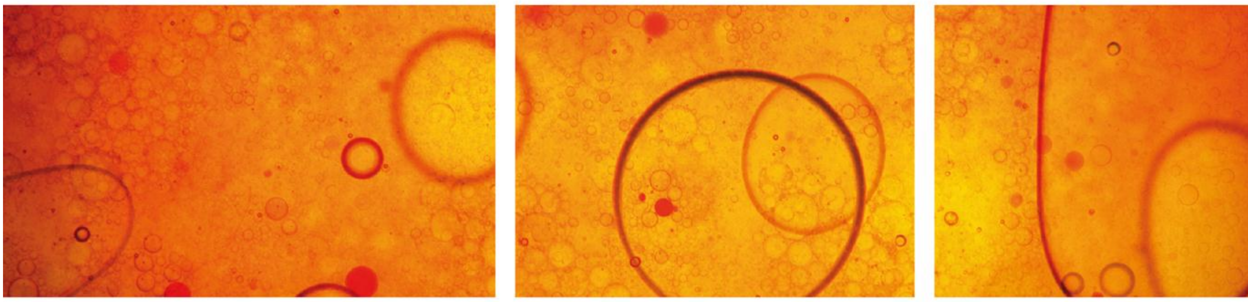
Dr. Dietmar Hunold



PARABOLIC TROUGH SOLAR POWER PLANTS – THE LARGEST THERMAL OIL PLANTS IN THE WORLD

White Paper

Content

1 Background

Already in the middle of the 80's of the last century parabolic trough solar power plants with a total electric capacity of more than 350 MW were erected in the Californian Mojave Desert. These plants have been steadily in operation until today.

Since the middle of 2007, the power generation using solar thermal power plants has been subsidized in Spain by a feed-in tariff of 0,12 €/kWh above the respective market price. And this is assured by law for a period of 20 years. After that still 80 % of the last subsidy will be guaranteed unlimited in time for the remaining running time of the power plants. Through this a real "solar boom" was triggered in Spain: As per March 2011 already more than 14 power plants with a total of 700 MW of electric peak capacity are in operation in Spain, additional 28 power plants (1.400 MW) are under construction as well as additional 19 power plants (950 MW) are in concrete planning. In the next years in Spain, the installed electric total capacity of solar thermal power plants will thereby increase to more than 3.000 MW. This corresponds approximately with the capacity of four conventional coal-fired power plants or three nuclear power plants. At an approximately power plant price of 250 million € the total investments accumulate to around 15 billion €. With this the solar thermal power generation has reached big industrial character also in Europe now. The used technology of the solar thermal power generation thereby is extensively based on the power plants in California, for the most part however supplemented by thermal energy storages (see below).

The first plants are already in operation also in Northern African countries (Egypt, Algeria, Morocco). Here the values of irradiation (DNI = Direct Nominal Irradiation in kW/year) are considerably higher than the corresponding values of the south of Spain which increases the efficiency of solar thermal power plants in direct proportion (cp. Fig. 1).

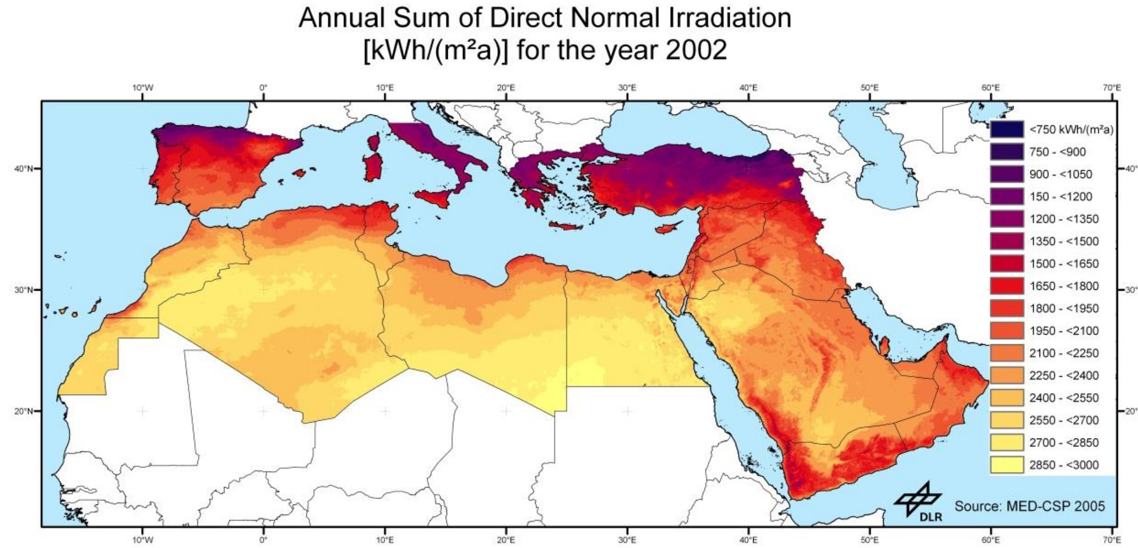


Figure 1: Annual solar direct irradiation in Southern Europe and the MENA countries in kWh/year. (Source: DLR)

The Desertec Industrial Initiative (Dii) develops in a study the technological and geopolitical conditions for a significant supply of Southern and Central Europe with renewable generated electricity from North Africa. In the coastal regions this should be done by wind farms, in the Sahara by solar thermal power plants. The power transmission to Europe can take place by high-voltage direct-current transmission (HVDC). This technology to the relatively low-loss transport of electricity over long distances is already available and used in Northern and Central Europe. For example, hydropower plants in Norway and off-shore wind farms being built in increasing numbers in the North Sea, are connected to the German power grid by HVDC.

2 The technology of parabolic trough solar power plants

In parabolic trough solar power plants, the sunlight is concentrated by parabolic shaped mirrors onto a vacuum-insulated absorber tube along the focal line, in which a special heat transfer fluid (HTF) flows and which is heated up to maximum 400 °C – the thermal stability limit of the HTF. Collectors of the current design have an opening (aperture) of just under 6 m and concentrate the solar radiation by about a factor of 80 (cp. Fig. 2).

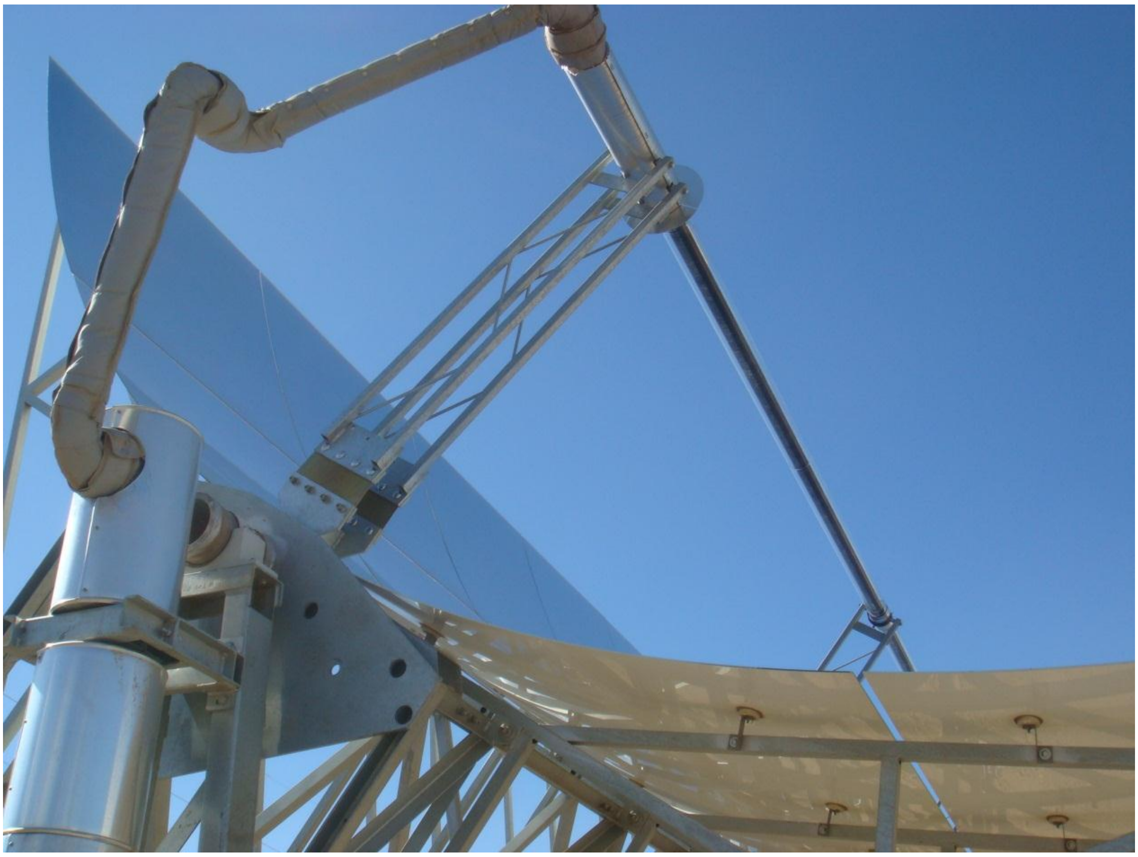


Figure 2: Parabolic trough collector (Source: LUZ)

The HTF releases the thermal energy via heat exchangers (preheater, vaporizer, superheater, reheater) to a conventional water / steam circuit with single reheating (steam parameter 371 °C / 100 bar / 30 bar) operating a turbine with generator. The overall process is shown schematically in Fig. 3.

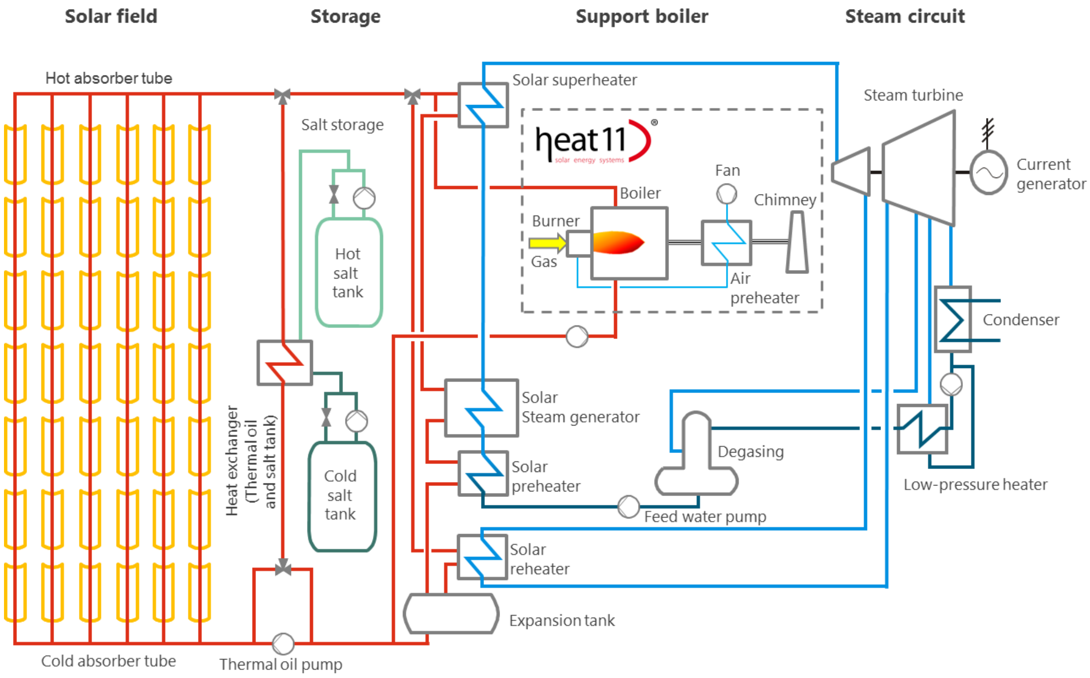


Figure 3: Schematic diagram of a parabolic trough solar power plant (Source: heat 11 GmbH)

Some technical boundary conditions:

Due to the overall efficiency of the plant, around 160 MW of thermal capacity must be made available from the solar field to reach an electric capacity of 50 MW. For a location as in the south of Spain around 330.000 m^2 reflecting surface will be required. This results in a demand of space of approximately 1 km^2. Fig. 4 presents the three parabolic trough solar power plants Solnova 1, 3 and 4 near Sevilla with each 50 MW of electric capacity. Two solar tower power plants with 10 respectively 20 MW of electric capacity are operated also there.

Figure 4: Parabolic solar power plants Solnova 1, 3 and 4 (3 x 50 MWel) in San Lucar near Sevilla. In the upper part of the picture there are the two solar tower power plants PS 10 and PS 20 with a capacity of 10 respectively 20 MW. (Source: Wikipedia)

Thermal solar power plants have a number of advantages in comparison to photo-voltaic systems (PV) where solar radiation is directly converted into electricity:

1. The specific investment costs and electricity production costs are significantly below those of PV systems.

2. Due to the relatively large thermal inertia of the entire plant resulting from the widely use of large HTF volume (> 1.000 tons), the performance of a solar power plant does not break down immediately at short-term fluctuations of the radiation intensity, as it occurs for example in clouds passes.

To illustrate this, a small numerical example: If the temperature of the entire thermal oil filling (assumption: 1.000 tons) of the power plant drops down at a temperature difference of 50 K within ½ hour due to lack of sunlight, a capacity of just under 70 MW will be released in this period which still corresponds to approximately half of the thermal capacity of the solar field.

1. The integration of thermal energy storage (TES) offers in particular the possibility to decouple in time the provision of the solar process heat from the conversion into electricity ("load management"). That means the power generation can be moved in peak load times when higher feed-in tariffs are paid. The power generation even in times of little or lack of solar radiation is possible due to TES (securing base load and peak load covering). For this reason, numerous solar power plants are equipped with energy storages on the basis of molten salt-hot/cold storages. For a storage capacity of approximately 8 hours full-load operation of a 50 MW_{el} power plant around 30.000 tons of salt are required. In this case the size of the solar field grows from around 330.000 m² to around 520,000 m² up to 530.000 m² (based on radiation conditions as they are found in the south of Spain).

   By using TES, thermal solar power plants – unlike PV systems – can be integrated very well in existing electric grid infrastructures. Especially the growing proportion of renewable technologies in electricity generation poses increasingly a challenge for energy providers (utilities) to ensure coverage of stable power supply with a highly variable offer of renewable generated electricity.

2. Solar thermal solar power plants furthermore can be fitted easily with fossil supplementary firing in form of gas- or oil-fired thermal oil boilers to allow an additional flexible operation of the power plant (to say the power generation) and a longer use of the capital-intensive power plant block that leads to an increase of profitability. Moreover the morning start-up procedure of the steam power process can be expedited by the thermal oil boilers with which an improved use of the solar field is attained. By means of the fired thermal oil boilers, the warm-up of the appliances (steam generator, super heater etc.) is already before the sunrise and just after the sunrise the thermal energy of the solar field can be used directly to generate electricity.

   The total capacity of the thermal oil boilers with 45 to 50 MW comes to around 1/3 of the thermal capacity of the solar field. Due to manufacturing issues, limitations resulting from the road transport, and to ensure sufficient redundancy the total capacity of the fossil supplementary firing is divided on two or three boilers. By the use of air preheaters and burners with O_2 control, these thermal oil boilers attain a thermal efficiency higher than 90 % despite of an inflow temperature of 395 °C.

3 Qualification of parabolic trough collector panels – Mobile Test Unit

For the thermal and fluid dynamical qualification of parabolic trough collector loops a so-called Mobile Test Unit (MTU) can be used. Thereby different operating parameters (mass or volume flow through the collector panel, temperature level of the HTF) are varied under consideration of the current meteorological data (DNI, air humidity and temperature, wind speed) to determine the energy efficiency of collector loops.

The main components of such a plant are:

1. Speed controlled circulating pump with which the volume flow can be variably adjusted through the absorber tube in the range of six to 45 m^3/h.
2. Combined expansion and collecting tanks for receiving the HTF.
3. Air-cooled re-cooler with maximum 2.500 kW of capacity which releases the heat that is absorbed in the collector loops to be tested to the ambient. Here the capacity control is also via a variable speed of the cooling fans.
4. Control and measured value data-processing unit in which in particular the thermodynamical calculation of the collector loop is made.

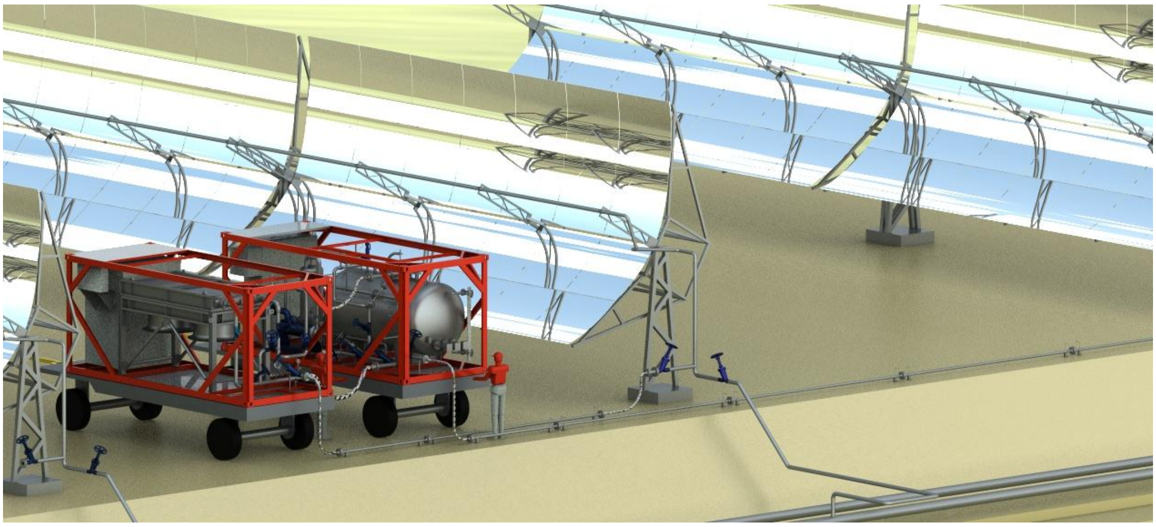


Figure 5: A Mobile Test Unit (MTU) in the solar field (Source: 3D animation heat 11)

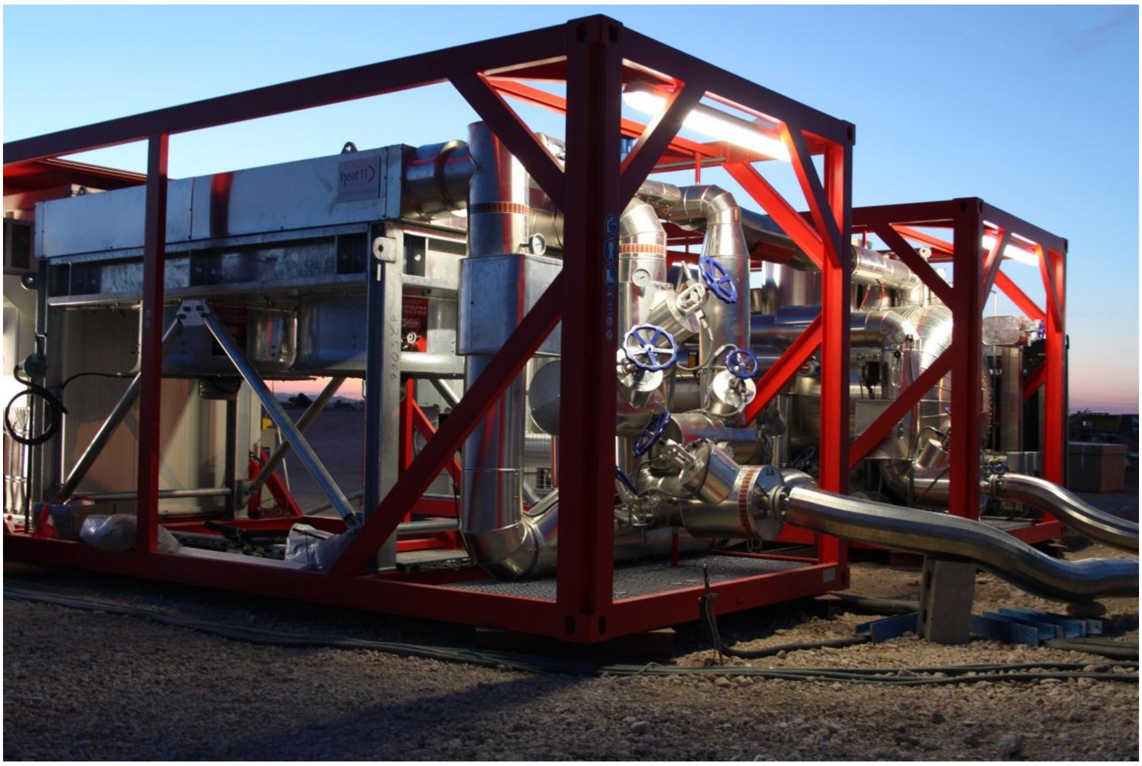


Figure 6: MTU in operation (Source:: heat 11)

The MTU consists of two each 20´ wide modules which are mounted on trailers for the transportation in the solar field. The exchange of the measured data between the modules is via W-LAN.

4 Further developments – Technical trends

The efficiency and economy of parabolic trough solar power plants beyond any doubt have to be further increased to realize marketable electricity generation costs quickly as possible that are determined by fossil CO_2 emitted power plants ("grid parity").

The following points come in the center of attention:

- Reduction of the investment costs by an optimization of the overall concept
- Utilization of the cost advantages by series production of components („effects of scale")
- Longer use of the „power blocks" (night operation with additional fossil firing)
- Reduction of the expenditure of equipment and the internal consumption („parasitics") by direct solar steam generation
- Improving efficiency

From a thermodynamic point of view, the increase of the efficiency in the energy conversion process is the main focus above all, thus an improved utilization of the thermal energy provided by the solar radiation.

Although the „fuel" of a solar power plant is provided free of charge by the sun, the energetic efficiency of the overall energy process – from parabolic reflector via the absorber tube to the steam power process – is determining for the economy of a solar power plant.

The efficiency of the steam power process is described thermodynamically by the Carnot efficiency. This means that the efficiency is higher, the further the upper and lower process temperature is apart. The lower process temperature is determining solely by the condensation temperature in the cooling tower of a power plant – regardless of whether it is a conventional or a solar-powered power plant. Only the method of cooling (wet or dry cooling tower) and the ambient temperature are important here. Both factors are dependent on the relevant location and therefore only conditionally to be influenced.

So the upper process temperature remains as important parameter for increasing the efficiency of a steam power process. In fossil power plants this temperature is determined only by the stability of the materials of the steam generator and the super heater. Today, steam temperatures of > 700 °C already are realized in fossil power plants and thus achieving an efficiency of > 50 %.

In solar thermal power plants, the thermal stability limit of the HTF however limits the upper process temperature and therefore the efficiency. With an outlet temperature of 395 °C from the solar field, the parabolic trough solar power plants now operate at the maximum possible inflow temperature of the used HTF (a eutectic mixture of Diphenyl/Diphenylether, also known as Diphyl, VP-1 or Dowtherm A).

4.1 Liquid salt as HTF

A possibility to further increase the process temperature – and thus the efficiency – is the use of liquid salt as HTF. It is a eutectic mixture from the three components $NaNO_3/KaNO_3/NaNO_2$ with a melting point of approximately 145 °C and an upper application temperature of about 500 °C. The use of liquid salt allows simultaneously the direct storage of the thermal energy without any additional intermediate circuits or heat transfer in large, pressure-less tanks. To get first experiences with this technology, a small solar field with 5 MW of thermal capacity was integrated in a conventional power plant in Prioli Gargallo (Sicilia).

The radiation losses of the solar field however increase with the 4^{th} potency of the temperature of the HTF in the absorber tube of the solar field and are contrary to the increase of the efficiency in the steam power process which arises due to the higher process temperature.

Furthermore it is to consider that the solidification temperature („freezing point“) of liquid salt is at approximately 145 °C (in comparison: Diphyl solidifies at +12 °C). This means considerably higher thermal losses of the solar field during the night or in general in periods at standstill, since the liquid salt in the entire HTF circuit have to be kept constantly above the solidification temperature.

4.2 Direct solar steam generation

The direct steam generation in the solar field offers a number of advantages compared to the previously realized power plant concepts, such as the reduction of the overall process to one single heat transfer circuit. This is associated with less expenditure of equipment (heat exchanger, pumps etc.) and an increase of the efficiency as a result of a generally higher process temperature and a less internal consumption („parasitics").

Technological challenges are, however, the high pressure (> 120 bar) in the widely ramified solar field (e.g. rotary joints on the rows of collectors). The process control of the two-phase flow occurring in the numerous and connected in parallel rows of collectors has to be dominated also. Last but not least, the question of the energy storage is to be considered completely new at the direct evaporation since the direct steam storage of large amounts of energy in a pressure gradient storage (so-called Ruths storage) cannot be presented economically, that means the energy must be transmitted in any case to a secondary, pressure-less storage material. Due to the condensation processes to be considered at the direct solar steam generation (charging of the storage) and the steam generation process (discharging of the storage), at which in each case large amounts of energy are transformed through the phase change, a TES can not only be run as pure sensible storage but latent heat storage systems with phase change materials must be used. Different phase change materials – for the medium temperature range are these for example $NaNO_3$, KNO_3/KCL, KOH, MgCl and mixtures out of it – can be combined to a so-called „cascaded storage" which covers a wide temperature range.

Despite of intensive research within the last 20 years on the field of the direct solar steam generation and the associated energy storage, still numerous questions for the large-scale industrial application are open till this day so that with the application of this technology in parabolic trough solar power plants cannot yet be expected in the coming years, in particular also in the view of the "bankability".

Contact

heat 11 solar GmbH & Co. KG | Otto-Brenner-Straße 203 | 33604 Bielefeld | Germany
fon +49 521 989 110-0 | fax +49 521 989 110-60 | contact@heat11.com | www.heat11.com