Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 49 (2014) 71 – 79

Energy Procedia

SolarPACES 2013

Blue sky cooling for parabolic trough plants

E. du Marchie van Voorthuysen[a] , R. Roes[b]

[a] *SOLAq BV, Nieuwe Kerkhof 30a, NL 9712 PW Groningen, The Netherlands,*
b. SOLAq BV.

Abstract

At most locations with sufficient solar resources for a viable exploitation of solar power plants water is too precious to be wasted in cooling towers. However, application of air cooling increases the levelized cost of electricity up to 16%. An alternative for air cooling is radiation cooling. A new function is given to the parabolic trough mirror, which is the realization of optical contact between a radiating plane and the sky. The sky is cold, therefore the radiating plane cools down. This cooling is available day and night and can supply most of the cooling power that is needed for the condenser of the Rankine cycle. When there is wind, the radiating plane also dissipates heat. Radiation cooling and wind are sufficient for cooling the solar thermal power plant.
Storage of cold in a water basin is an essential component, because wind cooling and radiation cooling are more effective at night, when the air temperature is low. Pumping the cold night-air through heat exchangers in the basin is an alternative when wind speeds are generally low.
An additional function is given to the water basin, namely the support of a floating parabolic mirror field. A field of floating parabolic trough mirrors that are stationary with respect to each other rotates collectively around a vertical axis in order to follow the sun. We expect that this simple concept will lead to a substantial cost reduction, in spite of the less favorable average angular orientation of the mirrors. Floating parabolic trough fields are most suited for applying radiation cooling in solar power plants.

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
Keywords: Floating mirror field; Cooling,; Blue Sky Cooling,; Wind cooling; Storage of cold.

1. Introduction

The solar efficiency of a thermal power plant depends on the temperature of the condenser of the Rankine cycle. Fossil-fuel and nuclear power plants are therefore preferably located at the coast, where the sea delivers an unlimited amount of cooling. The need for a vast area for the mirror field makes the location of a CSP-plant at the coast less probable. At inland locations the lowest cooling temperatures are achieved with cooling towers where the evaporation heat of water is used. However, the water consumption makes this approach not very sustainable, as water is always scarce in the regions where CSP is most viable, and therefore should be used for better purposes then

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
doi:10.1016/j.egypro.2014.03.008

cooling thermal power plants. The alternative is air cooling, resulting in a higher condenser temperature and consequently a lower efficiency of the power plant. Liqreina [1] calculated a 16% increase of the levelized cost of electricity if the water cooling is replaced by air cooling. This calculation was done with the Greenius program for a standard parabolic trough plant at Ma'an in Jordan.

In this paper we investigate the potential of radiation cooling, complemented with wind cooling, for cooling large parabolic trough solar power stations. Before the invention of the refrigerator, radiation cooling used to be a common method for producing ice in countries with a desert climate, like Western India. Radiation cooling utilizes the low effective temperature of the cloudless, blue sky. Therefore we call this new method for cooling thermal power stations "Blue Sky Cooling" (BSC). First the elemental principles of infrared radiation are summarized, next the enhancement for radiation cooling by means of infrared mirrors is explained. Next we propose an addition to the standard parabolic trough in which the mirror is not only supplying heat but also cooling. Finally we propose the floating parabolic trough field as the optimum design for a blue sky cooled CSP plant.

2. Radiation cooling

Any surface A radiates electromagnetic radiation, the intensity P depends on the temperature T and the average emissivity coefficient ε according to the Stefan-Bolzmann law:

$$P_{out} = \varepsilon \,.\, \sigma \,.\, A \,.T^4 \qquad (1)$$

with T the absolute temperature of the surface and σ the Stefan-Bolzmann constant, $\sigma = 5.67 \text{ x } 10^{-8}$ Wm^{-2}K^{-4}. The emissivity coefficient of electrical insulators is generally near to one, for example the ε value of glass is 0.9, a thick layer of paint 0.96 and water 0.95 – 0.963. The ε value of polished metals is low, silver 0.02 – 0.03, aluminum 0.04. At $T = 300$ K (27^{o}C) and for $\varepsilon = 1$, the radiation intensity $P_{out} = 459$ W/m^2.

A horizontal surface outside emits infrared radiation with intensity P_{out} and absorbs radiation from the surroundings. If there is an unobstructed view on the clear blue sky during the day, or the clear black sky during the night, the surface absorbs radiation which is emitted by the gases in the sky with an intensity P_{in} ,

$$P_{in} = \sigma \,.\, A \,.T_{sky}^{\;4} \qquad (2)$$

The sky is a continuous, thick layer with varying temperatures. Nevertheless, the approximation of the sky by one surface being a black emittor with effective temperature T_{sky} is reasonably justified. This effective temperature T_{sky} is easily measured with an infrared thermometer. At clear sky, T_{sky} turns out to be 20 to 30 degrees lower than the air temperature at ground level.

For simplicity reasons we assume first a one-dimensional geometry, with view factors equal to 1, and for $\varepsilon = 1$, as indicated in Figure 1. The surface will lose heat, or generate cold, which is the same, by subtracting Eqs. 1 and 2:

$$P = \sigma \,.\, A \;(T^4 - T_{sky}^{\;4}) \qquad (3)$$

When we want to generate cooling at $T = 27^o$C = 300 K, and T_{sky} is 25 K lower, 275 K, we calculate a radiation cooling power P = 135 W/m^2.

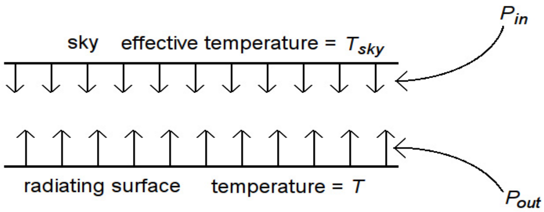

Fig 1. Exchange of infrared radiation between a surface and the sky, simple one-dimensional approach.

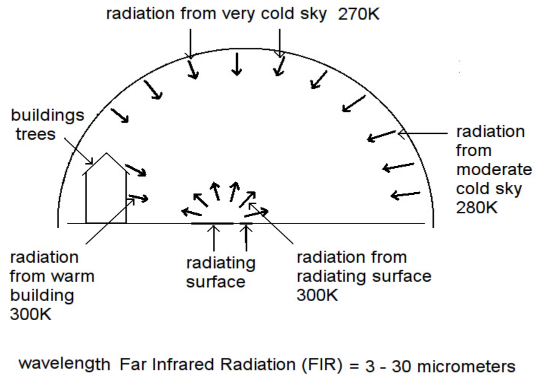

Fig. 2 Exchange of infrared radiation between a radiating surface and the sky, realistic approach.

Next we consider a more realistic situation, Figure 2. The radiating surface is heated from different objects: surrounding buildings at a relative high temperature, the regions of the sky near to the horizon which are colder, and the regions of the sky above, which have the lowest temperature. So the cooling capacity is smaller than in the ideal situation given in Figure 1.

3. **Enhancing radiation cooling with solar mirrors**

A method to restore the large cooling capacity which is available in Figure 1 was given by G.B.Smith [2]. With infrared mirrors it is possible to screen the sources which emit high temperatures, like the buildings in figure 2. The radiation coming from the direction of the buildings is then replaced by radiation coming from the cold sky above. In principle this can be achieved in a concentrating solar system. We illustrate this concept by adding a concentrating device, in this case a lens, see Figure 3. The lens focuses the radiation from the sun on a small part of the surface. This part becomes very hot, and functions as the receiver of the concentrating solar system. In Figure 4 the effect of the lens on the cooling power of the radiating surface is analyzed. The intensity P_{out} of the radiation which is emitted by the radiating surface depends only on the parameters of the radiating surface itself, and cannot be manipulated by an optical arrangement outside. Therefore we omit this radiation in this figure, and in the following figures. The outgoing radiation from a surface element P_{out} is given by Eq.1. The total incoming radiation P_{in} towards a surface element is the integral over all directions pointing towards the element. The effect of the lens is that most incoming radiation originates from parts of the sky with a rather small zenith angle, where the effective temperature of the radiating atmosphere is low. The lens restores the ideal situation given by Figure 1. The most remarkable effect of the lens is the shielding of the radiation from the sun. All solar rays towards the lens are refracted to the receiver, no solar ray will heat the radiating surface. So the cooling effect from the sky exists also during the day when the sun is shining and the sky is blue. Therefore we call radiation cooling which is enhanced by solar concentrators "Blue Sky Cooling" (BSC).

4. **Application of Blue Sky Cooling in conventional parabolic troughs**

In all CSP applications mirrors are applied, not lenses. From the four basic CSP techniques the parabolic troughs are most suited for the application of Blue Sky Cooling (BSC). Figures 5 and 6 give a parabolic trough mirror which is optimized for maximum BSC. In the symmetry plane of the parabolic trough two radiating surfaces are added, one below and one above the receiver. The trough mirrors must not only reflect the solar rays, which are in the

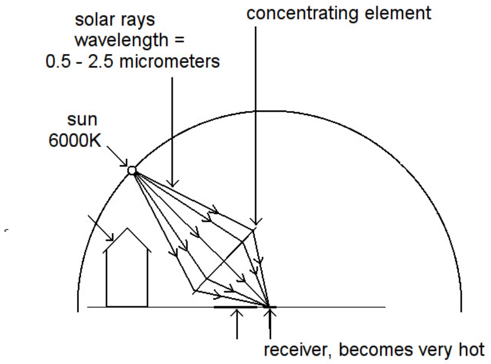

Fig. 3. Concentrating solar power, in this example applying a lens instead of a parabolic mirror

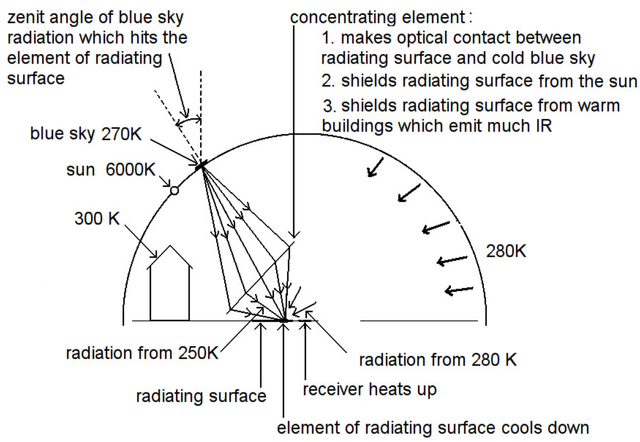

Fig.4. Simultaneous harvesting of solar heat on the receiver and cooling on the radiating surface.

wavelength region 0.5 - 2.5 µm, but also reflect the Far Infrared Radiation (FIR) with wavelengths 3 - 30 µm. So the incoming radiation on the radiating surfaces is not originating from the parabolic mirror, having a temperature equal to the surroundings, but from the cold blue sky. All metal surfaces fulfill this condition. In most mirrors however, the layer of glass or polymers which protects the silver or aluminum from weathering absorbs FIR, and these mirrors are therefore not suited for BSC. Aluminum mirrors can be covered by a layer of titanium dioxide, which is transparent for FIR [3], and become therefore useful for the application of Blue Sky Cooling (BSC) in a CSP plant.

In Figure 5 the solar rays are shown for one parabolic trough. All reflected rays are absorbed by the receiver. The ratio between the width and the focal distance is larger than usual in order to increase the radiating surface, giving a maximum amount of BSC. Narrow screens prevent solar rays and infrared rays emitted by the hot receiver from hitting the radiating surfaces.

Figure 6 gives a cross section of a parabolic trough field in which BSC is implemented. For each of four different spots on the radiating surfaces a representative set of incoming infrared rays is shown. We observe that the big majority of them originate from the cold, blue sky. Most of them have been reflected by the mirror. Limited fractions originate from the backside of neighboring mirror rows and from the ground. At noon these fractions are

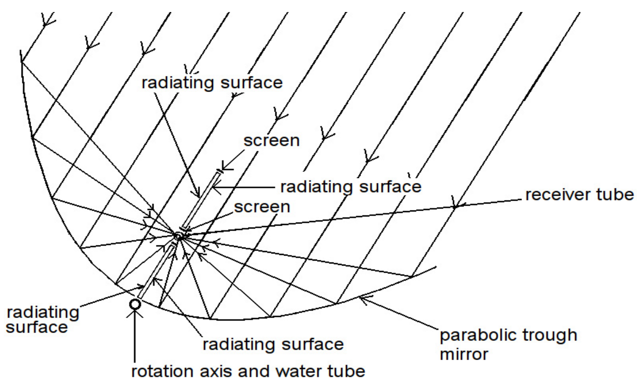

Fig.5. Parabolic trough mirror with radiating surfaces. The solar rays only are shown, heating the receiver tube.

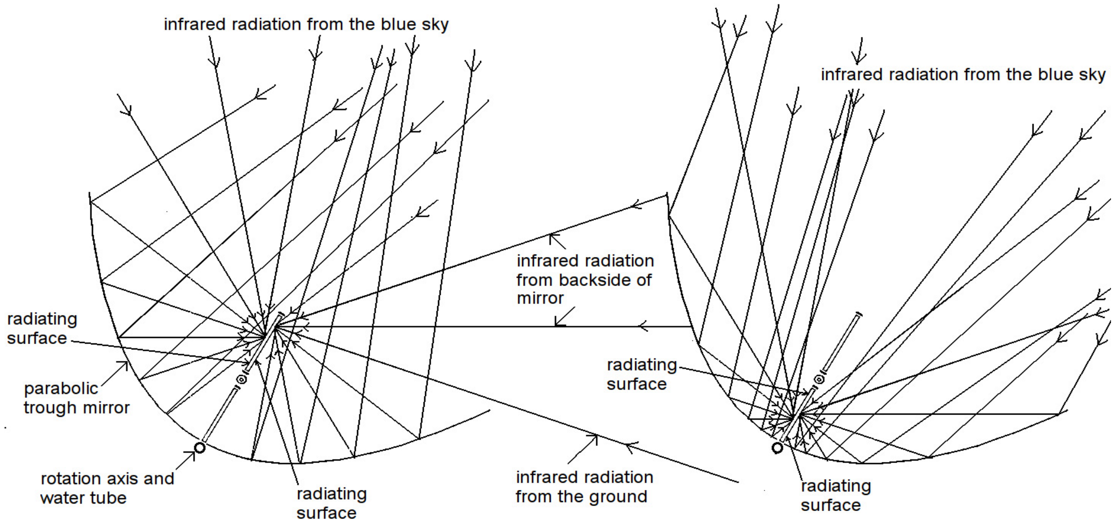

Fig.6. Parabolic trough mirror with radiating surfaces. The infrared rays only are shown, cooling the radiating surface.

absent, but in the morning and the evening they become substantial. The amount of BSC is then reduced with respect to the theoretical maximum value given by Eq.3 for the model of Figure 1.

A convenient way for transporting the heat from the condenser to the radiating surfaces is using a continuous water tube as the horizontal axis for the rotation of the parabolic trough mirrors. The radiating surfaces can be connected to the water tube by means of heat tubes. A heat tube is an efficient method to transport heat in an upwards direction, opposite to the direction of the gravitational field. As soon as the radiating surfaces become colder than the water in the tube, because of BSC and convection cooling, heat is extracted from the water. In other words, cold is transported towards the water, and further towards the condenser of the CSP plant.

Blue Sky Cooling is available night and day, but CSP plants only operate during the day, and part of the night, if heat storage is applied. Therefore cold storage in a water tank or water basin is a necessary component of a BSC cooled solar thermal power plant.

In order to obtain an idea of the physical feasibility of a BSC cooled parabolic trough plant we make the following rough calculation. A parabolic trough plant in Seville (Spain) collects on a bright day in June useful heat to an amount of about 6.5 kWh per square meter trough aperture. If the heat-to-electricity efficiency is 33%, we need each day an amount of cooling in the condenser equal to (1-0.33) x 6.5 = 4.4 kWh per square meter trough aperture. There are 24 hours available to produce this amount of cold, at night the trough mirrors are pointing to the zenith. So the average needed cooling power is 4.4 / 24 = 0.18 kW per square meter trough aperture. In trough mirrors with the shape of Figures 5 and 6 the total area of the radiating surface is equal to 71% of the aperture of the trough. So we need an average BSC cooling power of 180 / 0.71 = 255 W/m^2.

Next we make the following assumptions. The air temperature is 30^{o}C = 303 K during the day and 15^{o}C = 288 K during the night. The effective sky temperature is 25 K lower than the air temperature. We neglect the reduction of BSC during the early morning and the late afternoon. So we use the simple formula Eq. 3 and calculate the cooling power as a function of the temperature of the radiating surface in the parabolic trough, Table 1. We observe that the temperature of the radiating surface will stabilize at an average temperature of 42^{o}C.

Table 1. Cooling capacity of a radiating surface as a function of its temperature according to Eq.3. Assumed effective sky temperatures: -10°C at night and +5°C during the day.

Radiating surface temperature T (C)	Cooling capacity P P (W/m^2)		
	Day	Night	Average
30	139	207	173
35	172	239	205
40	206	273	239
45	241	309	275
50	278	346	312
55	318	385	351
60	359	426	392

Parabolic troughs normally are not as sharp as in the Figures 5 and 6, and more like in Figure 7, in which the area of the radiating surface is about 50% of the aperture area. Now we need 180 / 0.50 = 360 W/m^2 of cooling power from the radiating surface. From Table 1 we read an average temperature of the radiating surface of 56°C.

We observe that Blue Sky Cooling (BSC) as illustrated by the Figures 5-7 is insufficient to provide the necessary cooling for the solar thermal power plant. However, there are two methods to obtain additional cooling. As mentioned before, storage of cooling in a water basin forms an essential component of the BSC-cooled plant. At most locations where where solar power plants are most viable, like the deserts of America and Africa, the air temperatures are low at night. When the cold night air is pumped through heat exchangers in the water basin, additional cooling can be supplied.

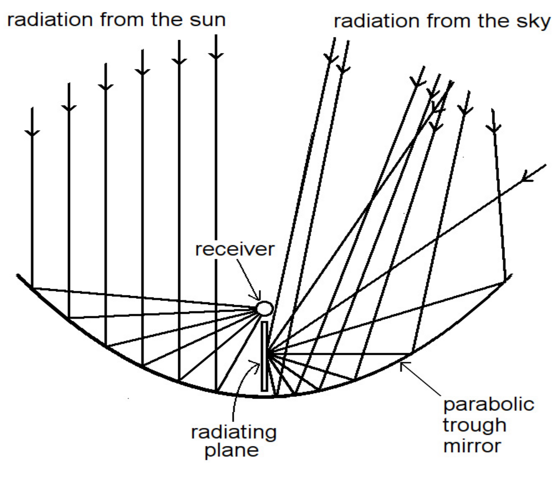

Fig.7. Parabolic trough mirror with radiating surfaces only below the receiver tube.

The second method, which does not need any extra investment, is the cooling which is provided by the wind. As the temperature of the radiating surface is generally higher than the air temperature, the air can remove heat from the surface by convection. So we extend Eq.3 with a wind-cooling term with a proportional dependence on the temperature difference with the air:

$$P = \sigma . A \ (T^4 - T_{sky}^4) + L . (T - T_{air}) \tag{4}$$

The wind cooling factor L depends on the wind speed v in a complicated way, dependent on the geometry, the orientation of the trough and the angle between the wind and the focal line of the parabolic trough. For the time being we assume a proportional dependence on the wind speed v :

$$L = W . v \tag{5}$$

From our preliminary measurements we conclude to a value of $W = 6$ $Wm^{-2}K^{-1}$ per ms^{-1}. Using this value for W we extend Table 1 to a table which gives the radiation cooling together with the convection cooling by the wind for two values of the wind speed, Table 2. We observe that parabolic troughs which are shaped as given by the Figures 5 and 6 reach a cooling temperature of 29.5°C at a light breeze, force 2, and 26.8°C at a gentle breeze, force 3. Parabolic troughs that are shaped according to Figure 7 produce cooling temperatures of 35.2°C at a light breeze, force 2, and 30.2°C at a gentle breeze, force 3.

We conclude that parabolic trough mirrors with radiating surfaces, together with a water basin, are sufficient to deliver the necessary cooling for the solar thermal power plant if there is a minimum amount of wind most of the time. If windless periods occur frequently, the basin has to be additionally cooled using the cold air at night.

Table 2. Cooling capacity of a radiating surface as a function of its temperature according to Eq.4 for two wind speeds. Assumed effective sky temperatures: -10°C at night and +5°C during the day. Assumed air temperatures: 15°C at night and 30°C during the day. Wind speed factor $W = 6$ $Wm^{-2}K^{-1}$ per ms^{-1}.

Radiating surface temperature T (C)	Cooling capacity P P (W/m^2) wind speed 2 m/s light breeze, beaufort 2			Cooling capacity P P (W/m^2) wind speed 4 m/s Gentle breeze, beaufort 3		
	Day	Night	Average	Day	Night	Average
26	67	314	190	19	446	232
28	103	350	226	79	506	292
30	139	387	263	139	567	353
32	176	423	300	200	627	414
34	213	460	337	261	688	475
36	250	498	374	322	750	536
38	288	535	411	384	811	597
40	326	573	449	446	873	659

5.Application of Blue Sky Cooling in a floating parabolic trough field

The concept of a floating solar mirror field has been proposed long ago [4], and motivated by the unlimited availability of space on the seas and oceans of the earth. However, concentrating mirror systems need to be stable within one tenth of a degree because the size of the sun is only half a degree. This condition is impossible to meet in the waves and swells of the high seas. In small lakes, ponds and artificial basins waves cannot develop well, and it must be possible to make a mirror field of many hectares which rotates around one vertical axis. The advantages of a floating parabolic trough mirror field with respect to the conventional parabolic trough mirrors with horizontal rotation axes are:

- Enormous reduction of the number of bearings and motors
- Substantial reduction of the number of high-temperature bellows

- Less stringent demands on the rigidity of the construction

- More economic usage of the available space

We expect that these advantages will more than compensate the main disadvantage of the floating mirror field, which is the smaller average cosine of the incoming solar rays, and will lead to a lower levelized cost of electricity. We also foresee a hybrid concept where cheap floating parabolic trough fields will be used as pre-heater for central-receiver solar power plants.

We have built a small demonstration field of floating parabolic mirrors on the island of Texel, The Netherlands, see Figure 8. The total aperture area is 76 m^2. The field rotates around a thick vertical axis which is mounted on the bottom of an artificial pond with diameter 14 meters. The depth of the water is 0.5 meter. The mirrors were produced in a mould in which two 2 mm thick glass fiber sheets (GRP) are glued on a 20 mm sheet of polyurethane foam (PUR) in order to form a rigid plate with the right parabolic shape. One part of the mirrors is covered by reflecting mirror foil [5], the other part by reflecting aluminum sheet [6]. The supporting structure is constructed out of flat plates of GRP-PUR sandwich, L-profile of extruded GRP and blocks of expanded polystyrene (EPS). The position of the field is controlled by thin cables made out of dyneema [7] having a very high elasticity constant. The cables are mounted on reels which together with the pump, the valves, thermometers and flow meters are controlled by two PLC's, one on the field, and one ashore [8].

The field will become a CPV/T system. Photo-voltaic cells with small internal resistance will be mounted on the aluminum receiver. Water is pumped through the receiver in order to cool the PV cells and to utilize the heat for a second purpose, in this case the heating of a swimming pool 100 meter away. The water is transported from the rotating field to the shore by means of two swivels containing rubber O-rings and two flexible polybutene tubes inside of the thick vertical rotation axis. The water is transported by polybutene tubes which are isolated by expanded polypropylene [9].

In the future the heat from the CPV/T systems will amongst others be utilized for desalination and adsorption cooling.

A floating parabolic trough is excellently suited for the application of Blue Sky Cooling (BSC). The main reason is that the water of the basin can be used for cold storage at the same time. A second reason is the simplicity of the radiating surfaces, which consist of simple vertical aluminum plates covered by a suitable infrared emitting coating, connected to the water by heat pipes at regular intervals. A third reason is the fact that floating parabolic troughs are always pointing to the zenith, resulting in a perfect optical connection between the radiating surfaces and the cold blue sky.

Fig.8. Floating parabolic trough mirror field in an artificial pond at Texel, The Netherlands.

6. Conclusion

A solar power plant using parabolic trough mirrors can be cooled by a combination of radiation cooling and wind cooling, eventually supported by additional air cooling of the water basin during the night. The best results from an economic point of view will be obtained when floating parabolic mirror fields are applied.

References

[1] Liqreina, AAM. Evaluation of dry cooling option for parabolic trough (CSP) plants including related technical and economic assessment, Masters Thesis, Kassel University and Cairo University.
[2] G.B. Smith, GB. Amplified radiative cooling via optimized combinations of aperture geometry and spectral emittance profiles of surfaces and the atmosphere, Solar Energy Materials & Solar Cells 2009; 93: 1696–1701
[3] S.Ziegler, Alanod GmbH, private communication (2013).
[4] Brent, CC. US Patent 4296731; Laing, N. US Patent 4350143.
[5] Solar Mirror Film 1100, produced by 3M, USA.
[6] Produced by Alanod, Ennepetal, Germany.
[7] Produced by DSM, The Netherlands
[8] ICT activities were performed by Dethline, Amsterdam, The Netherlands.
[9] Isolating water tubes were delivered by Thermaflex BV, Waalwijk, The Netherlands.