ANALYSIS OF SOLAR THERMAL POWER PLANTS WITH THERMAL ENERGY STORAGE AND SOLAR-HYBRID OPERATION STRATEGY

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Abstract

Selected solar-hybrid power plants for operation in base-load as well as mid-load were analyzed regarding supply security (due to hybridization with fossil fuel) and low CO_2 emissions (due to integration of thermal energy storage). The power plants were modeled with different sizes of solar fields and different storage capacities and analyzed on an annual basis. The results were compared to each other and to a conventional fossil fired combined cycle in terms of technical, economical and ecological figures.

The results of this study show that in comparison to a conventional fossil fired combined cycle the potential to reduce the CO_2 emissions is high for solar thermal power plants operated in base-load, especially with large solar fields and high storage capacities. However, for dispatchable power generation and supply security it is obvious that in any case a certain amount of additional fossil fuel is required. No analyzed solar-hybrid power plant shows at the same time advantages in terms of low CO_2 emissions and low LEC. While power plants with solar-hybrid combined cycle (SHCC®, Particle-Tower) show interesting LEC, the power plants with steam turbine (Salt-Tower, Parabolic Trough, CO_2-Tower) have low CO_2 emissions.

Keywords: solar thermal power plant, solar-hybrid power plant, solar tower plant, parabolic trough.

1. Introduction

Solar thermal power plants can guarantee supply security by integration of thermal energy storages and/ or by using a solar fossil hybrid operation strategy. Only few technologies among the renewables offer this base-load ability. Therefore it is predicted that they will have a significant market share of the future energy sector.

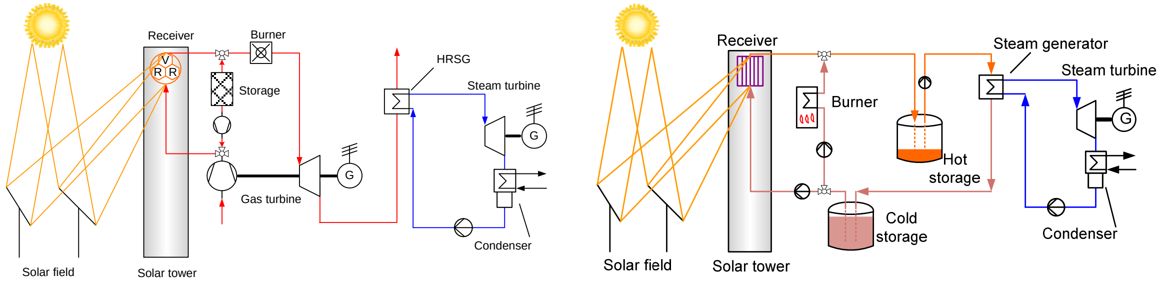
The sun is an intermittent source of energy. Solar power plants that are operated with a solar-only operation strategy and use thermal energy storages to extend the operation to hours when the sun does not shine cannot entirely provide power on demand and account at the same time for economical aspects. Therefore those solar power plants do not have a real ability for base-load and the utilities have to provide backup power from conventional fossil fired power plants. This situation can be overcome by the use of additional fossil fuel to generate the heat in a solar-hybrid power plant.

However, the transition from a solar-only power plant to a solar-hybrid power plant incorporates some conflicts. While the economy of the power plant is improved as the annual utilization of the plant is increased, the emission of green house gases (e.g. CO_2) is also increased. Is there an optimum existing for the solar share and the share of hybridization to account for economical and ecological aspects? What is the influence of increasing fuel prices and increasing carbon trading costs coupled with high power block efficiencies?

In this study five different types of solar-hybrid power plants with different sizes of solar fields and different storage capacities are modeled and analyzed on an annual basis. The results of the solar-hybrid power plants are compared to each other and to a conventional fossil fired combined cycle power plant in terms of technical, economical and ecological figures. Beside of state of the art solar power plant concepts (Fig. 1b and c) also new and innovative solar power plant concepts (Fig. 1a, d and e) were analyzed in detail for this study.

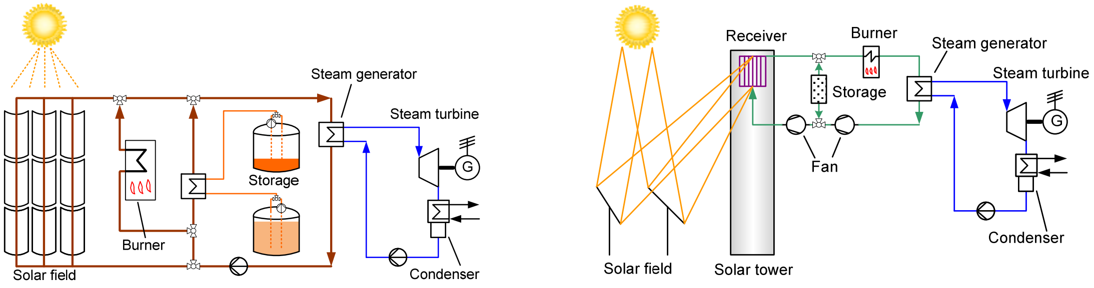
a) Solar-hybrid Combined Cycle (SHCC®)
Solar tower with solar-hybrid combined cycle and pressurized solid media thermal energy storage

b) Salt-Tower
Solar tower with steam turbine and molten salt as heat transfer medium and for thermal energy storage



c) Parabolic Trough
Parabolic Trough with steam turbine and with thermal oil as heat transfer medium and molten salt thermal energy storage

d) CO_2-Tower
Solar tower with steam turbine and pressurized gas receiver (CO_2) and pressurized solid media thermal energy storage



e) Particle-Tower
Solar tower with solar-hybrid combined cycle and with solid media particles as heat transfer medium and for thermal energy storage

f) Combined Cycle (CC)
Conventional fossil-fired combined cycle as reference plant

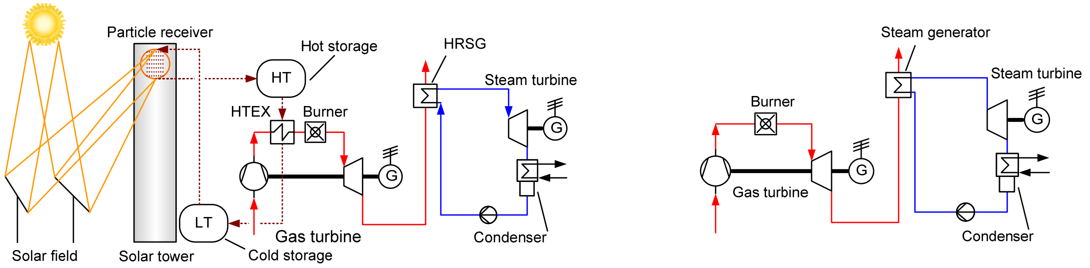


Fig. 1. Analyzed solar-hybrid power plants.

2. Solar-hybrid power plants

For this study the solar-hybrid power plants shown in Fig. 1 were designed and modeled for a site in Northern Africa (Hassi R'Mel, Algeria) for a power level of 30 MW_{el} with dry cooling towers. Due to the integrated fossil burner each analyzed solar-hybrid power plant can be operated in solar-only, fossil-only or solar-hybrid mode. To increase the solar share of the plant a thermal energy storage is used.

All solar-hybrid power plants were modeled with different sizes of solar fields and different storage capacities. Therefore for a solar field with solar multiple 1 (SM1)[1] no storage is used, for SM2 a storage capacity of 7.5h (i.e. 7.5h of nominal load operation at design point conditions) and for SM3 a storage capacity of 15h is used. It is clear that this combination of SM and storage capacity is not optimal e.g. for the lowest electricity generation cost (levelized electricity cost or LEC). But for this study this combination is appropriate to perform the intended comparison with equal boundary conditions.

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[1] A solar field with SM1 can deliver the required design thermal power to run the power plant on nominal load at design point conditions.

Following each solar-hybrid power plant is briefly described and some specifications are given. Further detail specifications as well as the definition of the design point conditions are summarized in Table 1 in the annex.

2.1. Solar-hybrid Combined Cycle (SHCC®)

The solar-hybrid combined cycle is a solar tower power plant. It consists of a heliostat field (solar field), a solar receiver mounted on top of a tower and a gas turbine that is modified for solar-assisted operation. In solar-hybrid combined cycles the concentrated solar power is used to heat the pressurized air before entering the combustion chamber of the gas turbine cycle of a combined cycle. The solar heat can therefore be converted with the high thermal efficiency of combined gas turbine cycles. Fig. 1a shows the flow schematic of this system. The combustion chamber closes the temperature gap between the receiver outlet temperature (850°C at design point) and the turbine inlet temperature (~1100°C) and provides constant turbine inlet conditions despite fluctuating solar input. For this study a model of a solarized gas turbine of the MAN THM1304-12 with bottoming steam cycle was used [1]. Because of size dependency of steam turbine efficiency and costs a 2+1 combined cycle with two gas turbines and one steam turbine was chosen in the SHCC project co-founded by the German BMU.

The pressurized air in this system is sequentially heated in two receivers. In the low temperature receiver, which is a cavity receiver with metal tubes the air is heated up to 650°C. In the following pressurized volumetric air receiver for high temperatures the air is heated up to 850°C and then led to the combustion chamber of the gas turbine. This receiver concept was already successfully tested in the SOLGATE project [2]. The solar share at design point condition for this system is about 60%. Generally the pre-heating of the air could be done up to about 1000°C, what would increase the solar share. For this study a pressurized solid media thermal energy storage (TES) was used in addition to the layout in [1]. The gross efficiency at design point conditions of this dry cooled 30 MW_{el} power block is 46.4%.

2.2. Salt-Tower

The Salt-Tower is a solar tower power plant with a steam turbine and molten salt as heat transfer medium (HTF), which is also used for thermal energy storage. This system is mainly based on the Solar Two power plant [3]. Fig. 1b shows the flow schematic of this system. The fossil burner allows an operation of the plant in solar-hybrid or fossil-only mode (storage bypass not shown in the schematic). Molten salt at 290°C is pumped out of a “cold” storage tank to the external receiver on top of a tower where it is heated to 565°C and delivered to a “hot” storage tank. The hot salt is then extracted for the generation of 552°C/ 126bar steam in the steam generator. The steam powers the turbine to generate electricity. The steam turbine is designed as a reheat turbine with several feed-water pre-heaters to allow a gross efficiency of 42.5% at design point conditions. The solar share at design point is 100%.

2.3. Parabolic Trough

The Parabolic Trough power plant for this study is mainly based on the commercial Andasol 1 plant that was connected to the Spanish grid at the end of 2008. The layout was scaled to a power level of 30 MW_{el} and designed for the operation with dry cooling towers. The fossil burner has unlike the Andasol 1 plant the ability to run the plant on full load with fossil-only mode. Fig. 1c shows the flow schematic of this system. Thermal oil is used as HTF in the collector field. This HTF transfers the heat collected in the solar field via heat exchangers either to a conventional water steam cycle or to the molten salt storage system. If not enough solar energy for solar operation of the power block is available, the HTF can be heated from the storage or the fossil burner and transfer its heat to the water steam cycle. The HTF temperature in the cold headers is 293°C and in the hot headers 393°C. The steam turbine has steam parameters of 371°C/ 100bar and is designed as reheat turbine with several feed-water pre-heaters. The gross efficiency at design point conditions of the power block is 37.2%. The solar share at design point is 100%.

2.4. CO_2-Tower

The CO_2-Tower is a solar tower power plant with a steam turbine, a pressurized gas receiver and a pressurized solid media thermal energy storage. Fig. 1d shows the flow schematic of this system. CO_2 is used as HTF, which is heated up in the cavity receiver with metal tubes on top of a tower from 310-600°C. The hot pressurized CO_2 is then used for generation of 570°C/ 126bar steam in the steam generator and/ or to load the TES. The steam powers the turbine to generate electricity. The fossil burner allows an operation of the plant in solar-hybrid or fossil-only mode. The steam turbine is designed as reheat turbine with several feed-water pre-heaters to allow a gross efficiency of 43.0% at design point conditions. The solar share at design point is 100%.

The TES is based on the actual development of the advanced adiabatic compressed air energy storage technology [4]. Therefore, like for the AA-CAES application, a pressure of 65bar was chosen for the HTF circuit. Generally several pressurized gases like air, helium, nitrogen, etc. could be used. CO_2 was chosen for this application because of its interesting thermophysical properties allowing low pressure losses and therefore low parasitic consumption. However, the pressure of the system is an optimization parameter what should be optimized more in detail for this system in a subsequent study.

2.5. Particle-Tower

The Particle-Tower is a solar tower with a combined cycle and with solid media particles as heat transfer medium and for thermal energy storage. This is one of several possible systems for the integration of high temperature heat from particle receivers that are currently assessed at DLR. Fig. 1e shows the flow schematic of this system. Particles are pumped out of a “cold” storage tank at 360°C to the direct contact particle receiver on top of a tower where they are heated to 1000°C and delivered to a “hot” storage tank. In the direct contact heat exchanger (having an internal lock system for pressure balance and filters) the pressurized air is heated up to about 995°C before entering the combustion chamber of the gas turbine cycle of a combined cycle. The combustion chamber closes the temperature gap to the turbine inlet temperature (~1100°C). At design point the solar share is about 80% and the gross efficiency of the power block is 46.4%. In this study the same combined cycle like for the SHCC® power plant was used.

2.5. Combined Cycle (CC)

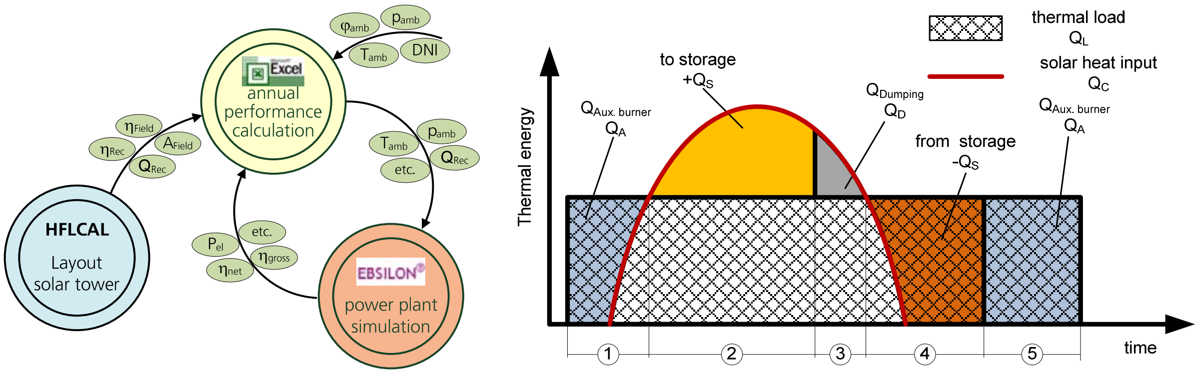
The combined cycle (CC) is a conventional fossil-fired combined-cycle that is used as reference plant. Fig. 1f shows the flow schematic of this system. This combined cycle was modeled with a Siemens-Westinghouse V64.3A gas turbine and a bottoming steam cycle. In contrast to the solar-hybrid power plants the power level of this power plant is about three times bigger. The gross design power is about 95 MW_{el}. The gross efficiency at design point conditions of the dry cooled power block is 51.7%.

3. Methodology for System Simulation and Economic Assessment

For design optimization and annual performance prediction of the analyzed solar-hybrid power plants different software tools were used. Fig. 2a shows the work flow and the interaction of the used software tools HFLCAL, Ebsilon® and Excel®.

For the layout, the optimization and the simulation of operation of the selected power plants the commercial software Ebsilon® was used. The layout of cost optimized solar fields for solar towers was done with HFLCAL software [5]. For the layout of the solar fields for parabolic troughs the new solar library of Ebsilon® was used. To allow the calculation of solar-hybrid power plants over a full year with hourly time series an interface was adapted for this study in Excel®. For each hour of a year the performance of the plant was calculated, for the hourly values of the solar irradiation (DNI), the actual weather conditions (temperature, pressure) as well as the solar position angles according to the geographic location of the site and the time in the year. Additionally the operation strategy was modeled in detail to account on the several operation modes during solar mode, storage mode, hybrid (fossil) mode and mixed mode. Fig. 2b shows the general schematic for the operational strategy what needs to be adapted and modeled for each solar-hybrid power plant individually [6]. For this study the power plants were always in their possible full load during the operating time, no specific load characteristic is followed.

The analysis for this study was carried out for two different load situations: 1. operating time from 0-24h, which is representing base-load operation and 2. from 6-22h, which is representing mid-load operation. This means that the power plants in base-load are operated 8760 h/a and the ones in mid-load 6205 h/a.



a) Work flow of simulation software

b) Operation mode and operational strategy

Fig. 2. Methodology for system simulation.

The economic assessment was made to obtain the LEC for the entire plant as well as the solar LEC (i.e. the effective cost of the electricity produced by the solar contribution [7]). The main task of the economic assessment was to elaborate the differences between the solar-hybrid power plants to each other and to a conventional reference fossil-fired combined cycle. The essential figure of merit is the LEC which is calculated according to a simplified IEA method [8]. This approach is kept simple, but it appears to be appropriate to perform the relative comparison necessary to quantify the impact of a technical innovation. Important to mention is, that this cost model neglects any project specific data (e.g. tax influences, financing conditions). The simplified IEA method contains following simplifications: 100% debt finance, plant operation time = depreciation period, neglect of taxes, neglect of increase in prices and inflation during construction and neglect of increase in prices and inflation regarding O&M cost.

The data used in this study for the economic assessment like the investment cost, the financial boundary conditions, O&M cost and the specific life cycle fuel cost are summarized in Table 1 in the annex.

4. Results

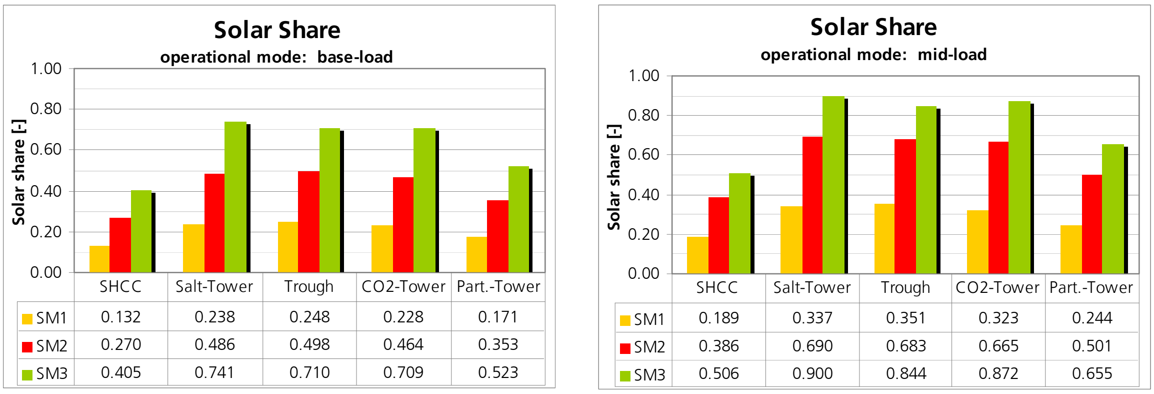
The results of the annual performance calculations show that with increasing solar field size and storage capacity the solar share of the solar-hybrid solar plants is also increasing (Fig. 3a). For the operation in base-load (Fig. 3a) a maximum solar share of 74.1% is reached for the Salt-Tower with SM3 and 15h storage capacity. The CO_2-Tower and the Parabolic Trough are close to this, while the SHCC and the Particle Tower are falling behind. This is a direct consequence from the design point solar share of those two plants. For the operation in mid-load (Fig. 3b) the comparison between the analyzed systems generally shows the same interrelations, but as the plants are not operated around the clock and especially not in large extends at fossil-only mode, the solar share is higher than for base-load operation. Obvious from these results is that even with large solar fields (SM3) and high storage capacities (15h) each solar-hybrid power plant needs additional fossil fuel to provide real power on demand. It is clear that this chosen scenario is not the most economic one for a solar power plant but it shows the upper technical bound for the chosen site and boundary conditions.

The results of the specific CO_2 emissions for base-load operation (Fig. 3c) show that compared to the conventional fossil-fired combined cycle not all solar-hybrid power plants can reduce the CO_2 emissions. Especially power plants with small solar fields and without storage that have additionally low power block efficiency or low solar share at design point, have no or low potential to reduce CO_2 emissions. Larger solar fields and the integration of TES allow the reduction of the CO_2 emissions up to 68% compared to the fossil-fired combined cycle. It is clear that the specific CO_2 emissions are directly depending on the solar share. But important for the operation of the solar thermal power plant in fossil mode is also the efficiency of it, as can be seen in (Fig. 3c) comparing the Salt-Tower and the Parabolic Trough. Both have about the same solar share (Fig. 3a) but a higher deviation in specific CO_2 emissions. The results for the operation in mid-load (Fig. 3d) generally show the same interrelations like for base-load, but with another order of magnitude.

The LEC and the effective cost of the electricity produced by the solar contribution - the solar LEC - are summarized in Fig. 3e for the base-load operation. The LEC of the reference combined cycle is 6.0 €ct/kWh$_{el}$. Power plants that have a high fossil fuel consumption and thus low solar share (SHCC, Particle-Tower) are close to this with 7.3 €ct/kWh$_{el}$ with SM1 and without storage. The lowest solar LEC is achieved with 9.8 €ct/kWh$_{el}$ by the Particle-Tower. However, this is with SM1 and no storage and therefore the specific CO_2 emissions are high. In mid-load (Fig. 3f) this increases to 12.0 €ct/kWh$_{el}$ as the annual utilization of the plant is decreased. Also interesting is that the LEC as well as the solar LEC are increasing with the SM and storage capacity. This is caused mainly due to the high investment cost of the TES. This is especially remarkable for the CO_2-Tower, where the specific storage cost for the 65bar storage is high. But also for the Parabolic Trough it is remarkable, as the specific storage costs are high (due to low ΔT) and the low power block efficiency requires bigger amounts of stored thermal energy.

Some further results of the annual performance calculations are listed in Table 1 in the annex.

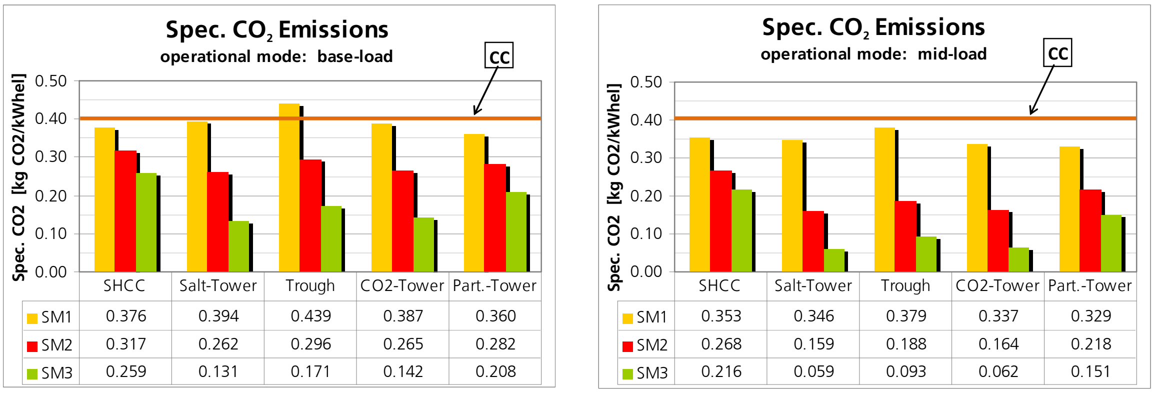
a) Solar share in base-load operation *b) Solar share in mid-load operation*



base-load	SHCC	Salt-Tower	Trough	CO2-Tower	Part.-Tower
🟨 SM1	0.132	0.238	0.248	0.228	0.171
🟥 SM2	0.270	0.486	0.498	0.464	0.353
🟩 SM3	0.405	0.741	0.710	0.709	0.523

mid-load	SHCC	Salt-Tower	Trough	CO2-Tower	Part.-Tower
🟨 SM1	0.189	0.337	0.351	0.323	0.244
🟥 SM2	0.386	0.690	0.683	0.665	0.501
🟩 SM3	0.506	0.900	0.844	0.872	0.655

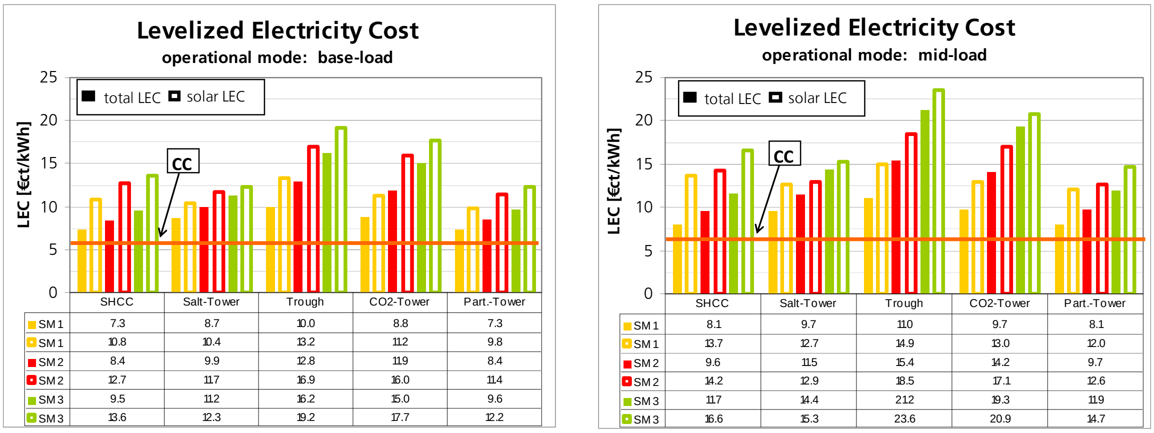
c) Specific CO_2 emissions in base-load operation *d) Specific CO_2 emissions in mid-load operation*



base-load	SHCC	Salt-Tower	Trough	CO2-Tower	Part.-Tower
🟨 SM1	0.376	0.394	0.439	0.387	0.360
🟥 SM2	0.317	0.262	0.296	0.265	0.282
🟩 SM3	0.259	0.131	0.171	0.142	0.208

mid-load	SHCC	Salt-Tower	Trough	CO2-Tower	Part.-Tower
🟨 SM1	0.353	0.346	0.379	0.337	0.329
🟥 SM2	0.268	0.159	0.188	0.164	0.218
🟩 SM3	0.216	0.059	0.093	0.062	0.151

e) LEC and solar LEC in base-load operation *f) LEC and solar LEC in mid-load operation*



base-load	SHCC	Salt-Tower	Trough	CO2-Tower	Part.-Tower
🟨 SM 1	7.3	8.7	10.0	8.8	7.3
◘ SM 1	10.8	10.4	13.2	11.2	9.8
🟥 SM 2	8.4	9.9	12.8	11.9	8.4
◘ SM 2	12.7	11.7	16.9	16.0	11.4
🟩 SM 3	9.5	11.2	16.2	15.0	9.6
◘ SM 3	13.6	12.3	19.2	17.7	12.2

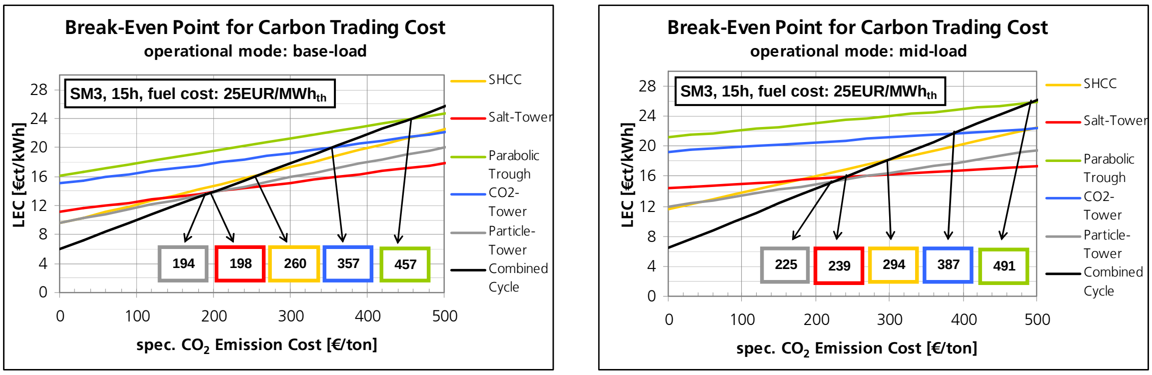
mid-load	SHCC	Salt-Tower	Trough	CO2-Tower	Part.-Tower
🟨 SM 1	8.1	9.7	11.0	9.7	8.1
◘ SM 1	13.7	12.7	14.9	13.0	12.0
🟥 SM 2	9.6	11.5	15.4	14.2	9.7
◘ SM 2	14.2	12.9	18.5	17.1	12.6
🟩 SM 3	11.7	14.4	21.2	19.3	11.9
◘ SM 3	16.6	15.3	23.6	20.9	14.7

Fig. 3. Annual results for the solar-hybrid power plants.

The results for the assessment of the power plants on an annual basis regarding solar share, specific CO_2 emissions and LEC allow no concluding rating or statement because of the complex interrelations. That solar-thermal power plants have currently no economical advantage compared especially to modern, efficient fossil fired power plants is already known. But how shall the advantage in reduced CO_2 emissions of solar-thermal power plants be assessed? A possibility is the introduction of carbon trading cost.

Fig. 4 shows the break-even point for the required carbon trading cost at same LEC for the individual solar-hybrid power plant compared to the reference combined cycle. Solely the results for *SM3 und 15h storage capacity* are shown, as here the lowest specific CO_2 emissions are reached and therefore the highest potential for reduction of CO_2 emissions. In base-load operation the brake-even point with lowest carbon trading cost is reached by the Particle-Tower at 194 EUR/ ton_{CO2} (Fig. 4a) (for assumed life cycle fuel cost of 25 EUR/ MWh_{th}). However, the LEC of the fossil-fired combined cycle will then be more than doubled. The Parabolic Trough has a break-even point with the highest carbon trading cost at 457 EUR/ton_{CO2}. SHCC and Particle Tower have without additional carbon trading cost about the same LEC. However, the solar share of SHCC is at design point as well as on annual basis lower and thus the specific CO_2 emissions are higher. Therefore the break-even point is reached for the SHCC at 260 EUR/ ton_{CO2}. The results for operation in mid-load (Fig. 4b) show that the required carbon trading cost would have to increase further to reach the break-even point. This is the case although the solar-hybrid power plants have lower specific CO_2 emissions here. The reason for this can be found in the higher LEC of the solar-hybrids power plants in mid-load compared to the ones in base-load.

If higher life cycle fuel costs are assumed e.g. 50 EUR/ MWh_{th} the break even point is earlier reached for all solar-hybrid power plants (Fig. 4c, d). With this, the LEC are becoming more interesting compared to the reference combined cycle. However, the magnitude of order for LEC is then also increased for all.


a) Break-even point for base-load operation:SM3, 15h storage capacity, specific life cycle fuel cost 25 EUR/ MWh_{th}

b) Break-even point for mid-load operation: SM3, 15h storage capacity, specific life cycle fuel cost 25 EUR/ MWh_{th}

c) Break-even point for base-load operation: SM3, 15h storage capacity, specific life cycle fuel cost 50 EUR/ MWh_{th}

d) Break-even point for mid-load operation: SM3, 15h storage capacity, specific life cycle fuel cost 50 EUR/ MWh_{th}

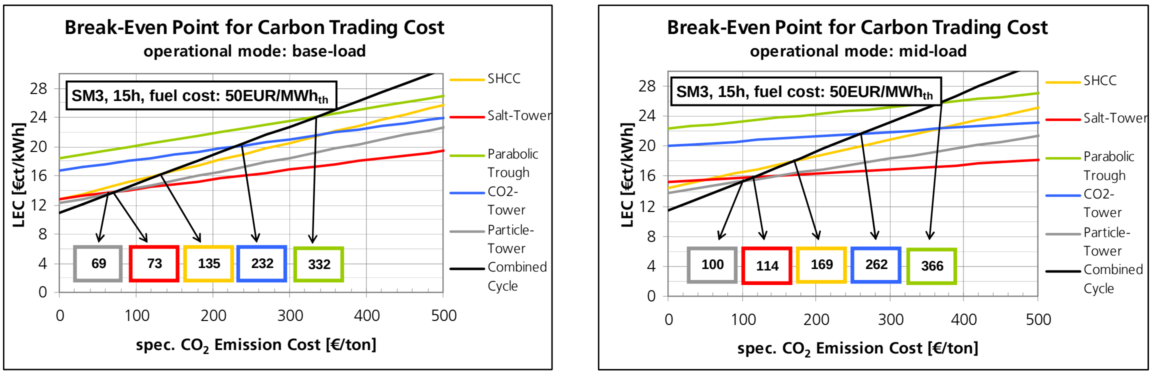


Fig. 4. Break-even point for carbon trading cost.

5. Conclusions

Selected solar-hybrid power plants for operation in base-load as well as mid-load were analyzed regarding supply security (due to hybridization with fossil fuel) and low CO_2 emissions (due to integration of thermal energy storage). Therefore those power plants were modeled with different sizes of solar fields and different storage capacities and analyzed on an annual basis. The results were compared to each other and to a conventional fossil fired combined cycle in terms of technical, economical and ecological figures.

The results of this study show that in comparison to a conventional fossil fired combined cycle the potential to reduce the CO_2 emissions is high, especially with large solar fields and high storage capacities. However, for dispatchable power generation and supply security it is obvious that in any case a certain amount of additional fossil fuel is required. No analyzed solar-hybrid power plant shows at the same time advantages in terms of low CO_2 emissions and low LEC. While power plants with solar-hybrid combined cycle (SHCC$^{®}$, Particle-Tower) show interesting LEC, the power plants with steam turbine (Salt-Tower, Parabolic Trough, CO_2-Tower) have low CO_2 emissions (especially those with large solar fields and high storage capacities).

All solar-hybrid power plants show increasing LEC with increasing solar field sizes and storage capacities. This is mainly caused by the high investment cost of the TES. However, those are a fundamental requirement for low CO_2 emissions for base-load operation of solar thermal power plants. The LEC could generally be reduced by choosing a site with better solar resources i.e. higher annual insulation or by up-scaling of the power plants using the economy of scale. However, to be competitive to conventional fired combined cycles in *base-load operation*, it is necessary in future to further reduce the investment cost of the solar-hybrid power plants and/ or to increase the efficiency and/ or the increase the solar share. Higher cost of fossil fuels and higher cost for carbon trading can generally reduce the advantage in LEC for the fossil fired combined cycles. However, this will also dramatically increase the cost of common electricity supply.

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References

[1] Heide S., Gampe U., Orth U., Beukenberg M., Gericke B., Freimark M., Langnickel U., Pitz-Paal R., Buck R., Giuliano S., “Design And Operational Aspects Of Gas And Steam Turbines For The Novel Solar Hybrid Combined Cycle SHCC$^{®}$”. In Proceedings of the ASME Turbo Expo 2010: Power for Land, Sea and Air (2010).

[2] “SOLGATE – Solar Hybrid Gas Turbine Electric Power Systems”, Final Technical Report, European Commission (2004).

[3] Zavoico, A., et al., „Solar Power Tower - Design Basis Document Revision 0“, Sandia National Laboratories, (2001).

[4] Marquardt R., Hoffmann S., Pazzi S., Klafki M., Zunft S.:”AA-CAES - Opportunities and challenges of advanced adiabatic compressed air energy storage technology as a balancing tool in interconnected grids.”, Technische Universität Dresden (Ed.): 40. Kraftwerkstechnisches Kolloquium 2008, 14.-15. Okotober 2008, Vol. 2, (2008).

[5] Schwarzbözl P., Schmitz M., Pitz-Paal R., “Visual HFLCAL – a Software Tool for Layout and Optimization of Heliostat Fields”. 15. International SolarPACES Symposium, Berlin, Germany, (2009).

[6] Eguiguren S., “Systemsimulation und wirtschaftliche Analyse von solarthermischen Kraftwerken mit solarhybrider Betriebsstrategie”, Diploma Thesis, DLR, (2010).

[7] Schwarzbözl, P., Buck R., Sugarmen C., Ring A., Crespo J.M., Altwegg P., Enrile J., “Solar gas turbine systems: Design, cost and perspectives”, Solar Energy, Vol. 80, Elsevier, (2006).

[8] International Energy Agency (IEA), Guidelines for the Economic Analysis of Renewable Energy Technology Applications, Publication, (1991).

Annex

Site Specification																		
Site			Hassi R'Mel, Algeria															
Latitude/ Longitude/ Altitude		[°]N / [°]E/ [m]	32.9/ 3.2/ 746															
Ambient Temperature (mean)		[°C]	19.2															
Annual Solar Resource - DNI		[KWh/ m2 a]	2,258															
Design Point Definition																		
Design point definition		[-]	21.03. noon 912 W/m²															
Design point conditions		[-]	25 °C, 60 % r.h. , 1013 mbar															
System layout			**SHCC**			**Salt-Tower**			**Parabolic Trough**			**CO2-Tower**			**Particle-Tower**			**Ref. CC**
Configuration: SM - storage capacity		[-] - [h]	**SM1 - 0**	**SM2 -**	**SM3 - 15**	**SM1 - 0**	**SM2 -**	**SM3 - 15**	**SM1 - 0**	**SM2 -**	**SM3 - 15**	**SM1 - 0**	**SM2 -**	**SM3 - 15**	**SM1 - 0**	**SM2 -**	**SM3 - 15**	
Design Point Specifications																		
Net Power @DP		[MW$_{el}$]	30.2	29.5	28.8	28.1	27.5	26.9	27.8	26.1	24.5	28.9	28.7	28.5	29.7	29.5	29.3	93.7
Gross Power @DP		[MW$_{el}$]	30.6	30.6	30.6	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.3	30.3	30.3	94.8
Net Efficiency (Power Plant) @DP		[-]	0.459	0.448	0.437	0.389	0.381	0.371	0.338	0.317	0.296	0.413	0.411	0.408	0.456	0.452	0.449	0.515
Design Thermal Power PB @ DP		[MW$_{th}$]	65.9	65.9	65.9	70.5	70.5	70.5	80.7	80.7	80.7	69.8	69.8	69.8	65.3	65.3	65.3	183.2
Solar Receiver Design Power		[MW$_{th}$]	39.6	79.2	118.8	70.5	141.0	211.5	80.7	161.4	352.1	69.8	139.6	209.4	52.0	104.0	156.0	-
Solar Share		[-]	0.601	0.601	0.601	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.797	0.797	0.797	-
Tower height		[m]	118	149	164	103	147	170	-	-	-	140	185	203	135	169	180	-
Total Solar Field Area		[m²]	72,813	148,925	226,992	135,120	270,118	413,179	150,804	301,609	452,414	120,460	243,363	370,664	90,650	187,653	293,575	-
Total Plant Area		[km²]	0.275	0.374	0.475	0.356	0.531	0.717	0.573	1.146	1.719	0.337	0.496	0.662	0.298	0.424	0.562	0.050
Thermal Storage Capacity		[MWh$_{th}$]	0	297	594	0	529	1058	0	605	1210	0	524	1047	0	390	780	-
Auxiliary Burner		[MW$_{th}$]	0	0	0	74.6	74.6	74.6	85.0	85.0	85.0	75.0	75.0	75.0	0	0	0	-
Annual Yields																		
Operating Hours	0h…24h	[h/a]	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,750	8,760	8,760	8,760	8,760	8,760	8,760
	6h…22h		6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205	6,205
Thermal Solar Energy used	0h…24h	[MWh$_{th}$/a]	80,092	162,092	240,887	149,603	301,545	456,774	177,406	345,296	478,932	143,948	286,874	426,600	103,482	211,148	310,282	-
	6h…22h		80,092	161,763	210,332	149,604	300,984	447,415	177,410	331,320	402,833	144,792	286,492	370,884	103,488	209,159	271,693	-
Fuel Energy	0h…24h	[MWh$_{th}$/a]	525,713	438,368	354,140	479,768	318,475	159,817	539,192	348,361	195,332	488,369	330,748	175,359	501,084	387,585	283,517	1,515,300
	6h…22h		344,499	257,496	204,956	294,384	135,309	49,722	327,854	154,033	74,193	303,558	144,540	54,535	319,894	208,467	142,996	1,067,485
Net Electric Energy	0h…24h	[MWh$_{el}$/a]	279,605	276,574	273,413	243,822	243,443	243,256	245,530	235,207	227,835	252,190	249,857	246,834	278,483	275,247	272,345	770,701
	6h…22h		195,306	192,280	189,699	170,139	169,747	168,842	173,075	163,820	158,833	180,077	175,756	175,631	194,261	191,078	189,085	541,533
Efficiency Net Power Plant	0h…24h	[-]	0.462	0.461	0.459	0.387	0.393	0.395	0.343	0.339	0.338	0.399	0.405	0.410	0.461	0.460	0.459	0.509
(Heat to Electric)	6h…22h		0.460	0.459	0.457	0.383	0.389	0.340	0.343	0.338	0.333	0.402	0.408	0.413	0.459	0.458	0.456	0.507
Efficiency Net Solar	0h…24h	[-]	0.225	0.222	0.216	0.190	0.194	0.193	0.179	0.172	0.159	0.211	0.211	0.209	0.233	0.229	0.215	-
(DNI to Electric)	6h…22h		0.224	0.221	0.187	0.188	0.192	0.163	0.179	0.165	0.132	0.214	0.213	0.183	0.232	0.226	0.188	-
Spec. CO2 emissions	0h…24h	[kg$_{CO2}$/kWh$_{el}$]	0.396	0.334	0.273	0.414	0.275	0.138	0.462	0.312	0.181	0.408	0.279	0.150	0.379	0.297	0.219	0.414
	6h…22h		0.371	0.282	0.228	0.364	0.168	0.062	0.399	0.198	0.098	0.355	0.173	0.065	0.347	0.230	0.159	0.415
Solar full load hours	0h…24h	[h]	1,223	2,530	3,846	2,061	4,302	6,709	2,186	4,479	6,616	1,990	4,049	6,142	1,603	3,290	4,862	-
	6h…22h		1,219	2,514	3,338	2,039	4,255	5,657	2,185	4,278	5,484	2,016	4,102	5,343	1,597	3,244	4,232	-
Solar Share	0h…24h	[-]	0.132	0.270	0.405	0.238	0.486	0.741	0.248	0.498	0.710	0.228	0.464	0.709	0.171	0.353	0.523	-
	6h…22h		0.189	0.386	0.506	0.337	0.690	0.900	0.351	0.683	0.844	0.323	0.665	0.872	0.244	0.501	0.655	-
Investment																		
Total Investment		[T€]	57,443	97,982	139,052	74,272	131,848	190,217	88,937	175,656	262,375	81,459	174,808	267,359	62,300	108,676	155,359	62,707
Spec. Investment Cost		[€/kWel]	1,878	3,203	4,546	2,476	4,395	6,341	2,965	5,855	8,746	2,715	5,827	8,912	2,058	3,590	5,132	662
Financial Boundary Conditions																		
Economic Lifetime		[a]	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25
Interest Rate		[%]	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Annual Insurance Cost		[%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Fixed Charge Rate (inl. insurance)		[-]	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104
Annual Cost																		
Capital & Insurance Cost		[T€/a]	5,956	10,159	14,417	7,700	13,670	19,722	9,221	18,212	27,203	8,446	18,124	27,719	6,459	11,267	16,107	6,501
Fuel Cost	0h…24h	[T€/a]	13,143	10,959	8,853	11,994	7,962	3,995	13,480	8,709	4,883	12,209	8,269	4,384	12,527	9,690	7,088	37,882
	6h…22h		8,612	6,437	5,124	7,360	3,383	1,243	8,196	3,851	1,855	7,589	3,613	1,363	7,997	5,212	3,575	26,687
Spec. Life Cycle Fuel Cost		[€/MWhth]	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
O&M Cost	0h…24h	[T€/a]	1,332	2,057	2,784	1,510	2,536	3,576	1,760	3,268	4,782	1,635	3,301	4,952	1,371	2,192	3,019	2,158
	6h…22h		1,163	1,889	2,617	1,363	2,389	3,427	1,615	3,126	4,644	1,491	3,153	4,810	1,203	2,024	2,853	1,699
Total Annual Cost	0h…24h	[T€/a]	20,430	23,175	26,055	21,205	24,168	27,293	24,461	30,189	36,868	22,290	29,694	37,055	20,357	23,149	26,214	46,541
	6h…22h		15,731	18,485	22,158	16,423	19,441	24,392	19,033	25,188	33,702	17,525	24,891	33,892	15,659	18,503	22,535	34,888
LEC																		
LEC	0h…24h	[€ct/kWhel]	7.31	8.38	9.53	8.70	9.93	11.22	9.96	12.84	16.18	8.84	11.88	15.01	7.31	8.41	9.63	6.04
	6h…22h		8.05	9.61	11.68	9.65	11.45	14.45	11.00	15.38	21.22	9.73	14.16	19.30	8.06	9.68	11.92	6.44
LEC Solar	0h…24h	[€ct/kWhel]	10.79	12.75	13.62	10.42	11.74	12.26	13.23	16.92	19.22	11.22	16.00	17.70	9.78	11.39	12.23	-
	6h…22h		13.66	14.21	16.56	12.66	12.92	15.25	14.91	18.47	23.57	12.96	17.06	20.86	12.03	12.60	14.66	-

Table 1. Specifications, results of performance calculations and economic assessment.