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CSP Scenarios in South Africa: Benefits of CSP and the Lessons Learned

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Abstract. The dispatchibility potential of CSP in South Africa was investigated in the previous study. This was done by proposing a virtual hybrid system including the planned Open Cycle Gas Turbines and an optimized fleet of CSP plants. The study revealed a number of benefits; mitigates costs of capital, incrementally reduces fuel dependency, adds reserve margin and leads to a lower LCOE of the system. The subsequent paper to that, investigated the effects of the two-tier tariff structure, introduced in the Independent Power Producer Programme of the Department of Energy, which has on the proposed 3 300 MW capacity of CSP plants that is proposed as a peaking CSP system. The former study showed that the proposed CSP system generates 29 % less revenue under the two-tier tariff. However, when the CSP system is optimized for the two-tier tariff, it becomes profitable – with a smaller storage capacity of 5 hours.

This report investigates and presents the results and beneficial strategies from the previous reports. In addition, this report investigates the strategies of increasing the CSP energy share to the peak energy. The results show that the two-tier tariff results in a smaller storage optimized system – due to profitability. The implications would not reflect an increase in the share of CSP energy during peak time. In addition, it reduces the share of CSP energy during the winter season.

INTRODUCTION

We draw our work from the previously proposed studies: The Short Term Hybrid CSP Peaking System Study (peaking CSP system) [1] and the South African Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) two-tier CSP tariff – Implications for a proposed hybrid CSP peaking system (implications for a peaking CSP system) [2]. The former study proposed a virtual hybrid system comprising of a planned Open Cycle Gas Turbine (OCGT) and an optimized fleet of CSP plants. The dominant focus of the study was to investigate the feasibility of using the CSP plants to supply peak energy demands in South Africa. The success criteria used was to compare the LCOE of the CSP system with the LCOE of the OCGT. The later study adopted the proposed peaking CSP system and investigated the effects of the two-tier tariff on the proposed peaking CSP system. The focus of the study was to investigate the implications of the two-tier tariff structure, introduced in the Independent Power Producer Programme (IPP) of the Department of Energy (DoE), on the proposed CSP system.

The objective of this study is to investigate the strategies of increasing CSP energy shares to the peak energy in South Africa. The following part of the report provides background to this study. Subsequent sections describe the previous work proposed for the CSP system and the implications on the CSP system, current work on. The final sections present key results and conclusions to the study.

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Nomenclature

A_a	aperture area of the solar field	r	discount rate
A_i	receiver emitting area	T_a	ambient temperature
E_t	electricity generation in the year t	T_H	receiver outlet temperature
F_i	receiver view factor	$\overline{T}_{r/ri}$	mean temperature receiver
F_t	fuel expenditures in the year t	$\dot{W}$	work done
h	heat transfer coefficient receiver	η_{th}	thermal efficiency
I_t	investment expenditure in the year	$\eta_{optical}$	solar field optical efficiency
M_t	O&M expenditures in the year t	ε_r	receiver emissivity
n	life of the system	σ	Stefan-Boltzmann constant
$\dot{Q}_{in/out}$	heat flow receiver	α	receiver absorptivity

BACKGROUND

The South African electricity is controlled by the national electricity company – Eskom. Eskom generates 90 % of the national electricity supply; also, it controls and maintains the national electricity grid [3]. The SA electricity supply is derived from 90 % coal, which typically services the base load demand. The OCGT system services the peak load demand. One of the challenges that are facing the electricity supply is the reserve margin. FIGURE 1 shows the installed reserve margin over the past 6 years. The most pressing issue is the small reserve margin during peak periods. The average peak shown in FIGURE 1 considers the morning and the evening peak. The peak periods are shown in vertical lines in FIGURE 2. Considering the difference between the reserve margin between average at peak and the average at 22:00, this shows the sudden increase and drop in demand during peak period. This challenge requires that all the energy systems that are able to operate during this period, and deliver energy at competitive costs be brought on line.

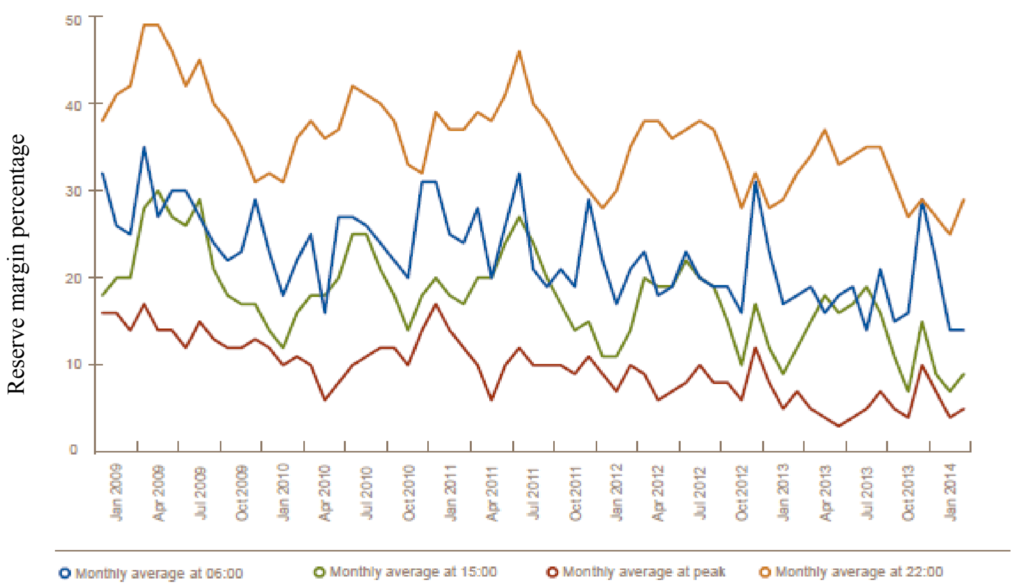

FIGURE 1. South Africa reserve margin

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FIGURE 2 shows the typical SA load demand. The figure illustrates the winter and the summer load demand. The South African load profile and its features can be characterized as being noticeably predictable. In general, for an electricity supply industry, peak load is supplied with quick response electricity systems – typically Brayton cycle. However, for the SA industry, an optimal application of the Rankine based system can be used to supply the electricity industry. Proper remuneration structure will deem the CSP system to be feasible, and it would make sense for the CSP developers to build plants.

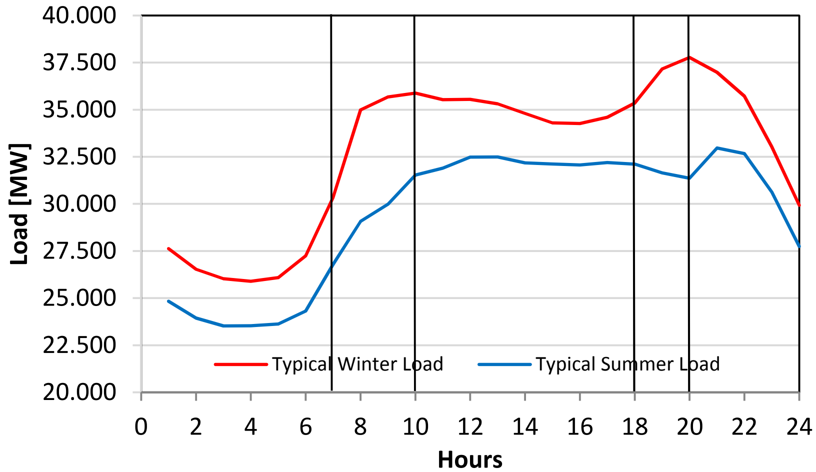

FIGURE 2. South Africa load demand profile

The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) is a DoE programme that implements the renewable energy (RE) allocation in the Integrated Resource Plan (IRP) in South Africa [3]. The REIPPPP is responsible for allocating capacity for various renewable technologies. The Independent Power Producers (IPPs) submit bids for the systems that they intend to build, depending on the capacity allocated [4].

So far, there have been four rounds of bidding in the REIPPPP. The first and the second bidding rounds, the bidding tariff was capped at 2 850 ZAR/MWh. For the third round, the new tariff structure was introduced – the two-tier tariff structure. The two-tier tariff structure is implemented as follows: a base tariff of 1 650 ZAR/MWh for off-peak generation – 5:00 am to 4:59 pm, 9:00 pm to 9:59 pm and a multiplier of 2.7 for the peak hour generation – 5:00 pm to 8:59 pm.

During the first and second bidding rounds, the average tariff from IPPs were 2 690 ZAR/MWh and 2 510 ZAR/MWh, respectively. The average indexed tariff for the third and fourth round were 1 640 ZAR/MWh and 1500 ZAR/MWh, respectively [5]. There was a significant drop in the indexed tariff from round three – after the introduction of the two-tier tariff. This also proves the feasibility of utilising CSP systems to supply peak energy, as was proposed in the hybrid CSP study [1].

The total CSP capacity allocation that has been approved in the REIPPPP programme is 600 MW. This is allocated as follows, 150 MW for the first round, 50 MW for the second round, 200 MW for the third round and 200 MW for the fourth round. The pressing issue with regards to the CSP, in particular is; how can the uptake of CSP help to address the peak energy challenges? Also, how can the tariff structure be crafted in a manner that encourages the CSP developers to increase the peak energy CSP share?

PREVIOUS WORK

In the previous work, we investigated the feasibility of utilizing the CSP plants to deliver peak energy in SA over a short term. Also, we investigated how CSP can guarantee the delivery of peak energy. An important message from the study was that the CSP allocation in the IRP was insufficient. One of the objectives of the study was to show that a fleet of CSP plants has added-benefits for the SA energy system. For this study, we proposed a fleet of 10 CSP plants with the proposed total capacity of 3 300 MW. The CSP nodes (spatial solar data) were allocated along the high voltage line – running from Gauteng to the Western Cape.

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This was done by modelling a contemporary central receiver system using the model developed by Gauché [6] [7]. For the CSP peaking study, the LCOE was used to determine the feasibility of the CSP peaking system. The energy costs of the CSP system were compared to the energy costs of the OCGT.

The previous studies [1], [2] investigated and presented some of the benefits that the proposed peaking CSP system provides in South Africa. The highlighted benefits constituted; capital costs mitigation, incremental fuel dependence reduction, local CSP learning rate, additional reserve margin and lower system LCOE.

The significant finding of the peaking CSP system was that the CSP can guarantee dispatch of energy and can deliver energy at competitive costs. The modelled CSP system had a LCOE of 1.89 ZAR/kWh. The first consideration on the implications for a peaking CSP system was to look at how the part load operation affects the LCOE of the CSP system. Due to part load operation – reduced daytime energy generation, less energy is generated (sent to the grid) which slightly increases the LCOE. The analysis showed that the tariff structure significantly influences the CSP plant configuration. When the CSP system is not optimized to deliver energy based on the two-tier tariff, and not operated at part load, the 4 hour storage size appears feasible. This is due to the fact that there is no incentive to store energy during the day when the standard tariff applies. The LCOE ranges between 1.64 ZAR/kWh – 2.86 ZAR/kWh for various storage configurations. For part load operation, the LCOE ranges between 1.64 ZAR/kWh – 2.07 ZAR/kWh.

The methodology considered two main components – the technical modeling of plants and the financial analysis of the energy system. The technical model is systematic for a CSP tower system. For that, we assumed a contemporary central receiver system. The model aims to replicate the Gemasolar plant, with the understanding that it is a real plant providing the ability to dispatch. The design parameters of the Gemasolar plant are adopted for this study [8]. The plant's technical model evaluates the plant performance by considering the optical-to-thermal energy conversion. The key inputs for the technical model are: hourly DNI solar resource, the solar field configuration, ambient temperature, wind speed and receiver operating temperatures. The model by Gauche [7] was adapted and used for this study.

The solar field optics is derived by acknowledging the continuous determination of the sun position. The equation of time, derived in [7].

$$\eta_{optical} = 0.4254\theta_Z^6 - 1.148\theta_Z^5 + 0.3507\theta_Z^4 + 0.755\theta_Z^3 + 0.5918\theta_Z^2 + 0.0816\theta_Z + 0.832 \quad (1)$$

The energy balance on the receiver is performed by considering the contemporary receiver, by replicating the Gemasolar plant operating parameters. The receiver output temperature is kept at 565 °C, as per the Gemasolar plant. The equations (2) and (3) are used to perform the energy balance. The inlet and the outlet of the receiver are fixed, and the radiation component is solved for this range.

$$\dot{Q}_{in} = DNI * \eta_{optical} * \eta_{other} * A_a \quad (2)$$

$$(1-\alpha) * \dot{Q}_{in} = \sigma * \varepsilon_r \sum_{i-1}^{n} A_i * F_i * \left(T_{ri}^4 - T_a^4\right) + h * A_r * \left(\overline{T_r} - T_a\right) + \dot{Q}_{out} \quad (3)$$

The contemporary thermal energy storage with a round trip efficiency of 90 % or higher is assumed for the study. This gives an average loss of 10 % / 24 hours or 0.5 % / hour. The LCOE was used to determine the energy generation costs of the CSP system. The definition of LCOE is shown by the equation (4), and it the default method of determining the LCOE. The formula was adapted from the IRENA report on RE systems costs analysis [9].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (4)$$

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TABLE 1. CSP tower system capital costs estimates [10]

Item	Value (ZAR)	Unit	Value (US $)	Unit
Heliostat Field	1600	R/m^2	200	$\$/m^2$
Receiver	1600	R/kW_{th}	200	$\$/kW_{th}$
Thermal storage	240	R/kWh_{th}	30	$\$/kWh_{th}$
Power block	8000	R/kW_e	1000	$\$/kW_e$
Steam generation	2800	R/kW_e	350	$\$/kW_e$
O&M	520	R/kW_{yr}	65	$\$/kW_{yr}$

The TABLE 1 shows the assumed financial parameters of the CSP system. The LCOE assumed 8 % interest rate on the loan and 10 % discount rate. The predicted life time of the CSP system is 30 years. Currently, the IPPs sign a 25 years lease with the energy uptake company in South Africa. However, the IRP indicates that the OCGT and CSP plans have a life span of 30 years.

CURRENT WORK

The technical modeling of the proposed CSP system demonstrated the ability of the CSP plants to deliver peak period energy. In addition, it demonstrated the ability of the CSP to deliver peak energy at competitive costs – when comparing it to the LCOE of the OCGT. The subsequent study demonstrated the financial viability of the CSP system to deliver peak energy when optimized for the two-tier tariff structure. The optimization of the CSP system for the two-tier tariff structure revealed that the CSP system is financially viable with a smaller storage – 5 hours.

The TES is one of the key factors for integrating the fluctuating generation of RE technologies[11], [12]. Previous studies have demonstrated the ability of CSP with thermal energy storage to dispatch energy.

There is work that has been done on the optimization of CSP plants under different tariff structures, in order to maximize revenue. The 1-day and 2-day optimization method has been presented in [11]. This is based on the Spanish market – the spot market rules. Typically, the bids are sent to the market operator a day before, setting the expected production [11]. This requires that the CSP plant is optimized to shift the energy production to times of a higher tariff. This optimization requires estimates of day-ahead market prices, also, it requires accurate day-ahead solar predictions. What is clear from the day ahead optimization is that, in most cases, the storage is empty at the end of the day [11]. The idea of conducting CSP optimization for more than 2 days ahead, or even up to more than a week has been done and is presented in [12] and [13].

The modelling that was done in this study was based on hourly data. The model seeks to meet the hourly demand, based on the availability of solar energy and thermal energy. The model tries to first dispatch energy from CSP plants with higher energy stored. It also tries to keep a certain level of energy storage in order to service future energy demands [1]. The SA load demand is predictable, and characterized by the morning and the evening peaks. The optimization idea is that the CSP plant would follow the load. The model energy output tries to follow the load demand. The objective function of the optimization is the level of fulfillment of the annual energy supply. FIGURE 3 shows the non-optimized and optimized operation and the load demand.

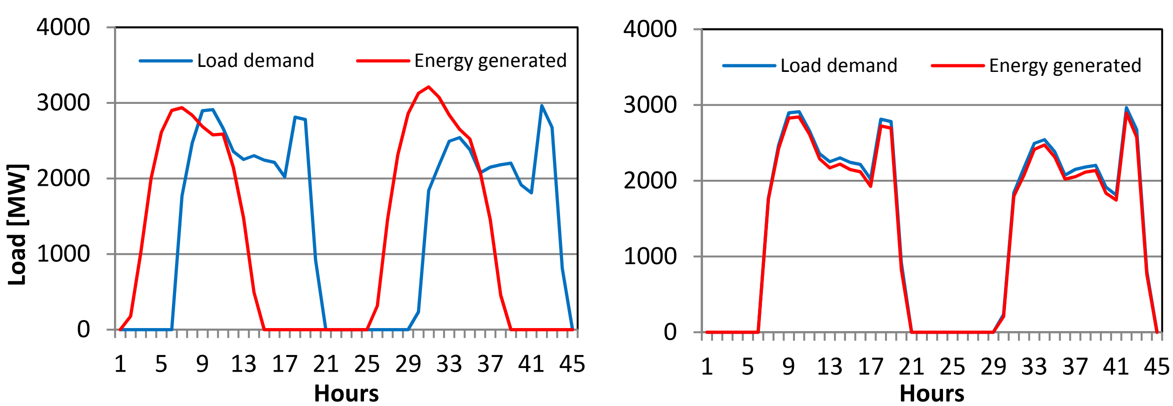

FIGURE 3. Non optimized and optimized energy generated and the load demand

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KEY RESULTS

The dominant focus of this paper is to investigate and propose strategies on how to increase the share of CSP energy to the South African grid, especially focusing on the peak energy demand. FIGURE 4 shows the two CSP system operational mechanisms, optimized for the peak energy (fixed percentage) delivery and the two-tier tariff structure optimized CSP system. The peak energy optimized means setting a threshold on the base load / mid merit load. Any Load demand above that becomes peak load. The CSP system is then required to deliver a certain amount of this energy, in combination with other peakers. The two-tier tariff optimized CSP system is optimized to deliver energy based on the highest paying tariff in order to maximize profits.

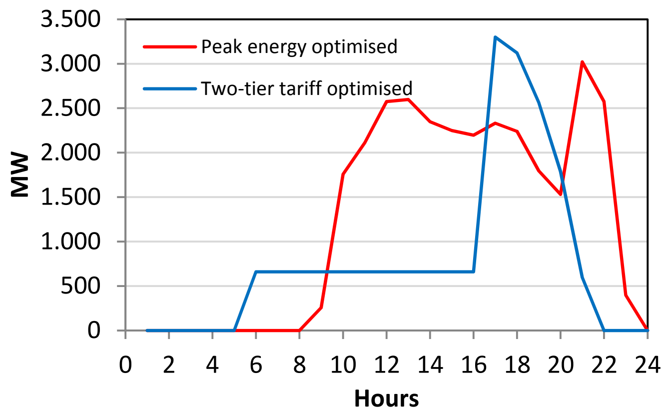

FIGURE 4. Peak energy optimized and two-tier tariff optimized energy delivery

The report done on the profitability of the CSP system in SA, based on the two-tier tariff showed that, the optimal CSP plant would have 5 hours storage [2]. This configuration would make the CSP plant profitable by directly focusing on delivering energy during the highest paying period. What this means is that, a CSP plant operator would be able to be profitable with a small storage plant. This means less energy penetration or energy delivery to the grid, especially during the peak period. Based on annual energy delivery, the peak energy optimized delivers 20 % more energy than the two-tier tariff optimized system. This is based on the same capacity, however, the storage hours is different – 7 hours for the peak energy optimized and 4 hours for the two-tier tariff optimized. The LCOE is 1.89 ZAR/kWh and 1.94 ZAR/kWh, respectively.

When looking at the SA load demand, the load is higher during the winter period than the summer period. This challenge is compounded by the limited reserve margin during this period. CSP can contribute to this challenge due to its dispatchibility potential. However, the irony with that is; this is the period of low solar resource. In order to encourage the CSP peak energy delivery, there should be adequate support mechanisms.

FIGURE 1 showed the reserve margin based on the time of the day and how it has decreased over the past years. The pressing issue about the reserve margin is that it becomes severely small during the peak periods. That could be due to the increase in load demand and in adequate availability of capacity. FIGURE 2 showed the typical load demand of South Africa for the winter and summer periods. This reveals that the reserve margin is small during the peak period. In addition, the peak energy demand increases during winter, which puts pressure on the reserve margin.

The idea of increasing the energy share contributions from CSP is two-fold. The first is to increase energy share contribution based on daily peak demand. This seeks to ensure that there is adequate capacity during evening peak, in order to increase the reserve margin. The second is to increase the energy share contribution based on the season of the year.

The most prominent strategy of increasing share of CSP plant energy is to increase the storage hours relative to the plant turbine. This allows the CSP plant to have adequate thermal energy stored in order to service the peak period load demand. FIGURE 5 shows the percentage of maximum output from the CSP system. This is based on the peak load assumed load demand. The load demand is assumed from the 2010 national load demand and the SolarGIS is supplied by GeoModel solar. The peak load assumed load demand is assumed as a percentage of the peak load. The CSP system have a capacity of 3 300 MW and the LCOE of 1.89 ZAR/kWh. Due to the fact that peak energy optimized CSP system is optimized to deliver a certain amount of energy, it constantly delivers energy operating at higher percentage of maximum output.

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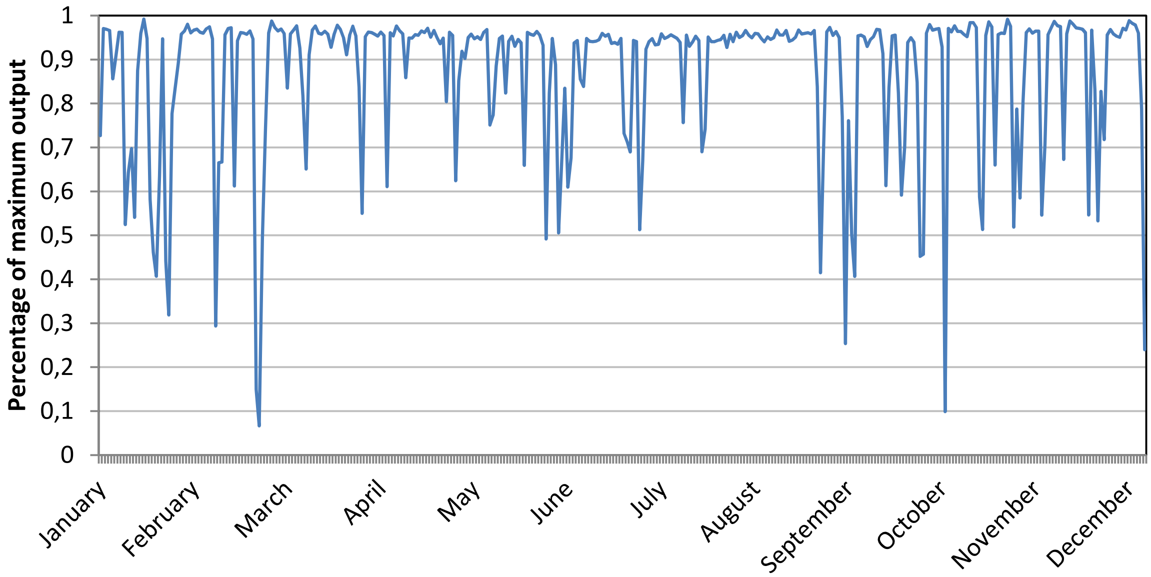

FIGURE 5. Percentage of maximum output – peak load assumed demand

FIGURE 6 shows the percentage of maximum output from the CSP system. This is based on the two-tier tariff assumed load demand. The CSP system has a capacity of 3 300 MW and the LCOE of 1.94 ZAR/kWh. The TES hours are relatively small as compared to the peak load assumed demand. As compared to the peak load optimized CSP system, the two-tier tariff optimized system energy delivery drops during winter. As stated earlier, it generates 20 % less energy annually.

The drop in energy delivery from the CSP system in winter still makes the CSP to be profitable. However, it does not assist in increasing the share of CSP energy during peak period. Having a seasonal tariff would assist in increasing the CSP energy share by encouraging the CSP developers to optimize the plants to deliver energy during winter. The seasonal tariff structure has not investigated in detail in this report. However, the idea behind it is that the IPPs would be paid a higher tariff during winter.

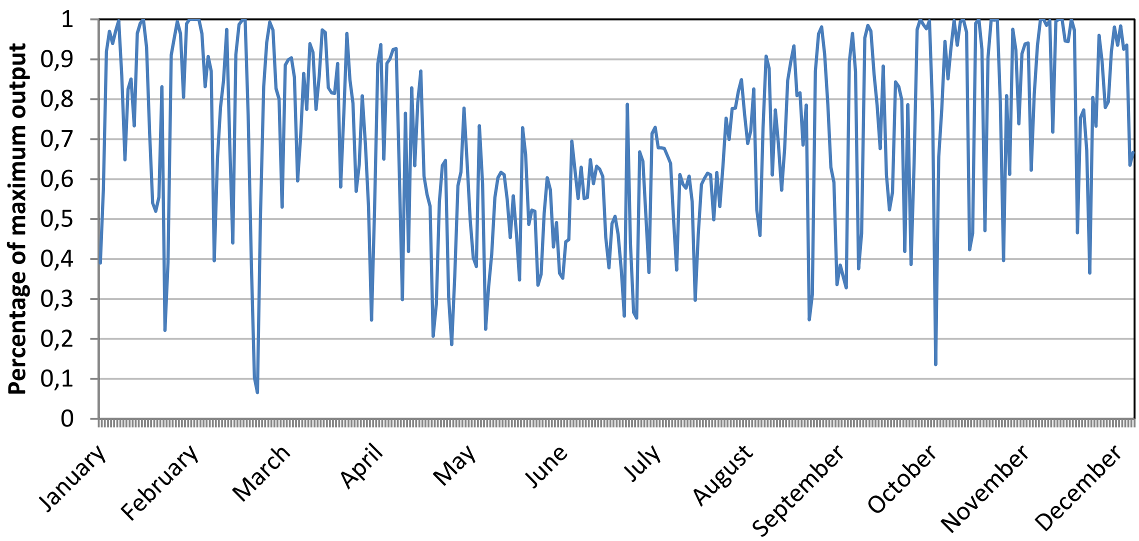

FIGURE 6. Percentage of maximum output – two-tier assumed demand

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CONCLUSION

The first part of this report presented the report that was done to investigate the feasibility of using CSP plants to supply peak period energy in South Africa. That was done by proposing a CSP system, comprised of fleet of spatial optimized 10 CSP plants, with combined capacity of 3 300 MW. This study established that the CSP system generates peak energy at 1.89 ZAR/kWh. This LCOE is significantly lower that the LCOE of OCGT which is currently used in South Africa as peaking plants. The second part of the study presented the report that investigated the implications of the two-tier tariff structure on the proposed CSP system. The study showed that the proposed CSP system generates 29 % less revenue under the two-tier tariff. However, when the CSP system is optimized for the two-tier tariff it becomes profitable – with a smaller storage capacity of 5 hours. This report investigated strategies of increasing share of CSP energy to the peak energy. Two scenarios were investigate; the operation of CSP system optimized for the two-tier tariff structure, and the operation of the CSP system optimized to be peak load follower. Based on annual energy delivery, the peak energy optimized generates 20 % more energy than the two-tier tariff optimized system. The operation is based on the same capacity, however, the storage hours is different – 7 hours for the peak energy optimized and 4 hours for the two-tier tariff optimized. The LCOE is 1.89 ZAR/kWh and 1.94 ZAR/kWh respectively.

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