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Review of the Operational Phase of the South African Concentrated Solar Power Projects

Overall Performance to Date

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Abstract. This paper provides an overview of the six Concentrated Solar Power (CSP) projects in operation in South Africa, comprising 500 MW generation capacity. These projects, in addition to the seventh (100 MW) CSP project currently in construction, were awarded under various bid windows of the Renewable Energy Independent Power Producer's Procurement Programme (REIPPPP) and commenced operations during 2015-2019. Key operational data up to the end of 2023 are presented, as of when the combined cumulative electricity generation by the six CSP projects reached 10.1 TWh. This represents approximately 81% of the sum of the P50 Energy Yield Forecasts (EYFs) in the respective project Power Purchase Agreements (PPAs), and 9.6% of all electricity generated by the REIPPPP projects by the end of 2023, while the CSP projects constitute 8.1% of total installed capacity (6180 MW) as of December 2023. Factors affecting performance are discussed, including meteorology and outages. Consumption of major utilities is also discussed, comparing to expected values or limits.

Keywords: CSP, Operations, REIPPPP, South Africa

1. Background

Electricity in South Africa is supplied predominantly by Eskom, the state-owned power utility, accounting for approximately 87% of electricity generated in 2023 [1]. However, since October 2007 [2] Eskom has failed to consistently meet the demand for electricity due to the declining energy availability factor of its largely (~80%) coal-fired generation fleet, resulting mostly from unplanned outages at its aging coal-fired plants [3]. This has resulted in more frequent rolling blackouts known as "load shedding" [2]. In 2011, the Department of Mineral Resources and Energy (DMRE) promulgated the Integrated Resource Plan for Electricity 2010-2030 (IRP 2010) [4], setting out an investment strategy for development of new electricity generation capacity. The IRP 2010 ("Policy-Adjusted" scenario) aimed to add 42.5 GW of new-build (not yet committed) capacity to the national grid by 2030, including 17.8 GW of wind, solar photovoltaic (PV) and CSP renewable power projects, of which 1 GW was envisaged to be CSP [4]. The REIPPPP – a sub-programme of the greater Independent Power Producers (IPP) Procurement Programme (IPPPP) – was established in 2011 as a competitive procurement programme, coordinated by the IPP Office, to procure independently owned grid-connected Renewable Energy IPPs [5]. The tender process has established competition to reduce tariffs and ensure contribution to economic development [5]. The outcomes of the REIPPPP Bid Windows (BWs) are summarised in Table 1 in terms of contracted capacity at financial close.

Table 1. *IPPs awarded under the REIPPPP per bid window (official as at 31-Mar-2024) [6, 7]*

	BW 1		**BW 2**		**BW 3**		**BW 3.5**		**BW 4**		**BW 5**		**Totals**	
Tech.	Capacity (MW)	Qty	Capacity (MW)	Qty	Capacity (MW)	Qty	Capacity (MW)	Qty	Capacity (MW)	Qty	Capacity (MW)	Qty	**Capacity (MW)**	**Qty**
Wind	649	8	559	7	787	7	–	–	1363	12	784	6	**4142**	**40**
Solar PV	627	18	417	9	435	6	–	–	813	12	375	5	**2667**	**50**
CSP	150	2	50	1	200	2	200	2	–	–	–	–	**600**	**7**
Landfill gas	–	–	–	–	13	1	–	–	–	–	–	–	**13**	**1**
Biomass	–	–	–	–	–	1	–	–	25	1	–	–	**25**	**2**
Small hydro	–	–	14	2	–	–	–	–	5	1	–	–	**19**	**3**
Total	**1426**	**28**	**1040**	**19**	**1435**	**17**	**200**	**2**	**2206**	**26**	**1159**	**11**	**7466**	**103**
Notes:	BW6: 6 PV projects (1000 MW) preparing for financial close. BW7: List of BW7 bids received published by IPPO in Aug-24, including 8526 MW Solar PV and 1692 MW onshore wind.													

In the updated IRP 2019 [8], CSP was excluded from further development beyond the 600 MW already awarded under the REIPPPP and has not featured in subsequent REIPPPP bid windows. CSP was omitted on a least-cost basis, considering cost reductions of CSP since the IRP 2010 were less than other renewable generation technologies, including wind and solar PV [8]. The worsening energy crisis in recent years has prompted the IRP to shift focus to solving the short-term electricity supply deficit [9]. This has seen the establishment of other sub-programs following the IPP model, including the Risk Mitigation IPPPP (RMIPPPP) and others. However, in the long term the IRP plans to replace most of Eskom's coal fleet by 2050 [8]. In the draft IRP 2023 [10], various pathways for further development post-2030 ("Horizon Two") were presented, including the "Renewable Energy" pathway that envisages 34.5 GW of CSP development from 2031-2050 [10]. However, critics have suggested the scenario is unrealistic [11] given the size of development equates to approximately four times the current global capacity of CSP projects operating and under construction. Furthermore, the other proposed scenarios in the IRP 2023 Horizon Two make no provision for CSP [10]. Thus, the future of CSP in South Africa remains uncertain. Despite this, South Africa's excellent solar resource [12], the requirement for security of supply [10], and international commitments to decarbonise suggest that further CSP development could still play a role in the transformation of the country's energy mix. The Direct Normal Irradiation (DNI) map of South Africa is shown in Figure 1, indicating the seven REIPPPP CSP projects, located in the Northern Cape province, where for large areas the average annual DNI exceeds 3 MWh/m^2/year.

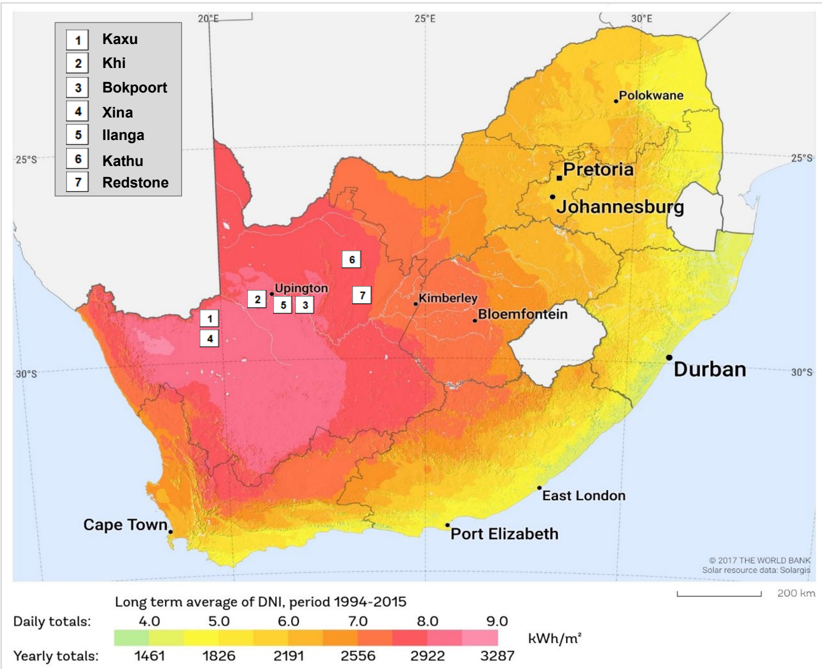


Figure 1. *Direct Normal Irradiation solar resource map of South Africa – adapted from [12]*

2. Performance of the South African CSP projects

2.1 Existing CSP projects in South Africa

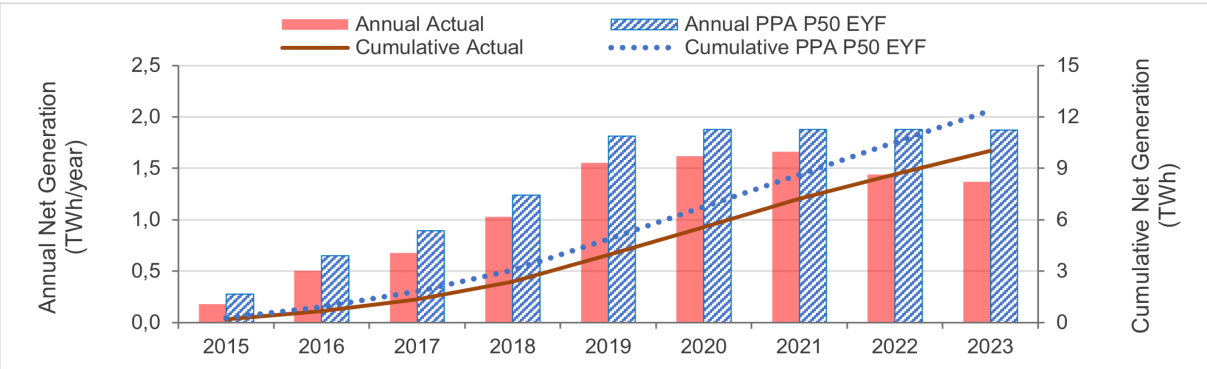
An overview of the CSP projects in South Africa is provided in Table 2, showing some of the distinct technological differences / similarities at a high level, as well as important project dates.

Table 2. *General overview and specifications of the (REIPPPP) CSP projects in South Africa*

Project	Kaxu	Khi	Bokpoort	Xina	Ilanga	Kathu	Redstone
REIPPPP Bid Window	1	1	2	3	3	3.5	3.5
Capacity (MW)	100	50	50	100	100	100	100
Storage	MS indirect (3hrs)	Direct steam (2hrs)	MS indirect (9hrs)	MS indirect (5.5hrs)	MS indirect (5hrs)	MS indirect (4.5hrs)	MS direct (12hrs)
CSP Technology	PT	CR	PT	PT	PT	PT	CR
Power Block	STG	STG	STG	STG	STG	STG	STG
Condenser	A-frame ACC	Natural Draft Tower ACC	Water Cooled	A-frame ACC	A-frame ACC	A-frame ACC	A-frame ACC
COD	6 Feb 2015	5 Feb 2016	19 Mar 2016	1 Aug 2017	30 Nov 2018	31 Jan 2019	Pending
Construction (mths)	26	38	32	28	37	32	Pending
Time of day tariff	No	No	No	Yes	Yes	Yes	Yes
Notes:	All info. originates from project documentation or first-hand experience of the authors. ACC = Air-Cooled Condenser; COD = Commercial Operation Date; CR = Central Receiver; MS = Molten Salt; PT = Parabolic Trough; STG = Steam Turbine Generator; Construction duration = Notice-to-Proceed (NTP) to COD.						

2.2 Electricity generation

The combined net electricity generated by the CSP projects since start of operation of the first project in 2015 is presented in both annual and cumulative terms in Figure 2. Net electricity refers to the total electricity exported to the grid at the point of connection minus electricity imported from the grid. The PPA P50 EYF is the "expected" generation recorded in each of the project PPAs with Eskom. By the end of 2023, the six CSP projects accounted for 9.6 % of the total electricity supplied by all REIPPPP projects [9]. The combined net generation by the CSP projects at the end of 2023 was 10.1 TWh, which is approximately 81 % of the combined projection of the P50 EYFs – namely, 12.4 TWh. During 2020-2023 when all six CSP projects were operational for the full year (in the operations phase post-COD, not referring to outages), the combined net generation of all the projects ranged from 1.37-1.66 TWh/year.

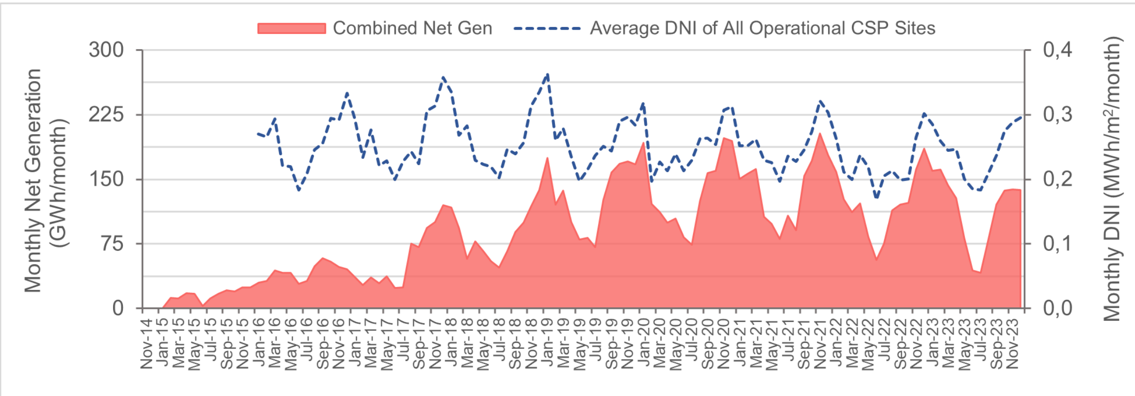


Note: In the respective PPAs, the EYFs were generally expressed in annual terms (year 1, 2, …) starting from Scheduled COD (SCOD), and therefore do not align with calendar years (1 Jan – 31 Dec). For the comparison to EYFs in this section, some approximations were made to determine the total EYF "expected generation" for each project per calendar year. Two of the projects had monthly EYFs, where month 1 was stipulated in the PPA to be the first full month post-SCOD – these EYF values were used as they were, without approximations. For the other four projects, monthly values were approximated by dividing the annual values by 12 (standardised weightings not available). In each case, month 1 was the first full month post-SCOD. Because the EYFs are only used in annual or long-term cumulative terms in this section, the error introduced by these approximations is small. Furthermore, the P50 EYF is by definition a long-term avg. projection and therefore the comparison with EYF should be regarded as high-level and for the purpose of this section is to show the distinct shortfall of the CSP projects against the respective EYFs as the standardised "baselines."

Figure 2. *Combined net electricity generation by the six CSP projects up to 31 Dec 2023*

The initial ramp up of annual generation from 2015-2019 (0.18-1.56 TWh/year) was due to the six CSP projects coming online during this period. Since 2019, the combined generation of the CSP projects has remained relatively stable year-on-year given that no new CSP projects have been added. However, there has been a decline in the combined generation in the past two years (2022-2023) of 11-15% compared to the average generation in 2019-2021. Contributing factors include poorer meteorological conditions, performance related issues, scheduled outages, and / or in some cases extended downtimes due to repairs / maintenance on major equipment.

The monthly net generation is presented in Figure 3 against the average DNI across the six CSP projects. From 2020-2023, when all six CSP projects were operational for the full year (post-COD), the combined monthly generation by the projects ranged from 41.7 (Jul-2023) to 203 GWh/month (Nov-2021). The significant regular fluctuation in electricity generation demonstrates the seasonal nature of CSP, subject to the seasonal variation in meteorology, where higher DNI in summer correlates to greater electricity generation, and vice versa in winter. This also explains the decline in electricity generation in recent years due partly to a decline in DNI and increasing frequency of high wind speeds. Furthermore, most of the CSP projects' major scheduled outages are during 2023-2024, while some minor scheduled outages were conducted in 2022, which has further reduced annual generation in recent years. One project experienced extended downtime during 2023, reducing the combined generation of the CSP projects by approximately 150 GWh (assuming similar generation as in 2022).



Note: The monthly average DNI refers to the average of all available monthly DNI data from the projects for each respective month. E.g. for a month where only four projects were in operation for the full month and therefore DNI data was only available for four projects for that month, then the average monthly DNI is the total DNI of the four projects for that month divided by 4.

Figure 3. *Combined monthly net electricity generation and average DNI across the six CSP projects*

A significant portion of electricity generated by the CSP projects is generated during the summer months (Dec-Feb, stretching into Nov and Mar). This is evident in Figure 4, which shows the monthly distribution of electricity generated (left) and DNI (centre) considering only full operation years from 2020-2023. During this period, the average generation during November to March (approx. 42% of the calendar year) ranged from 740-851 GWh, representing 50-54% of annual generation. The least electricity was generated around winter (May-Sep, approx. 42% of the calendar year), ranging from 368-543 GWh and accounting for 27-34% of total annual generation during 2020-2023.

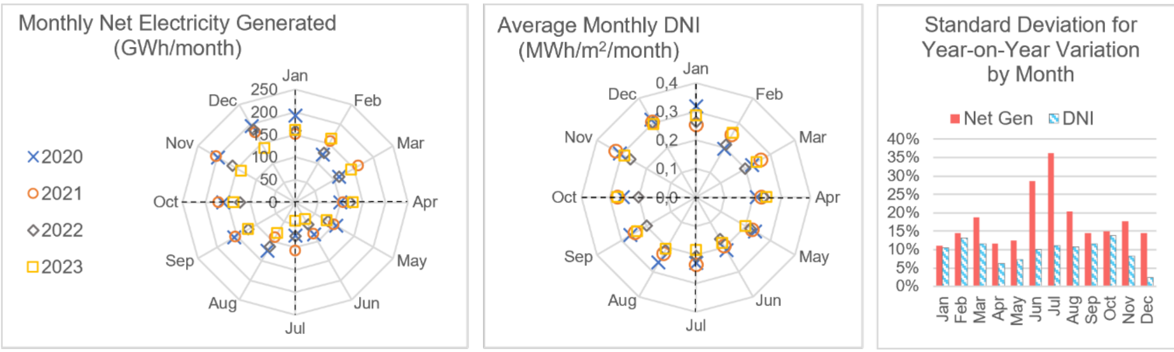


Figure 4. *Variation of combined net electricity gen. and DNI on the six CSP projects for 2020-2023*

Reduced generation in winter is primarily due to lower DNI, meaning reduced overall solar energy available and less excess solar energy for thermal energy storage that would allow the plant to mitigate against cloudy or hazy conditions while operating or during start-up. Generation in winter is further reduced in years with scheduled outages because projects generally target winter for outages to reduce overall generation losses. The standard deviation data in Figure 4 (right) shows that the year-on-year fluctuation of electricity generated (std. dev. 11-36%) is more significant than for DNI (std. dev. 2-14%), demonstrating that electricity generation is not proportional to DNI and is subject to factors such as availability of excess solar energy for thermal energy storage, wind speeds, outages, and equipment availability.

2.3 Meteorological conditions

Solar resource (DNI) has predominantly been higher for each of the sites than anticipated in the respective P50 Typical Meteorological Year (TMY) DNI determined at financial close. Figure 5 shows the on-site measured DNI for all full years of operation with available data. Overall, the annual DNI recorded on any of the sites ranged from 2.42 (project A in 2022) to 3.29 MWh/m^2/year (project C in 2019). In recent years DNI has been lower for all sites, which could be a cyclical variation, but it remains to be seen whether DNI will recover to similar levels observed during 2016-2020.

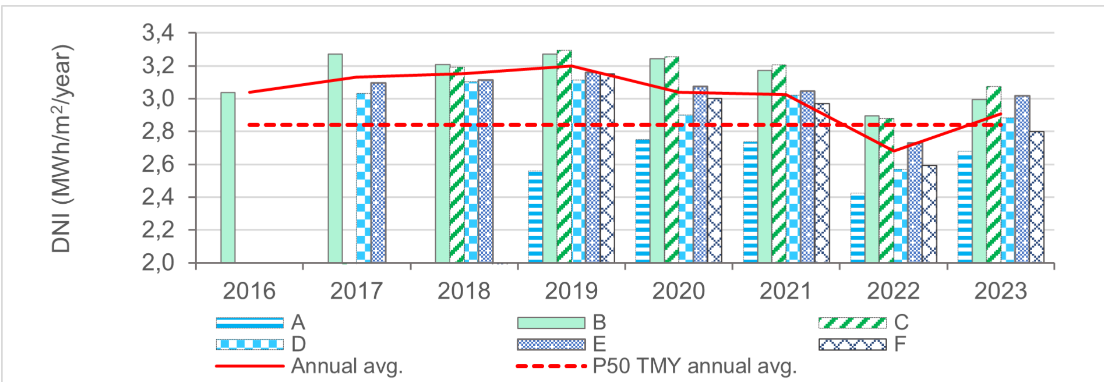


Figure 5. *Annual DNI for the six CSP projects for all full years of operation (anonymous A-F)*

The average annual DNI for each of the sites ranged from 2.65-3.15 MWh/m^2/year, while the P50 TMY DNI for the different sites varied from 2.74-3.04 MWh/m^2/year. Figure 6 shows the comparison of measured DNI to P50 TMY DNI for each of the sites, including only full years of available data. In the available data, the average annual DNI for each site has differed by -3.5% to +8.7% relative to the respective TMY DNI. On average, the DNI across all the sites has been 4.5% greater than the TMY DNI (based on the annual average for each site, determined for all full years of available data).

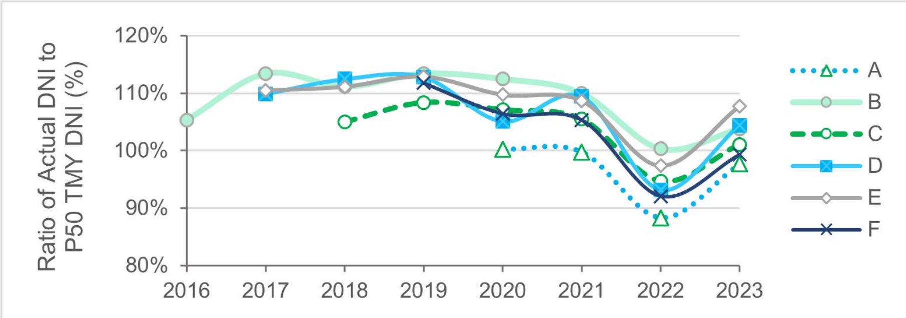
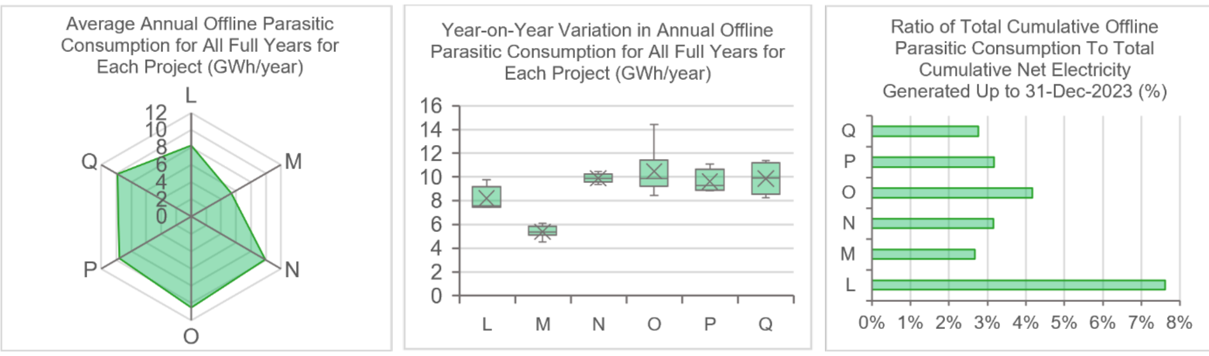


Figure 6. *Annual DNI compared to the respective P50 TMY DNI (anonymous A-F)*

On several of the CSP projects, more frequent high wind speeds have occurred than originally anticipated in TMY wind data. One project obtained updated TMY wind data showing a 7.0 % increase in the annual average wind speed compared to the original TMY. Generally, high wind speeds have resulted in significant generation losses. Regular in-operation wind-related generation losses have been primarily due to defocusing of the solar field as heliostats or parabolic trough collectors are placed in stow position. This occurs when wind speeds exceed the thresholds in the plant control system, to protect the solar field equipment from wind damage. On the other hand, generation losses due to wind have also been caused by isolated instances of extreme wind events where solar field equipment sustained significant damages. These damages often take extended periods to repair and have at times been delayed by insurance claims processes (e.g. root cause analyses).

2.4 Consumption of primary utilities

Offline parasitic consumption is the electricity consumed from the grid when the plant is offline and not producing electricity for self-consumption. The overall average annual offline parasitic consumption for all full years of operation (post-COD) for each of the projects has varied from 5.4 (Project M) to 10.5 GWh/year (Project O), as shown in Figure 7 (left). However, in isolated instances projects have consumed below 5 GWh/year and above 14 GWh/year, as shown in Figure 7 (centre, box & whisker). For most of the projects, the ratio of total cumulative offline parasitic consumption to net electricity generated by the project up to end of 2023 ranged from 2.7-4.2%, while for one project it was much higher at 7.6%, as shown in Figure 7 (right).

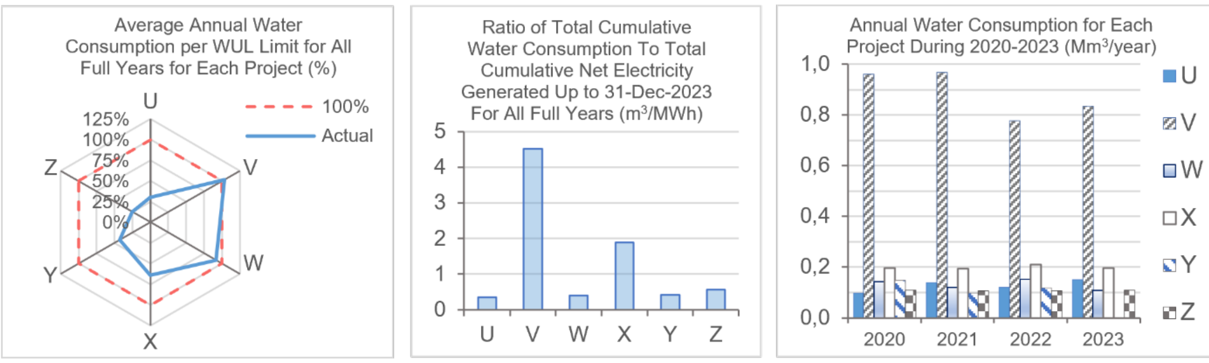


Note: For project "P", no offline parasitics data were available for 2018 and 2023 at the time of writing this paper. The data from these years were therefore excluded when determining the averages and cumulative values presented in this section of the paper. For the ratio of offline parasitic consumption to net electricity gen. to date, both the numerator and denominator for this ratio exclude data from 2018 and 2023 for project P. For project "N", offline parasitics data were provided in annual terms running from 1 Feb - 31 Jan. These data were used approximately as the annual values for the calendar year containing most of the data. For instance, data for 1 Feb 2020 - 31 Jan 2021 was assigned to 2020.

Figure 7. *Annual offline parasitic consumption (anonymous L-Q)*

For each of the projects, offline parasitic consumption has generally remained stable year-on-year, as shown in Figure 7 (centre). Unusually high offline parasitic consumption can occur in years with major scheduled outages, due to little / no electricity generation by the plant to self-consume during the outage. Similarly, consumption has been higher in winter due to reduced solar resource, resulting in a greater proportion of offline periods compared to other seasons. In cumulative terms, the CSP projects have to date consumed from 74-137% of the “warranted” consumption according to the respective plant performance models, with two projects exceeding 100%. This excludes one project for which performance model data for several years were unavailable to the authors. One project saw a notable reduction in online and offline parasitic consumption from 2022 when it introduced an auxiliary solar PV facility to service the CSP plant. Some of the other CSP projects are considering similar solar PV developments.

Raw water (from municipal supply or natural water source such as a river) is consumed for purposes such as cooling, cleaning solar field equipment, steam cycle working fluid make-up, and use in staff facilities. Figure 8 (left) presents the average annual water consumption by each of the projects relative to the Water Use Licence (WUL) limits for all full years of operation. Most projects have operated within the WUL limits, except one project (V) which has exceeded the WUL limit by 4% to date, considering only full years of operation. The WUL allowable limits vary significantly across the projects from 1397-17900 $m^3/year/MW_{name\ plate}$ (avg. up to 31 Dec 2023 for variable WUL limits) subject to various factors such as the type of cooling used and water availability in the area.



Note: For project “Y”, raw water consumption data were unavailable for 2018 and 2023 at the time of writing this paper, so these years were excluded from the analysis. E.g. for the ratio of cumulative water consumption to cumulative net gen. to date, the data from 2018 and 2023 were excluded from both the numerator and denominator. For the same ratio, the first calendar year of operations (COD - 31 Dec) was excluded for each of the projects because water consumption data for the first few months of operations were unavailable for some of the projects. For project “W”, water consumption data were provided in annual terms running from 1 Feb - 31 Jan. These data were used as the (approx.) annual values for the respective calendar years containing most of the data. For instance, annual data for 1 Feb 2020 - 31 Jan 2021 was assigned to 2020.

Figure 8. *Raw water consumption (anonymous U-Z)*

When comparing water consumption to the electricity generated by the projects – as in Figure 8 (centre) – it is clear that two projects (V and X) have consumed significantly more water per unit net electricity generated – on average 1.90 and 4.53 m^3/MWh compared to 0.35-0.56 m^3/MWh by the other four projects. The total water consumption for project V is also significantly higher in simple volumetric terms – as shown in Figure 8 (right) – having consumed 0.89 Mm^3/year on average during 2020-2023, compared to 0.11-0.20 Mm^3/year by the other five projects. For each of the projects, water consumption has generally remained stable year-on-year. One project had high water consumption during the first few years of operation but has reduced annual consumption to approximately 36% of the amount originally consumed in the first full calendar year. Water consumption has generally also been slightly higher in summer than winter, due primarily to higher demand for steam cycle make-up and cooling water resulting from higher DNI and therefore more electricity generation.

3. Conclusion

By the end of 2023, six of the seven REIPPPP CSP projects in South Africa have been in commercial operation for 5-9 years. The seventh was still in construction and set to start operation in the second half of 2024, as of when the REIPPPP CSP projects would reach a total capacity of 600 MW and offer South Africa in excess of 2 TWh/year of net electricity. The first few years of operations has seen the CSP projects contribute 9.6% of the total electricity generated by all the REIPPPP projects up to the end of 2023, thereby contributing to the ongoing national effort of meeting electricity demand and decarbonizing the South African energy mix. Generally, the REIPPPP CSP projects have generated less electricity to date than expected in the PPA P50 EYFs. Performance has been affected by various factors on each of the projects – including adverse weather conditions, equipment issues, and learning curves of the operators. Consequently, the various operators have had to adapt their operational strategies and in some cases modify or replace plant equipment. Consumption of major utilities (offline parasitic power and raw water) has predominantly been within the licensed or warranted limits, while some projects have exceeded these limits to date. Certain technological differences have affected consumption of utilities and might affect design preferences in future projects. Furthermore, the capabilities of the operators, local businesses supporting the projects, as well as supply chains, have matured significantly since construction started on the first REIPPPP CSP projects.

This review has considered the first few years of operations of the first six REIPPPP CSP projects, with some performance trends already evident. The long-term performance of the projects remains to be seen, subject to various ongoing efforts to improve performance by each of the operators and project companies.

Data availability statement

Performance data used to obtain the results in this paper are subject to strict confidentiality agreements with each of the respective projects and thus are not available for public sharing.

Underlying and related material

This paper has no underlying and related material.

Author contributions

J. van Zyl: conceptualization, data curation, formal analysis, methodology, visualization, writing – original draft and editing. P. Perumal: conceptualization, data curation, writing – review. A. Cuellar: conceptualization, data curation, supervision, writing – review.

Competing interests

The authors declare that they have no competing interests.

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References

[1] Department of Statistics South Africa, “Electricity generated and available for distribution (prelim.) – Dec 2023,” Dep. of Stats. SA, Pretoria, South Africa, Rep. P4141, Jan. 2024.
[2] K. Walsh, R. Theron, A. Seedat, C. Reeders, “Estimating the economic cost of load shedding in South Africa,” Nova Economics, Stellenbosch, South Africa, Dec. 2020.

[3] W. Pierce, M. Le Roux, “Statistics of utility-scale power generation in South Africa – 2022,” CSIR Energy Centre, South Africa, Feb. 2023.
[4] Department of Mineral Resources and Energy, “Integrated resource plan for electricity 2010-2030”, DMRE, Pretoria, South Africa, Final Rep., Mar. 2011.
[5] A. Eberhard, R. Naude, “The South African renewable energy IPP procurement programme,” UCT Graduate School of Business, Cape Town, South Africa, 2017.
[6] IPP Office, private communication, Aug. 2024.
[7] IPP Office, “IPPP programme – an overview as at 31 March 2024,” IPP Office, Centurion, South Africa, 2024.
[8] Department of Mineral Resources and Energy, “Integrated resource plan (IRP2019),” DMRE, Pretoria, South Africa, Oct. 2019.
[9] IPP Office, “IPPP programme – an overview as at 31 December 2023,” IPP Office, Centurion, South Africa, 2024.
[10] Department of Mineral Resources and Energy, “Publication for comments: integrated resource plan, 2023”, DMRE, Pretoria, South Africa, Jan. 2024.
[11] Meridian Economics, “Review of the IRP 2023,” Meridian Economics, Cape Town, South Africa, Mar. 2024.
[12] SolarGIS. “Solar resource maps of South Africa.” SolarGIS.com. https://solargis.com/resources/free-maps-and-gis-data?locality=south-africa. (accessed Apr. 2024).