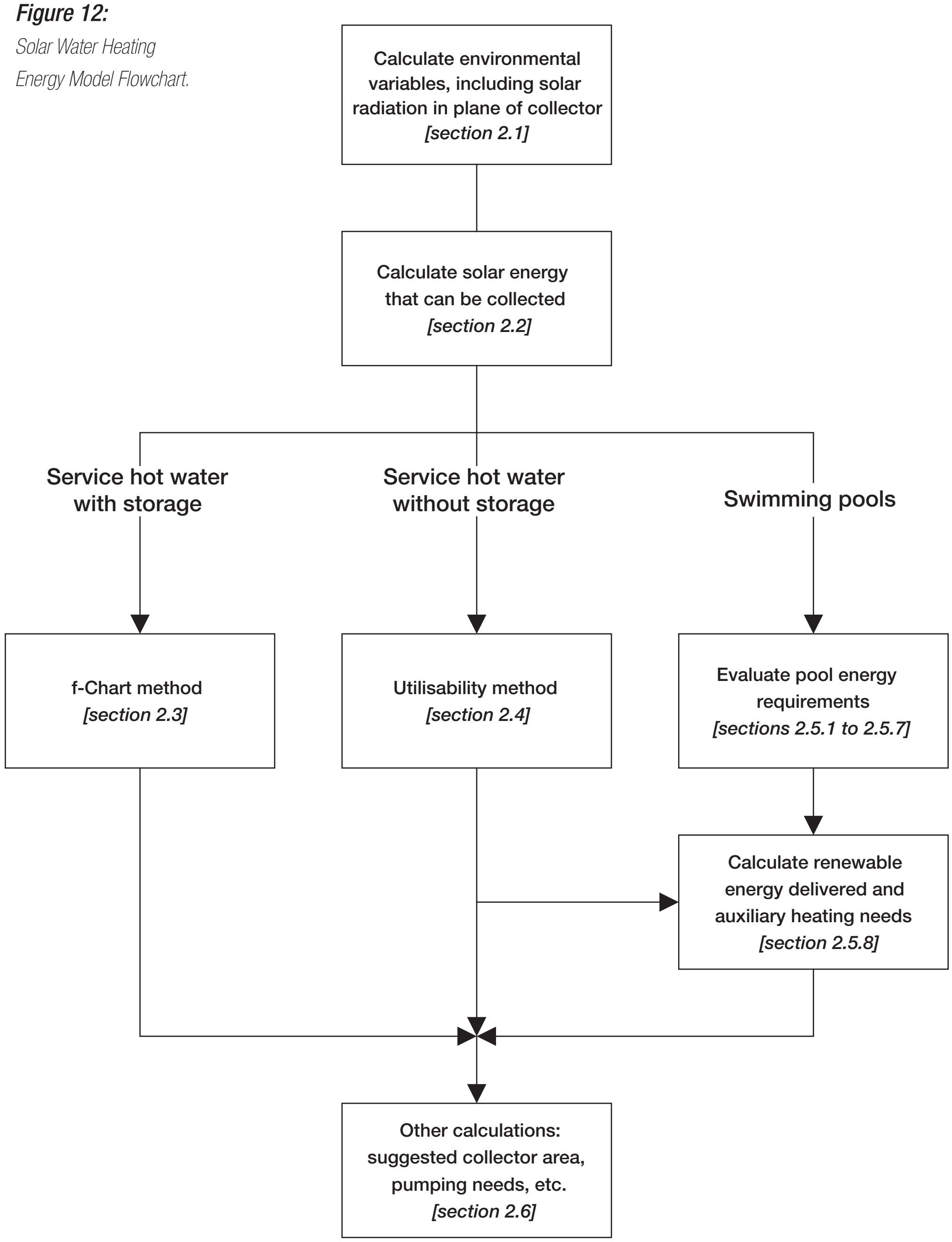
Because of the simplifications introduced in the models, the RETScreen Solar Water Heating Project Model has a few limitations. First, the process hot water model assumes that daily volumetric load is constant over the season of use. Second, except for swimming pool applications, the model is limited to the preheating of water; it does not consider stand-alone systems that provide 100% of the load. For service hot water systems *without storage*, only low solar fractions (and penetration levels) should be considered as it is assumed that all the energy collected is used. For swimming pools with no back-up heaters, results should be considered with caution if the solar fraction is lower than 70%. And third, sun tracking and solar concentrator systems currently cannot be evaluated with this model; neither can Integral Collector Storage (ICS) systems. However, for the majority of applications, these limitations are without consequence.

2.1 Environmental Variables

A number of environmental variables have to be calculated from the weather data supplied by the user (or copied from the RETScreen Online Weather Database). The values to compute are the:

- Monthly average daily irradiance in the plane of the solar collector, used to calculate collector efficiency and solar energy collected;
- Sky temperature, used to calculate energy collected by unglazed collectors, and radiative losses of swimming pools to the environment;
- Cold water temperature, used to determine the heating load the system has to meet; and the
- Load (except for swimming pools).

Figure 12:
Solar Water Heating Energy Model Flowchart.



2.1.1 Basics of solar energy

Since the solar water heating model deals with solar energy, some basic concepts of solar energy engineering first needs to be explained. This section does not intend to be a course on the fundamentals of solar energy; the reader interested in such topics could benefit from consulting a textbook on the subject, such as Duffie and Beckman (1991), from which most of the equations in this section are derived. This section does intend, however, to detail the calculation of a few variables that will be used throughout the model. The first few variables are also defined in the textbook in the Photovoltaic Project Analysis Chapter.

Declination

The *declination* is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by Cooper's equation:

$$\delta = 23.45 \sin\left(2\pi \frac{284+n}{365}\right) \tag{1}$$

where n is the day of year (i.e. n =1 for January 1, n =32 for February 1, etc.). Declination varies between -23.45° on December 21 and +23.45° on June 21.

Solar hour angle and sunset hour angle

The *solar hour angle* is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon. For example at 7 a.m. (solar time[2]) the solar hour angle is equal to –75° (7 a.m. is five hours from noon; five times 15 is equal to 75, with a negative sign because it is morning).

The *sunset hour angle* ω_s is the solar hour angle corresponding to the time when the sun sets. It is given by the following equation:

$$\cos\omega_s = -\tan\psi \ \tan\delta \tag{2}$$

where δ is the declination, calculated through equation (1), and ψ is the latitude of the site, specified by the user.

2. Solar time is the time based on the apparent motion of the sun across the sky. Solar noon corresponds to the moment when the sun is at its highest point in the sky.

Extraterrestrial radiation and clearness index

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface, H_0, can be computed for the day of year n from the following equation:

$$H_0 = \frac{86400 G_{sc}}{\pi}\left(1 + 0.033\cos\left(2\pi\frac{n}{365}\right)\right)\left(\cos\psi\cos\delta\sin\omega_s + \omega_s\sin\psi\sin\delta\right) \qquad (3)$$

where G_{sc} is the *solar constant* equal to 1,367 W/m^2, and all other variables have the same meaning as before.

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the *clearness index*. Thus the monthly average clearness index, $\bar{K}_T$, is defined as:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \qquad (4)$$

where $\bar{H}$ is the monthly average daily solar radiation on a horizontal surface and $\bar{H}_0$ is the monthly average extraterrestrial daily solar radiation on a horizontal surface. $\bar{K}_T$ values depend on the location and the time of year considered; they are usually between 0.3 (for very overcast climates) and 0.8 (for very sunny locations).

2.1.2 Tilted irradiance

Solar radiation in the plane of the solar collector is required to estimate the efficiency of the collector (*Section* 2.2) and the actual amount of solar energy collected (*Sections* 2.3 and 2.4). The RETScreen SWH Project Model uses Liu and Jordan's isotropic diffuse algorithm (see Duffie and Beckman, 1991, section 2.19) to compute monthly average radiation in the plane of the collector, $\bar{H}_T$:

$$\bar{H}_T = \bar{H}_b\bar{R}_b + \bar{H}_d\left(\frac{1+\cos\beta}{2}\right) + \bar{H}\,\rho_g\left(\frac{1-\cos\beta}{2}\right) \qquad (5)$$

The first term on the right-hand side of this equation represents solar radiation coming directly from the sun. It is the product of monthly average beam radiation $\bar{H}_b$ times a purely geometrical factor, $\bar{R}_b$, which depends only on collector orientation, site latitude, and time of year[3]. The second term represents the contribution of monthly average diffuse radiation, $\bar{H}_d$, which depends on the slope of the collector, β. The last term represents reflection of radiation on the ground in front of the collector, and depends on the slope of the collector and on ground reflectivity, ρ_g. This latter value is assumed to be equal to 0.2 when the monthly average temperature is above 0°C and 0.7 when it is below -5°C; and to vary linearly with temperature between these two thresholds.

Monthly average daily diffuse radiation is calculated from global radiation through the following formulae:

- for values of the sunset hour angle ω_s less than 81.4°:

$$\frac{\bar{H}_d}{\bar{H}} = 1.391 - 3.560\bar{K}_T + 4.189\bar{K}_T^2 - 2.137K_T^3 \tag{6}$$

- for values of the sunset hour angle ω_s greater than 81.4°:

$$\frac{\bar{H}_d}{\bar{H}} = 1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.821K_T^3 \tag{7}$$

The monthly average daily beam radiation $\bar{H}_b$ is simply computed from:

$$\bar{H}_b = \bar{H} - \bar{H}_d \tag{8}$$

2.1.3 Sky temperature

Sky long-wave radiation is radiation originating from the sky at wavelengths greater than 3 μm. As will be seen in *Sections* 2.2.2 and 2.5.5, it is required to quantify radiative transfer exchanges between a body (solar collector or swimming pool) and the sky. An alternate variable intimately related to sky radiation is the *sky temperature*, T_{sky}, which is the temperature of an ideal blackbody emitting the same amount of radiation. Its value in °C is computed from sky radiation L_{sky} through:

3. The derivation of $\bar{R}_b$ does not present any difficulty but has been left out of this section to avoid tedious mathematical developments, particularly when the solar azimuth is not zero. For details see Duffie and Beckman (1991) sections 2.19 and 2.20.

$$L_{sky} = \sigma \left(T_{sky} + 273.2\right)^4 \tag{9}$$

where σ is the Stefan-Boltzmann constant (5.669×10^{-8} (W/m^2)/K^4). Sky radiation varies depending on the presence or absence of clouds – as experienced in everyday life, clear nights tend to be colder and overcast nights are usually warmer. Clear sky long-wave radiation (i.e. in the absence of clouds) is computed using Swinbank's formula (Swinbank, 1963):

$$L_{clear} = 5.31 \times 10^{-13} \left(T_a + 273.2\right)^6 \tag{10}$$

where T_a is the ambient temperature expressed in °C. For cloudy (overcast) skies, the model assumes that clouds are at a temperature $(T_a - 5)$ and emit long wave radiation with an emittance of 0.96, that is, overcast sky radiation is computed as:

$$L_{cloudy} = 0.96\, \sigma \left(T_a + 273.2 - 5\right)^4 \tag{11}$$

The actual sky radiation falls somewhere in-between the clear and the cloudy values. If c is the fraction of the sky covered by clouds, sky radiation may be approximated by:

$$L_{sky} = \left(1 - c\right) L_{clear} + c\, L_{cloudy} \tag{12}$$

To obtain a rough estimate of c over the month, the model establishes a correspondence between cloud amount and the fraction of monthly average daily radiation that is diffuse. A clear sky will lead to a diffuse fraction $K_d = H_d / H$ around 0.165; an overcast sky will lead to a diffuse fraction of 1. Hence,

$$c = \frac{\left(K_d - 0.165\right)}{0.835} \tag{13}$$

K_d is calculated from the monthly average clearness index $\bar{K}_T$ using the Collares-Pereira and Rabl correlation (cited in Duffie and Beckman, 1991, note 11, p. 84), written for the "average day" of the month (i.e. assuming that the daily clearness index K_T is equal to its monthly average value $\bar{K}_T$):

$$K_d = \begin{cases} 0.99 & for\ K_T \leq 0.17 \\ 1.188 - 2.272\,K_T + 9.473\,K_T^2 - 21.865\,K_T^3 + 14.648\,K_T^4 & for\ 0.17 < K_T < 0.75 \\ -0.54\,K_T + 0.632 & for\ 0.75 \leq K_T < 0.80 \\ 0.2 & for\ K_T \geq 0.80 \end{cases} \tag{14}$$

2.1.4 Cold water temperature

Temperature of the cold water supplied by the public water system is used to calculate the energy needed to heat water up to the desired temperature. There are two options to calculate cold water temperature. In the first option, cold water temperature is computed automatically from monthly ambient temperature values entered by the user (or copied from the RETScreen Online Weather Database). In the second option, it is computed from minimum and maximum values specified by the user.

Automatic calculation

Diffusion of heat in the ground obeys approximately the equation of heat:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \tag{15}$$

where T stands for soil temperature, t stands for time, α is the thermal diffusivity of soil (in m^2/s), and z is the vertical distance. For a semi-infinite soil with a periodic fluctuation at the surface:

$$T(0,t) = T_0 e^{i\omega t} \tag{16}$$

where T_0 is the amplitude of temperature fluctuation at the surface and ω is its frequency for month i. The solution to equation (16), giving the temperature $T(z,t)$ at a depth z and a time t, is simply:

$$T(z,t) = T_0\, e^{-(1+i)z/\sigma} e^{i\omega t} \tag{17}$$

where σ is a spatial scale defined by:

$$\sigma = \sqrt{\frac{2\alpha}{\omega}} \tag{18}$$

In other words, a seasonal (yearly) fluctuation of amplitude ΔT at the surface will be felt at a depth z with an amplitude $\Delta T(z) = \Delta T\, e^{-z/\sigma}$ and with a delay $\Delta t = z / \sigma\omega$.

The RETScreen SWH Project Model assumes that cold water temperature is equal to soil temperature at an appropriate depth. The model takes α = 0.52x10^{-6} m^2/s (which corresponds to a dry heavy soil or a damp light soil, according to the 1991 ASHRAE Applications Handbook; see ASHRAE, 1991), and z = 2 m, the assumed depth at which water pipes are buried. This leads to:

$$\sigma = 2.28 \text{ m} \tag{19}$$

$$\Delta T(z) = \Delta T\,(0) \times 0.42 \tag{20}$$

$$\Delta t = 51 \text{ days} \sim 2 \text{ months} \tag{21}$$

This theoretical model was tuned up in light of experimental data for Toronto, Ontario, Canada (see ***Figure 13***). It appeared that a factor of 0.35 would be better suited than 0.42 in equation (20), and a time lag of 1 month gives a better fit than a time lag of 2 months. The tune up is necessary and methodologically acceptable given the coarseness of the assumptions made in the model.

The model above enables the calculation of water temperature for any month, with the following algorithm. Water temperature for month i is equal to the yearly average water temperature, plus 0.35 times the difference between ambient temperature and average temperature for month ***i-1***. In addition, the model also limits water temperature to +1 in the winter (i.e. water does not freeze). ***Table 1*** and ***Figure 13*** compare measured and predicted water temperatures for Toronto and indicate that this simplified method of cold water temperature calculation is satisfactory, at least for this particular example.

Month	T ambient [°C]	T water (calculated) [°C]	T water (measured) [°C]
1	-6.7	3.5	4.0
2	-6.1	2.4	2.0
3	-1.0	2.6	3.0
4	6.2	4.4	4.5
5	12.3	6.9	7.5
6	17.7	9.0	8.5
7	20.6	10.9	11.0
8	19.7	11.9	12.0
9	15.5	11.6	10.0
10	9.3	10.2	9.0
11	3.3	8.0	8.0
12	-3.5	5.9	6.0
Yearly average	7.28	7.30	7.12

Table 1: Tabular Comparison of Calculated and Measured Cold Water Temperatures for Toronto, Ontario, Canada.

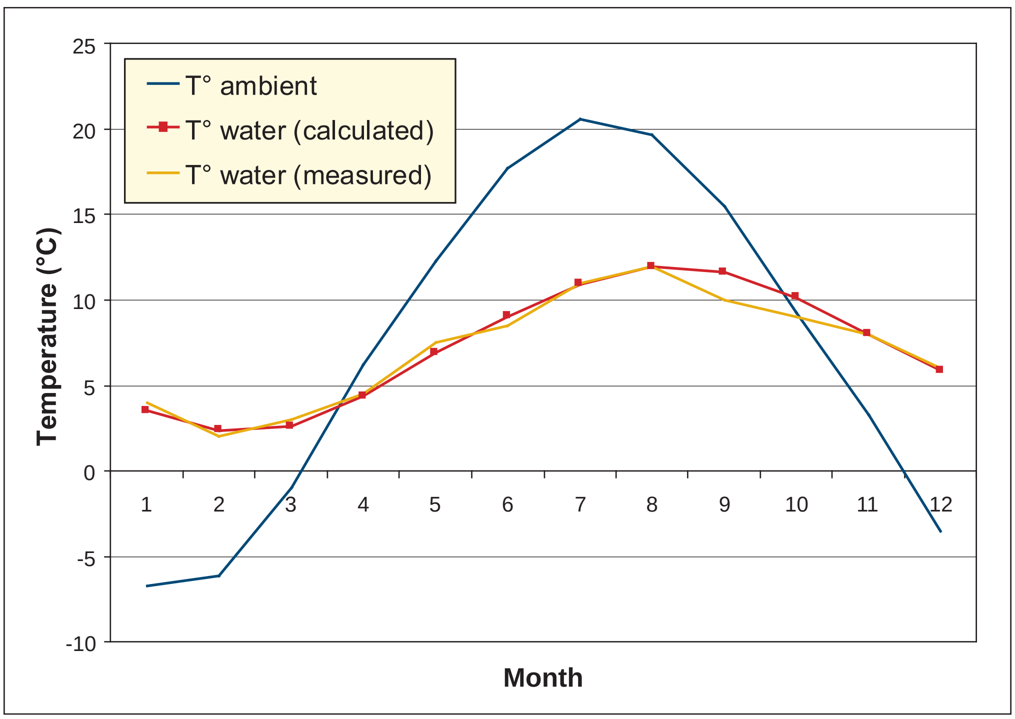


Figure 13:

Graphical Comparison of Calculated and Measured Cold Water Temperatures for Toronto, Ontario, Canada. [Hosatte, 1998].

Manual calculation

A sinusoidal profile is generated from the minimum and maximum temperatures specified by the user, assuming the minimum is reached in February and the maximum in August in the Northern Hemisphere (the situation being reversed in the Southern Hemisphere). Hence the average soil (or cold water) temperature T_s is expressed as a function of minimum temperature $T_{\min}$, maximum temperature $T_{\max}$, and month number n as:

$$T_s = \frac{T_{\min} + T_{\max}}{2} - \frac{T_{\max} - T_{\min}}{2} h \cos\left(2\pi \frac{n-2}{12}\right) \tag{22}$$

where h is equal to 1 in the Northern Hemisphere and –1 in the Southern Hemisphere.

2.1.5 Estimated load calculation

Load calculation is necessary for the service hot water (with or without storage) models. The load calculation for the pool model is detailed in *Section 2.5*.

Hot water use estimates are provided for service hot water systems. These are derived from the tables published in the ASHRAE Applications Handbook (ASHRAE, 1995); for car washes and for laundromats, the estimates are from Carpenter and Kokko (1988). No estimate of hot water use is done for aquaculture, industrial or “other” applications. The actual load is calculated as the energy required to heat up mains water to the specified hot water temperature. If V_l is the required amount of water and T_h is the required hot water temperature, both specified by the user, then the energy required Q_{load} is expressed as:

$$Q_{load} = C_p \, \rho \, V_l \, (T_h - T_c) \tag{23}$$

where C_p is the heat capacitance of water (4,200 (J/kg)/°C), ρ its density (1 kg/L), and T_c is the cold (mains) water temperature. Q_{load} is prorated by the number of days the system is used per week.

2.2 Solar Collectors

Solar collectors are described by their efficiency equations. Three types of collectors are considered in the RETScreen SWH Project Model:

- Glazed collectors
- Evacuated collectors
- Unglazed collectors

Glazed and evacuated collectors share the same basic, wind-independent efficiency equation. Unglazed collectors use a wind-dependent efficiency equation. Effects of angle of incidence, losses due to snow and dirt, and loss of heat through the piping and the solar tank are accounted for through separate factors.

2.2.1 Glazed or evacuated collectors

Glazed or evacuated collectors are described by the following equation (Duffie and Beckman, 1991, eq. 6.17.2):

$$\dot{Q}_{coll} = F_R\left(\tau\alpha\right)G - F_R U_L\ \Delta T \tag{24}$$

where $\dot{Q}_{coll}$ is the energy collected per unit collector area per unit time, F_R is the collector's heat removal factor, τ is the transmittance of the cover, α is the shortwave absorptivity of the absorber, G is the global incident solar radiation on the collector, U_L is the overall heat loss cœfficient of the collector, and ΔT is the temperature differential between the working fluid entering the collectors and outside.

Values of $F_R\left(\tau\alpha\right)$ and $F_R U_L$ are specified by the user or chosen by selecting a solar collector from the RETScreen Online Product Database. For both glazed and evacuated collectors, $F_R\left(\tau\alpha\right)$ and $F_R U_L$ are independent of wind.

"Generic" values are also provided for glazed and evacuated collectors. Generic glazed collectors are provided with $F_R\left(\tau\alpha\right)$ = 0.68 and $F_R U_L$ = 4.90 (W/m^2)/ºC. These values correspond to test results for ThermoDynamics collectors (Chandrashekar and Thevenard, 1995). Generic evacuated collectors are also provided with $F_R\left(\tau\alpha\right)$ = 0.58 and $F_R U_L$ = 0.7 (W/m^2)/ºC. These values correspond to a Fournelle evacuated tube collector (Philips technology; Hosatte, 1998).

2.2.2 Unglazed collectors

Unglazed collectors are described by the following equation (Soltau, 1992):

$$\dot{Q}_{coll} = (F_R\alpha)\left(G + \left(\frac{\varepsilon}{\alpha}\right)L\right) - (F_R U_L)\,\Delta T \tag{25}$$

where ε is the longwave emissivity of the absorber, and L is the relative longwave sky irradiance. L is defined as:

$$L = L_{sky} - \sigma\left(T_a + 273.2\right)^4 \tag{26}$$

where L_{sky} is the longwave sky irradiance (see *Section 2.1.3*) and T_a the ambient temperature expressed in °C.

$F_R\alpha$ and $F_R U_L$ are a function of the wind speed V incident upon the collector. The values of $F_R\alpha$ and $F_R U_L$, as well as their wind dependency, are specified by the user or chosen by selecting a collector from the RETScreen Online Product Database. The wind speed incident upon the collector is set to 20% of the free stream air velocity specified by the user (or copied from the weather database). The ratio ε / α is set to 0.96.

Because of the scarcity of performance measurements for unglazed collectors, a "generic" unglazed collector is also defined as:

$$F_R\alpha = 0.85 - 0.04\,V \tag{27}$$

$$F_R U_L = 11.56 + 4.37\,V \tag{28}$$

These values were obtained by averaging the performance of several collectors (NRCan, 1998).

Equivalence between glazed and unglazed collectors

As can be seen from equations (24) and (25), equations for glazed and unglazed collector efficiency are different. A problem arises when using the *f-Chart* method (see *Section 2.3*) or the *utilisability* method (see *Section 2.4*), both of which were developed for glazed collectors. The approach taken in RETScreen was to re-write equation (25) into the form of (24), by defining an effective radiation on the collector G_{eff} as:

$$G_{eff} = G + \frac{\varepsilon}{\alpha} L \tag{29}$$

where G is the global solar radiation incident in the plane of the collector , α is the shortwave absorptivity of the absorber, ε is the longwave emissivity of the absorber (ε / α is set to 0.96, as before), and L is the relative longwave sky irradiance. In the RETScreen algorithms, effective irradiance is substituted to irradiance in all equations involving the collector when an unglazed collector is used. The reader has to keep this in mind when encountering the developments of algorithms in *Sections* 2.3 and 2.4.

2.2.3 Incidence angle modifiers

Part of the solar radiation incident upon the collector may bounce off, particularly when the rays of the sun hit the surface of the collector with a high angle of incidence. At the pre-feasibility stage it is not necessary to model this phenomenon in detail. Instead, the average effect of angle of incidence upon the collector was estimated through simulations to be roughly 5%. Therefore, $F_R(\tau\alpha)$ is multiplied by a constant factor equal to 0.95.

2.2.4 Piping and solar tank losses

The water circulating in the pipes and the tank is hot, and since the pipes and the tank are imperfectly insulated, heat will be lost to the environment. Piping and solar tank losses are taken into account differently for systems with storage and for systems without storage (including pool). In systems without storage the energy delivered by the solar collector, Q_{dld} , is equal to the energy collected Q_{act} minus piping losses, expressed as a fraction f_{los} of energy collected (f_{los} is entered by the user):

$$Q_{dld} = Q_{act}\left(1 - f_{los}\right) \tag{30}$$

For systems with storage, the situation is slightly different since the system may be able, in some cases, to compensate for the piping and tank losses by collecting and storing extra energy. Therefore, the *load* $Q_{load,tot}$ used in the *f-Chart* method (see *Section 2.3*) is increased to include piping and tank losses:

$$Q_{load,tot} = Q_{load}\left(1 + f_{los}\right) \tag{31}$$

2.2.5 Losses due to snow and dirt

Snow and dirt impact on the irradiance level experienced by the collector. Therefore, $F_R\left(\tau\alpha\right)$ is multiplied by $\left(1 - f_{dirt}\right)$ where f_{dirt} are the losses due to snow and dirt expressed as a fraction of energy collected (this parameter is entered by the user).

2.3 Service Hot Water: f-Chart Method

The performance of service hot water systems with storage is estimated with the *f-Chart* method. The purpose of the method is to calculate f, the fraction of the hot water load that is provided by the solar heating system (*solar fraction*). Once f is calculated, the amount of renewable energy that displaces conventional energy for water heating can be determined. The method is explained in detail in Chapter 20 of Duffie and Beckman (1991) and is briefly summarized here. The method enables the calculation of the monthly amount of energy delivered by hot water systems with storage, given monthly values of incident solar radiation, ambient temperature and load.

Two dimensionless groups X and Y are defined as:

$$X = \frac{A_c F_R' U_L \left(T_{ref} - T_a\right)}{L} \tag{32}$$

$$Y = \frac{A_c F_R' \left(\overline{\tau\alpha}\right) H_T N}{L} \tag{33}$$

where A_c is the collector area, F_R' is the modified collector heat removal factor, U_L is the collector overall loss cœfficient, T_{ref} is an empirical reference temperature equal to 100°C, T_a is the monthly average ambient temperature, L is the monthly total heating load, $\left(\overline{\tau\alpha}\right)$ is the collector's monthly average transmittance-absorptance product, H_T is the monthly average daily radiation incident on the collector surface per unit area, and N is the number of days in the month.

F_R' accounts for the effectiveness of the collector-storage heat exchanger (see ***Figure 14*** for a diagram of the system). The ratio F_R' / F_R is a function of heat exchanger effectiveness ε (see Duffie and Beckman, 1991, section 10.2):

$$\frac{F_{R'}}{F_R} = \left[1 + \left(\frac{A_c F_R U_L}{\left(\dot{m}\, C_p \right)_c} \right) \left(\frac{\left(\dot{m}\, C_p \right)_c}{\varepsilon \left(\dot{m}\, C_p \right)_{\min}} - 1 \right) \right]^{-1} \tag{34}$$

where $\dot{m}$ is the flow rate and C_p is the specific heat. Subscripts c and min stand for collector-side and minimum of collector-side and tank-side of the heat exchanger.

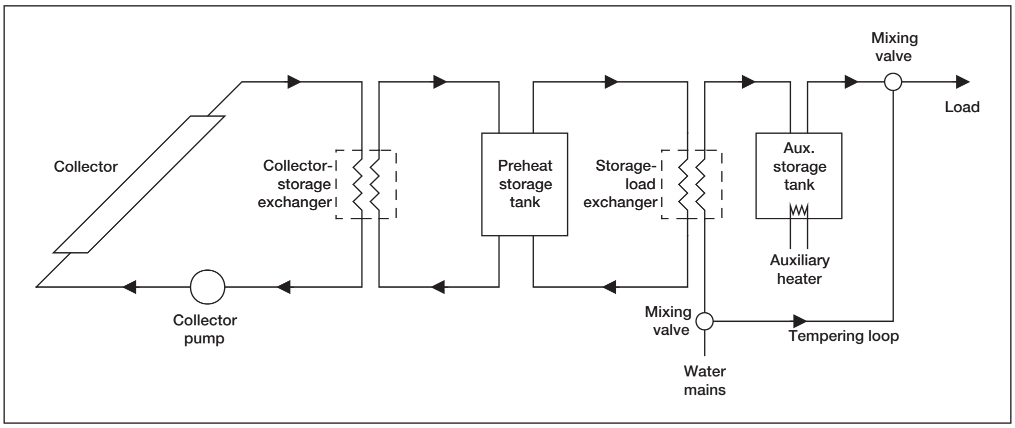


Figure 14:
Diagram of a Solar Domestic Hot Water System.

If there is no heat exchanger, F_R' is equal to F_R. If there is a heat exchanger, the model assumes that the flow rates on both sides of the heat exchanger are the same. The specific heat of water is 4.2 (kJ/kg)/°C, and that of glycol is set to 3.85 (kJ/kg)/°C. Finally the model assumes that the ratio $A_c / \dot{m}$ is equal to 140 m^2 s/kg; this value is computed from ThermoDynamics collector test data (area 2.97 m^2, test flow rate 0.0214 kg/s; Chandrashekar and Thevenard, 1995).

X has to be corrected for both storage size and cold water temperature. The *f-Chart* method was developed with a standard storage capacity of 75 litres of stored water per square meter of collector area. For other storage capacities X has to be multiplied by a correction factor X_c / X defined by:

$$\frac{X_c}{X} = \left(\frac{\text{Actual storage capacity}}{\text{Standard storage capacity}} \right)^{-0.25} \tag{35}$$

This equation is valid for ratios of actual to standard storage capacities between 0.5 and 4. Finally, to account for the fluctuation of supply (mains) water temperature T_m and for the minimum acceptable hot water temperature T_w, both of which have an influence on the performance of the solar water heating system, X has to be multiplied by a correction factor X_{cc} / X defined by:

$$\frac{X_{cc}}{X} = \frac{11.6 + 1.18\, T_w + 3.86\, T_m - 2.32\, T_a}{100 - T_a} \tag{36}$$

where T_a is the monthly mean ambient temperature.

The fraction f of the monthly total load supplied by the solar water heating system is given as a function of X and Y as:

$$f = 1.029\, Y - 0.065\, X - 0.245\, Y^2 + 0.0018\, X^2 + 0.0215\, Y^3 \tag{37}$$

There are some strict limitations on the range for which this formula is valid. However as shown in ***Figure 15***, the surface described by equation (37) is fairly smooth, so extrapolation should not be a problem. If the formula predicts a value of f less than 0, a value of 0 is used; if f is greater than 1, a value of 1 is used.

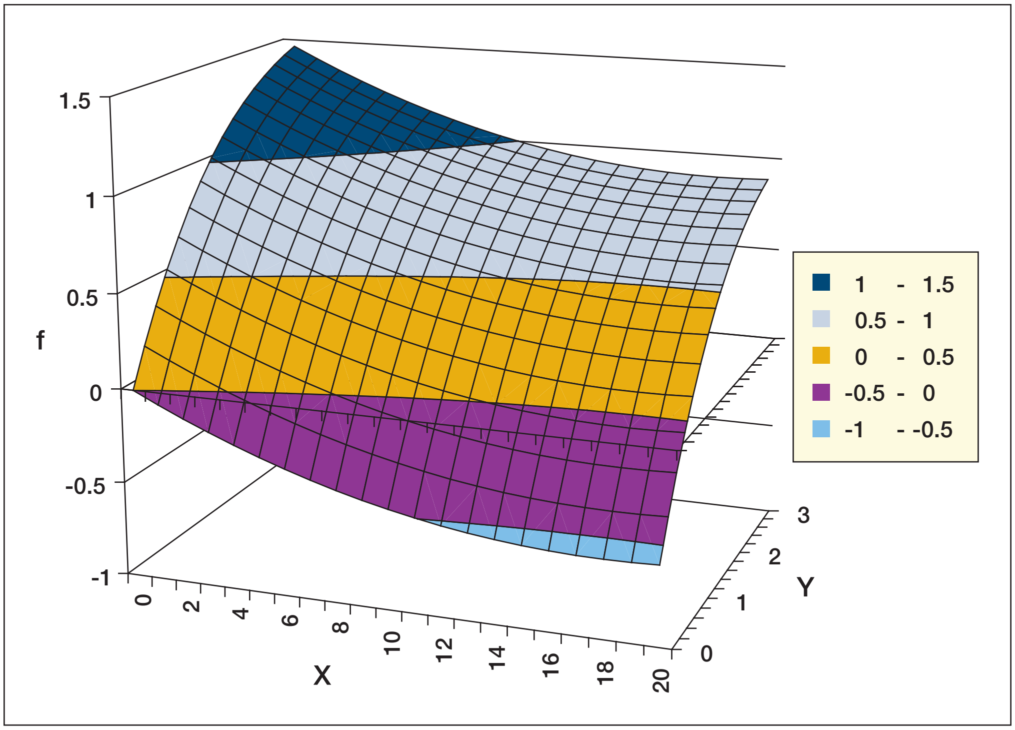


Figure 15:
f-Chart Correlation.

2.4 Utilisability Method

The performance of service water heaters without storage is estimated with the *utilisability* method. The same method is also used to calculate the energy collected by swimming pool solar collectors. The utilisability method is explained in detail in Chapters 2 and 21 of Duffie and Beckman (1991) and is summarised in a condensed form here. The method enables the calculation of monthly amount of energy delivered by hot water systems without storage, given monthly values of incident solar radiation, ambient temperature and load.

2.4.1 Principle of the utilisability method

A solar collector is able to collect energy only if there is sufficient radiation to overcome thermal losses to the ambient. According to equation (24), for a glazed collector this translates into:

$$G \geq \frac{F_R U_L \left(T_i - T_a\right)}{F_R \left(\tau\alpha\right)} \tag{38}$$

where T_i is the temperature of the working fluid entering the collector and all other variables have the same meaning as in equation (24). This makes it possible to define a critical irradiance level G_c which must be exceeded in order for solar energy collection to occur. Since the model is dealing with monthly averaged values, G_c is defined using monthly average transmittance-absorptance $\left(\overline{\tau\alpha}\right)$ and monthly average *daytime* temperature $\bar{T}_a$ (assumed to be equal to the average temperature plus 5°C) through:

$$G_c = \frac{F_R U_L \left(T_i - \bar{T}_a\right)}{F_R \left(\overline{\tau\alpha}\right)} \tag{39}$$

Combining this definition with equation (24) leads to the following expression for the average daily energy Q collected during a given month:

$$Q = \frac{1}{N} \sum_{days} \sum_{hours} A_c F_R \left(\overline{\tau\alpha}\right) \left(G - G_c\right)^+ \tag{40}$$

where N is the number of days in the month, G is the hourly irradiance in the plane of the collector, and the + superscript denotes that only positive values of the quantity between brackets are considered.

The *monthly average daily utilisability* $\bar{\phi}$, is defined as the sum for a month, over all hours and days, of the radiation incident upon the collector that is above the critical level, divided by the monthly radiation:

$$\bar{\phi} = \frac{\sum_{days} \sum_{hours} \left(G - G_c\right)^+}{\bar{H}_T N} \tag{41}$$

where $\bar{H}_T$ is the monthly average daily irradiance in the plane of the collector. Substituting this definition into equation (40) leads to a simple formula for the monthly useful energy gain:

$$Q = A_c F_R \left(\overline{\tau\alpha}\right) \bar{H}_T \bar{\phi} \tag{42}$$

The purpose of the utilisability method is to calculate $\bar{\phi}$ from the collector orientation and the monthly radiation data entered by the user (or copied from the RETScreen Online Weather Database). The method correlates $\bar{\phi}$ to the monthly average clearness index $\bar{K}_T$ and two variables: a geometric factor $\bar{R}/R_n$ and a dimensionless critical radiation level $\bar{X}_c$, as described hereafter.

2.4.2 Geometric factor $\bar{R}/R_n$

$\bar{R}$ is the monthly ratio of radiation in the plane of the collector, $\bar{H}_T$, to that on a horizontal surface, $\bar{H}$:

$$\bar{R} = \frac{\bar{H}_T}{\bar{H}} \tag{43}$$

where $\bar{H}_T$ is calculated as explained in *Section 2.1.2*. R_n is the ratio for the *hour centered at noon* of radiation on the tilted surface to that on a horizontal surface for an average day of the month. This is expressed through the following equation:

$$R_n = \left(1 - \frac{r_{d,n} H_d}{r_{t,n} H}\right) R_{b,n} + \left(\frac{r_{d,n} H_d}{r_{t,n} H}\right)\left(\frac{1+\cos\beta}{2}\right) + \rho_g \left(\frac{1-\cos\beta}{2}\right) \tag{44}$$

where $r_{t,n}$ is the ratio of hourly total to daily total radiation, for the hour centered around solar noon. $r_{d,n}$ is the ratio of hourly diffuse to daily diffuse radiation, also for the hour centered around solar noon. This formula is computed for an "average day of month," i.e. a day with daily global radiation H equal to the monthly average daily global radiation $\bar{H}$; H_d is the monthly average daily diffuse radiation for that "average day" (calculated through equation 14), β is the slope of the collector, and ρ_g is the average ground albedo (see *Section 2.1.2*).

$r_{t,n}$ is computed by the Collares-Pereira and Rabl equation (Duffie and Beckman, 1991, ch. 2.13), written for solar noon:

$$r_{t,n} = \frac{\pi}{24}(a+b)\frac{1-\cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \tag{45}$$

$$a = 0.409 + 0.5016 \sin\left(\omega_s - \frac{\pi}{3}\right) \tag{46}$$

$$b = 0.6609 - 0.4767 \sin\left(\omega_s - \frac{\pi}{3}\right) \tag{47}$$

with ω_s the sunset hour angle (see equation 2), expressed in radians. $r_{d,n}$ is computed by the Liu and Jordan equation, written for solar noon:

$$r_{d,n} = \frac{\pi}{24} \frac{1 - \cos\omega_s}{\sin\omega_s - \omega_s \cos\omega_s} \tag{48}$$

2.4.3 Dimensionless critical radiation level $\bar{X}_c$

$\bar{X}_c$ is defined as the ratio of the critical radiation level to the noon radiation level on the typical day of the month:

$$\bar{X}_c = \frac{G_c}{r_{t,n} R_n \bar{H}} \tag{49}$$

where $r_{t,n}$ is given by (45) and R_n by (44).

2.4.4 Monthly average daily utilisability $\bar{\phi}$

Finally, the correlation giving the monthly average daily utilisability $\bar{\phi}$, as a function of the two factors $\bar{R}/R_n$ and $\bar{X}_c$ calculated previously, is:

$$\bar{\phi} = \exp\left\{\left[a + b\frac{R_n}{\bar{R}}\right]\left[\bar{X}_c + c\bar{X}_c^2\right]\right\} \tag{50}$$

with:

$$a = 2.943 - 9.271\,\bar{K}_T + 4.031\,\bar{K}_T^2 \tag{51a}$$

$$b = -4.345 + 8.853\,\bar{K}_T - 3.602\,\bar{K}_T^2 \tag{51b}$$

$$c = -0.170 - 0.306\,\bar{K}_T + 2.936\,\bar{K}_T^2 \tag{51c}$$

With this, the amount of energy collected can be computed, as shown earlier in equation (42).

2.5 Swimming Pool Model

The energy requirements of the pool are established by assuming that the pool is maintained *at the desired pool temperature*. Therefore, the model does not include calculations of heat storage by the pool, nor does it consider possible excursions in temperature above the desired pool temperature (both of which would require iterative calculations beyond the scope of a spreadsheet-based tool).

The energy requirements of the pool are calculated by comparing the pool's energy losses and gains (see ***Figure 16***). Losses are due to evaporation, convection, conduction, radiation, and the addition of makeup water. Gains include passive solar gains, active solar gains and gains from auxiliary heating. In the sections that follow, those gains and losses are expressed as *rates* or *powers*, i.e. per unit time. The conversion from a power $\dot{Q}$ to the corresponding monthly energy Q is done with a simple formula:

$$Q = 86400\,N_{days}\,\dot{Q} \tag{52}$$

where N_{days} is the number of days in the month and 86,400 is the number of seconds in a day.

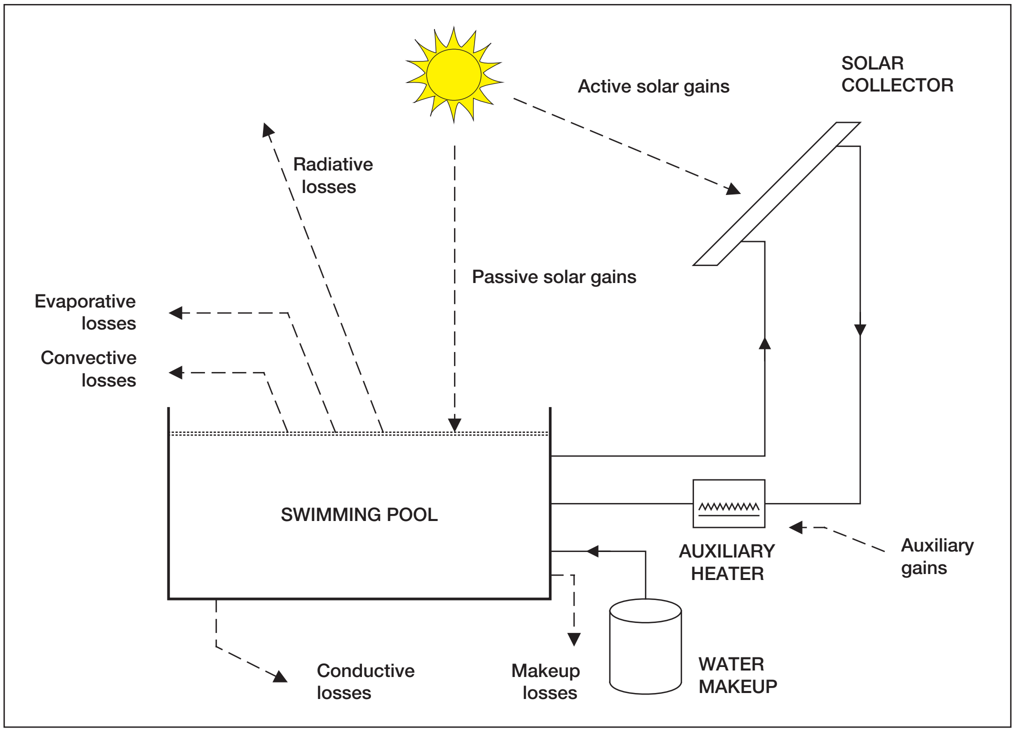


Figure 16:

Energy Gains and Losses in a Swimming Pool.

2.5.1 Pool climatic conditions

Climatic conditions experienced by the pool depend on whether the pool is inside or outside. In the case of an indoor pool, the following conditions are assumed:

- Dry bulb temperature: the maximum of 27°C (ASHRAE, 1995, p. 4.6) and the ambient temperature;
- Relative humidity: 60% (ASHRAE, 1995, p. 4.6);
- Wind speed: 0.1 m/s. This is consistent with assuming that there are 6 to 8 air changes per hour, i.e. air flows across a characteristic dimension of the pool in 450 s; thus if the pool is 25 m long, assuming a 5 m wide walking area around the pool, one obtains a flow rate of 35/450 = 0.08 m/s; and
- Sky temperature: computed from pool ambient temperature.

In the case of an outdoor pool, the local climatic conditions are those entered by the user (or copied from the RETScreen Online Weather Database), with the exception of wind speed and relative humidity which receive special attention, as explained below.

Wind speed

Simulations show that if a pool cover (also called blanket) is used for part of the day and the monthly average wind speed is used for the simulation, evaporative losses are underestimated. This can be related to the fact that wind speed is usually much higher during the day (when the pool cover is off) than at night. Observations made for Toronto, ON; Montreal, QC; Phoenix, AZ; and Miami, FL roughly show that the maximum wind speed in the afternoon is twice the minimum wind speed at night. Consequently wind speed fluctuation during the day is modelled in RETScreen SWH Project Model by a sinusoidal function:

$$V_h = \bar{V} + \frac{\bar{V}}{3} \cos\left(\frac{2\pi \left(h - h_0 \right)}{24} \right) \tag{53}$$

where V_h is the wind velocity at hour h, $\bar{V}$ is the average of the wind speed fluctuation, and h_0 represents a time shift. The model assumes that the maximum wind speed occurs when the cover is off; averaging over the whole period with no cover leads to the following average value:

$$\bar{V}_{off} = \bar{V} + \bar{V} \frac{8}{\pi \left(24 - N_{blanket} \right)} \sin\left(\pi \frac{24 - N_{blanket}}{24} \right) \tag{54}$$

where $N_{blanket}$ is the number of hours per day the cover is on. Similarly, the average wind speed when the pool cover is on is:

$$\bar{V}_{on} = \bar{V} - \bar{V} \frac{8}{\pi N_{blanket}} \sin\left(\pi \frac{N_{blanket}}{24} \right) \tag{55}$$

Finally, wind speed is multiplied by the user-entered sheltering factor to account for reduction of wind speed due to natural obstacles around the pool.

Relative humidity

Evaporation from the pool surface depends on the moisture contents of the air. In RETScreen, the calculation of evaporation cœfficients is done using the *humidity ratio* of the air, rather than its *relative humidity*; this is because the humidity ratio (expressed in kg of water per kg of dry air) is usually much more constant during the day than the relative humidity, which varies not only with moisture contents but also with ambient temperature. The humidity ratio calculation is done according to formulae from ASHRAE Fundamentals (ASHRAE, 1997).

2.5.2 Passive solar gains

Passive solar gains differ depending on whether or not a cover (also called blanket) is installed on the pool.

Passive solar gains without cover

In the absence of cover, passive solar gains can be expressed as:

$$Q_{pas,no\ blanket} = A_p \left((1-r_b)(1-s)\bar{H}_b + (1-r_d)\,\bar{H}_d \right) \tag{56}$$

where A_p is the pool area, r_b is the average reflectivity of water to beam radiation and r_d is the average reflectivity of water to diffuse radiation. As before, $\bar{H}_b$ and $\bar{H}_d$ are the monthly average beam and diffuse radiation (see equations 6 to 8). The user-specified shading cœfficient s applies only to the beam portion of radiation.

A short mathematical development will explain how r_b and r_d are calculated. A ray of light entering water with an angle of incidence θ_z will have an angle of refraction θ_w in the water defined by Snell's law (Duffie and Beckman, 1991, eq. 5.1.4; see ***Figure 17***):

$$n_{air}\sin(\theta_z) = n_{water}\sin(\theta_w) \tag{57}$$

where n_{air} and n_{water} are the indices of refraction of air and water:

$$n_{air} = 1 \tag{58}$$

$$n_{water} = 1.332 \tag{59}$$

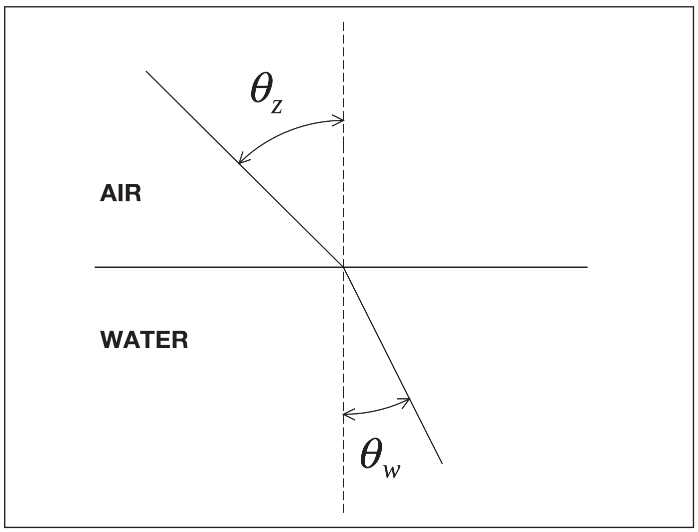


Figure 17:
Snell's Law.

r_b can be computed with the help of Fresnel's laws for parallel and perpendicular components of reflected radiation (Duffie and Beckman, 1991, eqs. 5.1.1 to 5.1.3):

$$r_\perp = \frac{\sin^2(\theta_w - \theta_z)}{\sin^2(\theta_w + \theta_z)} \tag{60}$$

$$r_{//} = \frac{\tan^2(\theta_w - \theta_z)}{\tan^2(\theta_w + \theta_z)} \tag{61}$$

$$r_b = \frac{1}{2}\left(r_\perp + r_{//}\right) \tag{62}$$

Once all calculations are made, it is apparent that r_b is a function of θ_z only. ***Figure 18*** shows that r_b can be safely approximated by:

$$r_b = 0.0203 + 0.9797\left(1 - \cos\theta_z\right)^5 \tag{63}$$

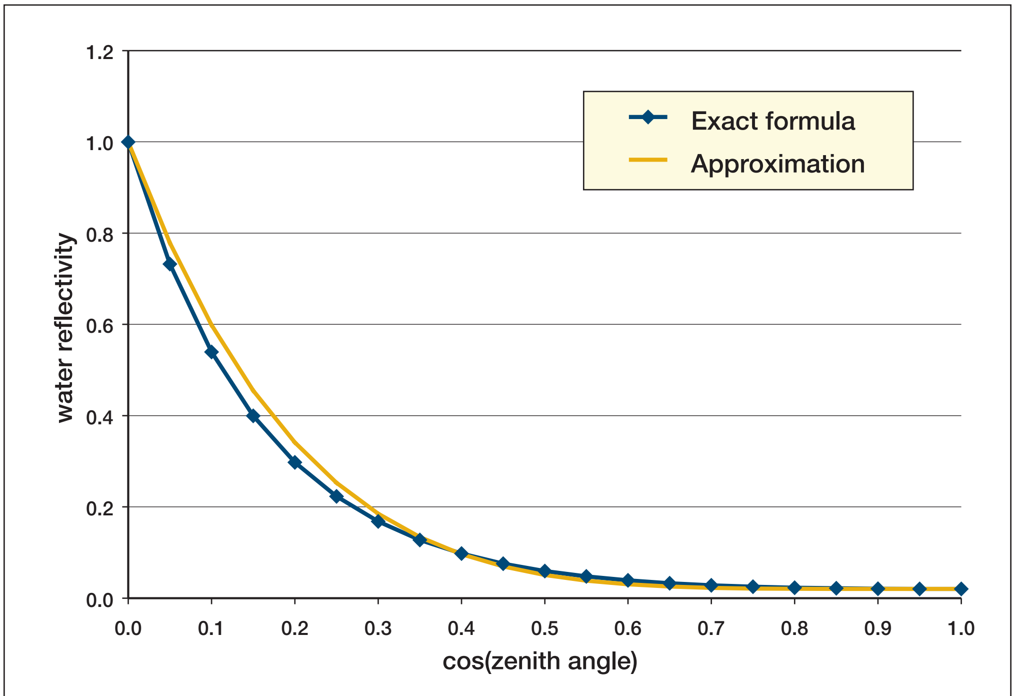


Figure 18:

Reflectivity of Water as a Function of the Cosine of the Zenith Angle.

To account for the fact that the sun is lower on the horizon in the winter, a separate value of r_b is computed for each month. The equation above is used with θ_z calculated 2.5 h from solar noon (the value 2.5 h comes from Duffie and Beckman, 1991, p. 244).

Reflectivity to diffuse radiation is independent of sun position and is basically equal to the reflectivity calculated with an angle of incidence of 60º (Duffie and Beckman, 1991, p. 227). Using the exact equation, a value of r_d = 0.060 is found.

Passive solar gains with cover

In the case of a pool with a blanket, passive solar gains are expressed as:

$$Q_{pas,blanket} = A_p \, \alpha_c \, \bar{H} \tag{64}$$

where α_c is the absorptivity of the blanket, set to 0.4, and $\bar{H}$ is, as before, the monthly average global radiation on the horizontal.

Total of passive solar gains

Passive solar gains are a combination of gains with the blanket on and off. The model assumes that the blanket is on predominantly at night. If the blanket is on $N_{blanket}$ hours per day, and for the average day of the month the day length is $N_{daytime}$, then the number of hours $N_{no\ blanket}$ the blanket is off *during daytime* is:

$$N_{no\ blanket} = \min\left(24 - N_{blanket},\, N_{daytime}\right) \tag{65}$$

and the passive solar gain is simply assumed to be equal to the sum of passive solar gains with and without cover, prorated by the number of hours the blanket is off during daytime:

$$Q_{pas} = \frac{N_{no\ blanket}}{N_{daytime}} Q_{pas,no\ blanket} + \left(1 - \frac{N_{no\ blanket}}{N_{daytime}}\right) Q_{pas,blanket} \tag{66}$$

Expressed per unit time, the passive solar gain rate is calculated according to equation (52):

$$\dot{Q}_{pas} = \frac{Q_{pas}}{86400 \;\; N_{days}} \tag{67}$$

2.5.3 Evaporative losses

There are several methods in the literature to compute evaporative losses, including that of ASHRAE (ASHRAE, 1995) revised by Smith et al. (1994) and those cited in Hahne and Kübler (1994). The RETScreen SWH Project Model adopts the equation of ISO TC 180 (Hahne and Kübler, 1994):

$$\dot{Q}_{eva} = A_p h_e \left(P_{v,sat} - P_{v,amb} \right) \tag{68}$$

where $\dot{Q}_{eva}$ is the power (in W) dissipated as a result of evaporation of water from the pool, h_e is a mass transfer cœfficient, and $P_{v,sat}$ and $P_{v,amb}$ are the partial pressure of water vapour at saturation and for ambient conditions. The mass transfer cœfficient h_e (in (W/m^2)/Pa) is expressed as:

$$h_e = 0.05058 + 0.0669\, V \tag{69}$$

where V is the wind velocity at the pool surface, expressed in m/s. The partial pressure of water vapour at saturation, $P_{v,sat}$, is calculated with formulae from ASHRAE (1997). The partial pressure of water vapour for ambient conditions, $P_{v,amb}$, is calculated from the humidity ratio, also with formulae from ASHRAE (1997).

The rate of evaporation of water from the pool, $\dot{m}_{eva}$, in kg/s, is related to $\dot{Q}_{eva}$ by:

$$\dot{m}_{eva} = \frac{\dot{Q}_{eva}}{\lambda} \tag{70}$$

where λ is the latent heat of vaporisation of water (2,454 kJ/kg).

When the pool cover is on, it is assumed to cover 90% of the surface of the pool and therefore evaporation is reduced by 90%. When the pool cover is off, losses are multiplied by two to account for activity in the pool (Hahne and Kübler, 1994).

2.5.4 Convective losses

Convective losses are estimated using the equation cited in Hahne and Kübler (1994):

$$\dot{Q}_{con} = A_p h_{con} \left(T_p - T_a \right) \tag{71}$$

where $\dot{Q}_{con}$ is the rate of heat loss due to convective phenomena (in W), T_p is the pool temperature, T_a is the ambient temperature, and the convective heat transfer cœfficient h_{con} is expressed as:

$$h_{con} = 3.1 + 4.1\ V \tag{72}$$

with the wind speed V expressed in m/s.

2.5.5 Radiative losses

Radiative losses to the ambient environment in the absence of pool blanket, $\dot{Q}_{rad,no\ blanket}$ (in W) are expressed as:

$$\dot{Q}_{rad,no\ blanket} = A_p\ \varepsilon_w\ \sigma\ \left(T_p^4 - T_{sky}^4 \right) \tag{73}$$

where ε_w is the emittance of water in the infrared (0.96), σ is the Stefan-Boltzmann constant (5.669x10^{-8} (W/m^2)/K^4), T_p is the pool temperature and T_{sky} is the sky temperature (see *Section 2.1.3*). In the presence of a blanket, assuming 90% of the pool is covered, radiative losses become:

$$\dot{Q}_{rad,blanket} = A_p \left(0.1\ \varepsilon_w + 0.9\ \varepsilon_c \right) \sigma\ \left(T_p^4 - T_{sky}^4 \right) \tag{74}$$

where ε_c is the emissivity of the pool blanket. Depending on the cover material the emissivity can range from 0.3 to 0.9 (NRCan, 1998). A mean value of 0.4 is used. Combining the two previous equations with the amount of time the cover is on and the values of ε_w and ε_c mentioned above one obtains:

$$\dot{Q}_{rad} = A_p \left(0.96\ N_{blanket} + 0.456\ \left(24 - N_{blanket}\right)\right)\ \sigma\ \left(T_p^4 - T_{sky}^4\right) \tag{75}$$

2.5.6 Water makeup losses

Fresh water is added to the pool to compensate for: evaporative losses, water lost because of swimmers' activity, and voluntary water changes. If f_{makeup} is the makeup water ratio entered by the user (which does *not* include compensation for evaporative losses), expressed as a fraction of the pool volume renewed each week, the rate of water makeup (in kg/s) can be expressed as:

$$\dot{m}_{makeup} = \dot{m}_{eva} + f_{makeup} \frac{\rho\ V_p}{7 \times 86400} \tag{76}$$

where ρ is the water density (1,000 kg/m^3) and V_p is the pool volume. The pool volume is computed from the pool area assuming an average depth of 1.5 m:

$$V_p = 1.5\, A_p \tag{77}$$

The rate of energy requirement corresponding to water makeup, $\dot{Q}_{makeup}$, is:

$$\dot{Q}_{makeup} = \dot{m}_{makeup} C_p \left(T_p - T_c\right) \tag{78}$$

where T_c is the cold (mains) temperature (see *Section 2.1.4*) and C_p is the heat capacitance of water (4,200 (J/kg)/°C).

2.5.7 Conductive losses

Conductive losses are usually only a small fraction of other losses. The RETScreen SWH Project Model assumes that conductive losses $\dot{Q}_{cond}$ represent 5% of other losses:

$$\dot{Q}_{cond} = 0.05 \left(\dot{Q}_{eva} + \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{makeup} \right) \tag{79}$$

2.5.8 Active solar gains

Maximum possible active solar gains $\dot{Q}_{act}$ are determined by the utilisability method (see *Section 2.4*), assuming the pool temperature is equal to its desired value.

2.5.9 Energy balance

The energy rate $\dot{Q}_{req}$ required to maintain the pool at the desired temperature is expressed as the sum of all losses minus the passive solar gains:

$$\dot{Q}_{req} = \max \left(\dot{Q}_{eva} + \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{makeup} + \dot{Q}_{cond} - \dot{Q}_{pass}, 0 \right) \tag{80}$$

This energy has to come either from the backup heater, or from the solar collectors. The rate of energy actually delivered by the renewable energy system, $\dot{Q}_{dvd}$, is the minimum of the energy required and the energy delivered by the collectors:

$$\dot{Q}_{dvd} = \min \left(\dot{Q}_{req}, \dot{Q}_{act} \right) \tag{81}$$

If the solar energy collected is greater than the energy required by the pool, then the pool temperature will be greater than the desired pool temperature. This could translate into a lower energy requirement for the next month, however this is not taken into account by the model. The auxiliary power $\dot{Q}_{aux}$ required to maintain the pool at the desired temperature is simply the difference between power requirements and power delivered by the renewable energy system:

$$\dot{Q}_{aux} = \dot{Q}_{req} - \dot{Q}_{dvd} \tag{82}$$

2.6 Other Calculations

2.6.1 Suggested solar collector area

The suggested solar collector area depends upon the load, the type of system, and the collector.

- For service hot water with storage, the sizing load for each month is the monthly load including tank and piping losses.

- For service hot water without storage, the sizing load for each month is set to 14% of the monthly load, times $(1+f_{los})$ to account for piping losses. The value of 14% is chosen so that the energy delivered does not exceed the recommended 15% of the load.

- For swimming pools, the sizing load is equal to the energy required, times $(1+f_{los})$ to account for piping losses.

The suggested solar collector area is based on the utilisability method. Optimally, for each month the usable energy should be equal to the sizing load. Using equation (42):

$$Q_{load} = A_c F_R \left(\overline{\tau\alpha}\right) \bar{H}_T \bar{\phi} \tag{83}$$

which is then solved for the collector area, A_c. This provides 12 monthly values of suggested solar collector area. Then:

- For service hot water, the model takes the smallest of the monthly values. For a system without storage this ensures that even for the sunniest month the renewable energy delivered does not exceed 15% of the load. For a system with storage, 100% of the load would be provided for the sunniest month, if the system could use all the energy available. However because systems with storage are less efficient (since they work at a higher temperature), the method will usually lead to smaller solar fractions, typically around 70% for the sunniest month.

- For swimming pools, the method above does not work since the load may be zero during the sunniest months. Therefore the model takes the average of the calculated monthly suggested solar collector areas over the season of use.

The number of solar collectors is calculated as the suggested collector area divided by the area of an individual collector, rounded up to the nearest integer.

2.6.2 Pumping energy

Pumping energy is computed as:

$$Q_{pump} = N_{coll}\ P_{pump}\ A_c \tag{84}$$

where P_{pump} is the pumping power per collector area and N_{coll} the number of hours per year the collector is in operation. A rough estimate of N_{coll} is obtained through the following method: if the collector was running without losses whenever there is sunshine, it would collect $A_c F_R \left(\overline{\tau\alpha}\right) \bar{H}_T$. It actually collects $Q_{dld}\left(1+f_{los}\right)$ where Q_{dld} is the energy delivered to the system and f_{los} is the fraction of solar energy lost to the environment through piping and tank. N_{coll} is simply estimated as the ratio of these two quantities, times the number of daytime hours for the month, $N_{daytime}$:

$$N_{coll} = \frac{Q_{dld}\left(1+f_{los}\right)}{A_c F_R \left(\overline{\tau\alpha}\right) \bar{H}_T} N_{daytime} \tag{85}$$

Comparison with simulation shows that the method above tends to overestimate the number of hours of collector operation. A corrective factor of 0.75 is applied to compensate for the overestimation.

2.6.3 Specific yield, system efficiency and solar fraction

The specific yield is simply energy delivered divided by collector area. System efficiency is energy delivered divided by incident radiation. Solar fraction is the ratio of energy delivered over energy demand.

2.7 Validation

Numerous experts have contributed to the development, testing and validation of the RETScreen Solar Water Heating Project Model. They include solar water heating modelling experts, cost engineering experts, greenhouse gas modelling specialists, financial analysis professionals, and ground station and satellite weather database scientists.

2.7.1 Domestic water heating validation – compared with hourly model and monitored data

This section presents two examples of the validations completed for domestic water heating applications. First, predictions of the RETScreen Solar Water Heating Project Model are compared to results from the WATSUN hourly simulation program. Then, model predictions are compared to data measured at 10 real solar water heating project sites.

Comparison with hourly model

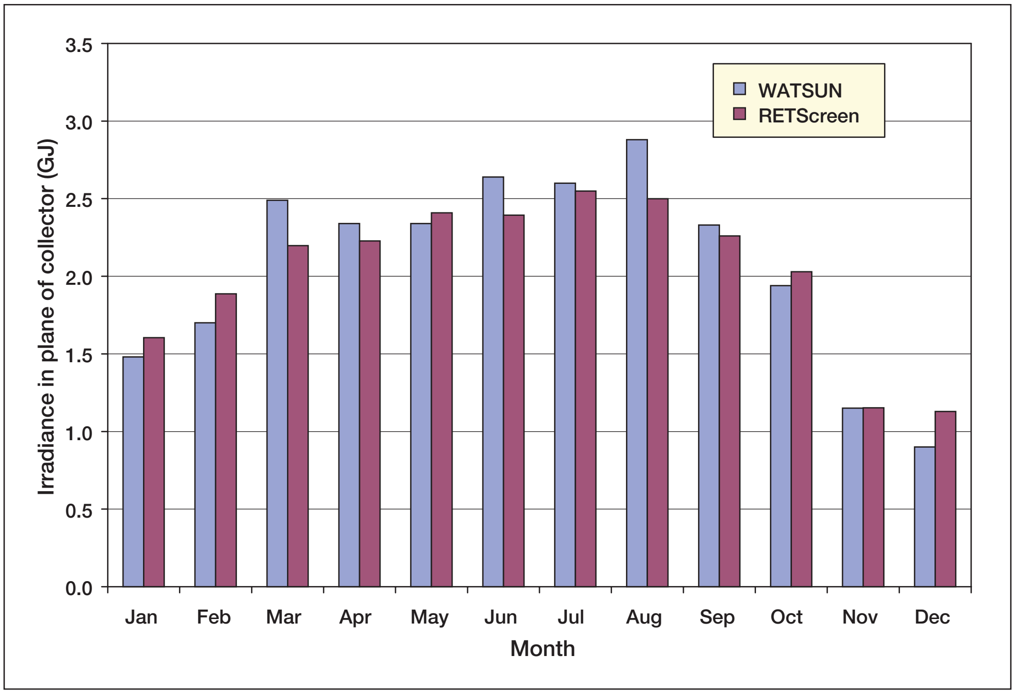
WATSUN (University of Waterloo, 1994) is a computer program devoted to the simulation of active solar energy systems. It performs an hour-by-hour simulation of the system with user-defined system parameters and, for example, Typical Meteorological Year (TMY) weather data. It then provides a monthly summary of energy flows in the system. Although RETScreen is not designed as a monthly simulation tool, the user can specify individual months for which to perform the analysis. In this section RETScreen's monthly predictions are compared to those of WATSUN for a typical domestic water heating system, the parameters of which are summarized in ***Table 2.*** Predicted annual values (***Table 3***) show that the agreement between the two programs is excellent. ***Figure 19a*** to ***Figure 19d*** compare RETScreen predictions to WATSUN calculations on a month-by-month basis. There is good agreement for solar irradiance in the plane of the collector (***Figure 19a***), load (***Figure 19b***), and energy delivered (***Figure 19c***). For pump run time (***Figure 19d***) the agreement is also acceptable, although the model currently used in RETScreen makes only a rough estimate of that variable.

Parameter	Description
Collector	Glazed, 5 m^2
Slope	60 degrees facing south
Storage	Fully mixed, 0.4 m^3
Heat exchanger	70% effectiveness
Location	Toronto, ON, Canada

Table 2: Domestic Water Heating System Parameters.

Predicted Annual Value	RETScreen	WATSUN	Difference
Incident radiation (GJ)	24.34	24.79	-1.8%
Load (GJ)	19.64	19.73	-0.5%
Energy delivered (GJ)	8.02	8.01	0.1%
Pump run time (h)	1,874	1,800	4.1%

Table 3: Comparison of Predicted Annual Values – Domestic Water Heating System.



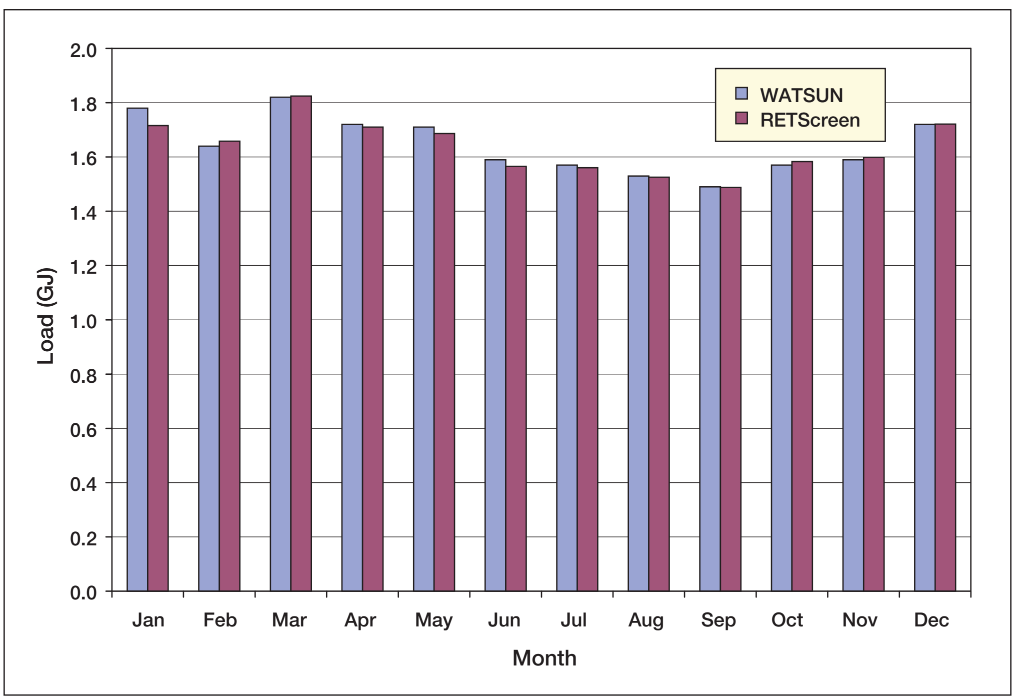
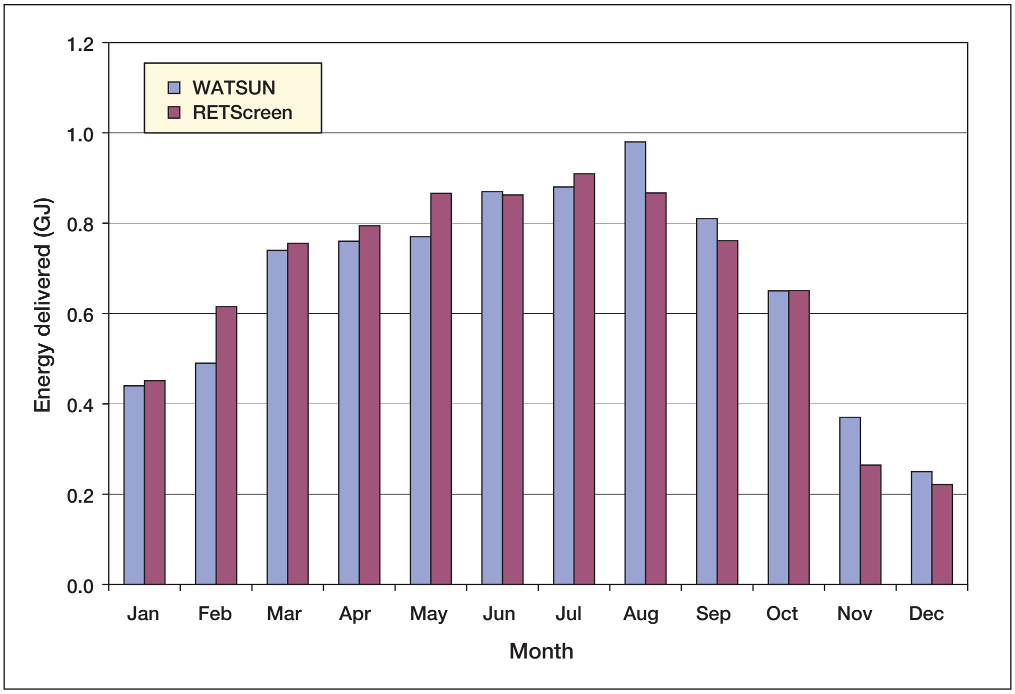


Figure 19a and 19b:

Comparison of Predicted Monthly Values – Domestic Water Heating System.



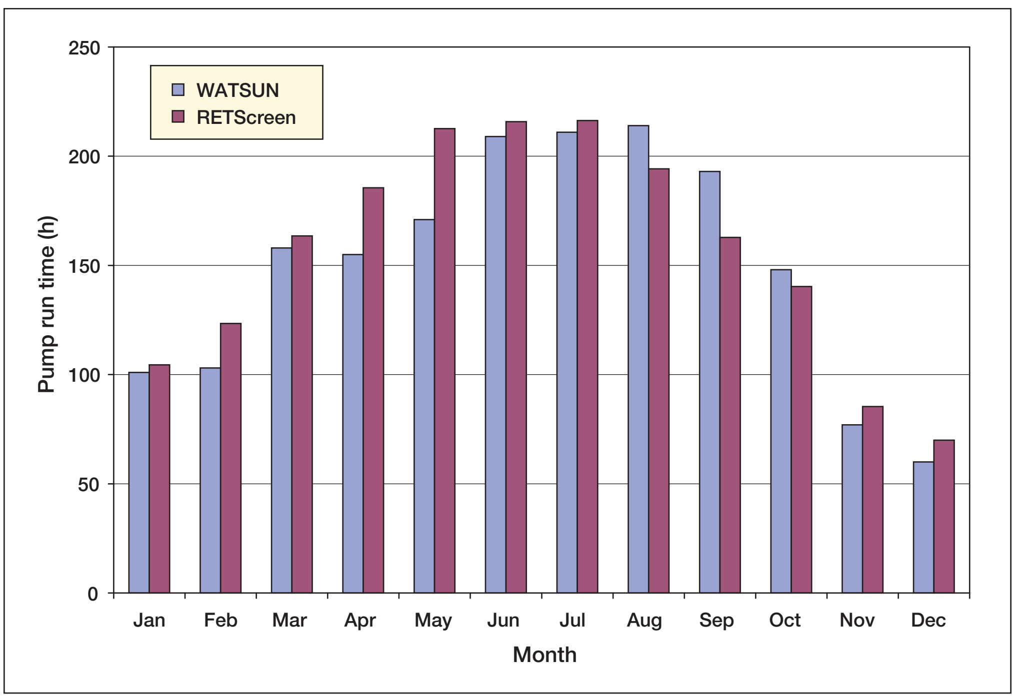


Figure 19c and 19d:

Comparison of Predicted Monthly Values – Domestic Water Heating System.

Comparison with monitored data

To further validate the RETScreen Solar Water Heating Project Model for domestic water heating applications, the model predictions were compared to monitored data gathered for 10 systems under the S2000 project in Guelph, Ontario, Canada (Enermodal, 1999). These systems feature a 5.9 m^2 solar collector, a 270 L tank, a heat exchanger (assumed to be 60% efficient in RETScreen), and loads varying on average from 90 L/day to 380 L/day. Results are shown in ***Figure 20***. It is apparent from the figure that RETScreen is somewhat optimistic in its energy predictions, particularly for systems with low loads (these systems end up mostly in the left part of the figure). The agreement is better for systems with a high load (right part of the figure). For the 10 systems under consideration, the overestimation averages 29% which is well within the range required for pre-feasibility and feasibility analysis studies; the overestimation falls to 15% if only the three systems with highest loads are considered.

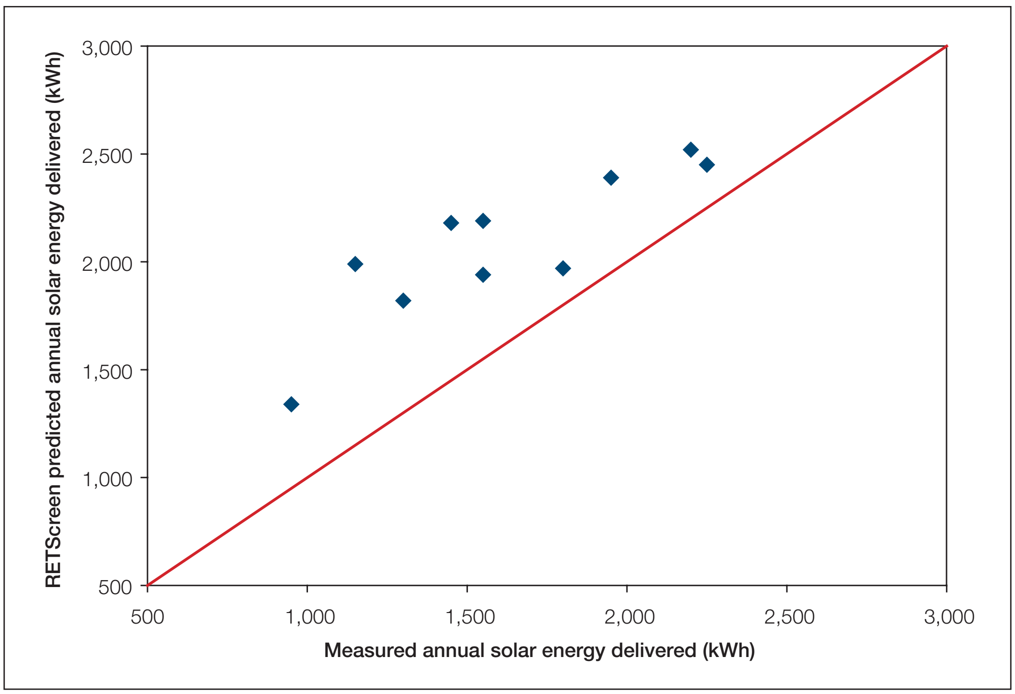


Figure 20:

Comparison of RETScreen Predictions to Monitored Data for Guelph, Ontario, Canada.

2.7.2 Swimming pool heating validation – compared with hourly model and monitored data

This section presents two examples of the validations completed for swimming pool heating applications. First, predictions of the RETScreen Solar Water Heating Project Model are compared to results from the ENERPOOL hourly simulation program. Then, model predictions are compared to data measured at a real solar pool heating project site.

Comparison with hourly model

ENERPOOL (NRCan, 1998) is an hourly simulation program very similar in concept to WATSUN, but devoted to the simulation of indoor and outdoor swimming pools. It provides a monthly summary of energy requirements and fraction solar for the swimming pool, which can be compared to RETScreen predictions.

The main parameters of the outdoor pool simulated are summarized in ***Table 4***. Pool losses, passive solar gains, energy required (equal to losses minus passive solar gains), and energy from solar are shown in ***Figure 21a*** to ***Figure 21d***. There is good agreement for the prediction of pool losses and passive solar gains (+2.5% and +5.7% respectively over the whole swimming season), and so is energy required (-2.0%). ***Figure 21d*** is interesting and calls for comments. Compared to ENERPOOL, solar energy gains are underestimated by RETScreen, especially for July when the energy requirements of the pool are minimal. This has to do with the methods chosen to estimate solar gains in RETScreen and in ENERPOOL. RETScreen calculates the amount of solar energy required to maintain the pool at the *minimum* desired temperature, whereas ENERPOOL allows the pool temperature to fluctuate between a minimum (27°C) and a maximum (30°C). Therefore, even if no active solar heat would be required to maintain the pool at the minimum temperature, ENERPOOL still allows heat to be collected, which mimics the way real pool heating systems work. As shown in this example RETScreen predicts only the *minimum* heat gain that could be realized with the addition of a solar collector, that is, the amount of auxiliary heating from non-renewable sources that could be simply displaced by solar energy. For July, for example, energy from solar is simply the pool's energy requirement for that month (4.5 GJ), despite the fact that more energy could be collected.

Parameter	Description
Pool area	48 m^2
Pool open	8h/day
Minimum pool temperature	27°C
Collector area	25 m^2
Pool opens	May 1st
Pool closes	September 30th
Location	Montreal, QC, Canada

Table 4: Swimming Pool Heating System Parameters.

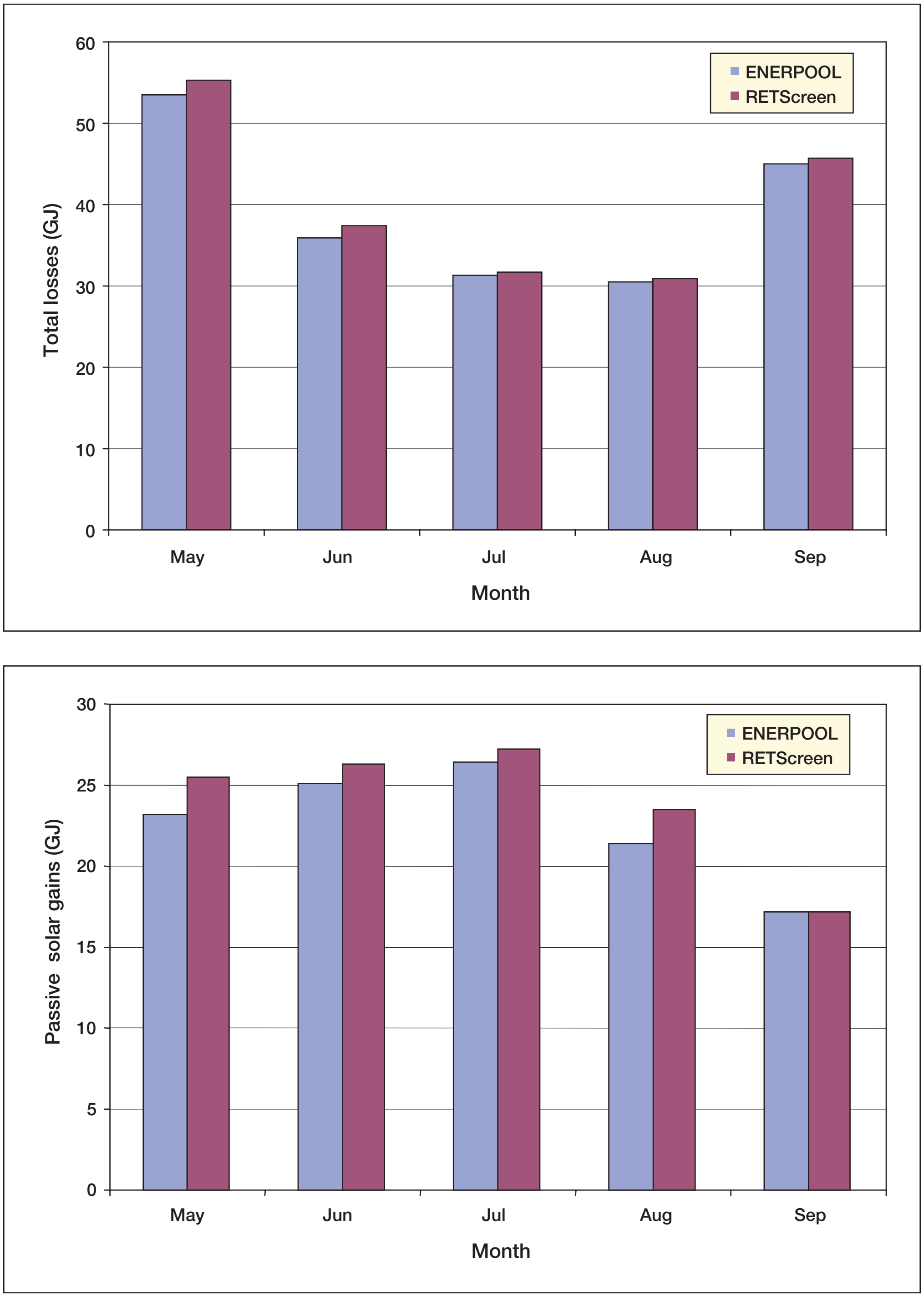
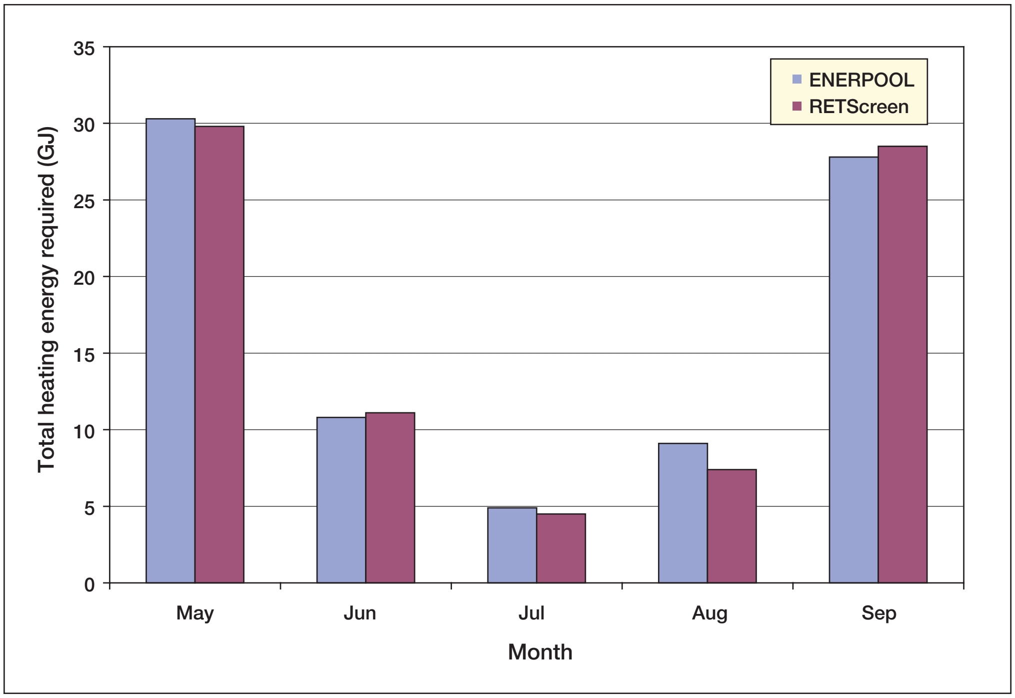


Figure 21a and 21b:

Comparison of Predicted Monthly Values – Swimming Pool Heating System.



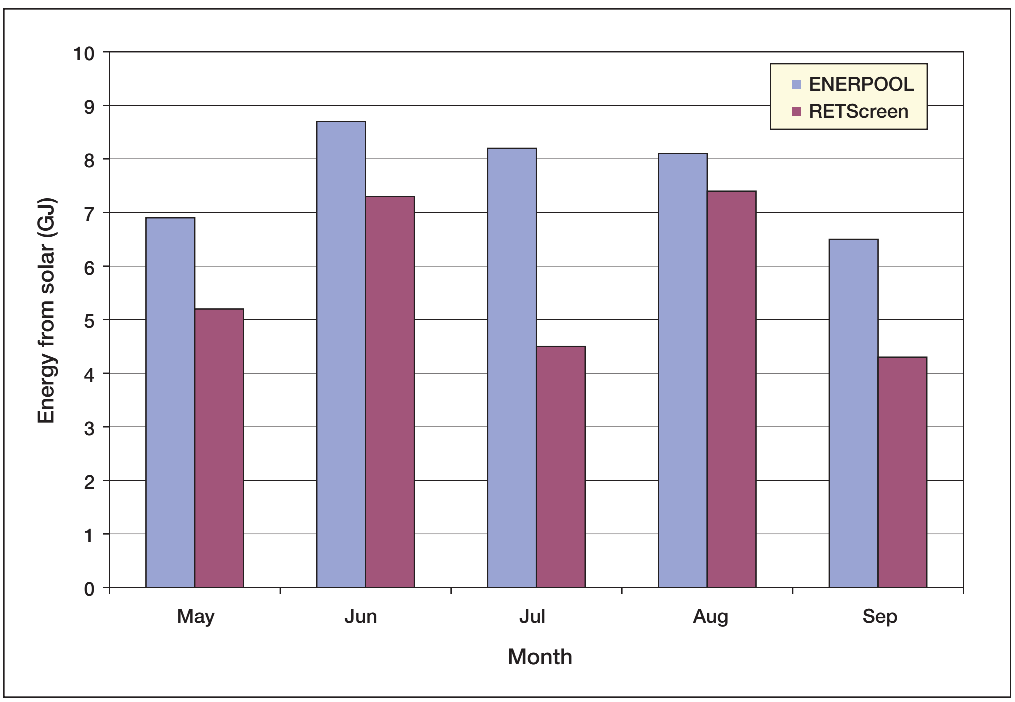


Figure 21c and 21d:

Comparison of Predicted Monthly Values – Swimming Pool Heating System.

Comparison with monitored data

To further validate the RETScreen Solar Water Heating Project Model for swimming pool heating applications, the model predictions were compared to monitored data gathered for a pool located in Möhringen, Germany, based the results reported in Hahne and Kübler (1994). Main parameters for the pool are summarised in ***Table 5***.

Parameter	Description
Pool area	1,200 m^2
Pool open	14h/day*
Minimum pool temperature	24°C
Collector area	650 m^2
Pool opens	May 5^{th}
Pool closes	September 6^{th}

Table 5: Swimming Pool Heating System Parameters for Möhringen, Germany (* = estimated).

Over the pool's swimming season energy requirements are measured at 546 MWh and estimated at 528 MWh by RETScreen (-3%). Energy from the solar collectors is measured at 152 MWh with system efficiency around 38%; RETScreen predicts 173 MWh (+14%) and 44% efficiency, respectively. As for domestic water heating the errors in the estimates of RETScreen are well within the range required for pre-feasibility and feasibility analysis studies.

2.8 Summary

In this section the algorithms used by the RETScreen Solar Water Heating Project Model have been shown in detail. The tilted irradiance calculation algorithm, the calculation of environmental variables such as sky temperature, and the collector model are common to all applications. Energy delivered by hot water systems with storage is estimated with the *f-Chart* method. For systems without storage, the *utilisability* method is used. The same method is also used to estimate the amount of energy actively collected by pool systems; pool losses and passive solar gains are estimated through a separate algorithm. Comparison of the RETScreen model predictions to results of hourly simulation programs and to monitored data shows that the accuracy of the RETScreen Solar Water Heating Project Model is excellent in regards to the preparation of pre-feasibility studies, particularly given the fact that RETScreen only requires 12 points of data versus 8,760 points of data for most hourly simulation models.

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