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Water and CSP – A Preliminary Methodology for Strategic Water Demand Assessment

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Abstract. CSP is highly dependent on water resources. Water resources have been shown to be both less abundant and more variable in high DNI areas. The water consumption of CSP varies according to design considerations and spatiotemporally varying conditions. Water-related risks threaten to further exacerbate the costs of CSP generation. Similarly, water demand from CSP poses a potential risk to already stressed water resources. Adequate planning of CSP fleet deployment is thus necessary to mitigate these risks. Such planning must include detailed assessments of both variable water resource availability, and variable water demand from CSP facilities. This paper presents a preliminary methodology for strategic water demand assessment from CSP plants

INTRODUCTION

There have been many studies to determine the amount of potential CSP capacity in a region or country. Understandably, these studies look at the solar resource (DNI) as a primary criterion, accompanied by other land-suitability criteria, summarized in Table 1. From Table 1, it is clear that very little consideration is given to the availability of water for the demands from CSP plants. Certain reports mention the scarcity of water as a potentially limiting factor [1,2]. However, they then simply proceed to state that dry cooling will address this issue. Although the demands from dry-cooled CSP plants are around 90% less than wet-cooled plants [3], water is still a prerequisite for its successful operation.

It therefore follows that, when determining the CSP potential of any region, not only must the proximity of a potential CSP site to water be considered, but attention must be given to the ability of regional water sources to supply the demand from CSP plants at these sites [4]. Furthermore, when the consumption rate of CSP plants is mentioned in the above studies, crude approximations of different CSP and cooling technology combinations are used. These take the form of over-simplified consumption factors, such as 3.27 m^3/MWh [5,6]. While [5] does briefly mention the need for more detailed consideration of the limits placed by water availability on CSP potential, no study has done this quantitatively.

Hence, this paper aims to present a structured methodological framework, for the case of South Africa. However, it is argued that the framework is reproducible in any region where CSP is considered viable. The framework can then be used to assess potential water demand from CSP and identify constraints placed on potential sites due to water availability.

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TABLE 1. Summary of CSP suitability criteria from other studies

Criteria	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**5**	**14**	**15**	**16**	**17**	**18**	**6**	**19**
Min DNI ($MWh/m^2/y$)	2	2	1.8	2.2	1.7	1.8	1.8	2.6	1.5	2	1.5	2	1.8	1.8	NA
Max Slope (%)	2.1	1-4	3	2	3	0-3	2	1	1-5	4	2[g]	2.1	3	2.1	2
Excluded areas, buffer*(km)															
Wetlands	NA	0.5	NA	0	0[a]	NA	NA	NA	NA[d]	0	NA	0	NA	0	0
Lakes	NA	0.5	NA	0	0[a]	NA	0	0	NA	0	NA	0	NA	0	0
Rivers	NA	0.5	NA	0.5	0[a]	NA	0.5	0	NA	0	NA	0	NA	0	0
Sandy soil	NA	0.5	NA	10	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Forests	NA	1	NA	0	0	NA	0	NA	NA	NA	NA	NA	NA	0	0
Protected areas	NA	1	NA	0	0[b]	NA	0	0[c]	NA	0[e]	0	0[e]	NA	0	NA
Agriculture	NA	2	NA	0	0[b]	NA	NA	NA	NA	NA	35%[h]	NA	NA	0	0
Roads	NA	2.5	NA	0.05	NA	NA	0.5	NA	NA	NA	NA	NA	NA	NA	NA
Railways	NA	NA	NA	NA	NA	NA	0.5	NA	NA	NA	NA	NA	NA	NA	NA
Mines	NA	NA	NA	3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Populated areas	NA	0	NA	0	0	NA	0	0	NA	NA	NA	0	NA	6-8	0
High Wind Areas**	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	NA	NA
Min area (km^2)	NA	NA	NA	NA	NA	NA	NA	2	NA	NA	4	NA	NA	NA	NA
Maxi distance to (km)															
Grid	NA	NA	NA	NA	NA	NA	NA	20	20-100	NA[f]	NA	30[i]	40	50[i]	NA[J]
Roads/Rail	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	40	20[i]	NA[J]
Dams	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	9[i]	NA[J]
Rivers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA[J]

* An area beyond the explicit reach of the unsuitable area, also considered unsuitable, i.e. 0km means only the area itself, 0.5km means the area itself with an extended perimeter of 0.5km around it.
** Areas identified to pose potential risks to CSP structures.
[a] The use of buffers is mentioned but no detail on their extent is given.
[b] The study considered three different scenarios: one excluding, one including protected areas, and one including agricultural areas.
[c] The study used vegetation maps categorized as “critically endangered”, “endangered”, “vulnerable” and “least threatened”, excluding all categories but “least threatened”.
[d] The study limited all areas remaining after applying the other suitability criteria to only 1% of the identified area, in order to allow for reduced availability due to other exclusion considerations.
[e] “Environmentally sensitive lands” and Aboriginal Heritage sites are excluded.
[f] While the benefit of closer proximity to transmission infrastructure is discussed, it is not used as a limiting factor.
[g] Slopes up to 7% are considered along with restrictions on the orientation of the slope (North or South), but only <2% is considered explicitly suitable.
[h] Percentage of land cover type considered for CSP development. Similar percentages are applied to other land cover types.
[i] The study used a weighted approach to identify more and less suitable areas according to stakeholder inputs; thus, areas closer to the grid are considered more suitable, an those further are less.
[J] The study modelled the costs associated with building the required infrastructure according to the distance from the infrastructure.

METHODOLOGY

The approach used to assess spatiotemporally varying water demands from CSP consists of the following fundamental steps:

1. Determine suitable areas for CSP based on solar resource and land suitability criteria.
2. Evaluate monthly generation potential based on CSP technology selection and design, and impact of ambient conditions on cycle efficiency.
3. Evaluate monthly consumption factor for each identified area based on cooling and CSP technology selection and design, and impact of ambient conditions.

Hereafter, CSP fleet deployment scenarios can be evaluated in order to determine the impact of water resource availability on CSP plants, and vice-versa. Such an assessment is part of on-going research and will be published separately.

CSP AREA SUITABILITY ASSESSMENT

Table 1 provides a detailed list of the various suitability criteria used in previous CSP potential assessments. These criteria are then used to create exclusion and inclusion layers in Geographical Information Systems (GIS). After all the layers have been generated and the required actions have been performed (merging, dissolving, cutting etc. of layers), a final result is produced showing the suitable areas. The particular details of the applied method can be found elsewhere [20]. The results from this detailed, updated CSP capacity analysis of South Africa was used in this paper. It employed the suitability criteria listed in Table 2.

TABLE 2. CSP suitability criteria in this study

Criteria	Selected value (buffer in km)	Information Source
Minimum DNI	2400 kWh/m^2/y	[21]
Maximum Slope	4 %	[22]
Minimum area	3km^2	NA
Excluded areas (buffer in brackets)		
Formal protected and conservation areas[a]	Yes (0)	[23] EGIS updated
Sensitive bird and biodiversity areas[a]	Yes (0)	[24]
Indigenous forests[b]	Yes (0)	[25]
Wetlands[b]	Yes (0)	[26]
Dams[b]	Yes (0)	[27]
Rivers[b]	Yes (0)	[27]
All Cultivated Lands (Except low-yield and subsistence) [b]	Yes (0)	[25]
All Forest Plantations[b]	Yes (0)	[25]
All built-up areas[b]	Yes (0)	[25]
All Mining activities[b]	Yes (0)	[25]
Square-kilometer array[a]	Yes (37)	[personal communication]

[a] – Indicated as "Miscellaneous" on map.
[b] – Indicated as "Landcover" on map.

For the purposes of this study, distance to infrastructure, such as roads and transmission networks, were not considered. The rationale is that since the focus is on water resources and its consumption, the maximum possible ceiling thereof must be evaluated. This requires consideration of all possible suitable land, based on natural resources. A minimum DNI of 2400 kWh/m^2/y, avoiding the unnecessary consideration of lower-yield areas. Further, a detailed list of exclusion criteria was used from various sources, to ensure flat, high-DNI areas that coincide with any inherently unsuitable, or ecologically sensitive areas, were not considered. The resulting suitable areas, based on the criteria and rationale above, are shown in Fig. 1. They consist of a grid of 1km x 1km squares that indicate areas that are suitable, and those that are not. Suitable areas have also been graded according to the annual DNI.

MONTHLY GENERATION POTENTIAL

In South Africa, hydrological planning takes place at four levels of detail, based on river basins, from primary to quaternary catchments [28]. These quaternary catchments (QCs) are shown in Fig. 1. To evaluate water demand, and ultimately availability too, it therefore makes sense to do so at the same geographical scale at which other hydrological planning is done within a region or country. Accordingly, the total CSP generation potential of the suitable areas identified above, per QC, can be evaluated.

To do so, a similar approach to that of [29] was used. The approach uses the following definitions, in Equations 1 to 3, to calculate potential monthly generation: solar-to-electric efficiency (η_{SE}), annual net power generation (Q_{El}), annual direct irradiance on aperture area (DNI), land use factor (LUF), aperture area of reflectors (A_{SF}), total land area required (A_{Tot}), and land use efficiency (LUE).

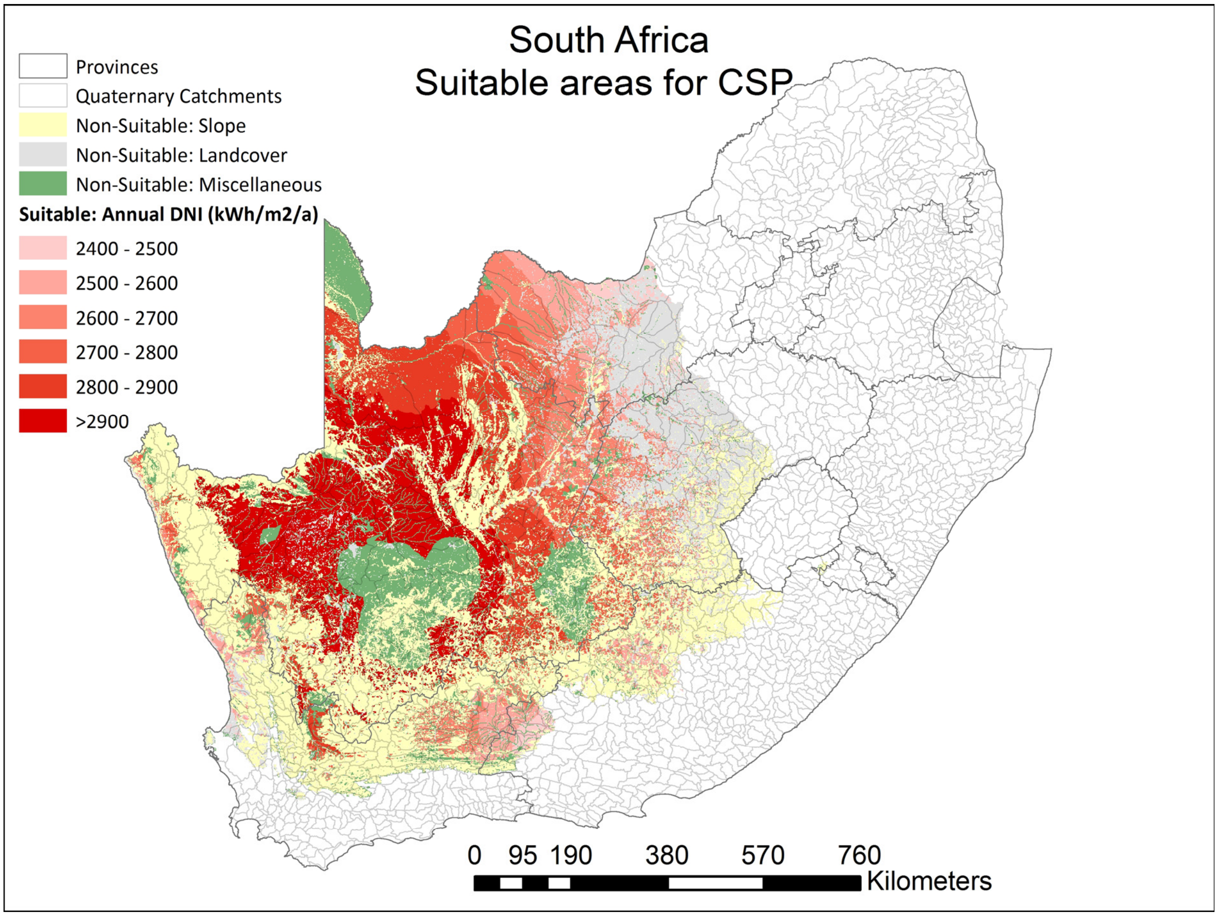

FIGURE 1. CSP suitable areas

$$\eta_{SE} = \frac{Q_{El}}{DNI} \tag{1}$$

$$LUF = \frac{A_{SF}}{A_{Tot}} \tag{2}$$

$$LUE = \eta_{SE} \times LUF \tag{3}$$

Average land use factors for parabolic troughs (PT) and central receiver (CR) systems were calculated from the NREL database on global CSP projects as 25% and 17%, respectively [30]. The η_{SE} is calculated separately for wet-cooled (WC) and dry-cooled (DC) PTs and CRs, based on the simplified method presented in [31], and shown in Equation 4.

$$\eta_{SE} = \eta_{optical} \times \eta_{receiver} \times \eta_{power} \tag{4}$$

Here, $\eta_{optical}$ represents the annual average optical efficiency of the collector area. For PT plants, this value has been shown to be in the order of 59.8%, and for CR plants in the order of 56.3% [32]. The relationship between the energy absorbed by the receiver and that which is transferred as thermal energy to the HTF, is represented by the annual average receiver efficiency, $\eta_{receiver}$. These values are around 85.2% and 83.1% [32], for PT and CR plants, respectively. The power cycle efficiency, η_{power}, is a composite term representing all losses and efficiencies between the absorbed energy in the solar field and the final generation of electricity, in Equation 5.

$$\eta_{power} = \eta_{PAR} \times \eta_{PIP} \times \eta_{STOR} \times \eta_{AV} \times \eta_{B} \times \eta_{ST} \tag{5}$$

In this study, values from various literature sources were used, and are summarized in Table 3. The steam cycle efficiency (η_{ST}) is the component of the power cycle efficiency, which is most dependent on cooling technology and ambient conditions, especially for dry-cooled plants [33–36]. In order to reflect this spatially varying dependence in the modelling, the steam cycle efficiency was quantified according to the Chambadal-Novikov cycle efficiency [37,38]. This method has been shown to be suitable in high-level modelling of CSP operation [39–41].

TABLE 3. Annual Average power cycle efficiency composites

CSP+cooling configuration	Efficiency component	Value (%)	Description and rationale	Information Source
PTWC	Parasitic efficiency (η_{PAR})	89.0	Efficiency resulting from parasitic losses.	42
PTDC	Parasitic efficiency (η_{PAR})	86.0	Lower efficiency resulting from higher parasitic losses due to fans.	42
PTWC/DC	Piping thermal efficiency (η_{PIP})	96.7	Efficiency resulting from thermal losses from the solar field header and HTF piping.	43
PTWC/DC	Storage thermal efficiency (η_{STOR})	99.6	Efficiency resulting from thermal losses from the thermal storage system.	43
PTWC/DC	Power plant availability(η_{AV})	94.0	Efficiency resulting from forced and scheduled outages and dumping.	43
CRWC	Parasitic efficiency (η_{PAR})	92.2	Efficiency resulting from parasitic losses.	44
CRDC	Parasitic efficiency (η_{PAR})	91.5	Lower efficiency resulting from higher parasitic losses due to fans.	44
CRWC/DC	Piping thermal efficiency (η_{PIP})	99.9	Efficiency resulting from thermal losses from the solar field header and Salt piping.	43
CRWC/DC	Storage thermal efficiency (η_{STOR})	99.5	Efficiency resulting from thermal losses from the thermal storage system.	43
CRWC/DC	Power plant availability(η_{AV})	94.0	Efficiency resulting from forced and scheduled outages and dumping.	43
PT/CR WC/DC	Boiler efficiency (η_B)	99.7	Losses in steam generating system	44

The Chambadal-Novikov cycle efficiency takes the form of Equation 6, where T_L is determined by the cooling technology in place and ambient conditions. T_H is the temperature of the steam entering the turbine(s) and depends on the load at which the CSP plant is operating and the CSP technology in place. In this study, T_H is defined as 371^{O}C for PT [45] and 540 ^{O}C for CR [44]. T_L is defined as the dry-bulb temperature plus an effective approach of 25^{O}C for dry-cooled plants, and as the wet-bulb temperature plus an effective approach of 10^{O}C for wet-cooled plants [46]. This value is added to ambient temperatures to reflect heat-exchange effectiveness for the different cooling technologies and is dependent on cooling system design as well as ambient conditions. This value should be approximated more closely, but such a detailed approach is beyond the needs of this study. Steam cycle efficiencies calculated in this way are generally 5-8% lower for PT plants and 2-6% lower for CR plants, than reported cycle efficiencies in [44] and [45], and therefore provides a conservative estimation of power generation for CSP plants. Wet-bulb temperatures are calculated based on available dry-bulb temperatures and relative humidity, according to the formula derived in [47].

$$\eta_{ST} = 1 - \sqrt{\frac{T_L}{T_H}} \qquad (6)$$

The final annual η_{SE} for the four CSP+cooling configurations have the following ranges, depending on ambient conditions: 12.13% to 12.97% for PTWC, 11.36% to 12.53% for PTDC, 15.02% to 15.75% for CRWC and 14.58% to 15.49% for CRDC, respectively. The surprisingly high maximum η_{SE} for CRDC plants are for locations with very low winter temperatures of around 6 ºC. These values correspond well with those in literature [1,43,44,48,49]. It is, however, known that larger installed net capacities result in higher overall η_{SE} [42]. Based on the above equations, the final monthly electrical generation potential (Q_{tot}) for each suitable 1 km x 1 km grid (A_{km2}) can now be calculated according to Equation 7. Hence, A_{km2} equals 1 square kilometre, or 1,000,000 m^2. The total potential per QC can then be calculated. Long-term monthly DNI values were calculated from satellite derived data between 1983 and 2013, as provided by [50] and validated in [51].

$$Q_{tot} = LUE \times DNI \times A_{km2} \quad (7)$$

MONTHLY CONSUMPTION FACTOR

The monthly water consumption factor is calculated for each CSP+cooling configuration and each suitable area 1 km x 1 km grid. This value is critical in highlighting the trade-offs between lower consumption factors and higher cycle efficiencies between WC and DC plants [2]. This consumption factor is calculated based on the system-level generic model (S-GEM) of water use in thermoelectric power plants, by [52]. The formula derived for consumption factors (I_{WC}) (i.e. consumption intensities) of wet tower-cooled plants (recirculating wet cooled), is given in Equation 8.

$$I_{WC} = 3600 \frac{(1-\eta_{TE}-k_{OS})}{\eta_{TE}} \frac{(1-k_{SENS})}{\rho h_{fg}} \left(1+\frac{1}{n_{CC}-1}\right) + I_{PROC} \quad (8)$$

Here, η_{TE} refers to the thermal-to-electric efficiency of the CSP plant, considering heat input at the steam generating system (boiler) and the electrical energy generated. It is calculated as the product of η_{ST} and η_{B}. The value k_{OS} is heat lost to other sinks, which is particularly applicable to combustion-based thermoelectric power plants, since a large amount of heat is dissipated through the flue stack. For this study, however, k_{OS} is calculated as 1 minus the product of η_{PIP} and η_{STOR}, from Table 3. In Equation 8, k_{SENS} is the fraction of heat load rejected through sensible heat transfer and depends on the temperature of the incoming air and the design of the cooling tower. It is calculated according to Equation 9, from [52]:

$$k_{SENS} = -0.000279 T_{DB}^{\ 3} + 0.00109 T_{DB}^{\ 2} - 0.345 T_{DB} + 26.7 \quad (9)$$

h_{fg} is the latent heat of vaporization of water, assumed constant at 2.45 MJ/kg, and ρ is the density of water, taken as constant at 0.9982 kg/L. n_{CC} refers to the number of cycles of concentration used in the cooling tower, to account for water lost through blow-down, assumed to be 5 for this study. I_{PROC} is the sum of consumption factors allocated to other processes, in this case mirror cleaning, steam cycle blow-down, and air-cooled condenser (ACC) tube-bundle cleaning. For mirror cleaning needs by cleaning trucks, a water usage of 1 L/m^2 and 1.2 L/m^2 was used for CR and PT respectively [53]. Multiplying this value by the LUF and the surface area of each suitable area, as well as the amount of cleans per year (assumed to be once a week, i.e. 52 per year), and dividing by the total annual electrical generation, results in consumption factors around 0.18 m^3/MWh. Values for steam cycle make-up are estimated at 0.24 m^3/MWh [54]. Values for ACC tube-bundle cleaning were estimated at around 0.033 m^3/MWh, based on data from ACC cleaning systems manufacturers [55,56]. The total amounts for I_{PROC} are around 0.4 m^3/MWh, which compare well with values reported in [54]. Improvements on the quantification of I_{PROC} are required. Furthermore, as stated in [52], k_{SENS} is an empirically derived formula as implemented by [57], and is based on results from the more complicated, but more accurate, Poppe cooling tower model. In light of this, better approximations of k_{SENS} will contribute to the accuracy of water consumption estimations at thermoelectric plants.

The use of k_{SENS} in this methodology provides an acceptably accurate quantification of the change in water consumption with air temperature and relative humidity. This sensitivity of water consumption by WC plants to ambient conditions is clearly demonstrated in [58]. Results for I_{WC}, for the suitable areas identified in South Africa, with varying T_{DB} data from 6^{O}C to 29^{O}C, were calculated. The results for PTWC plants are between 3.29 and 4.15 m^3/kWh, and between 2.55 and 3.14 m^3/kWh, for CRWC plants. These values agree well with those reported in [59], such as between 2.74 and 4.20 m^3/kWh for PTWC, and between 2.84 and 3.45 for CRWC. Other values reported for PTWC, with varying locations and varying thermal storage capacities, are between 3.1 and 4.1 m^3/kWh, for a cold and a hot site, respectively, both with 6h of TES [60].

RESULTS

The spectrum of results from this spatiotemporal model of CSP water demand and generation potential are summarised in Table 4. There are a total of 288 different possible results-based maps or graphs that can be generated, when considering each of the six results for the four CSP+cooling configurations are per month (6x4x12). Furthermore, there are a total of 314,931 1km x 1km grid cells (i.e. 314,931 km² of suitable land for CSP), for which calculations had to be done to generate these results. This means that each of the cells must have the input data (dry-bulb temperature, relative humidity and DNI) required for these calculations, as shown in Equations 1 to 9, and therefore a further group of 48 maps/results can be generated to show the monthly variance in these.

TABLE 4. Maximum (top), average (middle) and minimum (bottom) results ranges from spatiotemporal model

Configuration	Power efficiency (%)	Turbine efficiency (%)	Net solar to electric efficiency (%)	Generation potential (GWh/km² /month)	Consumption factor (m^3/kWh)	Total consumption (1000 x m^3/month)
	25.46	31.69	12.13	10.63	4.15	42.14
PTWC	24.56	30.57	12.51	7.13	3.69	26.41
	23.81	29.64	12.97	4.17	3.29	14.70
	24.60	31.69	12.53	10.28		4.60
PTDC	23.68	30.50	12.06	8.44	0.4	3.92
	22.31	28.73	11.36	5.84		2.90
	33.67	39.20	15.75	8.92	3.14	26.86
CRWC	32.81	38.20	15.35	5.95	2.83	16.87
	32.10	29.64	15.02	3.46	2.55	9.41
	33.11	38.84	15.49	8.66		3.52
CRDC	32.06	37.62	15.00	7.13	0.4	3.00
	31.17	36.57	14.58	4.96		2.21

Considering this large amount of results, two maps per CSP+cooling configuration are shown. These eight maps show the Summer (January) and Winter (June) generation potentials and consumption factors per configuration. The generation potentials (GWh per month) are shown at the 1km x 1km grid level, while the consumption factors are shown as an average within each QC. All the maps have the same scale for generation potential. Each configuration has the same scale for consumption factor between summer and winter, for comparative purposes.

From Fig.2 A and 2 B, and 2 C and 2 D, one can compare both the change in monthly generation potential and average consumption factor between summer and winter, for PTWC and CRWC configurations, respectively. Not only does the generation potential drop dramatically from summer to winter, across all suitable CSP sites, but likewise, the consumption factor drops from an average of 3.89 to 3.42 m^3/kWh. What also becomes clear is that the consumption factor varies dramatically from site to site. Even though the range in consumption factors for Fig.2 A and 2B is only 0.65 m^3/kWh, this impact translates to a large amount of water over time, when total consumption is considered. For example, a difference in consumption factor of 0.3 m^3/kWh between two locations with a hypothetically similar monthly generation potential of 7 GWh, translates into a difference in total consumption of around 2.1million m^3 for that month.

The maps in Fig.2 E and 2 F, and 2 G and 2 H, show the seasonal differences for PTDC and CRDC. As one might expect, the dry-cooled configurations have substantially lower consumption factors than for wet cooled ones, ranging between 0.4 and 0.5 m^3/kWh for both PT and CR technologies. These spatial variances in consumption factor are, however, only due to the statistical calculation of average per QC, and is higher in QC's with more suitable locations than those with fewer. In practice, the consumption factor for all QCs will be the same since in this methodology, there is no spatially-dependent variables forming part of its calculation at this stage. When comparing generation potential, the average for January is lower, at around 7.64 GWh, compare to 8.12 GWh for PTWC, demonstrating the impact of reduced efficiency from DC systems. Furthermore, the change in generation potential between winter and summer is greater for dry-cooled plants than for wet-cooled ones, when comparing Fig.2 B and 2 F, or 2 D and 2 H.

Finally, if Fig.2 A and 2 C are compared, it is clear that PTWC consumption factors are considerably higher than those for CRWC. This stems from the fact that central receiver systems reach higher temperatures and therefore higher cycle efficiencies, resulting in more efficient use of water in cooling. However, due to the lower LUF of CR systems (17% vs. 25 for PT), there is less generation potential per suitable area than for PT systems.

WAY FORWARD

These results can now be incorporated into further studies on water resource availability and variability at QC scales. This can then be used to determine limits placed by water resource availability on CSP capacities in different areas, for different CSP+cooling configurations. Once verified, this methodology can be used to do high-level estimations of generation potential and water demands (and resulting hydrological impact assessments). Furthermore, it can be updated to incorporate improved water use approaches (cleaning strategies and/or technologies, cooling technologies, CSP plant water management strategies, desalination, and alternative sources, for example), and evaluate the likely impact on water resource balances, as well as the impact of variable water supply on plant operations.

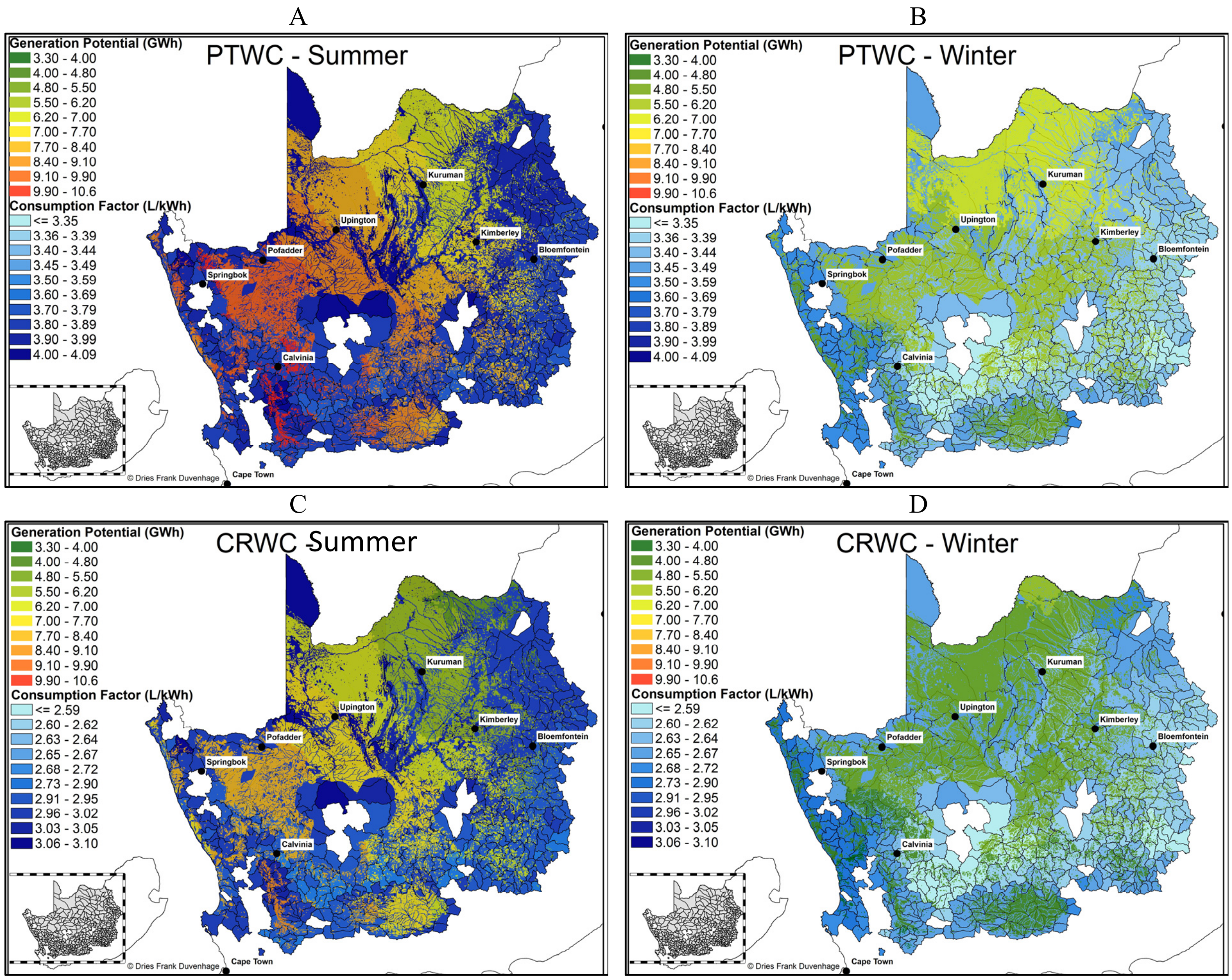

FIGURE 2. Wet-cooled CSP consumption factor and generation potential maps for South Africa

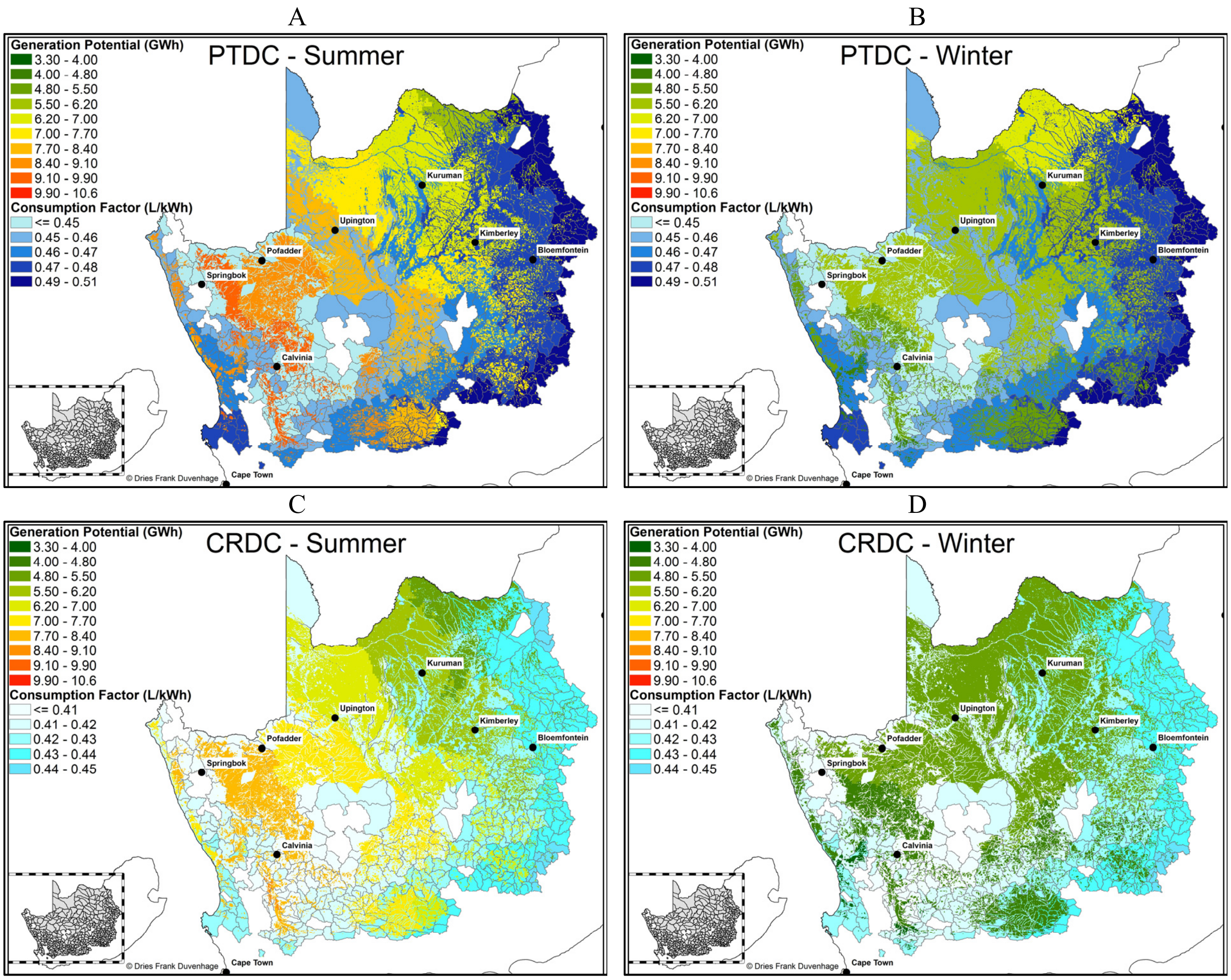

FIGURE 3. Dry-cooled CSP consumption factor and generation potential maps for South Africa

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REFERENCES

1. U.S Department of Energy, *Solar Parabolic Trough* (1997).
2. N. Bracken, J. Macknick, A. Tovar-hastings, P. Komor, M. Gerritsen, and S. Mehta, *Concentrating Solar Power and Water Issues in the U.S. Southwest* (Joint Institute for Strategic Energy Analysis, Golden, Colorado, 2015).
3. U.S. DEPARTMENT OF ENERGY, *Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation. Report to Congress* (2009).
4. D.F. Duvenhage, A.C. Brent, and W.H.L. Stafford, Renew. Energy **132**, 813 (2019).
5. T.P. Fluri, Energy Policy **37**, 5075 (2009).
6. A. Aly, S.S. Jensen, and A.B. Pedersen, Renew. Energy **113**, 159 (2017).

[7] R. Mahtta, P.K. Joshi, and A.K. Jindal, Renew. Energy **71**, 255 (2014).
[8] J.N. Gathu, P.A. Odera, and E.H. Waithaka, Nat. Resour. **08**, 1 (2017).
[9] K. Kaygusuz, Renew. Sustain. Energy Rev. **15**, 808 (2011).
[10] Y. Le Fol and K. Ndhlukula, J. Energy South. Africa **24**, 90 (2013).
[11] K. Ummel, *Concentrating Solar Power in China and India: A Spatial Analysis of Technical Potential and the Cost of Deployment* (2010).
[12] T. V. Ramachandra, R. Jain, and G. Krishnadas, Renew. Sustain. Energy Rev. **15**, 3178 (2011).
[13] A.A. Merrouni, A.B. Mezrhab, and A. Mezrhab, Energy Procedia **49**, 2270 (2013).
[14] E.W. Ramdé, Nat. Resour. **04**, 146 (2013).
[15] J. Clifton and B.J. Boruff, Energy Policy **38**, 5272 (2010).
[16] J. Dominguez Bravo, X. Garcia Casals, and I. Pinedo Pascua, Energy Policy **35**, 4879 (2007).
[17] L. Dawson and P. Schlyter, Energy Policy **47**, 91 (2012).
[18] D. Dahle, D. Elliott, D. Heimiller, M. Mehos, R. Robichaud, M. Schwartz, B. Stafford, and A. Walker, *Assessing the Potential for Renewable Energy Development on DOE Legacy Management Lands. DOE/GO-102008-2435* (NREL, Golden, Colorado, 2008).
[19] H. Broesamle, H. Mannstein, C. Schillings, and F. Trieb, Sol. Energy **70**, 1 (2001).
[20] D.F. Duvenhage, A.C. Brent, W. Stafford, and D. van den Heever, *The Potential of Concentrating Solar Power in South Africa: An Updated Approach and Results* (Working Paper, Department of Industrial Engieneering, Stellenbosch University, 2018).
[21] SolarGIS, (2018).
[22] South African Environmental Observation Network, (n.d.).
[23] P. Bradshaw, *GIS METADATA : DETAILED REPORT. Formal Protected Areas in South Africa* (Port Elizabeth, RSA, 2010).
[24] BirdLife SA, *GIS METADATA : DETAILED REPORT. Important Bird and Biodiveristy Areas.* (Randburg,RSA, 2015).
[25] GEOTERRAIMAGE, *2013 - 2014 South African National Land Land-Cover Dataset. Data USer Report and MetaData* (2015).
[26] J. Nel, *GIS METADATA : DETAILED REPORT. Wetland Freshwater Priority Areas.* (Stellenbosch, RSA, 2011).
[27] A. Bailey and W. Pitman, *Water Resources of South Africa 2012 Study (WR2012) Executive Summary* (HaskoningDHV Ltd, WRC and DWS, Pretoria, 2015).
[28] Department of Water Affairs and Forestry, *National Water Resource Strategy, First Edition, September 2004* (Pretoria,RSA, 2004).
[29] F. Trieb, Conf. Proc. (2009).
[30] NREL, (2018).
[31] P. Gauché, J. Rudman, M. Mabaso, W.A. Landman, T.W. von Backström, and A.C. Brent, Sol. Energy **152**, 106 (2017).
[32] Sargent and Lundy, *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts. NREL/SR-550-34440* (Golden, Colorado, 2003).
[33] A. Ramani, B. Paul, and D. Saparia, Int. Conf. Curr. Trends Technol. 1 (2011).
[34] D.V.. B. Manish Baweja, Int. J. Mod. Eng. Res. **3**, 411 (2013).
[35] N. Nirmalakhandan, V. Gadhamshetty, and A. Mummaneni, 6th Int. Conf. Heat Transf. Fluid Mech. Thermodyn. 1 (2008).
[36] T. Tang, J. Xu, S. Jin, and H. Wei, Energy Power Eng. **5**, 651 (2013).
[37] I.I. NOVIKOV, J. Nucl. Energy **7**, 125 (1958).
[38] F.L. Curzon and B. Ahlborn, Am. J. Phys. **43**, 22 (1975).
[39] L. Heller, (2012).
[40] P. Gauché, S. Pfenninger, A.J. Meyer, T.W. von Backström, and A.C. Brent, in *South. African Sol. Energy Conf.* (2012), pp. 1–11.
[41] P. Gauché, Spatial-Temporal Model to Evaluate the System Potential of Concentrating Solar Power Towers in South Africa, Stellenbosch University, 2016.
[42] L. Qoaider and A. Liqreina, Sol. Energy **122**, 976 (2015).
[43] L. Llc and C. Group, Group **October**, 344 (2003).
[44] G.J. Kolb, *An Evaluation of Possible Next-Generation High-Temperature Molten-Salt Power Towers. SAND2011-9320* (Sandia National Laboratories, Albuquerque, New Mexico, 2011).
[45] C. Turchi, (2010).

[46] J.E. Hoffmann, (2018).
[47] R. Stull, J. Appl. Meteorol. Climatol. **50**, 2267 (2011).
[48] H. Müller-Steinhagen and F. Trieb, Ingenia **1**, 1 (2004).
[49] O. Behar, A. Khellaf, and K. Mohammedi, **23**, 12 (2013).
[50] R. Müller, Richard; Pfeifroth, Uwe; Träger-Chatterjee, Christine; Cremer, Roswitha; Trentmann, Jörg; Hollmann, (2015).
[51] A. Riihelä, T. Carlund, J. Trentmann, R. Müller, and A. V. Lindfors, Remote Sens. **7**, 6663 (2015).
[52] M.J. Rutberg, Modeling Water Use at Thermoelectric Power Plants, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 2012.
[53] ECILIMP Termosolar, (2018).
[54] A. Colmenar-santos, D. Borge-diez, C.P. Molina, and M. Castro-gil, **34**, 565 (2014).
[55] F. Noack, (2015).
[56] N. Bester, (2018).
[57] J.C. Kloppers and D.G. Kröger, Int. J. Heat Mass Transf. **48**, 765 (2005).
[58] S. Taghian Dehaghani and H. Ahmadikia, Appl. Therm. Eng. **125**, 1002 (2017).
[59] J. Macknick, R. Newmark, G. Heath, and K.C. Hallett, Environ. Res. Lett. **7**, (2012).
[60] C. Turchi, M. Wagner, and C. Kutscher, *Water Use in Parabolic Trough Power Plants: Summary Results from WorleyParsons' Analyses* (NREL, Golden, Colorado, 2010).