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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 tohybridization 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, economic 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 operatedin 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 powerplant 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 CO2 emissions.

Key Word*: Salt-Tower; Parabolic Trough; CO_2-Tower; Solar- hybrid Combined cycle; Particle-Tower*

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I. 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 thatthey will have a significant market share of the future energy sector. The sun is anintermittent source of energy. Solar power plants that are operated with a solar-onlyoperation strategy and use thermal energy storages to extend the operation to hours when thesun 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 heatin a solar-hybrid power plant. However, the transition of from a solar-only power plant to asolar-hybrid power plant incorporates some conflicts. While the economy of the power plantis improved as the annual utilization of the plant is increased, the emission of greenhouse 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. 2 and 3) also new and innovative solar power plant concepts (Fig. 1, 4 and 5) were analyzed in detailfor this study.

In this paper we discuss on how to produce low carbon dioxide emissions, to utilize maximum power generated and to produce low tariff energy supply with the help of solar hybrid power plants by comparing with fossil fired combined cycle.

II. Material And Methods

Solar Hybrid Power Plants:

Solar hybrid power plants are hybrid power systems that combine solar power from a photovoltaic system with another power generating source. A common type is a photovoltaic diesel hybrid systems combining photovoltaic (PV) and diesel generators, as PV has hardly any marginal cost and is treated with priority on the grid. The diesel generating source are used to constantly fill the gap between the actual present load and the actual generated power by the PV system. As Solar energy is fluctuating, and the generation capacity of the diesel generators is limited to a certain range, it is often viable option to include battery storage in order to optimize solar contribution to overall generation of the hybrid system. 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 MWel 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. The types of solar power plants discussed in this study are solar hybrid combined cycle, salt tower, parabolic trough, CO_2 Tower, particle tower and combined cycle (conventional fossil fired combined cycle) which is used as reference plant.

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. (1) 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 [2]. 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. 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 [3]. 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 [2]. The gross efficiency at design point conditions of this dry cooled 30 MWel power block is 46.4%.

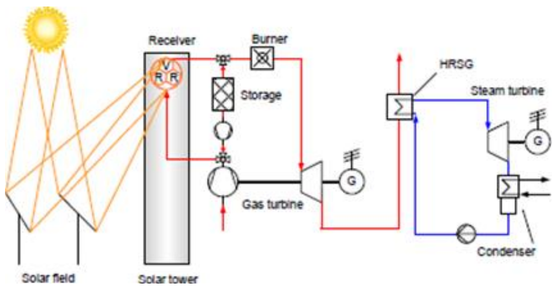


Fig (1): Solar tower with solar-hybrid combined cycle and pressurized solid mediathermal energy storage

[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

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 mainlybased on the Solar Two power plant. Fig. (2) 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 turbineis designed as a reheat turbine with several feed-water pre-heaters to allow a gross efficiencyof 42.5% at design point conditions. The solar share at design point is 100%

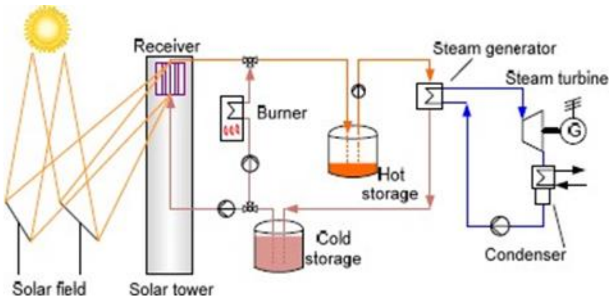


Fig (2): Solar tower with steam turbine and molten salt as heat transfer medium andfor thermal energy storage

Parabolic Trough:

The Parabolic Trough power plant for this study is mainly based on the commercial Andasol1 plant that was connected to the Spanish grid at the end of 2008. The layout was scaled toa power level of 30 MWel and designed for the operation with dry cooling towers. The fossilburner has unlike the Andasol 1 plant the ability to run the plant on full load with fossil-onlymode. Fig. (3) 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 enoughsolar energy for solar operation of the power block is available, the HTF can be heated fromthe 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. 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%.

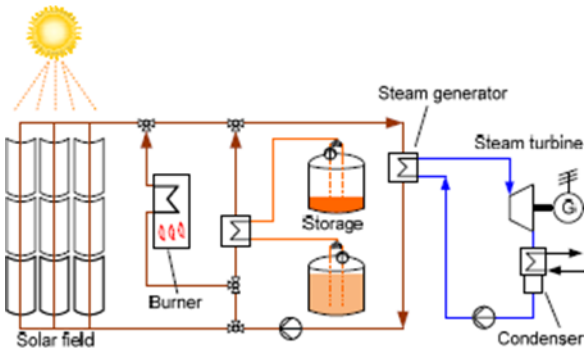


Fig (3): Solar tower with solar-hybrid combined cycle and pressurized solid media thermal energy storage

CO_2 Tower:

The CO_2-Tower is a solar tower power plant with a steam turbine, a pressurized gas receiverand a pressurized solid media thermal energy storage. Fig. (4) 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 energystorage technology. 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 thermo physical 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.

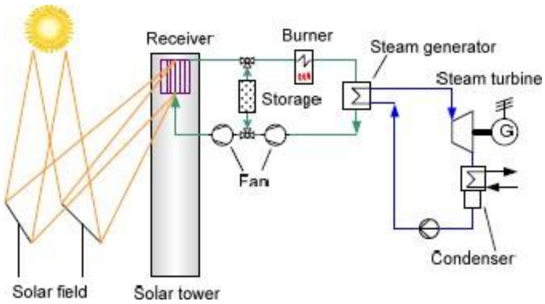


Fig (4): Solar tower with steam turbine and pressurized gas receiver (CO_2) and pressurized solid media thermal energy storage

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 systemsfor the integration of high temperature heat from particle receivers that are currently assessedat DLR. Fig. (5) 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 efficiencyof the power block is 46.4%. In this study the same combined cycle like for the SHCC powerplant was used.

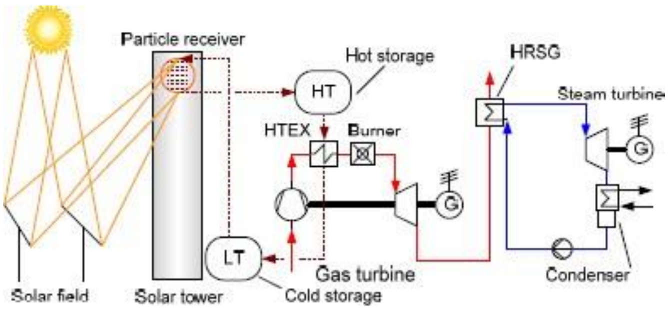


Fig (5): Solar tower with solar hybrid combined cycle and with solid media particles as heat transfer medium and for thermal energy storage

Combined Cycle:

The combined cycle (CC) is a conventional fossil-fired combined-cycle that is used as reference plant. Fig. (6) 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 MWel. The gross efficiency at design point conditions of the dry cooled power block is 51.7%.

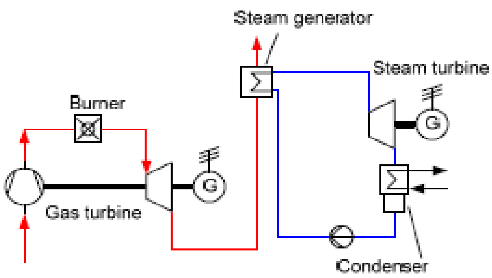


Fig (6): Conventional fossil-fired combined cycle as reference plant

Procedure methodology

For design optimization and annual performance prediction of the analyzed solar-hybrid power plants different software tools were used. Fig. (7) 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 [6]. 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. 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.

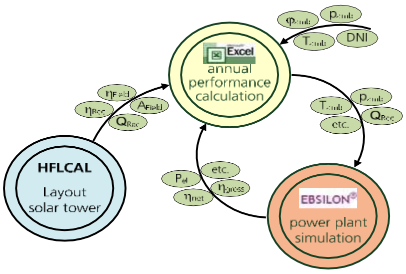


Fig (7): Work flow of Simulation Software

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 [8]). 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 [9]. 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.

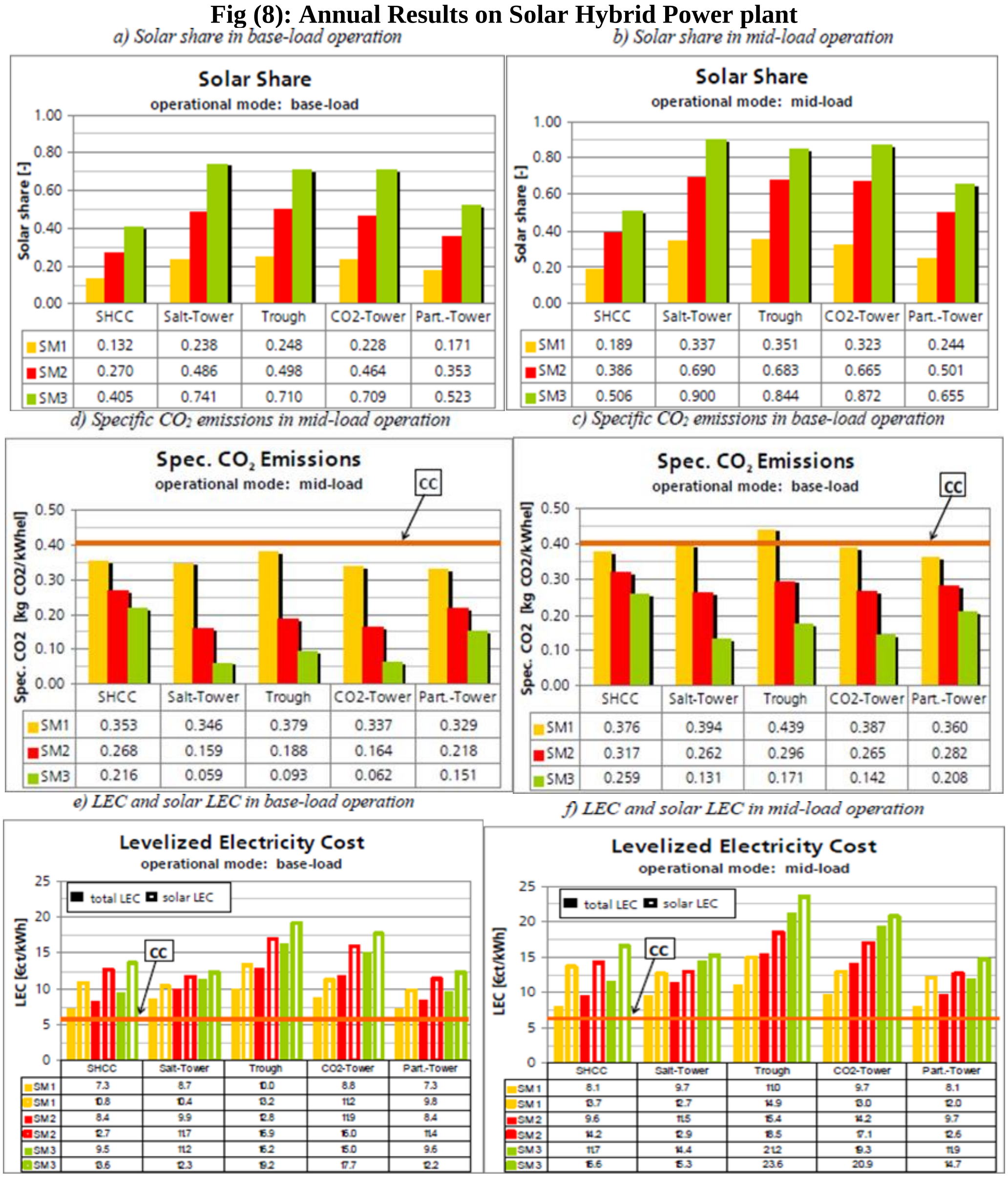
III. Result

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. 8.a) For the operation in base- load (Fig. 8.a) a maximum solar share of 74.1% is reached for the Salt-Tower with SM3 and 15h storage capacity. The CO2-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. 8.b) 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. 8.c) show that compared to the conventional fossil-fired combined cycle not all solar-hybrid power plants can reduce the CO2 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 CO2 emissions. Larger solar fields and the integration of TES allow the reduction of the CO2 emissions up to 68% compared to the fossil- fired combined cycle. It is clear that the specific CO2 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. 8.c) comparing the Salt-Tower and the Parabolic Trough. Both have about the same solar share (Fig. 8.a) but a higher deviation in specific CO2 emissions. The results for the operation in mid-load (Fig. 8.d) 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. 8.e) for the base-load operation. The LEC of the reference combined cycle is 6.0 €ct/kWhel. 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/kWhel with SM1 and without storage. The lowest solar LEC is achieved with 9.8 €ct/kWhel by the Particle Tower. However, this is with SM1 and no storage and therefore the specific CO2 emissions are high. In mid-load (Fig. 8.f) this increases to 12.0 €ct/kWhel 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 CO2-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 T) and the low power block efficiency requires bigger amounts of stored thermal energy. The results for the assessment of the power plants on an annual basis regarding solar share, specific CO2 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.

Fig (8): Annual Results on Solar Hybrid Power plant



IV. Conclusion

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 weremodeled with different sizes of solar fields and different storage capacities and analyzed onan 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 thisstudy show that in comparison to a conventional fossil fired combined cycle the potential toreduce 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 thatin 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 asite 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 cangenerally reduce the advantage in LEC for the fossil fired combined cycles. However, this will also dramatically increase the cost of common electricity supply.

Although many solar technologies have been demonstrated, parabolic trough solar power plant represents one of the major renewable energy success stories of the last two decades. Parabolic troughs are one of the lowest cost solar electric power options available today andsignificant potential for further cost reduction. Nine parabolic troughs plants, totaling over 350MW of electric generations, have been in daily operation in the California Mojave Desert for up to 18 years. These plants provide enough solar electricity to meet the residential needsof city with 350,000 people. They have demonstrated excellent availabilities (near 100% availability during solar hours) and have peak electric loads, especially during California energy crisis of 2000-2001. Several new parabolic troughs have been built or are currently under development. Growing interest in green power and CO_2 reducing power technologieshave developed to increase interest in this technology around the world. New parabolic trough plants are currently under construction or in the early stages of operation in support of solar portfolio standards in Nevada and Arizona and a solar tariff premium in Spain.

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