# Advances in concentrating solar power in the Southern African Development Community

## Energy Insight

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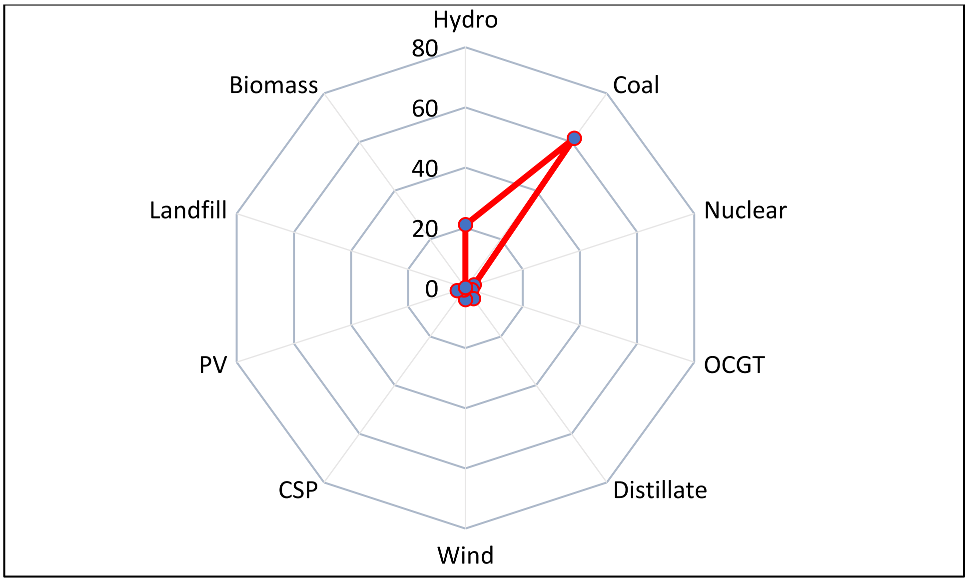
January 2019

## 1. Introduction

Electricity generation from solar radiation is becoming more prominent in the Southern African Development Community region. At present, most of the electricity in this region is produced from coal (Figure 1), and the regional rate of access to modern energy services stands at an average of 42% overall, and 10% amongst rural communities (SADC, 2016). A high proportion of the people living in these rural areas are poor (Mungwe *et al.*, 2016), and the demand for electricity within the Southern African Power Pool (SAPP) is expected to increase from 285.6 terawatt hours (TWh) in 2015 to 1060.6 TWh in 2040 (Ouedraogo, 2017). Consequently, there is a need to augment the capacity of electricity production from renewable energy resources, such as solar radiation, at an affordable cost.

**Figure 1: Technology share (%) of the energy mix in the SADC region**




CSP = concentrating solar power, OCGT = open cycle gas turbine, and PV = photovoltaic. Chart drawn by author using data from SAPP (2017a)

*Solar power has made great advances in Southern Africa in the last decade, predominantly through solar PV*

Solar energy is converted to electricty mainly by using PV and CSP technologies. PV technology directly converts solar radiaton to electricity, and the cost of PV-based electricity is approaching parity with that from fossil fuel-powered power plants (Labordena *et al.*, 2017). Many micro-grid projects based on PV farms have lately been developed but only a limited number of them possess large-scale energy storage systems, because of the high cost of batteries (Cen *et al.*, 2018). Within the SADC region, solar power has made great advances in the last decade. Many PV power plants have been commissioned in different countries in the region (Jadhav *et al.*, 2017). By mid-2018, the total installed capacity of PV technology in the SADC region was 2502.8 MW, while that of CSP was only 600 MW (SADC, 2018), which demonstrates the dominance of PV over CSP technology. About 96% of this PV capacity was contributed by South Africa.

*Whereas PV is limited by the intermittency of solar resource, CSP can harness solar energy and store it for electricity generation during nights and cloudy days*

CSP technology generates electricity by utilising thermal energy from solar radiation (Dowling *et al.*, 2017). In a CSP system, solar radiation is concentrated onto a receiver, where it heats a working fluid to a high temperature (Figure 2). The hot fluid can be utilised to drive a gas turbine or Rankine cycle (a steam engine cycle) for electricity generation. It is possible to integrate CSP with a thermal energy storarge (TES) component. TES is the short-term storage of heat for later use to generate electricity during nights and cloudy days. Heat can be stored by using three different techniques: sensible heat, latent heat, and thermochemical heat storage (Dutta, 2017). In sensible heat storage, the gain or loss of heat causes a temperature change in the storage material without phase change (such as solid to liquid, or liquid to gas). The storage medium changes phases from one state of matter to another when it gains or loses heat, in the process of latent heat storage. In thermochemical energy storage, heat is added to the storage material to stimulate a forward chemical reaction. Thermochemical energy storage is at an early stage of development (Fernandes *et al.*, 2012). Molten salt is the most widely exploited thermal storage material in commercial applications of CSP technology because of its attractive thermal properties, and it can be used in sensible and latent heat storage processes.

**Figure 2: Schematic representation of CSP integrated with a generalised engine**

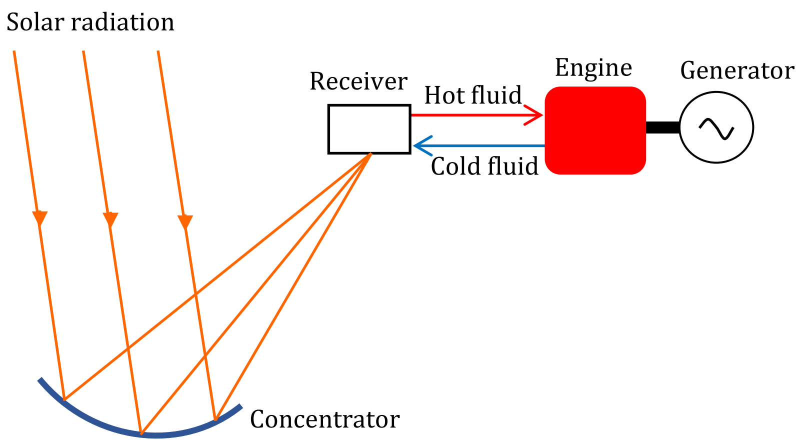



Diagram drawn by author

*One factor affecting CSP costs is whether a gas turbine or steam engine cycle is used*

A comparison of the levelized cost of electricity (LCOE) of CSP with TES and PV with lithium-ion (Li-ion) batteries shows that CSP with storage is more cost-effective than PV with batteries for electricity storage over the same number of hours for peak and intermediate power coverage, based on present and 2020-projected costs (Feldman *et al.*, 2016). In addition, the 2020-projected costs of both technologies are similar when they are compared based on a net system cost and CSP with thermal storage and PV with Li-ion batteries, but PV with batteries exhibits a higher degree of uncertainty in future prices (Mehos *et al.*, 2016). In spite of these advantages, CSP technology is struggling to get established in the SADC electricity generation mix, but this may change in the future.

One factor affecting the cost-effectiveness of CSP is whether a steam engine cycle or gas turbine is used. Generally, the thermal efficiency of a gas turbine is greater than that of a steam engine (Petrakopoulou *et al.*, 2017), and the LCOE of power plants tends to diminish with increasing efficiency. At present, four main types of CSP technology are commonly deployed worldwide: linear Fresnel reflector, parabolic trough concentrator (PTC), parabolic dish concentrator, and solar tower (ST) (Wagner *et al.*, 2018). Of these four CSP technologies, PTC is the most prevalent technology on a global scale.

## 1.1 Objectives

The objective of this paper is to analyse the progress in the development of CSP in the SADC region. Specifically, the paper: a) assesses the potential of direct normal irradiation (DNI) resource, and b) maps out CSP plants and investigates the economic competitiveness of CSP in the region.

## 1.2 Significance

The Energy and Economic Growth programme (EEG) is investigating sustainable ways of using renewable energy resources, such as solar energy, to augment the generation capacity of energy systems in the SADC and other countries. In the SADC region, CSP is a promising technology option with potential to completely or partially displace fossil-fuelled power plants, and to enhance energy security. This paper analyses the state of the

CSP technology in the region by taking into consideration the economic dimension of development. Such knowledge is critical for promoting the uptake of the technology in the region.

## 2. Methodology

A desktop method was used to determine the potential of solar resource, and to establish the status of CSP plants and their economic sustainability in the region. The potential of DNI resource was evaluated by using a chart reported by Prăvălie *et al.* (2019). Data on CSP power plants in the SADC region were obtained from the website of the National Renewable Energy Laboratory (NREL, 2018). Other data were obtained from various sources (academic and non-academic publications), and the data were analysed using Excel software.

## 3. Key findings

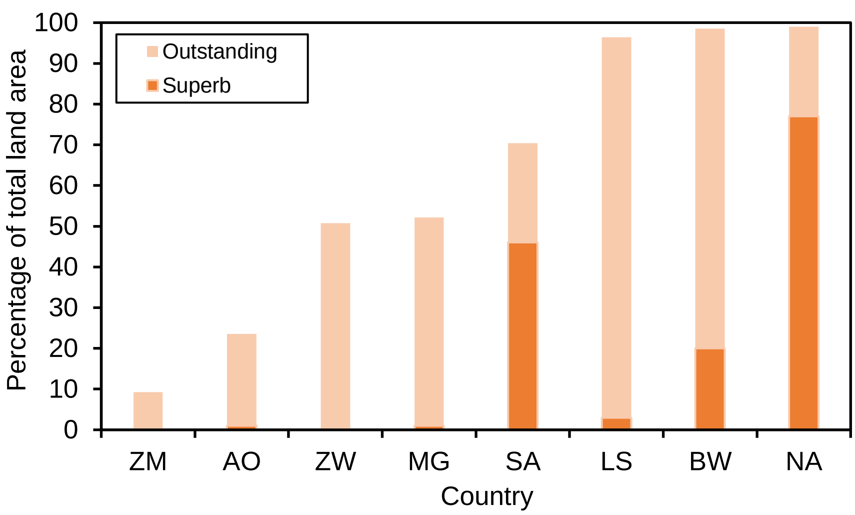
### 3.1 Solar resource potential

*Southern Africa has outstanding DMI resources*

Global (total) solar radiation that reaches the earth's surface is made up of direct and diffuse components (Zhou *et al.*, 2018). CSP technology harnesses only the direct component of solar radiation to generate electricity (Enjavi-Arsanjania *et al.*, 2015), and the level of DNI is a good indicator of the suitability of a site for deploying different types of CSP technology.

There is a high potential of DNI resource for the development of CSP in Southern Africa. Namibia (NA) exhibits the highest percentage (77%) of land area with an annual sum of superb DNI resource (>2533.7 kWh/m$^2$), as shown in Figure 3. This country is one of six hotspots in the world (Prăvălie *et al.*, 2019). Other countries with superb levels of DNI in the region are Angola, Botswana, Lesotho, Madagascar, and South Africa. All the countries shown in Figure 3 have percentages of land area with DNI greater than 2149.9 kWh/m$^2$. According to Spelling (2013), CSP technology is economically feasible when the annual sum of DNI is greater than or equal to 2000 kWh/m$^2$. Consequently, most of the locations in these countries meet the annual DNI threshold for the exploitation of CSP technology.

**Figure 3: Percentage of land area of each country with outstanding (2149.9 - 2533.7 kWh/m$^2$) and superb (>2533.7 kWh/m$^2$) levels of DNI**




AO = Angola (1,252,357 km$^2$), BW = Botswana (581,775 km$^2$), LS = Lesotho (30,213 km$^2$), MG = Madagascar (596 077 km$^2$), NA = Namibia (826,564 km$^2$), SA = South Africa (1,223,912 km$^2$), ZM = Zambia (756,486 km$^2$), and ZW = Zimbabwe (391,408 km$^2$). The land area of each country is given in brackets. Chart drawn by author using data from Prăvălie *et al.* (2019)

## 3.2 Concentrating solar power projects in Southern Africa

*Only South Africa has installed CSP plants, but other SADC nations plan to add CSP capacity*

Table 1 depicts that CSP plants in the SADC region are currently found only in South Africa, with a total capacity of 600 MW, which was procured by the national utility (Eskom) through the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). This programme was initiated as an implementation stage for the White Paper on Renewable Energy development in South Africa, which came into effect in 2003 (South Africa Department of Minerals and Energy (DME), 2003). The White Paper is the most comprehensive policy document concerning the vision of the South African government on the development of renewable energy in the country. Botswana and Namibia have planned capacities of 200 and 120 MW, respectively, with no CSP plant at present.

**Table 1: CSP projects in SADC region. Source of data: NREL (2018)**

| Country | Name of power plant | Capacity (MW) | Thermal storage (hours) | Engine cycle | Technology type | Status | Start year |
|---|---|---|---|---|---|---|---|
| South Africa | KaXu Solar One | 100 | 2.5 | Rankine | PTC | Operational | 2015 |
| South Africa | Bokpoort | 50 | 9.3 | Rankine | PTC | Operational | 2016 |
| South Africa | Ilanga I | 100 | 4.5 | Rankine | PTC | UC* | - |
| South Africa | Kathu Solar Park | 100 | 4.5 | Rankine | PTC | Operational | 2018 |
| South Africa | Khi Solar One | 50 | 2 | Rankine | ST | Operational | 2016 |
| South Africa | Redstone Solar Thermal Power Plant | 100 | 12 | Rankine | ST | UD** | - |
| South Africa | Xina Solar One | 100 | 5 | Rankine | PTC | UC* | - |

*UC = under construction. **UD = under development.

*All the current CSP power plants in SADC have thermal energy storage*

CSP power plants can be designed with or without thermal energy storage. All the current CSP power plants in the SADC region have thermal storage, which enables them to produce electricity even during hours of low or no sunshine. There is also a possibility of scheduling such CSP plants to produce electricity during peak-demand hours (Wagner *et al.*, 2018). Thus, the development of CSP in the region is aligned to the policy of producing dispatchable electricity which enhances the reliability of the supply.

*Existing CSP projects predominantly use a Rankine steam engine cycle. However, our research shows that a combined gas cycle turbine is more efficient. This technology has proven effective elsewhere in the world.*

All the CSP plants in South Africa utilise the Rankine steam engine cycle (see Table 1). However, this engine cycle exhibits a high loss of low-grade heat at the condenser (Stein and Buck, 2017). Petrakopoulou *et al.* (2017) observe that solar thermal power plants based on the Rankine steam engine cycle achieve thermal efficiencies of up to 42%. However, the integration of CSP plants with gas turbines yields a significantly higher total efficiency (Amelio *et al.*, 2014). For instance, Al-Sulaiman and Atif (2015) report values of thermal efficiency of up to 52% for ST-driven gas turbines that utilise supercritical carbon dioxide as a working fluid. Values of thermal efficiency of 50–58% have been reported for combined cycle gas turbines for producing electricity (Poullikkas, 2005; Madhlopa, 2018). Integration of CSP technology with gas cycles is therefore more attractive than the Rankine cycle.

**Potential job creation through CSP**

Job creation is one of the most common social indicators of energy sustainability. In South Africa, the development of renewable energy has taken place through a bidding process in the REIPPPP. It has been found that 59,679 and 45,682 job years per unit of installed capacity (job years/GW) are created during the construction phase of CSP and coal power plants, respectively (Meridian Economics, 2018). Most jobs in the CSP sub-sector are created during the manufacturing and installation phases. CSP and coal power plants provide about 251 and 274 jobs/TWh, respectively, in the operational phase (Meridian Economics, 2018). For coal, this value of job intensity (jobs/TWh) takes into consideration coal and coal mining operational jobs. Rural communities also benefit from the general development that takes place around them, which also helps uplift their standard of living.

### 3.3 Economic performance

The economic performance of CSP technology is influenced by the selected operating mode, regional subsidies, solar availability, and market prices for electricity and electricity services (Dowling *et al.*, 2017). In this vein, the LCOE is one of the most widely accepted metrics for comparing the economic performance of different energy technologies (Hernández-Moro and Martínez-Duart, 2012; Silinga and Gauché, 2014). LCOE is the ratio of the sum of costs incurred to the sum of all the energy produced during the lifetime of the project.

*CSP is not yet economically competitive, but this may change in the coming years*

As shown in Section 3.2, the only place where CSP power plants are in the operational, construction, and development stages in the SADC region at present is in South Africa. In this country, the current value of LCOE is 0.120 USD/kWh but this is predicted to drop down to 0.029 USD/kWh in 2050 (Craig *et al.*, 2017). Most of the electricity is produced from coal (about 85%), and the average price of coal-based bulk electricity is about 0.06 USD/kWh (Amsterdam and Thopil, 2017). Average tariffs in other SAPP member countries are also less than 0.120 USD/kWh, except for Namibia (NamPower utility), which has a high average value of about 0.17 USD/kWh (SAPP, 2017a). For Namibia, Le Fol and Ndhlukula (2013) found LCOE of 0.174 to 0.225 USD/kWh for CSP when the cost of infrastructure was taken into consideration. The implication of these results is that CSP-based electricity is not competitive on the market at present but this may change in future.

Member states of SADC (excluding Mauritius) established SAPP in 1995. It aims to promote regional cooperation in the production and trade of power. Within SAPP, market clearing is applied in sales of electricity. This is a process in which the supply of goods or services traded is equated to the demand, in order to have no excess supply or demand: a market-clearing condition is achieved when supply equals demand (Pereira-Neto and Saavedra, 2014) and the price at this point is said to be a market-clearing price. Figure 4 shows the variation of the market clearing price within SAPP in 2017 for peak and off-peak demand of electricity. As expected, prices during peak-demand times are higher than the corresponding prices during off-peak times. The highest observed peak-demand price was 0.102 USD/kWh in 2017, which is still lower than the LCOE of CSP-based electricity (0.120 and 0.174-0.225 USD/kWh for South Africa and Namibia, respectively). It should be noted that the aim of investing in a project is to make profit. Consequently, electricity is sold at a price that is higher than LCOE. In all these previous studies, CSP was integrated with the Rankine engine cycle. The foregoing observations show that CSP technology integrated with the Rankine engine cycle is currently not competitive on the electricity market at national and regional levels. For CSP integrated with gas turbines, a range of LCOE values of 0.06–0.40 USD/kWh has been reported in studies done outside the SADC region (Kribus *et al.*, 1998; Selwynraj *et al.*, 2015). These results show that CSP-driven gas turbine engines have greater potential to be competitive on the SADC electricity market. However, information is scarce on the economic performance of gas turbine engines propelled by CSP in this region.

**Figure 4: Variation of the market clearing price within SAPP in 2017 for peak and off-peak demand of electricity**

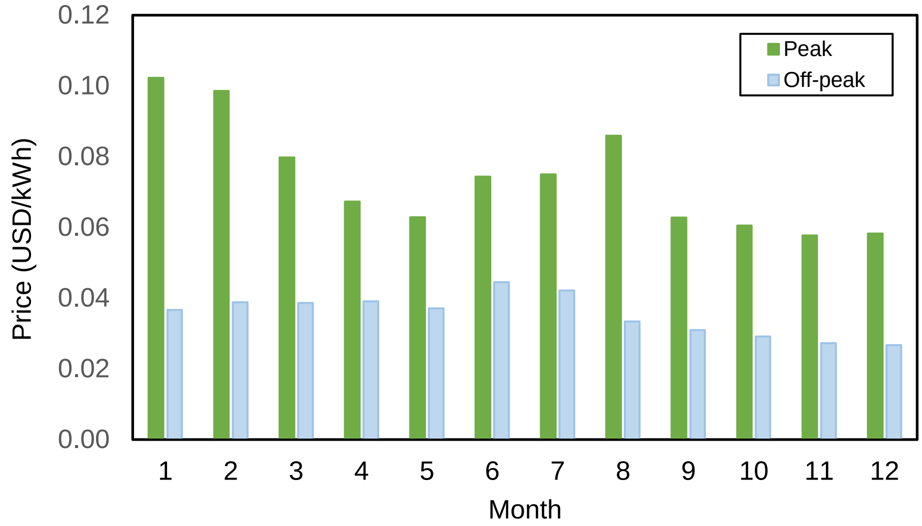



Chart drawn by author using data from SAPP (2017b)

## 4. Policy implications

*Suitable mechanisms for financing CSP projects can assist in reducing the costs of CSP-based electricity*

It has been shown in Section 3.3 that CSP plants are less competitive on the market within the SADC region. Therefore, it is necessary to develop policies that assist in reducing the cost of CSP-based electricity at national and regional levels. It should also be noted that local funding resources are scarce in developing countries (Weir, 2018). Thus, there is a need for governments to review or create mechanisms for financing CSP projects in the region. For example, the government of South Africa formulated a policy on a carbon tax (South Africa Department of National Treasury (DNT), 2013). In this policy, part of the revenue from the carbon tax will be used to offer financial support for the development of new and renewable energy technologies. The policy stipulates that the funding will mostly comprise concessional loans for small-scale renewable energy projects (capacity of 1–5 MW), which excludes some of stakeholders who could benefit from this incentive (Msimanga and Sebitosi, 2014). Consequently, it would be useful to carry out a review of the policy, in order to reduce the cost of CSP-based electricity.

*A demonstration CSP plant integrated with a gas turbine in one of the SADC countries could assist in the adoption of this emerging technology*

CSP plants are currently based on the Rankine cycle engine, which is less efficient than advanced engine cycles, such as the gas turbine. Studies done outside the SADC region show that the integration of CSP with gas turbines is approaching commercial scale. In this regard, there is a need to formulate policies on research and development that promote the integration of CSP with gas turbine engines. The development of a demonstration CSP plant integrated with a gas turbine in one of the SADC countries could assist in accelerating the adoption of this emerging technology.

*The future of CSP in the SADC region is promising*

The international community has initiated various interventions, including the transformation of policy and regulatory instruments, to promote sustainable energy production and consumption. Some of these global initiatives include the United Nations Framework Convention on Climate Change, the United Nations Sustainable Energy for All Initiative, and the Sustainable Development Goals (SDGs). For instance, SDG 7 states: ‘Ensure access to affordable, reliable, sustainable and modern energy for all’. In line with these efforts, many member states of the SADC are making policy shifts towards sustainable energy sources. South Africa formulated the

White Paper on Renewable Energy, which came into effect in 2003 (DME, 2003). At a regional level, SADC has formulated the Renewable Energy and Energy Efficiency Strategy & Action Plan, which provides a roadmap for the development of renewable energy (including CSP) in the region over the time horizon of 2016–2030 (SADC, 2016). All these and other relevant policies aim to promote sustainable energy production and consumption at national and regional scales. Consequently, the future of CSP in the region is very promising.

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