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CSP Opportunity and Challenges in a National System: The WWF Renewable Vision for a 2030 South African Electricity Mix

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Abstract. The WWF proposes a renewable energy vision scenario for South Africa as an alternative to the currently mandated policy which favors additional nuclear in reducing greenhouse gas emissions. Current policy also blends additional coal, hydropower, renewables and gas turbine (open and combined cycle) capacity. We validated and refined the WWF scenario showing that a renewable favored scenario potentially leads to the lowest cost system while also demonstrating better resilience. This paper focusses on the role that CSP plays within the WWF scenario. For the WWF scenario to lead to a low cost and reliable system, significant CSP capacity was needed and the optimal storage rating was high (avg. 12 hours). Through initial sensitivity analysis of the WWF scenario, we try to understand this role. Our findings suggest that provided CSP capacity is planned well, it indeed can play a pivotal role in our future. Not just in justifying a renewable path, but as essential in the best solution for South Africa in the period leading to 2030.

INTRODUCTION

Concentrating solar power (CSP) is a technology promising to offer dispatch-type electricity in order to serve electricity needs flexibly in a system. We have conducted several studies that consider the potential of CSP to serve base-load power in South Africa and worldwide [1][2]. We have also studied the potential for CSP to offset the avoided cost of diesel powered generators in terms of cost to the system [3].

The Worldwide Fund for Nature - South Africa (WWF-SA), set forth a vision for an alternative 2030 electricity system that would have many advantages over the currently mandated Integrated Resource Plan of 2030 [4][5]. We recently completed a spatial-temporal study in order to test and improve the WWF-SA renewable energy vision [6]. This initial validation study makes use of the same basic spatial-temporal model in the aforementioned references and it incorporates sufficiently detailed models of all other generating technologies in the South African present and future national grid.

The CSP model in the WWF validation study is by a considerable measure the most complex of the various technology models. This is due to the technology's inherent definition but also due to the relationship that CSP assumes within the overall grid. The WWF validation study doesn't however have a CSP emphasis, rather the study aims to perform "equal fairness" of all technologies in order to arrive at a lowest cost and most reliable system for 2030. Thus the WWF scenario presents a techno-economically sensible lowest cost electricity system for South Africa.

In this paper we explore the role, value and limitations of CSP within the WWF scenario. Direct and marginal values of CSP are investigated recognizing that these virtues are a function of the system definition. The goal is to

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provide an initial assessment of how CSP can be positioned in terms of the national interest and in terms of guidance for policy and economic activity. To this end, the paper summarizes the WWF spatial-temporal method and the resulting 2030 proposed WWF scenario before exploring the CSP value. Conclusions provide our initial recommendations and next steps.

METHOD

The overall system model is based on an hourly spatial-temporal method as used in several previous studies [1][2][3]. All hours of a single year are synchronously modeled in a quasi-steady-state manner and hourly outputs are reasonably validated against what is expected from actual technology outputs in terms of aggregated power generation over each hour. An annual hourly aggregated demand model is used to dictate the generation and supply constraints on an hourly basis. Figure 1 presents the spatial nodes used in the WWF scenario and illustrates the annual average solar DNI map, itself derived from multi-year temporal data aggregation.

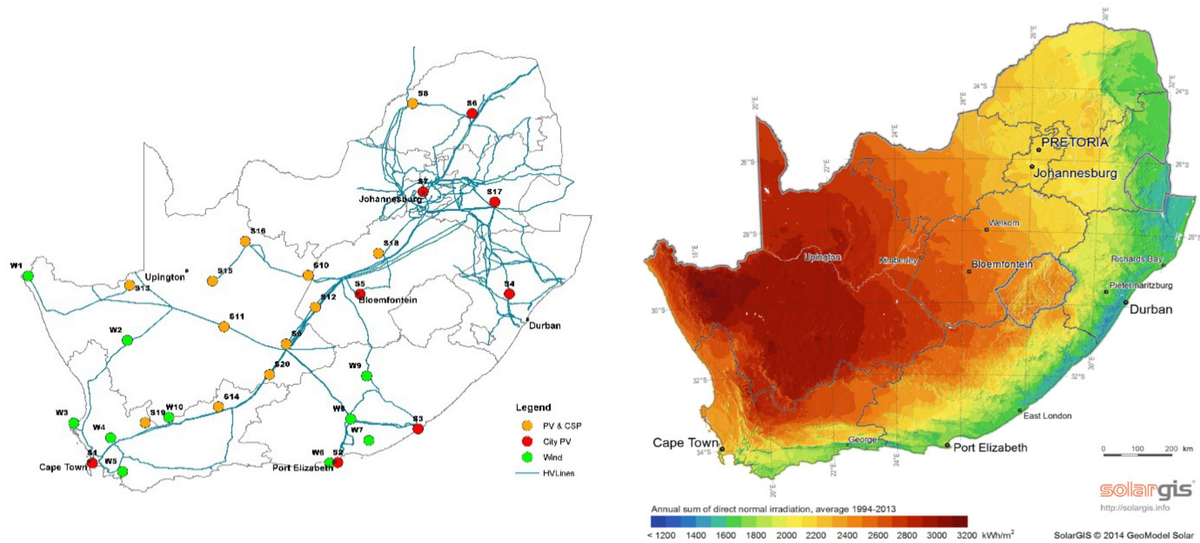

FIGURE 1. (a) WWF nodes located near existing HV transmission lines. (b) DNI map of South Africa (GeoModel Solar 2014).

The WWF study only performs an analysis on a 2030 electricity system, but it does so in some detail. The method does not attempt to replicate or replace well known energy systems methods that typically use linear programming to optimally define how to plan for a multi-decadal evolution of an energy system. Typically these methods use time slices within a year and treat time and resource on a stochastic basis.

A recognized limitation of the spatial-temporal method is that historical solar, wind and weather data is required over a multi-year period in order to sufficiently cover extra-annual variances in the renewable resources. The spatial-temporal method is however expected to provide a more accurate result when renewable energy penetration becomes significant. A significant implication of the spatial-temporal method is that for a given definition of the system and its underlying technology characteristics, the result is deterministic.

The primary goal of the WWF validation study was to investigate the cost of the various scenarios using some form of levelised cost of electricity (LCOE). Due to uncertainty about the year 2030, we treat all cost parameters as probabilistic to avoid needing to look at a limited set of cost scenarios. The outcome is therefore not a single solution, but rather a cumulative probability distribution of cost for the year 2030. We therefore try to synthesize the result capturing all sensitive parameters into a single comparative probability and cumulative distribution of LCOE. The remainder of this section provides more detail on this hybrid deterministic-probabilistic method.

System Logic, Resource, Demand and Technology Constraints

The technical performance of the system is deterministic and is modeled using a cascaded set of behaviors, rules and constraints which are elaborated in the WWF report [6]. Figure 2 summarizes the system logic of the model.

Each hour of a calendar year is simulated in sequence. For a given definition of the system, the demand and the energy resources, the model evaluates plants and technologies in a merit order manner. Each time step is treated as a steady-state solution while linked to the initial and end conditions of each time step in sequence for storage elements in the system.

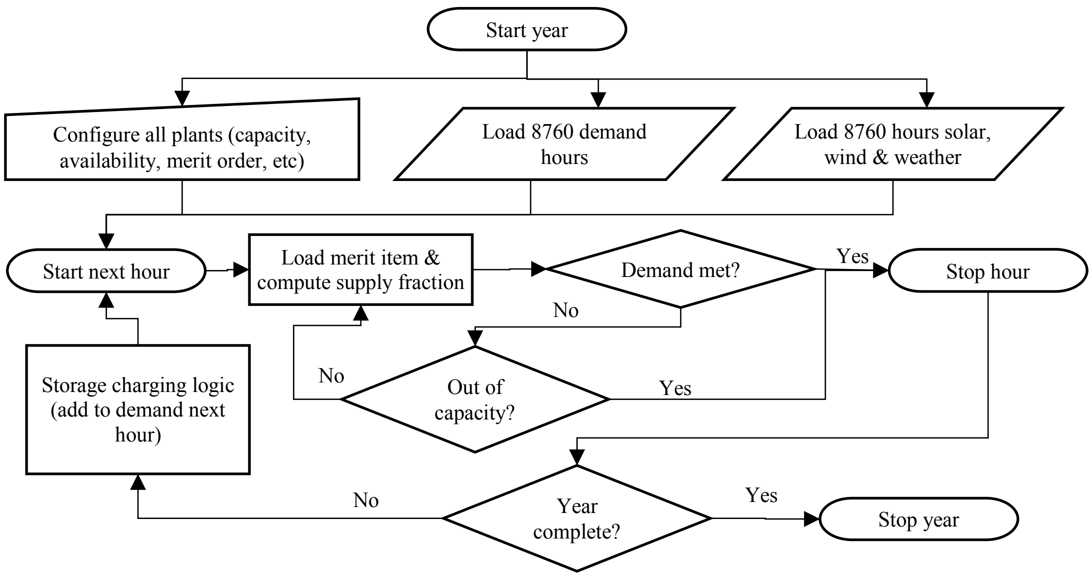

FIGURE 2. System spatial-temporal model logic.

The model uses a completely synchronous set of 2010 data including national (Eskom) demand, solar, wind and weather. It is important that this be the case due to dependencies spatially, temporally and behaviorally. We scale the actual 2010 hourly demand (see Figure 3) for each scenario by keeping the shape but ensuring that we satisfy annual forecasted demand for 2030. The multipliers for each scenario are listed in Table 1. We use best-in-class satellite derived solar data supplied by GeoModel Solar [7] and wind data from the Wind Atlas of South African (WASA) [8].

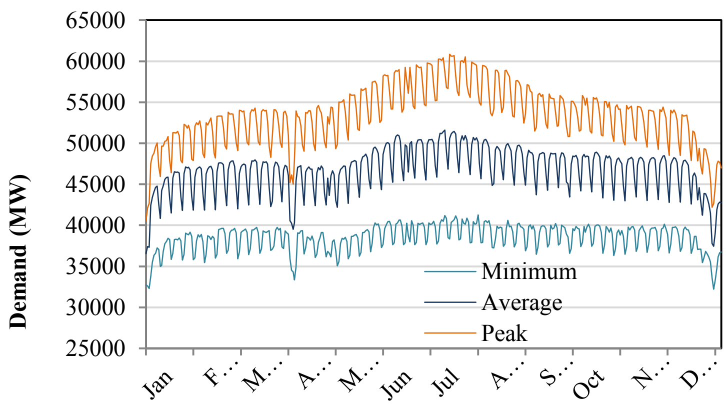

TABLE 1. Demand shape and scale

Annual demand (TWh)	Scenario	Multiples
250	2010	n/a
358	WWF Low	1.43
407	WWF High	1.625
409	IRP Update	1.634
454	IRP 2010	1.816

FIGURE 3. Demand shape (complete 8760 hours of the year) and scale

Technology and Plant Models

All technologies are modelled using a steady-state energy conversion efficiency method with varying levels of detail ranging from simple behavioral to component-wise detailed. A "lowest common denominator" approach is used for all definitions, assumptions and simplifications in order to attempt at least some degree of equivalence between technologies and in order to provide clear knowledge in the use and interpretation of the model and results.

The model techno-economic and relies on the assumptions made in Table 2. This table summarizes all technologies in the model in terms of cost ranges we expect on average between 2015 and 2030. Principle operating constraints and rules such as availability and ramp rate are dictated while the model determines actual capacity factor.

TABLE 2. An abbreviated summary of costs and technology characteristics for the options included in the proposed WWF scenarios. Sources: Black & Veatch 2012; DoE 2013a; IEA 2013; IRENA 2012a-d), WWF-SA 2014; Own analysis.

Technology	**Range**	**CAPEX**	**Fixed OPEX**	**Variable OPEX**	**Fuel Costs**	**Availability**	**Turndown limit**	**Ramp rate (%/min)***	**Maximum life Span (years)****
		R/kW	**R/kW/a**	**R/MWh**	**R/GJ**				
PV Fixed tilt	Upper	13 115	484	0	0	90%	NA		25
	Lower	11 210	208	0	0				
CSP (6h)	Upper	37 610	573	29	0	90%	0	6%	30
	Lower	36 726	573	0	0				
Wind	Upper	19 463	400	0	0	90%	NA		20
	Lower	14 502	310	0	0				
CCGT	Upper	8 708	163	0.7	92	90%	0	5%	30
	Lower	8 524	163	0.7	70				
Nuclear	Upper	87 754	1017	29.5	10	90%	0.8	5%	60
	Lower	60 000	532	29.5	6.8				

Power produced by a plant over 1 hour is a product of the energy resource averaged over 1 hour multiplied by all conversion efficiencies to the point of reaching the transmission system and limited to the rating of the plant. Ramp rates, turndown limits and availability are accounted for either collectively (such as with coal) or at nodes (wind and solar) or in some instances of known plants. Availability is treated as an efficiency and not specified in any discrete manner in order to simplify the model and to preserve its deterministic outputs.

The primary capabilities, behaviors and limitations of the CSP model are highlighted in Table 3.

TABLE 3. Primary CSP model capabilities, behaviors and limitations

Item	**Description**
CSP type	Central receiver with state-of-the-art two tank molten salt storage
Dimensioning	Per node, the following can be set • Total node capacity [MW] • Unit (plant) rating [MW] • Optical field size [aperture m^2] • Storage size [Hours at full rating]
Operating modes	All nodes can collectively operate based on combinations of the following • Supply to demand only: "Sacrificial availability" mode forcing CSP to play mid-merit to peaking role. • Minimum demand override (MDO): Capacity factor based threshold forcing demand above that value. E.g. MDO = 1 would enable CSP plants to generate at all times possible. • Storage limit override (SLO): Enables CSP plants to generate above demand when storage is fully charged to avoid excessive curtailment.
CSP network supply	At each hour, each node is ranked in order of the storage charge level of that node. In order to preserve the maximum amount of availability in the system, CSP nodes dispatch in order of that ranking.
Forecasting and incentives	The needs and limitations of the system are summarized by the following • System is purely demand-driven and seeks lowest cost. Therefore there are no time of day tariffs or determination of revenue. • No multi-hour demand or supply forecasting. Forecasting and response is houly.

Cost Model

The cost model can be described by the following three steps that result in a single LCOE probability distribution function (PDF) and cumulative distribution function (CDF) per scenario.

1. LCOE per technology or plant

The simple LCOE used by NREL and the WWF scenario (WWF 2014) is also used in this study. We selected the simple LCOE method due to considering a fixed year in the future without defining how this system evolves over time.

$$LCOE_{plant} = \frac{I_{plant} + M_{plant} + F_{plant}}{E_{plant}} \quad (1)$$

Where I is the investment expenditure in the year 2030 based on assuming that all plants newly commissioned from 2015 will require this; M is the cost of operating and maintaining (O&M) the plant and has a fixed and variable component; F is the fuel cost; and E is the annual generation of the plant.

2. System LCOE

In order to compare scenarios, the sum of all costs of generation and the cost of unserved electricity are combined. The cost of unserved energy (*COUE*) is formally defined in the IRP [5] and used in our system cost model.

$$LCOE_{system} = \frac{\sum\left(LCOE_{plant} \times E_{plant}\right) + COUE_{system} \times E_{unserved}}{D_{system}} \quad (2)$$

Where $E_{unserved}$ is the annual shortfall of electricity and D is the annual demand of electricity.

3. Probability costing of system LCOE

Each technology has a range of costs for capital, O&M (fixed and variable) and fuel as shown in the technology table (Table 2). COUE is treated in the same manner and ranges from R10/kWh to R150/kWh. Once the technical model results are generated, a basic Monte Carlo simulation is performed assuming a constant probability function for each cost range. A PDF and CDF is generated from 300 cost simulations per scenario.

WWF SCENARIO BASELINE

The WWF vision makes a case for a renewable-focused evolution of the South African electricity system as opposed to a blended route of additional baseload capacity (from nuclear and fossil plants) and renewables. Table 4 compares the WWF High scenario with the IRP of 2010 and the IRP draft update of 2013.

TABLE 4. Capacity allocation of the IRP, IRP draft update and WWF High scenarios

	IRP (MW)	IRP Update (MW)	WWF High (MW)
Wind	9,200	4,360	14,000
PV	8,400	9,770	17,000
CSP	1,200	3,300	8,000
(Storage hours)	(~6 assumed)	(~6 assumed)	(12)
Coal	40,995	38,680	36,230
Nuclear	11,400	6,660	1,800
CCGT	2,370	3,550	4,000
OCGT	7,330	7,680	7,680
Pumped storage	2,900	2,900	2,900
Hydro	4,809	3,690	3,690
Other	915	760	760
Total	89,519	81,350	96,060

It should be noted that these scenarios are not defined for the same demand expectation in 2030 and the table only serves to illustrate the capacity proportions. The WWF scenario results in a more equally balanced allocation between wind, PV and CSP when accounting for annual capacity factor. These arguments for why this occurred amongst many other findings is out of scope in this paper and comprehensively covered in the validation report. A key item to note is the significant increase in CSP capacity and storage. CSP appeared to play a vital role in a low cost system and the sizing of the storage was particularly important.

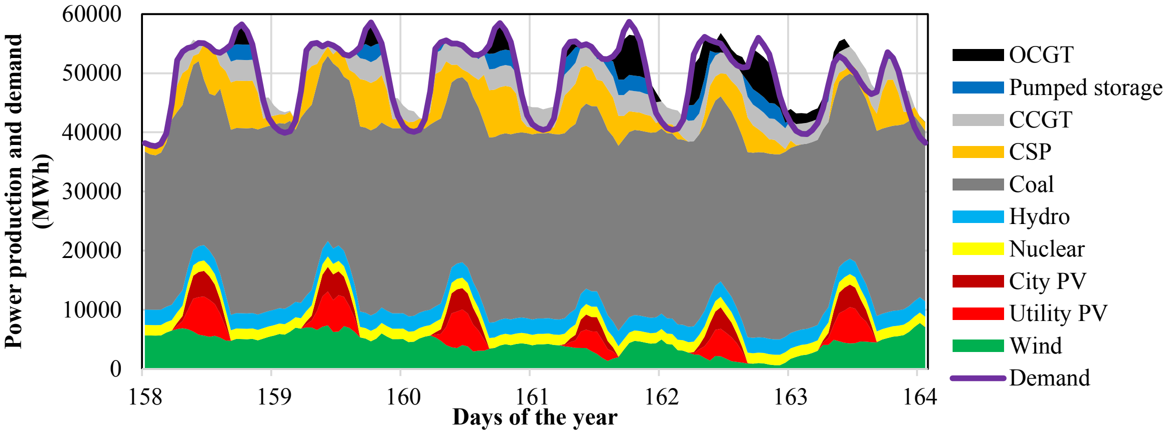

FIGURE 4. Winter week illustrating CSP in non-forecasting role: WWF High scenario

Figure 4 shows a system temporal result for a 6 day period in winter illustrating a number of model and scenario behaviors. This period is the most stressed period in the full calendar year showing minor unmet demand in some hours of that week.

The plot attempts to graphically represent merit order. For this reason, wind and PV power is plotted first due to those technologies lack of control in dispatch. Nuclear, hydro and coal follow in order and based on those technologies ability to ramp. CSP is assigned a mid-merit role together with combined cycle gas turbines (CCGTs) and some coal. Pumped storage and open cycle gas turbines (OCGTs) provide backup and peaking generation. The purple line represents demand. Unmet demand is shown as a white gap and energy required to charge pumped storage reservoirs is shown as generation exceeding demand. Excess generation and unmet demand can occur due to ramp rate limitations but such events were negligible in all tested scenarios. The six day period illustrates the following additional aspects of CSP in a system context.

- When there is significant CSP capacity and storage hours are high (with associated scaling down of turbine size or larger solar multiples), CSP successfully demonstrates a moderating function between demand and the rest of the system. The shift in generation towards the end of the day compliments PV most of the time and clearly illustrates response to evening peak.
- Even with a significant increase in CSP capacity, its total contribution is still quite limited. This may be a result of the cost assumptions made for CSP and our assumption that the system will be lower cost if the existing fossil fleet is preserved.
- Days 161 and 162 are poor for both wind and solar. CSP reserves completely deplete and all emergency generators are used. The lack of forecasting is most visible during this period. Had the system known how to optimally dispatch the CSP fleet, there would have been less need for last resort generators and there would have been no unmet demand in this case. The small unmet demand is a manifestation of a manual trial and error cost optimization of the system but is useful at illustrating the issue.
- CSP and CCGT capacities work well together, jointly covering the mid-merit role. This implies that gas is an important fuel in the future where currently we don't have reserves for such a fleet. While out of scope for discussion here, the reliance on gas needs to be put in context [6]. We did observe that a well-balanced renewable scenario relies less on annual gas (and diesel) consumption than other scenarios.

Figure 5 is a plot of the cost probabilities in each scenario. These scenarios are not directly comparable due to variances in demand and in the case of the IRP, the model is severely strained by the costs associated with significant unmet demand due to our assumptions. The most interesting aspect of the WWF scenario costs is the steepness of the CDF. This is due mostly to the lower uncertainty of fuel costs and the cost advantage of renewables in the timeframe allowing for more spare capacity, thus avoiding last resort generation more often.

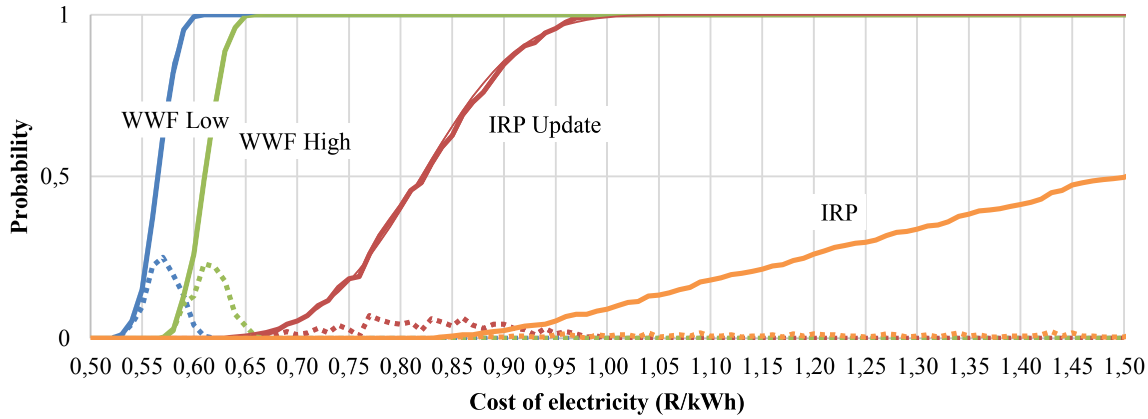

FIGURE 5. Cost probabilities of the scenarios using simple LCOE. The solid lines are cumulative distributions made up of probability distribution data represented by the dotted lines. Cost values use the simple LCOE technique.

TESTING VALUE OF CSP

Due to the complexity of the model, the reasons why the WWF scenario resulted in lower cost than the IRP are not explicitly clear. We needed to study the model by running sensitivity analyses and by breaking down cost and cost margins within the scenario to assist our conclusions. We could not define a lower cost system by substituting nuclear power or by other balances of technology.

Of interest in this paper, the LCOE of CSP is higher than expected in the 15 year period to 2030. At around R1.20/kWh, it is higher in cost than nuclear power, yet when substituted by nuclear in our tests, the system LCOE increased. CSP in this scenario plays a "sacrificial availability" role as described earlier. All CSP plants operate based only on system need with the exception that we were able to allow CSP plants to utilize the storage limit override (SLO) without penalty to the system. To explore this further, a sensitivity analysis of the cost of the CSP fleet and the related cost of the system is possible by varying the minimum demand override (MDO) operating feature of the CSP fleet. MDO in this case is actually a CSP fleet independence parameter ranging from zero to one.

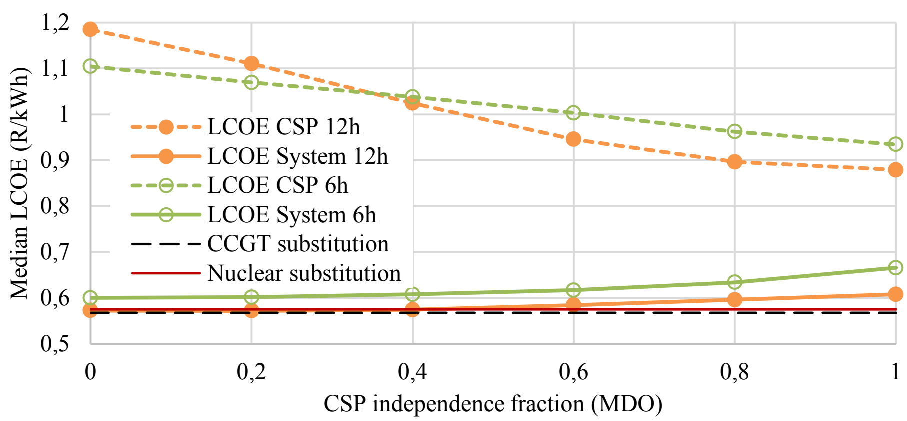

FIGURE 6. LCOE of the CSP fleet and the whole system for CSP plants with 6 or 12 storage hours as a function of system independence (or MDO). An MDO of zero implies that the CSP fleet serves only a system availability function.

Figure 6 plots two variants of the WWF scenario. All other things equal, the 8 GW of CSP capacity is equipped with either 6 or 12 hours of storage on average. The turbine rating is slightly altered in each case for improved usage of the collector field. From a system point of view, the higher storage hour case (12 hours at rating) almost always results in lower cost and is less sensitive to the degree of dependence of the CSP fleet. When the CSP fleet serves the system needs, the system LCOE is about R0.57/kWh. This increases to about R0.61/kWh when the CSP fleet serves its own needs (assuming uniform tariffs). The "sacrificial" nature of the CSP fleet can be observed in the LCOE trend of the CSP fleet (dotted lines). Thus, within the system model as defined, the overall WWF scenario leads to a low cost system as reported in the WWF validation report [6] and within that, CSP appears to plays a surprisingly important role.

One possible argument for an alternative would be substitution of CSP capacity for additional CCGT capacity. For us to do this, we would need to consider the risks associated with a substantial increase of gas supply or increased reliance on diesel to power these units. This risk would translate into a higher cost range for these fuels which in turn could result in a system cost increase and a wider CDF on system cost. We performed a simple test of substituting CSP capacity for CCGT capacity without adjusting the fuel cost range. We also show the same test for additional nuclear capacity substitution. In both instances, 1,000 MW of the substitute were added and a capacity factor weighted equivalent of CSP was removed. As shown in Figure 6, the CCGT substitution showed an insignificant marginal reduction in median system cost while the nuclear substitution showed an insignificant marginal increase in median system cost and an increase in the cost range (not shown), apparently due to an increase in the amount of unserved power.

CONCLUSIONS

The contribution of CSP when playing a pure system role is clear. When substituting for the likely alternatives, only OCGT contributes to a comparable cost system when disregarding the risk associated with increased gas availability. It is also clear that a large gap exists between the CSP fleet operating at its lowest cost vs that of the system. Previously we claimed that the CSP fleet needs to be geographically distributed in order to serve the system. Here we also state that, given the many assumptions, when the CSP fleet dispatches electricity is also of primary importance. Accordingly, remuneration incentives will need to be devised that encourage the placement, sizing and operation of the CSP capacities.

CSP is beginning to show its relevance in South Africa with first plants now coming on line and with some acceleration in the allocation of capacity. During this steep learning period, we encourage greater emphasis on system analysis for decision making which should include critical analysis of ideal tariff structures whereby independent power producers automatically act on behalf of the system. In the 15 year period of this study, CSP appears to be a pivot in a lowest cost, lowest risk system. Due to the long run cost implication of technology, this scenario should be even more beneficial.

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