Lecture 5: Solar Thermal Power Plants

http://www.cs.kumamoto-u.ac.jp/epslab/APSF/

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Time and Venue:
Wednesdays: 10:20 – 11:50, Room No.: 208
Contents:

1. Introduction & Principles
2. Solar Tower Power Station
3. Parabolic trough Power Plants
4. Dish/Stirling Systems
5. Solar Updraft Tower Power Plants

*Technical Descriptions
*Economic & Environmental Analysis
Solar thermal power plant comprises power plants which first convert solar radiation into heat. The resulting thermal energy is subsequently transformed into mechanical energy by a thermal engine, and then converted into electricity.

For thermodynamic reasons high temperatures are required to achieve the utmost efficiency. Such high temperatures are reached by increasing the energy flux density of the solar radiation incident on a collector.

*Concentrated radiation or concentrating collectors

*Alternative, with regard to technical/economic optimization of the overall system, also lower temperatures, resulting in considerably reduced costs may be desired in some cases (use of large-surface cost-efficient collectors).

rise to a whole series of different solar thermal power plant concepts.
According to the type of solar radiation concentration, solar thermal power plants are subdivided into:

* concentrating (point and line focussing systems)
* non-concentrating systems. The former

Classification can be further made according to:

* type of receiver of the solar radiation
* the heat transfer media and the heat storage system
* additional firing based on fossil fuel energy

Concentrating systems concepts:
- **solar tower power plants** (i.e. central receiver systems) as point focussing power plants,
- **dish/Stirling systems** as point focussing power plants
- **parabolic trough and Fresnel trough power plants** as line focussing power plants.

Concentrating collectors **can reach temperature levels similar** to that of existing fossil-fuel fired thermal power stations (e.g. power plants fired with coal or natural gas)

Non-concentrating systems concepts:
* **solar updraft tower power plants**
* **solar pond power plants**
Process of solar thermal power generation:
- concentrating solar radiation by means of a collector system;
- increasing radiation flux density (i.e. concentrating of the solar radiation onto a receiver), if applicable;
- absorption of the solar radiation (i.e. conversion of the radiation energy into thermal energy (i.e. heat) inside the receiver);
- transfer of thermal energy to an energy conversion unit;
- conversion of thermal energy into mechanical energy using a thermal engine (e.g. steam turbine);
- conversion of mechanical energy into electrical energy using a generator.
Table 5.1  Concentration factors and technical parameters of selected solar thermal power generation technologies

<table>
<thead>
<tr>
<th></th>
<th>Solar tower</th>
<th>Dish/Stirling</th>
<th>Parabolic trough</th>
<th>Fresnel reflector</th>
<th>Solar pond</th>
<th>Solar updraft tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical capacity in MW</td>
<td>30 – 200</td>
<td>0.01 – 1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10 – 200&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10 – 200&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.2 – 5</td>
<td>30 – 200&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Real capacity in MW</td>
<td>10</td>
<td>0.025</td>
<td>80</td>
<td>0.3&lt;sup&gt;d&lt;/sup&gt;</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>Concentration factor</td>
<td>600 – 1,000</td>
<td>up to 3,000</td>
<td>50 – 90</td>
<td>25 – 50</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Efficiency&lt;sup&gt;b&lt;/sup&gt; in %</td>
<td>10 – 28</td>
<td>15 – 25</td>
<td>10 – 23</td>
<td>9 – 17&lt;sup&gt;d&lt;/sup&gt;</td>
<td>1</td>
<td>0.7 – 1.2</td>
</tr>
<tr>
<td>Operation mode</td>
<td>grid</td>
<td>grid/island</td>
<td>grid</td>
<td>grid</td>
<td>grid</td>
<td>grid</td>
</tr>
<tr>
<td>Development status&lt;sup&gt;e&lt;/sup&gt;</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>grid</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>

<sup>a</sup> by interconnection of many individual plants within a farm; <sup>b</sup> conversion of radiation energy into electrical energy, annual average is site-specific; <sup>c</sup> assuming a solar multiple of 1.0; <sup>d</sup> incorporated into a conventional power station; <sup>e</sup> 0 successful operation of demonstration plants, + successful continuous operation of demonstration plants, ++ commercial plants in operation.
2. Solar Tower Power Station

• Main principals and components:
  • Central receiver systems in the tower
  • Mirrors tracking the course of the sun in two axes (Heliostats)
  • Heliostats reflect the direct solar radiation onto a receiver, centrally positioned on a tower.
  • In the receiver, radiation energy is converted into heat and transferred to a heat transfer medium (e.g. air, liquid salt, water/steam).
  • This heat drives a conventional thermal engine.
  • To ensure constant parameters and a constant flow of the working medium also at times of varying solar radiation, either a heat storage can be incorporated into the system or additional firing using e.g. fossil fuels (like natural gas) or renewable energy (like biofuels) can be used.
Heliostats

• Heliostats are **reflecting surfaces** provided with a two-axis tracking system which ensures that the incident sunlight is reflected towards a certain target point throughout the day.
• Heliostats commonly concentrate sunlight by means of a curved surface or an appropriate orientation of partial areas, so that radiation flux density is increased.

Faceted glass/metal heliostat
metal membrane heliostat
Heliostats...cont.

**Heliostats** consist of:
- the reflector surface (e.g. mirrors, mirror facets, other sunlight-reflecting surfaces)
- a sun-tracking system provided with drive motors
- foundations and control electronics.

The **individual heliostat’s orientation** is commonly calculated on the basis of:
- the current position of the sun
- the spatial position of the heliostats
- the target point.

The target value is communicated electronically to the respective drive motors via a communication line. This information is updated every few seconds.

The concentrator surface size of currently available heliostats **varies between 20 and 150 m²; to date, the largest heliostat surface amounts to 200 m².**

The **heliostat field** accounts for about half the cost of the solar components of such a power plant. This is why tremendous efforts have been made to develop heliostats of **good optical quality, high reliability, long technical life and low specific costs.**

*Due to economic considerations there is a tendency to manufacture heliostats with surfaces ranging **between 100 and 200 m²** and possibly beyond.*

*However, there are also approaches to manufacture **smaller heliostats** to reduce costs by efficient mass-production*
Controller:
• Heliostats are usually centrally controlled and centrally supplied with electrical energy.
• As an alternative, autonomous heliostats have been developed which are controlled locally.
• There, the energy required for the control processor and the drives is provided by photovoltaic cells mounted parallel to the reflector surface.
Heliostat fields

The layout of a heliostat field is determined by technical and economic optimization:
• Heliostats located closest to the tower present the lowest shading,
• Heliostats placed north on the northern hemisphere (or south on the southern hemisphere) show the lowest cosine losses.
• Heliostats placed far off the tower, by contrast, require highly precise tracking and, depending on the geographic location, have to be placed farer from the neighboring heliostats.

Notes:

Cosine losses: representing the difference between the amount of energy falling on a surface pointing at the sun, and a surface parallel to the surface of the earth

The cost of the land, the tracking and the orientation precision thus determine the economic size of the field.
The height of the tower, on which the receiver is mounted, is also determined by technical and economic optimization.

- Higher towers are generally more favorable, since bigger and denser heliostat fields presenting lower shading losses may be applied.
- However, this advantage is counteracted by the high requirements in terms of tracking precision placed on the individual heliostats, tower and piping costs as well as pumping and heat losses.

- Common towers have a height of 80 to 100 m.
- Lattice as well as concrete towers are applied.
Receivers of solar tower power stations serve to transform the radiation energy, diverted and concentrated by the heliostat field, into technical useful energy. Nowadays, common radiation flux densities vary between 600 and 1,000 kW/m². Receivers classification according to:
• the applied heat transfer medium (e.g. air, molten salt, water/steam, liquid metal)
• the receiver geometry (e.g. even, cavity, cylindrical or cone-shaped receivers)

According to heat transfer medium:
• Water/steam receiver
• Salt receiver
• Open volumetric air receiver
• Closed (pressurised) air receivers
**Water/steam receiver**

first solar tower power stations (e.g. Solar One in California, CESA-I in Spain)

• Similar to conventional steam processes, water is vaporized and partly superheated in such a heat exchanger (i.e. tube receiver).
• Since superheating is prone to unfavorable heat transmission, and due to the fact that start-up operation or part-load operation require complicated controls, this approach is currently not developed further.

Vertical tube receivers using salt as heat transfer medium
Salt receiver

• The difficulties of heat transmission with a vertical tube receiver, exemplarily shown in the previous figure, can partly be avoided by an additional heat transfer medium circuit.
• The heat transfer medium applied for this secondary circuit should have a high heat capacity and good thermal conduction properties.
• Molten salt consisting of sodium or potassium nitrate (NaNO$_3$, KNO$_3$) complies with these requirements.

One disadvantage of all such salt receiver:
* the salt must be kept liquid also during idle times when there is no solar radiation. This requires to either heat the whole part of the installation that is filled with salt (including, among other components, tanks, tubes, valves) and thus increases the energy consumption of the plant itself, or to completely flush the salt circuit.
* The highly corrosive gas phase of the used salts also has a detrimental effect, since, for certain operations, undesired evaporation of small amounts of salt due to local overheating cannot be entirely ruled out.
**Open volumetric air receiver**

Such volumetric receivers are characterized by a high ratio of absorbing surface to flow path of the absorbing heat transfer medium air.

**Principals:** Ambient air is sucked in by a blower and penetrates the radiated absorber material. The air flow absorbs the heat, so that those absorber areas facing the heliostat are cooled by the inflowing air.

**Advantages:** Air as heat transfer medium presents the advantages of being non-toxic, noncorrosive, fire-proof, everywhere available and easy to handle.

**Disadvantages:**
* low heat capacity requiring large heat transmission surfaces (generally feasible with volumetric receivers).
* their lower thermal masses ensure a smooth start-up of the plant.

![Diagram of Open volumetric air receiver](image)

*Fig. 5.8 Open volumetric air receiver according to the Phoebus principle*
Closed (pressurized) air receivers

- Receivers of solar tower power plants may also be designed as closed pressurized receivers.
- The aperture of such receivers is closed by a fused quartz window, so that the working medium air may be heated under overpressure and may, for instance, be directly transferred to the combustor of a gas turbine.
- E.g: a group of closed air receivers of a heat capacity of up to 1,000 kW has been tested at 15 bar.
- The obtained air outlet temperatures are slightly above 1,000 °C
- For commercial applications several module groups may be added

Closed volumetric air receiver cluster equipped with secondary concentrators
Power Plant Systems

Solar tower power plants are mainly based on conventional power plant components commercially available today;
*the currently achievable pressures and temperatures of the working media applied for solar tower power plants are in line with the current power plant technology.
*Solar tower power plants within the capacity range from 5 to 200 MW can thus be designed using commercially available turbines and generators including all required auxiliaries

✓ According to the applied heat transfer fluid or working medium, different system concepts are applied
✓ Since open or cavity tube receivers reach working temperatures of approximately 500 to 550 °C, they are predominantly applied for Rankine cycles run by steam.
✓ Steam is either generated directly inside the receiver or by the secondary circuit (e.g. molten salt).
Power Plant Systems...cont.

• Hot air of approximately 700 °C generated by **open volumetric receivers** can be used within existing steam generators, similar to e.g. heat recovery boilers.
• **The inlet temperature** can, for instance, be maintained constant by an incorporated natural gas-fired duct burner, so that this concept is particularly suitable for **hybridization** (i.e. application of solar energy in combination with fossil fuels like e.g. natural gas).
• Outlet gas/air is re-transferred to the receiver by means of a blower so that at least up to **approximately 60 % are re-circulated**.

Another possibility is the so called **inverse gas turbine process**. Within such a cycle an open volumetric air receiver is used and the hot air is directly fed into the gas turbine where the air is expanded. One advantage compared to a steam cycle is a much simpler design. But so far such cycles have **only been analyzed theoretically**.

Some examples of power plant/projects....
Solar Two

• With the aim to solve the problems encountered with the Solar One plant, the latter was remodeled to the Solar Two plant.
• As heat transfer and heat storage medium, molten salt consisting of 40% potassium and 60% sodium nitrate was applied.
• Thanks to the use of additional thermal energy storage the system is more independent from the available solar radiation.

• Salt is pumped from a "cold" salt storage onto the tower and transferred from there into the receiver, where it is heated by the reflected solar radiation. Subsequently,
• It reaches the "hot" tank. Hot salt, and thus energy is taken as needed from the storage facility and pumped through a steam generator that generates steam for a conventional steam turbine cycle.
• Afterwards, the salt cooled inside the steam generator reaches again the "cold" salt storage.

Solar Two shows an electric output of 10 MW which can be maintained up to three hours after sunset thanks to the plant’s energy storage.
Phoebus/TSA/Solair

TSA: Technology Program Solar Air Receiver

- Phoebus/TSA/Solair is a power plant concept with an open volumetric air receiver that provides hot air
- The hot air is subsequently passed through a steam generator providing superheated steam that can be used to drive a turbine/generator unit

A natural gas-fired duct burner placed in between the receiver and the steam generator adds heat to the air if solar radiation is insufficient to supply the desired steam quantity.
- The Phoebus plant can thus not only generate power in times of sunshine but also during spells of bad weather and during the night; power generation is thus not exclusively dependent on the available solar radiation.
Economic Analysis

Assumption: a technical lifetime of 25 years for all machine equipment & an interest rate of 4.5 %

The installation of solar thermal plants only makes sense in areas with a high share of direct radiation:

- A reference site with a total annual global radiation on the horizontal surface of 2,300 kWh/m² and a direct radiation total of 2,700 kWh/m² has been defined.

Based on these site conditions a 30 MW solar tower power plant provided with an open volumetric receiver is assessed.

<table>
<thead>
<tr>
<th>Technical data of the assessed 30 MW solar tower power plant</th>
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</thead>
<tbody>
<tr>
<td>Nominal capacity</td>
</tr>
<tr>
<td>Mirror surface</td>
</tr>
<tr>
<td>Full-load hours</td>
</tr>
<tr>
<td>Storage capacity</td>
</tr>
<tr>
<td>Solar share</td>
</tr>
<tr>
<td>Technical lifetime</td>
</tr>
</tbody>
</table>
Economic Analysis...cont

Table 5.4 Mean investment and operation costs as well as resulting power generation costs for the reference solar tower power plant

<table>
<thead>
<tr>
<th>Nominal capacity</th>
<th>30 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investments</td>
<td></td>
</tr>
<tr>
<td>heliostat field</td>
<td>30 Mio. €</td>
</tr>
<tr>
<td>receiver and steam generator system</td>
<td>20 Mio. €</td>
</tr>
<tr>
<td>tower</td>
<td>15 Mio. €</td>
</tr>
<tr>
<td>other components</td>
<td>20 Mio. €</td>
</tr>
<tr>
<td>assembly and commissioning</td>
<td>10 Mio. €</td>
</tr>
<tr>
<td>design, engineering, consulting, miscellaneous</td>
<td>5 Mio. €</td>
</tr>
<tr>
<td>Total</td>
<td><strong>99 Mio. €</strong></td>
</tr>
<tr>
<td>Operation and maintenance costs</td>
<td><strong>1.5 Mio. €/a</strong></td>
</tr>
<tr>
<td>Power generation costs</td>
<td><strong>0.13 €/kWh</strong></td>
</tr>
</tbody>
</table>

**Power generation costs** are largely influenced by the number of full-load hours per year, the investment costs and the mean interest rate.
Environmental analysis

Manufacture (construction):
• Environmental effects related to solar thermal plants may already arise during production of the different plant components.
• They are to a large share the same as for conventional power plants and other industrial production processes.
• However, the resulting environmental effects are restricted to very limited periods of time, and in many countries they are subject to extensive legal requirements.
• Furthermore, solar thermal power plants are primarily located in deserts and steppes where the population density is relatively low. This is why there is so far only a very limited knowledge on the potential effect on human beings and on the environment.
Solar thermal power plants use solar radiation as a source of energy, i.e. an energy source with a **comparatively low energy density**. *This is why such plants necessarily require large collector areas and thus extensive land areas.*

- Soil (dessert & steppe): erosion $\rightarrow$ foundation & extensive drainage system
- highly grown plants may disturb operation and reduce the technical lifetime of the collectors
- Fence (entire plant): the glass reflectors, the collector fields are susceptible to damages caused by e.g. extreme winds
**Visual impact:** Due to their central tower, mainly tower and solar updraft power plants have a non-negligible impact on the appearance of the natural scenery; the higher the tower the bigger this influence is (approximately 100 m in case of solar tower power plants, and 1,000 m for solar updraft tower power plants).

*the disturbance of the scenery is static since no moving parts compared to (such as the rotors of wind energy converters) → are more readily accepted by the spectator*

*At night time, indispensable aviation warning lamps might be perceived as disturbing*

**Reflections:** Provided that power plants are operated properly, i.e. mirrors are precisely tracking, none of the known environmental effects will occur. However, due to the partly very high energy flow densities of the focused solar radiation, persons and/or assets may be exposed to considerable hazards *in case of improper operation.*

**Emissions:** Since some solar thermal power plants also apply conventional power plant technology they are also potential sources of airborne emissions. However, greenhouse gas emissions as well as other types of emissions are only released into the atmosphere *during hybrid operation* involving fossil or biogenous combustibles.
End of operation:
To avoid undesired environmental effects, the plants are properly dismantled and discarded at the end of operation.
They are mostly similar to those of conventional machine technologies, which are relatively low due to the applicable legal requirements.

Malfunction:
at the most, the same environmental effects as for conventional power stations fired by fossil or biogenous energy carriers are to be expected.
Further malfunctions that may arise with regard to solar farms are: 
operating failures due to heat transfer fluid leakage causing personal and environmental damages.
Solar Pond Power Plants

Introduction:
• Solar ponds are power plants that utilize the effect of water stratification as a basis for the collector.
• A basin filled with brine (i.e. a water/salt mixture) functions as collector and heat storage.
• The water at the bottom of the solar pond serves as primary heat storage from which heat is withdrawn.
• The deeper water layers and the bottom of the solar pond itself serve as absorber for the impinging direct and diffuse solar radiation.
• Due to the distribution of the salt concentration within the basin, which increases towards the bottom of the basin, natural convection and the ensuing heat loss at the surface due to evaporation, convection and radiation is minimized.
• This is why heat of an approximate temperature between 80 and 90 °C (approximate stagnation temperature 100 °C) can be extracted from the bottom.
• Heat can then be used for power generation.
Technical Description

*System components:*
- Pond collector
- Heat Exchangers
- Thermal Engine
*Plant concepts*
System components: Pond collector

- Pond collectors are either natural or artificial lakes, ponds or basins that act as a flat-plate collector because of the different salt contents of water layers due to stratification.
- The upper water layers of relatively low salt content are often provided with plastic covers to inhibit waves.
- This upper mixing zone of such pond collectors usually is approximately 0.5 m thick.
- The adjacent transition zone has a thickness of 1 to 2 m, and the lower storage zone is of 1.5 to 5 m thickness.

Mechanism:
- If deeper layers of a common pond or lake are heated by the sun, the heated water rises up to the surface since warm water has a lower density than cold water.
- The heat supplied by the sun is returned to the atmosphere at the water surface.
- This is why, in most cases, the mean water temperature approximately equals ambient temperature.
- In a solar pond, heat transmission to the atmosphere is prevented by the salt dissolved in deeper layers, since, due to the salt, water density at the bottom of the pond is that high, that the water cannot rise to the surface, even if the sun heats up the water to temperatures that are close to the boiling point.
System components: 
Pond collector…cont.

◆ The salt concentration of the different layers must thus increase with increasing depth
◆ In a first phase, this ensures stable water stratification.
◆ The upper, almost salt-less layer only acts as transparent, heat-insulating cover for the cooling, heat-storing deeper layers at the pond bottom.
System components:
Pond collector…cont.

**Attentions:**
- To ensure stable stratification of a solar pond, with increasing depth the temperature increase must not exceed density increase (i.e. salt content). This is why all relevant parameters must be continuously monitored in order to take appropriate measures (e.g. heat withdrawal, salt supply) in due time.
- To achieve the utmost collector efficiency, a high portion of the solar radiation must reach the absorption zone. Yet, this can only be achieved, if the top layers are of sufficient transmission capability.

**Monitoring:**
During the operation of a solar pond, the transmissivity, the salt content and the temperature must be regularly monitored.
The timely course of these parameters must be measured from the water surface to the ground in order to determine the heat quantity that can be withdrawn from the pond or to determine the measures to maintain the respective required salt concentration and the water quality (prevention of turbidity due to particulate matter, algae or bacteria).
System Components: Heat exchangers

Basically, there are two methods to withdraw heat from a solar pond:
- The working fluid of the thermal engine flows through tube bundle heat exchangers installed within the storage zone of the solar pond, and is thereby heated up.
- The hot brine can also be pumped from the storage zone by means of an intake diffuser, subsequently be transmitted to the working fluid of the thermal engine and eventually be re-supplied to greater depths of the pond by another diffuser, once the brine has cooled down.

*The technical approach allows adjusting the position of the intake diffuser to the depth of the highest temperature. Secondly, heat losses by the pond bottom are reduced, since the cooled water is recycled to the pond near the bottom.*
To convert solar thermal energy into mechanical and afterwards in electrical energy, usually **Organic Rankine Cycles (ORC)** processes are applied.

These are basically steam cycles which utilize a low-boiling, generally organic, cycle fluid.

Such processes permit to provide electrical energy also at **low useful temperature differences**.
Plant Concepts

- The water absorbs the incident direct and diffuse radiation, similar to the absorber of a conventional solar collector, and is heated up.
- The technically adjusted salt concentration prevents natural convection and the resulting heat loss at the surface due to evaporation, convection and radiation.

*Water can thus be withdrawn from the storage zone at the bottom at an approximate temperature of 80 – 90°C. This heat can subsequently be used for power generation by an ORC process.
Solar pond power plants of electric capacities from a few ten kW up to a few MW have been built in Israel, the US (Texas), Australia (for process heat provision), among other countries.

With approximately one percent, solar thermal efficiencies are low; the mean specific capacities range from 5 to 10 W/m² depending on radiation, salt content and maximum temperature.

For the short-term, also higher capacities can be withdrawn; however, in such a case the solar pond would cool down much faster.

<table>
<thead>
<tr>
<th>Plant Concepts…cont.</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Capacity</th>
<th>El Paso, Texas, USA</th>
<th>Beit Ha’Arava, Israel</th>
<th>Pyramid Hill, Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (kW&lt;sub&gt;th&lt;/sub&gt;)</td>
<td>300 kW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>5 MW&lt;sub&gt;el&lt;/sub&gt; max.</td>
<td>60 kW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Capacity (kW&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>70 kW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>570 kW&lt;sub&gt;el&lt;/sub&gt; (average)</td>
<td></td>
</tr>
<tr>
<td>Pond surface (m²)</td>
<td>3,350 m²</td>
<td>250,000 m²</td>
<td>3,000 m²</td>
</tr>
</tbody>
</table>
Economic and environmental analysis

Economic analysis:
* Investment costs
* Operation costs
* Electricity generation costs

Environmental analysis:
Economic analysis

**General:**
- The costs for construction and operation are determined and assessed in the form of annuities.
- On this basis and the produced electrical energy, the power generation costs are calculated. For this purpose, a technical lifetime of 25 years and an interest rate of 4.5% have been assumed.
- Since such plants are only installed in areas with a high share of solar radiation, a reference site has been assumed which is characterized by an annual total global radiation on the horizontal axis of **2,300 kWh/m²**.

<table>
<thead>
<tr>
<th>Outlines the main parameters of the assessed solar pond (capacity of 5 MW):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity</td>
</tr>
<tr>
<td>Collector surface</td>
</tr>
<tr>
<td>Heat exchanger</td>
</tr>
<tr>
<td>Full-load hours</td>
</tr>
<tr>
<td>Storage</td>
</tr>
<tr>
<td>Solar share</td>
</tr>
<tr>
<td>Net efficiency</td>
</tr>
</tbody>
</table>

*a* The average capacity amounts to approximately 650 kW; at short-term higher capacities are possible so that higher revenues can be achieved (peak-load power); *b* efficiency between incident solar radiation and produced electric energy.
Economic analysis

Investment costs

• Since there are only a few solar ponds, all of them being unique, there are virtually no market prices available that could serve as a basis for these analyses.
• This is why the following cost estimations have been based on literature values.
• For this purpose, specific investment costs of 40 €/m² of pond surface have been assumed.
• Literature values are based on cost estimations for civil engineering works and geomembranes; other sources indicate values between 15 and 75 US$/m². For the overall plant, in total, specific investment costs of approximately 2,000 €/kW are assumed.

<table>
<thead>
<tr>
<th>Table 5.18</th>
<th>Estimation of the power generation costs of a 5 MW solar pond provided with external heat exchanger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific investment costs</td>
<td>2,000 €/kW</td>
</tr>
<tr>
<td>Operation costs</td>
<td>100,000 €/a</td>
</tr>
<tr>
<td>Power generation costs</td>
<td>0.14 €/kWh</td>
</tr>
</tbody>
</table>
Economic analysis

Operation and electricity generation costs

Operation costs:
• Operation costs are estimated at a lump-sum of 1% of the investment costs.
• Besides the maintenance of the heat exchangers and the ORC plant further measures are required since the salt that diffuses from the bottom to the surface has to be retrieved.
• Compared to conventional steam power plants, the required water quantity is thus many times higher.

Electricity generation costs:
• The power generation costs for a solar pond of a surface of 250,000 m² and annual operation costs of approximately 100,000 €, amount to approximately 0.14 €/kWh.
• However, it has been assumed that brine or appropriate salt are available at the site free of charge, so that only transportation measures are required.

For an economic assessment within the scope of operational optimization:
It also has to be considered that electric capacity must be available at any time of the day. Solar ponds can thus generally also serve as peak-load power stations.
Environmental analysis

- The environmental effects of solar pond power plants are largely similar to those of solar tower power plants.
- Additionally, the salt brine might cause environmental effects when polluting the surroundings of a solar pond.
- Also, the use of fresh water during the operation of such plants might be considerable.
  *In areas with a shortage of water this could lead to environmental effects.