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Combined Solar Thermal and Photovoltaic Power Plants – an Approach to 24h Solar Electricity?

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Abstract. Solar thermal power plants have the advantage of being able to provide dispatchable renewable electricity even when the sun is not shining. Using thermal energy storage (TES) they may increase the capacity factor (CF) considerably. However in order to increase the operating hours one has to increase both, thermal storage capacity and solar field size, because the additional solar field is needed to charge the storage. This increases investment cost, although levelised electricity cost (LEC) may decrease due to the higher generation. Photovoltaics as a fluctuating source on the other side has arrived at very low generation costs well below 10 ct/kWh even for Central Europe. Aiming at a capacity factor above 70% and at producing dispatchable power it is shown that by a suitable combination of CSP and PV we can arrive at lower costs than by increasing storage and solar field size in CSP plants alone. Although a complete baseload power plant with more than 90% full load hours may not be the most economic choice, power plants approaching a full 24h service in most days of the year seem to be possible at reasonably low tariffs.

INTRODUCTION

The combination of concentrated solar thermal power (CSP) with photovoltaics (PV) has gained some attentions recently. Developers indicate that this integration has advantages with respect to lower electricity tariffs. Already three projects of this kind are announce for Chile combining in one case a 130 MW CSP project with a 150 MW PV project by Solar Reserve, in the other two cases 110 MW CSP plus 100 MW PV by Abengoa [1]. As in such a case the plant allows the generation via PV during daytime and via CSP and storage during hours without sufficient sunshine, the operational characteristics are different, and modelling is not straight-forward with classical tools. A modelling approach with first results has been presented [2] and is now used to investigate the idea of 24h solar electricity generation.

DESCRIPTION OF METHODOLOGY

For an approximate calculation of annual performance a detailed dynamical simulation seems not to be necessary. Tools like Greenius operate with quasi-static steady state hourly energy calculations for the solar thermal field performance and the conversion of heat into electricity by steam turbines. Even a simulation program such as TRNSYS is based on quasi-static calculations, although shorter time steps often are used. For the calculation of the annual yield therefore we used hourly calculations based on steady state equations. Start-up procedures and similar dynamical operations are neglected. If one wants to investigate these detailed transient effects and control issues, optimizing the operation of a power plant in detail, one has to use dynamical simulation tools with short time steps and modelling of capacity effects. For the latter purpose Fraunhofer ISE has developed Colsim-CSP, a sophisticated dynamical simulation platform including a large number of component models. Many types of solar thermal power plants using different heat transfer media, storage and collector types, and thermo-dynamical cycles can be modelled in large detail,

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The combination of PV and CSP however is conceptual work where high flexibility and quick computation of a yearly performance is required. Thus we implemented collector models for linear concentrating collectors and a two-tank storage model in an Excel tool, calculating 8760 hourly performance values per year. Also a simplified photovoltaic array model has been implemented both for tilted flat-plate photovoltaic modules (FPV) and for two-axis tracked concentrator modules (CPV).

For calculation of the solar irradiation, direct and diffuse, on tilted aperture planes or on tracking collectors, the well-known isotropic sky model has been used. Albedo effects have been treated with constant reflectance of 20%. The basis for the global and diffuse horizontal irradiation and temperature data was the METEONORM software.

Collector models which can be used for parabolic trough (PTC) and linear Fresnel collectors (LFC) take into account incidence angle modifiers, end effects and mutual shading of collector rows in the case of PTC. These models have been described elsewhere [3] and are implemented in the Excel calculation sheet. In this study a generic Linear Fresnel Collector model based on a single tube collector with geometrical concentration C=54 and optical efficiency for normal incidence (sun in zenith) of 65% has been used [7]. Longitudinal and transversal incidence angle modifiers IAM are shown in FIGURE 1

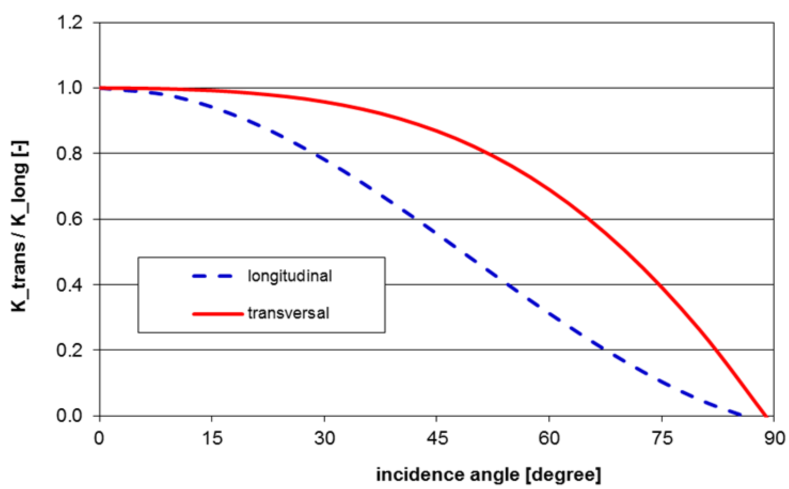

FIGURE 1: Longitudinal and transversal incidence angle modifier for the generic Linear Fresnel Collector

The thermal losses of the collector are modelled using the following relation [5]:

$$Q_{loss} = 0.15\ T_{abs} + 7.5x10^{-9}\ T_{abs}^{4} \qquad (1)$$

Here T_{abs} is the absorber temperature in °C and Q_{loss} the heat loss per m absorber length. A collector efficiency factor F'=0.95 [8] has been used to take into account the temperature difference between fluid and absorber surface. The collector has been modelled using molten salt as a heat transfer fluid with inlet temperature 295 °C and 565 °C. The thermal losses of the piping within the solar field are larger than in a typical thermo-oil plant. This is due to elevated temperatures on the one hand side, and due to night circulation preventing a freezing of salt in then pipes on the other side. It has been approximately considered by an additional heat loss of 20.9 W/m^2 per aperture area.

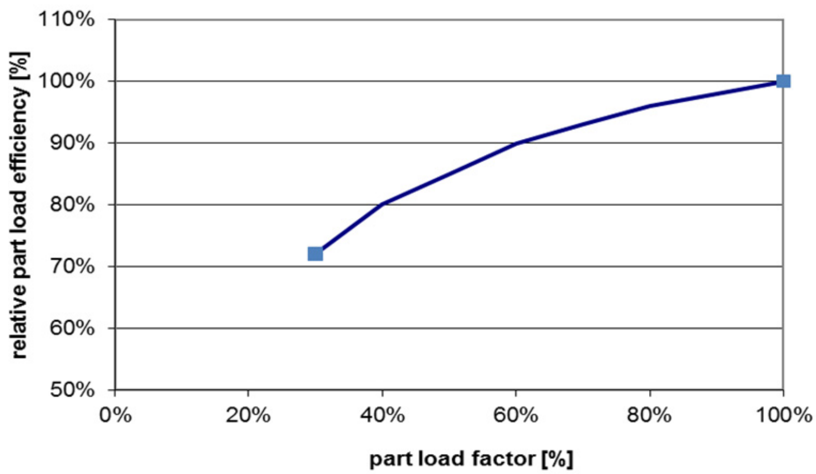

FIGURE 2: Factor for turbine efficiency at part load between 30% and 100% nominal load

The storage has been modelled very simply as a direct two-tank molten salt storage with a hot tank at 565 °C and a cold tank at 295 °C, just be changing the filling levels according to charging, de-charging and (small) temperature losses.

The power block was modelled by a simple efficiency factor model with a turbine having 38.5% efficiency heat to power at nominal operation. Part load operation starts at 30% nominal load. The reduction in efficiency is shown in FIGURE 2.

The flat-plate PV modules have been modelled as tilted modules with tilt 30°. Row shading has been neglected – is assumed that the distance between module rows is sufficiently large. The ASHRAE incidence angle modifier has been used with a coefficent b_0=0.5. Temperature effects (reduction of efficiency due to cell temperature) has been modelled using the approach of Kratchovil [5] for simplicity.

$$\mathrm{T_{module}} = \mathrm{T_a} + \mathrm{E}/(\mathrm{Wm^{-2}K^{-1}})\exp(-3.473 - 0.0594\ \mathrm{v_{wind}}/(\mathrm{ms^{-1}})) \qquad (2)$$

with ambient temperature T_a, irradiation on the module E, and wind speed v_{wind}=2.3 m/s. The temperature coefficient of -0.38%/K was used for the power reduction delivered from the module. For the module efficiency under standard operating condition at 25 °C 16% was assumed. The concentrator module has been modelled with an overall average annual efficiency of 28%.

DEFINITION OF CASE STUDY

The question to be investigated was how investment costs could be saved in a CSP power plant by substituting the solar thermal electricity generation during the day by photovoltaics. As a first demand profile a 24h constant electricity demand (base line) has been assumed. The location of the CSP plant has been chosen as Upington, South Africa, because at the moment in the South African electricity system aged coal fired power plants are less and less reliable, and a substitution of dispatchable power is urgently needed.

The technology modelled is a molten salt based Fresnel power plant. Firstly a molten salt power plant allows the combination with direct molten salt storage, which for the moment seems to be the most cost-efficient storage technology commercially available. Secondly the daily thermal energy production by a Fresnel collector – which is less constant than the one of a parabolic trough collector – does not have negative effects on generation when all energy is first delivered to a thermal energy storage (TES). The solar multiple of the Fresnel field is variable and has been optimized, as well as the storage capacity of the TES.

The optimization process aims at base load production profile with a capacity factor of 80% which is the target of the South African utility Eskom for the next years [4].

The power plant modelled has a 100 MW power block with turbine efficiency 38.5% nominal operating with steam of 550 °C. The solar field has inlet temperature 290 °C and outlet temperature 565 °C. The cases investigated were a) A CSP power plant with storage without PV, b) A CSP power plant with additional FPV and c) a CSP power plant with additional CPV. In the latter two cases b) and c) the PV field was also optimized in order to reach the capacity factor of 80% (CF defined in relation to 100 MW CSP see below). The operation of the power plants b) and c) is trying to avoid direct production of CSP power during the day. In most times the solar field charges the storage, which then provides the energy for the steam turbine at night time. Only in times when PV is not sufficient to cover the 100 MW demand, the turbine may add the additional electricity in part load. In times when the storage is fully charged and PV is producing electricity,there may be a surplus of power production exceeding 100 MW. This is accepted but not enforced.

The direct investment cost for solar field, storage, power block and indirect costs used in the standard case haves been taken from a parallel paper presented at this conference [6]. The levelised electricity costs were calculated using a simplified model using the following financial parameter

TABLE 1: Financial parameter

Analysis period	25a
Insurance cost	1.0%/a
Capital cost (WACC)	8.0%/a
Operation and maintenance	1.5%/a

For the FPV and CPV power plant costs have been chosen in a way that both power plants deliver electricity for about the same tariff. Of course in a real project the actual comparison of individual products for these plants is important, but for the present conceptual study it was more important to look at inherent advantages and disadvantages of combining the technologies with CSP.

TABLE 2: Investment cost data for PV power plants

Flat plate PV	1000 €/kW
Concentrator PV	1400 €/kW

Indirect costs for project development, EPC and owner's cost were taken as 20% of the direct investment.

RESULTS

CSP Power Plant without PV

For comparison with the new hybrid concept a molten salt Fresnel power plant with direct 2-tank storage has been modelled and results are compiled in the following TABLE 3.

TABLE 3: Calculation results for MS-LFC with direct 2-tank storage, optimized for LEC at Upington, South Africa

Aperture area	1000 m^2	614	960	1152	1382.4	1536
Solar multiple	SM	1.48	2.31	2.78	3.33	3.7
Storage cap.	h	0	6	9	12	15
Q_{el} (gross)	GWh/a	205.6	353.7	429.8	517.2	571.5
Q_{el} (net)	GWh/a	187.6	324.7	394.9	475.2	524.9
Op. Hours	h	2980	4018	4693	5517	5979
Cap. Factor CF	%	21%	37%	45%	54%	60%
CAPEX	€/kW	3043	5018	6072	7260	8181
LEC	€/kWh	0.192	0.183	0.182	0.181	0.185

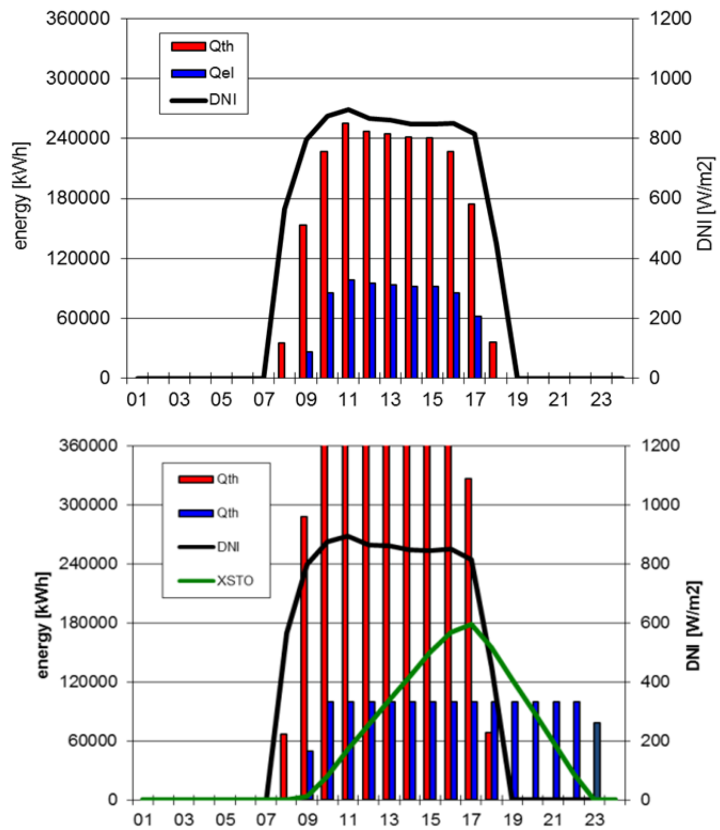

FIGURE 3: Hourly DNI (black), produced thermal energy Qth (red) and generated electricity Qel (blue) for the case SM=1.48 w/o TES (top) and SM=2.78 with 9h TES (bottom); the green curve XSTO shows the filling level of the hot storage (1000 on the right axis equivalent to 100%)

The generation pattern of a typical autumn day in March is shown for two plant configurations in FIGURE 3. Without storage one may notice the variation during the day typical for a Fresnel collector (a parabolic trough would generate according to the well-known “hat” profile). A startup phase in the morning leads to delayed production of electricity. With storage the generation continues until 23 o’clock in the evening. As can be seen in TABLE 3 CSP plants with solar field area optimized for LEC do not reach capacity factors larger than CF=60%. Therefore in a second step the storage cost where decreased from 40 €/kWh_{th} to 25 €/kWh_{th}, which seems to be realistic for direct storage. Then the solar fields for the largest storage were successively increased beyond the optimum size in order to reach larger CF. At last with a solar multiple of SM=5.1 we can reach a capacity factor of 70%, with operation - sometimes part load - during 80% of the year!

TABLE 4: Calculation results for MS-LFC with direct 2-tank storage@25 €/kWh similar to TABLE 3

Aperture area	1000 m^2	1382	1536	1728	1920	2112
Solar multiple	SM	SM 3.33	SM 3.7	SM 4.16	SM 4.60	SM 5.09
Storage cap.	h	12	15	15	15	15
Q_{el} (gross)	GWh/a	517.2	571.5	613.6	648.8	674.7
Q_{el} (net)	GWh/a	475.2	524.9	562.1	590.6	614.0
Op. Hours	h	5517	5979	6360	6667	6928
Cap. Factor CF	%	54%	60%	64%	67%	70%
CAPEX	€/kW	6677	7452	8118	8784	9450
LEC	€/kWh	0.167	0.169	0.171	0.177	0.183

Due to the latitude and the performance characteristics of the Linear Fresnel collector the generation is much lower in winter time (June) than in summer (FIGURE 4).

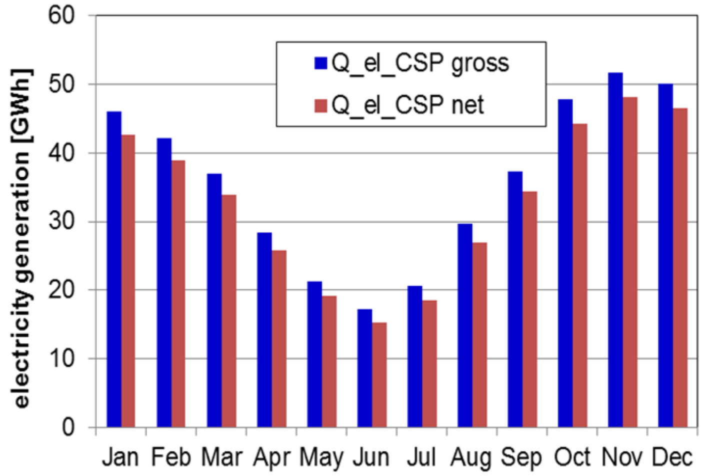

FIGURE 4: Monthly electricity generation (gross and net) for the LFC plant with SM=2.78 and 9h TES

Combination of CSP and FPV

Flat-plate PV (FPV) rows are oriented in East-West directions facing North with a tilt of 30°. A 100 MW plant is modelled having the same nominal peak power as the CSP plant. The FPV performance is relatively constant over the months as the tilt is optimized for that (FIGURE 5). The overall production is 223 GWh/a, which corresponds to a CF of 25.5%. The levelised cost of electricity LEC is 0.064 €/kWh.

In a next step we combine the CSP plant with our FPV plant which produces electricity during the day. The CSP plant is operated in a different way. The solar field only charges the storage, and only when the PV cannot deliver 100 MW full load, an operation of the steam turbine is considered. In this way solar field area may be reduced, compared to full CSP operation, even with the same night time operation hours. In the case of hybrid operation, the capacity factor CF in this paper is defined as the net electricity production Q_{el}(net) divided by 8760 hours full load generation of the CSP turbine. CF thus is always related to 100 MW of the CSP power plant part.

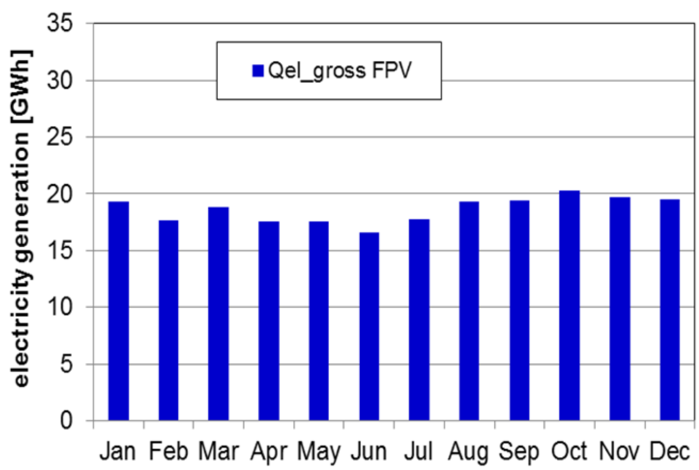

FIGURE 5: Monthly electricity generation for a 100 MW FPV plant, Upington, South Africa

TABLE 5: Results for a combined 100 MW FPV-100 MW LFC power plant (15h TES)

Aperture area	1000 m^2	2112	1920	1728	1536	1344	1152
Q_{el} (gross)	GWh/a	802.5	775.1	742.9	707.8	665.7	614.6
Q_{el} (net)	GWh/a	735.8	712.8	685.3	654.9	617.7	571.9
Op. Hours	h	8113	7963	7783	7576	7350	7044
CF	%	84%	81%	78%	75%	71%	65%
CAPEX	€/kW	10800	10134	9468	8802	8137	7471
LEC	€/kWh	0.172	0.166	0.162	0.157	0.154	0.152

TABLE 6: Results for a combined 150 MW FPV -100 MW LFC power plant (15h TES)

Aperture area	1000 m^2	1728	1536	1344	1152	960	768
Q_{el} (gross)	GWh/a	857.6	824.4	786.6	740.4	683.4	612.2
Q_{el} (net)	GWh/a	795.4	766.9	733.9	692.7	641.2	575.8
Op. Hours	h	8047	7875	7686	7437	7110	6814
CF	%	91%	88%	84%	79%	73%	66%
CAPEX	€/kW	10143	9477	8812	8146	7480	6814
LEC	€/kWh	0.148	0.143	0.139	0.136	0.134	0.136

A first set of calculations were made starting from the CSP case with 15h storage and corresponding SM=5.09 adding a 100 MW FPV power plant. This increases largely the capacity factor. The solar field size can be reduced by about 40% until CF=70% is reached again (TABLE 5). However this time the LEC is much smaller due to the lower cost of PV installations. On the other hand 100 MW nominal power is only reached a few hours a year, so in order to compensate that the PV field size was increased to 150 MW nominal (TABLE 6). The Fresnel solar field can be decreased even further if a capacity factor of CF=70% is the target. Of course, on very sunny days the midday peak of PV is larger than the nominal 100 MW demand.

Combination of CSP and CPV

A disadvantage of flat-plate PV can be the variable production during the day due to the changing incidence angle. This can be avoided by using concentrator PV with a two-axis tracking, always following the sun position. For a 100 MW extension of the CSP power plant with CPV about 1.5 Mio m^2 solar field aperture are needed for a capacity factor of 80%, and a LEC of 0.14 €/kWh is reached (TABLE 7). Oversizing the nominal power of CPV, extending it to 150 MW one may reach the 80% at about 0.9 Mio m^2 (TABLE 8).

TABLE 7: Results for a combined 100 MW CPV-100 MW LFC power plant (15h TES)

Aperture area	1000 m^2	2112	1920	1728	1536	1344	1152
Q_{el} (gross)	GWh/a	848.7	822.3	791.9	758.8	719.1	672.5
Q_{el} (net)	GWh/a	779.9	757.9	732.2	703.5	668.9	627.3
Op. Hours	h	8042	7897	7728	7529	7316	7064
CF	%	89%	87%	84%	80%	76%	72%
CAPEX	€/kW	11215	10549	9883	9217	8552	7886
LEC	€/kWh	0.154	0.15	0.145	0.141	0.138	0.136

TABLE 8: Results for a combined 150 MW CPV -100 MW LFC power plant (15h TES)

Aperture area	1000 m^2	1536	1344	1152	960	768	576
Q_{el} (gross)	GWh/a	900.8	865.4	823.8	771.6	708.3	635.6
Q_{el} (net)	GWh/a	840.0	809.4	772.8	725.8	668.1	601.2
Op. Hours	h	7759	7566	7349	7066	6673	6082
CF	%	96%	92%	88%	83%	76%	69%
CAPEX	€/kW	10100	9434	8768	8102	7437	6771
LEC	€/kWh	0.129	0.126	0.122	0.120	0.120	0.121

With the optimum combination one may reach electricity costs of 0.12 €/kWh which is to be compared to e.g. a generation costs for a new coal fired power plant. The combination of CSP and CPV is able to provide electricity with a very high capacity factor 80% the plant operating about 7800 h a year. Taking into account that future CSP cost will decrease still appreciably when more plants are being built worldwide, this combination provides a very attractive option for base load electricity production. On top of that the production is characterized by negligible CO_2-emission during operation.

The net generation of 715 GWh/a is split up into generation by CPV of 412 GWh/a and by the storage CSP plant of 303 GWh/a. Due to the Fresnel collector optical system during the winter time with lower sun altitudes the monthly generation is lower than in Summer (FIGURE 6).

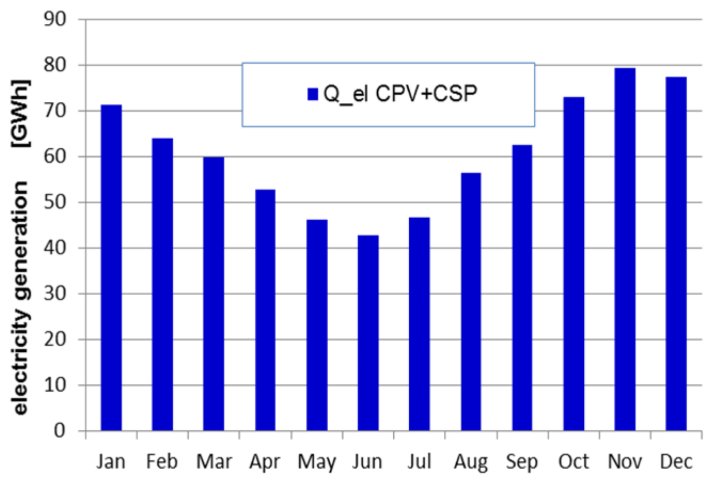

FIGURE 6: Monthly electricity production by combined CSP-CPV power plant 100 MW_e for Upington, South Africa; (150 MW CPV, 15h TES, Solar field SM 2.2**)**

For the combination of CPV with CSP the solar thermal electricity production is only used to complement missing production during the day. Usually CPV provides electricity at daytime. The collector charges a thermal storage which then drives the turbine during nighttime. In FIGURE 7 an example of a day in autumn (21st March) is shown.

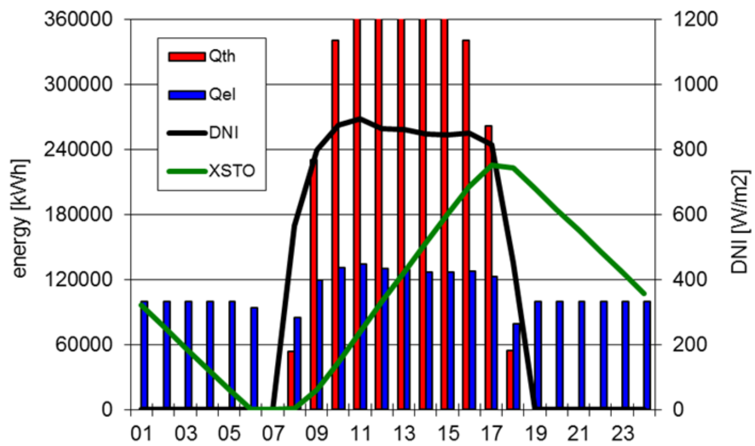

FIGURE 7: Hourly electricity production by combined CSP-CPV power plant 100 MW_e
Upington, 21st March, SM 2.2, 15h storage, 150 MWe CPV
X_{STO}: relative charge state (0=empty, 1000=full), Q_{th}: thermal production of collector, Q_{el}: gross electricity generation

CONCLUSION

It could be shown that using the new concept of a combining CSP and CPV a capacity factor of 80% can be reached and simultaneously the LEC is lower than for a CSP power plant without photovoltaics. The use of a molten salt Linear Fresnel collector with a large direct 2-tank storage is offering attractive cost options for this concept. The power plant design has to be optimized in details like storage size and reduction of excess generation above the nominal 100 MW. The operational details also need more investigation. For example also the electricity used for operating the solar field can be generated easily by PV.

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