Solar Water Heating Project Development Assessment

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Velimir Lackovic, Char. Eng.

Continuing Education and Development, Inc.
9 Greyridge Farm Court
Stony Point, NY 10980

P: (877) 322-5800
F: (877) 322-4774

info@cedengineering.com

SOLAR WATER HEATING DEVELOPMENT ASSESSMENT

This course covers the assessment of potential solar water heating developments including a technology background and a detailed description of the calculation algorithms.

Solar Water Heating Background

Using the sun's power to heat water is not a new idea. More than one hundred years ago, black painted water storage tanks were used as simple solar water heaters around the world. Solar water heating (SWH) technology has progressed during the past century. Today there are more than 30 million m^2 of solar collectors operating around the world. Hundreds of thousands of modern solar water heaters are in service in various countries. In fact, in some countries the law actually requires that solar water heaters be operated with any new residential development.

In addition to the power cost savings on water heating, there are several other advantages deducted from using the sun's power to heat water. Most solar water heaters come with an extra water storage tank, which feeds the conventional warm water storage tank. Users benefit from the bigger warm water storage capacity and the reduced likelihood of running out of warm water.

Some solar water heaters do not require electricity to operate. For these systems, warm water supply is secure from power outages, as long as there is sufficient sunshine to operate the system. Solar water heating systems can also be applied to directly heat swimming pool water, with the added benefit of extending the swimming season for outdoor swimming pool purposes.

Solar Water Heating Practical Application Markets

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

Service warm water

There are a number of service warm water purposes. The most common practical application is the use of domestic warm water systems (DHWS), normally sold as “off-the-shelf” or standard kits.

Other common uses include providing process warm water for commercial and institutional purposes, including multi-unit houses and residential buildings, housing developments, and in schools, health centres, hospitals, office buildings and restaurants. Solar water heating systems can also be applied for big industrial loads and for providing power to district heating networks. A number of big systems have been installed in northern Europe and other locations.

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 power prices. The basic principle of these systems is the identical as with solar service warm water systems, with the difference that the swimming pool itself acts as the thermal storage. For outdoor swimming pools, a properly sized solar water heater can replace a conventional heater; the swimming pool water is directly pumped through the solar collectors by the existing filtration system.

Swimming pool practical applications can range in size from small summer only outdoor swimming pools to big Olympic size indoor swimming pools that operate 12 months a year. There is a strong demand for solar swimming pool heating systems. In the United States, for example, the majority of solar collector sales are for unglazed panels for swimming pool heating practical applications. When considering solar service warm water and swimming pool practical application markets, there are a number of factors that can assist check if a particular development has a reasonable market potential and chance for successful implementation. These factors include a big demand for warm water to reduce the relative importance of development fixed prices; high local power prices; unreliable conventional power supply; and/or a strong environmental interest by potential customers and other development stakeholders.

Description of Solar Water Heating Systems

Solar water heating systems use solar collectors and a liquid handling unit to transfer heat to the load, normally via a storage tank. The liquid handling unit includes the pump(s) (applied 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 warm, sunny days. Many systems also have a back-up heater to ensure that all of a consumer's warm water needs are met even when there is insufficient sunshine. Solar water heaters perform three basic operations as displayed in Figure 1:

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

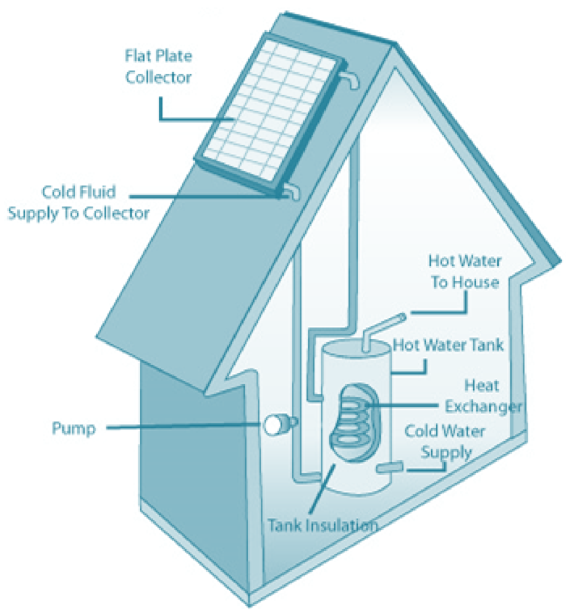

Figure 1. System schematic for typical solar domestic water heater

Solar collectors

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

There are several types of solar collectors to heat liquids. Selection of a solar collector type will depend on the temperature of the practical 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
- evacuated tube solar collectors.

Unglazed liquid flat-plate collectors

Unglazed liquid flat-plate collectors, as depicted in Figure 2, are typically established 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 typically simply laid on a roof or on a wooden support. These low-cost collectors are effective at capturing the power 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 applied for purposes requiring power delivery at low temperatures (swimming pool heating, make-up water in fish farms, process heating purposes, etc.); in colder climates they are typically only operated in the summer season due to the high thermal losses of the collector.

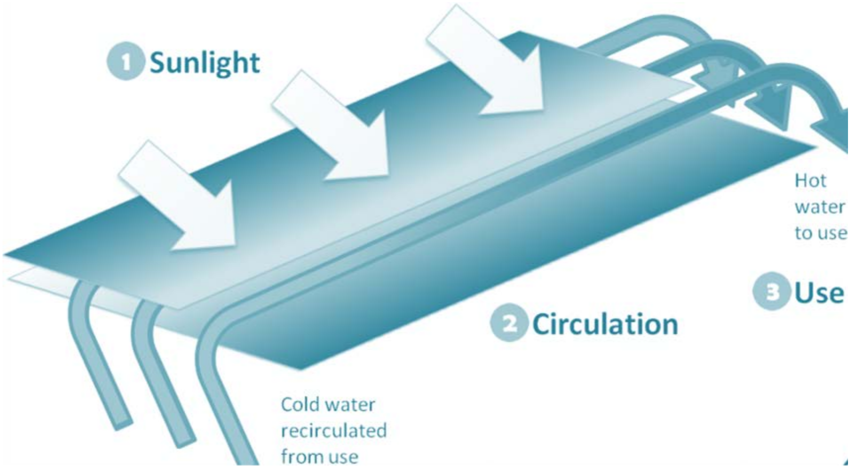

Figure 2. System schematic for unglazed liquid flat-plate collectors

Glazed liquid flat-plate collectors

In glazed liquid flat-plate collectors, as depicted in Figure 3, a flat-plate absorber (which normally 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 sunshine (solar power) is prevented from escaping due to the glazing (the "greenhouse effect"). These collectors are commonly applied in moderate temperature practical applications (e.g. domestic warm water, space heating, year-round indoor swimming pools and process heating practical applications).

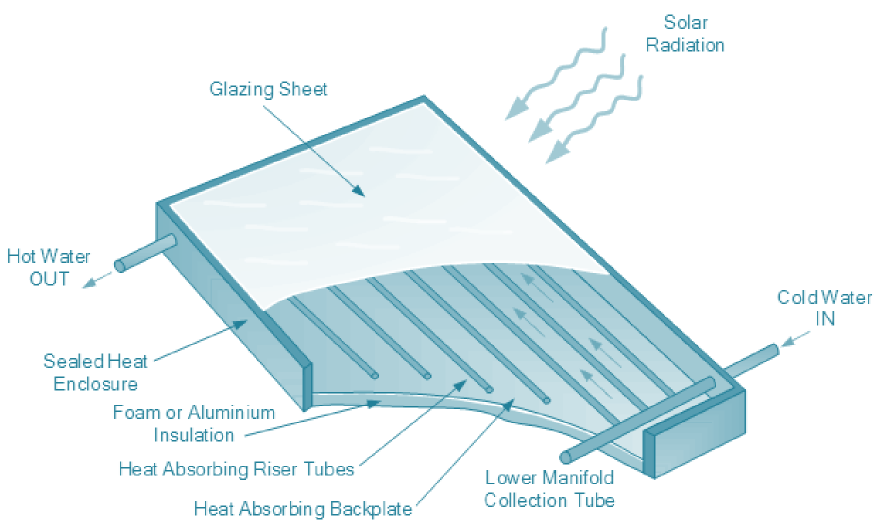

Figure 3. System schematic for glazed liquid flat-plate collectors

Evacuated tube solar collectors

Evacuated tube solar collectors, as depicted in Figure 4, have an absorber with a selective coating enclosed in a sealed glass vacuum tube. They are good at capturing the power 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 vaporized while in contact with the heated absorber, heat is recovered at the top of the tube while the vapor condenses, and condensate returns by gravity to the absorber). Evacuated collectors are efective for purposes requiring power delivery at moderate to high temperatures (domestic warm water, space heating and process heating practical applications typically at 60°C to 80°C depending on outside temperature), particularly in cold climates.

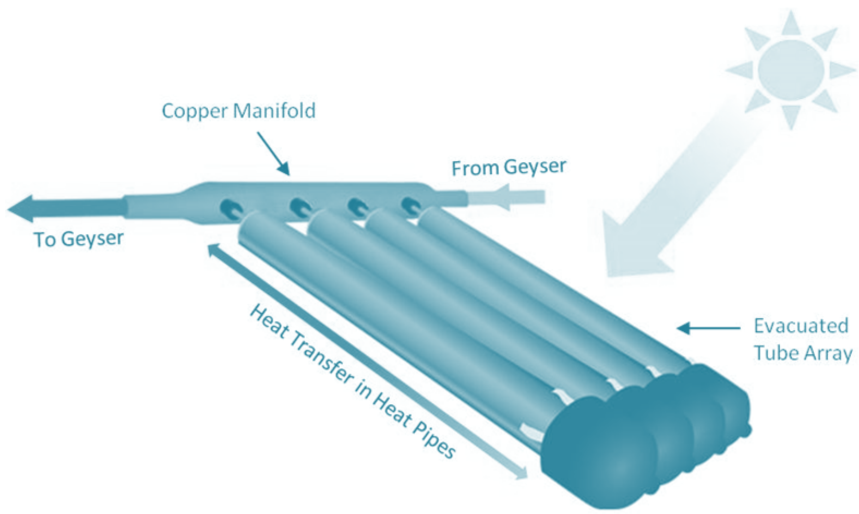

Figure 4. System schematic for evacuated tube solar collectors

Balance of systems

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

- Solar collector array support structure;

- Warm water storage tank (not needed in swimming pool practical applications and in some big commercial or industrial practical applications when there is a continuous service warm water flow);

- Liquid handling unit, which includes a pump needed to transfer the fluid from the solar collector to the warm water storage tank (except in thermosiphon systems where circulation is natural, and outdoor swimming pool practical applications where the existing filtration system pump is normally applied); it also includes valves, strainers, and a thermal expansion storage tank;

- Controller, which activates the circulator only when useable heat is useable from the solar collectors (not needed for thermosiphon systems or if a pwarmovoltaic-powered circulator is applied);

- Freeze protection, needed 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 warm water in the storage tank by a heat exchanger; and

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

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

Solar Water Heating Development Modelling

A solar water heating development model can be applied to evaluate solar water heating developments, from small-scale domestic warm water purposes and swimming pools, to big-scale industrial process warm water systems. There are three basic purposes that can be evaluated using the following determined methodologies:

- Domestic warm water

- Industrial process heat

- Swimming pools (indoor and outdoor)

The annual performance of a solar water heating system with a storage tank is dependent on system features, useable solar radiation, ambient air temperature, and on heating load features. The determined methodology has been designed to assist to define the warm water needs. To assist the user characterize a SWH system before evaluating its cost and power performance, some values are necessary for component sizing (e.g. number of collectors). Approximated values are based on input parameters and can be applied as a first step in the assessment and are not necessarily the optimum values.

This course defines the various calculation methods applied to calculate, on a month-by-month basis, the power savings of solar water heating systems. A flowchart of the calculation process is displayed in Figure 5. The behavior of thermal systems is quite complex and changes from one instant to the next, depending on useable solar radiation, other meteorological variables such as ambient temperature, wind speed and relative humidity, and load. Simplified models that are given enable the calculation of mean power savings on a monthly basis. There are essentially three models which cover the basic purposes:

- Service water heating with storage, determined with the f-Chart method;

- Service water heating without storage, determined with the utilisability method; and

- Swimming pools, determined by an ad-hoc method. There are two variants of the last model, addressing indoor and outdoor swimming pools.

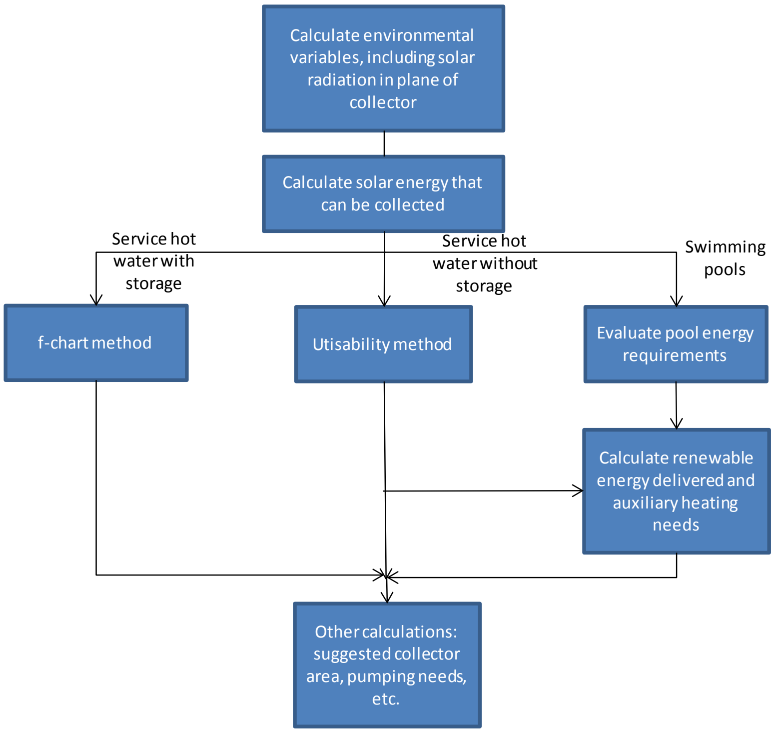

Figure 5. Solar water heating power model flowchart

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. Another common feature of all models is that they need to calculate solar collector efficiency.

Because of the simplifications introduced in given models, there are also few limitations. First, the process warm water model assumes that the daily volumetric load is constant over the season of use. Second, except for swimming pool practical applications, the model is limited to the preheating of water; it does not consider standalone systems that offer 100% of the load. For service warm water systems without storage, only low solar fractions (and penetration levels) should be considered as it is assumed that all the power collected is applied. For swimming pools with no back-up heaters, findings 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 practical applications, these limitations are without consequence.

Environmental Variables

A number of environmental variables have to be determined from the weather data. The values to compute are the:

- Monthly mean daily irradiance in the plane of the solar collector, applied to calculate collector efficiency and solar power collected;

- Sky temperature, applied to calculate power collected by unglazed collectors, and radiative losses of swimming pools to the environment;

- Cold water temperature, applied to check the heating load the system has to meet; and

- Load (except for swimming pools).

Basics of solar power

Since the solar water heating model deals with solar power, some basic concepts of solar power engineering first needs to be explained. This section does not intend to be a course on the fundamentals of solar power. This section intends to detail the calculation of a few variables that will be applied throughout the course.

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:

$$\cos \omega_s = -\tan \psi \tan \delta \qquad (2)$$

where δ is the declination, determined through Equation (1), and ψ is the latitude of the site, defined by the user.

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:

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

where G_{sc} is the solar constant equal to 1,367 W/m^2, and all other variables have the identical 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 mean clearness index, K_T, is determined as:

$$\overline{K_T} = \frac{\bar{H}}{\overline{H_0}} \qquad (4)$$

where H is the monthly mean daily solar radiation on a horizontal surface and H_0 is the monthly mean extraterrestrial daily solar radiation on a horizontal surface.

K_T values depend on the location and the time of year considered; they are typically between 0.3 (for very overcast climates) and 0.8 (for very sunny locations).

Tilted irradiance

Solar radiation in the plane of the solar collector is needed to approximate the efficiency of the collector and the actual amount of solar power collected. The given calculation method uses isotropic diffuse algorithm to compute monthly mean radiation in the plane of the collector, H_T:

$$\overline{H_T} = \overline{H_b}\,\overline{R_b} + \overline{H_d}\left(\frac{1+\cos\beta}{2}\right) + \overline{H}\rho_g\left(\frac{1-\cos\beta}{2}\right) \qquad (5)$$

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 mean beam radiation H_b times a purely geometrical factor, R_b, which depends only on collector orientation, site latitude, and time of year. The second term represents the contribution of monthly mean diffuse radiation, 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 mean temperature is above 0°C, and 0.7 when it is less than – 5°C; and to vary linearly with temperature between these two thresholds.

Monthly mean daily diffuse radiation is determined from global radiation through the following calculations:

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

$$\frac{\overline{H_d}}{\overline{H}} = 1.391 - 3.560\,\overline{K_T} + 4.189\overline{K_T^2} - 2.137K_T^3 \qquad (6)$$

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

$$\frac{\overline{H_d}}{\overline{H}} = 1.311 - 3.022\,\overline{K_T} + 3.427\overline{K_T^2} - 1.821K_T^3 \qquad (7)$$

The monthly mean daily beam radiation H_b is simply computed from:

$$\overline{H_b} = \overline{H} - \overline{H_d} \quad (8)$$

Sky temperature

Sky long-wave radiation is radiation originating from the sky at wavelengths greater than 3 μm. It is needed 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 identical amount of radiation. Its value in °C is computed from sky radiation L_{sky} through:

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

where σ is the Stefan-Boltzmann constant (5.669x10-8 (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 typically warmer. Clear sky long-wave radiation (i.e. in the absence of clouds) is computed using Swinbank's formula:

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

where T_a is the ambient temperature shown 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:

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

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:

$$L_{sky} = (1 - c)L_{clear} + cL_{cloudy} \quad (12)$$

To get a rough approximation of c over the month, the calculation process establishes a correspondence between cloud amount and the fraction of monthly mean 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,

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

K_d is determined from the monthly mean clearness index $\overline{K_T}$ written for the "mean day" of the month (i.e. assuming that the daily clearness index K_T is equal to its monthly mean value $\overline{K_T}$):

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

Cold water temperature

Temperature of the cold water supplied by the public water system is applied to calculate the power needed to heat water up to the desired temperature. There are two alternatives to calculate cold water temperature. In the first option, cold water temperature is computed automatically from monthly ambient temperature values. In the second option, it is computed from minimum and maximum values.

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:

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

where σ is a spatial scale determined 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 given calculation methodology assumes that cold water temperature is equal to soil temperature at an adequate depth. The model takes $\alpha = 0.52x10^{-6}\ m^2/s$ (which matches to a dry heavy soil or a damp light soil) and $z = 2\ m$, the assumed depth at which water pipes are buried. This leads to:

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

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

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

This theoretical methodology was tuned up in light of experimental procedures. 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 established in the model.

The model above enables the calculation of water temperature for any month, with the following calculation process. Water temperature for month i is equal to the yearly mean water temperature, plus 0.35 times the difference between ambient temperature and mean 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 compares measured and predicted water temperatures and indicates that this simplified method of cold water temperature calculation is satisfactory, at least for this particular example.

Table 1. Tabular Comparison of determined and measured cold water temperatures

Month	T ambient [°C]	T water (determined) [°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 mean	7.28	7.30	7.12

Manual calculation

A sinusoidal profile is produced from the minimum and maximum temperatures defined 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 mean soil (or cold water) temperature T_s is shown as a function of minimum temperature T_{min}, maximum temperature T_{max}, and month number n as:

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

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

Approximate load calculation

Load calculation is necessary for the service warm water (with or without storage) calculation models. Warm water use approximations are offered for service warm water systems. No approximation of warm water use is done for aquaculture, industrial or “other” purposes. The actual load is determined as the power needed to heat up mains water to the defined warm water temperature. If V_l is the needed amount of water and T_h is the needed warm water temperature, both defined by the user, then the power needed Q_{load} is shown as:

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

where,

C_p is the heat capacitance of water (4,200 (J/kg)/ºC), 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 applied per week.

Solar Collectors

Solar collectors are determined by their efficiency formulas. Three types of collectors are considered in these calculations:

- Glazed collectors
- Evacuated collectors
- Unglazed collectors

Glazed and evacuated collectors share the identical basic, wind-independent efficiency equation.

Unglazed collectors use a wind-dependent efficiency equation. Implications of angle of incidence, losses due to snow and dirt, and loss of heat through the piping and the solar storage tank are accounted for through separate factors.

Glazed or evacuated collectors

Glazed or evacuated collectors are determined by the following equation:

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

where,

Q_{coll} is the power 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 coefficient of the collector, and ΔT is the temperature differential between the working fluid entering the collectors and outside.

Values of $F_R(\tau\alpha)$ and $F_R U_L$ are manually determined. For both glazed and evacuated collectors, $F_R(\tau\alpha)$ and $F_R U_L$ are independent of wind.

"Generic" values are also offered for glazed and evacuated collectors. Generic glazed collectors are offered with $F_R(\tau\alpha)$= 0.68 and $F_R U_L$ = 4.90 (W/m^2)/ºC. These values correspond to test findings for thermo dynamics collectors. Generic evacuated collectors are also offered with $F_R(\tau\alpha)$= 0.58 and $F_R U_L$ = 0.7 (W/m^2)/ºC.

Unglazed collectors

Unglazed collectors are determined by the following equation:

$$\dot{Q_{coll}} = (F_R\alpha)\left(G + \left(\frac{\varepsilon}{\alpha}\right)L\right) - (F_R U_L)\Delta T \quad (25)$$

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

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

where,

L_{sky} is the longwave sky irradiance and T_a the ambient temperature shown 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 manually defined. The wind speed incident upon the collector is set to 20% of the free stream air velocity. The ratio $\varepsilon\ /\alpha$ is set to 0.96.

Because of the scarcity of performance measurements for unglazed collectors, a “generic” unglazed collector is also determined 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.

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 or the utilizability method, both of which were developed for glazed collectors. The approach taken here 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. Effective irradiance is substituted to irradiance in all formulas involving the collector when an unglazed collector is applied.

Incidence angle modifiers

A portion 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 mean effect of angle of incidence upon the collector was approximated through simulations to be roughly 5%. Therefore, $F_R(\tau\alpha)$ is multiplied by a constant factor equal to 0.95.

Piping and solar storage tank losses

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

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

For systems with storage, the situation is slightly different since the system may be able, in some cases, to compensate for the piping and storage tank losses by collecting and storing extra power. Therefore, the load $Q_{load,tot}$ applied in the f-Chart method is enhanced to include piping and storage tank losses:

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

Losses due to snow and dirt

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

Service Warm Water: f-Chart Method

The performance of service warm water systems with storage is approximated with the f-Chart method. The purpose of the method is to calculate f, the fraction of the warm water load that is offered by the solar heating system (solar fraction). Once f is determined, the amount of alternative power that displaces conventional power for water heating can be checked. The method enables the calculation of the monthly amount of power provided by warm water systems with storage, given monthly values of incident solar radiation, ambient temperature and load.

Two dimensionless groups X and Y are determined as:

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

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

where A_c is the collector area, F_R' is the modified collector heat removal factor, U_L is the collector overall loss coefficient, T_{ref} is an empirical reference temperature equal to 100°C, T_a is the monthly mean ambient temperature, L is the monthly total heating load, $\overline{\tau\alpha}$ is the collector's monthly mean transmittance-absorptance product, H_T is the monthly mean 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 shown in Figure 6. The ratio F_R'/F_R is a function of the heat exchanger effectiveness ε:

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

where $\dot{m}$ is the flow rate and Cp is the unique heat. Subscripts c and min stand for collectorside and minimum of collector-side, as well as the storage tank-side of the heat exchanger.

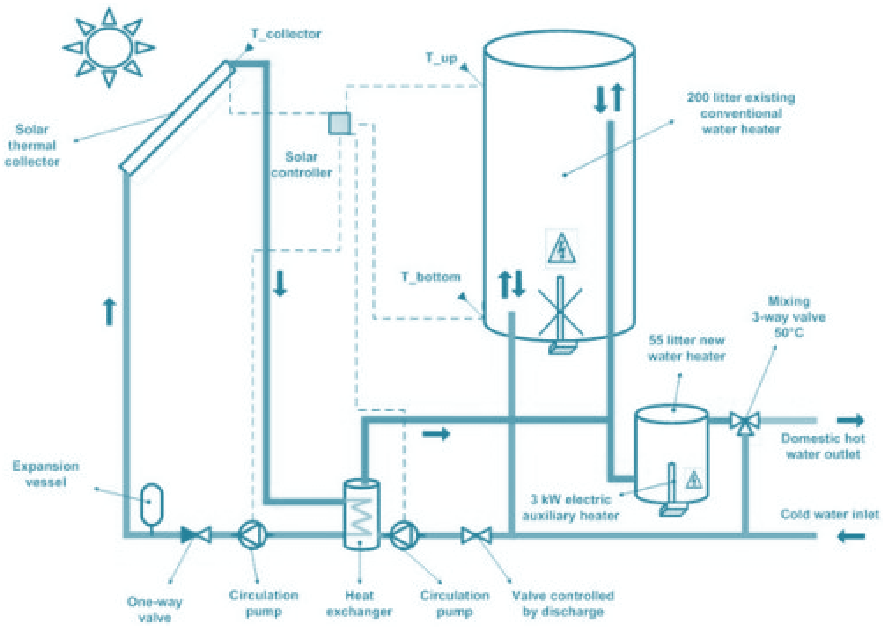

Figure 6. Diagram of a solar domestic warm water system

If there is no heat exchanger, F_R' is equal to F_R. If there is a heat exchanger, the calculation method assumes that the flow rates on both sides of the heat exchanger are identical. The unique heat of water is 4.2 (kJ/kg)/ºC, and that of glycol is set to 3.85 (kJ/kg)/ºC. Finally the model assumes that the ratio $A_C/\dot{m}$ is equal to 140 m^2 s/kg. This value is computed from the thermodynamics collector test data.

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 determined by:

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

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 warm 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 determined by:

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

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:

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

There are some strict limitations on the range for which this formula is valid. If the formula predicts a value of f less than 0, a value of 0 is applied; if f is greater than 1, a value of 1 is applied.

Utilisability Method

The performance of service water heaters without storage is approximated with the utilisability method. The identical method is also applied to calculate the power collected by swimming pool solar collectors. The method enables the calculation of the monthly amount of power provided by warm water systems without storage, given monthly values of incident solar radiation, ambient temperature and load.

Principle of the utilisability method

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

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

where T_i is the temperature of the working fluid entering the collector, and all other variables have the identical meaning as in Equation (24). This makes it possible to define a critical irradiance level G_c which must be exceeded in order for the solar power collection to occur.

Since the model is dealing with monthly averaged values, G_c is determined using the monthly mean transmittance-absorptance and the monthly mean daytime temperature T_a (assumed to be equal to the mean temperature plus 5°C) through:

$$G_c = \frac{F_R U_L (T_i - \overline{T_a})}{F_R(\overline{\tau\alpha})} \quad (39)$$

Combining this definition with Equation (24) leads to the following expression for the mean daily power Q collected during a given month:

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

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 mean daily utilisability, φ, is determined as the sum for a given month (overall hours and days) of the radiation incident upon the collector that is above the critical level, divided by the monthly radiation:

$$\overline{\emptyset} = \frac{\sum_{days}\sum_{hours}(G-G_c)^+}{\overline{H_T}N} \quad (41)$$

where $\overline{H_T}$ is the monthly mean daily irradiance in the plane of the collector. Substituting this definition into Equation (40) leads to a simple formula for the monthly useful power gain:

$$Q = A_c F_R(\overline{\tau\alpha})\overline{H_T}\overline{\emptyset} \quad (42)$$

The purpose of the utilisability method is to calculate φ from the collector orientation and the monthly radiation. The method correlates φ to the monthly mean clearness index $\overline{K_T}$ and two variables: a geometric factor $\bar{R}/R_n$ and a dimensionless critical radiation level $\overline{X_c}$, as determined hereafter.

Geometric factor $\bar{R}/R_n$

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

$$\bar{R} = \frac{\overline{H_T}}{\overline{H}} \quad (43)$$

where $\overline{H_T}$ is determined as explained in previous sections. R_n is the ratio for the hour centered at noon of radiation on the tilted surface to that on a horizontal surface for a mean day of the month. This is shown through the following equation:

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

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

$r_{t,n}$ is written for solar noon as:

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

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

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

with ω_s the sunset hour angle (Equation 2), expressed in radians. $r_{d,n}$ is written for solar noon as:

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

Dimensionless critical radiation level $\overline{X_c}$

$\overline{X_c}$ is determined as the ratio of the critical radiation level to the noon radiation level on the typical day of the month:

$$\overline{X_c} = \frac{G_c}{r_{t,n}R_n\bar{H}} \quad (49)$$

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

Monthly mean daily utilisability $\bar{\emptyset}$

Finally, the correlation giving the monthly mean daily utilisability φ, as a function of the two factors $\bar{R}/R_n$ and $\overline{X_c}$ determined previously, is:

$$\bar{\emptyset} = exp\left\{\left[a + b\frac{R_n}{\bar{R}}\right][\overline{X_c} + c\bar{X}_c^2]\right\} \quad (50)$$

with:

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

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

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

With this, the amount of power collected can be computed as displayed earlier in Equation (42).

Swimming Pool Model

The power requirements of the swimming pool are established by assuming that the swimming pool is maintained at the desired swimming pool temperature. Therefore, the model does not include calculations of heat storage by the swimming pool, nor does it consider possible excursions in temperature above the desired swimming pool temperature.

The power requirements of the swimming pool are determined by comparing the swimming pool's power losses and gains (Figure 7). 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 shown as rates or powers, i.e. per unit time. The conversion from a power $\dot{Q}$ to the corresponding monthly power Q is done with a simple formula:

$$Q = 86400\,N_{days}\,\dot{Q} \qquad (52)$$

where,

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

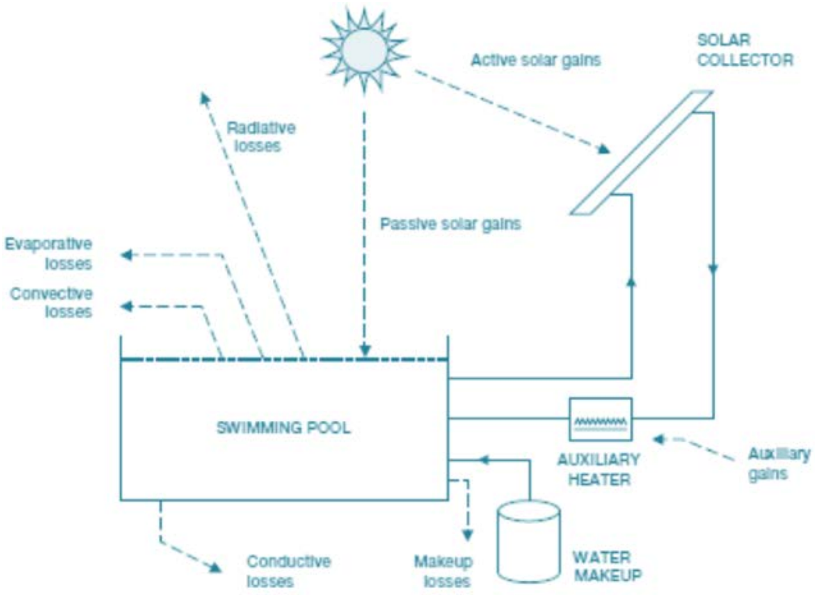

Figure 7. Power gains and losses in a swimming pool

Swimming pool climatic conditions

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

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

Wind speed

Simulations show that if a swimming pool cover (also called blanket) is applied for part of the day and the monthly mean wind speed is applied for the simulation, evaporative losses are underestimated. This can be related to the fact that wind speed is typically much higher during the day (when the swimming pool cover is off) than at night. Observations established at various locations show that the maximum wind speed in the afternoon is twice the minimum wind speed at night.

Accordingly wind speed fluctuation during the day is modelled by a sinusoidal function:

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

where,

V_h is the wind velocity at hour h, $\bar{V}$ is the mean 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 mean value:

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

where $N_{blanket}$ is the number of hours per day the cover is on. Similarly, the mean wind speed when the swimming 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-defined sheltering factor to account for reduction of wind speed due to natural obstacles around the swimming pool.

Relative humidity

Evaporation from the swimming pool surface depends on the moisture contents of the air. Calculation of evaporation coefficients is done using the humidity ratio of the air, rather than its relative humidity. This is because the humidity ratio (in kg of water per kg of dry air) is typically much more constant during the day than the relative humidity, which varies not only with moisture contents but also with ambient temperature.

Passive solar gains

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

Passive solar gains without cover

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

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

where A_p is the swimming pool area, r_b is the mean reflectivity of water to beam radiation, and r_d is the mean reflectivity of water to diffuse radiation. As before, $\bar{H}_b$ and $\bar{H}_d$ are the monthly mean beam and diffuse radiation, respectively (Equations 6 to 8). The shading coefficient s applies only to the beam portion of the radiation.

A short mathematical development will explain how r_b and r_d are determined. A ray of light entering water with an angle of incidence θ_z will have an angle of refraction θ_w in the water determined by Snell's law (Figure 8):

$$n_{air} \sin\theta_z = n_{water} \sin\theta_w$$

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

$$n_{air} = 1 \qquad (58)$$

$$n_{water} = 1.332 \qquad (59)$$

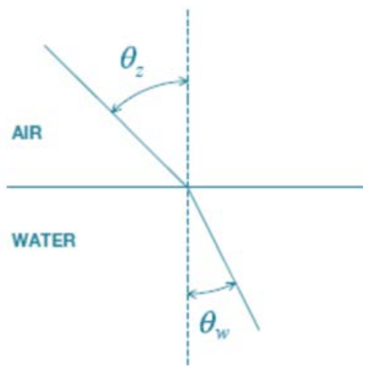

Figure 8. Snell's law

r_b can be computed with the assistance of Fresnel's laws for parallel and perpendicular components of reflected radiation:

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

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

$$r_b = \frac{1}{2}(r_{\perp} + r_{II}) \quad (62)$$

Once all calculations are established, it is apparent that r_b is a function of θ_z only. r_b can be safely approximated by:

$$r_b = 0.0203 + 0.9797\,(1 - \cos\theta_z)^5 \quad (63)$$

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 applied with θ_z determined 2.5 h from solar noon. Reflectivity to diffuse radiation is independent of sun position and is basically equal to the reflectivity determined with an angle of incidence of 60º. Using the exact equation, a value of r_d=0.060 is found.

Passive solar gains with cover

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

$$Q_{pas,blanket} = A_p \alpha_c \overline{H} \quad (64)$$

where α_c is the absorptivity of the blanket, set to 0.4, and $\overline{H}$ is, as before, the monthly mean 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 mean 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:

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

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:

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

Expressed in unit time, the passive solar gain rate is determined according to Equation (52):

$$\dot{Q}_{pas} = \frac{Q_{pas}}{86400\ N_{days}} \quad (67)$$

Evaporative losses

There are several methods in the literature to compute evaporative losses. The following formula is proposed here:

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

where

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

$$h_e = 0.05058 + 0.0669\ V \quad (69)$$

where V is the wind velocity at the swimming pool surface, expressed in m/s.

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

$$\dot{m}_{eva} = \frac{\dot{Q}_{eva}}{\lambda} \quad (70)$$

where λ is the latent heat of vaporization of water (2,454 kJ/kg). When the swimming pool cover is on, it is assumed to cover 90% of the surface of the swimming pool and therefore evaporation is reduced by 90%. When the swimming pool cover is off, the losses are multiplied by two to account for activity in the swimming pool.

Convective losses

Convective losses are approximated using the following equation:

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

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

$$h_{con} = 3.1 + 4.1\,V \quad (72)$$

with the wind speed V expressed in m/s.

Radiative losses

Radiative losses to the ambient environment in the absence of a swimming pool blanket, (in W) are expressed as:

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

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 swimming pool temperature, and T_{sky} is the sky temperature. In the presence of a blanket, assuming 90% of the swimming pool is covered, radiative losses become:

$$\dot{Q}_{rad,no\ blanket} = A_p (0.1\varepsilon_w + 0.9\varepsilon_c)\sigma (T_p^4 - T_{sky}^4) \quad (74)$$

where ε_c is the emissivity of the swimming pool blanket. Depending on the cover material, I the emissivity can range from 0.3 to 0.9. A mean value of 0.4 is applied. Combining the two previous formulas with the amount of time the cover is on and the values of ε_w and ε_c mentioned above, the following equation is obtained:

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

Water makeup losses

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

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

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

$$V_p = 1.5\,A_p \qquad (77)$$

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

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

where T_c is the cold (mains) temperature and C_p is the heat capacitance of water (4,200 (J/kg)/^{o}C).

Conductive losses

Conductive losses are typically only a small fraction of other losses. Conductive losses $\dot{Q}_{cond}$ typically represent 5% of the other losses:

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

Active solar gains

Maximum possible active solar gains $\dot{Q}_{act}$ are checked by the utilisability method, assuming the swimming pool temperature is equal to its desired value.

Power balance

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

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

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

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

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

$$\dot{Q}_{aux} = \dot{Q}_{req} - \dot{Q}_{dvd} \qquad (82)$$

Other Calculations

Suggested solar collector area

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

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

- For service warm 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 power provided does not exceed the recommended 15% of the load.

- For swimming pools, the sizing load is equal to the power needed, 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 useable power should be equal to the sizing load. Using Equation (42):

$$Q_{load} = A_C F_R(\overline{\tau\alpha})\overline{H}_T\overline{\emptyset} \qquad (83)$$

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

- For service warm water, the model takes the smallest of the monthly values. For a system without storage, this ensures that even for the sunniest month the alternative power provided does not exceed 15% of the load. For a system with storage, 100% of the load would be offered for the sunniest month, if the system could use all the power useable. However because systems with storage are less efficient (since they work at a higher temperature), the method will typically 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 mean of the determined monthly suggested solar collector areas over the season of use. The number of solar collectors is determined as the suggested collector area divided by the area of an individual collector, rounded up to the nearest integer.

Pumping power

Pumping power is computed as:

$$Q_{pump} = N_{coll} P_{pump} A_c \quad (84)$$

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 approximation of N_{coll} is obtained through the following method: if the collector is running without losses whenever there is sunshine, it would collect $A_c F_R (\overline{\tau\alpha}) \overline{H_T}$. It actually collects $Q_{dld}(1 + f_{los})$ where Q_{dld} is the power provided to the system and f_{los} is the fraction of solar power lost to the environment through piping and storage tank. N_{coll} is simply approximated as the ratio of these two amounts, times the number of daytime hours for the month, $N_{daytime}$:

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

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

Unique yield, system efficiency and solar fraction

The unique yield is simply the power provided divided by the collector area. System efficiency is the power provided divided by the incident radiation. Solar fraction is the ratio of power provided over power demand.

Summary

In this course, calculations methods for typical solar water heating development were illustrated. The tilted irradiance calculation method, the calculation of environmental variables such as sky temperature, and the collector model are common for all purposes. Power provided by warm water systems with storage is approximated with the f-Chart method. For systems without storage, the utilisability method is applied. The identical method is also applied to approximate the amount of power actively collected by swimming pool systems. Swimming pool losses and passive solar gains are approximated through a separate calculation method.

References:

Clean Power Project Analysis RETScreen® Engineering & Cases Textbook, Third Edition, © Minister of Natural Resources Canada 2001-2005, September 2005