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Submerged PV Solar Panel for Swimming Pools: SP3

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Abstract

The possibility to use photovoltaic (PV) modules submerged in water or simply covered by a water veil suggest the possibility to use this renewable energy source (RES) integrated with swimming pools or with decorative pools and fountains. SP3 solution (Submerged PV Solar Panel for Swimming Pools) is discussed for underflow pools as well as for pools with skimmer. The extension of this concept to the possibility to store solar radiation for heating the water of the pool is explored using the results of experimentation already done for hybrid photovoltaic/thermal (PV/T) modules. Simulation results for Mediterranean latitudes are discussed.

Peer-review under responsibility of KES International.

Keywords: Submerged PV Modules; Swimming Pool; Thermal electric hybrid systems

1. Introduction

Within the renewable energy sources, there are many possibilities to exploit water as an energy vector, both freshwater (hydroelectric) and seawater (waves and tides, now under rapid techno-economic development). These sources of energy can provide a considerable contribution to satisfy the electricity demand. There is another renewable source, the solar photovoltaic (PV), that is growing up very rapidly in terms of installed power and produced energy, and it is forecast to be the main source of energy at level of distributed generation (small and medium power plants [1]).

The use of PV systems in a water context can create a positive synergy increasing the cost effectiveness of such systems (e.g. reduction of thermal drift), satisfying the local demand for energy (distributed generation) and creating

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positive effects on water (e.g. limiting evaporation and algae bloom problem). Of course, PV systems do not use the water as energy vector (aside from photovoltaic/thermal, PV/T, systems [2]), but they can exploit the water effectively as operating ambient. In this context, they can be classified according to different criteria, such as:

- position in relation to the water surface: i.e. over (floating system) or under (submerged);
- type of water: fresh (lake, river) or salty water (sea water and off-shore PV);
- type of module: rigid or flexible.

Submerged PV plants are suggested as a solution of minimal environmental impact, as they avoid or reduce the cleaning problem and increase efficiency owing to the elimination of the thermal drift effect. The literature provides few analysis of the efficiency of submerged modules: PV module in deep water [3] and PV module in shallow water [4].

The optical, thermal and electrical effects of water on submerged PV modules are presented in [5] and [6] where the concept of a Submerged PV solar module (SP2) is discussed and checked experimentally.

Pure water is a strong light absorber; the absorption mainly depends on the wavelength of incident solar radiation. It behaves like high-pass filter, specifically the water blocks the photon with long wavelength (red-infrared region), whereas the light transmission in pure water reaches its maximum in the wave length interval between 350 nm and 550 nm (in the visible spectrum), where the main photovoltaic technologies work.

In Figure 1 the variation of the solar spectrum at different water depths, from zero m (PV module outside the water) to 1 m, is reported. The black line is the plot of the water absorption in a logarithm scale. It is worth observing as in the visible spectrum of the solar radiation the absorption of water is very low.

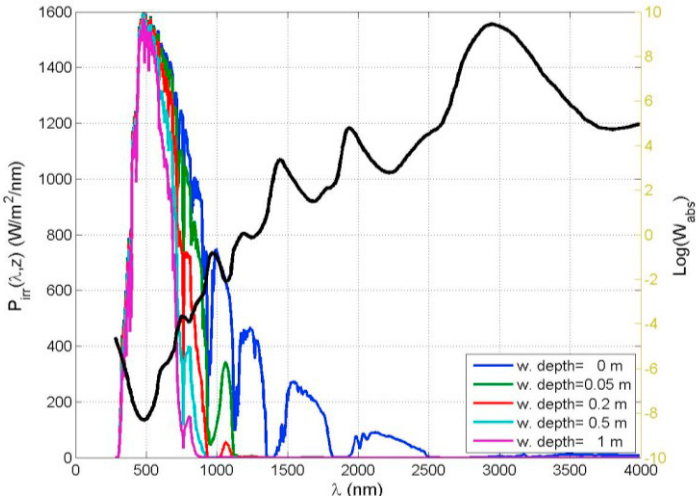

Figure 1 Variation of solar radiation spectrum with water depth

The level of energy production of a PV module depends on both the operating temperature and the irradiance on the cell. In this regard the different PV technologies are characterized by the spectral answer and by thermal coefficients [6]. The submersion impacts on both by decreasing and stabilizing the PV module temperature and by reducing the irradiance, so the energy yield of a submerged PV module can be greater or smaller depending on water depths, water temperature and PV technology. If the water layer is thin (1-2 cm) and the water temperature is about 15 °C, the gain due to the lower temperature largely overcomes the small loss due to the radiation absorption. In Figure 2 we assume that the water temperature is T_W = 20°C, the dry panel temperature is T_D = 65°C and the quantity η(TW,z)/η(TDP,0) and the rate of efficiency of SP2 (submerged PV module) with the efficiency of the dry panel, hereafter TDP, is given for individual crystalline Si, Cadmium Telluride, amorphous Si and CIS panels. The temperature drift coefficient has been assumed to be 0.45, 0.25, 0.4 and 0.25 %/°C respectively.

Furthermore the material is characterized by its band gap Energy, E_G (eV) and cut-off wavelength, λ_G (nm) and this value determines the characteristic loss of energy for each material with the water depth.

It is evident that there is an efficiency increase if the water layer is below 5 cm and that for a thin water layer, the gain can be around 20% with respect to a dry panel without cooling system.

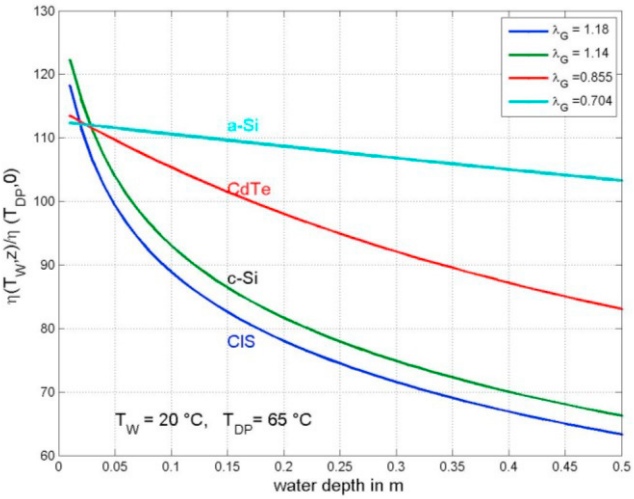

Figure 2 Relative efficiency in % versus water depth for different PV technologies

According with this theoretical result and to realize the maximum exploitation of photovoltaic technology, it is worth investigating design solutions of PV system where PV modules under water are used.

However, in real applications, other technical aspects have to be considered, especially when the submerged PV modules are installed in confined places where problems of shading can arise.

Partial shading in PV modules creates failure in local overheating of shaded area and causes malfunction to the entire string of module. The impact of shading on power production depends on the pattern of the shadow (shading to the module along its length-side or breath-side). With the increasing of partial shade on a PV module, power output decreases depending on the PV material used, the structure of PV module and the connection of bypass diodes. In general, the shade on a module along breadth-side causes higher power drop than the shade on the module along its length-side. According PV technology, thin-film PV modules are more tolerant of the partial shading than mc-Si module. Under partial shading, a-Si PV module performs best, followed by CdTe module, mc-Si module with bypass diode, CIGS module and mc-Si module without bypass diode.

In some cases, for example PV/T modules that use water in front of the PV cell [2], thermal and irradiance mismatches can be present at the same time. In this case, to evaluate the global effect, also the type of PV connections inside the PV module has to be considered [7]. In [8] Photovoltaic and Photovoltaic/Thermal Module/String Under Non-uniform Distribution of Irradiance and Temperature are studied numerically and experimentally.

Figure 3a and Figure 3b show the distribution of temperature in a PV/T module when the substrings are connected in series, and the water flows are, respectively, vertical and horizontal. Under uniform irradiance condition, the power produced by the module does not depend on the vertical or horizontal water circulation pattern, because the cells are in series and the mean temperature of the modules is the same (Figure 3c). Under partial shadow conditions, it is not possible to say which of the two modules produces more power because this depends on which substring is shaded. For example, when the third substring (on the right part) of the two modules is shaded, the model with vertical water circulation has an efficiency higher than the other (Figure 3c) because the average temperature of cells in module (a) is lower than the one in module (b).

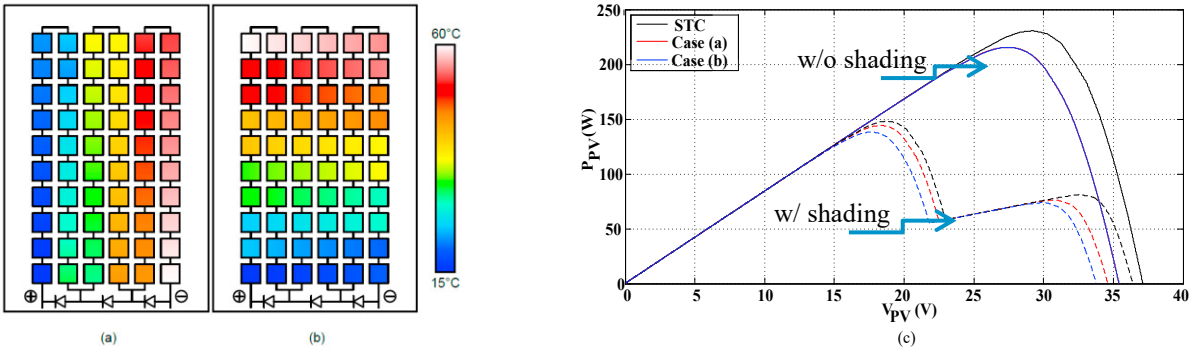

Figure 3 Distribution of PV cell temperatures in a PVT module with substrings in series: (a) vertical water flow pattern, (b) horizontal water flow pattern, (c) P-V curve for the PV module at 1000W/m^2 (solid curves), with a 30% of the module shaded, that is the third substring (dashed curves) [8]

When the substrings of the module are connected in parallel, the efficiency of the module is closely linked to the type of water flow. Under uniform irradiance conditions, the power produced by the module with the vertical water flow is always less (about 3%) than that of the module with horizontal water flow pattern, as the voltage of the parallel substrings is imposed by the substring with the lowest voltage (Figure 4c). Also in this case, under uneven distribution of temperatures, the MPP depends on what substring is shaded. Figure 4c shows the case when the third substrings in each modules is shaded.

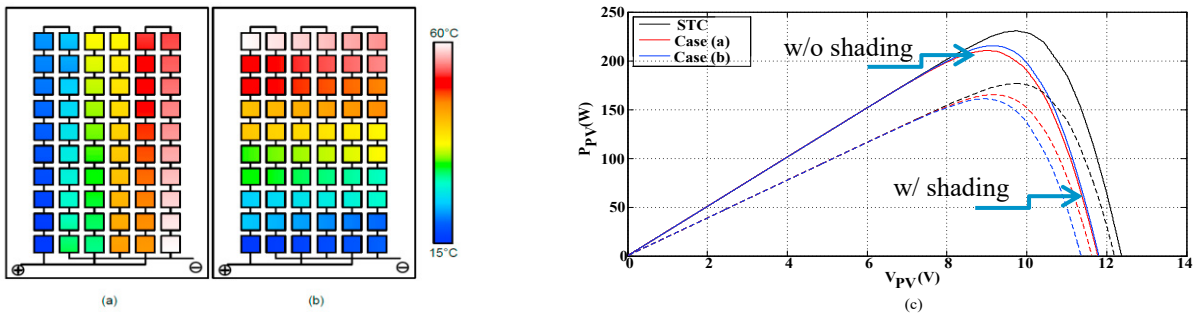

Figure 4. Distribution of PV cell temperatures in a PV/T module with substrings in parallel: (a) vertical water flow pattern, (b) horizontal water flow pattern, (c) P-V curves at 1000W/m^2 (solid curves) and with a 30% of the module shaded, that is the third substring (dashed curves) [8]

Under these considerations, our suggestion is to use submerged PV systems to produce electrical energy in standard open space swimming pools and to extend this approach also for increasing the water temperature, extending the period of use of open space swimming pools.

The techniques to use modules covered with water layer can also be proposed for shallow decorative water basins and fountains and finally we suggest applying the technique for hybrid modules to be positioned on house roofs in order to add the possibility to heat water for domestic uses.

2. PV power generation and swimming pools

Swimming pools are rather expensive luxury equipments, requiring continuous maintenance, often installed outside in zones with strong solar radiation. Therefore it could be useful to exploit the solar energy impinging on the swimming pool or shallow ponds with the following goals:

1. to produce electric power for the electric network taking advantage of the space available in a swimming pool with minimal modifications and without any unaesthetic impact.
2. to increase the water temperature, therefore extending the possibility to use the pool without expensive heating systems.

In order to test this idea, it is useful to apply this concept to a standard swimming pool. A typical configuration could be the following: 60 m^2 (6 m x 10 m) swimming pool, 1.2 meter-deep, except the last two meters where the depth reaches 1.8 meters with a total water volume of 75 m^3.

Several systems are analyzed:

1. Overflow swimming pool: one edge of the swimming pool is covered with a thin layer of water, or a small cascade in equilibrium with the pool surface.
2. Skimmer swimming pool: the edge of the pool is several centimeters above the water surface. A skimmer takes water from the pool, and pumps it through a filtering system.

In both cases, part of the PV panels is positioned on the pool edge. Both single-crystalline and poly-crystalline panels are suitable for this purpose. Another group of PV panels is positioned on the pool floor. In such case amorphous silicon seems to be the best technical solution.

Thermal aspects are further discussed. In this case a water basin covered with a transparent glass or polycarbonate layer is added to the swimming pool and allows an increase of the water temperature without heating with external conventional sources (methane or electricity) and also an increase of the electrical energy production ([9] and [6]). Application to hybrid PV/T panel, able to produce both electrical energy and heat are studied.

2.1. Overflow swimming pool

An example of integration of PV module in a swimming pool is reported in Figure 5 that shows the optimal solution for overflow swimming pools, whereas the details are given in Figure 6.

Figure 5 Overflow swimming pool with PV panels on the edge

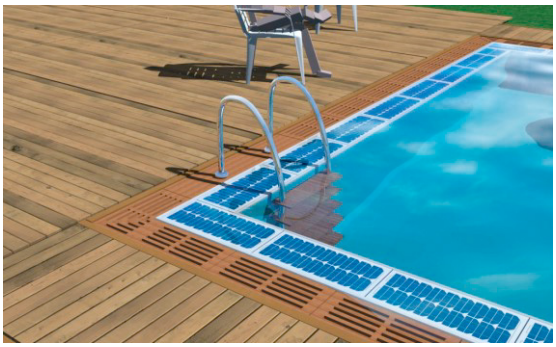

Figure 6 Detail of an Overflow swimming pool

The water falling down the grating encircling the swimming pool skims over the PV panels. These panels can be of any PV type or material. Experimental tests have verified that the system works well, and that the increase in PV efficiency ranges between 10-20% (without considering the effect of shading of any obstacles installed in the pool).

A second series of panels is submerged in water and is embedded in the bottom of the swimming pool.

The available surface is 60 m^2 and the panels are in polycrystalline or in amorphous silicon panels. The choice of amorphous silicon can be interesting because it gives good yields of conversion up to a depth of 1.5 meters, while single and polycrystalline silicon looses up to 20% efficiency at one meter depth. On the other hand polycrystalline allows a higher energy production per square meter and, due to the fact that it is submerged, is not affected by the large negative thermal drift which reduces the panel efficiency during sunny days [10]. Also thin film technologies are less impacted by shading [11]. Figure 7 shows an external view of the floor of the swimming pool with the structure of the lines used to design the bottom swimming lanes. Figure 8 shows the same solution but from an underwater solution.

Figure 7 PV panels on the bottom of the swimming pool

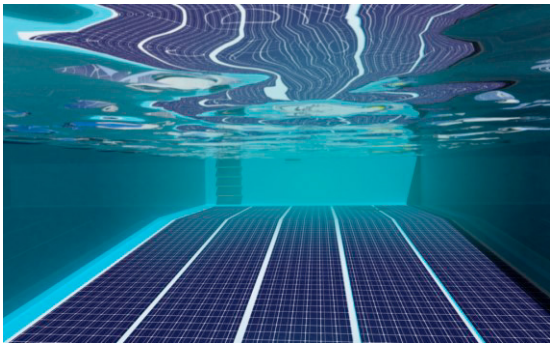

Figure 8 Underwater view of the bottom of the swimming pool

Outdoor swimming pools are normally used for six months a year, from April to September. Table 1 shows the expected yields in kWh/month, at Rome's latitude (41° 53') extending the analysis from March to October included. We assumed an available surface of 60 m^2 for the panels in amorphous silicon on the bottom of the swimming pool (10% efficiency), and a panel in polycrystalline silicon on the edge of the pool. The estimate energy yield is given in Table 1. The table has been obtained using the following inputs:

- Radiation yield for horizontal PV panels is taken from PVGIS for Rome latitude and longitude.
- Energy harvesting on the edge panels in polycrystalline silicon has been increased by 15% due to the effect of water veil.
- The energy yield of amorphous silicon has been reduced by 10% because of the reduction of the solar energy impinging on panels at a depth of 1.2 meters.

As shown in Table 1, the energy harvesting is almost 10.000 kWh a year. This energy can in part be used for the pool managing, and most of it can be used for house lighting and other civic use. In this case, battery storage can be the best solution and could allow the managing of a whole villa.

Table 1. Energy yields in kWh/month, in a swimming pool located at Rome latitude (41° 53')

Month	kWh/month	Edge kWh	Bottom kWh	Total kWh
Mar	104	274	632	906
Apr	129	340	784	1123
May	160	421	972	1393
Jun	169	445	1027	1472
Jul	177	466	1075	1541
Aug	155	408	942	1350
Sep	112	295	680	975
Oct	82	216	498	714
Total	1088	2865	6610	9475

2.2. Skimmer swimming pools

If the swimming pool has a curb with inner water circulation, then it is necessary to change the design.

Figure 9 and Figure 10 illustrate today's most widely used solution: it is the common solution for open air swimming pools since the overflow technique, although giving better performances, is more expensive and less easy to manage in open spaces.

Figure 9 A detail of the pool with skimmer

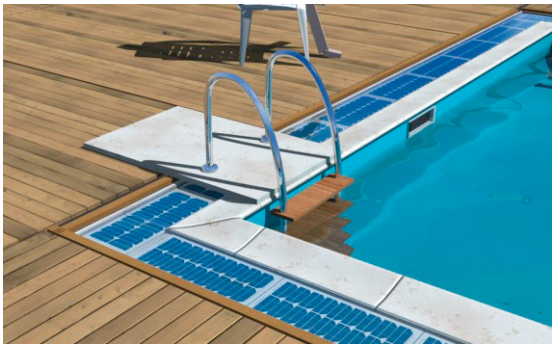

Figure 10 Outline of the edge for a skimmer pool

The PV solution looks more complicated and we suggest adding a set of PV panels, arranged as shown in Figure 11 and in Figure 12, to the concrete channel encircling the pool. In this scheme the PV panel, protected by a suitable lass, is cooled by the water circulating in the skimmer edge.

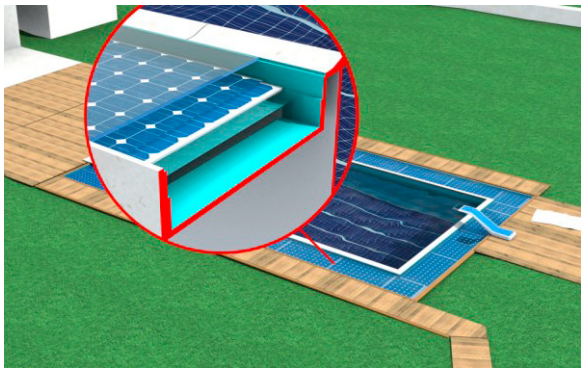

Figure 11 Solution for PV integration with skimmer

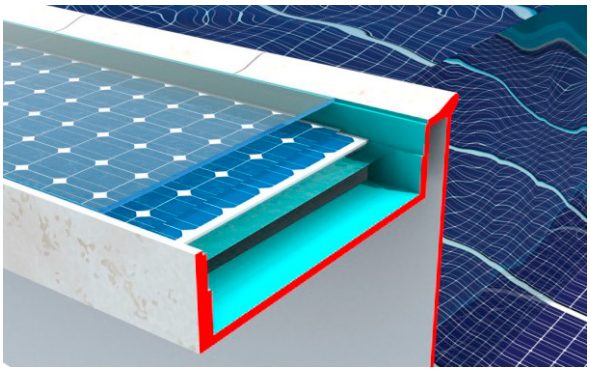

Figure 12 Detail of the PV panel and water cooling

This solution suggests a more appropriate use of the PV modules in the presence of water and is reminiscent of the proposal of hybrid panels that are able to collect solar radiation for producing electricity and thermal energy optimizing in this way the solar energy harvesting. This possibility has been analyzed in [2] and [7], where TESPI (Thermal Electric Solar Panel Integration) PV/T model is studied and in other solutions such as [12].

3. Thermal Electric Solar Panel Integration (TESPI)

TESPI works thanks to the already mentioned physical principle of the water strong infrared absorption, whereas the electricity production through PV panels works mainly on the visible part of the solar radiation.

Such considerations are at the base of the idea that allows the realization of a hybrid system in which the production of heat and electricity go together in a unique apparatus made with a photovoltaic system shielded from a water layer by a box of glass or of polycarbonate.

Data on the first experiments in Pisa are given in [6]. A systematic analysis of the PVT solution is given in [9]. Further experiments have been carried out in the towns of Pisa and Enna, comparing similar apparatus.

In our final experimental setup, the thermal-photovoltaic panel TESPI is constituted by a water layer, of a few centimeters, superimposed to the photovoltaic panel. In the back part of the cell, an insulating layer reduces the thermal losses. The water circulates in the front part of the panel where it reaches the temperature of 40°-50°C, and is extracted and stored in a tank for domestic uses. The photovoltaic cell, at the same time, is protected from an excess of radiation

and can produce the electrical energy without losing efficiency due the unavoidable problems of thermal drift. The apparatus therefore can take full advantage of the solar energy, proposing a thermal efficiency comparable to that of a standard thermal panel and an electrical efficiency slightly better than a conventional photovoltaic system.

Although state-of-the-art projects present several solutions that couple the production of thermal energy with the electrical one, the TESPI particular architecture gives better performances optimizing the conversion of solar energy into thermal and electrical energy. Two tests were done with a simple experimental setup in Pisa (Italy) and in Enna (Italy). The system in Enna was tested for several months with satisfactory results. Thermal heat harvesting depends strongly on the threshold temperature but on sunny days it is normally above 50% of the solar radiation income.

Finally, we stress that TESPI can be added without any modification to existing PV plants by simply superimposing the water boxes to PV panels (Figure 13). This causes a small reduction of electrical energy harvesting, but also a significant production of thermal energy, thus approximately doubling the system efficiency.

Figure 13 Tespi rendering: water boxes superposed to PV panel plant.

4. Swimming pool with heat storage tank

The positive results for TESPI suggest a very simple extension of SP3 to the swimming pools equipped with skimmer. In this case we can use the channel encircling the pool as a system for producing heat and electricity by positioning the PV panel directly inside the channel, covered by a thin water layer. Several studies exist suggesting the use of solar heating for swimming pool, see for example [13] and [14], and we suggest coupling the heating system to the electric PV production. The transverse swimming pool section is shown in Figure 14 where the orange lines represent the PV panel on the bottom (in amorphous silicon) and near the water surface inside the skimmer channel (in polycrystalline silicon). In this case the radiation arriving on the pool edge slightly increases the temperature of water circulating inside the channel and the electricity produced by the PV panels is improved by the cooling effect.

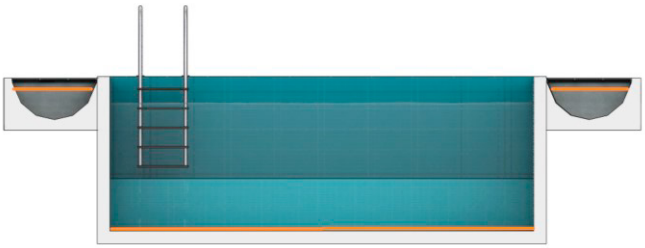

Figure 14 Pool transverse cross section

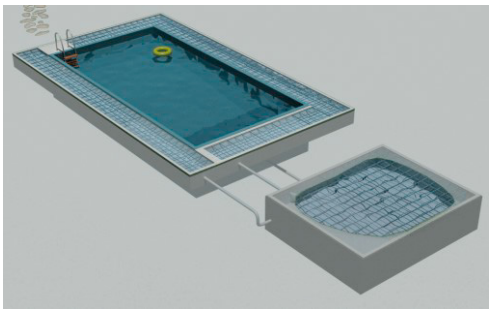

Figure 15 Swimming pool with storage tank

This solution can be further extended if there is space for a storage tank near to the swimming pool.

In this case we show a schematic project of a shallow tank covered with a transparent sheet (glass, for example) and with a surface half that of the pool (30 m^2).

a) The surface available for the photovoltaic panels is larger as it can take advantage of the tank roof if properly designed (see Figure 16)

b) Heat can be recovered by using the tank as a heat storage system.

We suggest using this system in order to collect both electrical energy (from submerged PV panels) and heat from the giant collector constituted by the edge of the pool and by the heat tank.

This latter option allows us to heat the pool water in the early hours of the morning using the heat accumulated during the previous day and put into the storage tank.

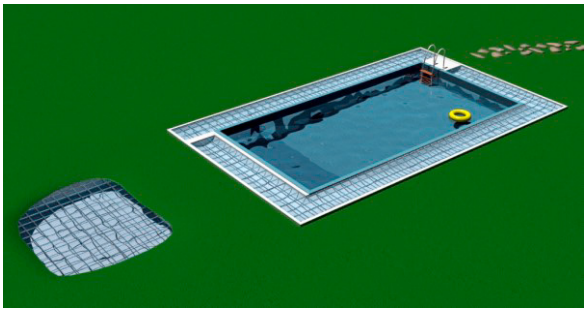

Figure 16 Swimming pool with external heat storage

The storage tank is one meter deep and contains a quantity of water equal to 30 m3 at a temperature several degrees higher than that of the pool. The system is an alternative to traditional Swimming Pool Heaters operating with natural gas and, if not sufficient for the heating during cold days, can be advantageously integrated with them.

Some details in the channel structure below the pool edge is given Figure 17. In this figure the position of PV panels has been indicated by orange lines and clearly shows how the PV panels submerged in shallow water operate for producing electrical energy and heat.

Figure 17 Section of the heat storage system

The electrical and thermal balance is given in Table 2, which shows that the temperature increase of the water tank ranges from 4 to 7.5 degrees. So this water can be exchanged with the water in the swimming pool during the first hours of the day when the temperature is low, increasing the temperature by 2-3 °C and thus extending the period of use of the outdoor pools.

Table 2. Electrical energy and heat balance for swimming pool with heat tank and PV panels, located at Rome latitude (41° 53')

Month	kWh	Edge	Bottom	tank	Total	Heat (kWh)	ΔT in °C
Mar	104	214	632	446	1292	4824	4,1
Apr	129	266	784	553	1602	6048	5,2
May	160	330	972	686	1987	7632	6,6
Jun	169	348	1027	724	2099	8244	7,1
Jul	177	365	1075	759	2199	8712	7,5
Aug	155	319	942	664	1925	7560	6,5
Sep	112	231	680	480	1391	5436	4,7
Oct	82	169	498	353	1020	3924	3,4
Tot kWh	1088	2242	6610	4665	13517	52380	

5. Conclusion

Solar heating together with electrical energy production coming from PV effects can be naturally coupled to water basins such as swimming pools, fountains etc. The possibility to capture solar radiation efficiently to produce both electric power and heat is proved in several tests already done and documented in the scientific literature.

The most interesting aspect however is the possibility to use already existing structures with a specific use (recreational or aesthetic) for producing power without any visible impact and without changing the basic function of the structures.

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