Solar Thermal Power Generation

Dr. Stefan Bockamp*[1], Thomas Griestop[1], Mathias Fruth[1], Dr. Markus Ewert[2], Hansjörg Lerchenmüller[3], Max Mertins[3], Gabriel Morin[3], Dr. Andreas Häberle[4], Dr. Jürgen Dersch[5]

[1] E.ON Engineering GmbH, Germany

[2] E.ON Energie AG, Germany

[3] Fraunhofer Institute for Solar Energy Systems (ISE), Germany

[4] PSE GmbH, Germany

[5] German Aerospace Centre (DLR), Germany

*** PRIMARY CONTACT Author** Bergmannsglueckstr. 41-43; 45896 Gelsenkirchen
Tel / Fax ++49-209-601 3021 / ++49 - 209-601 8426
Email stefan.bockamp@eon-energie.com

1 Introduction

Solar thermal power generation is an attractive option for cost efficient renewable electricity production. In countries with high solar resources this technology is capable to produce solar electricity at below 15 €cent/kWh on a scale of 50 – 200 MW_{el} plants. Depending on location, technology and size, cost projections for those power plants range between 10 and 20 €cent/kWh using today's level of technology. The technology is still in the very beginning of its development, so the future cost price of electricity will be reduced by increasing efficiency and by decreasing total system costs. According to a study prepared for the world bank, levelised electricity costs (LEC) for solar thermal power plants are expected to reach a level below 4-6 €cent/kWh on a long term basis [1].

Large solar thermal power systems use the concentrated sunlight to attain the high temperatures required for subsequent power generation processes. The general way to generate electricity is to use high temperatures for producing steam which is used in conventional water/steam cycles. For large scale power production there are two main solar concentrating technologies:

- Line focusing systems like parabolic trough and Fresnel-type collectors
- The central receiver or power tower concept.

In California, nine parabolic trough plants (figure 1.1) with a total plant capacity of 354 MW_{el} have reliably been producing solar thermal electricity for more than a decade.

Figure 1.1: Solar thermal trough plant in Kramer Junction, California (Source: Sandia National Laboratories, Albuquerque)

In August 2002, Spain passed a new law according to which solar thermal electricity is refunded at app. 16 €cent/kWh. Due to this law solar thermal power generation is given new impetus. At present several solar plant projects in Spain and also in other sunny countries all over the world are in the planning phase.

The Belgian company Solarmundo [1] developed a very promising Fresnel-type collector which in the mid or long term may lead to even lower LEC than parabolic trough plants. However, whereas parabolic trough plants are already a proven technology, solar steam generation on the basis of the Fresnel collector has only been tested in a prototype without power bloc (see figure 1.2) but not yet on a large scale in combination with a power plant.

Figure 1.2: Prototype of the Fresnel collector at Liege (Belgium) developed by Solarmundo

Together with the Fraunhofer Institute for Solar Energy Systems (ISE) – Europe's largest solar energy research institute – and the German Aerospace Centre (DLR) – one of the leading institutions in solar thermal power generation, E.ON Energie AG – the largest private provider of energy services in Europe - started a project to examine the technical and economic feasibility of Fresnel-type collectors. The utilisation is assessed in combination with conventional power plants and in solar only mode. Electricity costs from solar only plants mentioned above could be reduced by running the solar field in hybrid mode. Full load hours of the power are increased by the factor 4. The project is supported by the German Federal Environmental Ministry.

This paper gives a technical description of the Fresnel collector and several system-level integration concepts:

- hybrid plants: integration of the Fresnel collector into a coal-fired power plant, a combined cycle power plant and a biomass power plant

[1] Solarmundo NV., Meir 44A, 2000 Antwerpen, Belgium, www.solarmundo.be

- and solar only variants

First results from calculations of the solar energy yield and finally the economic assessment and outlook are presented for the solar only concepts.

2 Fresnel Collector

Starting point for the simulations and the plant design was the Fresnel collector as it was designed by the Belgian company Solarmundo.

In the Solarmundo collector large fields of modular reflectors concentrate beam radiation to a stationary receiver at a height of several meters. This receiver contains a second stage reflector that directs all incoming rays to a tubular absorber (see figure 2.1). The absorber tube is specially coated for good absorption properties of the sunlight and low thermal emission in the infrared spectrum.

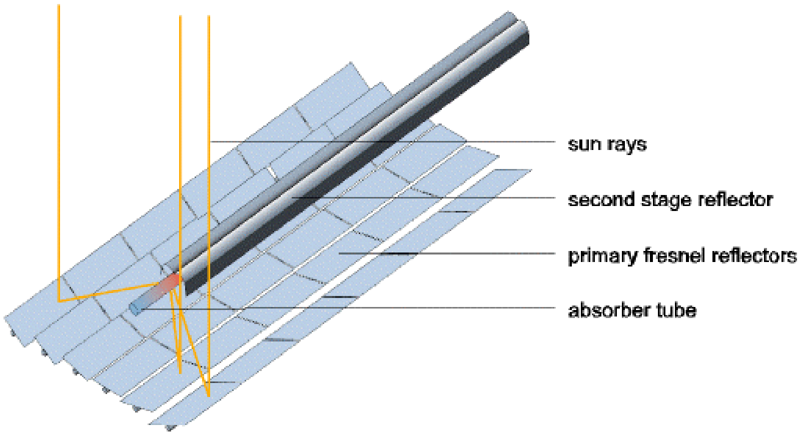


Figure 2.1: Principle of the Solarmundo Fresnel Collector.

The collector consists of 48 parallel rows of flat mirrors, each having a width of 0.5 m. This leads to a total collector width of 24 m. The second stage concentrator not only enlarges the target for the Fresnel reflectors but additionally insulates the absorber tube. To the back the second stage reflector is covered by an opaque insulation and to the front a glass pane reduces convective heat losses. In contrast to trough technology the volume around the absorber is not evacuated.

The basic design of a whole collector field for direct steam generation is shown in figure 2.2. The solar field for a 50 MW_{el} solar thermal power plant will be built up in 15 - 20 collector rows each with a length of about 1000 m. The rows can be installed one close to another so that the land use of the solar field is practically not more than the mirror area. Thus the land use is only 50% per kW_{el} compared to the trough technology, what is important in regions with considerable land costs. The collector rows are linked in parallel and in series and the solar field is divided into three sections for preheating, evaporation and superheating.

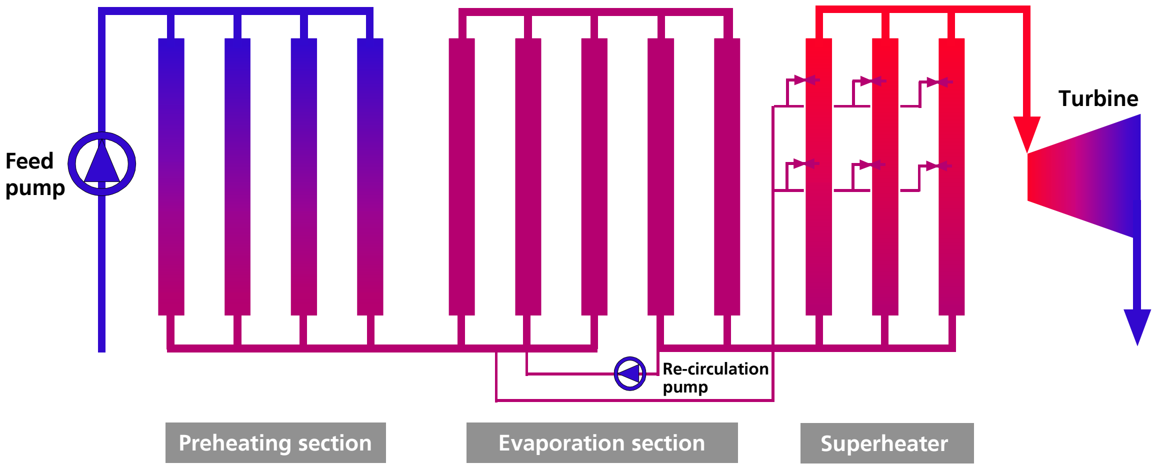


Figure 2.2: Flow sheet of a collector field

The main advantages of the Solarmundo Fresnel collector, compared to trough collectors are:

- inexpensive planar mirrors and simple tracking system
- no vacuum technology and no metal glass sealing
- one absorber tube with no need for thermal expansion bows
- due to the planarity of the reflector, wind loads are substantially reduced. So the reflector width for one absorber tube can easily be three times the width of parabolic troughs
- due to direct steam generation no heat exchanger and no expensive thermo-oil as heat transfer fluid is necessary.
- reduced maintenance costs.
- land use per kW_{el} is reduced by factor of 2

These advantages can lead to a substantial cost reduction for the solar field compared to parabolic trough technology. Cost reduction due to economies of scale and due to an optimised design of the collector will further diminish the investment costs for the solar field. In addition to the lower investment costs for the solar field, there is a potential for considerable savings offered by lower operation and maintenance costs.

3. Collector and solar field simulation

The efficiency of a solar thermal collector strongly depends on its operation temperature and on the momentary solar insolation conditions. Figure 3.1 shows the efficiency of a Fresnel collector for different vertical radiation intensities in dependency of the operation temperature.

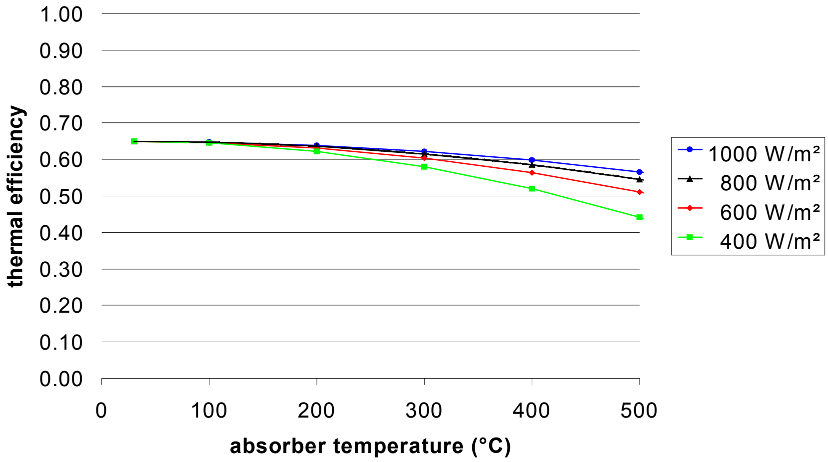


Figure 3.1: Efficiency of a Fresnel collector for vertical irradiation of varying intensity at 30°C ambient temperature.

The additional effect of angular variation of the incident radiation is modelled by the so called incident angle modifier (see Figure 3.2), which has to be multiplied with the momentary thermal efficiency to yield the overall efficiency. It can be seen that the collector starts operation in the morning with relatively low efficiency which then rises towards its maximum at solar noon (12:00). The maximum values to be reached depend on the time of the year with the highest values in summer and considerably lower values in winter.

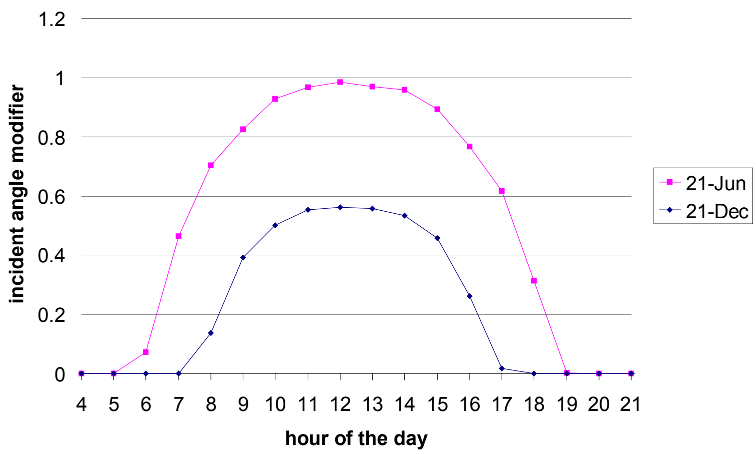


Figure 3.2: Incident angle modifier of the Fresnel collector in Hurghada, Egypt

The solar collector field can be described by a set of analytical and differential equations, which take into account all material parameters, optical parameters (including angular and spectral effects), thermal losses, heat transfer mechanisms, heat capacities and of course the total size of the illuminated aperture area.

Dynamic simulation tools that model all transient effects and which use time series of irradiation and load patterns as input are necessary to achieve reliable performance calculations. Fraunhofer ISE has developed such a dynamic simulation tool called ColSim, which is similar to the widely used simulation tool TRNSYS. However ColSim is especially well suited to simulate dynamic behaviour on a rather small time scale. In a first step quasi stationary system simulations were used to calculate the results presented in Chapter 5 »Solar energy yields and economic aspects«.

4 Plant and system integration concepts

Different types of hybrid and solar-only power plants were chosen to calculate the electrical yield and economic aspects. In most of the integration concepts the solar field is acting as a fuel saver, but also solar only variants are being considered. This part of the paper describes the technical concepts of the different systems investigated in the project. The power plant integration concepts in this paper are based on power plants operated in Germany. These plants were applied as representative examples, which could be found in regions of this world with high solar irradiation.

4.1 Hard coal fired power plant with solar field integration

<u>Plant description Staudinger 5</u>

Staudinger 5 is a hard coal fired power plant with an net power output of 510 MW_{el} at an net efficiency of 43 %. Staudinger 5 is connected to the local district heating system and has got the possibility to supply this heating system with an thermal output of 300 MW_{th}. The initial operation of this power plant was in 1992.

The Staudinger 5 boiler is a one through steam generator (height 100m) with dry-type firing system which can be operated at loads between 18% and 100% without an auxiliary oil fire. The power plant can be operated at pure variable-pressure operation with a load chance velocity of 7 %/minute (between 50 and 90 % load) [2]. This operating sector enables the Staudinger 5 power plant to produce electricity in the base load and the intermediate load and to provide an instantaneous reserve for the net frequency stabilisation. The used diagnosis system for the steam generator calculates the fouling of the heating surface to determine the optimal steam demand for the carbon black cleaning to realise minimal losses and a reduced material stress of the heat exchanger tubes. The main technical data are given in table 4.1. Further technical data and information about the flue gas cleaning system contains [2].

Table 4.1: Technical Data of coal-fired power station Staudinger 5 at 100 % load [2], [3]

Technical data	**Value**
Overall Power plant	
Net power output (electrical)	510 MW
Net efficiency	43 %
Firing system	
Fuel	hard coal
Firing thermal capacity	1180 MW
Fuel input at full load	150 t/h
Excess air coefficient	1.2
Feedwater	
feedwater pump output parameters	300 bar / 200 °C
Steam generator	
High pressure steam parameters	262 bar / 545 °C
High pressure mass flow	1500 t/h
Steam turbine	
High pressure steam turbine input	250 bar / 540 °C
Intermediate pressure steam parameters	53 bar / 562 °C
Condenser	
Condenser output parameters	0.064 bar / 37°C
Cooling	
Cooling process	Natural draft cooling tower
Cooling tower hight	141.5 m
Flue gas cleaning	
NO_x removal	1. Primary measures 2. SCR (selective catalytic reduction)
Dust removal	Electrostatic filter
Desulphurisation	limestone washing

The short transient behaviour of the unit control with a high level of automation and the wide range of applicable fuels are the reasons for choosing Staudinger 5 as a reference for hard coal fired power plants with the possibility to connect a solar field. The net efficiency of Staudinger 5 with approx. 43 % is significant higher than the world wide average of 36 % for conventional hard coal fired power plants.

Because of the limited outlet parameters of solar Fresnel field (p = 100 bar, t = 450 °C), the solar integration is only considered in the cold reheating zone (p = approx. 58 bar, t = approx. 320 °C) of the unit. This approach for the field integration was similar for all 3 variants (figure 4.1). Solar field size and solar field feedwater output from the water steam process are varied. The solar field operates as fuel saver.

In the first variant the solar field feedwater is directly supplied by the feedwater tank. The solar collector is equipped with a separate feedwater pump. The size of solar field is limited to 78 MW_{th} (6,6% of the firing thermal capacity). This size corresponds to the maximum heat capacity of the economiser fed by steam of the HP-turbine outlet, which is now supplied by the solar field.

In variant 2 the solar field size is set to 160 MW_{th} (13,6 % of the firing thermal capacity) and the solar field water inlet is linked to the condenser pump outlet. In contrast to variant 1 the solar field is oversized to supply the coal fired power plant with an increased amount of solar steam even under less solar insolation. Also variant 2 uses a separate feed water pump for the solar field in order to realise the required pressure level for the solar field operation.

In variant 3 a separate feedwater pump is not necessary. The 160 MW_{th} solar field is linked to the water steam cycle at the feedwater pump outlet of the unit. As the system pressure at the feedwater pump output is to high for the solar field tubes the solar field feedwater pressure has to be controlled by a pressure reduction station.

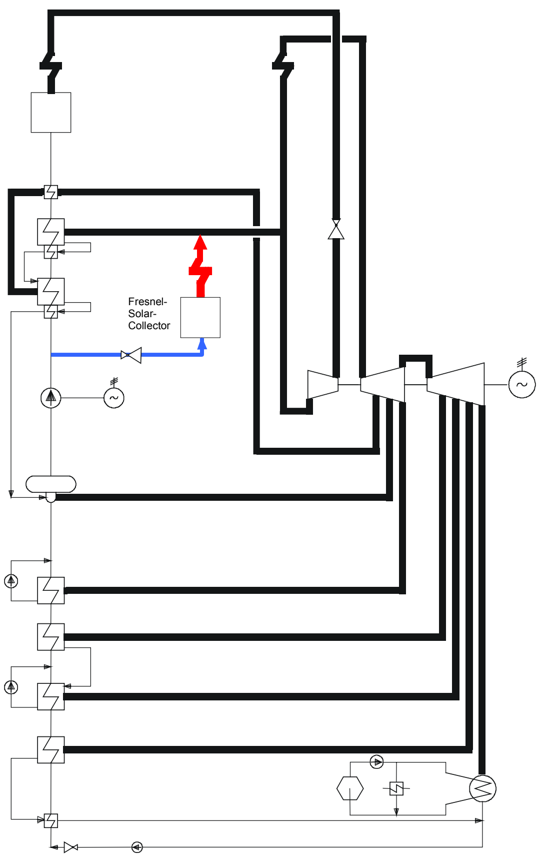
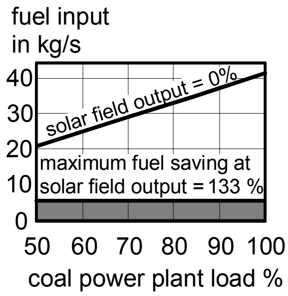


Figure 4.1: Water steam cycle Staudinger 5, variant 3

All 3 variants were modelled and simulated with a simulation tool called PS11, developed by E.ON Engineering. This program is based on thermodynamics, phenomenological relations for heat transfer and pressure drop and uses measured data determined by acceptance tests of the entire power plant.

Figure 4.2 shows the comparison of the simulation results of the 3 investigated variants. For different solar field outputs (66%, 100%, 133%[2]) the single diagrams show the calculated fuel savings. The fuel saving in variant 3 shows the best results. In addition to that, variant 3 provides a procedural advantage (no separate feedwater pump for the solar field is needed). The instantaneous fuel saving range with variant 3 lays between 13.2 % (at 100% unit output and 100% solar field output) and 25.5% (at 50% unit load and 100% solar field load). Simulations of the annual operational behaviour for a possible power plant site, like Hurghada (Egypt), point out a fuel saving of 40,360 t coal per year for a hybrid solar/coal fired unit. The total coal fired power plant fuel consumption without any solar power amounts to 1,248,000 t coal per year at 8560 full load hours. Therefore the annual fuel saving is about 3.2%.



	solar field size	coal power plant to solar field	solar field to coal power plant
variant1	78 MWth	15.28 bar 832.44 kJ/kg 36.38 kg/s	58.48 bar 2,977.19 kJ/kg 36.38 kg/s
variant 2	160 MWth	22.41 bar 164.38 kJ/kg 56.35 kg/s	58.74 bar 3,000.80 kJ/kg 56.35 kg/s
variant 3	160 MWth	273.73 bar 877.22 kJ/kg 74.92 kg/s	60.75 bar 3,012.84 kJ/kg 74.92 kg/s

data refering to 100% coal power plant load, 100 % solar field output, and an ambient temperature of 20°C

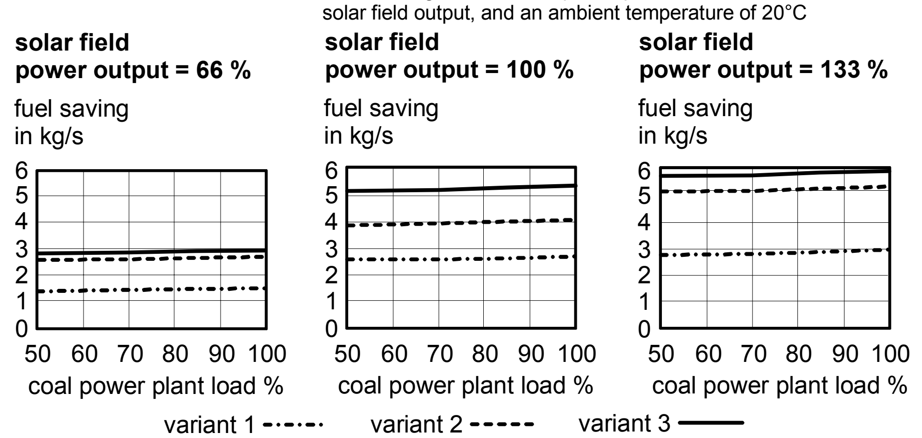


Figure 4.2: Simulation results for the fuel saving for different solar field power outputs depending on the coal power plant load for variant 1 - 3

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[2] 133 % solar field power output represent the maximum possible irradiation on midsummer , on June 21^{st}.

4.2 Integrated Solar Combined Cycle Systems

The combination of a solar collector field and a conventional combined cycle power plant is commonly called integrated solar combined cycle system (ISCCS). This type of power plant has an enlarged steam turbine (compared to the combined cycle system) and the solar collector field works as additional steam mass flow generator. The ISCCS plant concept was initially proposed by Luz Solar International [6]. The solar field proposed for this kind of power plant was a parabolic trough field using a heat transfer fluid inside the heat collecting tubes and some additional heat exchangers to feed this heat into the steam cycle. A field of Fresnel collectors with direct steam generation may be used instead of the parabolic troughs without changing the general concept. The advantages of such an integrated system are lower investment costs compared to a solar-only plant and lower fuel consumption and therefore lower carbon dioxide emissions compared to a pure fossil power plant.

Figure 4.3 shows a scheme of an ISSCS with Fresnel collector field. High pressure feedwater from the steam cycle is fed into the solar field. After preheating, evaporation and superheating, the steam is mixed with the steam from the heat recovery steam generator and admitted to the HP steam turbine.

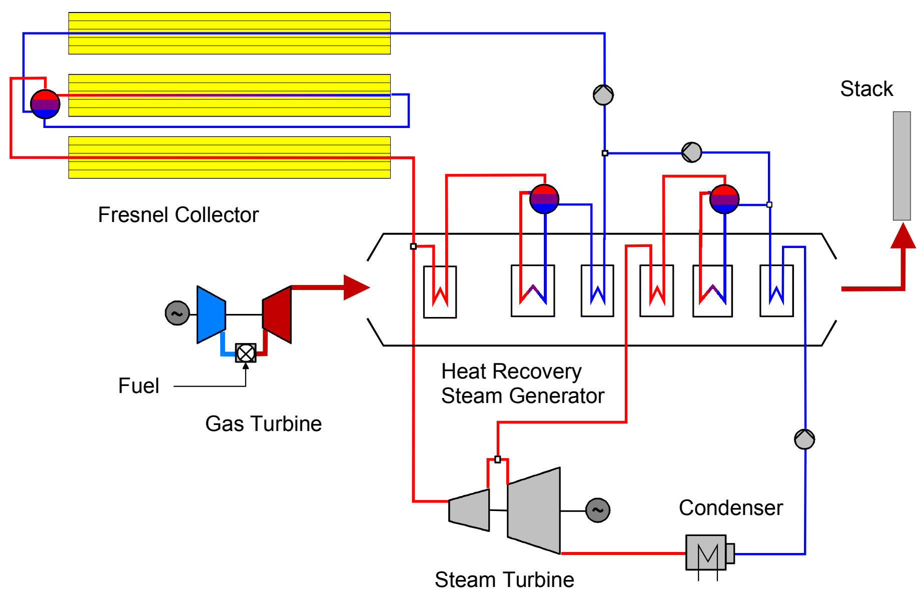

Figure 4.3: Scheme of an ISCCS with Fresnel collector field

During this project three different ISCCS were investigated, all based on an existing fossil CC power plant Kirchmöser with 165 MW net electrical output: a fuel saver concept with the same equipment size as the original combined cycle plant, an ISCCS with slightly enlarged

steam turbine (66 MW instead of 55 MW) and 33 MW solar thermal heat, and an ISCCS with a steam turbine of 110 MW_{el} nominal output and 173 MW solar thermal heat.
The power plant of Kirchmöser has been set up for transport power supply of "Deutsche Bahn AG" (German Railways) and was first power plant world-wide using gas and steam turbine technology for direct 16 2/3 Hz power generation. Constructions and electrical components as well as first operational results described in [5]. Table 4.2 contains the main technical data.

Table 4.2: Technical Data of combined cycle power plant Kirchmöser at 100 % load [5]

Technical data	**Value**
Overall Power plant	
Net power output (16 2/3 Hz, 110 kV)	160 MW
Net efficiency	49.6 %
Gas turbine	
Capacity	2 x 55 MW
Fuel	natural gas
Firing thermal capacity	2 x 180 MW
Fuel input at full load	2 x 18000 Nm^3/h
Steam turbine	
Capacity	1 x 55 MW
High pressure steam parameters	62 bar / 530 °C
Intermediate pressure steam parameters	4,5 bar / 198 °C
Heat recovery steam generator (HRSG)	
Number of HRSG	2
Operating gage pressure HP / LP	85 bar / 10 bar
Steam mass flow per HRSG HP / LP	85 t/h / 24 t/h
Flue gas temperature before HRSG	550 °C
Flue gas temperature after HRSG	110 °C

Cycle balance calculations were done for all three plant configurations as well as for the original combined cycle plant using the commercial computer code IPSEpro [7] which has been supplemented concerning concentrating solar power plant models by DLR. The results of these calculations are lookup tables for different ambient conditions and different solar field thermal output, which are used as input for the annual performance calculations described below. Figure 4.4 shows results of the cycle balance calculations for two ISCCS with 66 MW_{el} respectively 110 MW_{el} steam turbine. In this study the net solar electricity is defined as difference between the net electric output of the ISCCS and the fossil reference power plant. This fossil reference power plant is a CC power plant equipped with the same gas turbine and working under the same ambient conditions as the ISCCS. This is a more severe definition than the one solely based on the thermal input and it takes also into account that the solar heat input is limited to a temperature of 450°C by the selective absorber coatings available today. This graph shows negative net solar electricity for very low or zero thermal input from the solar field. The negative solar electricity output for zero solar field input is due to the part load operation of the steam turbine with decreasing solar input. This part load penalty is obviously more pronounced for the power plant with larger steam turbine.

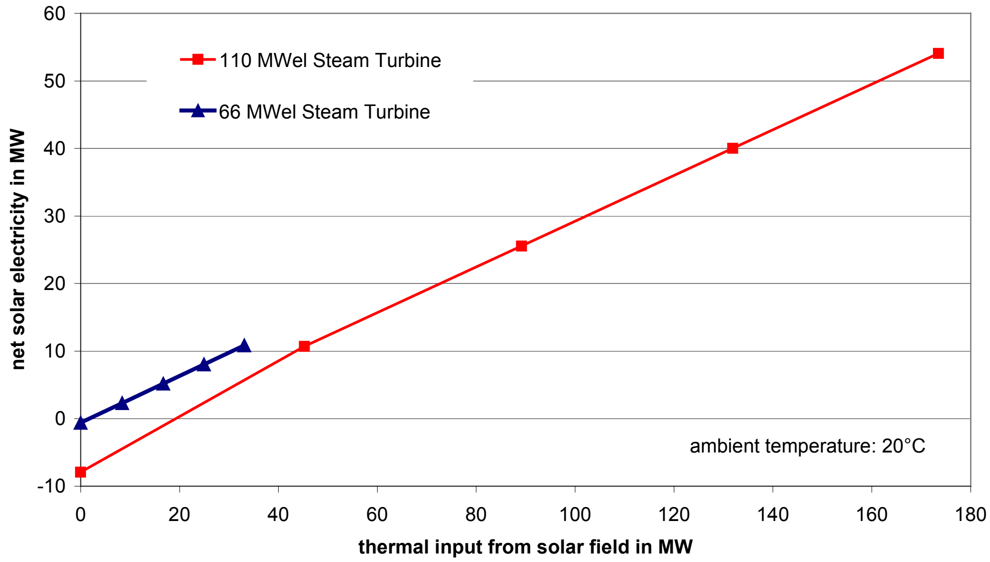

Figure 4.4: Results of cycle balance calculations for two ISCCS with different steam turbine oversizing

Due to the daily and seasonally variable solar irradiation, annual performance calculations for a specific site are necessary to investigate the total amount of electricity from an ISCCS and the fuel saving for a whole year.

The investigation of the fuel saver option were stopped, because the first results showed that the addition of a solar field to an existing combined cycle power plant will usually not lead to lower fuel consumption. This is valid for all those CC power plants where the steam turbine is operated close to the maximum steam mass flow rate, which should be the common case. For the integration of solar heat into the steam cycle of such a plant the gas turbine has to operate in part load, with rapidly decreasing total electricity output and efficiency, which is not considered as a realistic option.

4.3 Biomass power plant with solar flied integration

Within this part of the paper it will be examined how a solar collector can be integrated into the water/steam cycle of a biomass power plant. The following benefits will result from the combination of both technologies:

- The plant is operated exclusively with renewable energy-sources
- No net-production of CO_2 during operation
- Typical live steam parameters of a biomass plant correspond to those of the Fresnel collector (approx. 450°C and 70 bar)
- The plant can be operated 24 hours a day without the need for heat storage.
- Compared to solar only plants, the efficiency of converting solar radiation into electrical energy is higher in hybrid power plants since the steam cycle always runs at full load.

The simulations were done with the commercial process simulation tool Ebsilon [8]. The solar field was exemplarily integrated into the plant process likewise of E.ON's biomass power plant at Zolling or Landesbergen, Germany [9]. This kind of system would not be appropriate to be built in Germany because of the limited solar energy yields. The technology as described below is applicable for example in Spain or Italy.

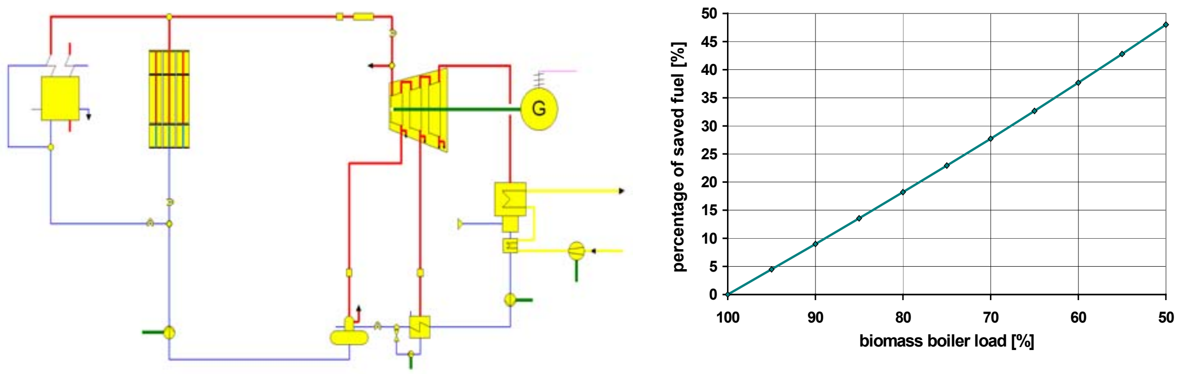

Figure 4.5: Hybrid plant (biomass / solar thermal) and simulation results

Figure 4.5 shows the water/steam cycle of the hybrid plant. Both heat sources – solar field and biomass boiler – are connected in parallel. The feedwater partly runs through the solar field including all thermodynamic sections: water preheating, evaporation and superheating of the steam (see figure 2.2). Depending on the availability of solar irradiation, the mass flow through the solar field is controlled in such a way that the desired live steam parameters (450°C / 70 bar) are always maintained. In order to supply a constant electricity output

(20 MW_{el}), the biomass boiler provides the amount of thermal energy that can not be supplied by the solar field.

To ensure reliable operation, the biomass boiler runs at 50% or more of thermal load. Accordingly, the solar thermal input rises up to 50% depending on the availability of solar irradiation. The size of the solar field may be varied within this configuration depending on economic aspects like levelised electricity costs or special electricity tariffs for different energy sources.

4.4 Solar Only Steam Plant

In the next step a solar only steam plant with the Fresnel collector as single heat source is examined. Using the power plant simulation software Ebsilon [8], more than 100 processes each with 9 loading cases were modelled in order to analyse systematically how the efficiency of a 50 MW_{el} solar steam cycle reacts to different influencing factors:

- variation of live steam-pressure and -temperature
- influence of intermediate superheating and number of extraction steam preheaters
- variation of condenser cooling systems
- influence of ambient conditions
- part load behaviour for all investigated processes
- fix live steam pressure versus sliding pressure mode:

  As the collector has three strictly separate sections for preheating, evaporation and superheating (see figure 2.2), pressure conditions within the collector have to be constant regardless of the mass flow. A throttle is used in the steam pipeline in front of the steam turbine. The efficiency of this steam cycle – being throttled in part load – was compared to a steam cycle without throttling.

One of the most important result of these investigations was, that the efficiency loss resulting from fix pressure mode was less than one percentage point in the whole range of loads. Based on the results of these preliminary examinations, solar only power plants were designed for two exemplary locations:

- Faro in Portugal, representative potential site in Europe for a solar thermal power plant with a high annual solar energy yield – direct normal irradiance (DNI) of 2247 kWh/m^2a.

- Hurghada in Egypt, being representative for locations with excellent solar conditions with a very high solar energy yield – DNI of 2785 kWh/m^{2}a.

At both locations sea water cooling is principally possible – Faro is located at the Atlantic, Hurghada on the Red Sea's coast. So the processes were designed for both locations with fresh water cooling.

Since suitable ground near the coast might not be available, open circuit water cooling may not be feasible. So the processes were also simulated with an air-cooled condenser. The plants were designed and optimised according to the given site conditions. Hourly data over one year for irradiation and ambient temperature – respectively monthly values for the temperature distribution of the sea water – were available for this purpose.

On the one hand a "simple" version of the steam plant with only the feedwater storage tank as single preheater was chosen (see figure 4.6).

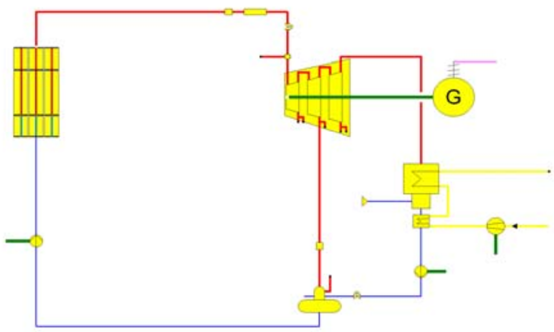

Figure 4.6: Simple solar only process

On the other hand the energy yield of a "high efficiency steam cycle" was examined, a process with intermediate superheating and multi-stage feed-water preheating (four low-pressure-preheaters and one high-pressure-preheater). A major problem concerning intermediate superheating is the relatively high pressure loss within the solar collector field. For live steam this pressure loss can easily be compensated by the feed-water pump without a significant drop in efficiency. But it can not be compensated in the intermediate superheating section. Therefore the medium pressure steam is reheated in a heat exchanger with live steam (see figure 4.7).

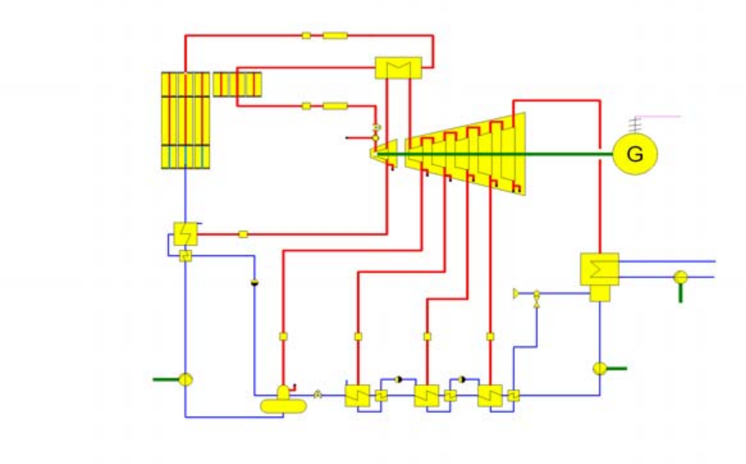

Figure 4.7: Process with intermediate superheating and five extraction steam preheaters

For each of the modelled processes the loading cases were simulated in 10%-steps between 20% and 100% of the nominal thermal input. To give an example, the efficiency of the steam cycle as shown in figure 4.8– with open circuit water cooling, live steam parameters (at the exit of the solar field) of 100bar / 440°C / 440°C – reaches up to 37.4%.

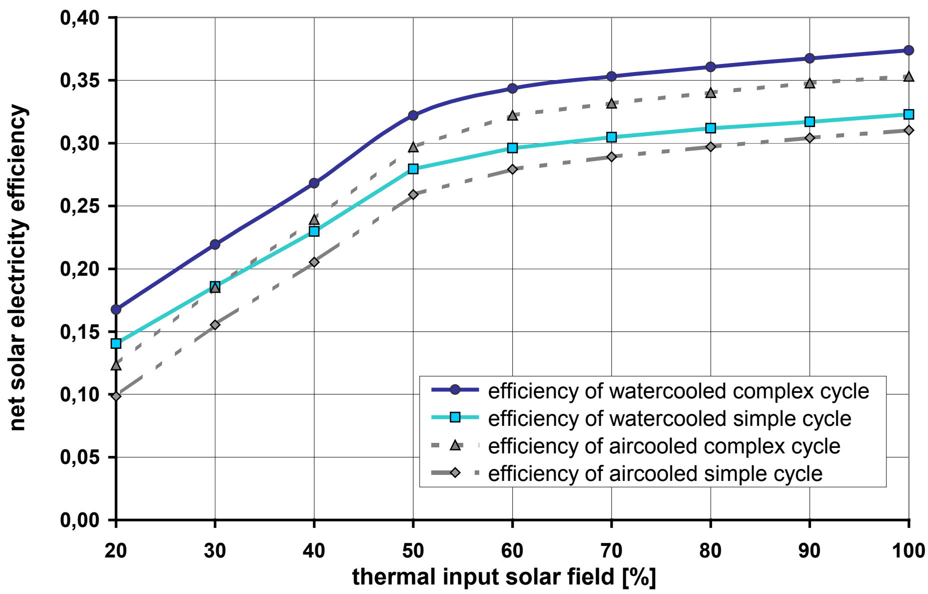

Figure 4.8: Efficiency characteristic of different solar only power plant cycles

The load diagram shows an advantage of the water-cooled cycle, especially in part load mode the efficiency rises up to 4.0 percentage points above the efficiency of an air-cooled process. For a complex cycle (with preheaters and reheating) - compared to a simple cycle (especially at full load mode) - the efficiency rises up to 5.1 percentage points. These processes were subsequently used to determine the optimum solar field size and the resulting energy yields of a 50 MW solar only plant.

5 Solar energy yields and economic aspects

The concept of the »solar only« plant as described above was evaluated by means of whole year system simulations and shall be discussed in the following. The other concepts will be analysed during the continually project. To compute the annual electricity yields or the fuel-savings of the different power plant concepts, the Fresnel collector was treated in the following way. Depending on the inlet and outlet conditions, the ambient temperature and the solar irradiation, each section of the collector (preheating, evaporation, superheating) is able to produce a certain mass flow, which can be calculated using the total energy balance. The absorbed energy depends on the angle of incidence and on the amount of direct normal irradiation (DNI).

Due to the fact, that the mass flow of the whole collector has to be the same in each section, the minimum reachable mass flow limits the total thermal performance.

The performance of the power plant is defined by the mass flow of the solar field, which depends itself on the feedwater temperature given by the power block data. So the resulting power can only be computed iteratively.

For each power plant concept and site location the lengths of each section and therefore the total area of the solar field varies. If one section could produce a higher mass flow than the others the mirrors of this section have to be defocused to maintain the desired output conditions. The ratio of the lengths of each section has to be chosen such, that the necessary defocusing is minimized. The total collector area depends on the part load behaviour and the specific costs of the solar field and the power plant. Finally the price per kWh was chosen as the criteria to optimise the collector length.

Different processes were designed as described above:

- Simple process with one single preheater, on the one hand with air-cooled condenser and on the other hand with fresh water cooling
- Complex process with intermediate superheating and five extraction steam preheaters also with both cooling systems

Reference sites are Faro, Portugal and Hurghada, Egypt (see table 5.1).

Table 5.1: Solar resource for the reference sites

	Hurghada, Egypt	Faro, Portugal
Direct normal irradiance	2782 kWh/m^{2}a	2247 kWh/m^{2}a

Details of the results are exemplarily described for the simple process with fresh water cooling at the Hurghada site. The performance depending on time for two different days are shown in figure 5.1. On June 21 the irradiation would last to generate a higher performance, but the design of the power block forces to dump a certain amount of solar energy. On December 21 the power can not reach its peak; the turbine runs in part load.

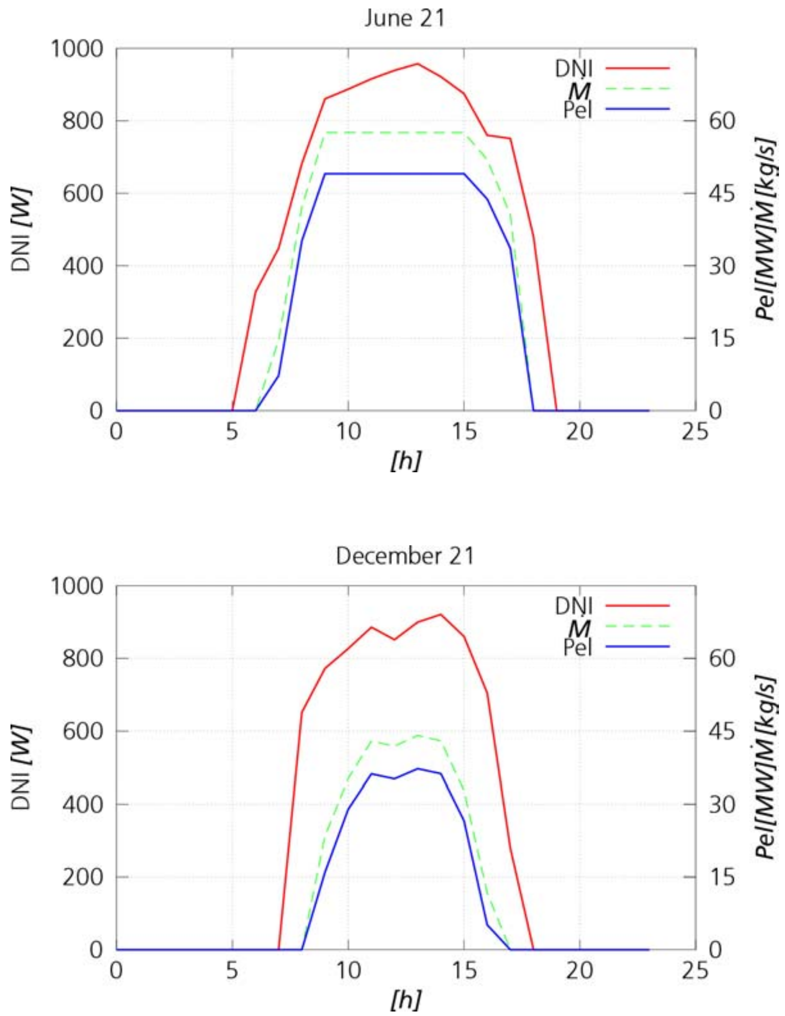

Figure 5.1: Exemplary performance in summer and in winter (available radiation: DNI, power output: P_{el} and steam mass flow: $\dot{m}$)

In figure 5.2 the monthly sums of generated electricity and direct normal radiation are shown. An assumed plant revision of three weeks leads to the smallest amount of produced electricity in January.

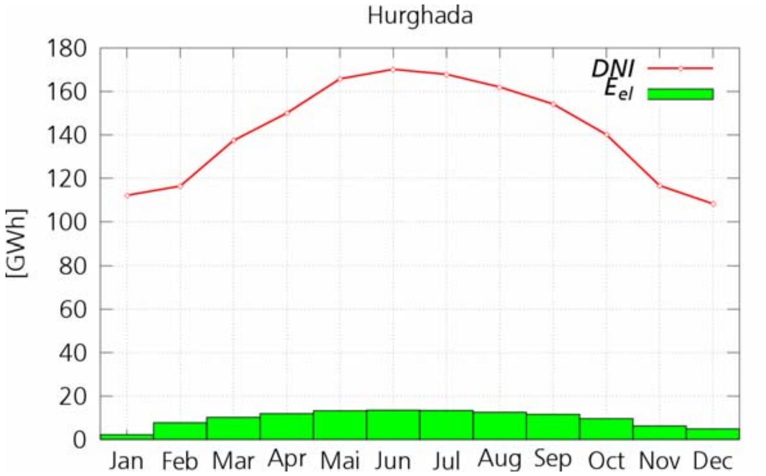

Figure 5.2: Monthly sums of available irradiation and generated power

The investment of a 50 MW solar only plant as treated in the following is based on information concerning the capital investment for the solar field provided by the company Solarmundo and typical prices for the power plant investments. The cost specifications will apply for the second or third plant to be realised. For the construction of the first plant a supplementary risk premium as well as elevated expenses for engineering should be added. The size of the solar field was determined according to economic criteria for the variants which are presented below. The total investment contains all kinds of costs including engineering, project development, land area, electric network connection, contingencies.

Since this kind of solar power plant has no fuel costs, the Levelised Electricity Costs (LEC) are determined by

- Depreciation
- Operation and Maintenance O&M
- Insurance

The depreciation depends on the economic life time which was set to 25 years and on the interest rate which was assumed to be 8%. The insurance was supposed to be 1% of the direct investment, the O&M-Costs were assumed to be 2% of the direct investment. The resulting O&M costs of 1.5 – 2.0 ct/kWh are below values of the trough plant in California from 4 ct/kWh at the beginning to 2.5 ct/kWh in the last years. Simplifications within the Fresnel-concept compared to the trough technology are the reason for that. Table 5.2 and Table 5.3 compile the resulting LECs.

Table 5.2: LEC calculations for solar-only power plants in a developing country

System Layout					
Rated Power	MW	50	50	50	50
Cooling System		fresh water	fresh water	dry	dry
Design		simple	sophist.	simple	sophist.
Specific Power Block Investment	€/kW	652	696	684	730
Specific Solar Field Investment	€/m²	120	120	120	120
Collector Area	m²	400,050	350,760	416,883	408,000
Investment					
Total Power Block Investment	T€	32,583	34,784	34,212	36,523
Total Solar Field Investment	T€	48,006	42,091	50,026	48,960
Total Investment	**T€**	**80,589**	**76,875**	**84,238**	**85,483**
Financial boundary conditions					
Economic Life Time in years	25				
Interest rate	8%				
Annual Costs					
Capital Cost		7,549	7,202	7,891	8,008
Operation & Maintenance	2%	1,612	1,538	1,685	1,710
Insurance	1%	806	769	842	855
Total annual cost	**T€**	**9,967**	**9,508**	**10,418**	**10,572**
Annual Yields					
Direct Normal Irradiance (DNI)	kWh/m²a	2,785	2,785	2,785	2,785
Solar ressource (DNI)	GWh/a	1,114	977	1,161	1,136
Usable thermal yield	GWh/a	379	321	390	347
Electricity yield	GWh/a	117	113	113	116
Efficiency (thermal to electric)		30.9%	35.3%	29.0%	33.4%
Efficiency (DNI to electric)		10.5%	11.6%	9.7%	10.2%
Electricity Cost	**ct/kWhe**	**8.51**	**8.40**	**9.22**	**9.14**

Table 5.3: LEC calculations for solar-only power plants in an European country

System Layout					
Rated Power	MW	50	50	50	50
Cooling System		fresh water	fresh water	dry	dry
Design		simple	sophist.	simple	sophist.
Specific Power Block Investment	€/kW	671	717	705	752
Specific Solar Field Investment	€/m²	150	150	150	150
Collector Area	m²	430,244	415,460	463,635	441,217
Investment					
Total Power Block Investment	T€	33,560	35,828	35,238	37,619
Total Solar Field Investment	T€	64,537	62,319	69,545	66,183
Total Investment	**T€**	**98,097**	**98,147**	**104,783**	**103,802**
Financial boundary conditions					
Economic Life Time in years	25				
Interest rate	8%				
Annual Costs					
Capital Cost		9,190	9,194	9,816	9,724
Operation & Maintenance	2%	1,962	1,963	2,096	2,076
Insurance	1%	981	981	1,048	1,038
Total annual cost	**T€**	**12,132**	**12,139**	**12,959**	**12,838**
Annual Yields					
Direct Normal Irradiance (DNI)	kWh/m²a	2,247	2,247	2,247	2,247
Solar ressource (DNI)	GWh/a	967	934	1,042	991
Usable thermal yield	GWh/a	301	269	316	277
Electricity yield	GWh/a	93	94	93	93
Efficiency (thermal to electric)		30.7%	35.1%	29.4%	33.6%
Efficiency (DNI to electric)		9.6%	10.1%	8.9%	9.4%
Electricity Cost	**ct/kWhe**	**13.10**	**12.88**	**13.93**	**13.79**

In spite of the better efficiency of about 15% (relative) of the sophisticated steam cycle the resulting LEC is only lower about 1%. This is caused by the following reasons:

- The sophisticated power block is approx. 7% more expensive.

- The five preheaters and the additional superheating section arise the temperature level of the solar field and lead to an increase of thermal losses.
- The additional superheating section worsens the suiting of the different sections, so that a higher defocus-dumping is necessary.

Because of the lower outlay in maintenance and control the simple plant-concept might be more interesting than the sophisticated layout.

The resulting LECs are far above conventional power production costs but considerably lower than other available solar technologies. Some subsidised sites (e.g. Spain) allow profit-making operation of a solar thermal power plant on the basis of the presented Fresnel technology. However, because of missing experience the electrical costs of the first plant will be noticeable higher. Taking the worldwide average CO_2-production of conventionally fired power plants at 0.814 t/MWh as a base line, the resulting CO_2 avoidance costs lay between 100 €/t and 170 €/t. From the calculations for hybrid systems remarkable lower electricity costs and CO_2-avoidance costs are expected.

6 Summary, Conclusions and perspective

Among solar technologies solar thermal power generation is the most economic option to produce electricity on a large scale. Parabolic trough systems have proven the technological maturity and reliability of the concept in continuous operation for over a decade.

Worldwide different groups have further developed the line focussing parabolic trough collector with the aim of reducing its costs or improving its efficiency. One approach is the so called Fresnel collector which divides the big parabolic reflector trough into many smaller and flat reflector segments.

In the frame of a project partly funded by the German Federal Environmental Ministry E.ON Energie together with two research institutes (Fraunhofer ISE and DLR) have intensively examined this Fresnel collector concept and have dedicated much attention to the question of how to integrate the collector's thermal output into conventional steam-cycles in an economically and technologically favourable way.

As an example of this work yearly simulations of a solar only plant situated at two sites with high solar irradiance have been presented. One basic result are levelised electricity costs (LEC) between 9 and 14 €cent/kWh for different scenarios which are below comparable trough systems. Conclusions from these results are:

- The corresponding CO_2 avoidance costs for solar only systems are between 100 €/t and 170 €/t.
- At subsidised sites (e.g. in Spain) the operation of a solar only power plant can be cost efficient even without a big thermal storage and without the additional costs for the first demo plant.
- The LEC for hybrid plants are even lower because of better depreciation conditions for the conventional steam cycle

The Fresnel collector concept is at the very beginning of its development with cost reductions still to be expected. From the pending results of hybrid systems lower electricity costs are expected. However, because all work presented here is only theoretical, the next step to further pursue this promising technology is to realise a small scale pilot plant that allows for experimental validation under real operation conditions.

7 Acknowlegement

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8 References

[1] Worldbank, Cost Reduction Study for Solar Thermal Power Plants (1999)

[2] N.N. "Technik - Wirtschaftlichkeit - Umweltschutz Staudinger Block 5 setzt neue Maßstäbe", PreußenElektra, Strom: Fachbericht 8, Hannover, November 1996.

[3] N.N. " Neue Energie macht Dampf - Strom und Wärme aus Kohle, Gas und Öl", EON Kraftwerke GmbH, Hannover, April 2001.

[4] Stellbrink, B. "Erste Erfolge mit innovativer Technik im Kraftwerk Staudinger 5", VGB Kraftwerkstechnik, S.322-326, April 1994.

[5] eb-Elektrische Bahnen, Jg. 93 (1995), H. 9/10, S.280-289

[6] Johansson, T.B., et al., Renewable Energy, Sources for Fuels and Electricity, Island Press, Washington D.C., Chapter 5, pp. 234-235, 1993.

[7] Heat balance and process simulation package IPSEpro: http://www.SimTechnology.com/

[8] Process simulation tool Ebsilon developed by sofbid, http://www.sofbid.com

[9] http://www.eon-kraftwerke.com/frameset_german/energy/inn_reg_ene/ene_ene_pro_reg_biomassekraft/ene_ene_pro_reg_biomassekraft_2_neu/ene_ene_pro_reg_biomassekraft_2_neu.jsp