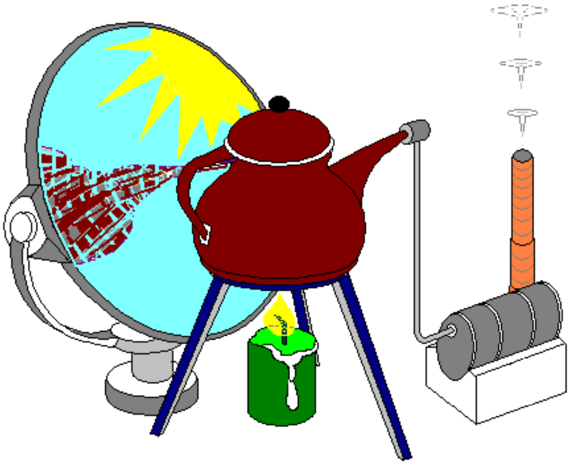
SIXTH INTERNATIONAL SUMMER SCHOOL
SOLAR ENERGY 2000

Workshop 2

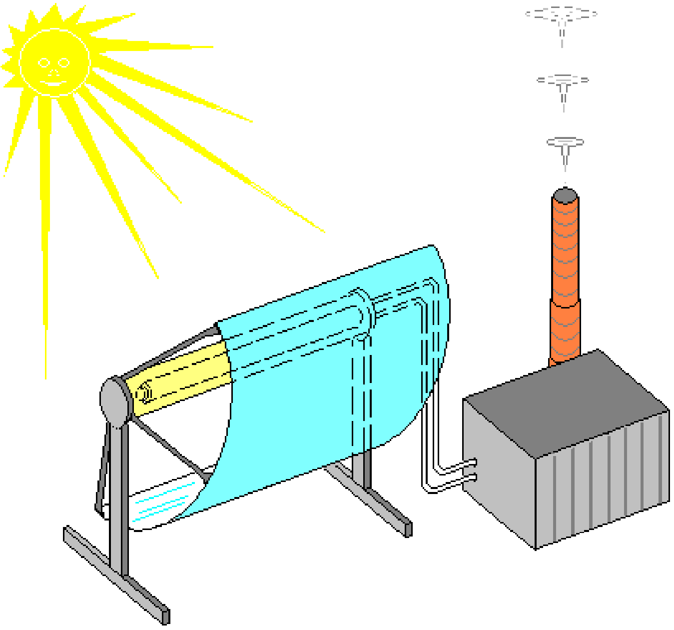
SOLAR THERMAL POWER PLANTS

Klaus-Jürgen Riffelmann et al.



Solar Power Plants

How big a plant is big enough?



Abstract Workshop II:
Solar Thermal Power Plants

Leader: **Klaus-Jürgen Riffelmann**
Participants: **S. Alexopoulos, S. Binkowski, S. Heidt, M. Sauerborn, G. Resch, A. Vormaier**

Introduction and goal of the workshop

Electricity generation by solar thermal power plants is the most economic way to produce solar electricity. In 1984 the first large scale parabolic trough power plant was built in the Californian Mojave desert. Up to now nine Solar Electricity Generating Systems (SEGS I to SEGS IX) with an total electrical power of 354 MW are in operation. Cylindrical parabolic mirrors concentrate solar radiation on to a black absorber tube transforming radiation into heat. A thermal oil flowing through the tube transports gained energy to heat exchangers, which are connected to a conventional power block with steam turbine and electrical generator.
It is obvious that solar thermal power generation is environmentally more benign than conventional power generation, the later driven by a fossil fuel. But, like other renewables too, it is not free of emission. During the whole life cycle– from planning, construction and engineering, over operation to dismantling of the plant - many processes are related to energy consumption.

Goal of the workshop was to quantify the total energy demand in relation to the energy output during the life time of a solar thermal power plant. Therefore a 80 MW_e parabolic trough plant near Barstow, California, was designed and finally compared with the real plant (SEGS IX). We focussed on the solar part only, comparing the energy demand for the whole life cycle of the collector field including its connection to the power block on the one hand to the net solar electricity output on the other hand.

Method

In the first part of the workshop the participants calculated step by step the amount of solar energy that can be gained by a parabolic trough collector:
First of all some astronomical and physical basics relevant for this problem were treated, sun angles were introduced. Applying the radiation laws by Planck and Stefan-Boltzmann and with the knowledge of the sun-earth distance and the surface temperature of the sun, the extraterrestrial irradiance (Solar Constant) was calculated. With a very simple atmospheric model and with geometrical calculations, the solar radiation energy that can be caught by a horizontally, one-axis tracking parabolic trough collector was estimated. The collector efficiency was estimated, considering the heat transfer mechanisms and applying energy balances of a short receiver length in a typical steady state. With these data the number of collectors (resp. collector aperture area) could be estimated.

In the second part of the workshop a life cycle analysis was carried out. We focused on the construction of the LS-3 collector and on the arrangement of such collectors in a 80 MW SEGS-plant. We discussed also energy consumption for planning work, transport, operation and maintenance, dismantling of the plant. The mass of the used materials could be estimated, using literature data. With the knowledge of the energy content of these materials, also taken from literature, the "grey energy" of the solar thermal power plant could be estimated.

Results

To operate a 80 MW solar thermal power plant (SEGS-type) in a hybrid mode (25 % fossil fuel, 75 % solar), 888 LS-3 collectors with 545 m² aperture area each are necessary. Such a plant produces 256 GWh electricity per year, thereof 192 GWh pure solar electricity. Assuming a life time of 30 years, 5760 GWh solar electricity are generated.

The life cycle analysis resulted in a grey energy content of 647 GWh (in mixed composition, mostly thermal energy!). The energy pay back time is then 3.4 years.

Workshop II:
Solar Thermal Power Plants

Klaus-Jürgen Riffelmann
S. Heidt, S. Binkowski, A. Vormaier, M. Sauerborn, S. Alexopoulos, G. Resch

Abstract

Electricity generation by solar thermal power plants is the most economic way to produce solar electricity. In 1984 the first large scale parabolic trough power plant was built in the Californian Mojave desert. Up to now nine Solar Electricity Generating Systems (SEGS I to SEGS IX) with an total electrical power of 354 MW are in operation. Cylindrical parabolic mirrors concentrate solar radiation on to a black absorber tube transforming radiation into heat. A thermal oil flowing through the tube transports gained energy to heat exchangers, which are connected to a conventional power block with steam turbine and electrical generator.

It is obvious that solar thermal power generation is environmentally more benign than conventional power generation, the later driven by a fossil fuel. But, like other renewables too, it is not free of emission. During the whole life cycle– from planning, construction and engineering, over operation to dismantling of the plant - many processes are related to energy consumption.

Aim of the workshop was to quantify the total energy demand in relation to the energy output during the life time of a solar thermal power plant. Therefore a 80 MW_e parabolic trough plant near Barstow, California, was designed and finally compared with the real plant (SEGS IX). We focussed on the solar part only, comparing the energy demand for the whole life cycle of the collector field including its connection to the power block on the one hand to the net solar electricity output on the other hand.

1 Solar Basics: Astronomical fundamentals, sun angles and radiation laws

1.1 Astronomical fundamentals

The sun is a sphere of intensely hot gaseous matter with a radius R_{sun} of $6.96 \cdot 10^8$m.

The distance between earth and sun from the point of the vernal or autumnal equinox is $1.496 \cdot 10^{11}$ m. This mean earth-sun distance is also called astronomical unit (1AU).

The eccentricity of the earth´s orbit is such that the distance between sun and earth varies by 1.7%. For this reason the distance between sun and earth at perihelion is 0.983 AU and between sun and aphelion 1.017 AU (see figure 1).

As the sun does not rotate as a solid body on an ellipse around the sun, the equator needs about 27 days, the poles nearly 30 days for each rotation, the obliquity of the ecliptic is 23°27´.

The exact value for the earth rotation period is 23h 56´04´´.

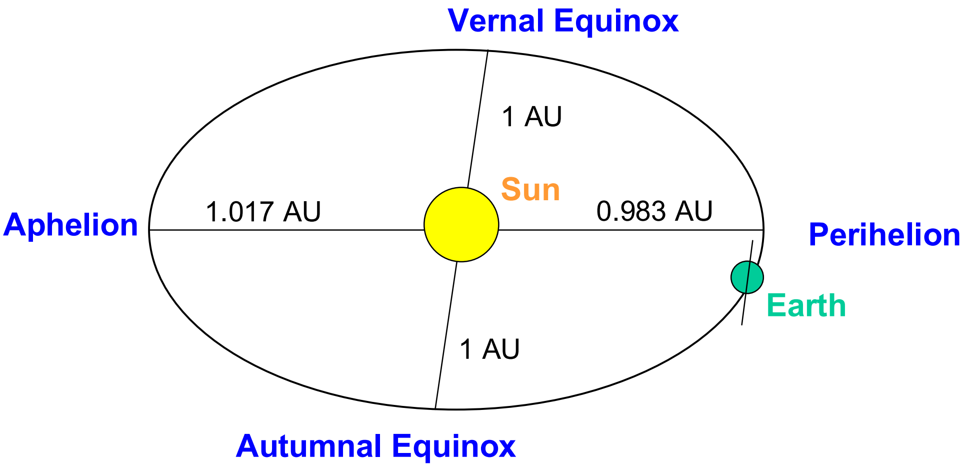


Figure 1: Distances between earth and sun on a revolution

1.2 Sun angles

The geometric relationship between a location on the surface the earth ("observer point O") at any time and the incoming beam solar radiation, that means the position of the sun relative to the location, can be described in terms of several angles (see figure 2 a - c).

The **latitude Φ** is the angel between the position of the observer and the equator plane north or south of the equator with earth's centre as vertex. The latitude is counted in north-direction positive: $-90° \leq \Phi \leq 90°$

The **declination δ** is the angel between the normal to the sun (line trough earth's centre and the point on earth's surface where the sun is in the zenith) and the plane of the equator. The declination varies yearly between $-23.45° \leq \delta \leq 23.45°$, negative in the south, positive in the north of the equator. The maximum rate of change of declination is at the position of vernal and autumnal equinox with about 0.5° per day.

The **hour angle ω** is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour. The hour angle is defined to be positive in the morning and negative in the afternoon.

The **elevation ε** or also called **altitude** is the angle between the horizontal plane and the line to the sun

The **azimuth ψ** is the angular displacement from south of the projection of beam radiation on the horizontal plane. The displacements east of south are positive, west of south are negative.

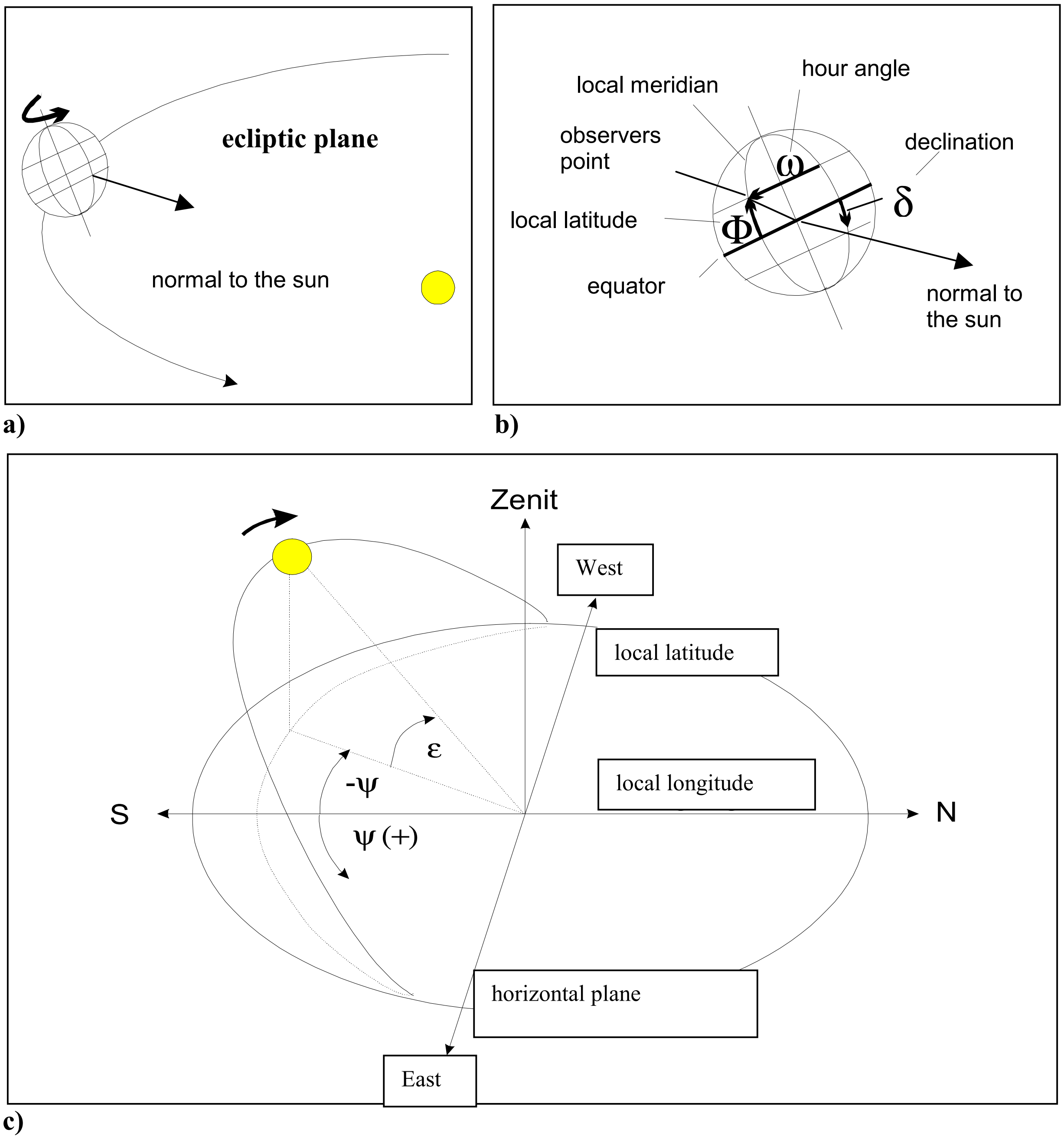


Figure 2: a) and b) explain the declination, hour angle and latitude, c) explains the azimuth and elevation angle with reference to the local horizontal plane

1.3 Radiation Laws

Regarding the three heat transfer mechanisms - conduction, convection and radiation - only radiation is feasible to get energy from sun to earth.

In the following the corresponding equations used for calculating the energy pay back time are introduced.

1.3.1 Max Planck's Law

Black bodies emit radiation according to their temperature:

$$I_\lambda = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{kT\lambda}\right) - 1\right]}$$

h:	Quantum of Action	6.6261 E-34	Js
c:	Speed of Light	2.9988 E8	m/s
k:	Boltzmann-Constant	1.38 E-23	Nm/K
T:	Temperature		K
λ:	Wavelength		m

The integration of this equation over all wavelengths leads to:

1.3.2 Stefan-Boltzmann Law

$$I = \sigma T^4$$

σ:	Stefan-Boltzmann-Constant	5.67 E-8	W/m^2K^4
T:	Temperature		K

These equations are valid for black bodies. This means their emissivity ε is 1 for all wavelengths. In contrast so called grey bodies have a emissivity between 0 and 1 independent of the wavelength. The emissivity of real (coloured) bodies depends on the wavelength.

Real body:	$I_\lambda = \varepsilon(\lambda)\cdot\ldots$
Black body:	$\varepsilon = 1$
Grey body:	$0 < \varepsilon < 1,\ \varepsilon \neq f(\lambda)$
Coloured body:	$0 < \varepsilon(\lambda) < 1$

1.3.3 The Solar Constant

Assuming the sun is a black body with a temperature of 5777 K and with the knowledge of the sun-earth distance, the solar constant can be calculated. This value gives the average amount of solar radiation reaching the earth for a certain area. Therefor a dilution factor is used describing the ratio of the suns surface towards the distance from sun to earth. Finally one gets:

$$I = 5.67\cdot 10^{-8}\cdot 5777^4\cdot\left(\frac{6.96\cdot 10^8}{1.496\cdot 10^{11}}\right)^2\frac{kW}{m^2} = \underline{\underline{1.367\frac{kW}{m^2}}}$$

1.3.4 Atmospheric Influences

The calculation above does not take into account any atmospheric influences. To get an expression describing the disturbance of the atmosphere the air mass (m) is introduced. This factor is the ratio of the way the incident rays take through the atmospheric layer (BP) towards the shortest way (AP).

$$m=\frac{\overline{BP}}{\overline{AP}}=\frac{1}{\sin\alpha}$$

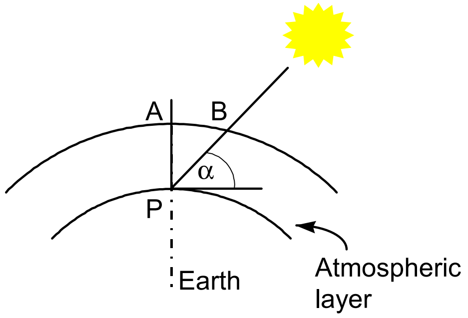


Figure 3: Definition of air mass

Now the atmospheric transmission can be estimated:

$$\tau_{atm}\approx\frac{I_{terr}}{I_{ext}}=\exp(-k\cdot m)$$

m: Air mass
k: Atmospheric turbidity factor

The atmospheric turbidity factor equals 0.2 for blue skies. In metropolitan areas it is about 0.5 and on a ‘grey in grey’ sky it is approximately 1.

With these expressions the irradiance on the earth’s surface is calculable.

The following figure shows the extraterrestrial irradiance and the filtered spectral irradiance on earth. In addition the part of the UV, IR and visible spectrum and the influences of atmospheric components (e.g. O_3, H_2O, CO_2) are indicated. Also assuming the sun being a black body is nearly correct.

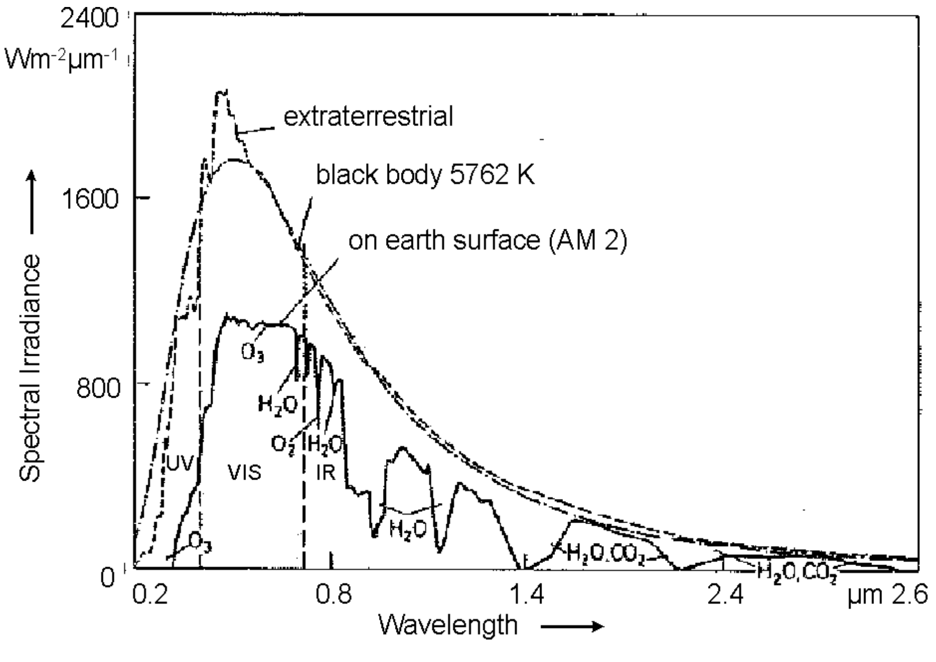


Figure 4: Black body radiation, extraterrestrial and AM 2 solar spectrum

2 Solar energy potential at Barstow, California, on a north-south-orientated one axis tracking parabolic trough

Our next goal is to asses the solar energy input to a power plant. The first step is to calculate the radiant energy coming down on the collector aperture. Crucial for that is the variation of the elevation of the sun, that controls the air mass factor, as well as the incidence angle, the angle between sun-rays and the perpendicular of the aperture plane.
The ensuing radiant energy influx calculation is – for comparison reasons - done for the village of Barstow, California, (latitude 35° N and longitude 117° W) which is next to the SEGS IX-plant. The standard longitude for the relevant time zone is 120° W.
The potential radiation influx on March 21, the vernal equinox is considered to be very close to the average of the days of the year. Higher influx during the summer season will be compensated by a lower one in winter.

The axis of the trough collector is N-S oriented. The collector is able to track the sun in the E-W direction. This is also to compensate the very high air mass factors after sun rise and before sun set. At these times, when the radiation - after a long way through the atmosphere - is low, the incidence angle is close to zero and the so called cosine-losses are the lowest.

Using the following equations, the elevation and the incidence angle can be calculated:

declination δ: $\delta = 23{,}45 * \sin(0{,}01721*(N+284))$
elevation ε: $\sin(\varepsilon) = \sin(\delta)*\sin(\Phi)+\cos(\delta)*\cos(\Phi)*\cos(\omega)$
azimuth ψ: $\cos(\psi) = (\sin(\varepsilon)*\sin(\Phi)-\sin(\delta)/\cos(\varepsilon)*\cos(\Phi)$
incidence angle γ: $\cos(\gamma) = (1-\cos^2(\varepsilon)*\cos^2(\psi))^{0,5}$

-with „N“ the number of the day in the year, (80 for March 21), „Φ“ the latitude, and „ω“ the hour angle.

The values of the elevation, the azimuth and the incidence angle are plotted over the local time.

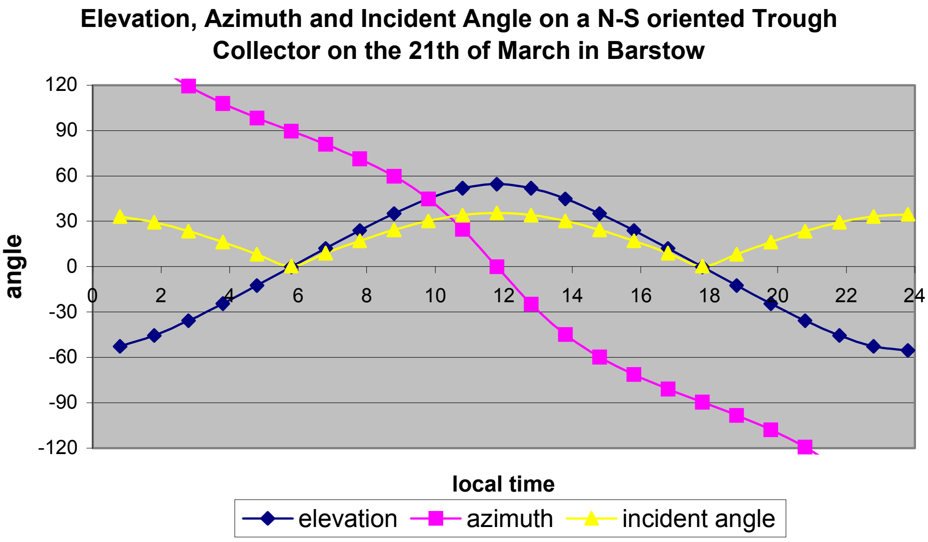


Figure 5

The azimuth, the angle between south direction and the projection of the sun rays to the horizontal plane, will be zero at noon solar time (about 11:40 local time) and + or – 180° at midnight.

The elevation, the angle between the sun rays and the horizontal plane for us – of course – is relevant only between sun rise and sun set, which on March 21 is 6:00 am and 6:00 pm respectively. At noon it will rise to 55° (90° minus the latitude).
The incidence angle, the angle between sun rays and the perpendicular of the aperture plane, - on March 21 - is zero at sun rise and sun set and is as high as 35° at noon. In other words: The sun rays come in perpendicular to the aperture at 6:00 am and 6:00 pm and reach the value of the latitude at 12:00.

Knowing the sun´s elevation as well as the incidence angle on the aperture and thus knowing the air mass factor ($m = 1/\sin(\varepsilon)$) and the „cosine losses“, we are able to estimate how many Watts per square meter are irradiated on the aperture with respect to date and time. The ensuing graph shows the variation of the direct irradiation over day time for March 21, June 21, and December 21 on a north-south oriented, horizontally one axis tracking trough. Note that the values for the global irradiation would be considerably higher. Those values however have to be corrected, as the diffuse irradiation cannot be used by a concentrating collector.

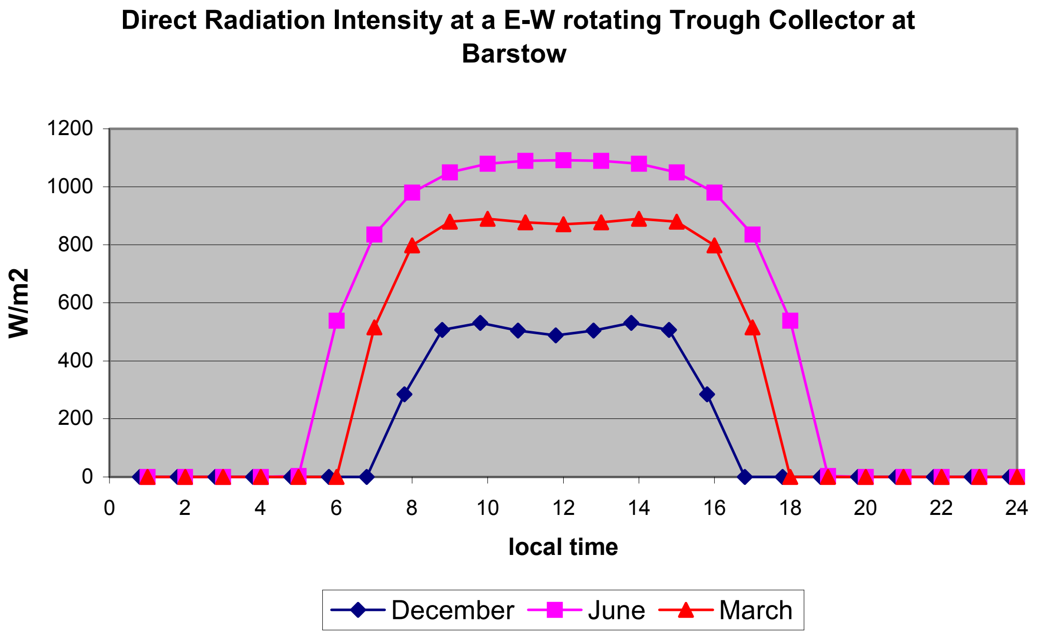


Figure 6

The sharp increase and decrease of the irradiation at sun rise and sun set as well as the maximal values at 10 am and 2 pm are because the effect of the elevation on the irradiance is – in part – compensated by the effect of the incidence angle.
If the irradiance is integrated over day time, the result is the input of radiation energy for one day. This value also corresponds to the area underneath the curve.
On June 21 the energy input is highest as the day is the longest in the year (from about 5 am to 7 pm) and also the elevation of the sun is the highest.

As mentioned above March 21 is considered to be very close to the average of the days of the year. The calculated radiant energy input for a clear day is 5,8 kWh.

Resuming chapter 2:
Looking at a N-S orientated, one-axis tracking trough collector at a latitude of 35° N and a longitude of 117° W, on a clear average day the input of radiant energy to one square meter, is 5,8 kWh.
If there would be clear sky all over the year the yearly gain per square meter would be 2117 kWh/m².

3 Energy balances of the Receiver

In this chapter we focus on the thermodynamic description of the receiver. Energy balances for a short length, steady state conditions and for the special case of solar radiation incoming perpendicular to the aperture are solved. Aim is to estimate the thermal losses of the receiver, resulting into the collector efficiency, that is the ratio of useful thermal energy gained by the oil to direct normal irradiance, multiplied with the aperture area:

$$\eta_{collector} = \frac{\dot{Q}_{used}}{I_{Dir} \cdot A_{Ap}}$$

3.1 Collector System of the Solar Power Plant

The parabolic trough collector mainly consists of the mirror, the receiver and the structure including the tracking device (figure 7). The receiver tube is located in the focal line of the cylindrical parabolic mirror. Most of the reflected and concentrated sunlight hits the tube and finally heats up the oil flowing inside the tube. The structure carries the whole collector and tracks the sun, controlled by a sensor. (More about the total power plant will be explained in the next chapter.)

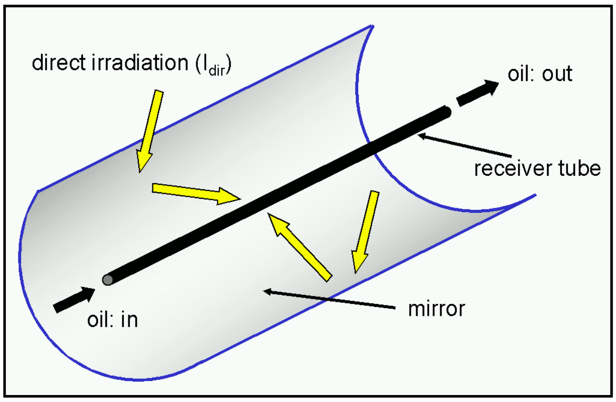


Figure 7: Collector system

3.2 Receiver System

The receiver consists of an absorber tube with a special selective coating surrounded by a glass envelope. The space between the tube and the glass envelope is evacuated to prevent convection and conduction heat losses.
In a first approximation the system can be described by the following temperatures:

- Temperature of the ambient: T_{amb}
- Temperature of the glass envelope: T_{glass}
- Temperature of the absorber tube: T_{tube}
- Temperature of the oil: T_{oil}

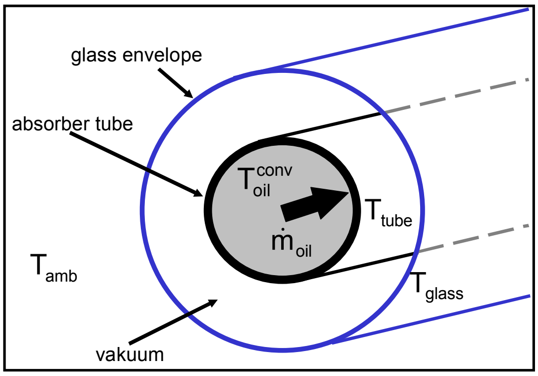


Figure 8: Receiver system

The heat resistances by conductivity of the absorber tube wall and of the glass envelope are neglected.

Figure 9 shows the energy fluxes that have to be taken into account:

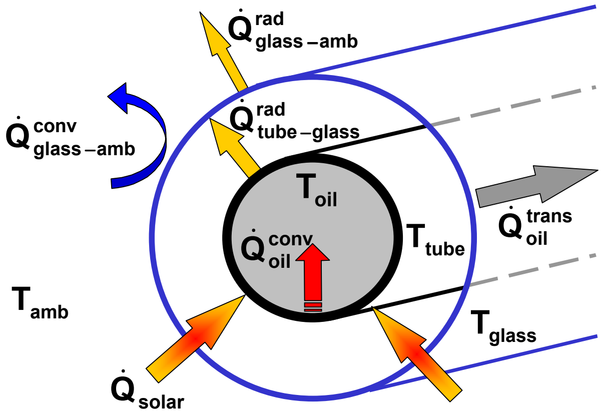


Figure 9: Energy flow of the Receiver System

The energy balance around the receiver tube leads to:

$$\dot{Q}_{solar} = \dot{Q}_{used} + \dot{Q}_{losses}$$

where $\dot{Q}_{solar}$ is the solar radiation absorbed by the black tube, $\dot{Q}_{used}$ is the energy gained by the oil and $\dot{Q}_{losses}$ describes the thermal losses of the hot absorber to the ambient.
$\dot{Q}_{solar}$ depends on the direct normal irradiance I_{dir}, the aperture area of the mirror A_{Ap} and the optical efficiency $\eta_{optical}$:

$$\dot{Q}_{solar} = \eta_{optical} \cdot I_{dir} \cdot A_{Ap}$$

The optical efficiency contains complex information about the reflectivity, absorption, transmission and spillage of the mirror, the glass envelope and the absorber tube. For the LS-3 collector the optical efficiency is about 0.73.

The ratio of useful energy to absorbed solar energy is defined as thermal efficiency:

$$\eta_{thermal} = \frac{\dot{Q}_{used}}{\dot{Q}_{Solar}}$$

Comparison with the above defined collector efficiency shows that

$$\eta_{collector} = \eta_{optical} \cdot \eta_{thermal} \cdot$$

The energy gained by the oil results into temperature increase of the oil and can be calculated by

$$\dot{Q}_{used} = \dot{m} \cdot c_p \cdot \left(T_{oil,out} - T_{oil,in}\right)$$

with the mass flow $\dot{m}_{oil}$ and the heat capacity c_p of the oil.
The useful energy passes firstly the absorber tube wall by heat conductivity and enters secondly the oil by heat convection. The first heat resistance can be neglected compared to the second one, so

$$\dot{Q}_{used} = \dot{Q}_{oil}^{conv} = \alpha_{tube} \cdot A_{tube} \cdot \left(T_{tube} - T_{oilaverage}\right)$$

with the heat transfer coefficient α_{tube} and with $T_{oilaverage} = \left(T_{oil,out} + T_{oil,in}\right)/2$ (for more accurate calculation the logarithm temperature difference has to be used!).

The rest of the incoming solar energy is lost from the absorber tube by radiation to the glass envelope. This equation is a function of the Stefan Boltzmann constant σ, the emissivity of the glass envelope ε_{glass} and the tube surface ε_{tube} , the area of both A_{glass} and A_{tube} and of the temperatures of the tube respectively the glass to the power of four. The special geometry – one tube surrounded by an other one – is respected using the following equation:

$$\dot{Q}_{lossed} = \dot{Q}_{tube-glass}^{rad} = \sigma \cdot \left[\frac{T_{tube}^4 - T_{glass}^4}{\frac{1}{\varepsilon_{tube}} \cdot \frac{A_{tube}}{A_{glass}} \left(\frac{1}{\varepsilon_{glass}} - 1 \right)} \right]$$

This energy heats up the glass envelope and – for the assumption of steady state conditions – is completely lost to the ambient by radiation and convection:

$$\dot{Q}_{lossed} = \dot{Q}_{lossed}' = \dot{Q}_{glass}^{rad} + \dot{Q}_{glass}^{conv}$$

In this case the equation for the radiation losses gets more simple:

$$\dot{Q}_{glass}^{rad} = \varepsilon_{glass} \cdot \sigma \cdot A_{glass} \cdot \left(T_{glass}^4 - T_{amb}^4\right)$$

The convection energy flux $\dot{Q}_{glass}^{conv}$ is a function of the glass surface A_{glass} and of the temperature difference between the glass and the ambient air. It includes also the heat transfer coefficient α_{glass} that is influenced by the geometry, the surface abilities, the properties of air and mainly the wind speed.

$$\dot{Q}_{glass}^{conv} = \alpha_{glass} \cdot A_{glass} \cdot \left(T_{glass} - T_{amb}\right)$$

This equation system can be solved for different boundary conditions.
With the following values, representing a typical state of the collector:

$\alpha_{glass} = 15$ W/(m²K),
$\alpha_{tube} = 10000$ W/(m²K),
$d_{tube} = 0.07$ m (diameter of absorber tube) and
$d_{glass} = 0.115$ m (diameter of the glass envelope)
and for the input data:
solar radiation = 960 W/m² (perpendicular to the aperture),
oil mass flow: = 14 kg/s,
inlet temperature of the oil: 350 °C,

the solution of the equation system results into two statements needed for the next chapter:

- **The oil with an inlet temperature of 350°C will be heated up by 0,12°C per meter tube length.**
- **The value for the collector efficiency is 0,68.**

4 Design of the hole plant

The next goal is to design a 80 MW$_e$ (net electricity output) solar thermal power plant at the location of Barstow in California. The question is: how many collectors are needed?

In the literature the number of full load hours for a 80 MW$_e$ plant (SEGS IX) was found to be 3200 h, whereof 25 % are by fossil fuel operation. The designed solar electricity energy output for one year is then

$$E_{design,year} = 0.75 \cdot 3200\,h \cdot 80\,MW = 192\ GWh\,.$$

Plant efficiency

In the last chapter the collector peak efficiency was estimated to be 68 %. The efficiency of the power block is assumed to be 37 %. The overall plant efficiency can be calculated by multiplying these two factors:

$$\eta_{plant} = \eta_{coll} \cdot \eta_{Block}$$

This yields to a "solar to electricity peak efficiency" of 25.2 % (the highest measured peak efficiency in the SEGS-Plants was about 22 %).

Calculation of the aperture area

In chapter 2 the average daily solar energy amount on a north-south oriented, one axis tracking parabolic trough collector was estimated to be 5.8 kWh/d. Assuming 300 clear sky days at the location of Barstow and an availability of the power plant of 90 %, the yearly solar energy input per square meter can be calculated:

$$E_{solar,year} = 0.9 \cdot 300 \cdot 5.8\,\frac{kWh}{m^2} = 1566\,\frac{kWh}{m^2}\,.$$

Now the aperture area can be calculated:

$$A_p = \frac{E_{designed,year}}{E_{solar,year} \cdot \eta_{plant}} = 486530\ \ m^2$$

Number of collectors

The aperture width of the LS 3 collector is 5.76 m, the length of one collector is 99 m.
The number of all collectors may then be calculated to be

$$N_{Collector} = \frac{A_p}{5.76\ m \cdot 99\ m} = 853\,.$$

This is very near to the number of 888 collectors, found in the literature for the SEGS IX plant.

Layout of the solar field

The next goal is to find the best arrangement of the collectors in order

- to achieve the required oil temperature difference between inlet (290 °C) and outlet (390 °C) and
- to minimise passive tube length.

In chapter 2 the temperature increase per meter receiver length was calculated to be 0.12 °C. This would yield to 8 collectors which have to be connected in a line. According to the literature the number of collectors in one line is only 6. To minimize passive tube length the collectors are arranged like an "U":

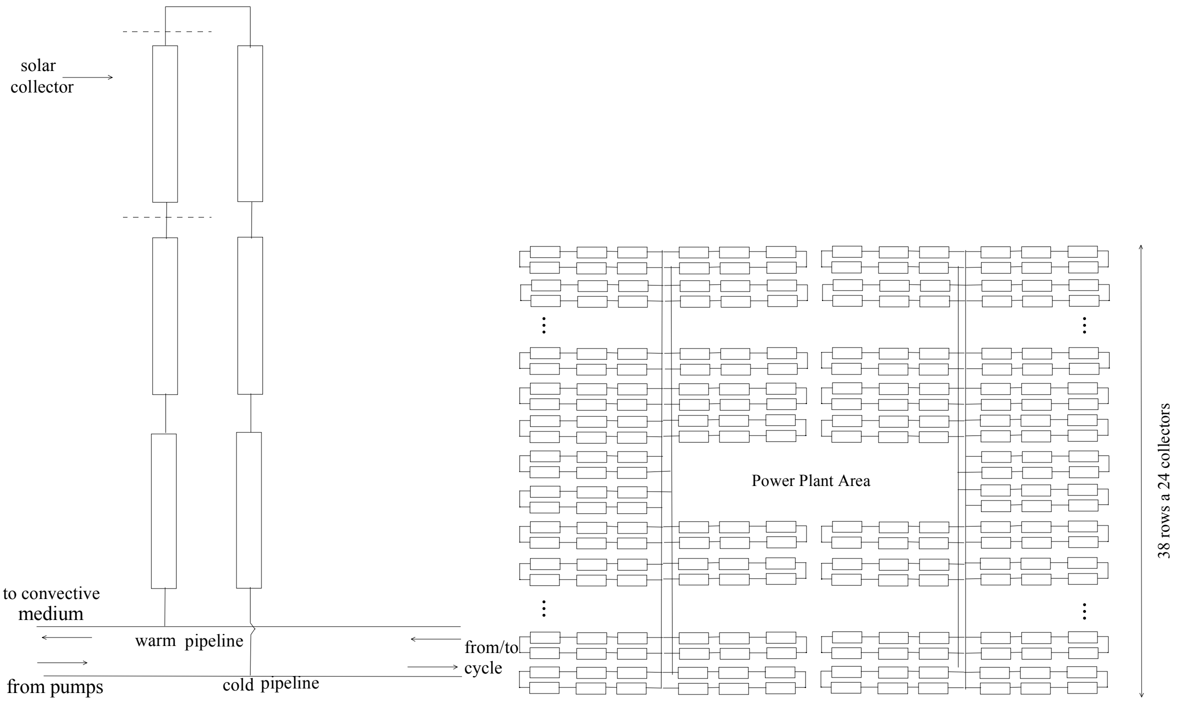


Figure 10: Layout of the collector field – left: one loop with 6 collectors in line, right: the whole plant

The whole collector field has been arranged rectangular, surrounding the power block in the centre of the field. 4 x 38 "U"-Loops with 6 collectors each minus 4 x 6 collectors (space for the power block) results into 888 collectors. By this arrangement the active pipe length (receiver length) is about 80 % of the total pipe length.

5 Energy Input / Grey Energy

The energy input of a product means – in simple words – the whole energy that is necessary to get the finished product and to dismantle later. It is often called the *grey energy* – the "hidden" energy.

The investigated product of this study is a Solar Thermal Power Plant with parabolic trough collectors. As mentioned above in this study only the solar part of the power plant is object of the investigation. Reason for this is on the one hand the better possibility to compare the results with the fuel input of an ordinary thermal power plant, and on the other hand there is also already some data available for the energy input of a conventional power block.

In this study a "Life-cycle analysis" was carried out, evaluating the following process chain with respect to the energy content:

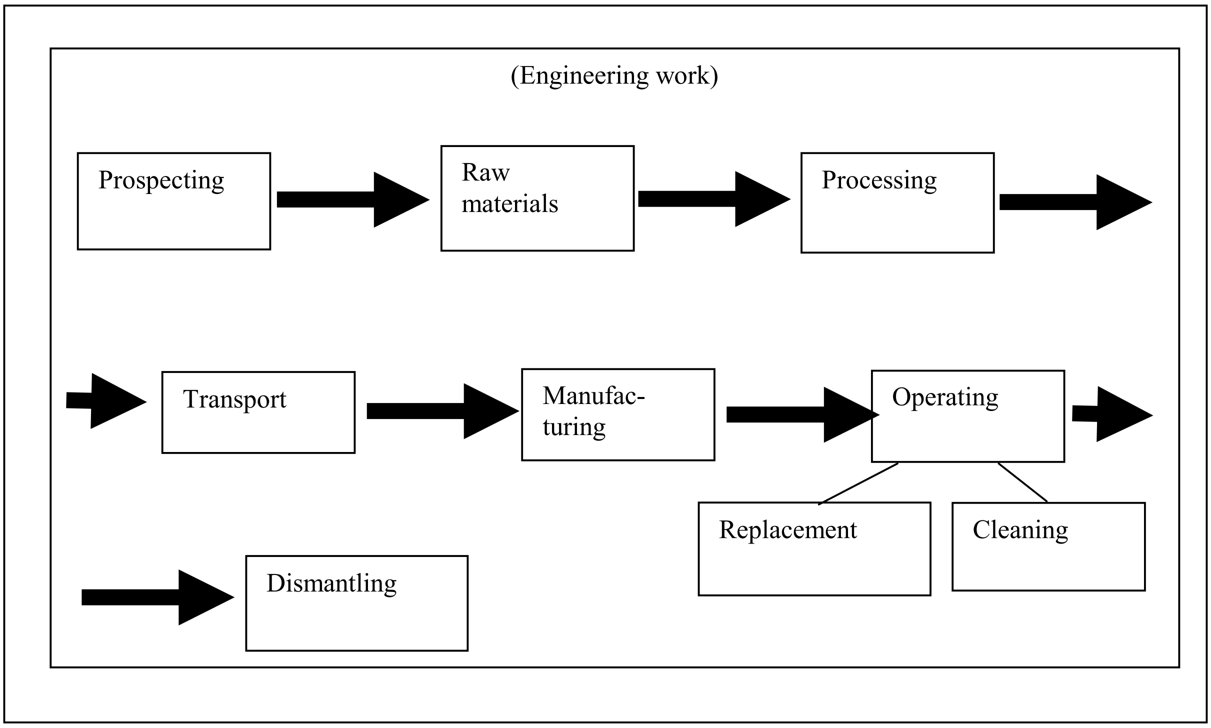


Figure 11: Life-cycle analysis: Process chain with hidden energy

Before the construction of the power plant begins, it will have to be planned. Therefore and during further processes some engineering work will have to be done. In this study this term is not assessed – reason is the missing data on the one hand, on the other it would not be necessary to take this term into account, because each type of power station will have to be planned and the planning efforts seem to correlate more with the size than with the type. So this analysis starts with the prospecting of the raw materials, which are needed to built up the plant. Secondly, the raw materials are regarded – they have to be worked out of the ore &c. – this needs energy, depending on the material the energy demand can be very high. Next term is the processing of the raw materials, then the component parts have to be transported to the construction site. Manufacturing also causes energy. Now the plant can be put into operation. During the operation time some replacements of - for instance – the heat fluid (oil) are necessary to keep the plant well functioning. Also the mirrors will have to be cleaned periodically. Two terms do not have to be taken into account: The energy demand for pumps, control &c. – it is included in the efficiency of the power block, and the fossil fuels used for co-firing – by looking only at the solar part and also only at the solar net energy. The analysis ends with the dismantling of the discarded plant.

The main question is, how this work can be done? Would it be better to make a very complex, detailed investigation or just make a rough estimation? Well, there does no proper answer exist if the important question is missing: What is the intention of the research-work?
The intention of this work is to get a “feeling” of the problem – the problem how to assess the environmental compatibility of a power plant.
Fortunately, a lot of work has been already done in the past /4,5/. Some results of an Australian study /4/ can be consulted to find an answer for this problem: Data for the energy content of different materials used to build up a solar thermal power plant already exists. That means, the specific value of the *grey energy* of different materials (and also of the transport efforts) can be taken to calculate the amount of the whole grey energy of the solar field. So the missing items are the masses – the masses of the needed materials to construct the solar field

of the 80 MW - SEGS solar thermal power plant. Doing own calculations using existing data is necessary now.

5.1 Specific energy content of different materials

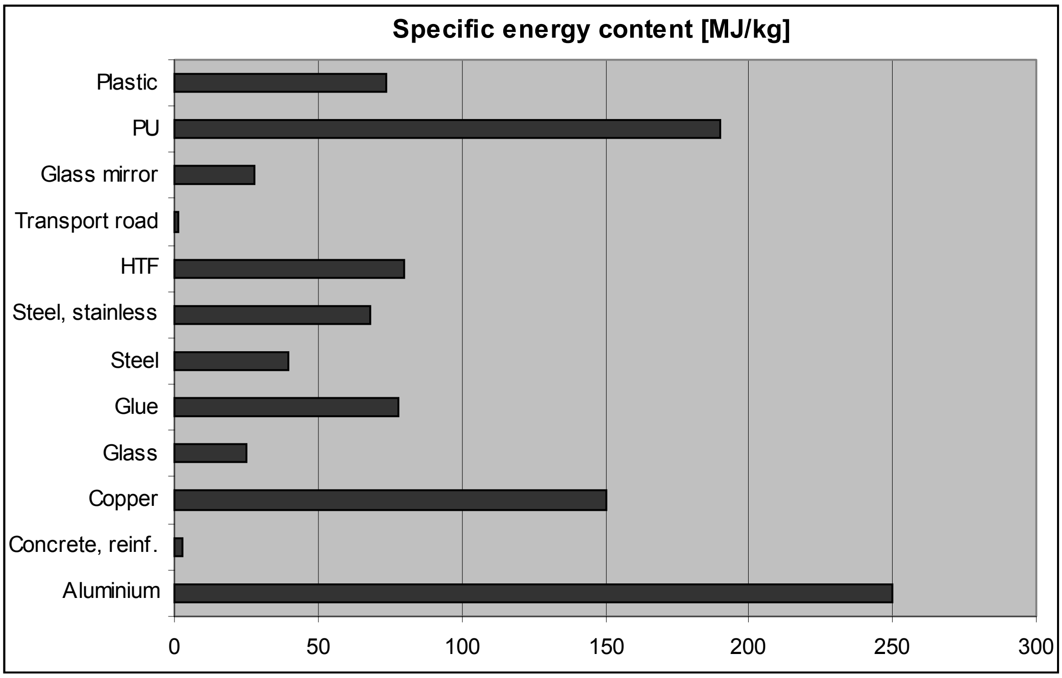


Figure 12: Specific energy content of used materials, according to /4/

The specific energy contents of the used materials – as shown in figure 12 – are quite different. Some materials like Aluminium, Copper or PU-foam, which are used for the insulation of the tubes, have a rather high specific energy content. The specific grey energy of concrete, steel and glass is on the other hand very low. HTF means the oil – the heat transfer fluid - inside the tubes.

5.2 Masses of the needed materials, transport efforts

The main parts of a solar field are the mirrors and the structure, but a lot of materials can not be categorized easily, so they are called miscellaneous. Operating and dismantling are the other categories. Figure 13 shows the results of the calculations after comparing them with data of the existing SEGS-plant /3,5/.

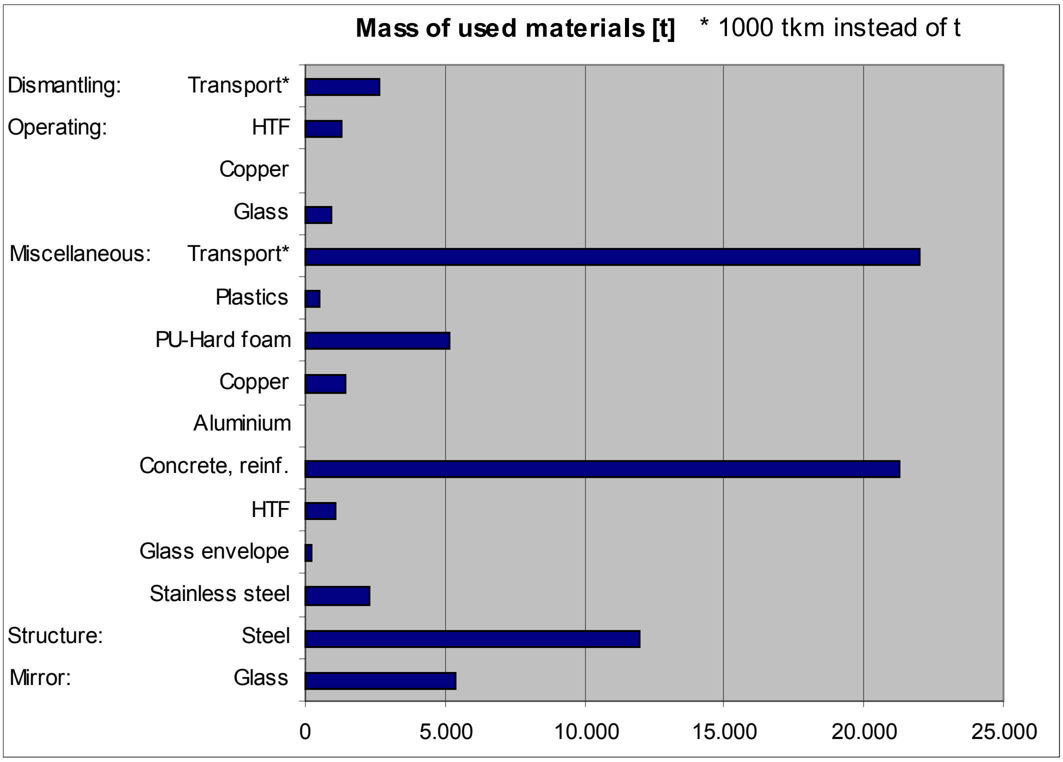


Figure 13: **Masses of needed materials, transport efforts**

A lot of concrete, steel and glass is necessary to build up a solar field, also the transport effort is high. The mass of the used PU-foam is also rather high.

5.3 Results of the calculations

Multiplying the calculated mass of a material with its specific energy content leads to the grey energy of the material. The results of this calculation are shown in figure 14:

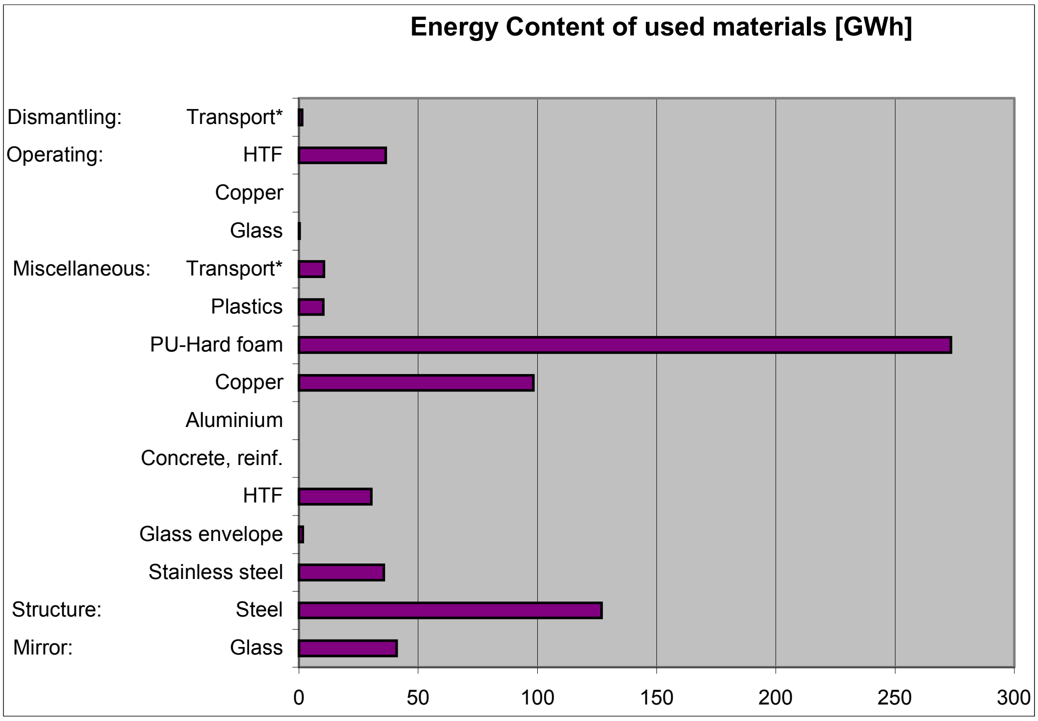


Figure 14: Energy content of used materials

The (surprising) results of the calculations: The biggest amount of grey energy contains the isolation-material – the PU-foam. Steel (big mass) and copper (high specific grey energy) have a rather high value of grey energy, too. On the other hand a lot of concrete contributes only few grey energy.

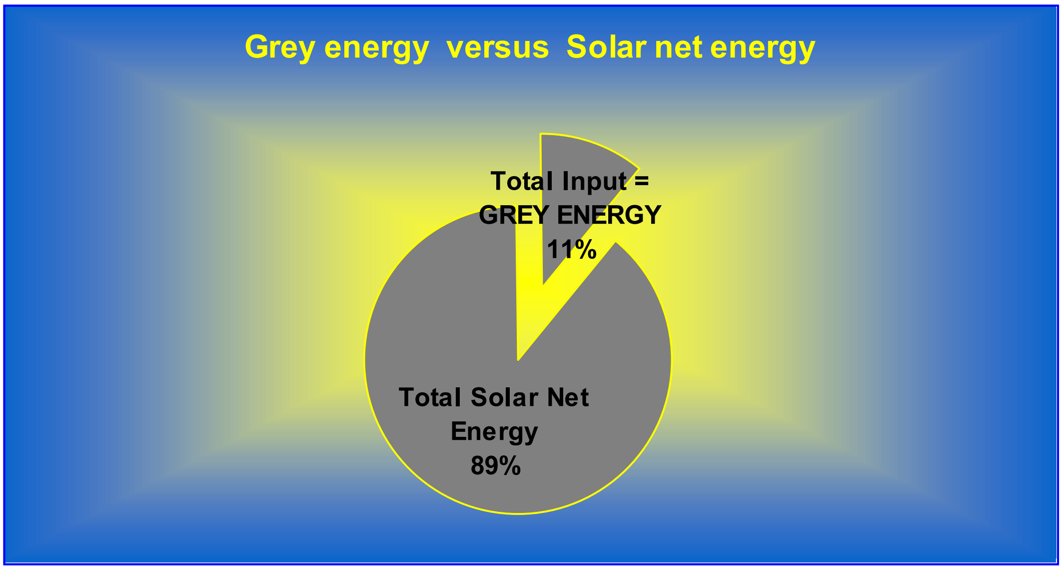


Figure 15: **Total grey energy versus total solar net energy, Source: Own Calculations**

The total amount of **grey energy** is **647 GWh** – the sum of the amounts shown in figure 14. To get a "feeling" for this value it has to be compared with other data. Investigating a power plant it is usual to compare the grey energy with the output of the plant.

Regarding only the solar field causes that the energy input of the solar field can only be compared to the solar energy output. In the calculations the output of the power block – the electricity – is taken, it is called the solar energy output. This leads to the **energy-payback-time** of **3.4 years**, which means that in 3.4 years the plant will have produced as much energy as the construction &c. of the solar field swallowed. Figure 15 shows the grey energy in comparison to the solar net energy.

But keep in mind: The solar output is electricity – a high-grade energy –, while the total grey energy is always a mixture of different kinds of energy.

5.4 Conclusions

To minimise the grey energy of the solar field it would be very effective to use a different isolation-material with a lower specific energy content.

The calculation of the grey energy of a plant (- a product &c.-) is always an estimation – it is a question of the necessary effort, depending on the purpose. To make a comparison to other – for instance – plants it is necessary to use the same methods or to be aware of getting only rough estimations.

6 Literature

For the preparation of the workshop and this paper the following literature was used:

1. M. Iqbal, An Introduction to Solar Radiation, Academic Press Canada Ontario 1983
2. Duffie, Beckmann, Solar Engineering of Thermal Processes, 2. edit., J. Wiley & Sons, Inc. 1991
3. M. Mohr, P. Svoboda, H. Unger, Praxis solarthermischer Kraftwerke, Springer-Verlag Berlin, 1999, ISBN 3-540-65973-0

4. M. Lenzen (1999), Greenhouse Gas Analysis of Solar-Thermal Electricity Generation, Solar Energy 65, No. 6, pp. 353 - 368
5. G. Weinrebe, M. Böhnke, F. Trieb (1998), Life Cycle Assessment of an 80 MW SEGS Plant and a 30 MW Phoebus Tower, in: Proceedings of the Intern. Solar Energy Conference, June 14-17, 1998, Albuquerque, New Mexico (Solar Engineering – ASME 1998)
6. M. Becker, W. Meinecke, Solarthermische Anlagentechnologien im Vergleich, Springer Verlag Berlin Heidelberg 1992
7. VDI-Wärmeatlas, 6. Auflage 1991