# ENERGY PAYBACK TIME AS AN OPTIMIZATION PARAMETER FOR SWIMMING POOL SOLAR SYSTEMS

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## 1. Introduction

This article deals with the calculation of energy payback time which is used as a parameter for the optimization of solar systems. The main goal is to calculate the energy payback time which results from the embodied energy of all system components, energy for the operation of circulation pumps per year and utilized solar energy in the building. As a consequence an optimization graph shows the lowest energy payback time for the input parameter. The calculations of energy amount are done hourly which ensures sufficiently detailed results.

The second part of the article presents an example of the optimization for a 20 year old swimming pool which is located in the Czech Republic near Prague. The pool is operated daily, mainly for school children, therefore the energy consumption is very high during the whole year. This example demonstrates the specific contribution of the energy payback time evaluation in the terms of sustainable development.

## 2. Assessment of solar systems

Nowadays, the most widespread method for building (or system) evaluation is the life cycle assessment (LCA). This methodology deals with the system over the whole life cycle from production of all components to recycling at the end of lifetime. The assessment using this methodology is very valuable due to the complexity. However, into this evaluation enters a wide range of parameters which are very often unknown.

There is the whole series of examples that can change the initial assumptions. The most questionable part of this evaluation in case of solar thermal systems for buildings is the certainty that the system will be operated during the whole life-cycle. We do not know either how the energy demands of the assessed building will change over the lifetime. Perhaps the most likely is the change in operation of the building - instead of the originally designed building for four persons a building only for two will be in place. The payback of the system will greatly increase. Similarly, a different operation temperature in the building may change the outcome. Another example is the destruction of the system before the end of lifetime which can occur for example due to a natural disaster. If the situation changes around the building in terms of shading (grown trees or new buildings) there will be again a reduction of energy gains.

### *2.1. Energy payback assessment*

The energy payback time can be a simple way to evaluate the overall effectiveness of solar systems. The energy payback time is equal to the duration when it is necessary to operate the solar system until the building utilized the same amount of solar energy which was inserted into the production of all system components. Whereas the payback period for the well designed systems is several years, we can assume with a high probability whether the system will be energy efficient.

## 3. Description of calculation tool

This paragraph deals with the description of a new calculation tool which is created for the evaluation of the energy payback for solar thermal systems. The main goal of this tool is to calculate the payback time of embodied energy and afterwards use this parameter to optimize the system of solar collectors. The calculation tool is processed in the program MS Excel using VBA. The calculation procedure consists of several parts: the calculation of incident solar energy, the energy from solar collectors, the estimation of the energy in a storage tank, the energy for the operation of pumps and controller, the calculation of embodied energy in all components of the solar thermal system. Then the embodied energy payback time is figured out and finally the optimization of different parameters in terms of energy payback is done. Calculations are done hourly for every day during the whole year. The whole procedure is based on formulas by U. Eicker (2003).

### *3.1. Incident solar energy*

Firstly it is necessary to estimate the hourly incident energy on the tilted surface $H_t$ (J m$^{-2}$) and then the usable energy gains from solar collectors. The incident energy is calculated from the direct normal irradiation $H_{bn}$ (J m$^{-2}$) and the total diffuse irradiation $H_{dh}$ (J m$^{-2}$) which consists of the sky and ground reflected radiation incident upon a horizontal surface. In this case an isotropic diffuse model is used. The data in the calculation tool (a typical metrological year) come from the METEONORM database for Czech localities (Prague, Ostrava, Hradec Kralove, Churanov, Kucharovice). The incident energy depends on the azimuth and tilt of the collector surface. The fig. 1 shows the incident energy for the tilted surface with orientation to the south which is located in Prague.

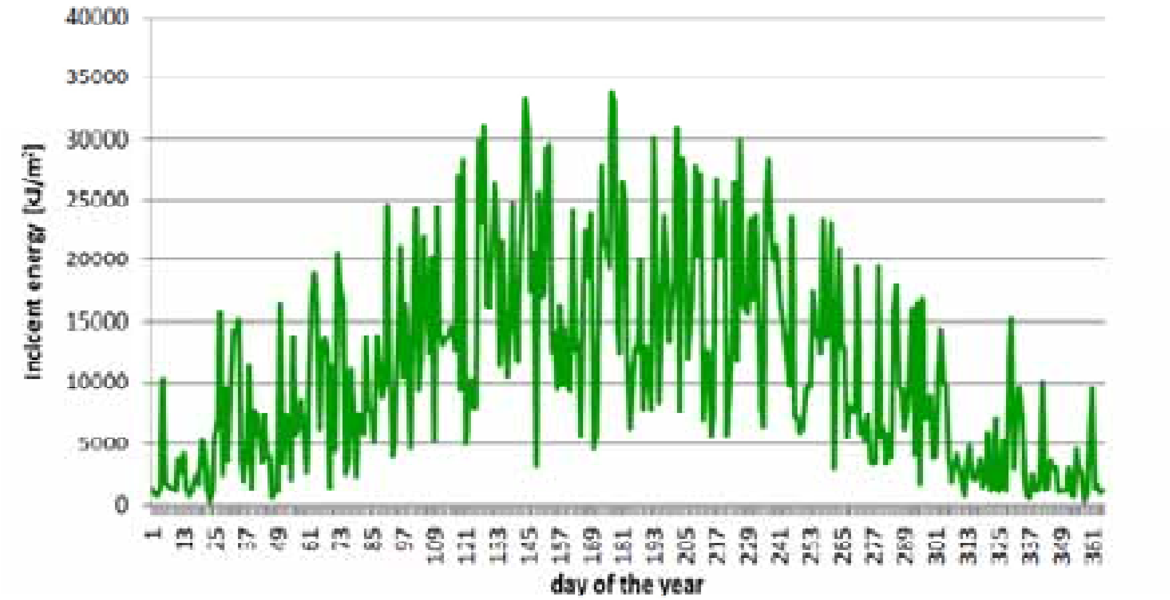

**Fig. 1 The incident solar energy on the tilted surface with a south orientation during the year**

### *3.2. Energy from solar collectors*

The total energy from the solar collectors $E_S$ (J) is calculated from the incident energy $H_t$ on a tilted surface, the efficiency of collectors $\eta_k$ (-), the incidence angle modifier $K_\theta$ (-) and the aperture area of the solar collector $A_a$ (m$^2$) as shown in following formulas:

$$E_s = K_\theta \, \eta_k \, H_t \, A_a \qquad \text{(eq. 1)}$$

$$\eta_k = \eta_0 - a_1 \frac{t_m - t_e}{G_t} - a_2 \left( \frac{t_m - t_e}{G_t} \right)^2 \qquad \text{(eq. 2)}$$

$$t_m = \frac{t_{k1} + t_{k2}}{2} \qquad \text{(eq. 3)}$$

where $t_e$ (°C) is the outside air temperature and $t_m$ (°C) represents the mean temperature of the fluid in the collector. $\eta_0$ (-), $a_1$ (W m$^{-2}$ K$^{-1}$), $a_2$ (W m$^{-2}$ K$^{-2}$) and incidence angle modifier $K_\theta$ are characteristic values which differs according to the type of collector. $G_t$ (W m$^{-2}$) is the mean global irradiance on solar collector. The mean temperature of the fluid is dependent on the temperature in the storage tank which depends on the total energy from the solar collectors; therefore there is an iteration process in the calculation tool.

### 3.3. Energy in a storage tank

The next part is based on charging and recharging of the storage tank and results in the total amount of energy which can be substituted by the solar collectors $E_{s,year}$ (J). The heat loss of the tank depends on the actual temperature and therefore the temperature in the tank is the main parameter for these calculations. The temperature differences are estimated from the energy amount from the solar gains $E_S$ (J), the heat losses of the storage tank $E_L$ (J) and the hourly energy demands of the building $E_{BD}$ (J). The difference of temperature in the tank is calculated hourly by following the formula:

$$\Delta T_1 = \frac{E_S - E_{BD} - E_L}{V_T\, c\, \rho} \qquad \text{(eq. 4)}$$

where $V_T$ ($m^3$) is the volume of the tank, $c$ (J $kg^{-1}$ $K^{-1}$) and $\rho$ (kg $m^{-3}$) represent the heat capacity and density of water or another liquid fluid. Hourly heat losses of the storage tank are estimated as follows:

$$E_L = S\, U\, (T_0 - 20\ °C) \qquad \text{(eq. 5)}$$

$T_0$ (°C) is the initial temperature in the storage tank, it is equal to the final temperature in the previous hour $T_0 = T_1$. $S$ ($m^2$) is the surface of the tank. $U$ (W $m^{-2}K^{-1}$) is the overall heat transfer coefficient of the tank surface.

If the temperature in the tank is higher than 90 °C then $T_1$ = 90 °C. If the temperature in the tank is lower than 50 °C then the secondary heat source starts to prepare hot water and in this case $T_1$ = 55 °C. At this point it is necessary to estimate the amount of energy from secondary heat source:

$$E_2 = V_T\, \rho\, c\, (55\ °C - T_1) \qquad \text{(eq. 6)}$$

Finally the daily amount of energy which can be substituted by solar collectors is:

$$E_{s,year} = \Sigma E_{BD} - \Sigma E_2 \qquad \text{(eq. 7)}$$

### 3.4. Calculation of energy payback

The payback time of energy which was used for the production of all components of the solar collector system (the embodied energy) can be evaluated by this formula:

$$n = \left( \frac{E_{s,year} - E_{o,year}}{E_{em}} \right) \qquad \text{(eq. 8)}$$

where $E_{o,year}$ (J) is the operation energy (the consumption of pumps and controller), $E_{em}$ is embodied energy of the whole system (the most significant parts being collectors, holders of collectors, storage tank and piping). Values used in the tool are derived from the data published by E. Streicher et al. (2004) and consist of the energy necessary for the production of the system components at all phases, including the extraction, mining of raw materials, semi-manufactured products and the production process itself.

### *3.5. Scheme of calculation process*

The previous calculation procedure is the basis of the calculation tool. The scheme of the procedure is shown in fig. 2. Input parameters for calculation are shown in tab. 1.

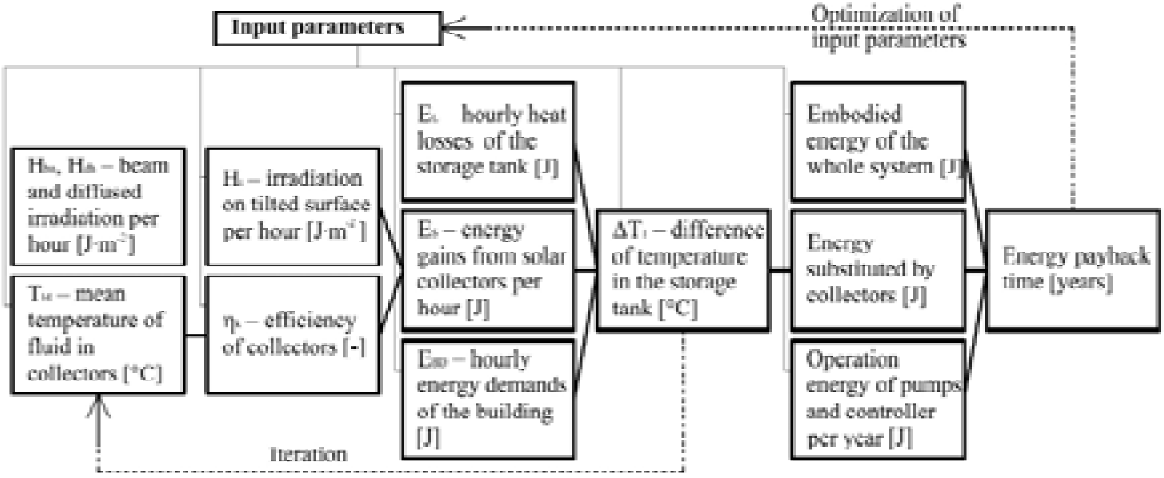

**Fig. 2: Calculation tool scheme**

**Tab. 1 Input parameters**

| **Input parameters:** | | | | |
|---|---|---|---|---|
| **LOCATION AND CLIMATE CONDITIONS** | **SOLAR COLLECTORS** | **STORAGE TANK** | **ENERGY DEMANDS OF THE BUILDING** | **OPERATION ENERGY** |
| Locality in the Czech Republic | Area | Volume of the tank | Space heating | Type of pump |
| | Tilt | Insulation of the tank | Hot water consumption | Pipe length |
| | Type of collector | Regulations temperature | Swimming pool water heating | Pipe dimension |
| | Azimute angle | Pipe insulation | | Type of fluid |

## 4. Optimization of the swimming pool solar system

As an example of the solar thermal system optimization an old swimming pool which is located in the Czech Republic near Prague have been chosen. The pool is operated daily mainly for school children, therefore the energy consumption is very high during the whole year. The heat source is a gas boiler which ensures the energy supply for the heating system, hot water preparation and swimming pool water heating. The boiler is considered as the secondary heat source, in the analysis with thermo solar system, in the case of low energy supply from solar collectors.

The measurement of the minute flow rate and the temperature difference of the swimming pool water was carried out during April 2011. The measured values together with the daily gas consumption lead to the determination of monthly consumption as shown in fig. 3.

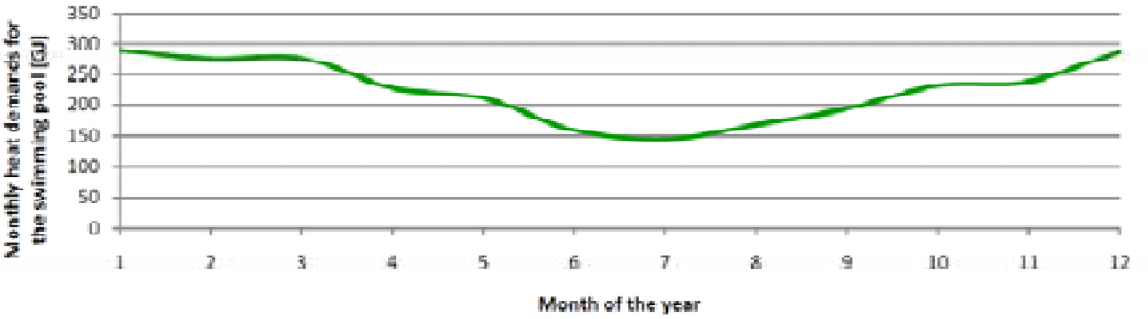

**Fig. 3: Swimming pool heat demands**

The volume of a new storage tank is designed in the tool according to the energy demands of the building. It is assumed that the storage tank can contain energy which is equal to 1.5 – 2 times of the daily consumption during the summer period. The input parameters of the collector for this analysis are in tab. 2. The detailed determination of embodied energy of the flat plate collector is shown in tab. 3 and the other components of the solar system are in tab. 4. The operation energy for the pumps and the controller is in the calculation tool dependent on the collector area. It is estimated that the pumps are approximately operated 1500 h per year with the power of 8 W per square meter of the collector and the controller is operated the whole year (8760 h) with a power of 2 W $m^{-2}$.

**Tab. 2: The flat plate collector characteristics**

| **Flat plate solar collector with black chrome coating** | | | | | |
|---|---|---|---|---|---|
| Height | 2 | m | $\eta_0$ | 0.778 | - |
| Width | 1 | m | $a_1$ | 4.207 | W $m^{-2}$ $K^{-1}$ |
| Thickness | 0.096 | m | $a_2$ | 0.024 | W $m^{-2}$ $K^{-2}$ |
| Aperture area | 1.87 | $m^2$ | Recommended flow rate | 0.017 – 0.033 | l $s^{-1}$ |
| Absorber area | 1.74 | $m^2$ | Maximum working temperature | 120 | °C |
| Weight without fluid | 37 | kg | Stagnation temperature | 139.9 | °C |
| Recommended fluid | propylene glycol | | | | |

**Tab. 3: Embodied energy of the flate plate collector with a supporting frame**

| COLLECTOR | Material | Unit | Quantity | [MJ/unit] | [MJ] |
|---|---|---|---|---|---|
| Absorber | copper | [kg] | 5 | 97 | 515 |
| | galvanic coating (black chrome) | [m²] | 1.74 | 45 | 77 |
| Casing | aluminium | [kg] | 7 | 152 | 1 011 |
| Cover | glass | [kg] | 15 | 13 | 204 |
| | glass hardening | [m²] | 1.87 | 20 | 37 |
| Insulation | mineral wool | [kg] | 1.67 | 18 | 30 |
| | polyurethane | [kg] | 2 | 100 | 167 |
| | silicone | [kg] | 0.33 | 101 | 34 |
| | | | | **TOTAL COLLECTOR** | **2 076** |
| **SUPPORTING FRAME** | stainless steel | [kg] | 2 | 97 | 230 |
| | aluminium | [kg] | 3.39 | 152 | 514 |
| | | | | **TOTAL FRAME** | **745** |

**Tab. 4: Embodied energy of other components of the system**

| | pcs. | MJ / unit | MJ |
|---:|---:|---:|---:|
| Storage tank 5000 l | 4 | 42483 | 169 932 |
| Tank´s insulation | 1 | 535 | 535 |
| Expansion tank | 1 | 18914 | 18 914 |
| Exchanger | 1 | 541 | 541 |
| Solar station | 1 | 444 | 444 |
| Piping Cu | 30 | 58 | 1740 |
| Piping insulation | 30 | 3 | 90 |
| Expansion tank for solar circuit | 1 | 18914 | 18914 |
| **Total** | | | **211 109** |

### *4.1. Results*

After the calculation of the energy payback time of the system it is possible to make an optimization of different parameters (area, tilt, different types of collectors and orientation of surface). In fig. 4 there is an analysis of a different angle of tilt for the swimming pool. It is possible to see the optimal point where the energy payback time is the lowest.

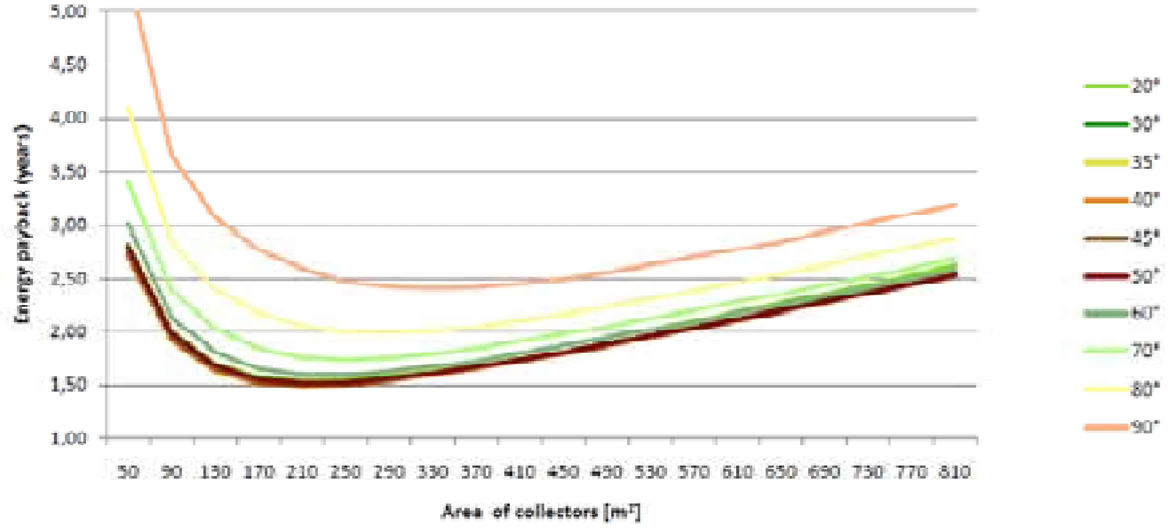

**Fig. 4: Payback time of embodied energy**

## 5. CONCLUSION

The main task of this article was to calculate the return time of embodied energy and show that this parameter can be easily used for the optimization of the solar system or for the consideration of which solution is better from the global point of view. The results enable the comparison of different systems in terms of the lowest energy payback time. This version of the calculation tool already enables to automatically make an optimization graph where the y-axe is the energy payback and x-axe is one of the input parameters, e.g. the collector area.

## 6. Acknowledgement

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## 7. References

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