SOLAR HEATING OF SWIMMING POOLS

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ABSTRACT

An Excel macro-programing model of the thermal behaviour of open and enclosed swimming pools is run in seven different scenarios of increasing complexity. To secure a swimming season for the whole year, the use of a tent, a battery of collectors and auxiliary heat, to cope with winter, is advice. The tent can be removed or vented from November to March and must be tightly closed the rest of the year. An area of collectors equal to half the pool area will avoid excessive overheat and will assure the use of the pool in the morning during summer. The calculated yearly solar participation in energy consumption is 43% for a water temperature greater than 26ºC.

INTRODUCTION

The open swimming pool season in Uruguay extends from December to March, but even in this short period, some days are too chilly for use and the first hours in the morning are generally too cold to plunge. The use of conventional heaters is getting increasingly prohibitive due to energy cost. For this reason a national project is proposed to solar heat open swimming pools so the season can be widened from November to April and the whole day use can be assured (Hahne, et al, 1994). Also the best way to make a year round use of swimming pools is considered. Necessarily we have to go to an enclosed swimming pool with auxiliary heat, because of a rather cold winter.

Despite local singularities, the country is quite homogenous from a climatic point of view and the results obtained in any site can well be extended to all others.

The reference swimming pool site we chose, is located in Carmelo, over the Uruguay River (34º S, 58º 16' W), with a size of 25 m x 12.5 m, a volume of 633 m^3 and has an average attendance of 200 persons per day.

The radiation values (Duomarco, et al. 1979) on the horizontal plane are used to calculate the direct capture of solar energy by the swimming pool. The 45º tilt angle and an orientation due North, is chosen as the best, for an yearly use of our solar collectors and a good one for April and November, months to which we expect to extend the open pool swimming season.

THERMAL GAINS AND LOSSES OF OPEN POOLS

The thermal equilibrium, on a monthly basis, sets the energy input equal to the losses, when the temperature of the pool is maintained almost constant throughout the year (Govaer, et al 1981) (Szeicz, et al, 1983).

We adopt a temperature comfort range extending from 26ºC to 32ºC, according to usual practice and normalization of swimming pools (NIDE, 1979).

To reduce the heat necessary to maintain the comfort temperature, heat losses must be held low. Using pool covers during the night can hinder the evaporation and radiation losses. Inhibiting air movements over the surface can reduce the convection loss. The conduction loss to the ground is usually very small.

The **monthly balance equation** of the water in the pool is the following,

$$G - Q - Q_S - L_{SH} = \rho_{H2O} V_P c_P \Delta T_W \quad (1)$$

where ρ_{H2O}, is the water density, V_P is the pool volume, c_P is the specific heat of water and ΔT_W is the difference in pool temperature between the end and the beginning of the month. For a monthly period, this right hand side term is generally negligible or null when the pool temperature is constant.

The **monthly gain** by the collectors and the auxiliary energy supply is,

$$G = g_C A_C N + G_{AUX} \quad (2)$$

where g_C is the specific gain in the solar collectors, A_C is the collectors area, N are the days in the month and G_{AUX}. is the auxiliary heat.

The **monthly loss** through the pool surface is,

$$Q = (q_R + q_C + q_E - g_{SH}) A_P N \quad (3)$$

where A_p is the pool surface, q_R is the specific radiation loss, q_C is the specific convection loss, q_E is the specific evaporation loss and g_{SH} is the specific solar gain by the open pool (Howell et al. 1979, Root, 1983)

These specific values, $\mathbf{q_R}$, $\mathbf{q_C}$, $\mathbf{q_E}$, $\mathbf{g_{SH}}$, $\mathbf{g_C}$ are defined with the following mathematical expressions:

Radiation loss *(Stefan-Boltzmann equation with σ = 5.6697.10 $^{-8}$ W / m^2 K^4, ε = 0.9 and assuming Ta as sky temperature and Tw as pool temperature, both in K),*

$$q_R = \varepsilon\,\sigma\left(T_W^4 - T_a^4\right) \qquad (4)$$

The equations, q_C *and* q_E *are in Btu / (ft^2 day) ,* p_w*, and* p_a *are in psi and are based on: monthly temperature data in ºF and local wind speed in mph. (Howell et al. 1979, Root, 1983)*

Convection loss*.(v_W wind velocity)*

$$q_C = \left(24 + 7.2\,v_W\right)\left(T_W - T_a\right) \qquad (5)$$

Evaporation loss *(f_{off} is the pool uncovered day fraction).*

$$q_E = f_{off}\left(4800 + 1440\,v_W\right)\left(p_W - p_a\right) \qquad (6)$$

Water saturation pressure at Tw*.*

$$p_W = e^{\frac{\left(T_w - 100\right)}{34}} - 0.05 \qquad (7)$$

Partial pressure of water in air *with HR% relative humidity and Ta air temperature.*

$$p_a = \left(\frac{HR}{100}\right)\left\{e^{\frac{\left(T_a - 100\right)}{34}} - 0.05\right\} \qquad (8)$$

Direct solar energy gain by the pool *(0.8 surface absorptance, 0.75 cover transmittance, I_H is the sun radiation on a horizontal surface)*

$$g_{SH} = 0.8\left(f_{OFF} + \left(1 - f_{OFF}\right)0.75\right)I_H \qquad (9)$$

Flat plate collector efficiency*. ($F_R(\tau\alpha)$ = 0.74 and F_RU_L = 0.79 BTU / ft^{2}hF for a single glazed, flat plate, black chrome selective sueface) (I_T is the sun radiation on a 45º tilted plane due north)*

$$\eta_C = F_R\left(\tau\,\alpha\right) - F_R U_L\left(\frac{T_W - T_a}{I_T}\right) \qquad (10)$$

Solar energy gain by collectors

$$g_C = \eta_C\,I_T \qquad (11)$$

The **monthly conduction loss to the soil** is,

$$Q_S = A_L U_L N\left(T_W - T_a\right) \qquad (12)$$

where U_L = 0.8 W/m^2 ºC, A_L is the pool envelope surface in contact with the soil, T_W the temperature of the water and Ts is the soil temperature, which we assume to be equal to Ta at 1 m from the envelope.

The **monthly thermal load in hot water for showers** and other sanitary services $\mathbf{L_{SH}}$ is calculated on an average of 200 showers per day.

THERMAL GAINS AND LOSSES OF ENCLOSED POOLS

We now turn to the case where the formerly open pool is enclosed in a big tent to enable the pool to be used in the winter season. Water is now in thermal contact with air enclosed in the tent, which in turn is in contact with the interior surface of the tent. We assume that owing to the convective air currents the temperature in the tent is uniform (T_T).

The **monthly balance equation** of the water in the pool is very similar to (1), but a few changes have to be done,

$$G - Q' - Q_S - L_{SH} = \rho_{H2O}\,V_P\,c_P\,\Delta T_W \qquad (13)$$

In the **heat loss through the pool surface Q'**, the temperature in the tent (T_T) takes the place of the ambient temperature (Ta), the air is assumed to have a velocity, a hundredth the velocity in the meteorological station, an iterative calculation is made of the relative humidity (HR%), and no solar gain is allowed if an opaque tent is used.

A **new monthly balance equation** for the air in the tent has to be added to take into account the thermal equilibrium between the air enclosed, the water in the pool and the ambient air outside, as well as the influence of a fan coil heating the air by G_T ,

$$G_T + Q' - Q'' = \rho_{air}\,V_T\,c_{PAIR}\,\Delta T_T \qquad (14)$$

where ρ_{AIR} is the air density, V_T, is the tent volume, c_P, is the specific heat of air and ΔT_t is the difference in tent temperature between the end and the beginning of the month. For a monthly period, this second term is generally negligible or null when the tent temperature is constant.

A **further relation is to be established** adding up in G_+ the gains in the pool G and the gains in the fan coil G_T. In the case where the heat captured in the solar collectors G_{SC45} goes indistinctly to the pool or to the fan coil a new auxiliary heat must be defined G'_{AUX}, different from the one defined in (2).

$$G_+ = g_C A_C N + G'_{AUX} = G_T + G \qquad (15)$$

In the **heat transfer through the tent surface (Q'')**, we consider a **global loss and gain term (Q''_{RCC}),** (that adds up losses by convection, conduction, radiation and solar heat gains that strike the surface of the tent) and **two ventilation terms that take into account the sensible heat (Q''_S) in air and the latent heat (Q''_L) of water in air infiltrations** (Savioli, 1976).

$$Q''_S = \rho_{air}\,c_{pair} V_T\,r\,N\left(T_T - T_a\right) \qquad (16)$$

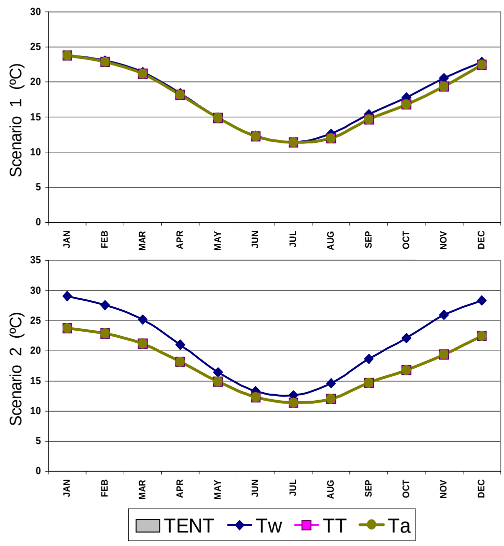
$$Q''_l = \frac{V_T\,r\,N\,l_{H2O}}{R_{gH2O}}\left(\frac{p_T}{\left(273 + T_T\right)} - \frac{p_a}{\left(273 + T_a\right)}\right) \qquad (17)$$

$$Q''_{RCC} = \frac{A_T\left(T_T - T_a - \dfrac{I_H\,(\alpha\tau)\,A_{TH}}{(h_{ra}+h_a)\,A_T}\right)}{\left[\dfrac{1}{(h_{ra}+h_a)} + \dfrac{e}{\lambda} + \dfrac{1}{(h_{rT}+h_T)}\right]} \quad (18)$$

where, V_T is the tent volume (m^3), r is the tent air volume renewable per day, N is the number of days in the month, T_T is the tent temperature (ºC), Ta is the ambient temperature outside (ºC), l_{H2O} is the water latent heat, R_{gH2O} is the gas constant of water vapor, p_T is the partial pressure of water in air in the tent (hPa), p_a is the partial pressure of water in the ambient air (hPa), A_T is the tent area (m^2), A_{TH} is the tent horizontal flat roof area (m^2), I_H is the solar radiation over the flat roof for the tent, $(\alpha\tau)$ is the radiation absorption –transmission of the tent fabric, e is its thickness, λ is its conductivity,
hra and ha are the linear radiation and convection coefficient in the exterior surface,
hrt and ht are the linear radiation and convection coefficient in the interior surface.

SCENARIOS

An iteration solution of the equations just mentioned was made with Excel macro programming. Several scenarios were studied changing parameters and a final selection was made. The figures 1, 2 and 3, shows the yearly profile of the ambient temperature (Ta), the water temperature (Tw) and the tent temperature (T_t) in the different scenarios studied.



.Figure 1 Scenarios ONE and TWO

Scenario one. The actual situation of the open pool with no solar collectors, with no auxiliary heat, with no cover during the night and with not enough shelter, represented by an air velocity half the value at the meteorological station, is shown in figure 1.

The water temperature T_w is too low for a normal swimming season (less or equal to 26ºC).

Scenario two. Our first advice is to cover the pool at night and to shelter it from winds. The improvements are shown in figure 1 where a swimming season from November to March is slightly assured. The air velocity over the pool is set equal to one tenth the value at the meteorological station and a rule is made about covering the pool during 16 hours a day.

Scenario three. Let us add a solar collector battery with an area A_c equal to 50% the area of the pool A_p , other parameters left the same as in Scenario TWO. The results, in figure 2, show a swimming season extending from October to April quite well assured, but the temperature T_w exceeds the 30ºC limit in summer which may be too much, for a training swimming pool.

Scenario four. The overheating problem can be dealt with, uncovering the pool from December to February. In this way the swimming season is assured from October to April as shown in figure 2 with a reasonable $T_{w.}$

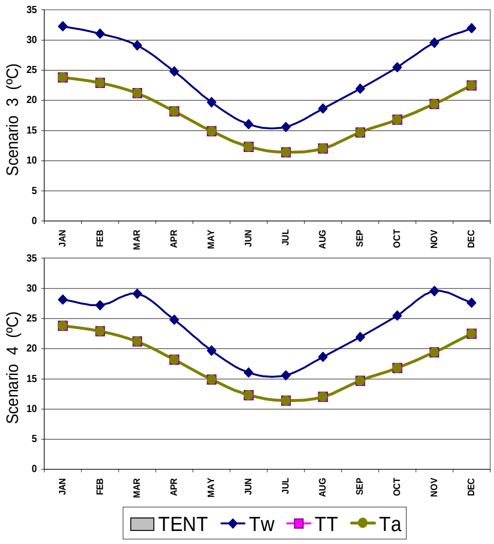


Figure 2 Scenarios THREE and FOUR

Scenario five. When entering in May the ambient temperature gets too low to even approach to an open pool and a hybrid solution imposes. The pool will be uncovered from November to March and enclosed into a tent the rest of the year. The temperature inside the tent (T_T) remains to be uncomfortable, as shown in figure 3.

Scenario six. The only solution to cope with winter is to use some kind of auxiliary heat. We consider the case in which the heat is set on whenever the water temperature is less than 26 ºC and is set off when the water temperature is greater or equal to 26ºC. The tent temperature gets a value in between the outside temperature (T_a) and the water temperature (T_w.). As a consequence, evaporation is high and an unpleasant mist appears inside the tent.

Scenario seven. According to the NIDE standards, in an enclosed pool, the air temperature should be at least 2 ºC greater than the pool temperature. In this way the fog formation is avoided.

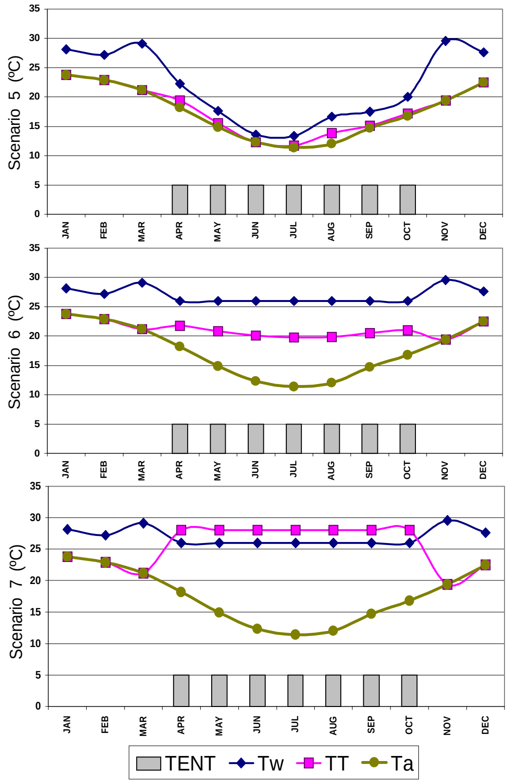


Figure 3 Scenarios FIVE, SIX and SEVEN

COLLECTORS AREA SELECTION CRITERIA

Method 1. Physical worth noticing features. We ran the model for different areas of collectors (Ac), with the parameters of scenario seven and setting the reference minimum pool temperature in three different values 26 ºC, 28 ºC and 30 ºC. The average annual water temperature fluctuations ($T_{wmax} – T_{wmin}$) are shown in figure 4, as function of collector area and for each of the three control reference temperatures.

Several interesting features can be extracted from this figure 4:

a) An excessive collector area conducts to an unnecessary summer overheat.

b) Taking into account that 30 ºC is not appropriate for a training swimming pool, we may rule out collector surfaces that produce any overheat on top of this value. This limit is equal to half the pool area and we will call it **first critical surface, Ac*** (Ac* = 50% Ap = 156.25 m^2).

c) For the reference control temperatures (26ºC, 28ºC, 30ºC), with collector areas equal to (500 m^2, 625 m^2, 750 m^2) that represents (160 %, 200%, 240%) of the pool area respectively, any additional increment in collector surface is used to increase the lower water temperature far more than its reference value. We will call them **second critical surfaces, Ac**.**

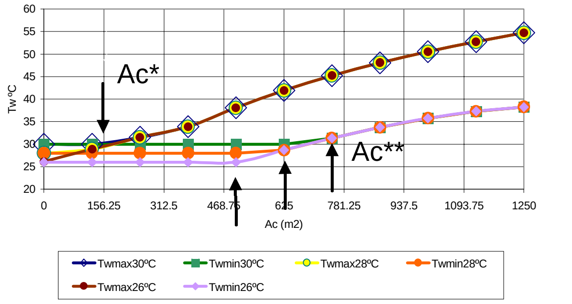


Figure 4 The difference (T_{wmax} - T_{wmin}) represents the mean maximum water temperature fluctuation as function of collector area (A_C) and for each reference temperature (26ºC, 28ºC and 30ºC) during the year The significance of the singular points in the Twmin curves in 500 m^2, 625 m^2 and 750 m^2 is discussed in the text.

The energy gained by the system with solar energy (G_{SC}) and with other auxiliary forms (G'_{AUX}), is shown in figure 5, as function of collector area and for a 26ºC reference temperature. The auxiliary gain G_{AUX} is represented when the fan coil is ON and when it is OFF.

When the fan coil is OFF, there is a first surface for which the auxiliary heat G_{AUX} is null. We will call this surface the **third critical surface Ac***.** It is equal to Ac**, because G_{AUX} is not requested any more, only when the water temperature T_w is higher than the reference value.

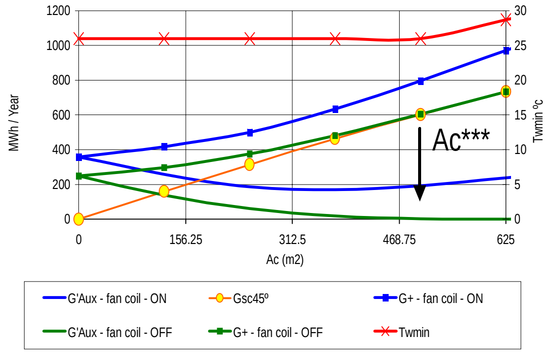


Figure 5 Energy gained by the system with solar energy (G_{SC}) and with other auxiliary forms (G_{AUX}), as function of collector area and for a 26ºC reference temperature. The auxiliary gain G_{AUX} is shown when the fan coil is ON and when it is OFF.

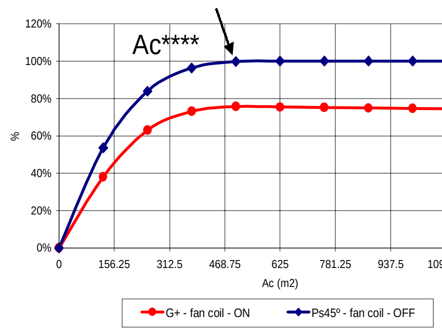


Figure 6 Annual load fractions supplied by solar energy as function of collector area and for a 26 ºC reference temperature when the fan coil is ON and when it is OFF.

The annual solar energy participation fraction is defined as follows,

$$P_S = \frac{G_{SC45}}{G_+} = \frac{G_{SC45}}{G_{SC45} + G'_{AUX}} \qquad (19)$$

and it is shown in figure 6, for a reference temperature of 26 ºC, in the case the fan coil is ON and in the case it is OFF.

When the fan coil is OFF there is a first surface for which the solar participation is 100%. We will call this surface the **fourth critical surface A****.** For this value G+ = G_{SC45} , G_{AUX} = 0 and so A****=A*** = A**.

Let us consider now the economics of the swimming pool that ultimately decides the most appropriate heating system (Ruegg et al, 1981).

In Table 1 the key assumptions of a sizing example are reunited.

TABLE 1 ENERGY TYPE	U$S / kWh	discount rate	escalate rate
firewood	0.01527	7.5%	7.5%
heat pump - cop = 4	0.01419	7.5%	7.5%
fueloil	0.04124	7.5%	7.5%
naturalgas	0.04308	7.5%	7.5%
electricity	0.05676	7.5%	7.5%
COLLECTOR TYPE & COST			
FR(UL) - BTU / (ft^2 h F)	0.79		
FR(τα)	0.74		
$(\tau\alpha)/(\tau\alpha)_n$	0.89		
FR'/FR	0.9		
surface - m^2 / collector	2		
cost - U$S / collector	$357		
fixed cost of solar system - U$S	$6,000		
solar energy system useful life - Y	25		
operation & maintenance - % initial investment	1%		
COLLECTOR FINANCING			
periods - Y	5		
annual interest	7.5%		
down payment	10.0%		

Method 2. Present value of life-cycle costs method. Following is the formula for calculating , in present value dollars, the total life-cycle costs associated with owning and operating any energy sustem.

$$PV = I + V_n a^n + \sum_{j=1}^{n} a^j M_j + \sum_{k=1}^{H} \sum_{j=1}^{n} P_k Q_k b^j \qquad (20)$$

where,

PV is the total present value life-cycle costs associated to a given energy system, I is the total initial costs associated with the energy system, V_n residual or salvage value at year n, last year of the evaluation, $a^j = (1+d)^{-j}$ the single present value formula for the j designated year and d discount rate, M_j maintenance, repair and replacement costs in year j., P_k the initial price of the kth type of conventional energy for energy types k= 1 to H, Q_k the quantity required of the kth type of conventional energy, $b_k^j = (1 + e_k)^j (1 + d)^{-j}$ a formula for finding the present value of an amount in the jth year escalated at a rate e_k, where k denotes the kth type of conventional energy, and discounted at a rate d.

In figure 7 Present Value costs of solar systems with different back up energy systems, heat pump, electricity, fuel oil, natural gas and firewood are plotted against the collectors area

Electricity, fueloil, naturalgas, have a equilibrium PV minimum in the collector area Ac = 312.5 m^2 equal to 100% the pool area, which we call **fifth critical surface Ac*****. Firewood and heatpump shifts its minimum to the y axis setting the collector area to 0.with no economical advantage whatsoever for the hybrid solar system.

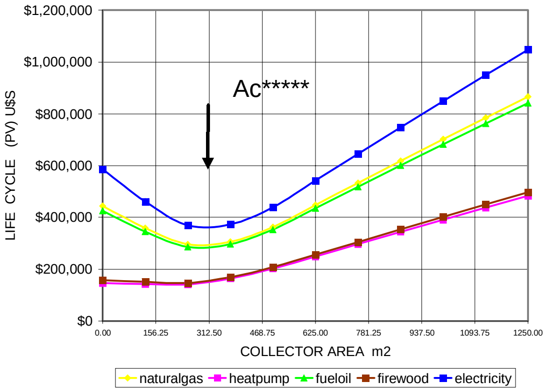


Figure 7 Present value of life- cycle costs for five solar systems with different backup energy systems, heat pump, electricity, fuel oil, natural gas and firewood as function of collector area, for a 26 ºC reference temperature and the Table 1 key assumptions.

Method 3. Present value of net savings method. A formula derived from (20) will compare a hybrid solar - conventional system with a purely conventional system.

$$PNS = - \Delta PV =$$

$$- (\text{solar \& conventional} - \text{conventional}) \quad (21)$$

In figure 8 the present value life cycle savings of solar systems with different back up energy systems, heat pump, electricity, fuel oil, natural gas and firewood are plotted against the collectors area. Electricity, fueloil, naturalgas, have a maximum ΔPV in the collector area Ac = 312.5 m^2 equal to 100% the pool area, which coincides with the **fifth critical surface Ac***** already defined, while firewood and heatpump shows no net saving.

The present value of life-cycle costs method and the present value of net savings method are essentially equivalent and are useful for an optimal sizing the collector area with an economic background.

The application of these methods has discouraged a solar hybrid solution, when the conventional heating is done already, with firewood or with a heatpump or when a first heating system has to be chosen and surely one of these would be elected.

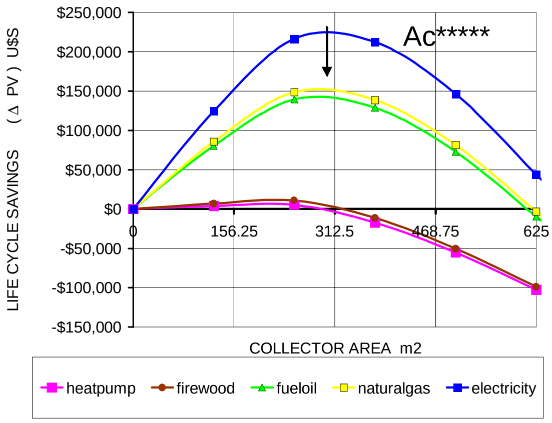


Figure 8 Present value of life- cycle savings for five solar systems with different backup energy systems, heat pump, electricity, fuel oil, natural gas and firewood as function of collector area, for a 26 ºC reference temperature and the Table 1 key assumptions.

Method 4. Payback method. This evaluation method measures the elapsed time between the point of a initial investment and the point at which accumulated savings are sufficient to offset the initial investment.

In Figure 9 the present value of net savings (PNS) is plotted as function of a varable life expectancy (n), for a 156.25 m^2 (50% pool area) collector surface and for Table 1 key assumptions. The intersection with the 0 life cycle saving axis are the payback periods that are reunited in Table 2.

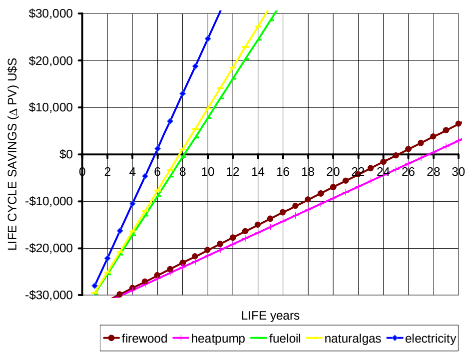


Figure 9 Present value life cycle savings for five solar systems with different backup energy systems, heat pump, electricity, fuel oil, natural gas and firewood, for a 26 ºC reference temperature, a collector surface equal to 156.25 m^2 and the Table 1 key assumptions, as funcion of a variable life cycle.The payback period is obtained when the life cycle savings is null.

Method 5. Internal rate of return method. This method calculates the rate of return an investment is expected to yield. In Figure 10 the present value of net savings (PNS) is plotted as function of a variable discount rate, for a 156.25 m^2 (50% pool area) collector surface and for Table 1 key assumptions. The intersection with the 0 life cycle saving axis are the internal rates of return, and are reunited in Table 2.

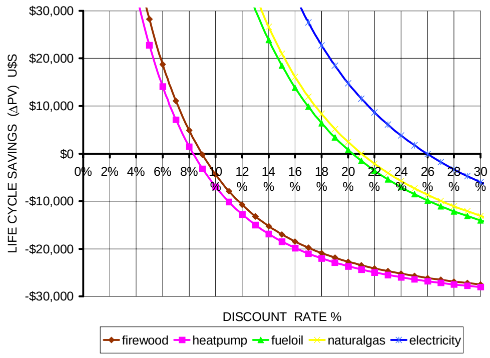


Figure 10 Present value life cycle savings for five solar systems with different backup energy systems, heat pump, electricity, fuel oil, natural gas and firewood, for a 26 ºC reference temperature, for a collector surface equal to156.25 m^2 and the Table 1 key assumptions, as funcion of the market discount rate. The return discount rate is obtained when the life cycle savings is null.

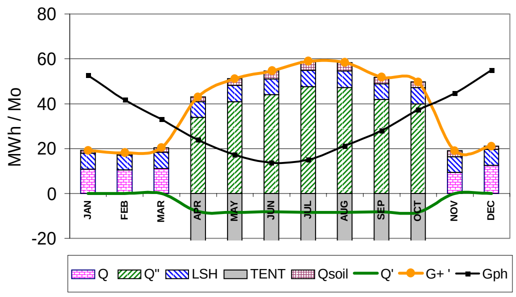


Figure 11 Monthly thermal losses of the system; Q summer loss by the pool surface, Q' negative winter loss (gain) by the pool surface, Q'' loss by the tent to the ambient, Qsoil loss to the soil through the envelope surface of the pool, Lsh load of the showers, Gph solar gain by a horizontal surface equal to the pool area, G+ total gain equal to all losses

Recommended application of the five methods.

The method 1 determines two thermal situations to be taken into account; a) the overheat problem in summer, which can be handled with a collector area A* = 156.25 m^2 and b) the saturation of the solar participation with an increasing collector area, which is attained for A** = (500 m^2, 625 m^2, 750 m^2), for Tw = (26 ºC, 28 ºC, 30 ºC) respectively.

The methods 2 and 3 are equivalent economical tests, useful for determining the optimal sizes. They show the impact of changes in investment in the life time costs and savings. The optimal value obtained is A***** = 312.5 m^2 .

The method 4 answers the doubts that may rise about the expected life or resale value of the major components of the investment, the results are in table 2.

The method 5 shares the advantage with methods 2 and 3, of providing a comprehensive evaluation of the investment in solar energy. A unique characteristic of this method, which might sometimes be an advantage, is the lack of necessity to specify the discount rate. However it is necessary to have an estimate of the minimally attractive rate of return against which the calculated internal rate of return can be compared to decide the desirability of the investment.

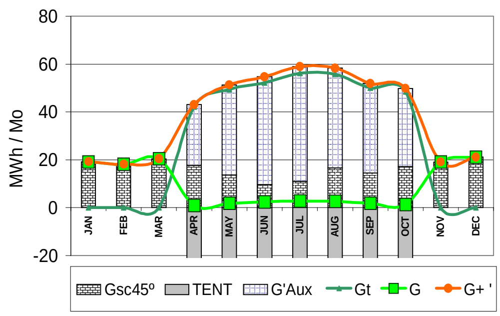


Figure 12 Monthly thermal gains of the system; Gsc45 heat gain from the solar collectors, Gt heat gain from the fan coil inside the tent, G heat gains by the water in the pool, G'aux heat gain from an auxiliary source, G+ total gain.

Table2	internal rate of return (%) Ac= 156.25 m^2 = 50 % Ap	payback (Y) Ac= 156.25 m^2 = 50 % Ap	maximum ΔPV	minimum PV	optimum surface (m^2)
firewood	8.95%	25.25	$10,643	$146,929	250
heatpump	8.31%	27.68	$5,259	$141,124	250
fueloil	20.33%	8.15	$139,534	$285,911	312.5
naturalgas	21.00%	7.78	$148,645	$295,736	312.5
electricity	25.93%	5.80	$216,562	$368,969	312.5

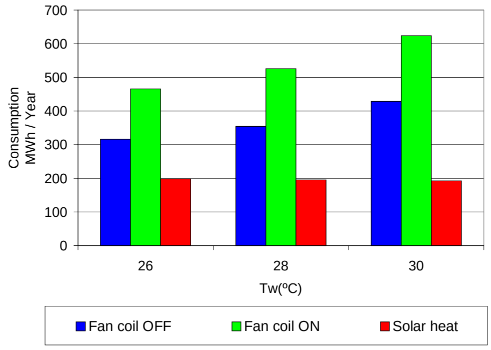


Figure 13 Energy consumptions with fan coil ON and OFF for three reference temperatures 26ºC, 28ºC and 30ºC and a collector area equal to 156.25 m^2.

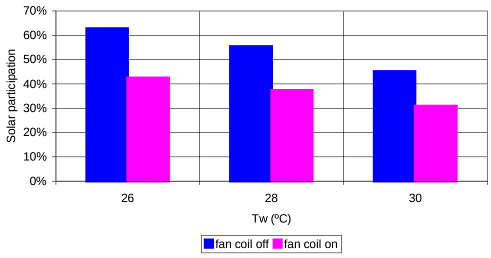


Figure 14 Solar energy participation in the total energy load with fan coil ON and OFF for three reference temperatures 26ºC, 28ºC and 30ºC and a collector area equal to 156.25 m^2

CONCLUSIONS

The most promising scenario, for a round year use of the pool, is the following:

1. A tight tent will be installed on top of the swimming pool from April to October and will be removed or vented the rest of the year.
2. During the night a cover will be used over the surface of the pool.
3. The pool will be sheltered from winds.
4. To maintain a constant temperature of comfort (Tw = 26ºC) through out the winter, an auxiliary conventional heat unit must be used.
5. Taking into account that the reference swimming pool has already a fuel oil boiler and giving priority to low temperature levels, we finally selected a collector area equal to half the pool area, Ac=156.25m^2
6. Monthly losses are shown in figure 11.
7. Monthly gains are shown in figure12.
8. The total auxiliary energy and solar energy requested are shown in figure 13.
9. The solar participation is shown in figure 14.
10. The internal rate of return of the solar fuel oil hybrid system compared with the actual fuel oil system is 20 %.
11. The payback period is 8 years.
12. The resulting maximum calculated temperature of summer (Tw = 30ºC) is acceptable for a training swimming pool.
13. No significant overheat problem is expected.
14. An appropriate use of covers may help to boost up early morning temperatures in summer when no auxiliary heat is to be used.

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