PDHonline Course E506 (5 PDH)

Solar Water Heating Project Analysis

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1. Solar Water Heating Project Analysis

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

2. Solar Water Heating Background

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, 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).

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.

3. 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.

4. 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.

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

5. 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 to large Olympic size indoor swimming pools that operate 12 months a year. 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.

6. 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 1:

- Collection: Solar radiation is "captured" by a solar collector;
- Transfer: Circulating fluids transfer this energy to a storage tank; circulation can be natural 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 transfer system.

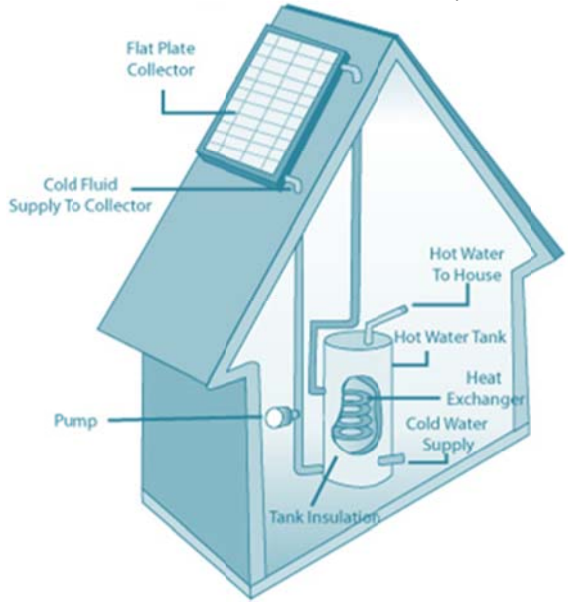

Figure 1. System schematic for typical solar domestic water heater

7. 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
- evacuated tube solar collectors

8. Unglazed liquid flat-plate collectors

Unglazed liquid flat-plate collectors, as depicted in Figure 2, 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.

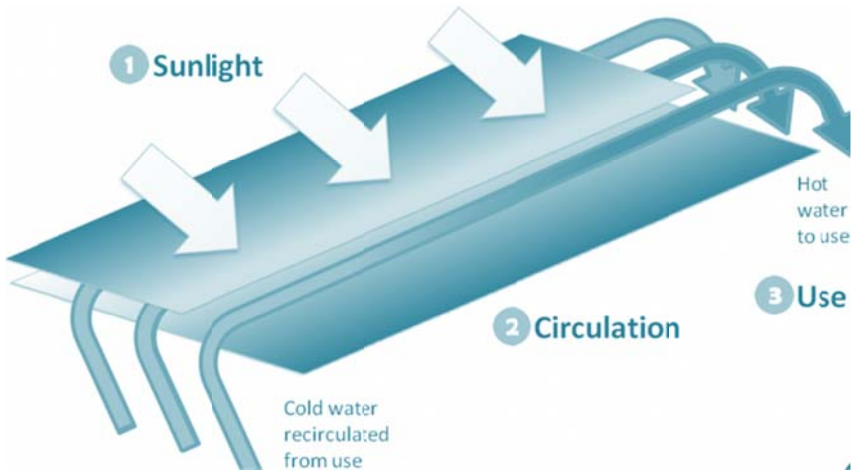

Figure 2. System schematic for unglazed liquid flat-plate collectors

9. Glazed liquid flat-plate collectors

In glazed liquid flat-plate collectors, as depicted in Figure 3, 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).

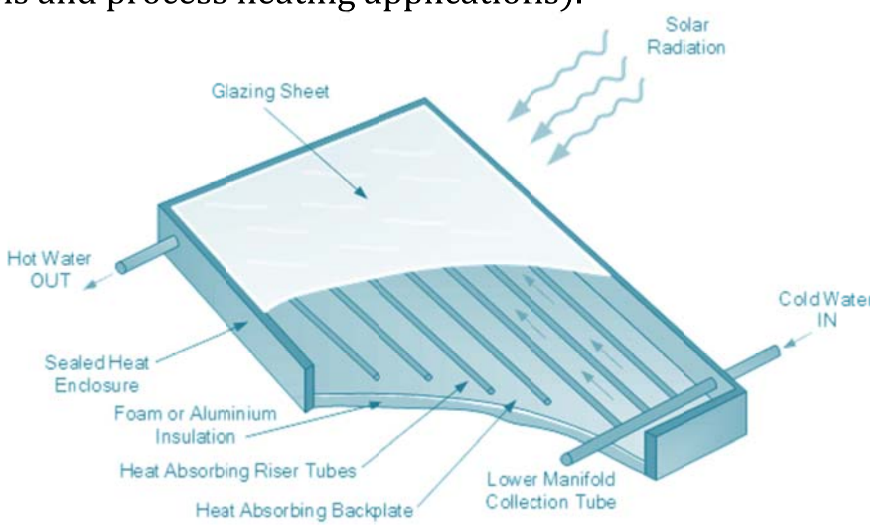

Figure 3. System schematic for glazed liquid flat-plate collectors

10.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 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.

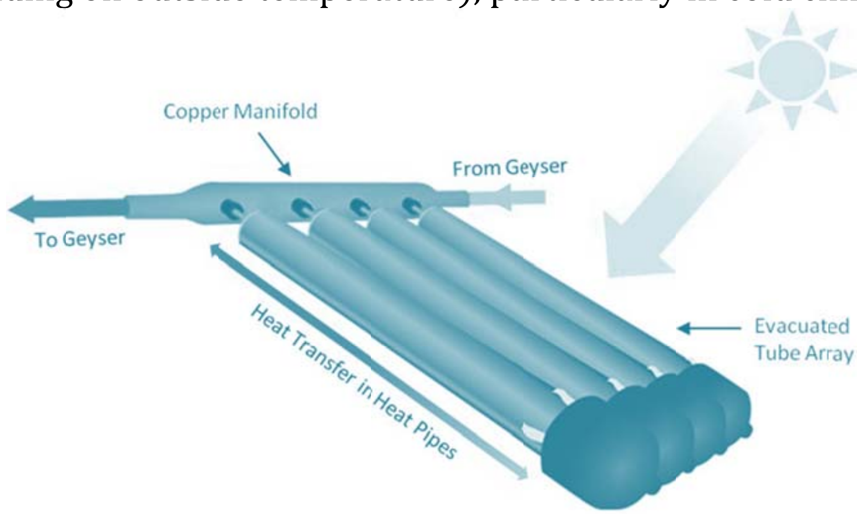

Figure 4. System schematic for evacuated tube solar collectors

11.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
- 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)
- 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;
- 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);
- 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
- 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.

12.Solar Water Heating Project Modelling

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. There are three basic applications that can be evaluated using below described methodology:

- Domestic hot 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 characteristics, solar radiation available, ambient air temperature and on heating load characteristics. Described methodology has been designed to help to define the hot water needs. To help the user characterize a SWH system before evaluating its cost and energy performance, some values are necessary for component sizing (e.g. number of collectors). 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.

This course describes the various calculation methods used to calculate, on a month-by-month basis, the energy savings of solar water heating systems. A flowchart of the calculation procedure is shown in Figure 5. 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. Simplified models that are presented enable the calculation of average energy savings on a monthly basis. There are essentially three models, which cover the basic applications:

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

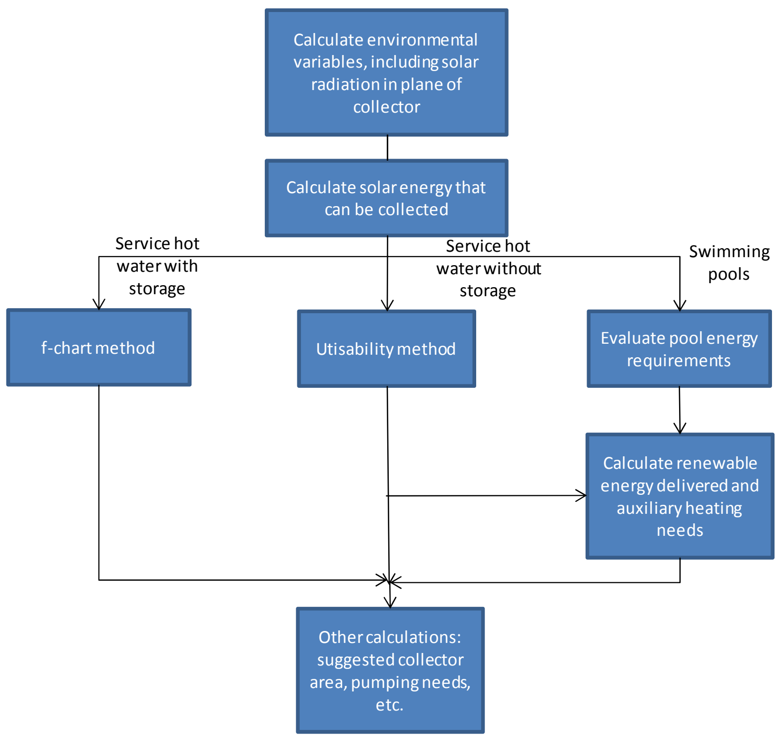

Figure 5. Solar water heating energy model flowchart

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 presented models, there are also 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 standalone 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.

13.Environmental Variables

A number of environmental variables have to be calculated from the weather data. 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;
- Load (except for swimming pools)

14.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. This section intends to detail the calculation of a few variables that will be used throughout the course.

15.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:

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

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.

16.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 ωs is the solar hour angle corresponding to the time when the sun sets. It is given by the following equation:

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

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

17.Extraterrestrial radiation and clearness index

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface, H0, can be computed for the day of year n from the following equation:

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

where Gsc is the solar constant equal to 1,367 W/m2, 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, KT, is defined as:

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

where H is the monthly average daily solar radiation on a horizontal surface and H0 is the monthly average extraterrestrial daily solar radiation on a horizontal surface.

KT 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).

18. Tilted irradiance

Solar radiation in the plane of the solar collector is required to estimate the efficiency of the collector and the actual amount of solar energy collected. Presented calculation method uses isotropic diffuse algorithm to compute monthly average radiation in the plane of the collector, HT:

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

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 average beam radiation Hb times a purely geometrical factor, Rb, which depends only on collector orientation, site latitude, and time of year. The second term represents the contribution of monthly average diffuse radiation, Hd, 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, ρg. 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 ωs 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 ωs 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 average daily beam radiation Hb is simply computed from:

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

19. Sky temperature

Sky long-wave radiation is radiation originating from the sky at wavelengths greater than 3 μm. 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, Tsky, which is the temperature of an ideal blackbody emitting the same amount of radiation. Its value in °C is computed from sky radiation Lsky through:

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

where σ is the Stefan-Boltzmann constant (5.669x10-8 (W/m2)/K4). 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:

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

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

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

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:

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

To obtain a rough estimate of c over the month, the calculation procedure 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,

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

K_d is calculated from the monthly average clearness index $\overline{K_T}$ 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 $\overline{K_T}$):

$$K_d = \begin{cases} 0.99 & \text{for } K_T \le 0.17 \\ 1.188 - 2.272K_T + 9.473K_T^2 - 21.865K_T^3 + 14.648K_T^4 & \text{for } 0.17 < K_T < 0.75 \\ -0.54K_T + 0.632 & \text{for } 0.75 \le K_T < 0.80 \\ 0.2 & \text{for } K_T \ge 0.80 \end{cases} \qquad (14)$$

20. 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. In the second option, it is computed from minimum and maximum values.

21. Automatic calculation

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

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \qquad (15)$$

where T stands for soil temperature, t stands for time, α is the thermal diffusivity of soil (in m2/s), and z is the vertical distance. For a semi-infinite soil with a periodic fluctuation at the surface:

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

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:

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

where σ is a spatial scale defined by:

$$\sigma = \sqrt{\frac{2\alpha}{\omega}} \qquad (18)$$

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 $\Delta t = z/\sigma\omega$.

Presented calculation methodology assumes that cold water temperature is equal to soil temperature at an appropriate depth. The model takes $\alpha = 0.52x10^{-6}\ m^2/s$ (which corresponds 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:

$$\sigma = 2.28\ m \qquad (19)$$

$$\Delta T(z) = \Delta T(0) \times 0.42 \qquad (20)$$

$$\Delta t = 51\ days \sim 2\ months \qquad (21)$$

This theoretical methodology was tuned up in light of experimental. 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 calculation process. 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 compares measured and predicted water temperatures and indicate that this simplified method of cold water temperature calculation is satisfactory, at least for this particular example.

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

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

22. 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:

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

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

23. Estimated load calculation

Load calculation is necessary for the service hot water (with or without storage) calculation models. Hot water use estimates are provided for service hot water systems. 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:

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

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 used per week.

24. Solar Collectors

Solar collectors are described by their efficiency equations. Three types of collectors are considered in these calculations:

- 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.

25. Glazed or evacuated collectors

Glazed or evacuated collectors are described by the following equation:

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

where

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 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 defined. For both glazed and evacuated collectors, $F_R(\tau\alpha)$ 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 $F_R(\tau\alpha)$= 0.68 and $F_R U_L$ = 4.90 (W/m2)/ºC. These values correspond to test results for thermo dynamics collectors. Generic evacuated collectors are also provided with $F_R(\tau\alpha)$= 0.58 and $F_R U_L$ = 0.7 (W/m2)/ºC.

26. Unglazed collectors

Unglazed collectors are described by the following equation:

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

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

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

Where

L_{sky} is the longwave sky irradiance 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 manually specified. The wind speed incident upon the collector is set to 20% of the free stream air velocity. 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:

$$F_R\alpha = 0.85 - 0.04\,V \qquad (27)$$

$$F_R U_L = 11.56 + 4.37\,V \qquad (28)$$

These values were obtained by averaging the performance of several collectors.

27. 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 utilisability method, both of which were developed for glazed collectors. 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:

$$G_{eff} = G + \frac{\varepsilon}{\alpha} L \qquad (29)$$

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 equations involving the collector when an unglazed collector is used.

28. 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.

29. 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:

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

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 is increased to include piping and tank losses:

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

30.Losses due to snow and dirt

Snow and dirt impact on 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 expressed as a fraction of energy collected (this parameter is entered by the user).

31.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 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:

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

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

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 average ambient temperature, L is the monthly total heating load, 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 Figure 6. The ratio F_R'/F_R is a function of heat exchanger effectiveness ε:

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

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

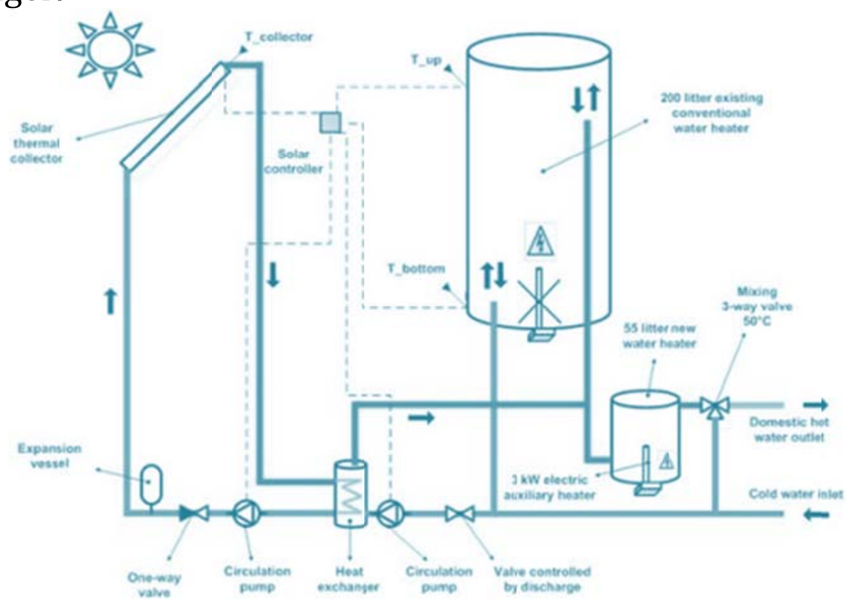

Figure 6. Diagram of a solar domestic hot water system

If there is no heat exchanger, F'_R is equal to F_R. If there is a heat exchanger, calculation method 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)/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 m2 s/kg. This value is computed from thermo dynamics 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 defined by:

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

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 Tm and for the minimum acceptable hot water temperature Tw, 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:

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

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:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215\,Y^3 \qquad (37)$$

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 used; if f is greater than 1, a value of 1 is used.

32. 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 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.

33. 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:

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

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 and monthly average daytime temperature T_a (assumed to be equal to the average temperature plus 5°C) through:

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

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

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

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 φ, 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:

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

where $\overline{H_T}$ 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:

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

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 average clearness index $\overline{K_T}$ and two variables: a geometric factor $\overline{R}/R_n$ and a dimensionless critical radiation level $\overline{X_c}$, as described hereafter.

34. Geometric factor $\overline{R}/R_n$

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

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

where $\overline{H_T}$ is calculated as explained 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 an average day of the month. This is expressed through the following equation:

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

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 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.

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

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

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

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

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

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

35.Dimensionless critical radiation level $\overline{X_c}$

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

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

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

36.Monthly average daily utilisability $\bar{\emptyset}$

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

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

with:

$$a = 2.943 - 9.271\bar{K}_T + 4.031\,\bar{K}_T^2 \tag{51}$$
$$b = -4.345 + 8.853\bar{K}_T - 3.602\,\bar{K}_T^2 \tag{51}$$
$$c = -0.170 - 0.306\bar{K}_T + 2.936\,\bar{K}_T^2 \tag{51}$$

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

37.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.

The energy requirements of the pool are calculated by comparing the pool's energy 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 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:

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

Where

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

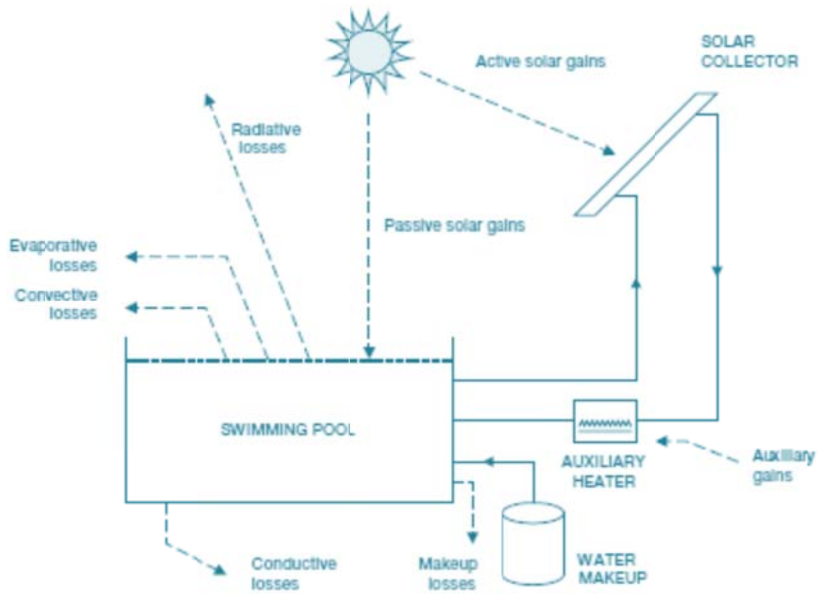

Figure 7. energy gains and losses in a swimming pool

38.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 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 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
- Sky temperature: computed from pool ambient temperature.

39. 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 at various locations 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 by a sinusoidal function:

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

where

V_h is the wind velocity at hour h, $\overline{V}$ 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:

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

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:

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

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.

40.Relative humidity

Evaporation from the 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 (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.

41.Passive solar gains

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

42.Passive solar gains without cover

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

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

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, $\overline{H}_b$ and $\overline{H}_d$ are the monthly average beam and diffuse radiation (equations 6 to 8). Shading coefficient 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 (Figure 8):

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

Where $n_{air} = 1$ and n_{water} are the indices of refraction of air and water:

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

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

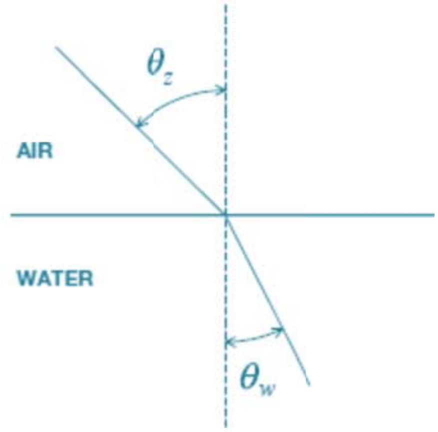

Figure 8. Snell's law

r_b can be computed with the help 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 made, 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 used with θ_z calculated 2.5 h from solar noon. Reflectivity to diffuse radiation is independent of sun position and is basically equal to the reflectivity calculated with an angle of incidence of 60º. Using the exact equation, a value of r_d=0.060 is found.

43.Passive solar gains with cover

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

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

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

44. 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:

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

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):

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

45. Evaporative losses

There are several methods in the literature to compute evaporative losses. Following equations is used proposed here:

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

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 coefficient, and $P_{v,sat}$ and $P_{v,amb}$ are the partial pressure of water vapour at saturation and for ambient conditions. The mass transfer coefficient the (in (W/m2)/Pa) is expressed as:

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

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

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

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

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.

46. Convective losses

Convective losses are estimated using the equation:

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

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 coefficient h_{con} is expressed as:

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

with the wind speed V expressed in m/s.

47. Radiative losses

Radiative losses to the ambient environment in the absence of pool blanket, (in

W) are expressed as:

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

where ε_w is the emittance of water in the infrared (0.96), σ is the Stefan-Boltzmann constant (5.669x10-8 (W/m2)/K4), T_p is the pool temperature and T_{sky} is the sky temperature. In the presence of a blanket, assuming 90% of the pool is covered, radiative losses become:

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

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. 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:

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

48. 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:

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

where ρ is the water density (1,000 kg/m3) and V_p is the pool volume. The pool volume is computed from the pool area assuming an average depth of 1.5 m:

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

The rate of energy 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)/ºC).

49. Conductive losses

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

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

50. Active solar gains

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

51. 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:

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

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:

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

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:

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

52.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):

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

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.

53.Pumping energy

Pumping energy 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 estimate of N_{coll} is obtained through the following method: if the collector was running without losses whenever there is sunshine, it would collect $A_c F_R(\overline{\tau\alpha})\overline{H_T}$. It actually collects $Q_{dld}(1 + f_{los})$ 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, $N_{daytime}$:

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

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.

54.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.

55.Summary

In this course, calculations methods for typical solar water heating project were shown. The tilted irradiance calculation method, 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 calculation method.