



Combination of PV and central receiver CSP plants for base load power generation in South Africa



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ABSTRACT

This paper introduces a novel concept of a PV enhanced central receiver concentrating solar power (CSP) plant for South Africa that can dispatch solar energy from daytime to the night in order to provide solar base load capacity to the grid. Various simulations of standalone PV and CSP plants were carried out and compared to simulation results of the new CSP/PV hybrid concept. A higher annual energy yield and capacity factors of up to 90% can be expected while, at the same time, system size, thus, costs can be reduced. The levelised costs of electricity (LCOE) vary in the range of 0.133–0.157 \$/kW h for base load-capable configurations which can substitute generation capacity from old coal-fired power plants. This replacement approach is backed by the high solar irradiation levels found in South Africa, making CSP/PV power plants a sustainable solution to reduce emissions and increase the share of renewables in South Africa.

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1. Introduction

South Africa's electricity generation is heavily dependent on old coal-fired power plants with a total share of 92%, followed by 5% nuclear power, 1.6% hydro and the residual 1.4% being supplied by gas, oil and renewables & waste (IEA, 2015). The state-owned power utility, Eskom, owns and manages 92.1% (42,090 MW) of the installed power plant capacity in South Africa as of 2015 (45,699 MW), whereas the residual 3609 MW are operated by independent power producers (IPPs) which sell their electricity to Eskom (2015). Only approximately 50% of the IPP's installed capacity (1795 MW) (Eskom, 2015) are from renewable generation including mainly wind, PV and concentrating solar power (CSP) but further generation capacity has been procured through the South African Department of Energy's (DoE) Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) and is currently under planning or construction. The total allocation amounts to 2660 MW of wind, followed by 1898.5 MW of PV and 600 MW of CSP (DoE, 2015; WWF, 2014).

In order to further increase the national generation capacity, South Africa has to increasingly make use of the world's largest energy source, the sun. With a GHI of up to 2300 kW h/m² a and DNI of up to 3200 kW h/m² a (Solargis, 2014a, 2014b), South Africa is one of the best sunspots on Earth and is therefore well-suited for

PV and CSP systems. According to Fluri (2009), the total potential for CSP generation capacity in South Africa is 547.6 GW with a net electricity generation of 1861.4 TW h/a considering an average capacity factor of 38.8%. Another study on CSP potential in SA depicts a short-term scenario (2011–2017) with a potential of 262 GW based on parabolic trough plants with seven hours of thermal storage (Meyer and van Niekerk, 2011). This significantly lower potential can be explained by the not fully developed transmission grid in the Northern Cape, whereby suitable locations are out of proximity of viable substations. A medium-term scenario (2018–2025) takes Eskom's grid expansion plans into account, enabling an additional 49 GW of potential in the Northern Cape. Additional potential can be unlocked by waterless next generation CSP plants where the proximity to suitable water sources is no longer necessary. Compared to the currently total installed generation capacity of 45.7 GW, there is a vast potential for CSP in South Africa.

In order to decarbonize South Africa's electricity generation, a substitute for coal-fired power plants is needed which can provide base load capacity to the national grid. Although large-scale commercial PV power plants are not yet financially viable to provide base load capacity in combination with storage systems, CSP has been found to be a “baseload-capable technology” (Pfenninger and Gauché, 2014). The researchers showed that 100 CSP power plants at ten geographically dispersed sites in South Africa could provide base load power generation by taking advantage of the spatial concurrence of cloud covers. However, this study takes a

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Nomenclature

AC	alternating current	O&M	operation and maintenance
CPV	concentrating photovoltaic	PV	photovoltaic
CSP	concentrating solar-thermal power	SM	solar multiple
DC	direct current	TES	thermal energy storage
DNI	direct normal irradiance in W/m^2		
LCOE	levelised costs of electricity		

different approach by introducing a novel concept of a combination of PV and CSP power plants (CSP/PV) in order to supply a constant base load capacity.

A similar concept of enhancing CSP generation with PV has already been introduced by Platzer (2014) by combining a 50 MW CSP plant (parabolic trough) with 12 h storage with a 75 MW concentrating PV (CPV) power plant to increase the operation time of the combined power plant. In another study, Platzer (2016) combined a flat-plate PV as well as a CPV power plant with a linear Fresnel collector plant using molten salt as heat transfer fluid. This resulted in higher capacity factors and lower LCOEs. Similar concepts are already in development for commercial use by SolarReserve, Abengoa and ACWA Power (Castillo, 2015). The focus of this study, however, is on demonstrating the capability of a 100 MW CSP central receiver plant combined with a 100 MW PV power plant to supply 100 MW base load capacity to the grid. This concept is presented in detail in Section 3.3.

2. Methodology

In order to demonstrate the base load-capability of a combined CSP/PV power plant and its advantages over a conventional CSP plant, a comparison with a standalone PV and CSP plant was made by simulating different power plant configurations with the System Advisor Model (SAM) from the National Renewable Energy Laboratory (NREL, 2017). The simulation approach was to first simulate a PV power plant with 100 MW nameplate capacity, followed by a CSP molten salt central receiver (100 MW) with various configurations, where the effect of different storage sizes and solar multiples (SM) on the annual energy yield and capacity factor was analysed. For the CSP/PV simulation, the PV plant from the first simulation was combined with a second 100 MW CSP plant in SAM and its power generation pattern was then adapted to the load profile supplied by the PV power plant in order to fill up the gap between the PV plant output and the desired 100 MW. This can be achieved by operating the steam turbine in part load. Fig. 1 illustrates the simulation concept. It can be seen that the CSP/PV option is a combination of two 100 MW power plants resulting in 200 MW installed capacity. However, the goal of this study was to only supply a total base load capacity of 100 MW and to not take advantage of the additional installed capacity when the

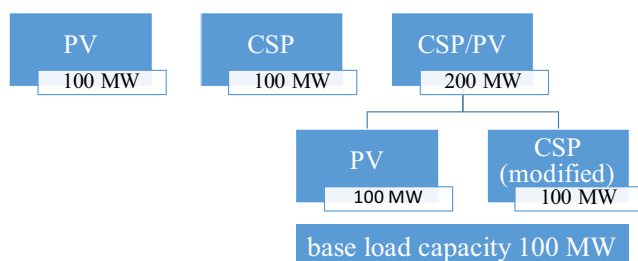


Fig. 1. Power plant simulation concept.

solar resource is high. It should be noted that any other capacity configuration of CSP and PV would be possible. The PV plant could for example be oversized to provide a 100 MW output during most of its operation time. However, because a 100 MW PV plant performs below its nominal capacity most of the time, there will most likely always be a need for the CSP plant to cover the additional capacity requirement. This is in favour of the CSP turbine, which can therefore be operated at part load, hence avoiding unwanted turbine stops.

Weather data from Upington, Northern Cape was used for the simulations due to its high solar radiation values and proximity to current CSP plants in operation and construction as well as the possibility of access to the Eskom grid. The results of the simulations were used to demonstrate the advantages of a combined CSP/PV power plant in terms of annual energy yield, capacity factor and 24/7 solar base load-capability.

Lastly, a parametric study on the effect of solar field size and storage size on the LCOE has been carried out.

3. PV, CSP and CSP/PV design and simulation assumptions

The first step was to simulate a PV power plant and a CSP plant with various configurations in order to be able to compare the results with those from the novel power plant concept in Section 3.3. The following sections describe the design parameters of the power plants and main assumptions.

3.1. PV power plant

The PV power plant was modeled with 110 MW_p multi-crystalline silicon modules and a total inverter capacity of 100.3 MW_{AC}. The modules were assumed to face direction north (azimuth 0°) with a tilt angle of 28.4°. The resulting module area was 727,699 m². The simulation results (Table 1) predict an annual electricity production of 223.6 GW h (without degradation) and a capacity factor of 23.2%. This PV plant model is later used to match the CSP generation to the PV output in the CSP/PV hybrid case.

The hourly electricity generation curve in Fig. 2 shows that there is no significant seasonality in the hourly supply from the PV power plant but the peaks are concentrated between 75 and 95 MW and never reach the desired capacity of 100 MW. Since the PV plant can only operate during sunshine hours, it is not possible to continuously generate electricity over the whole day.

Table 1
PV power plant performance.

Item	Unit	Value
Annual energy generation	GW h	223.6
Capacity factor	%	23.2
Specific yield	$\text{kW h}_{\text{AC}}/\text{kW}_{\text{DC}}$	2033
Performance ratio	%	84.0

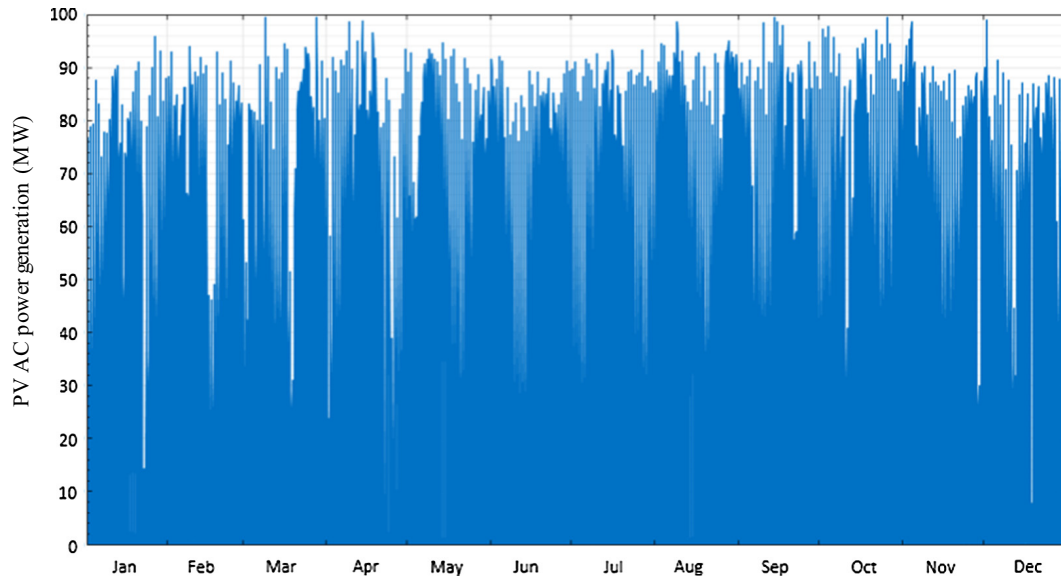


Fig. 2. Hourly PV power plant supply curve over a year.

3.2. CSP molten salt central receiver

The simulation of the CSP plant followed a much more complex approach than of the PV system due to its numerous input variables and the analysis of the effect of different solar multiples and thermal energy storage (TES) full load hours on the electricity yield. Table 2 shows the simulated configurations with solar multiples varying from 1.5 to 4 and TES hours from 14 to 20 h. All configurations were assumed to have 115 MW_e gross turbine capacity and 100 MW_e of net capacity.

Table 3 provides the design parameters of the tower and receiver. Molten salt (60% NaNO₃, 40% KNO₃) was used as heat transfer fluid (HTF) and the receiver inlet temperature was set to 290 °C whereas the outlet temperature was assumed to be 565 °C. These temperatures were also used for the steam generator (inlet: 565 °C, outlet: 290 °C). The power cycle features a Rankine-cycle steam turbine (150 bar live steam pressure) with a gross cycle efficiency of 42% and an air-cooled condenser. In order to simulate system downtimes for outages or scheduled maintenance, a plant availability of 96% was assumed. To complete the modelled system, a two-tank molten salt storage with a bypass valve is used to either pump the HTF from the receiver directly to the power cycle or to the storage. The built-in optimisation algorithm in SAM was used for sizing the solar field and tower.

3.3. PV enhanced CSP

Considering the study's goal to demonstrate a base load-capable solar technology able to replace coal-fired power plants, the above

CSP plant configurations are large systems resulting in high costs. In order to reduce these costs (and hence, the system size) and improve the power plant performance and its ability to supply base load, a combination of a PV and CSP plant is introduced. This concept uses the PV power plant from Section 3.1 to enhance the power generation from a smaller CSP plant of which the operating strategy is adapted to the hourly power output of the PV plant in order to always fill up the gap between the PV output and the set capacity of 100 MW. Hence, if there is no electricity supplied by the PV plant, the CSP plant covers the missing 100 MW of capacity. When the PV plant starts to produce electricity in the morning, on the other hand, the CSP plant reduces its power generation accordingly. During PV peak hours, the CSP plant reduces the power output to a minimum in order to just use as much solar energy as needed to keep the turbine running and residual heat from the receiver is stored in the thermal energy storage. When the sun starts to set in the afternoon and the PV power supply subsequently decreases, the CSP plant increases its power generation again to fill up the missing gap to the desired 100 MW. As soon as the PV plant does not deliver any electricity to the grid anymore, the CSP plant is running at full capacity throughout the night until the sun rises again by using the stored heat in the storage tank. By doing so, the two power plants virtually act together in order to supply 100 MW base load capacity.

The key of this concept is the TES from the CSP plant, allowing dispatching electricity generation from day to night time, hence, making it suitable for a combination with a PV power plant which can only generate electricity during day time. The principle of a combined CSP/PV power plant is outlined in Fig. 3. While an

Table 2
Simulated CSP configurations.

Item	Unit	Value											
Turbine capacity, gross	MW _e	115											
Turbine capacity, net	MW _e	100											
TES full load hours	h	14						16					
Solar multiple	–	1.5	2	2.5	3	3.5	4	1.5	2	2.5	3	3.5	4
TES full load hours	h	18						20					
Solar multiple	–	1.5	2	2.5	3	3.5	4	1.5	2	2.5	3	3.5	4

Table 3
Tower and receiver design parameters for SM 1.5–4.

Item	Unit	Value					
Heat transfer fluid	–	Salt (60% NaNO ₃ , 40% KNO ₃)					
Inlet temperature	°C	290					
Outlet temperature	°C	565					
Solar multiple	–	1.5	2	2.5	3	3.5	4
Tower height	m	170.7	200.6	207.7	227.8	250.4	275.0
Receiver height	m	20.54	23.04	23.87	25.46	24.32	28.64
Receiver diameter	m	14.03	16.55	17.44	19.84	27.13	28.86
Receiver aperture area	m ²	905	1198	1307	1587	2073	2596
Receiver thermal power	MW _{th}	410.7	547.6	684.5	821.4	958.3	1095.2

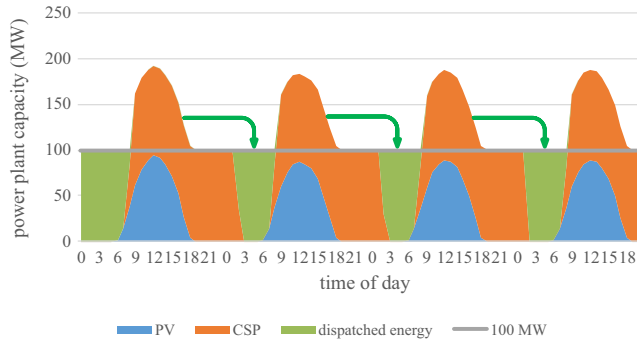


Fig. 3. Effect of PV with dispatchable CSP.

uncoordinated power production of both power plants would cause high peaks at noon and no generation capacity in the early morning hours, dispatching the thermal energy from hours where PV generation is available for later use at night, enables a continuous power generation at a set capacity. This also reduces the CSP system size (mainly the heliostat field size) because only a smaller solar multiple is needed to fill the TES due to its priority loading and only marginal turbine operation during sunshine hours. This decrease in heliostat field size results in drastic cost reduction potentials. Due to the expected reduction in system size, the CSP/PV hybrid plant is only simulated with solar multiples from 1.5 to 3.

The operating strategy of the CSP/PV hybrid plants is implemented in SAM by adapting the TES dispatch control. This allows the CSP plant to adapt its power generation to the PV system output. Since it is not possible to provide an hourly load profile in SAM this was done by manipulating the TES dispatch control on a monthly basis with 24 h representing an average day of the respective month. First, the average PV generation profiles for each month were generated and then subtracted from the desired 100 MW power, resulting in a residual load that must be covered by the CSP plant. This load demand was then converted into a percentage of the turbine output fraction and applies to the design turbine thermal input. Fig. 4 shows the resulting monthly TES dispatch control matrix with eight different periods and their corresponding turbine output fraction percentage in Table 4. It can be seen that during night time the turbine thermal input is only 95% from its design point due to the average parasitic consumption of approx. 8 MW at night and results in a net output of 101.25 MW, which is close to the desired 100 MW. This measure also assures that the TES is not discharged as quickly as if the turbine would run at 100% and thus, there is still thermal energy available in the early morning. It should be noted that this is a very simplified integration of the operating strategy and a more sophisticated and dynamic control logic is recommended. However, this workaround allows an initial analysis of a hybrid system with SAM.

4. Economic analysis

The LCOE is a financial indicator calculated over a whole economic lifetime of a power plant in order to make it possible to compare different technologies with different financial parameters and generation structures. It is calculated by dividing a power plant's accumulated costs for construction and operation by the sum of the annual energy generated during the power plant's operational lifetime. This approach follows the method of the net present value where the amount of money invested today is compared to the present value of the future cash amounts after they are discounted by a set rate of return. The LCOE for all considered options in this paper are calculated following the simplified approach from Fraunhofer ISE (2013):

$$LCOE = \frac{C_{invest} + \sum_{i=t}^n \frac{C_{O\&M,t}}{(1+i)^t}}{\sum_{i=t}^n \frac{E_{el,net,t}}{(1+i)^t}} \quad (1)$$

where n is the operational lifetime of the power plant and t the year of the lifetime (1, 2, ..., n). $E_{el,net,t}$ is the annual electricity generation in year t . For the PV plant $C_{invest,PV}$ are the total investment costs with

$$C_{invest,PV} = P_{peak} * (c_{sm} + c_{st} + c_{ep} + c_{inv} + c_{elc} + c_{si} + c_{tl} + c_{ss}) \quad (2)$$

where P_{peak} is the total DC peak power and c_x are the specific plant costs in \$/W_p. The total investment costs of the CSP plant $C_{invest,CSP}$ are

$$C_{invest,CSP} = (C_{HF} + C_{T+R} + C_{TES} + C_{PB} + C_{SG}) * (1 + f_{EPC}) \quad (3)$$

where C_x are the investment costs of the CSP plant components given as the specific investment costs per unit times their unit and f_{EPC} is a factor for the surcharge for EPC, project management and contingencies. The operation and maintenance (O&M) costs of the PV plant are calculated as

$$C_{O\&M,PV} = C_{invest,PV} * (f_{O\&M,PV} + f_{ins,PV}) \quad (4)$$

where $f_{O\&M,PV}$ and $f_{ins,PV}$ are the annual O&M and insurance costs, respectively. The O&M costs of the CSP plant are

$$C_{O\&M,CSP} = c_{O\&M} * P_{gross} + (C_{invest,CSP} * f_{ins,CSP}) \quad (5)$$

with $c_{O\&M}$ being the specific O&M costs and P_{gross} the turbine gross capacity. $f_{ins,CSP}$ is a factor accounting for the annual insurance costs for the CSP plant. The annual net electricity generation $E_{el,net,PV,t}$ of the PV plant is reduced by the factor f_{degrad} which takes an annual degradation of the modules into account.

$$E_{el,net,PV,t} = E_{el,net,PV,t-1} * (1 - f_{degrad}) \quad (6)$$

In order to combine the LCOEs from the CSP and PV system for the CSP/PV option, the following formula was used:

$$LCOE_{CSP/PV} = \frac{\sum_{i=t}^n E_{el,net,PV,t} * LCOE_{PV} + \sum_{i=t}^n E_{el,net,CSP,t} * LCOE_{CSP}}{\sum_{i=t}^n E_{el,net,PV,t} + \sum_{i=t}^n E_{el,net,CSP,t}} \quad (7)$$

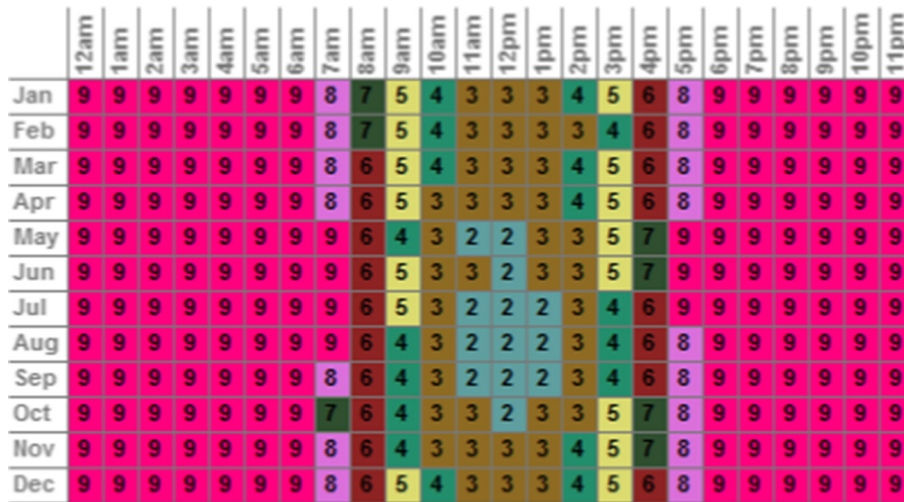


Fig. 4. TES dispatch control matrix in SAM.

Table 4
Turbine output fractions per period.

Period	Turbine output fraction [%]
2	20
3	30
4	40
5	50
6	60
7	70
8	80
9	95

The cost assumptions and financial parameters are listed in Table 5 for the PV plant and Table 6 for the CSP plant.

5. Results

The results obtained from the simulations are presented in the following sections. First, the power plant performances in terms of capacity factor and base load-capability are discussed and lastly the LCOEs for the various configurations are presented.

5.1. Power plant performance

The annual net electricity generation from all simulated configurations (Fig. 6) shows large differences in the annual output.

Table 5
Cost assumptions for the PV plant.

Item	Symbol	Value	Unit
Modules peak power DC	P_{peak}	110	MW _p
Solar modules	c_{sm}	0.44 ^a	\$/W _p
Structural	c_{st}	0.13 ^a	\$/W _p
Electrical parts	c_{ep}	0.11 ^a	\$/W _p
Inverters	c_{inv}	0.11 ^a	\$/W _p
Engineering and labour costs	c_{elc}	0.22 ^a	\$/W _p
Security and infrastructure	c_{si}	0.08 ^a	\$/W _p
Transport and logistics	c_{tl}	0.03 ^a	\$/W _p
Substation	c_{ss}	0.06 ^a	\$/W _p
Lifetime	n	25	years
Real interest rate	i	2.8	%
Annual O&M costs factor	$f_{O\&M,PV}$	1	%/a
Annual insurance costs	$f_{ins,PV}$	0.5	%/a
Degradation	f_{degrad}	1.0	%/a

^a Terblanche (2015).

Table 6
Cost assumptions for the CSP plants.

Item	Symbol	Value	Unit
Turbine capacity, gross	P_{gross}	115	MW _e
Heliostat field	c_{HF}	200 ^a	\$/m ²
Tower and receiver	c_{T+R}	200 ^a	\$/kW _{th}
Thermal storage	c_{TES}	30 ^a	\$/kW h _{th}
Power block	c_{PB}	1000 ^a	\$/kW _e
Steam generator	c_{SG}	250 ^a	\$/kW _e
Annual O&M	$c_{O\&M}$	65 ^a	\$/kWa
Lifetime	n	25	Years
Real interest rate	i	7.5	%
Annual insurance costs	$f_{ins,CSP}$	1	%/a
Surcharge for EPC, project management and risk	f_{EPC}	15	%

^a Kolb et al. (2011).

Generally, the net output of the CSP/PV hybrid option is always higher than from the standalone CSP plants with the same configurations (due to the additional 223.6 GW h from the PV plant). The two CSP/PV systems with a SM of 2.5 and 3 even generates more electricity than the largest CSP-only options with SM 4 for the various storage sizes. Increasing the solar multiple results in a substantially higher annual electricity yield, whereas increasing the TES size has only a marginal effect.

Although the simulated power plants have large TES sizes, most of these configurations are not capable to provide a 24/7 solar capacity supply. In the case of standalone CSP, only the options with a SM above 3.5 and more than 18 h of TES full load hours were found to be base load-capable. This can be seen in Fig. 5 where the annual average load profiles of the configurations with a SM of 3.5 and 4 are depicted. Configurations with 14 or 16 h of TES can generate electricity throughout the night on some days but they are too small to do that constantly on average. The same applies to the CSP/PV hybrid plants where only the larger configurations with a SM above 2.5 are capable of providing base load capacity on an annual average. However, a TES size of 14 h is too small to maintain a high level of base load capacity especially in the early morning hours.

The capacity factors of the individual configurations are plotted in Fig. 7. The CSP/PV hybrid power plants offer a substantially higher capacity factor with all configurations. The maximum value of 92.1% is achieved with the largest CSP/PV option with SM 3 and

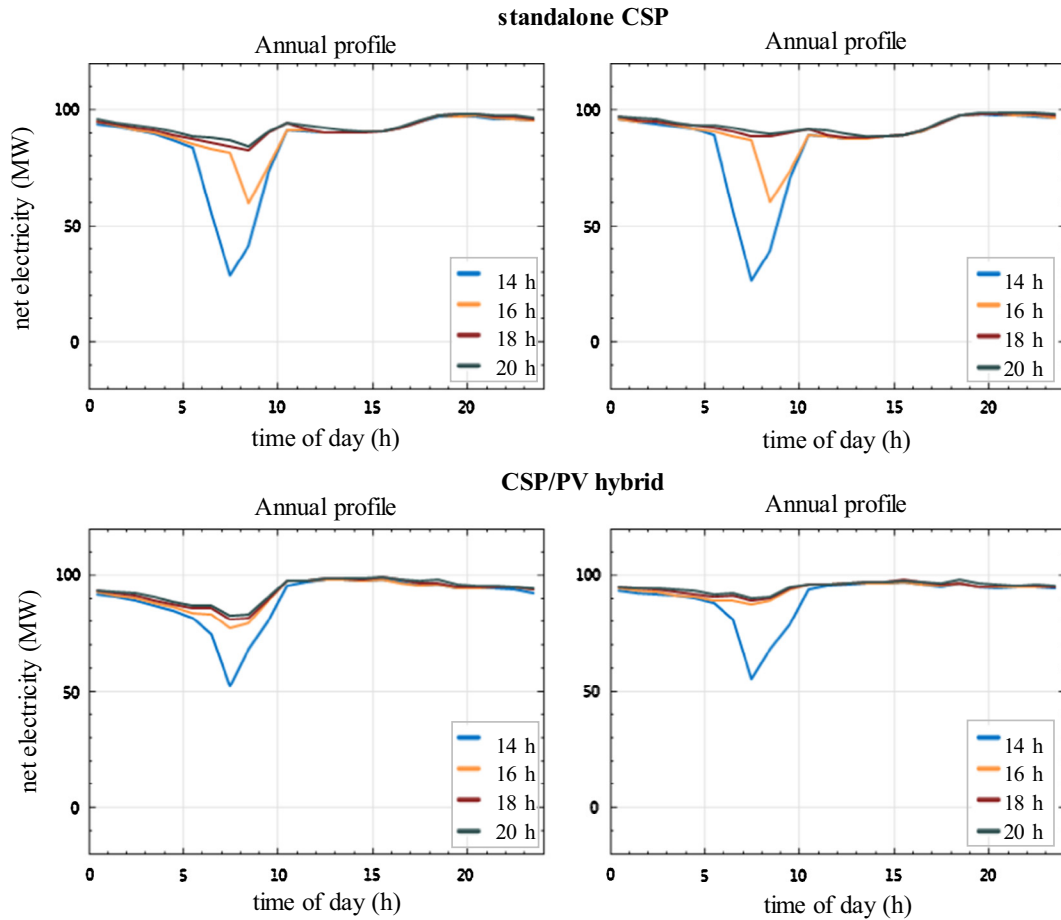


Fig. 5. Annual average profiles of standalone CSP and CSP/PV hybrid configurations.

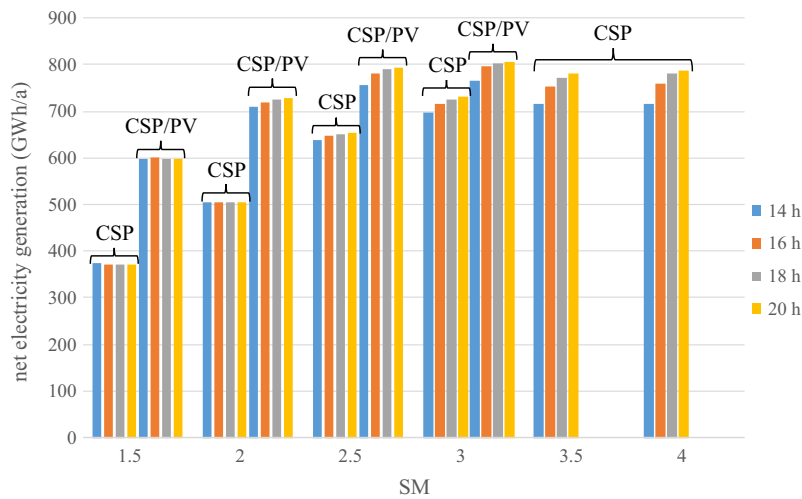


Fig. 6. Effect of storage size and SM on annual net electricity generation for CSP/PV and standalone CSP power plants.

20 h TES. Slightly smaller configurations in terms of solar multiple and TES still offer capacity factors in the 90% range. It should be noted that the capacity factor of the CSP/PV power plants is calculated based on the assumption that the CSP/PV power plant has 100 MW installed capacity although technically there are 200.3 MW installed (CSP plus PV capacity). However, because of the scope of this study to have a “virtual” power plant that has

100 MW as actual capacity it is assumed that the combined capacity is also 100 MW instead of 200.3 MW.

Fig. 8 shows the hourly load profile of the CSP/PV plant with SM 3 and 20 h TES during a typical winter. In the upper graph, the PV supply is depicted in blue and complemented by the CSP capacity in orange. The combined net output is fluctuating around 100 MW over several days, but with some generation drops of up to 15 MW

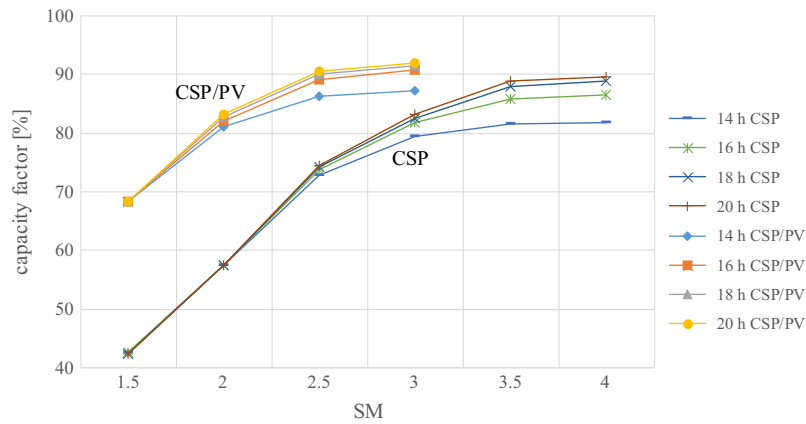


Fig. 7. Capacity factors for CSP standalone and CSP/PV hybrid plants.

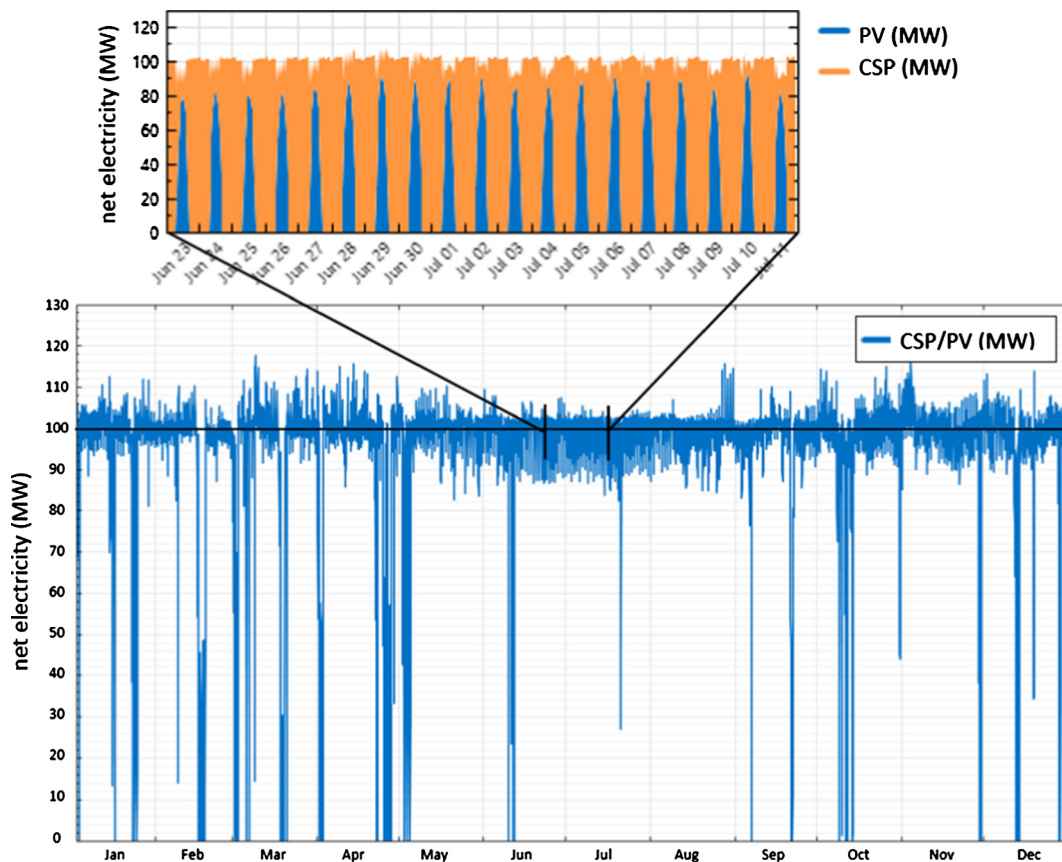


Fig. 8. Hourly combined CSP/PV load profile (SM 3, 20 h TES) over a year and close-up of individual PV and CSP generation capacity during a typical winter period (23rd June–11th July).

during daytime. This is due to the simplified and static CSP control strategy implemented in the simulations which controls the turbine output fraction based on a monthly average PV load profile. This results in deviations on days with higher or lower PV generation than the average of the respective month. However, the load curve could be smoothed to a more constant power supply with a more advanced and dynamic control strategy which reacts directly to the power output supplied by the PV plant. The graph also shows when times of no power generation occur. This can also be seen in Fig. 9 where the probability distribution of the power

output of the largest configurations of both the CSP (SM 4 and 20 h TES) and CSP/PV (SM 3 and 20 h TES) option are depicted. The desired base load of 100 MW is only supplied during 2% of the time with the CSP option, whereas the CSP/PV option supplies a base load of 100 MW at 24% of the time. During the residual times, the capacity ranges between 90 and 110 MW for the CSP/PV option. Alternatively, the standalone CSP option has a more uneven distribution and more times of an oversupply of 105 MW. Furthermore, the CSP option has a system down time of 6%, whereas the CSP/PV option is not generating any electricity during

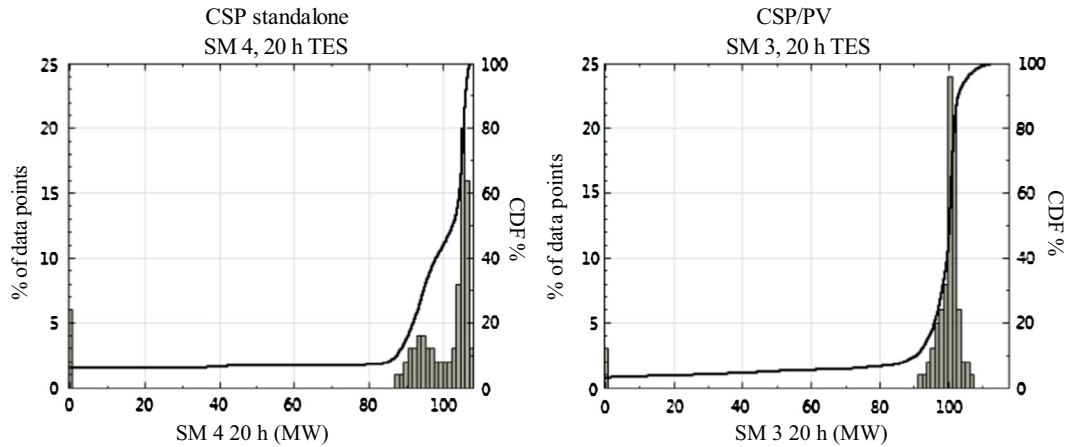


Fig. 9. Probability distribution of CSP (left) and CSP/PV (right) power output.

only 3% of the year (11 days). Such a small fraction of system downtime makes the concept of a CSP/PV power plant suitable as a base load power plant for 24/7 solar electricity generation.

5.2. LCOE analysis

The LCOEs of the various power plant configurations are depicted in Fig. 10 and tabulated in Table 7. It can be seen that the optimal solar multiple for a standalone CSP plant is between 2.5 and 3 with only small differences caused by the TES size. In the case of the CSP/PV hybrid plant, however, the storage size has a more significant impact on the LCOE due to its reliance on the availability for night time operation. The optimal solar multiple in this case is 2 for all storage sizes but the smaller storage sizes offer lower LCOE values because of the high investment costs of the larger systems. In comparison, the LCOE of the 100 MW PV plant is 0.046 \$/kW h.

Fig. 11 displays the LCOE values of the power plant configurations that were found to be base load-capable in Section 5.1 and highlighted in bold in Table 7. Although the standalone CSP options have lower LCOEs than some of the CSP/PV configurations, the overall benefit of the latter is the reduced system size and more uniform power output. The lowest LCOE is 0.133 \$/

kW h for the CSP/PV option with a solar multiple of 2.5 and 16 h storage. This is 2.7% cheaper than the lowest LCOE of the conventional CSP plant.

6. Discussion

Although the supply cannot be guaranteed for 365 days a year, it was shown that a continuous power supply over several weeks and even months is possible and that system downtimes are rare. This makes the CSP/PV plant a suitable base load generation plant that can supplement coal or nuclear power plants and at the same time increase supply security due to the independence from fossil or nuclear fuel supply shortages. Furthermore, the CSP plant for the largest CSP/PV option has far less hours where the turbine is shut down (393 h) than the same sized standalone CSP option with 1674 h. This extends the lifetime of the turbine and reduces maintenance costs.

When looking at the typical system load of South Africa's grid in summer and winter in Fig. 12, it can be seen that the base load is roughly constant between 24 and 25 GW during the night. However, a typical PV power plant is not suitable as a base load power plant due to the high peak time during noon and no supply capacity at night. The high peak at noon can help reducing capacity

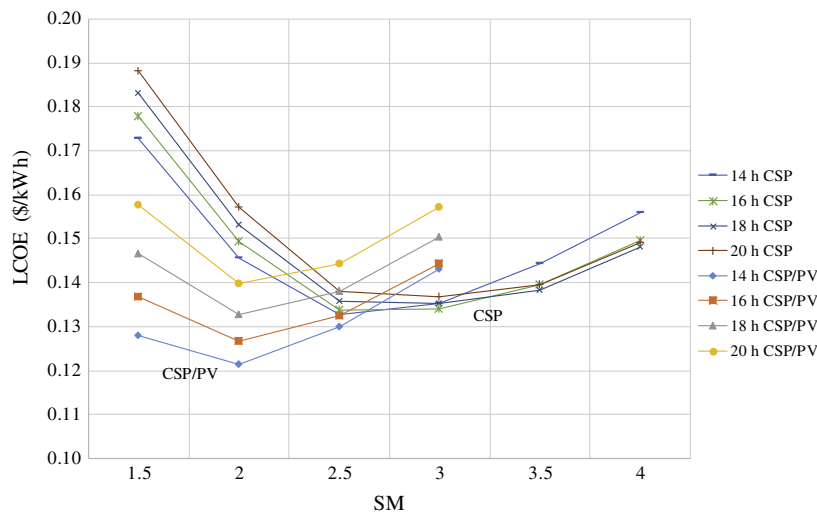
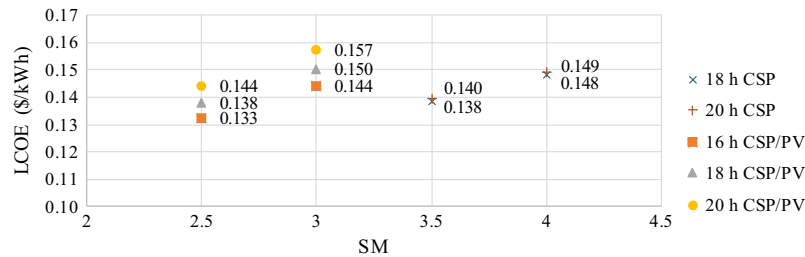


Fig. 10. LCOE of CSP and CSP/PV hybrid configurations.

Table 7

LCOE of CSP and CSP/PV power plants with varying SM and TES size (with base load-capable configurations in bold).

TES	CSP				CSP/PV			
	14 h	16 h	18 h	20 h	14 h	16 h	18 h	20 h
SM	<i>LCOE (\$/kWh)</i>							
1.5	0.173	0.178	0.183	0.188	0.128	0.137	0.147	0.158
2	0.146	0.149	0.153	0.157	0.121	0.127	0.133	0.140
2.5	0.133	0.134	0.136	0.138	0.130	0.133	0.138	0.144
3	0.135	0.134	0.135	0.137	0.143	0.144	0.150	0.157
3.5	0.144	0.140	0.138	0.140	–	–	–	–
4	0.156	0.150	0.148	0.149	–	–	–	–

**Fig. 11.** LCOE of base load-capable power plant configurations.**Fig. 12.** Typical system load in South Africa in July (winter) and January (summer) and PV, CSP & CSP/PV supply capacity.

shortfalls in the grid at peak demand hours but the low generation capacity in the early morning and late afternoon hours does not contribute significantly to the system supply. Furthermore, there is no electricity generation at night, especially during the peak system load at 7 pm.

A CSP plant, however, ramps up electricity generation in the morning as soon as the solar irradiation is strong enough to generate steam and can run at a constant power output throughout the day due to its thermal energy storage (TES). A large storage allows continuous power generation even after sunset. This is illustrated by the simulated CSP plant with a solar multiple of 2.5 and 14 full load hours of TES where electricity generation is constant until 1 am or 2 am on a typical winter day by using energy from the TES after sunset. A higher solar multiple of 3 and a larger TES of 16 h is able to provide continuous power generation until 6 am. A CSP/PV power plant with the same sized CSP system (SM 3 and 16 h TES) can generate electricity continuously throughout the night due to the additional PV system which allows to dispatch

the energy to the night time. CSP/PV plants can therefore gradually substitute base load coal or nuclear electricity generation with 24/7 solar energy. However, potential locations for the power plants are restricted to certain areas due to water availability and vicinity to transmission lines.

An additional advantage of the CSP/PV option is that technically there are 200.3 MW installed, but only 100 MW are needed to provide the defined base load capacity. This means that in special cases with high electricity demand from the demand side the power plant could provide additional capacity to the grid giving it an additional ability to provide balancing energy rather than just acting as a base load power plant.

Although this study used weather data for a South African location, it can be expected that this concept is also able to provide solar base load capacity in other regions in the world with a similar or higher solar resource. However, a more advanced control logic should be implemented in order to smoothen the electricity generation.

7. Conclusions

This study introduced a novel concept of a PV enhanced CSP power plant to supply solar base load capacity to the South African grid. It was shown that a combination of a PV and a central receiver CSP power plant allows dispatching energy from daytime to the night in order to supply a constant capacity. However, this is highly dependent on the CSP plant size in terms of solar multiple and TES.

It has been shown that a smaller CSP system is needed if combined with PV to supply a constant power generation and obtain a similar or even higher energy yield than with a conventional CSP plant. This results in cost reductions for the heliostat field and TES, leading to lower LCOE values in the range of 0.133–0.157 \$/kWh than a same-sized conventional CSP plant. Furthermore, a CSP/PV power plant generates more electricity per year and has higher capacity factors of up to 90% compared to a standalone CSP plant of the same size or larger.

In addition to those advantages, a CSP/PV power plant is base load-capable, making it a good option for replacing South Africa's aging coal-fired power plants which have to be substituted with a clean energy source in the future. South Africa has an excellent solar resource, thus making solar technologies like combined CSP/PV power plants a viable solution for a replacement programme.

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References

- Castillo, Á., 2015. Integration of CSP and PV: The Way Forward? [WWW Document]. CSP Today. <<http://beta.csptoday.com/technology/integration-csp-and-pv-way-forward>> (accessed 2.21.17).
- DoE, 2015. Bid Window 4 Preferred Bidders' Announcement [WWW Document]. <<http://www.ipprenewables.co.za/gong/widget/file/download/id/279>> (accessed 8.24.15).
- Eskom, 2015. Integrated Report 2015. Johannesburg, South Africa.
- Fluri, T.P., 2009. The potential of concentrating solar power in South Africa. Energy Policy 37, 5075–5080. <http://dx.doi.org/10.1016/j.enpol.2009.07.017>.
- Fraunhofer ISE, 2013. Levelized Cost of Electricity Renewable Energy Technologies. Freiburg, Germany.
- IEA, 2015. Electricity & Heat Statistics South Africa [WWW Document]. <<http://www.iea.org/statistics/statisticssearch/>> (accessed 3.18.15).
- Kolb, G., Ho, C., Mancini, T., Gary, J., 2011. Power Tower Technology Roadmap and Cost Reduction Plan. Sandia National Laboratories, Albuquerque, New Mexico. <http://dx.doi.org/10.2172/1011644>.
- Meyer, A.J., van Niekerk, J.L., 2011. Roadmap for the Deployment of Concentrating Solar Power in South Africa. In: Proceedings of Solar Power and Chemical Energy Systems Conference (SolarPACES 2011). Stellenbosch, South Africa.
- NREL, 2017. SAM (System Advisor Model) [WWW Document]. <<https://sam.nrel.gov/>> (accessed 2.20.15).
- Pfenninger, S., Gauché, P., 2014. Potential for concentrating solar power to provide baseload and dispatchable power. Nat. Clim. Chang. <http://dx.doi.org/10.1038/NCLIMATE2276>.
- Platzer, W., 2014. PV-Enhanced Solar Thermal Power. Energy Proc. 57, 477–486. <http://dx.doi.org/10.1016/j.egypro.2014.10.201>.
- Platzer, W.J., 2016. Combined Solar Thermal and Photovoltaic Power Plants – An Approach to 24 h Solar Electricity? 1734. <http://dx.doi.org/10.1063/1.4949173>.
- Solargis, 2014a. Solargis Global Horizontal Irradiation Map for South Africa, Lesotho and Swaziland [WWW Document]. <http://www.sauran.net/Docs/SolarGIS_GHI_South_Africa_width15cm_300dpi.png> (accessed 5.4.15).
- Solargis, 2014b. Solargis Direct Normal Irradiation Map for South Africa, Lesotho and Swaziland [WWW Document]. <http://www.sauran.net/Docs/SolarGIS_DNI_South_Africa_width15cm_300dpi.png> (accessed 5.4.15).
- Terblanche, U., 2015. Large Scale Solar PV Costs in South Africa. Research Engineer at CRSES (Center for Renewable and Sustainable Energy Studies), E-mail Correspondence, Stellenbosch, South Africa.
- WWF, 2014. Enabling Renewable Energy in South Africa: Assessing the Renewable Energy Independent Power Producer Procurement Programme [WWW Document]. <http://awsassets.wwf.org.za/downloads/enabling_re_in_sa.pdf> (accessed 8.6.15).