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The need for the use of Nuclear Power generation in the SADC region

Johannes Thomas Austin

A research report to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering with the focus on Nuclear Technology Leadership.

Cape Town, October 2020

DECLARATION

I, **Johannes Thomas AUSTIN**, hereby declare that this report is my own work except as indicated in the references and acknowledgements. It is submitted to the University of the Witwatersrand, Johannesburg in fulfilment of the requirements for the degree of Master of Science in Engineering with the focus on Nuclear Technology Leadership. It has not been submitted before for any degree or examination or to any other university or institute of learning.

Johann Austin Signature:----------

ABSTRACT

This report explores the possibility of having to make use of nuclear power for ensuring adequate electricity supply in the Southern African Development Community (SADC) countries while minimizing the unique risks associated with different technologies and in order to support an integrated regional electricity grid. The need is considered against the balance between the projected or potential energy demand in the future, based on regional populations, natural resource distributions and current infrastructure. The future energy projection is derived from assessing the energy use in other OECD countries as well as developing economies.

Available power generation resources, in each country, are considered and maximized according to availability, practical implications and managing risk by optimizing the use of the different resources and technologies.

The possibility of an integrated HV network is considered which will require power generation and consumption in a distributed fashion to ensure grid stability and allow for regional risks to be minimised. Due to the vast distances under consideration, the optimum distance between power plants is considered and optimum ways to stabilize the network is proposed. Factors like location, development opportunities and geotechnical considerations are considered.

The report concludes with determining what the expected nuclear capacity base will eventually have to be and where such plant would ideally be situated.

ACKNOWLEDGEMENT

I would like to acknowledge the assistance and support which I received from Professors Ian Moss and Craig Law, who served as my supervisors at different stages of compiling this work.

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INTRODUCTION

1.1. Background and Motivation

The Southern African Development Community (SADC) was formed on 17 August 1992 in Windhoek, Namibia, where the SADC Treaty was adopted. The member states are currently: Angola, Botswana, Comoros, Democratic Republic of the Congo (DRC), Eswatini (Swaziland), Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Tanzania, Zambia and Zimbabwe. According to the official SADC website: *"The main objectives of SADC are to achieve development, peace and security, and economic growth, to alleviate poverty, enhance the standard and quality of life of the peoples of Southern Africa, and support the socially disadvantaged through regional integration, built on democratic principles and equitable and sustainable development"* (Southern African Development Community, 2017).

Economies are built around the use of a number of resources, one of which is energy. Depending on the type of economy in a particular country or region, the amount of energy that is required could vary. However, no economy can develop extensively without access to a substantial amount of energy and as economies mature and beneficiation becomes more diversified, the average consumption of energy being consumed by each individual country becomes more predictable and closer to the world norm. Currently the average amount of energy being consumed per capita in the SADC countries is significantly less than what is consumed in developed countries and regions (Central Intelligence Agency, n.d.). Therefore, in order for the SADC community to realize their aspirations, as described in the objectives of the organization, the amount of power being generated in the region has to be increased and integrated in a manner that will maximize the benefits and minimize the risks for all member countries.

There is currently no clear strategy for the optimum use of the resources in the region in order to maximize the effective generation of electrical power, while protecting the environment. As a result there is no integrated development plan for the construction of additional infrastructure and for the parallel expansion of the electricity grid in order to achieve a long term industrialization goal.

Energy is made available into the economy by either:

- provision of primary energy, for the purposes of heating, or
- in the form of fuel, normally for the purposes of transport, or
- for the purposes of producing electricity, which can be used for many different purposes and can be transported and distributed as needed.

This report focusses specifically on the relationship between resources and the provision of an adequate amount of electrical energy in the SADC region, in a sustainable manner, with specific focus on how best to mitigate the limitations and risks that each of the different primary fuel sources and technologies introduce. The ultimate objective is to explore if nuclear energy will be required in the pursuit of reducing the risk exposure to the different resources.

The population numbers and distributions in the developed world and in the developing economies can be used as a reference (Leung & Meisen, 2005). By considering the amount of electricity that a developed or developing economy consumes, it is clear that, with the exception of South Africa, the SADC countries do not have adequate electrical generation and distribution capacity in order to drive the same level of development as those developed countries and regions (Leung & Meisen, 2005). This comparison can furthermore be utilized in order to better understand what amount of power generation will ultimately be required in order to support a more developed overall economy in the region.

The need for the use of Nuclear Power in SADC

The countries in the SADC region have historically made use of mostly coal and hydro power to generate electricity. However, coal is one of the biggest drivers of global warming and other environmental challenges. Hydro power, on the other hand, has a limited amount of further potential in the region, although there is still a lot of potential capacity in the Congo River (Stearns, 2019). Other resources are however available in the region, especially with regard to natural gas and renewable sources.

Although there are a vast amount of resources available, it will be beneficial for the region to provide integrated access to these resources through the use of an integrated grid. Such a grid could allow the risks associated with particular technologies and resources to be mitigated further and could contribute towards the optimum risk balance across the region. In order for that objective to be realized, such an integrated grid will have to be considered carefully and incorporated into a long term developmental plan, supported by all the different role players. For this reason, the SADC countries that are not geographically connected to the main continent, i.e. the island nations, of Comoros, Madagascar, Mauritius and Seychelles have not been considered and included in this report.

The different technologies that could potentially make use of the different resources in the region all have unique limitations and characteristics and are therefore prone to different risks. Each of these limitations and characteristics, as well as the subsequent risks, has to be considered when determining an integrated plan. Some of the technologies are place bound to a greater or lesser extent, while others have environmental impacts that cannot be ignored. None of the countries would want to rely on only one form of technology because that makes such an economy vulnerable to the different risks associated with that particular type of resource and technology. If one or more of the risks materialize, such an economy could be in a very difficult situation. A recent example of this situation is the large scale shortage of power suffered by Zimbabwe as a result of a severe draught and the fact that the country is very reliant on hydro power (Reuters News Agency, n.d.). When energy resources become constrained, countries tend to focus on their own needs first. An example of this is South Africa

reducing electricity exports to Zimbabwe when South Africa started suffering power shortages (Creamer Media, n.d.). Countries also have better control of pricing structures and the cost of primary energy within their own borders. Each country would therefore want to be self-sufficient, as far as possible, and not rely too extensively on their neighbours for the supply of electricity. It is assumed that by integrating the resources, allowing for different countries to have access to the resources in other countries, the inherent risks associated with each of the technologies can be reduced.

Having access to a number of different options for power generation reduces the risk of inadequate capacity and optimizes the potential for making use of the cheapest configuration. In order to provide for the ability for the different countries to have access to and make use of power generation capacity in the other countries and to optimize the use of the different power generating resources, an integrated grid will have to be established. Such an integrated grid needs to extend across the region in order to integrate all the different sources of power and to effectively distribute the power. Constructing large grids have uniquely challenging risks and considerations to overcome. Running large power lines over vast distances results in instability and could be unreliable if not stabilized appropriately (Eremia, et al., n.d.) (Liu, 2015) (Migliavacca, n.d.). However, there are also large areas of the sub-continent that has no access to power and therefore no real prospect of economic development (Southern African Development Community, 2012). The electricity grid therefore has to be expanded into these remote and under developed regions (Southern African Development Community, 2012).

The locations where nuclear power plants can be deployed are not dependent on the location where the raw uranium is being mined. The technology can furthermore be deployed in an extensive range of different environments. Renewables are mostly similar in this regard, but is limited in the percentage penetration before an integrated grid becomes unstable and cumbersome to manage (Boyle, et al., 2018). By establishing the total amount of resources that can be used in a particular country for generating energy, a balance can be derived to consider how much nuclear power will be required to balance the total projected capacity against the distribution of resources and demand.

In order to do this the particular proposed distribution of load and power generation centers have to be established as a function of location to natural resources, cities and technologies. The capacity and geographic relation between such centers have to be considered in order to identify the limitations of constructing an integrated grid. From these models, the optimum nuclear capacity and location can then be established and a conceptual architecture and capacity of the future grid determined.

1.2. Problem Statement

Considering the fact that most of the countries in the region are highly dependent on specific resources for the generation of their electricity and the extent to which power generation is going to have to be expanded, it is important to understand and consider the primary threats to the reliable and consistent generation of electricity in the region. Each resource and technology is subject to a set of external factors, like drought, climate change, market prices and environmental impact, which each carry a certain amount of uncertainty. The resource mix needs to consider these risks and best mitigate such by incorporating a variety of technologies and resources.

Ultimately, the broad aim of the study is to explore the necessity of having to make use of nuclear power in the SADC region. This is done by exploring the validity of the hypothesis that once the other resources have been utilized to a reasonable availability and risk exposure for each country, a deficit in generation capacity and grid stabilization remains. This can only be mitigated through the use of nuclear power plants.

The research question is: Would electricity generation through the use of nuclear power be required in order to ensure a suitable energy mix and stable integrated grid for the SADC region?

It is hypothesized that the construction and strategic placement of nuclear power plants in the SADC region will contribute towards both the bulk amount of power as well as the stability of the integrated power system, thereby reducing the energy risk by diversifying the power sources.

The specific objectives are:

a. To determine if nuclear power will be required to provide adequate diversification of technologies in order to mitigate the potential shortfall in capacity once resource limitations and the risk associated with each technology has been considered and mitigated;

b. To determine if nuclear power can assist with the stabilization of an integrated regional grid by providing base load generation capacity where no other fuels are generally available.

The premise that was considered is that the unique characteristics of nuclear power will be able to complement the other sources of primary energy that can be used for electricity generation in the region.

LITERATURE REVIEW

Although a lot of documentation was identified and utilized, this was not typically in the form of research papers. It would appear that the topic of electrification of Southern Africa is a sparsely researched topic. A lot of the statistical data was obtained from the Central Intelligence Agency of The United States of America website (Central Intelligence Agency, n.d.), and data published on the Southern Africa Development Agency website (Southern African Development Community, 2017).

A search was furthermore performed to identify any other author that has previously made use of the methodology proposed for this study to derive a similar projection. No such study has been identified by this author.

2.1. Energy Demand of Developed World vs Developing World

The study uses the per capita energy demand in the developed world, as well as some developing nations, as a reference for determining future demand profiles. This data was published by a number of international organizations, one of which is The World Bank (The World Bank, n.d.).

Figure 1 (International Energy Agency, n.d.) shows the large imbalance between energy consumed in the Developed World, the Developing World and the 3rd World. From this map the disproportional access to energy between the different regions is evident, with North America, Europe, Northern Asia and Australasia having the lion's share. The lack of access to power in Africa and by implication SADC, with the exception of South Africa, is clearly visible. From the map it can be seen that South Africa has, in comparison with the rest of the world, a substantial electricity generation capacity. When compared to the other BRICS countries, South Africa has one of the largest installed capacity per capita.

It is furthermore interesting to note that, although the European Union is economically successful, the per capita consumption of energy is about half that of the United States of America, Canada, the Scandinavian countries, Saudi Arabia and Australia. It is therefore possible to have a first world economy with the currently installed electricity generation capacity in place in South Africa.

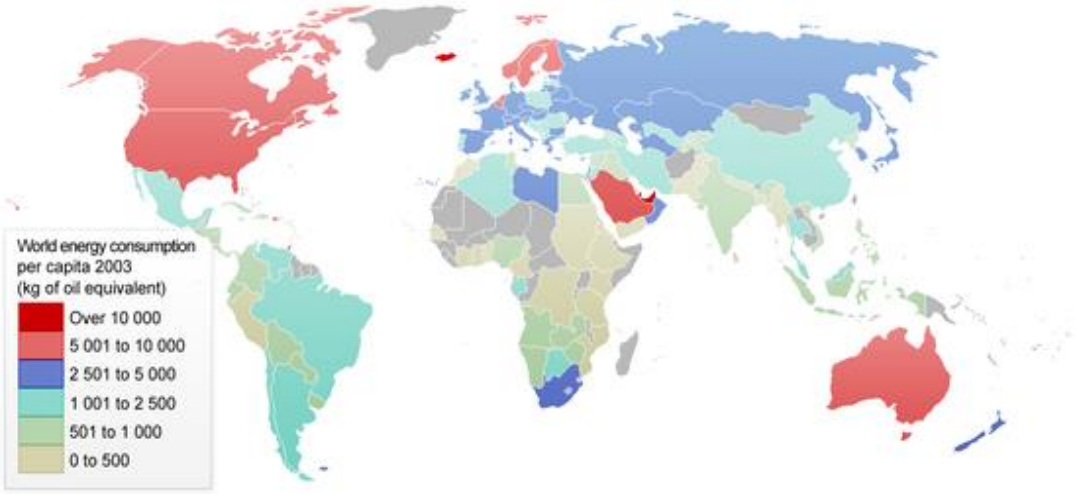


Figure 1 World Map of Energy Consumption per Capita (International Energy Agency, n.d.)

Figure 2 (International Energy Agency, n.d.) shows a subset of countries of interest. From this information it can be seen that South Africa is already relatively high up on the per capita electricity usage. In this regard it is comparable to many countries in Europe as well as Russia (Leung & Meisen, 2005). The amount of installed capacity per capita is even slightly more than China.

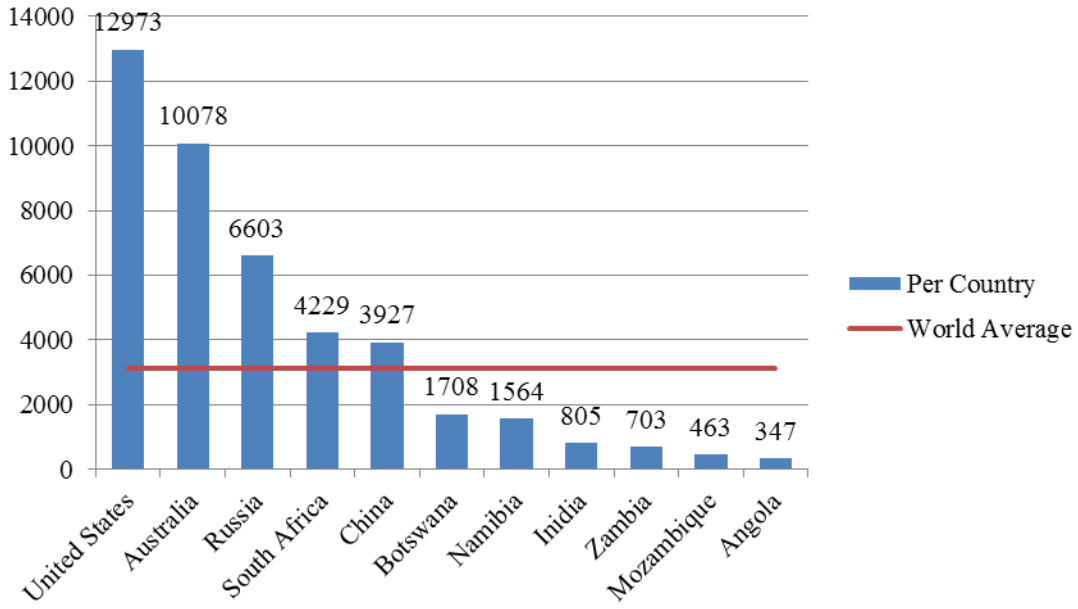


Figure 2 Electricity Consumption per Capita of Some Selected Countries (International Energy Agency, n.d.)

2.2. Population Distribution

A number of international organizations have published detailed statistics with regard to the population in the SADC countries. This data typically includes the distribution in each country as well as the population of the different cities (World Population Review, 2017).

Figure 3 (Southern African Development Community, 2017) shows the population distribution between the different countries in SADC. From this chart it is clear that about 2/3^{rds} of the population in the SADC region is distributed amongst three countries, being the Democratic Republic of Congo, Tanzania and South Africa, with the ½ of the remaining 1/3rd living in Mozambique and Angola.

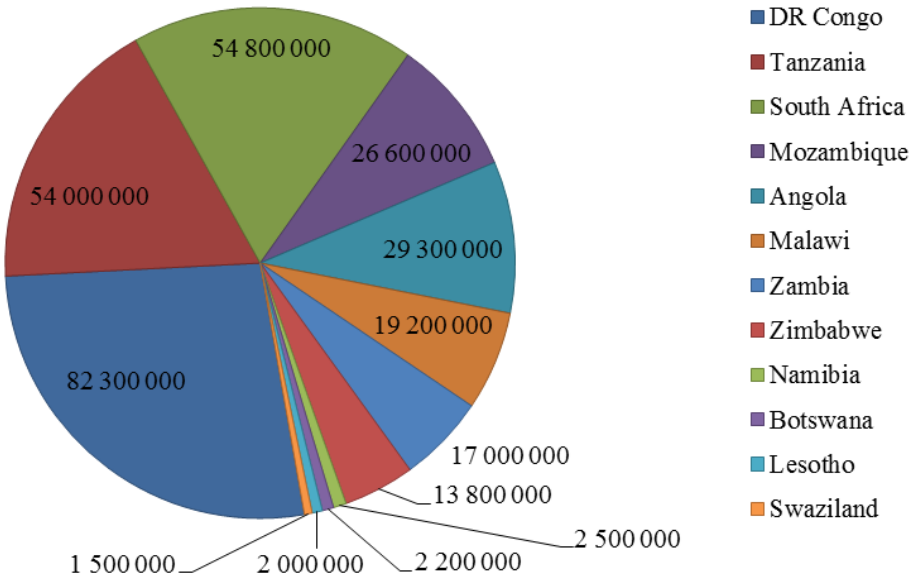


Figure 3 Population of Each SADC Country (Southern African Development Community, 2017)

The population density as a function of the surface area of each of the SADC countries was calculated and is shown in Figure 4 (Central Intelligence Agency, n.d.). From this information it can be seen that Malawi is by far the most densely populated country. Although Swaziland and Lesotho are densely populated, their actual population is very low. Tanzania is less than half the density of Malawi. Botswana and Namibia are incredibly sparsely populated and it should further be mentioned that the population in these countries is concentrated in relatively small areas. The Namib Desert forms a large part of Namibia and the Kalahari Desert a large part of both Botswana and Namibia. These areas are mostly uninhabited and being national parks and considered sensitive ecosystems, will most likely remain that way (Convention on Biological Diversity, n.d.).

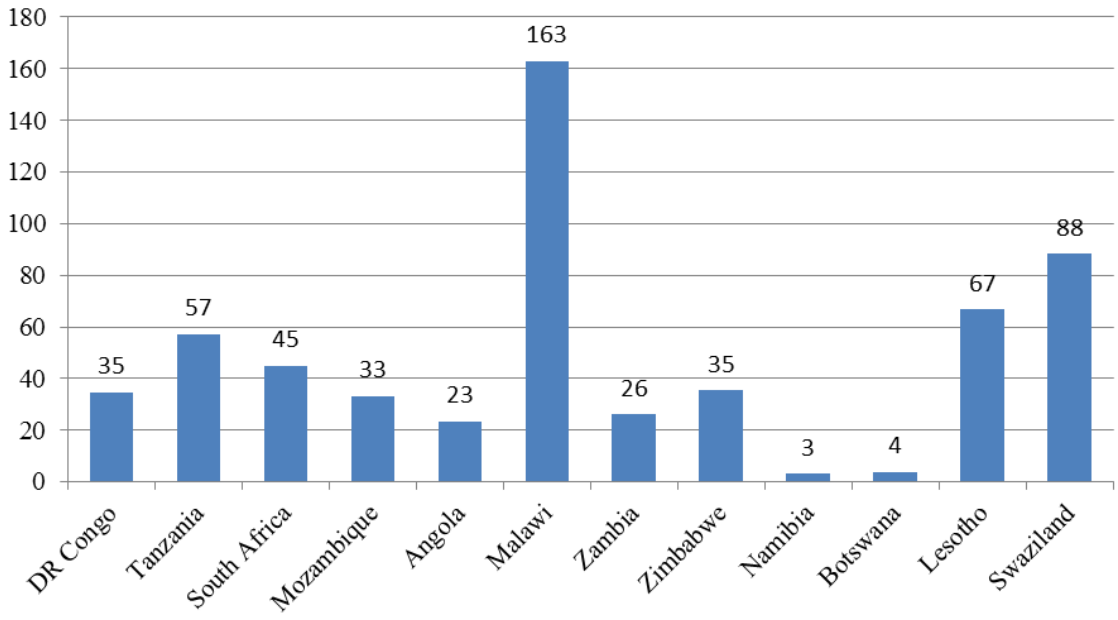


Figure 4 Population Density of SADC Countries (people/km^2)

In SADC the deserts and tropical forests are sparsely populated. However from the literature it can be seen how populations concentrate around opportunities for access to resources, with a concentration of load centers around rivers, the coast and resource rich areas like the copper belt in Zambia or the mineral deposits of the Witwatersrand. This results in many areas being underdeveloped, even though they do not fall within deserts and rain forests. Such areas are potentially further opportunities for development.

2.3. Current Infrastructure

The capacity and layout of the current infrastructure in the SADC countries is documented in the SADC annual reports as well as in the SADC development plan (Southern African Development Community, 2017). The energy regulators and utilities in the different countries furthermore have their infrastructure published on their websites as well as in their periodic reports. The SADC plan furthermore contains the expansion program, agreed to by the member states, for the region.



Figure 5 SADC Transmission System (Southern African Development Community, 2012)

The SADC integrated grid, as depicted in Figure 5, consists of a number of very long lines, carrying load over extensive distances. Outside of South Africa there are limited to no levels of redundancy in specific servitudes and virtually no alternative routing to move power from one region to another. This vulnerability became very evident in March 2019 when Cyclone Idai disabled the power line between Cahora Bassa and South Africa, resulting in South Africa having to implement large scale load shedding due to a lack of capacity (Bloomberg, n.d.). The information published on the SADC website furthermore describes planned grid infrastructure development. This will in future establish what is commonly known as the Western, Central and Eastern Corridor. These can be seen on Figure 5 extending through Namibia and Angola in the West, Zimbabwe and Zambia in the middle and Mozambique in the East.

Although the entire region is using 50Hz reticulation system, a number of Direct Current transmission lines are used, which results in different areas of the region not being synchronized. One such line is the DC power line extending from Inga in the Democratic Republic of Congo to the Copper Belt in Zambia. This is the Inga-Shaba line which covers 1700km (Madsen, 2015). This line was constructed with the sole purpose of transferring large amounts of power, with the lowest amount of line losses, from the hydroelectric power plant at Inga to the mines in the Zambian Copper Belt. This line provides no benefit to the population living along the route that it runs. DC systems make it difficult to provide for regular take-offs, thereby limiting the potential for wide scale rural electrification and the interconnection of distributed renewable sources. As per Madsen, 2015: *"These stations proved to be politically controversial, essentially since they were not "tapping stations." Power could not be drawn off the Inga-Shaba Line in mid-route to serve growing communities along the right-of-way, such as Tombagadio, Kamina, Kananga, and Mbuji-Mayi, the diamond-mining sector. Tapping stations would have cost 60 million dollars each, in U.S. funds of the period"*. Such lines are point to point connections and therefore provide no direct benefit to communities close to the servitude.

Figure 6 shows the current installed electricity production of each of the SADC countries in relation to each other (Southern African Development Community, 2017). From this chart it is clear that the bulk of the current electricity production capacity is situated in South Africa. The bulk of the power is based on thermal coal plants with the balance being mostly hydro. Of the 15 coal plants, 2 are new, 4 have a life expectancy of another 15 to 20 years, 3 have a life expectancy of another 10 to 15 years, one between 5 and 10 years and for the remaining 6, the end of their commercial life is imminent (Department of Mineral Resources and Energy, 2019). Koeberg Nuclear Power Plant, being the only nuclear powered electricity generation, is situated in Cape Town where there is neither coal nor hydro opportunities (Eskom, n.d.).

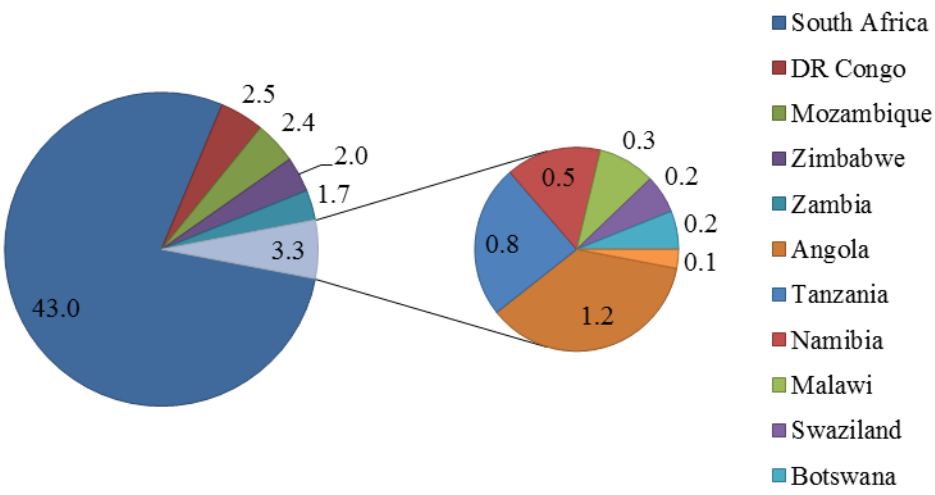


Figure 6 Installed Capacity of each Country (Southern African Development Community, 2017)

2.4. Resources and Proposed Infrastructure

The distribution of natural resources in SADC is well documented in geological reports and studies (Southern African Development Community, 2012). However, the well documented information pertains mostly to the current mining activities. The distribution of resources that are not currently being extracted actively on a large scale is less certain. For the purposes of this study such future opportunities will not be considered except where these relate to resources that can be used as energy sources for generating electricity.

Currently the SADC integrated planning documentation is mostly at the level of stating aspirations and has not yet been cascaded into a real step by step plan (Southern African Development Community, 2017). The only country that has cascaded the plan further is South Africa, in the form of a National Depevelopment Plan (National Planning Commission, n.d.) with more details on power generation contained in the Integrated Resource Plan 2019 (IRP 2019) having been gazetted on 18 October 2019 (Department of Mineral Resources and Energy, 2019)

2.4.1. Hydro Projects

The two main rivers in SADC are the Zambezi and the Congo Rivers. A number of smaller rivers in the countries to the North also have potential for hydro power. However, the flow rates and opportunities on these rivers are limited and currently planned projects are typically all below 1000MW in size. Although these smaller projects will benefit the local communities, it will not contribute significantly towards the larger macro-economic development of the region.

There are however some larger scale hydro projects currently planned or being constructed. In Angola, two new hydro power plants, with a total installed capacity of 3 000 MW, are under construction at Cambambe on the Kwanza River and on the Lauca Dam, situated on the Cuanza River. In Zambia, the Kafue Gorge Lower hydropower project, with an installed capacity of 750 MW, is being constructed on the Kafue River (Molekoa L, 2011). In Tanzania, Kikonge, Stiegler's Gorge and Songwe with a combined capacity of 2 600 MW is currently under construction.

Figure 7 shows the additional potential for hydro power to be generated from the flow of the Zambezi. The GRID Arendal website (GRID-Arendal, n.d.) states the following: "*SAPP estimates that the Zambezi River has the potential to produce more than 20 000 Megawatts (MW) of electricity (Tauya 2006). However, only 23 per cent of this potential is being harnessed, largely from two main sites: the Kariba Dam between Zambia and Zimbabwe, and the Cahora Bassa Dam in Mozambique (SARDC 2009c). To fully exploit its potential, various projects have been identified for commissioning in the Zambezi Basin."*

However, these projects all have a notable environmental consequence and are receiving significant opposition from environmental groups. As agriculture develops in the region, the hydro power generation schemes are also coming into competition with irrigation projects.

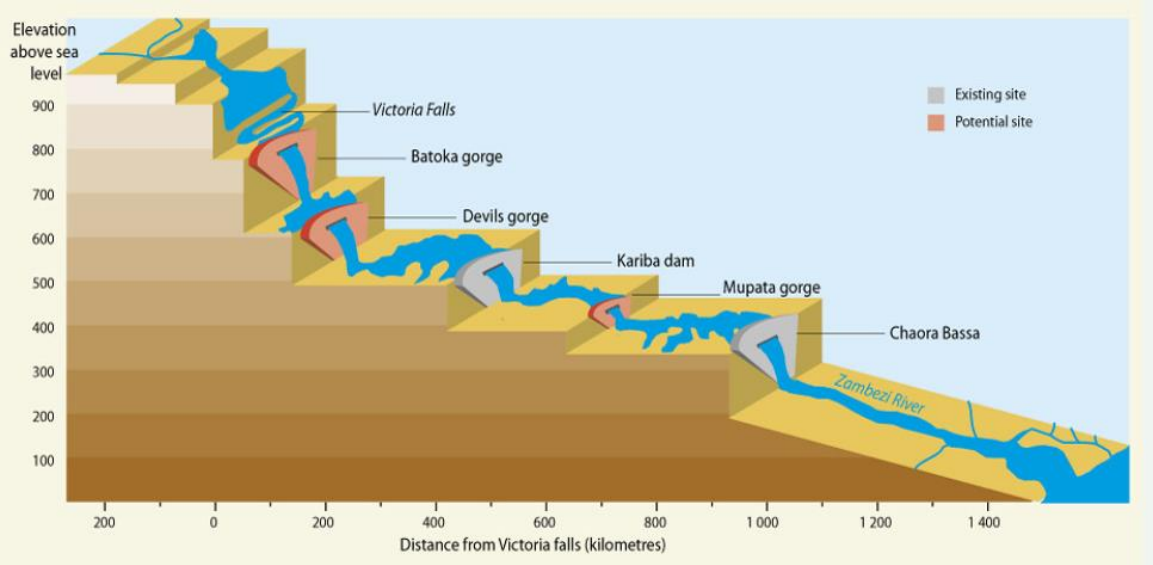


Figure 7 Existing and potential hydropower projects on the Zambezi River (GRID-Arendal, n.d.)

The Inga rapids are located in the Congo River in DRC, where an elaborate hydroelectric project is being built which will eventually consist of four dams (Stearns, 2019). Two of the dams have already been constructed, generating 351 MW and 1424 MW each. The next phase will see the construction of Inga 3, a 4 800 MW facility, eventually followed by Grand Inga which will generate an anticipated 40 000 MW. Figure 8 provides a layout of the facility. The construction of Inga 3 and 4 has had a number of setbacks over the years. However, for the purposes of this study, the potential for power generation from this resource is there and can be harnessed.

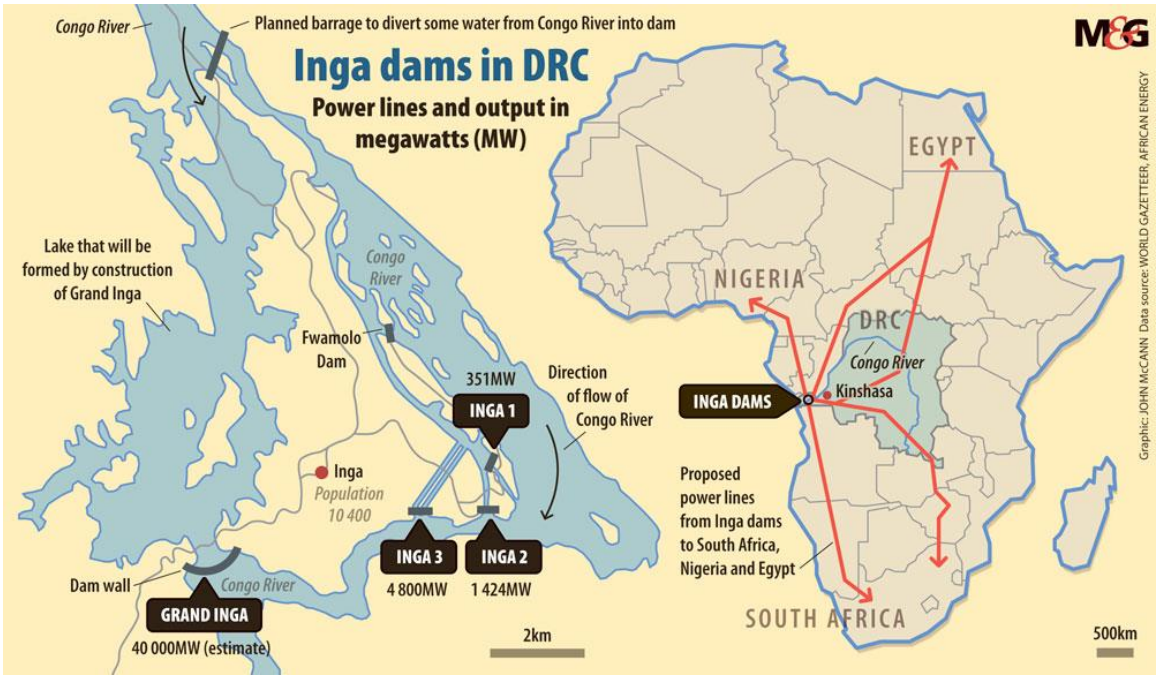


Figure 8 Inga dams in DRC (Stearns, 2019)

2.4.2. Natural Gas Projects

According to NAMCOR in Namibia (NAMCOR, 2019), the Kudu natural gas field, situated off shore, West of the country will be able to supply a combined cycle natural gas plant, producing 885MW of power which is relatively small in comparison to other power generating options in the region. Angola, Tanzania and Mozambique all have large natural gas resources off shore (Development Bank of Southern Africa, 2017). These deposits are of such a scale that it is difficult to determine optimum capacity of power that can be derived from this resource. In February 2019 Total announced the discovery of a natural gas field of similar proportions 180km South of South Africa. (Businesstech, 2019).

As depicted in Figure 9 Tanzania has some natural gas reserves. However, the quatity and extent is still under investigation. According to a study performed by the Natural Resource Governance Institute (Scurfield & Manley, 2017), the currently confimed and verified capacity is not adeqaute for making a long term, mass power generation investment feasable.

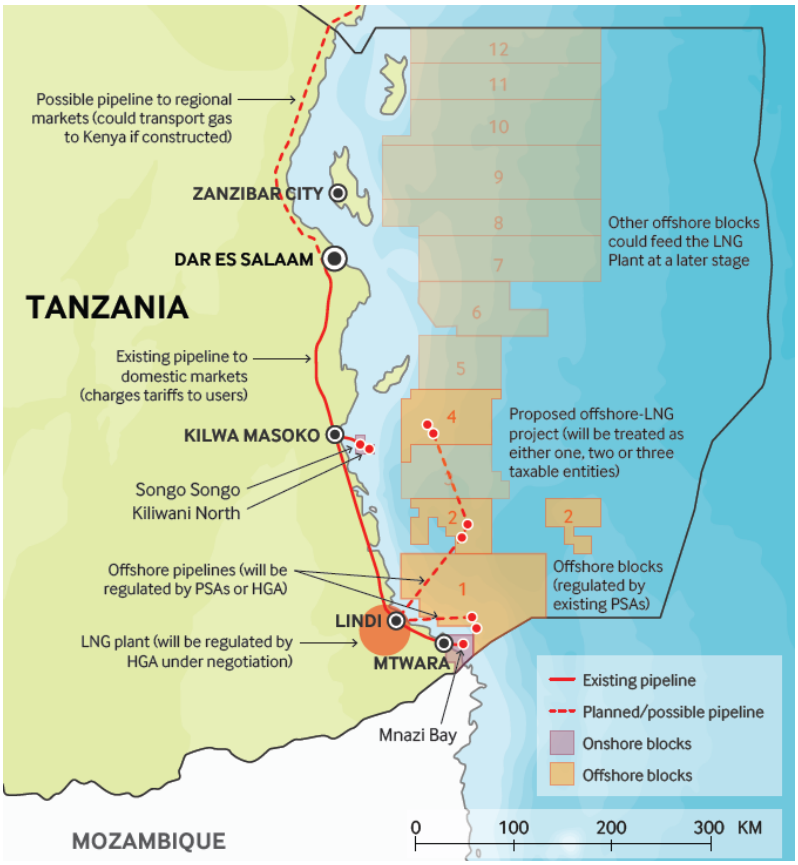


Figure 9 Natural Gas Projects in Tanzania (Scurfield & Manley, 2017)

The DRC has extensive natural gas reserves with the potential for large scale power generation. According to the International Trade Administration (International Trade Administration, n.d.), "*Oil and gas discoveries in the east of the country give the DRC the second largest crude oil reserves in Central and Southern Africa after Angola*." Some of these occur in the West of the country, but most is on the eastern border with Uganda.

In 2019, Total announced a large natural gas find 175km South of South Africa, in the Outeniqua basin (Dittrick, 2019). Figure 10 maps the location of the find relative to the survey area and the large towns and cities in the area. According to EPCM Holdings South Africa, *"the find is a form of gas condensate which is more of a light crude oil than an LPG or natural gas mixture"* and *"Mossgas is the only refinery in SA ready and equipped to run on condensate."* It would therefore appear that this gas will initially be

destines for being processes into fuel, rather than for power generation. Although the current find has been confirmed to be significant in size, the full extent of it is yet to be determined.

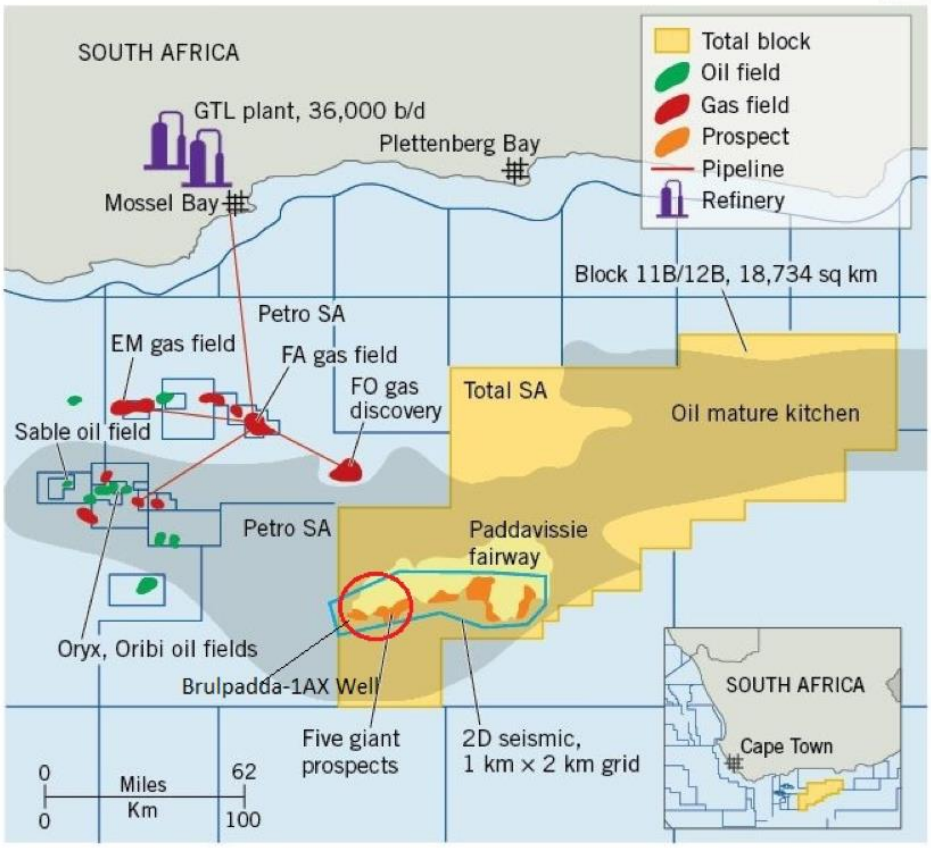


Figure 10 Exploration Block 11B/12B indicating the Paddavissie fairway and the approximate location of the Brulpadda well. (EPCM Holdings South Africa, 2020)

The cost of natural gas since 1997 is shown in Figure 11. This graph shows the historical high volatility in the price of natural gas. However, it also shows that since 2009, the price of natural gas has remained low and is slowly decreasing. When considering the effects of inflation it can be seen that the real price of natural gas has been decreasing over this period.

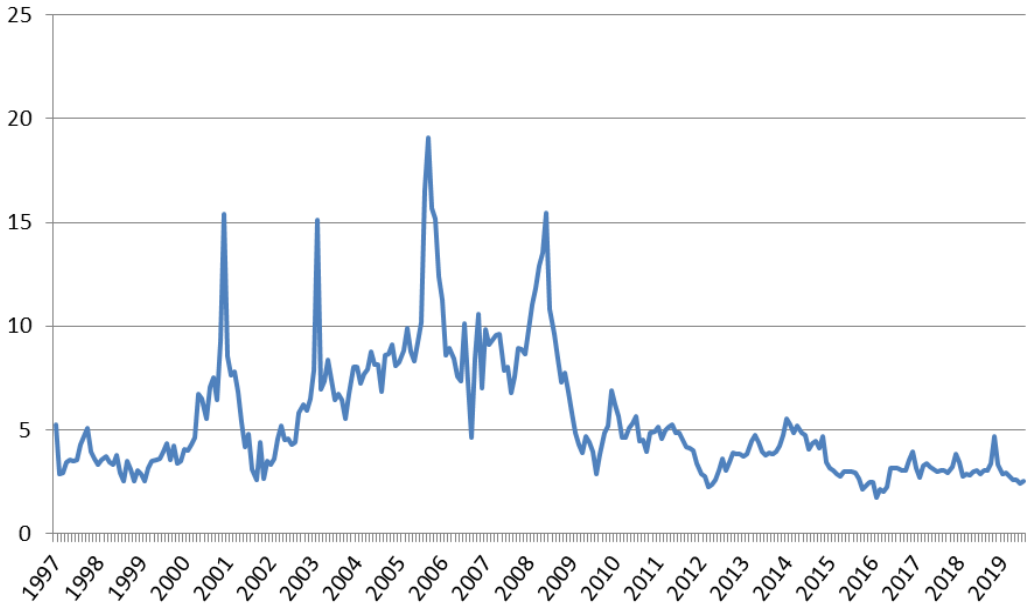


Figure 11 Natural Gas prices in $US since 1997

2.4.3. Coal Power Projects

There are currently two large new coal powered plants, Medupi and Kusile, under construction in South Africa. These two plants will be adding over 10 GW of additional capacity to South Africa and the SADC region. Malawi has a 300 MW coal powered plant under construction at Khammwamba.

Botswana has already invested significant funds into the planning phase of a new 300 MW coal fired power plant at Mmamabula. However, this project has been placed on hold pending the conclusion of a Power Purchase Agreement with South Africa.

The environmental impact of burning coal as well as mining of coal has become unsustainable. Financial institutions have already come to this conclusion with more and more banks, across the world, withdrawing and no longer funding coal power generation projects (Institute for Energy Economics and Financial Analysis, n.d.). The concerns around continuously adding Carbon Dioxide to the atmosphere is well known. However, these plants also contribute to other harmful chemicals being discharged into the atmosphere and the water resources. The mining techniques cause significant consequences in the forms of surface collapse, contamination of ground water and rivers, Sulphur releases, acid rain and underground fires. These effects can be observed extensively in Zambia, Zimbabwe and South Africa (Ashton P, n.d.). These effects don't only make the environmental impact of combusting coal unacceptable, but also the consequences of the mining of coal.

2.4.4. Renewable Energy Projects

Worldwide, the overall impact of large scale renewable power generation on integrated electrical grids is still being assessed. However, what is certain is that grid stability is negatively affected and the possibility for out of synchronism type events increases as the percentage of renewable energy generation increases.

As per Katrin S, 2017: *"Short-term fluctuations on the second and sub-second scale are a particular challenge for power system operation, since standard load balancing such as primary control does not operate yet on these time scales. As a consequence, frequency quality is significantly reduced. This problem is exacerbated by a side effect: as conventional power plants are progressively substituted by renewables, system inertia is decreased and the grid becomes more sensitive to sudden perturbations in terms of feed-in fluctuations."*

Specific studies on connecting wind generation into large integrated grids have identified similar challenges, as described by Boyle J, 2018: *"Unlike conventional synchronous generators, modern VSWTGs are either partially (Type C WTGs) or fully decoupled (Type D WTGs) from the grid frequency by power electronic converters [3]. This decoupling means that VSWTGs provide little or no natural active power response to frequency events."* However, these studies also recommed changes to control systems that would provide some mitigation to these challenges.

Many smaller scale renewable energy projects have been and are being deployed in the region. However, very few of these are connected to the grid and are normally deployed for the benefit of local projects. The option of infeeding from consumers is being considered by some governments, South Africa in particular, but no legistaltion has yet been passed to allow for this option. However, on 5 May 2020, draft amendments to the Electricity Regulations on New Generation Capacity, which, once approved, will allow for municipalities to generate electricity and procure electricity from Independent Power Producers, to be supplied into the South African national grid.

Some large scale renewable projects have been deployed successfully and many are under construction. In the South African model, making use of Indpenedent Power Producers that can bid for specific feed in tarifs, the deployement of renewables have been very successful. As can be seen in Table 1, the price has been reducing during every new bid cycle (Hansen U, 2014).

Table 1 Average PPA Price for PV in three bidding rounds in South Africa (Hansen U, 2014)

	Window 1 Average PPA price (EUR cent/kWh[1])	Window 2 Average PPA price (EUR cent/kWh[1])	Window 3 Average PPA price (EUR cent/kWh[1])
PV	22.44	13.39	7.17
CSP	21.86	20.44	11.88[2] (18.95 if adjusted by the peak-base hours payment schedule)

1 ZAR price base: April 2013. Assuming a exchange rate of 1 ZAR=0.07244 EUR as per 11/11/2013
2 Bid Window 3 base price payable for 12 hours every day and 270% of base price payable for 5 peak" hours every day. This pricing basis is not comparable with Bid Windows 1 and 2

2.4.5. Nuclear Energy Projects

Nuclear power was introduced into the world energy mix in the 1960s. Since then nuclear power has contributed extensively to the power being generated in specifically the OECD countries.

Since the technology is clean, producing almost no climate affecting waste, it does not suffer from the challenges that carbon fuels are posing to the natural environment. Figure 12, as supplied by the World Nuclear Association (World Nuclear Association, n.d.), shows the amount of greenhouse gasses produced by different technologies. From this it can be seen that nuclear is competing with the likes of hydroelectric power and wind generation, where CO_2 emissions are related primarily to construction and not operation.

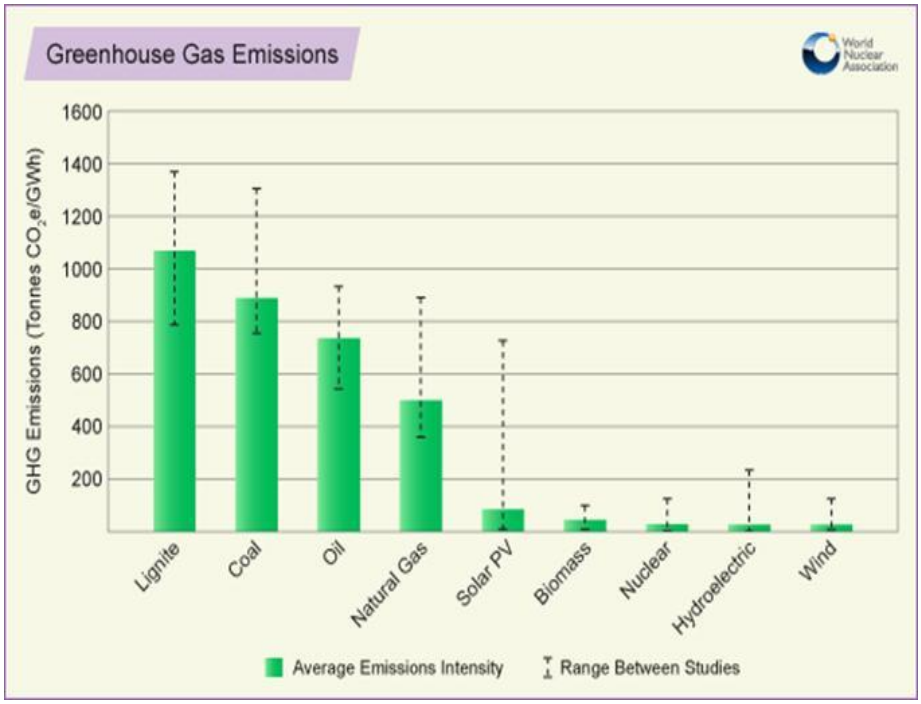


Figure 12 Greenhouse Gas Emissions from Different Technologies (World Nuclear Association, n.d.)

Nuclear power plants have an extensive value chain and provide more employment and supply chain opportnoities than any of the other technologies. This means that the construction and operation of nuclear power plants have one of the higests potentials for providing extensive upliftment opportunities to the local communities.

The United States Department of Energy (Unites States of America Department of Energy, n.d.) provides information on the extent to which different sectors provide employment opportunities within economies. From this information, Figure 13 shows how nuclear power generation employs more than double the amount of people than the next technology, which is coal. While this aspect increases the overhead and has therefore a direct impact on the cost of the elctricity, it also allows for the technology to provide direct economic benefits to the economy of the area where the plant is operating.

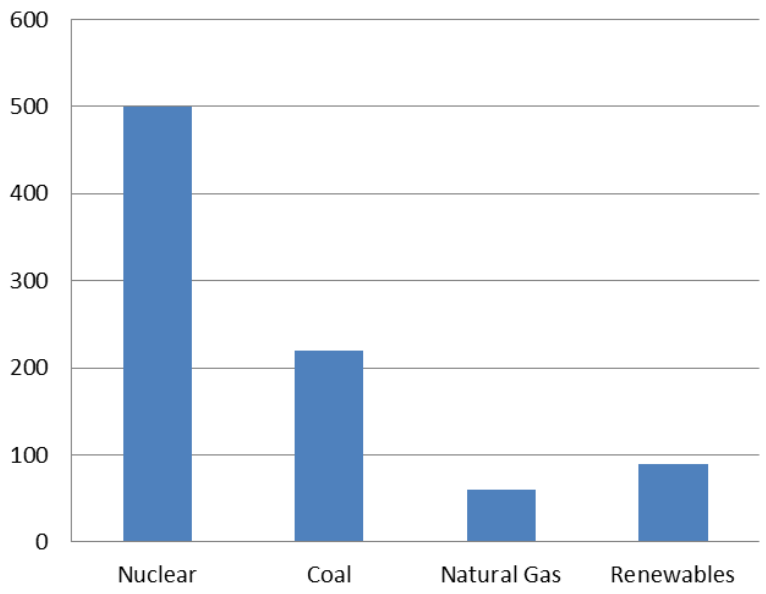


Figure 13 Jobs per 1000MW of Generation Capacity (Energy, n.d.)

Currently, the only country in Africa, and therefore in SADC, that generates electricity from nuclear power, is South Africa. However, a number of countries within Africa have approached the IAEA for assistance in starting implementation of the types of regulatory frameworks that would allow for the future development of nuclear power plants (International Atomic Energy Agency, n.d.).

South Africa has, in the recent past, considered the options of developing and constructing both smaller modular types of reactors as well as conventional large nuclear power plants. However, the modular reactor project (PBMR) was cancelled on 5 July 2010 (Times Live, 2010) and construction of a new conventional power plant has not been progressed for a number of years. Eskom, the State Owned Enterprise, responsible for generating the bulk of the electricity in the country, is experiencing substantial financial challenges and it is unlikely that the utility will be in a position to construct new nuclear power plants in the foreseeable future (Eskom, n.d.).

Figure 14 shows the historical price of Uranium on the open market. From this information it can be seen that, as per most other commodities, the price is determined by the supply and demand principle. When confidence in the market is high and supply is limited, the price increases and vice versa. The graph lists the events that dictated and influenced the price. In the early 70s the world was certain that nuclear power would be the energy of the future, which drove the price up. After the Three Mile Island event, this opinion changed, causing the price to reduce. At the start of the 2000s the confidence in nuclear power started to increase again and together with the shutting down of some suppliers, the price increased substantially. However, the economic down turn in 2008, together with the accident at Fukushima, forced the price to decrease again.

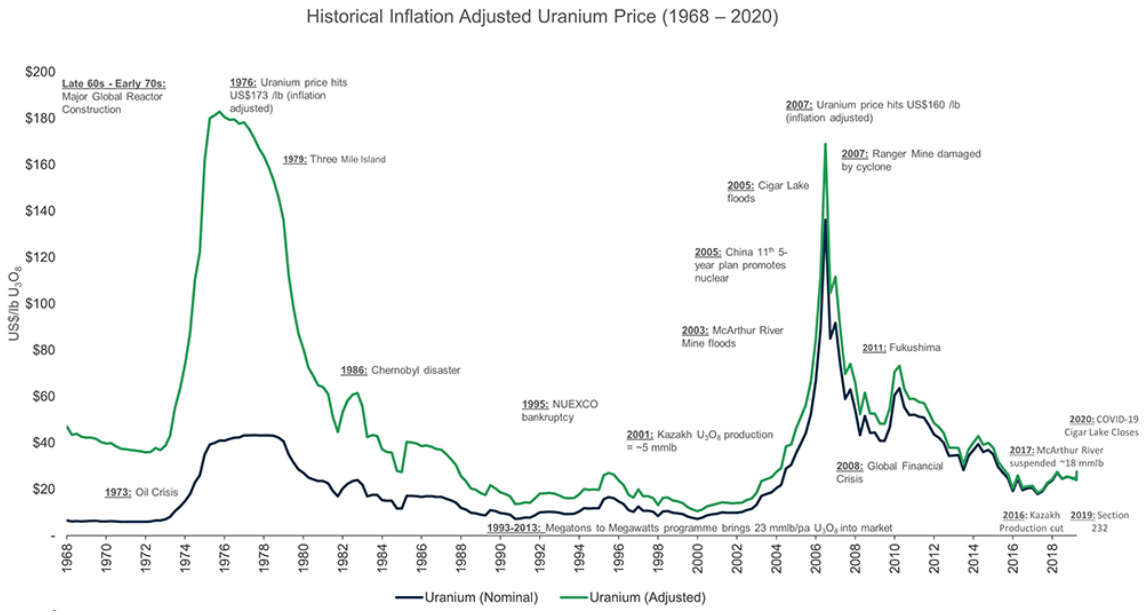


Figure 14 Historical Inflation Adjusted Uranium Price (1968 to 2020) (Yellow Cake plc, n.d.)

Some other SADC countries have started discussions with suppliers. One of these is Zambia where The Radiation Protection Authority of Zambia has already entered into agreements with Rosatom of Russia for the development of a research reactor; and to assist with the initial stages of preparing the country for the construction of nuclear power reactors (Radiation Protection Authority, n.d.).

2.4.6. Availability Factors

The IEA (International Energy Agency, n.d.) lists substantial statistical data for the average capacity factors for different technologies. These average capacity factors are the statistical percentage of energy generated as a function of the full power capacity, assuming a plant that is permanently on line. The data was collected from the industry, collated and the averages are published. These values are as follow:

- Efficient Gas: 30% to 65%
- Solar PV: 10 to 20%
- Onshore Wind: 25 to 45%
- Hydro: 35 to 50%
- Nuclear: 85 to 95%

The EIA (U.S. Energy Information Administration, n.d.) also publishes extensive information on the performance of various power generation technologies. These comparisons are shown in Figure 15, Figure 16 and Figure 17.

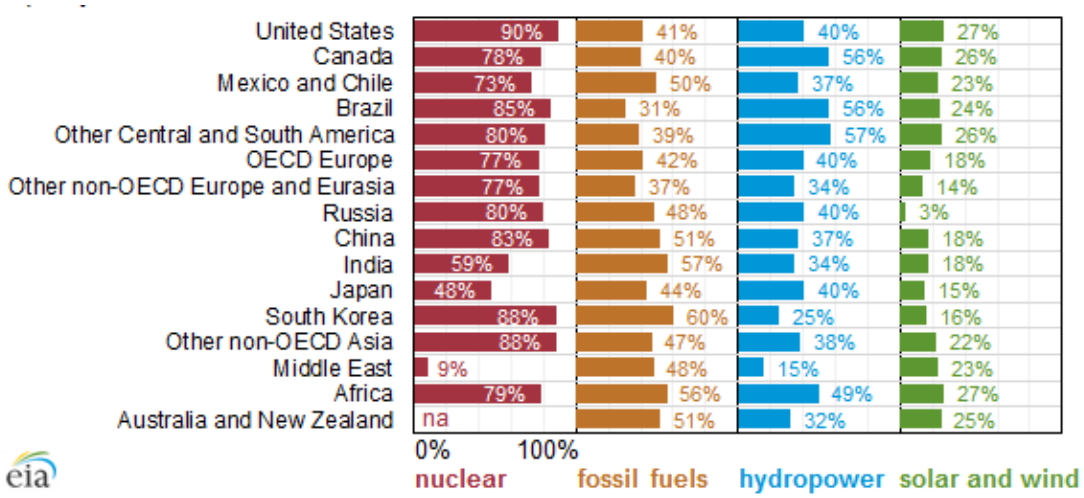


Figure 15 Electric generator capacity factors for nuclear fossil hydro and solar and wind in various countries and regions, 2008-12 average capacity factors (U.S. Energy Information Administration, n.d.)

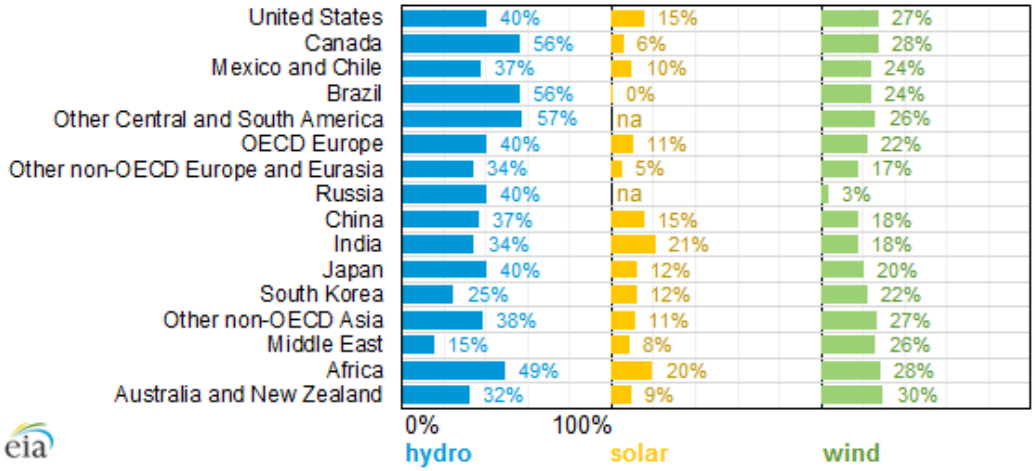


Figure 16 Electric generator capacity for hydro, solar and wind factors in various countries and regions, 2008-12 average capacity factors (U.S. Energy Information Administration, n.d.)

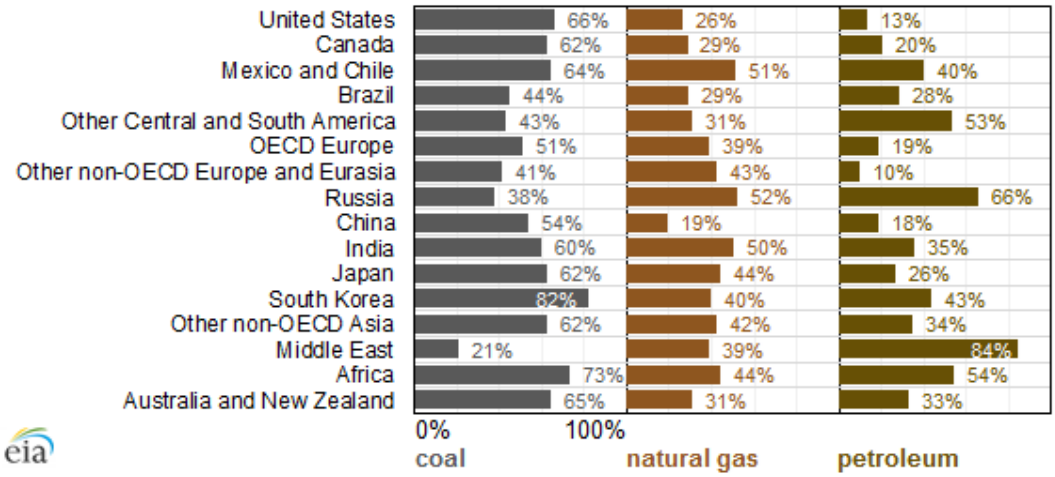


Figure 17 Electric generator capacity factors for coal natural gas and petroleum in various countries and regions, 2008-12 average capacity factors (U.S. Energy Information Administration, n.d.)

From the data it can be seen that Solar PV has the lowest performance. However, it has to be noted that a large percentage of the data is supplied by utilities operating the technology in higher latitudes, where solar power performs poorer than when used closer to the equator.

Onshore Wind generation performs better than solar power, but can still, on average, only produce about 30% of the rated power. It also has to be noted that both solar and wind are not dispatchable in as far as having the output controlled. Both these technologies will generate according to the weather conditions at the time.

Both Efficient Gas and Hydro power can be counted on up to half the capacity. The term Efficient Gas refers to combined cycle natural gas plants.

Nuclear power plants statistically generate 90% of their rated power.

2.4.7. Geotechnical Considerations

A review of seismic events in the region, with a magnitude of larger than 6 on the Richter scale, lists 6 events in the last 100 years. These events are mapped in Figure 18.

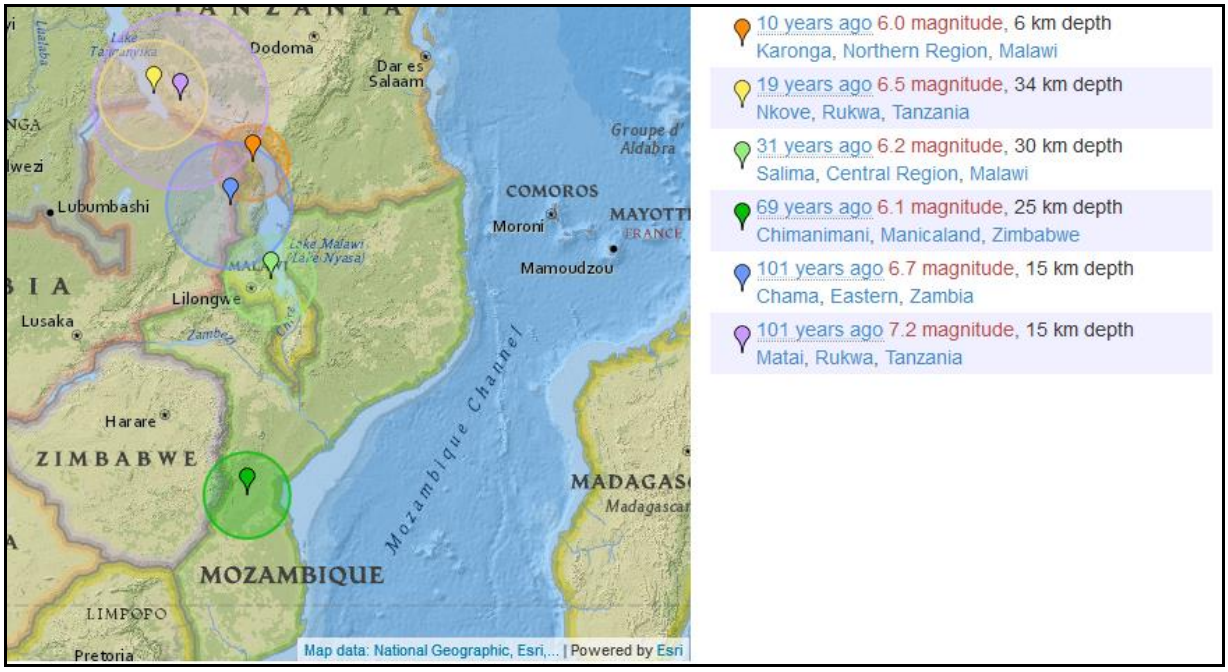


Figure 18 Seismic Events, greater than 6 in the rift valley (Earthquacke Track, n.d.)

These events have all taken place in the Great Rift Valley, which lies to the east of the SADC countries. As per Figure 19 it extends through the great lakes, through Malawi and Tanzania and into Mozambique. The geological instability of this region makes the construction of large nuclear and hydro power plants expensive and in many cases, for the rivers that follow the routes of the fault lines, impossible.

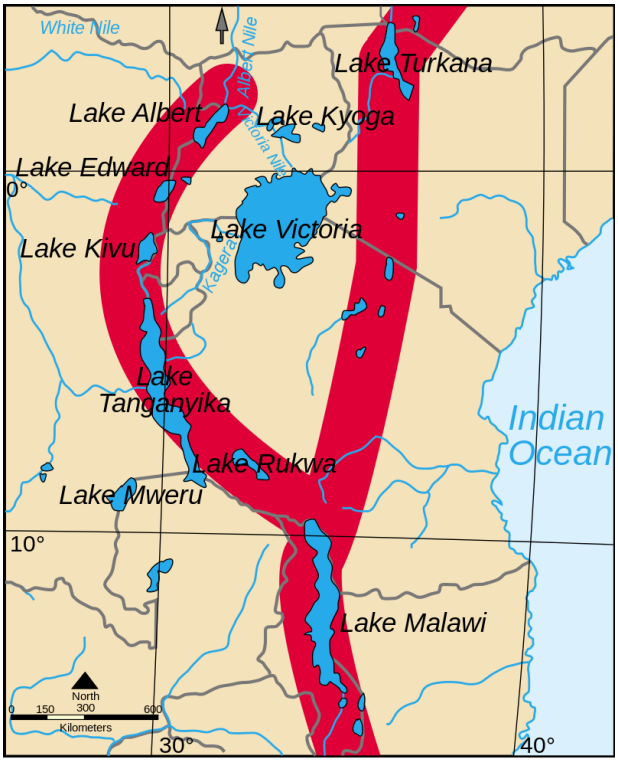


Figure 19 Great Rift Valley

Building large power generating plant in seismically active regions adds considerable cost to such projects, especially for quakes above 6 on the Richter scale. This is specifically true for nuclear and hydro power.

In the case of nuclear power it is because of the fact that the cooling of the nuclear fuel cannot be interrupted. In order to continue cooling the nuclear fuel, the plant safety systems have to operate both during and after a seismic event. Should these systems fail, the nuclear fuel can overheat resulting in a nuclear accident.

In the case of hydro power the risk is that the integrity of the dam wall could be compromised during a seismic event. When large dams fail, it leads to extensive damage and loss of life and could even cause cascading failures of other dams further down the same river. The land topography in seismically active regions is normally as a result of the seismic activity itself, meaning that large rivers often flow along the fault lines. This phenomenon removes the viability of constructing large hydro power plants on such rivers because the fault lines will often run under the dam. Even if such a configuration can be avoided, it is very difficult to ensure that the anchoring and integrity of large dam walls will remain secure during sever earthquakes.

RESEARCH METHOD

3.1. The research question:

Would electricity generation using nuclear power be required in order to reduce the risks associated with an overreliance on certain sources of power in order to establish a suitable energy mix and stable integrated grid for the SADC region?

3.2. Strategy

The objectives of answering the research question will be met by:

- Identifying what the currently installed infrastructure is, both in capacity and location, and deriving what the expected energy demand of each country and the region are likely to be in the future.
- Identifying what resources are available for energy generation, what the risks and limitations applicable to each of these energy resources are and the current geographic opportunities, limitations and risks.
- Establishing a strategy to mitigate and/or minimize the risks associated with each of the identified resources. Then incorporating the projected demand, resource availability and risk mitigation strategy into a model, which will establish the ideal energy mix for each country and the region, thereby calculating the resultant energy shortfall that would potentially require nuclear power. This information will be represented as load centers, as well as current and projected power generation centers, thereby identifying the ideal grid integration strategy and the optimum locations for nuclear power generation.

3.3. Models

Three models will be used in order to achieve the above objective:

3.3.1. Projected Energy Demand

This model is aimed at calculating the projected demand for each country. This will be achieved by making use of the relationship between population and energy demand for developed countries. This relationship has previously been shown by Chi Seng Meisen and Peter Leung (Leung & Meisen, 2005). The model will be validated by comparing the results against the currently installed capacity in other more industrialized and economically active countries and regions.

The model is based on the fact that economies develop around people and are powered by energy, a large percentage of which is electrical power. As discussed above, the amount of energy consumed in a developed country will be closely associated with the size of the population. By comparing the power consumption of cities and regions in first world countries, as a function of population, with the population in SADC, it will be possible to project what the future power consumptions in the region and sub regions would be.

The projected energy demand of each of the countries, as well as for the region as a whole, will be derived. This will be based on the current population. The reason for using the current population is the fact that the study is considering the current shortfall and does not take into consideration the time that it will take to install the projected capacity. This approach is a simplification of the actual future configuration. However, it does provide a proper reflection of the current deficit in infrastructure. Projected population growth is furthermore highly dependent on economic growth which is in turn interrelated to the provision of energy. This makes the prediction of future populations very complex and does not form part of the scope of this study.

3.3.2. Potential Nuclear Capacity

This model is used to calculate the power shortfall that could be filled through the use of nuclear power. It will be achieved by using the projected demand from the 1st model and incorporating the resource limitations and identified risk mitigation into a projected installed capacity per resource model, thereby establishing the shortfall.

The research model is based on firstly establishing the interdependence between renewables and hydro power and then the total availability and sustainability of the hydro-renewable combination together with the other primary energy sources. The resultant deficit in power could be supplied by nuclear power.

The model will utilize the following process:

a. In order to derive the real capacity deficit, for each country, the currently installed capacity, corrected by the load factor, will be deducted from the projected capacity calculated in the 1st model.

b. For each of the identified resources, the associated limitations, potential capacities, risk informed maximum deployment exposure and the projected load factor of the associated technology will be determined and discussed. The projected capacity of each of these technologies will then be ducted from the capacity shortfall according to the strategy derived and corrected by the projected load factor.

c. The remaining shortfall will be assumed to be using nuclear power. The projected load factor for nuclear power will be used to calculate the proposed installed nuclear capacity. From this calculation the total potential for nuclear power in the region will be derived.

d. In order to limit the risk associated with some of the technologies, the percentage exposure will be calculated as a function of the overall installed capacity. Once all the technologies have been incorporated, the new subsequent total installed capacity will have to be recalculated. This process will then have to be repeated in order to correct the capacities that are dependent on the overall. The iteration will have to be repeated until the deviation becomes minimal.

This model will be validated by arguing the relevance of each of the risks associated with each of the resources based on previously performed research or facts and by comparing the proposed resource spread against that which is currently installed in other countries and regions.

3.3.3. Stability Mapping

There are many advantages and disadvantages to the use of large scale AC or DC power systems. Since a large percentage of the population of SADC is still rural, the ability to distribute power in lower densities over a large area is paramount. The need to feed renewable power sources into the grid, which are by nature lower density, is an important consideration for modern networks. DC systems are useful for transferring large amounts of power from one geographical location to another. However, considering the distributed nature of the current and future power generation and the distributed nature of the consumption in the SADC region, it will have to be possible to provide for many points to feed into and take power out of the system. The use of DC systems will therefore not be optimum. For the purposes of this study the author will therefore be assuming a future integrated AC system and the considerations for ensuring the stability of such a system.

Large load blocks, like cities and large factories, make extensive use of rotating machines. These machines constitute a combined spinning mass that provides extensive momentum and inertia to the network. If the frequency of the system should change, these loads will resist such a change, thereby adding inherent short term stability to the system. In a similar manner, a large number of the equipment connected to the grid carry excitation that is supplied from the grid. This excitation has a similar inertia and will resist short term changes in the grid voltage. In the same way as what the load centers provide network stability, the large rotating machines in the power plants provide stability in the same manner. However, this stabilization effect decreases as the distance from the load or generating center increases. At some point, this stabilization effect can no longer be relied on. The distance from the load or generating center, up to where this effect is of use, can be represented by drawing a circle on map, around the load or generating center. This is will be referred to as a stability circle.

The future layout of the integrated grid will be highly dependent on the distances between generation and load centers, power transferred, generating technology used and the configuration of the overall system. Considerations with regard to grid stability have been extensively published (Eremia, et al., n.d.) (Liu, 2015) (Migliavacca, n.d.). Considering this information, it was concluded that AC transmission lines can be operated reliably for up to about 1400km. This is furthermore evident by the distance between the Northern part of South Africa and the Western Cape (Eskom, n.d.) as well as the Western Cape and Namibia. However, these lines are typically heavily loaded. The stability of long HV lines becomes less certain when the amount of power being transferred reduces. As the amount of power being transferred approaches zero, the probability of losing synchronism increases and the ability to manage the reactive power component becomes more challenging (Eremia & Shahidehpour, 2013). When synchronism is lost, it will, at some point return. When this occurs and the two systems are out of synchronism, it can cause serious and extensive damage to systems and components. This is a major concern for any integrated system, especially for large networks. The risk of loss of synchronism decreases with decreasing line lengths. The

maximum distance between large generation and load centers, for transmission lines, will therefore, conservatively, be assumed to be no more than 1000km.

The model involves plotting the location of notable load centers, power generating centers and projected future power generating centers. Since the maximum stable line length has been established to be about 1000 km, which is comprised of the stability provided by the two centers at either end, the stability "reach" of any given center is 500km. This reach will be represented by mapping a circle, with a radius of 500km around each of the large load or generating centers. These circles will be referred to as **Stability Circles**. Once all the centers have been mapped in this fashion, open spaces, not covered by circles, will be left on the map. The spaces, not covered by stability circles, will therefore represent the areas where grid stability will be weak and at risk.

These Stability Circles, placed onto the map of the region, will graphically show the inherent architecture, strengths and weaknesses of a future grid layout.

This overall mapping will exclude renewable power because of the fact that it will be well distributed with very low area specific penetration. It also excludes nuclear power because the result of this mapping will be used to determine the potential location of the nuclear power units. This will be done by recognizing the fact that the stability of the integrated network can be greatly enhanced by placing nuclear technology in appropriate areas where no other load or power center exists. The benefits of this approach will be argued in the actual analysis.

This model will be validated by confirming that the resultant mapping covers the area in an integrated manner and correctly represents areas of high density, where it could be expected that strong network integration would be present and areas of lower density, where there network integration will be challenging.

3.4. Interpretation of the results

The results from the models will provide information to understand the current state and configuration of the power consumption and generation, the projected future demand and the available resources and where these are located. The extent to which each resource can be utilized will be determined as well as the location of the power generation. The models will allow for the identification of the additional infrastructure that will be required to construct an integrated grid of adequate capacity and, if required, the optimum location for future diversified power generation, which could be in the form of nuclear power. It is expected that the analysis will show that:

a. If the amount of coal is not increased and the other resources are maximized within the available capacity limits and according to risk mitigation principles, that in some countries, the use of nuclear power will be inevitable.

b. The areas between the stability circles, where additional generation has to be provided in order to ensure a more stable and integrated regional power grid, and where no other primary fuels are readily available, to be the ideal location for nuclear power to be used.

It is expected that the study will conclude that electricity generation, using nuclear power, will be required in order to reduce the risks associated with an overreliance on certain sources of power in order to establish a suitable energy mix and stable integrated grid for the SADC region.

PROJECTED ENERGY DEMAND

This model will produce a chart showing the projected installed capacity for each of the countries in the SADC region.

4.1. The model

The principle of determining the projected installed capacity is based on the premise that in a more advanced economy, each individual person, on average, uses more power than in a less advanced economy (Figure 1). The amount of power that needs to be installed can therefore be derived by comparing the SADC region to another part of the world where the economic, beneficiation and industrialization objectives, which are being aspired to in SADC, have advanced further or have already been achieved. By comparing the amount of power installed in such a region as a function of the population, the power that would be required within SADC can be determined. The reference country or region cannot be of the first world, because the financial and developmental achievements and objectives of first world counties are different to that of the developing world. The energy consumption per capita in the first world countries is furthermore reducing as a result of efficiency improvements (Elgar, 2011).

The reference region/country that was chosen to derive the per capita installed capacity, for this project, is Russia. The reason for this is that the strategic objectives of SADC is beneficiation and industrialization which is what countries like Russia, India and China are in the process of achieving. Russia is, for historical reasons, in many ways, the furthest down this developmental path. Their current consumption is therefore the best indication of what the consumption of SADC would be, once the current development objectives have been achieved.

The per capita electricity consumption in Russia is currently about 7000kWh/year/capita. This value is relatively representative of countries at a similar level of development. Without correcting for availability factor, this amount equates to an installed capacity of 0.8kW/person. When assuming an availability factor of 70 % for the required installed capacity, the per capita requirement becomes 1.14 kW/person. The capacity that each country and the region as a whole will need to install, in order to meet this requirement, was therefore calculated. Electricity consumption per capita is not extensively impacted by the energy required for heating because most of the heating in the very cold countries are provided through the burning of primary energy, in the form of gas or oil products.

It needs to be noted that different technologies have different availability factors. The chosen 70% is a generalized average, based on the type of technology currently installed in the SADC region, which is dominated by coal generation, followed by hydro. The value of 70% is further supported by the values published in the latest South African Integrated Resource Plan (IRP 2019) (Department of Mineral Resources and Energy, 2019). Depending on the type of technology, this figure can be as high as 90% when considering nuclear power or as low as 30% when considering wind energy. When added up, the overall installed capacity that would be required to get SADC to the proposed 7000 kWh/year/per capita, at an availability factor of 70% was therefore calculated. With the exception of nuclear power, all the latest proposed electricity generation technologies for the region, like natural gas, wind and solar, have lower availability factors, which will eventually result in more capacity having to be deployed in order to meet the projected energy demands.

The analysis assumes that all the members in the region will develop at an equal rate and that the level of industrialization and beneficiation will be similar for all the participants and all will achieve the same objectives at roughly the same time. Considering the critical part that energy, and specifically electricity, plays in the economies of countries, it can be expected that each country would be weary to rely heavily on neighbouring countries for power, especially the countries that have competitive resources within their own borders. It is reasonable to consider that such countries would look after their own

interests first. This effect could be observed when Eskom, the South African power utility, reduced the supply of electricity to Zimbabwe as a result of a shortage of power within South Africa. According to Engineering News, *"Eskom had said it would only assist Zimbabwe if South Africa itself were not experiencing any load shedding."* (Creamer Media, n.d.)

4.2. Analysis

Figure 20 lists the resultant capacity that each country would require in order to achieve this objective.

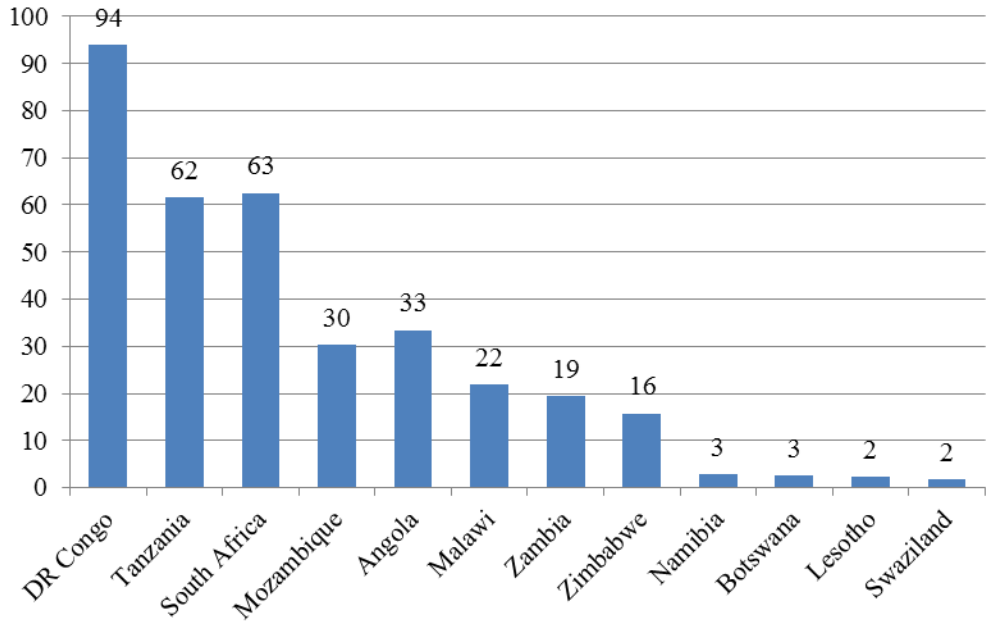


Figure 20 Installed Capacity Required assuming 70% availability factor (GW)

When the projection for each country is added up, the overall installed capacity that would be required to get SADC to the proposed 7000kWh/year/per capita, at an availability factor of 70% is 348 GW. That capacity will make the region the 4th biggest installed capacity base in the world, after China, The Unites States of America and the European Union. However, this, compared to the current installed capacity of 66 GW, leaves a deficit of 282GW.

4.3. Validation

The current total population in SADC is slightly more than 300 million people. In order to validate the result of the model, the projected installed capacity of 350GW can be compared to other regions or countries. Brazil, which has progressed further down the developmental path, has 200 million people and an installed capacity of 150GW, but still has to achieve a number of developmental objectives. China, which is further developed than Brazil, has 1,4 billion people and 1,5 TW of installed capacity. These two comparisons demonstrate that the projected capacity for SADC is in line with what it would be once the developmental objectives have been met. The South African 2019 Integrated Resource Plan (IRP) (Department of Mineral Resources and Energy, 2019) puts the installed capacity projection for the country by 2030 at 73GW, which is higher than the projection derived from this model. However, that IRP includes newer technologies like natural gas and renewables with an availability factor considerably lower than 70%. This projection therefore further validates the result of the model.

POTENTIAL NUCLEAR CAPACITY

This model will produce a pie chart comparing the projected primary fuel distribution in the region and the potential for nuclear capacity once the risks associated with all the other potential primary fuel sources have been considered and mitigated.

In order to constrain multiple different potential configurations, the analysis had to consider the different unique aspects of each type of technology that could potentially be utilized. These were then reflected in subsequent assumptions as described below.

This study assumes that currently installed capacity will remain available and does not consider the capacity required for replacing capacity scheduled for decommissioning.

5.1. The Hydro Power Proposition

The extensive reliance on hydro power in the rest of the region makes it highly dependent on the weather, with drought years affecting the security of supply, as could be observed in Zimbabwe towards the latter part of 2019, when the country and specifically the capital, Harare, suffered severe power shortages as a result of the extended drought in the region (Reuters News Agency, n.d.). The bulk of the power North of South Africa is currently supplied through the use of hydro generation. However, with the exception of the DRC and Mozambique, the rest of the region is relatively dry with the South Western region, which includes parts of Namibia, Botswana and South Africa, a desert.

There are only two major rivers in the region, the Congo and the Zambezi. There are however, a number of other smaller rivers, hosting a number of smaller hydro projects and providing opportunities for some newly proposed projects. While most of these rivers are perennial, the flow rates vary considerably over a year as a result of the very specific rainfall patters in the region.

Since bulk water is not an internationally traded commodity, it was assumed that all the countries will maximize their use of the hydro power option available to them. Although hydro is reliable and has a fairly good availability factor when there is adequate water, it is dependent on seasonal weather cycles. Once a drought sets in the hydro option soon becomes unusable. There is furthermore some competition between power generation, provision of potable water and irrigation needs. As agriculture and technology in the region expands and more irrigation schemes and water processing plants are established, the water that is available for power generation will be reduced. This study did not consider that trade off and assumed that the capacity, as currently identified, will remain available into the future. Nonetheless, as per the IEA, the international average hydro power capacity factor, which includes hydro power plants situated in regions where all the above factors are at play, is between 35 and 50% (International Energy Agency, n.d.). For this reason an overall availability factor of 40% was assumed for this report.

The Congo River has the capacity for an additional 40GW and the Zambezi an additional 20GW. On 13 July 2004, the Zambezi Watercourse Commission was established between Angola, Namibia, Botswana, Tanzania, Malawi, Zambia, Mozambique and Zimbabwe (South african Development Community, 2004). Through this agreement the member states agreed to share the resources of the Zambezi River in an equitable manner. However, the agreement is not specific on how this will be accomplished and provides for a framework that will ensure a case by case consideration of any development. This implies that the countries that will first be able to afford the construction of additional capacity will have first option. However, it is likely that some additional agreements will have to be drawn up once this occurs. For the purposes of this study the author assumed that the remaining capacity will be shared equally between the three member states where the option for additional hydro power exists, which are Zimbabwe, Zambia and Mozambique, leaving 7,6GW for each to utilize.

There is a lot of environmental opposition to the building of more dams in the region. One such aspect can be seen by the fact that the development plan issued by the Zambezi Watercourse Commission (Zambezi Watercourse Commission, 2019) does not include all the hydro power opportunities in the Zambezi River. Development of hydro power capacity at the Victoria Falls is for example excluded in this plan.

In order to maintain consistency, this study assumed that all potential hydro opportunities will be utilized at some stage in the future.

5.2. The Regional Grand Inga Proposition

It has, for a number of years, been assumed, that the power which will eventually be generated by the Grand Inga project could be distributed via large DC lines into other parts of SADC and to the rest of the continent and even Europe (Showers, 2011). However, from the figures in Chapter 1.12, it is clear that, should the DRC develop in line with what is proposed in this study, all the power from the entire Inga project will be consumed by the DRC itself. The prospect of long high voltage DC lines moving power to other parts of Africa is therefore based on the premise that the DRC will not develop economically. Even if the DRC only develops at half of what is anticipated, all the power from Inga will be required to power the country itself. The prospects of a Western Corridor, moving power South into South Africa, is therefore not credible in the long run, unless the DRC continues a low growth path, which will not be in the general interest of the region as a whole.

5.3. Fossil Power Propositions

Climate change has become the Achilles Heel of the power generation industry. From Figure 21 it can be seen that, as European countries increase the percentage of renewable energy, the cost of electricity increases (Mearns, 2017).

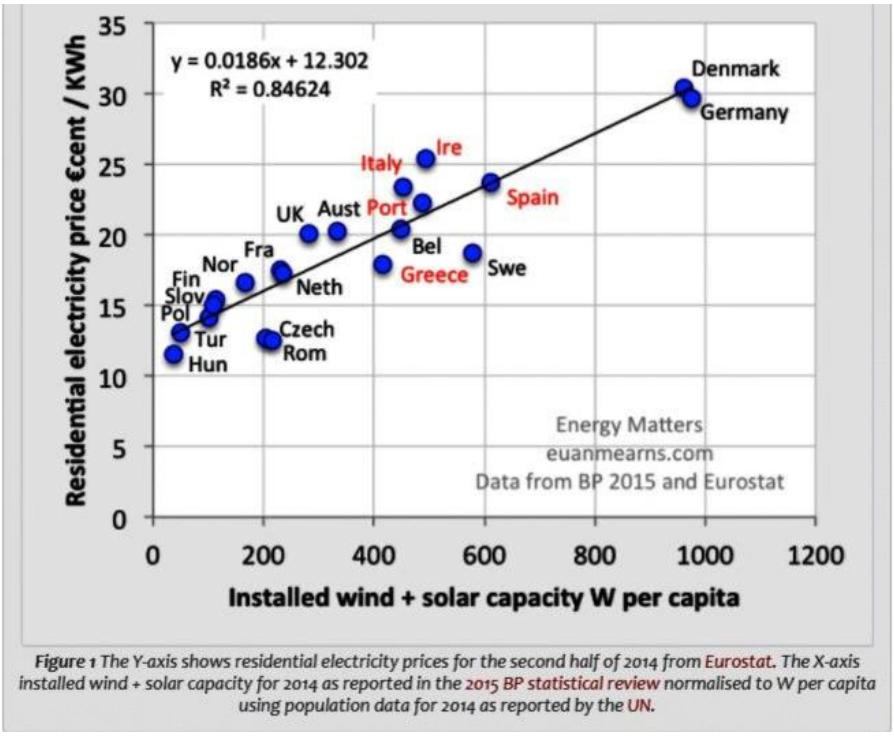
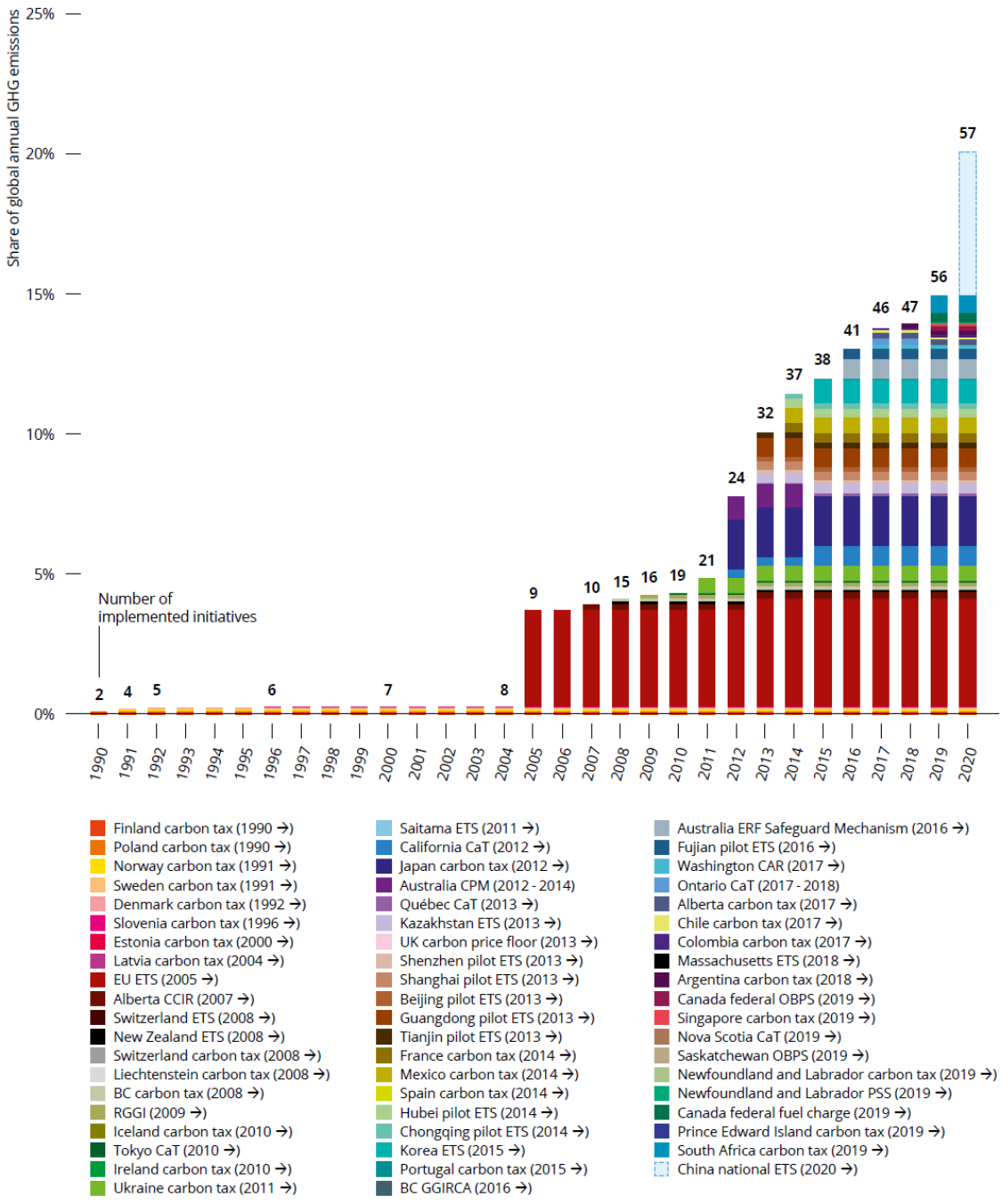


Figure 21 Europe Electricity Price versus Installed Wind and Solar Capacity (Mearns, 2017)

This, in turn, is resulting in the cost of manufacturing increasing, which makes the greener economies less competitive, but better for the environment. In order for these countries to protect their own economies, it can be expected that countries will in future start to increase the taxation on imports from other countries as a function of how clean their economies are. This is in line with the principles of the user is as guilty as the polluter or ultimately the polluter pays. This is furthermore evident through the progressive implementation of carbon taxes, by many governments around the world. As can be seen in Figure 22, the total amount of annual greenhouse gas emissions covered by carbon taxation has exponentially increased from 8% in 2008 to 20% in 2020 (World Bank, 2019). This trend is led by the countries, like those in Scandinavia, which are leading the trends of moving investment away from fossil fuels and into renewables and nuclear power.



Note: Only the introduction or removal of an ETS or carbon tax is shown. Emissions are presented as a share of global GHG emissions in 2012 from (EDGAR) version 4.3.2 including biofuels emissions. Annual changes in GHG emissions are not shown in the graph. In 2018, the Alberta Carbon Competitiveness Incentive Regulation (CCIR) replaced the Alberta Specified Gas Emitters Regulation, which was launched in 2007. The information on the China national ETS represents early unofficial estimates based on the announcement of China's National Development and Reform Commission on the launch of the national ETS of December 2017.

Figure 22 Regional, national and subnational carbon pricing initiatives: share of global emissions covered (World Bank, 2019)

5.4. Coal Power Proposition

Constructing coal power plants is expensive as well and the cost of operating them is high. However, the cost of coal, as the primary energy in these plants, has historically been very competitive. Because of the negative effect that these plants have on the environment the requirements for cleaning functionality is continuously being increased, adding substantial additional capital cost to both old and new coal powered plants. Some of these costs are listed in Table 2 (Nalbandian-Sugden, 2016). As can be seen by a report commissioned by the African Development Bank Group, even recently constructed coal power plants, like the Medupi Power Plant constructed in South Africa are already required to retrofit additional cleaning mechanisms (African Development Bank Group, 2018). As described above, the operational cost is furthermore increasing as a result of carbon taxation (World Bank, 2019). These principles will ultimately escalate the overall cost of power produced from coal, to more than the other technologies, making power produced from coal unaffordable. It would therefore not be advisable for SADC to continue construction of further coal plants. This realization is furthermore evident in the 2019 South African Resource Plan, showing most of the current coal plants being decommissioned over the next two decades and limited new coal capacity being installed (Department of Mineral Resources and Energy, 2019).

Table 2 Capital costs of SO_2 NO_x and PM control technologies, 2011 US$/kW (Nalbandian-Sugden, 2016)

Control technology	50 MW unit, US$/kW	200 MW unit, US$/kW	600 MW unit, US$/kW
Wet FGD scrubber	904	734	513
Spray Dry FGD scrubber	774	628	448
Duct sorbent injection	42	39	39
Selective catalytic reduction	273	234	188
Selective non-catalytic reduction	51	51	51
Fabric filtration/baghouse	504	387	219
Activated carbon injection	29	27	19

South Africa is already one of the largest operators of coal fired power plants in the world and therefore one of the largest generators of CO_2. As a result, this study assumed that coal, over and above what is currently being constructed, is no longer a credible source of power generation. It is unlikely to be constructed on a large scale into the future and the use of coal was therefore not considered as an option. This study assumes that the required money will be invested to maintain the current coal plants in the region. For this analysis the availability factor of the current coal fired plants will therefore remain at 70%, as projected in the South African IRP (2019) (Department of Mineral Resources and Energy, 2019)

5.5. The natural gas power proposition

In recent years the world has seen a strong trend to diversify to the use of natural gas. All the countries around the coast of SADC have offshore natural gas deposits. With the exception of Namibia, these fields are significant in capacity. The historical exception was South Africa. However, towards the end of 2018 it was announced that a major natural gas field, off the South coast of the country, had been identified. Nonetheless, the natural gas from the South African field is currently committed to be used for manufacturing of fuel. It is feasible to assume that all these countries, except for South Africa, will make use of this resource for power generation.

Even though, when compared to coal, it is a much cleaner source of energy, it still produces vast amounts of CO_2. The carbon taxes, as explained previously, will therefore still apply. Open cycle natural gas plants are relatively cheap to construct, when compared with other technologies, like coal. These plants show an early return on investment, when compared to other technologies. However, they are not very efficient and this increases the environmental footprint. The real benefit of natural gas plants can only be realized through the use of combined cycle plants. However, the cost of combined cycle plants increases the cost to be similar to that of coal plants, and also requires large capital investment. Since this technology is currently still supported by

most countries, it can be assumed that it will remain an option to be constructed and operated in the medium term.

Natural gas prices have historically been very volatile. However, since 2009, the price has stabilized and has remained low for the last decade. As carbon taxes increase further, the operational pressures on this technology will start to become more prohibitive thereby offsetting the advantages. Many of the large natural gas powered economies, like those in the Middle East and Asia, have come to realize this and have started diversifying by installing other technologies, including large scale nuclear.

Considering the fact that power generation from natural gas still has a significant environmental impact, it can be assumed that the technology will gradually fall out of favour and become progressively more expensive to operate. Currently, the amount of CO_2 being produced every year, from the use of non-coal based fossil fuels, to generate electricity, is significantly more than what is being generated in coal based plants (International Energy Agency, n.d.). The cost of natural gas is furthermore controlled by the international spot price and is therefore not directly within the control of the country making use of the resource. It is therefore prudent for any country to limit their exposure to this single source of energy. For the purposes of this study, natural gas was therefore limited to not be more than 1/3rd of the overall installed capacity for any specific country.

The international average availability factor for natural gas plants is 50% which is the amount that was assumed for this study (International Energy Agency, n.d.).

5.6. The Renewable Power Proposition

Worldwide, renewable power generation is on the increase. However, challenges with availability factor, lack of predictability and inability to control the output is limiting the percentage actual penetration into the generation environment. Countries, like Germany, that have achieved high levels of penetration, invariably rely on neighbouring countries to compensate for the variability, at huge cost. In the SADC region there are no neighbouring countries or regions that can compensate for this variability. Exceeding 30% of renewable energy generation, on a large scale, invariably results in significant reconfiguration of grid designs and operational methodologies, especially if there are no neighbours to rely on. Very few countries have currently exceeded this value (Nikoletatos & Tselepis, 2015).

Since renewable energy is generated as it becomes available and not as it is required, a large percentage of renewable generation still has to be duplicated in either additional generation or in the form of storage, thereby further reducing the contribution of the power source and further escalating the cost. The cost of this additional infrastructure is normally not accounted for in the capital cost of installing renewable technologies, even thou a grid cannot be operated reliably without compensating for this aspect of renewable energy. Financially, therefore renewable power generation only makes sense when the power source which is used to compensate for the variability is more expensive to operate than the renewable itself or if the renewable extends the availability of another form of power that is limited by resource availability. In SADC, the latter is true for the hydro plant capacity.

Since the major cost of operating technologies making use of Rankine steam cycles is normally attributed to maintenance and salaries, and not to the cost of the primary fuel, renewables do not compliment coal, nuclear and combined cycle natural gas power very well. If there is an over investment in renewable power it results in a situation whereby; when the sun is shining and the wind is blowing, the renewables are generating and the steam based power plants have to reduce load in order control the frequency of the system. However, for the steam plant the salaries and maintenance cost remains the same. For nuclear plants, since refueling outages are preplanned, there is also no saving in fuel cost. When this happens there is little to no reduction in expenses on the plant compensating for the additional generation, but the revenue reduces for these plants. They cannot be taken off line, because when the sun goes down and the wind stops blowing, they have to be ready to take over the load again. This configuration results in grid capacity being duplicated, which increases both the overall capital cost and the operational cost, with no actual benefit for the country or the consumer. Ultimately it increases the cost of electricity.

Open cycle natural gas turbines are cheap to build and to operate. However, they are inefficient, thereby escalating the operational cost directly associated with fuel. These features makes them ideal for being installed for the purposes of operating during peak loads and they are a more appropriate technology to compensate for the variability of renewables.

When trading off hydro and renewables, there is a good interrelationship in areas where there is a limitation on water storage capacity. In this case, when the renewable is generating and the hydro plant powers back to compensate, water (fuel) is preserved, to be used another day. In this case, these two technologies are therefore symbiotic. As the use of renewables increase, it would be advisable to incorporate storage technology with traditional hydro generation objectives when designing and constructing new dams and hydro plants. This will greatly reduce the cost of provision of storage capacity, thereby facilitating the use of more renewable sources, and limit excessive additional capital cost.

It can therefore be concluded that there is limited benefit in installing renewable capacity that exceeds the open cycle natural gas and water limited hydro capacity, unless additional water storage is built to accommodate the renewables. However, in such a scenario, the capital and operational cost of the water storage has to be included in the cost of the renewables.

Instantaneous power capacity from hydro can be greatly extended by installing additional hydro capacity, over and above what the source can provide on a continuous basis, when this capacity is offset against renewables. This system allows for hydro to be run when the renewables are not available, thereby saving on the need for additional water storage schemes. However, the overall amount of energy being produced still remains the same and will therefore have no effect on the outcome of this study.

Being a modern form of power generation, and because it incurs no primary fuel cost, it is accepted that countries will maximize their exposure to renewable energy. The main limitation on the overall capacity for renewable energy is the ability to maintain grid stability and to offset the variability against other generation options, including storage options. Internationally a penetration of up to 30% is considered to be manageable without extensive storage ability. Above this, grid stability is affected and when used in conjunction with steam cycle technologies, the additional capacity cannot be utilized effectively.

The study assumed a load factor of 30%, which is generous for renewables. It is anticipated that the financial implications of investing in renewable energy beyond the hydro and open cycle natural gas capacity, as described above, will not be observed initially and, if eventually required, storage plants will be constructed to compensate. It was therefore assumed that, due to the large amount of sunlight and wind in the region, all the countries in the region will maximize this option. Considering all the risks listed above, this study limited the penetration of renewables to 1/3rd of the overall installed capacity.

5.7. The Nuclear Power Proposition

Since the 1960s Nuclear Power has formed a substantial part of the energy being produced in the developed and, more recently, developing countries. However, to date, in Africa, only South Africa has made use of this technology in the form of Koeberg Nuclear Power Plant, a 2GW Pressurized Water Reactor facility, situated close to Cape Town.

Nuclear Power can be deployed almost anywhere, with the most limiting consideration the cost of constructing a plant in areas where there is an increased risk of seismic activity and, to a lesser extent, other potential natural risks, like cyclones and tsunamis. The fuel is compact and can easily be transported to remote locations, as is the waste, which is small in size and quantity and can just as easily be transported to adequate storage facilities. However, the spent fuel has to be reprocessed or stored in suitable facilities for a long time.

As per Figure 14 the cost of nuclear fuel is market related. In times of high demand, high confidence and low supply, the price increases. When demand and/or confidence decreases the price reduces. This fluctuation indicates that an over investment in nuclear power will be detrimental from a risk based as related to the cost of uranium. However, since uranium is a natural resource, which occurs in the region, the cost fluctuation will be somewhat offset for the region, provided that the mining rights are held locally and the money is incorporated back into the local economy. If the nuclear industry in the region expands sufficiently, it would become financially viable for the region to enrich and manufacture the fuel for the plants locally, thereby adding more beneficiation to the raw product and further stabilizing the cost.

For the deployment of nuclear power it is important to ensure a strong regulatory authority working within a well-established legal framework, responsible for overseeing safety and compliance. Such an authority needs to establish and implement clear licensing requirements for construction, operation and decommissioning. The risk of proliferation needs to be managed and mitigated through a strong international affiliation to the relevant bodies (International Atomic Energy Agency, n.d.).

Large scale Nuclear Power plants operate at just above the saturation point of water, but below the triple point. For this reason the enthalpy of the steam is low, thereby requiring large steam flows (Kehlhofer, et al., 2009). These large steam flows require large turbines to convert the energy into rotating mechanical power. For this reason the centerline mass of the main turbines is high, thereby providing a large amount of inertia to the electrical network. This in turn provides essential stability to the transmission systems where these plants are utilized and makes them ideal for being deployed in remote areas on long transmission lines. This additional stability then provides margin to allow for more, non-synchronized technologies, like renewables to be installed, which is also ideally suited for outlying and remote regions and locations.

One of the drawbacks of nuclear power plants is the extremely low, but possible risk of having a nuclear accident. Building nuclear power plants in close proximity to highly populated areas should therefore ideally be avoided. Because the population in outlying and remote areas is typically very low, nuclear is more suitable to such locations.

These aspects of nuclear power generation make it an ideal technology for increasing economic activity in underdeveloped and outlying regions. The construction of nuclear power plants in such regions will create an inflow of money in these areas, thereby increasing economic activity and uplifting these communities.

The overnight capital construction cost of new nuclear power plants, when compared to other technologies, is high. But, once constructed, these plants will be operating for 60 to 80 years into the future, thereby providing a long term return on the investment. This is furthermore supported by the fact that the life expectancy of the Koeberg nuclear power plant is, like most other nuclear power plants in the world, being extended, while most of the fossil plants in the region cannot be extended (Department of Mineral Resources and Energy, 2019).

At between 85% and 95%, depending on the type of reactors, the availability and capacity factor of the technology is the best in the industry. This makes the technology highly reliable and a consistent power generator. This is furthermore supported by the fact that the technology is not affected by climate change, weather and environmental conditions.

Nuclear power plants furthermore provide much needed additional stability to large electricity grids. Due to the potential of nuclear plants to be constructed in remote areas, this feature is furthermore very useful to stabilize long power lines when the technology is deployed in such regions.

5.8. The Power Deficit

Table 3 provides a summary of the proposed energy mix.

The table equates the current population of each of the countries into real capacity required. It then lists the current installed capacity. This is converted into actual capacity by applying a load factor of 70%, which is optimistic for the current reliability of the infrastructure in the region (refer to 1.12). From these numbers the current, actual, capacity deficit can be calculated.

The total remaining potential hydro power capacity, in each country, is then listed. As discussed in 1.14 a load factor of 40% is assumed. This provides the potential capacity for future hydro.

Table 3 Potential Capacity for Nuclear (GW)

	Population (mil)	Required Capacity	Current Capacity	Capacity after current load factor	Real current shortfall	Potential additional Hydro capacity	Actual Hydro after load factor	Real shortfall after Hydro	Potential additional Natural Gas capacity	Actual Natural Gas after load factor	Real shortfall after Hydro and Natural Gas	Potential additional Renewable capacity	Renewables after load factor	Real shortfall after Hydro, Natural Gas and Renewables	Additional capacity for Nuclear
Availability Factor				70%			40%			50%			30%		90%
DR Congo	82	66	3	2	64	40	16	48	49	25	23	49	15	8	9
South Africa	55	44	50	35	9	0	0	9	0	0	9	25	8	1	1
Tanzania	54	43	2	1	42	5	2	40	26	13	27	26	8	19	21
Angola	29	23	3	2	22	5	2	20	15	8	12	15	5	7	8
Mozambique	27	21	3	2	19	7	3	17	14	7	10	14	4	5	6
Malawi	19	15	0	0	15	1	0	15	0	0	15	8	2	12	14
Zambia	17	14	3	2	12	7	3	9	0	0	9	8	2	7	7
Zimbabwe	14	11	2	1	10	7	3	7	0	0	7	7	2	5	5
Namibia	3	2	1	0	2	0	0	2	1	1	1	1	0	1	1
Botswana	2	2	1	0	1	0	0	1	0	0	1	1	0	1	1
Lesotho	2	2	0	0	2	1	0	1	0	0	1	1	0	1	1
Swaziland	2	1	0	0	1	1	0	1	0	0	1	1	0	1	1
	305	**244**	**66**	**46**	**198**	**73**	**29**	**169**	**106**	**53**	**115**	**157**	**47**	**68**	**76**

The same principles are then used to calculate the potential contribution of natural gas. The total installed capacity for natural gas is limited to 1/3rd of the total projected installed capacity. This capacity is then corrected with a 50% availability factor. For South Africa, since the discovery of natural gas is a new development, and it would appear that this is currently destined for being processed into fuel, the capacity has been assumed to be 0 for the country. Finally, renewables are listed for each country, with a 1/3rd installed capacity limit and a 30% availability factor as explained in 1.19.

Since the assumption of not installing more than 1/3rd of the overall capacity in natural gas and 1/3rd in renewables, the analysis had to be performed using a number of iterations. Once an iteration has been completed, the resultant installed capacity was used as the input for the next iteration. The model converged after 3 iterations.

From the table it can be seen that the total shortfall in capacity for the region is close to 200GW. If converted to installed capacity shortfall, using the resources discussed, the installed capacity shortfall is almost 400 GW. The model therefore proposes that the following new capacity will need to be installed for the region:

- Hydro: 75 GW which is the maximum capacity that remains in the region.
- Natural Gas: 105 GW, which constrains each country by not investing more than 1/3 of the capacity in natural gas.
- Renewables: 150 GW which constrains each country by not investing more than 1/3 of the capacity in renewables.
- Nuclear: 65 GW which will ultimately equate to 14% of the capacity consisting of nuclear.

Of interest is the fact that the original assumption of a 70% average availability factor across technologies, resulted in an estimation of an overall installed capacity of 348 GW. The methodology used in the analysis, considering the availability factors of the different technologies separately and with the assumed constraints, results in a total installed capacity of 460 GW being required. The reason for this difference is because the 70% availability factor is representative of the currently installed technologies, most of which is coal based. With the exception of nuclear, all the other proposed technologies operate at an average availability factor below 70%, with renewables being as low as 30%. The last column indicates what the additional capacity would be if nuclear is used to bridge this deficit. For nuclear an availability factor of 90% was assumed (refer to 2.4.6).

Figure 23 provides the breakdown in capacities of the different technologies that the model proposes.

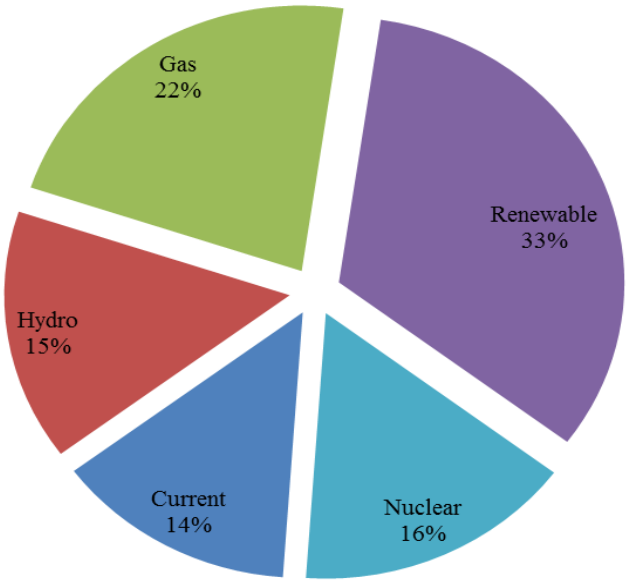


Figure 23 Proposed Installed Capacities by Technology

From this breakdown, at 33%, it can be seen that renewable power becomes the bulk of the installed capacity. This large amount of renewable energy is in line with the strategic direction of most countries in the world.

This is followed by gas, which is still a CO_2 generator, at 22% of the capacity. When considering that the current capacity is mostly coal based and it currently accounts for 14%, that means that the additional gas capacity will double the carbon footprint of the region. Such a trend is contrary to the global objective to reduce carbon emissions.

At 65GW, the nuclear power capacity will account for 16% of the overall, which is the same capacity as France and is more than the current capacity in China. At 16%, the relative capacity is similar to what is installed in the USA, which is 20%, but more than the world average of 10%. However, it is important to note that the traditional technology of choice instead of nuclear has been coal and as discussed already, this is not, in the longer term, a feasible option for SADC.

Hydro Power will constitute 15% of the overall capacity, which is the maximum capacity that can be utilized in the region.

While solar power only operates during the day, wind power generates at night as well. Although still variable, over as large a geographical area as SADC, the variability of wind will be mitigated to some extent. This means that wind will, to some extent supply base load capacity, even though the region where it will be generated will constantly be moving around. However, the rest of renewable generation will still be highly variable. As discussed in 5.6 it is possible to over invest in renewable energy when the capacity starts resulting in base load power plants having to compensate for the variability of the renewable power. Depending on the percentage of renewable base load power, the remaining percentage of capacity should ideally be balanced with the hydro power capacity, thereby optimizing the contribution of both technologies and minimizing the need for additional storage capacity. The 33% renewable power in relation to 15% hydro power implies about 15% base load capacity from wind, which is more than what is

likely to be achieved in practice. This suggests that the 1/3rd assumption of renewable power is probably more than ideal when considering the overall hydro capacity in the region.

This spread will result in over 60% of the installed capacity to be non-carbon based sources, which will place the region amongst the leaders in combatting global warming even though the amount of CO_2 being generated will be doubled.

Due to the fact that the different technologies have different availability factors, the amount of energy being derived from each technology will be different. Figure 24 shows this spread of energy per technology type.

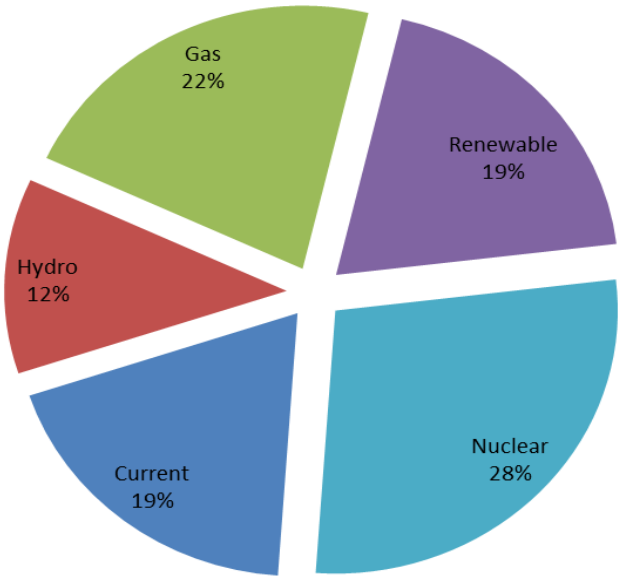


Figure 24 Resultant Energy produced per technology

When considering the energy contributions from the different technologies, the breakdown changes considerably from the breakdown based on installed capacities.

In this breakdown, nuclear contributes the largest amount of energy at 28%, or more than ¼ of the overall. Nuclear therefore contributes almost double the percentage of energy in relation to its percentage of installed capacity. This aspect demonstrates the highly reliable nature and predictable dispatching options that nuclear provides. With this contribution it will also become the energy back bone of the network, even though the installed capacity is only 16%.

Natural gas contributes 22%, which is on par with the 22% installed capacity. This indicates that the availability factor of the natural gas option is the statistical mean of the proposed spread of technologies.

The energy from renewables is slightly higher than from hydro power, implying that the balance between these two technologies is optimum. As discussed earlier, the significantly higher installed capacity from renewables in comparison to hydro power is still a concern. However, considering the large geographical area, it is highly unlikely that the renewable resources will ever deliver the full capacity at any given time. That mitigates this concern to some extent and supports the relation with regard to the energy produced.

The relatively even spread of energy contribution by each of the technologies minimizes the risk that each poses. The model shows that only about 40% of the energy will be produced by CO_2 producing technologies, which is not ideal, but is much better than most other countries and regions in the world.

The contribution from nuclear power will still be relatively high. However, this has to be considered against the fact that hydro power will be maximized and as discussed in 5.6 and earlier in this chapter, there is little benefit in increasing the amount a renewable energy much above the hydro power capacity. Increasing the amount of renewable energy will only decrease the energy contribution of nuclear, natural gas and of the currently installed capacity. That leaves only natural gas as an alternative to nuclear power, which will increase the amount of CO_2 being produced and the difference in

energy produced between the two options is only 6%, leaving only a possibility for a 3% change before natural gas becomes dominant.

The final spread of capacity, per technology type, that is proposed for each country is shown in Figure 25.

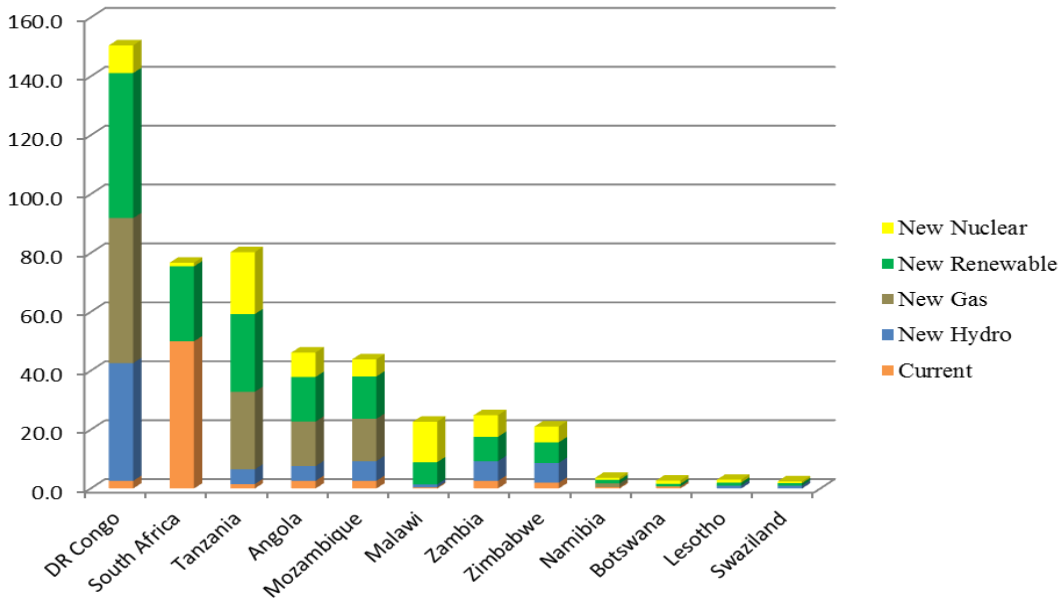


Figure 25 Projected Capacity by Technology Type for each country

The model prioritizes the use of the current infrastructure, hydro, natural gas and then renewable. The nuclear power option is therefore regarded as a last resort option.

Although the DRC has the highest population and is therefore projected to eventually have the highest demand for electricity, it is also the country with the most available resources for electricity generation. The abundant availability of hydro power options and natural gas reserves, results in a low projected percentage contribution from nuclear power. However, because of the large overall installed capacity that is being projected for the DRC, the absolute amount of nuclear power is still notable for the region.

Both South Africa and Malawi have very limited to no hydro and natural gas options. That only leaves renewable energy and nuclear power as an alternative. South Africa does however have the benefit of a large, already installed, generation capacity of 50 GW, thereby minimizing the need for additional nuclear. However, as this already installed capacity reaches the end of life and is decommissioned and the maximum practical renewable capacity is reached, nuclear will become the only alternative. This could change if the gas reserves discovered in 2018/2019 is adequate to provide adequate amounts of natural gas for power generation. Malawi on the contrary does not have any other options and will eventually have to derive the bulk of its generation from nuclear power, by installing up to 14GW. The eventual high percentage of renewables and traditional coal in these two countries will make the optimum use of the renewable power dependent on the hydro capacity of the neighboring countries. If the grid infrastructure cannot accommodate this then the benefit of the additional renewable energy will be reduced.

Tanzania, Angola and Mozambique all have limited hydro power capacity of between 5 and 7 GW, but do have extensive natural gas reserves. Zambia and Zimbabwe, on the other hand, have additional hydro power capacity of 7 GW each, but no gas reserves. In order to compensate for the lack of one of the potential sources of energy, all five these countries will require some nuclear power capacity, with Zimbabwe requiring the lowest at 5 GW and Tanzania the most at 21 GW.

Figure 26 shows the amount of energy, once the load factor for each technology has been applied to the installed capacity, that each country will be deriving from the different proposed technologies, once rolled out.

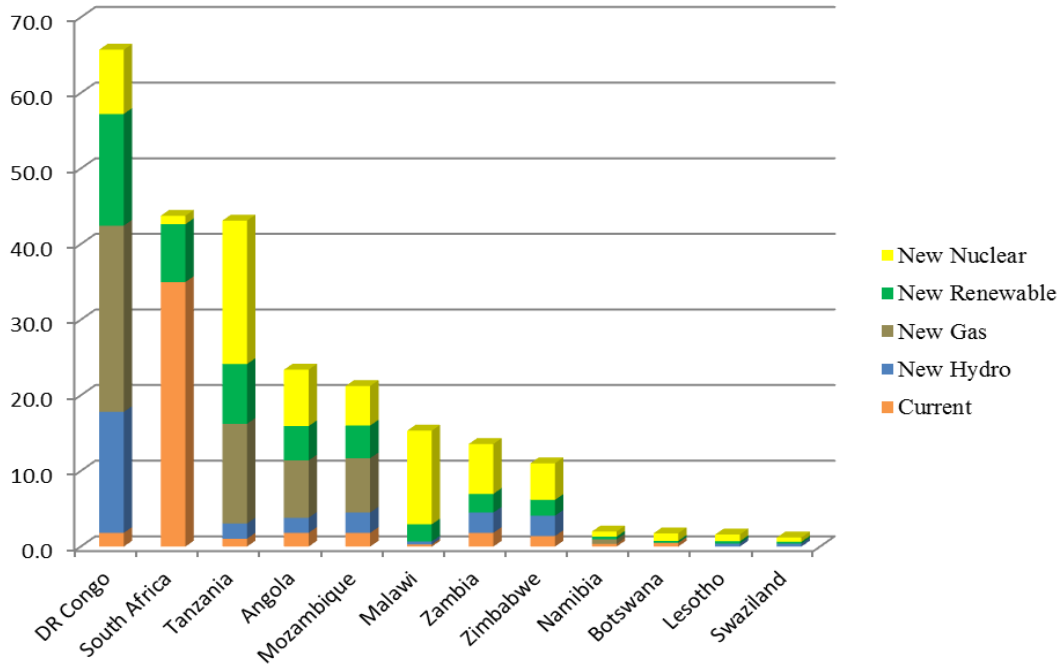


Figure 26 Energy produced per technology per country

As could be seen for the regional assessment of energy provided, the dominance of the nuclear option becomes evident once the capacity factors are incorporated into the analysis. This is as a result of the higher than average availability factor of nuclear power plants.

For the DRC, even with the large hydro capacity, at almost 40% or 40 GW installed, the dominant energy generation technology becomes natural gas.

Because of the already large installed capacity in South Africa, the additional nuclear power makes very little difference.

For Tanzania, at 19 GW, the projected energy contribution from nuclear is almost half of the overall. This is mainly as a result of the larger size of the population combined with the lack of hydro power options. For Angola and Mozambique, the population is smaller than in Tanzania, making the impact of the lack of hydro power options less dependent on nuclear. Nonetheless, nuclear power, at between 5 and 7GW, will still be contributing about ¼ of the energy in these countries. The same is true for Zambia and Zimbabwe, but in these cases it is the lack of natural gas that drives the need for nuclear power.

Malawi, having no hydro power options and no natural gas will be almost entirely dependent on renewables at 8 GW installed and nuclear power at 14 GW installed. This is the same situation that South Africa would have been in, was it not for the already large coal based installed capacity.

It can also be seen that, with the exception of South Africa and Malawi, the interaction between renewable generation and hydro power can be relatively well managed internally by all the countries. However, South Africa and Malawi will be dependent on the rest of the member states to ensure that their Rankine based technologies do not end up having to compensate for the variability of the renewable generation.

Some countries that have an environment that benefits certain technologies more than in some of the other countries, like Namibia for nuclear and Botswana for renewables, could opt to install more than what they require, with the aim at exporting energy.

5.9. Validation

The results of the model produce a balanced and considered use of all the available resources in the region, using sound logical principles. It demonstrates how the energy independence of each country can be secured, while the region as a whole benefits from a well-balanced distribution, thereby minimizing the risk introduced by any specific resource. It also confirmed how the resource spread in each country is different and how some countries will be more dependent on certain resources than others. However, it ultimately provides a good balance between different risks in the region.

The maximum utilization of the hydro power opportunities are utilized, extensive use of both natural gas and renewable power is predicted, but without taking unnecessary risk on the future of natural gas use and considering the practical limitations of the use of renewable power generation, taking into consideration variability and optimization of investments. The result is that the overall contribution of nuclear power is less than what is used in the United States of America, but more than the world average. However, the world average still makes considerable use of historical coal generation, a step in the natural historical progression that the SADC region will, with the exception of South Africa, be able to skip, allowing for an earlier investment in renewable energy and in nuclear power. Ultimately the model produces a more balanced approach to the utilization of resources and risk mitigation of the different technologies.

The model is furthermore validated by the strategic alignment with the South African Integrated Resource Plan, which plans and predicts diversification away from coal and initially onto renewable power and eventually also onto nuclear power.

STABILITY MAPPING

Alternating current networks provide many advantages like the ability to change the voltages and to tap power off and feed power into the system without much difficulty, as well as the ability to control the supply and demand balance by controlling the speed of the system. However, they do suffer from stability challenges, especially when being used over extended distances. The reason for these stability challenges is as a result of the fact that the long lines result in reactive power changes and the fact that synchronism has to be maintained between all the different parts of the network.

Large cities and factories operate many rotating machines that provide extensive momentum to the network, but also cause an increase in the reactive power component, thereby suppressing the voltage on the network and increasing the current flow. Power plants that make use of large rotating generators similarly provide rotational momentum to networks and compensate for the reactive power component induced by consumers (Eremia, et al., n.d.) (Liu, 2015) (Migliavacca, n.d.). The heavier the rotating center lines of these power plants are, the more angular momentum they provide and the more they contribute to ensuring system stability.

For these reasons AC networks are the most stable close to the load and generation centers. As the distance from these centers increase and the damping effect from the combined industry and power generating entities decreases, the stability of the AC networks decreases. While there are modern technologies like high voltage capacitors and inductors that can assist in controlling the reactive power components and voltages on long power lines, these cannot fully replace the stability that large rotating machines provide.

Large high voltage AC systems have been operated reliably across the world for many years. However, as discussed above, there are practical limits to how long high voltage AC networks can operate without the provision of angular momentum stability. This model uses circles, with the center of the circle at the load or generation center, to illustrate the distance from the load or generating center where this stability can be relied on.

Circles are therefore plotted with the generating or load center at the center of each circle. The result is that areas of the map which are not covered by circles represent regions where AC lines will be at risk of instability. In practical terms, the radius of these circles will be affected by many different parameters, like the overall rotating mass, the power being transferred, the voltage of the lines, the atmospheric conditions in the region, the use of capacitors and inductors and the size of the load center or generating plant. However, the intension of this model is not to provide an exact mathematical representation, but rather to provide an indicative picture of the potential areas of vulnerability in the region.

Considering the fact that Eskom has reliably operated 400kV lines between Johannesburg and Cape Town and between Cape Town and Windhoek, both distances of close to 1 400 km, for many years, the model used a stability radius of 500 km. The reason for the slightly lower radius is the fact that the high loads on both these lines provide additional stability that might not be relevant to all the future lines in the region.

By considering the shortfall in each country that would potentially have to be filled by nuclear and by comparing this shortfall against the integrated stability circles, it could then be determined where nuclear power would ideally be beneficial to the region, if at all.

6.1. Considerations of Locality

Most forms of electricity production require the presence of a natural resource in close proximity. By studying the distribution of these resources it was possible to identify areas where nuclear power could be beneficial and areas where other forms of energy would be more appropriate.

By studying the current and planned infrastructure layout of SADC it was possible to identify the long term shortfall in planned electricity production and transmission. Superimposing the projected consumption, resource layout and current infrastructure, the ideal locations for potential nuclear power plants was then derived.

Figure 27 maps where the largest mineral resources in Southern Africa can be found. These are predominantly located just east of the North-South center line of the continent. Mining and processing is heavily dependent on extensive electrical capacity and security of supply in order to operate. These areas will therefore require extensive power resources to facilitate both the mining and processing operations (African Bank, 2007).

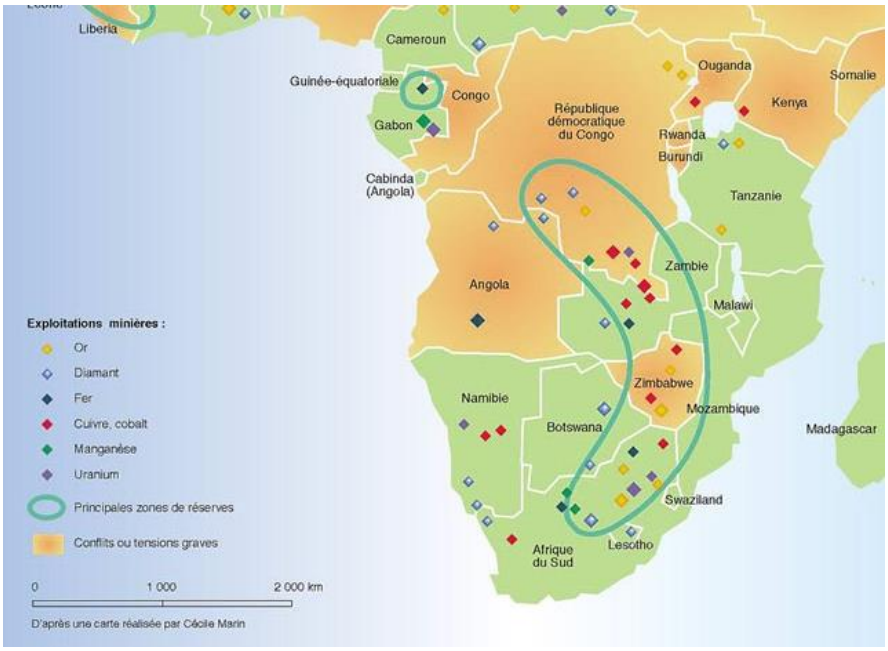


Figure 27 Mineral Resources in SADC (Rekacewicz, 2000)

The 1st level of beneficiation, which typically involves the extraction and separation processes are normally located close to transport infrastructure or large power production centers. The second level, involving manufacturing are mostly located in and around the large cities.

As a result of geotechnical considerations, construction requirements, types of fuel and economic practicalities, some technologies will not be suitable for some locations, areas and countries. These limitations were identified and incorporated into the analysis.

6.2. Benefit Considerations

Due to the nature and types of technologies, the direct and indirect contribution or the lack thereof to the surrounding area, region or country as a whole, was identified and discussed. The consideration is therefore that the technology is not only a contributor of energy, but also a contributor of other aspects of social development and economic growth.

6.3. Distribution of current Load Centers

The cities and large towns with populations in excess of 200 000 are depicted in Figure 28. Since large loads assist in stabilizing large networks, the principles associated with determining the optimal radius for the stability circles, as discussed above were applied. This clearly shows a relative even distribution across the region. However, the largest concentration of cities and populations is to the East of the center of the subcontinent and runs in almost a straight line from the North of South Africa up to Malawi, which has the highest population density in the region. This is as a result of the presence of natural resources, agricultural possibilities, water and tolerable climates.

There are a number of areas that fall outside of the stability circles around the load centers. Those regions constitute vast deserts in the South and tropical rain forests in the North. However, it also identifies areas that can be developed. In particular, the region on the border between Angola and Zambia, the South of the DRC, the South Western part of Tanzania and Southern Angola.

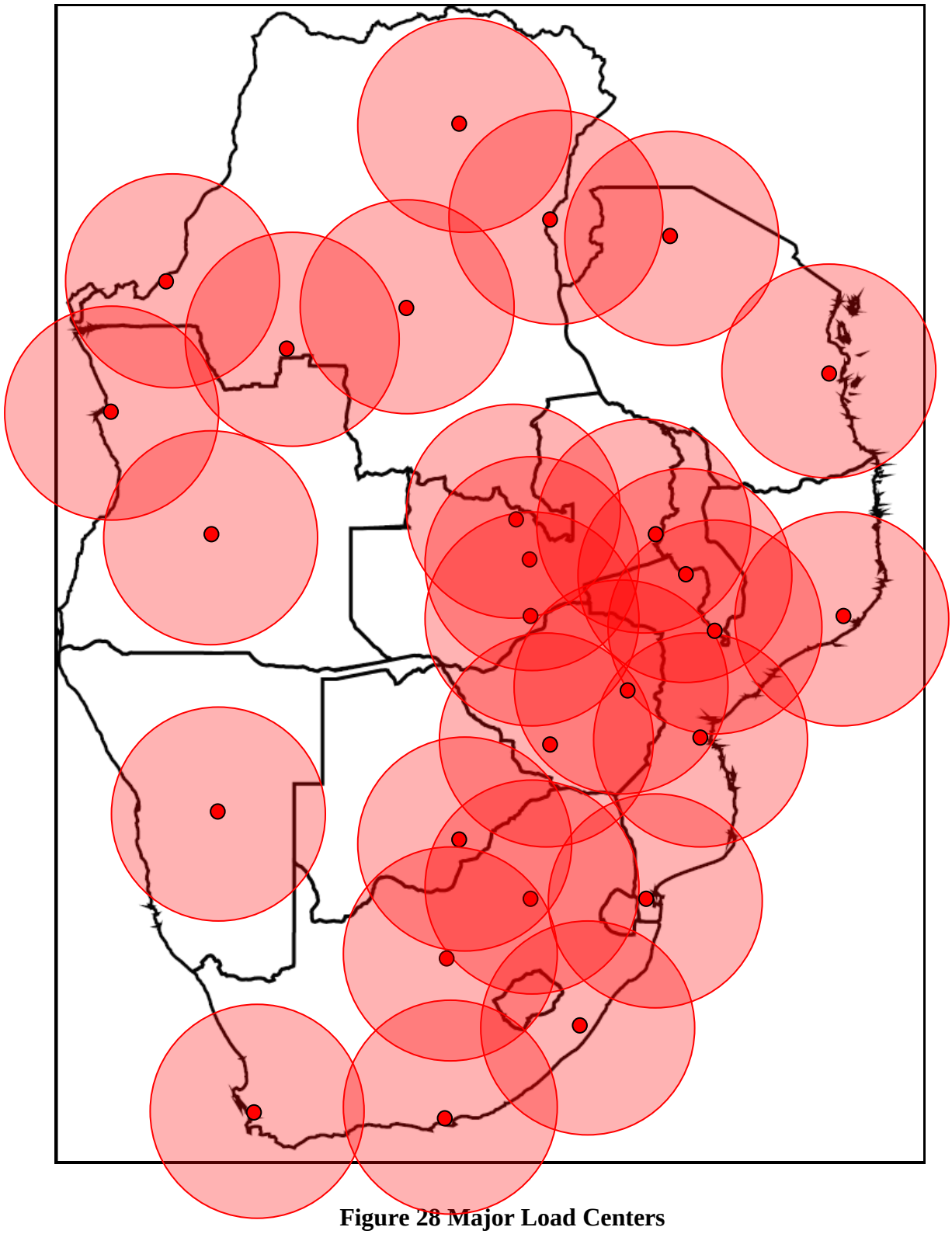


Figure 28 Major Load Centers

When comparing Figure 27 with Figure 28 it is clear how the higher density load centers overlaps with the areas where higher concentrations of mineral deposits are located. This situation is mostly driven by the fact that SADC still exports most of the natural resources and has not adequately started developing the next levels of beneficiation.

6.4. Current Generating Capacity

Figure 29 shows the current distribution of notable power generating centers within SADC. In some of these areas, where there are multiple plants in close proximity, like in the Eastern part of South Africa, groups of power plants were regarded as one entity. This was done in order to prevent unnecessary cluttering by placing multiple circles on top of one another. Each of the green circles represents the area around the generating center where the grid stability will be assured by the presence of the power plant or group of power plants. The closer the circles are to each other and the bigger the overlap, the more tightly connected is the grid and the more inherent stability is assured.

The distribution of technology, based on the regional energy resources is clearly visible. These are as follow:

- In the Southern Central part of the region, it is mostly coal based,
- In the South nuclear and diesel fuel and
- The balance on the main rivers where hydro power is used.

From this it can be seen, with the exception of South Africa, that the rest of the SADC countries only make use of water as a power source for notable generating capacity. The lack of generation capacity between the East and the West of the continent is very evident, as well as the very sparse overall capacity in the West.

It can also be seen that currently, with the exception of South Africa, those countries and/or regions that do not have access to large scale hydro have virtually no power generation capacity.

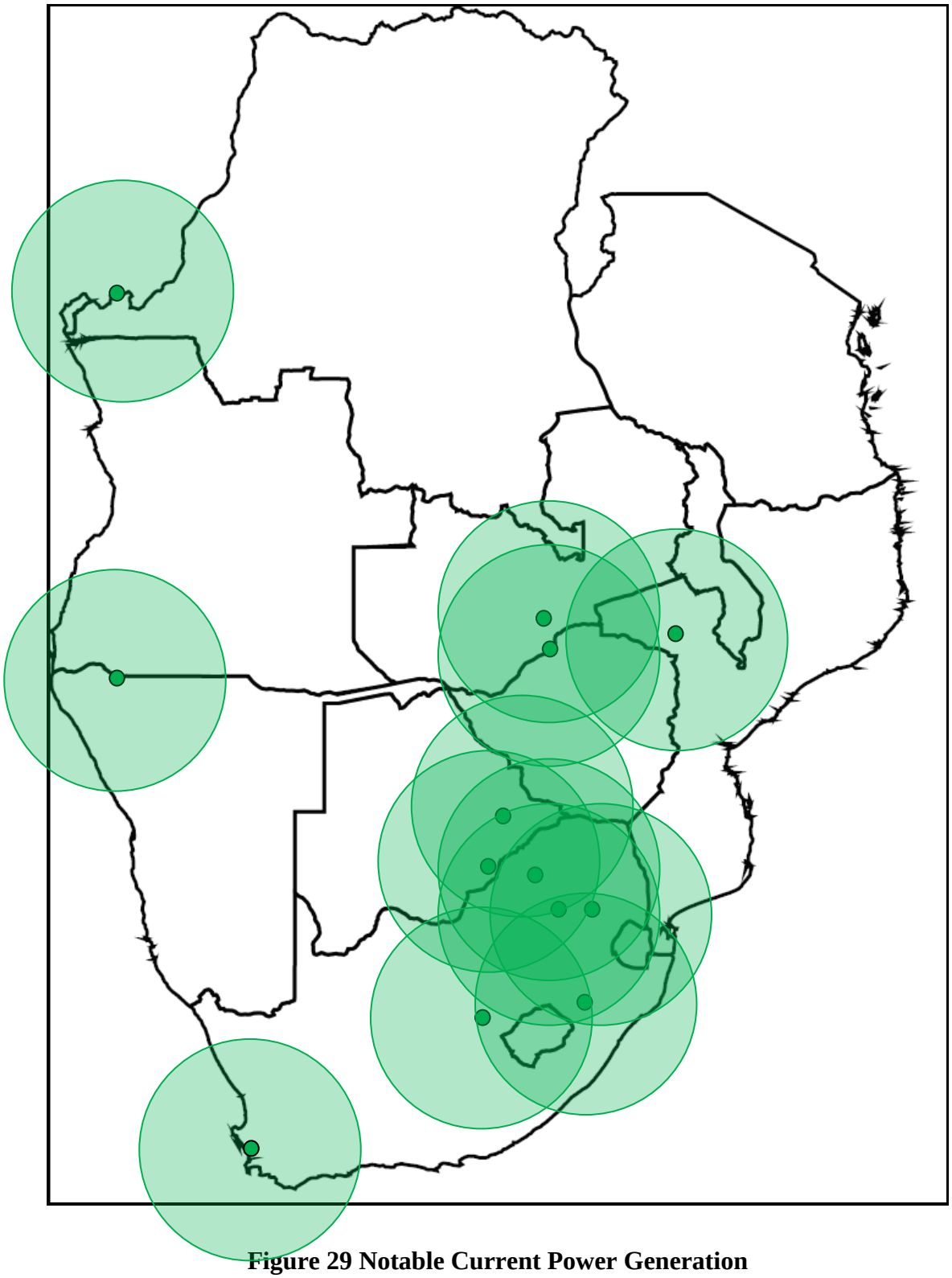


Figure 29 Notable Current Power Generation

6.5. Distribution of resources

Table 4 provides an indication of the positional relationship of fuel sources and generating plant relative to each other, when considering the siting of new power generation capacity. Transporting fuel also moves the area of beneficiation away from the fuel source. By transferring the actual fuel closer to a load center the beneficiation location is also transferred, thereby relocating the economic opportunities to a different place. Moving fuel over large distances is therefore not necessarily the optimum solution when the objectives are to also stimulate economic growth in outlying areas, thereby creating more economic hubs.

Table 4 Optimum Maximum Distances of power generation from natural fuel source

Technology	Distance from fuel source (km)	Comments
Hydro	0	Hydro power has to be constructed where the actual water source is and where the characteristics of the geology is suitable. Geological considerations include, an adequate change in elevation, a basin that can hold a large quantity of water, no underground river systems, secure bedrock for the dam wall, no geological fault in or close to the valley where the wall will be erected.
Renewable	0	Renewable power has to be constructed where the climatic conditions allow for it.
Coal	200	Coal power plants are ideally situated close to the coal fields. Coal can be transported via rail. However, that creates additional cost and overheads that have to be included in the operational considerations of the plant
Natural Gas	1000	Natural Gas can be piped over considerable distances. However, such infrastructure is very expensive and where possible, and if an integrated grid exists, utilities try to balance the length of the pipelines against the cost of a power line and the associated losses during transfer.
Nuclear	Unlimited	Nuclear power plants make use of fuel in a very concentrated format. For this reason there is no relationship between where the uranium is mined, processed and ultimately where the plant that uses the fuel is situated.

Figure 30 maps the areas where resources are located which can be utilized for bulk power generation. In most of these areas plans are already underway to construct new infrastructure. In the Southern Central region the presence of coal is currently utilized extensively. Around the coast there are large off shore natural gas deposits on the coast of Angola, Namibia, Mozambique, Tanzania and of late South of South Africa. However, the South African natural gas is currently destined for the production of fuel. With the exception of the DRC, these natural gas reserves are located off shore. Since the plants that would be utilizing these natural gas reserves will be located on land, the map placed the resource at the closest coastal point to the off shore fields. The stability circles are then drawn around that location. Since the natural gas will have to be piped to the on shore location, the position of the generation center and therefore the stability circle could therefore be moved to some extent.

The lack of natural resources in the desert areas of the continent is clearly visible. However, both Namibia and South Africa has substantial uranium deposits. Since Uranium is used in small compact quantities which are easily transportable, and has to be transported to enrichment facilities and fuel manufacturing plants before it can be utilized, the location of the uranium resource is not relevant and has therefore not been indicated on the map. There are currently no enrichment facilities in SADC. The raw uranium would therefore have to be sent to other countries for enrichment and fuel manufacturing. However, as the nuclear industry in the region grows, it will become feasible for the region to perform the enrichment and fuel manufacturing locally, thereby providing more economic opportunities and employment.

Renewable energy resources are also not depicted on the map because of the low density and of the utilization of the resource will result in a generally even spread across the sub-continent.

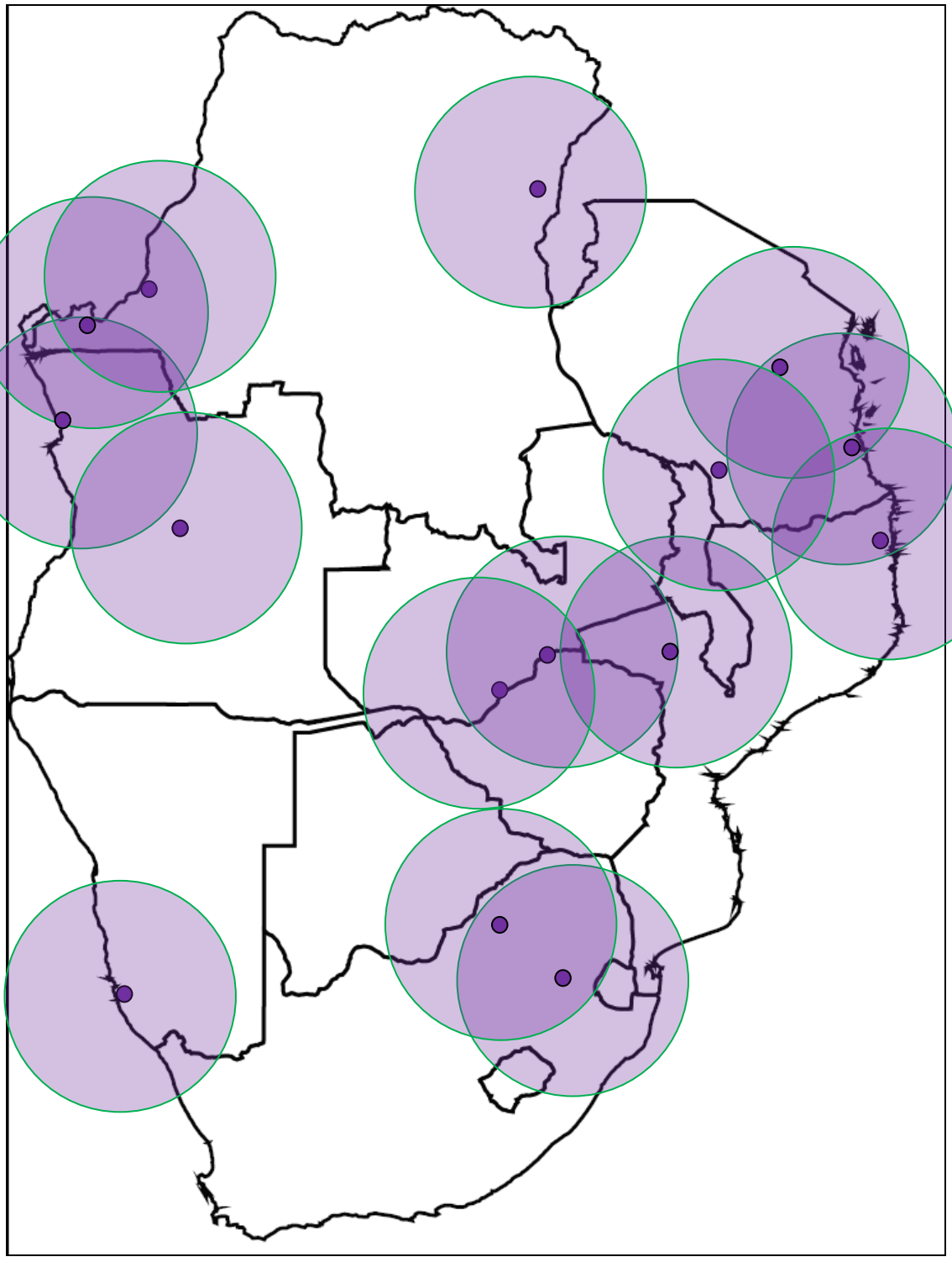


Figure 30 Distribution of power generating resources

6.6. The Stability Gaps

In Figure 31 the large power consumption blocks, current large power generation, as well as planned power generation, for the region, have all been mapped together. Where there are a large number of stability circles overlapping, the future network will have a lot of angular momentum as well as voltage and reactive power stability. This stability will decrease where the density of overlapping circles decreases. Power lines that cross the areas where there are no circles will be at an increased risk of becoming unstable, ultimately placing the entire system at risk. From this map it can therefore be determined which areas will require further stabilization in order to establish a strongly integrated network.

The reactive power component in large networks gets stabilized by large power generation as well as by large power consumption blocks. From the map it can be seen that there is a gap between the East and the West side of the sub-continent. If a large integrated grid is to be established, this gap will have to be breached by some form of load or ideally power generation. In order to create a stable integrated grid, it will not be adequate to breach this gap in only one or two places. It will have to breached in a number of places in order to allow for power to be moved around the continent in a way that will ensure that all the resources are adequately utilized.

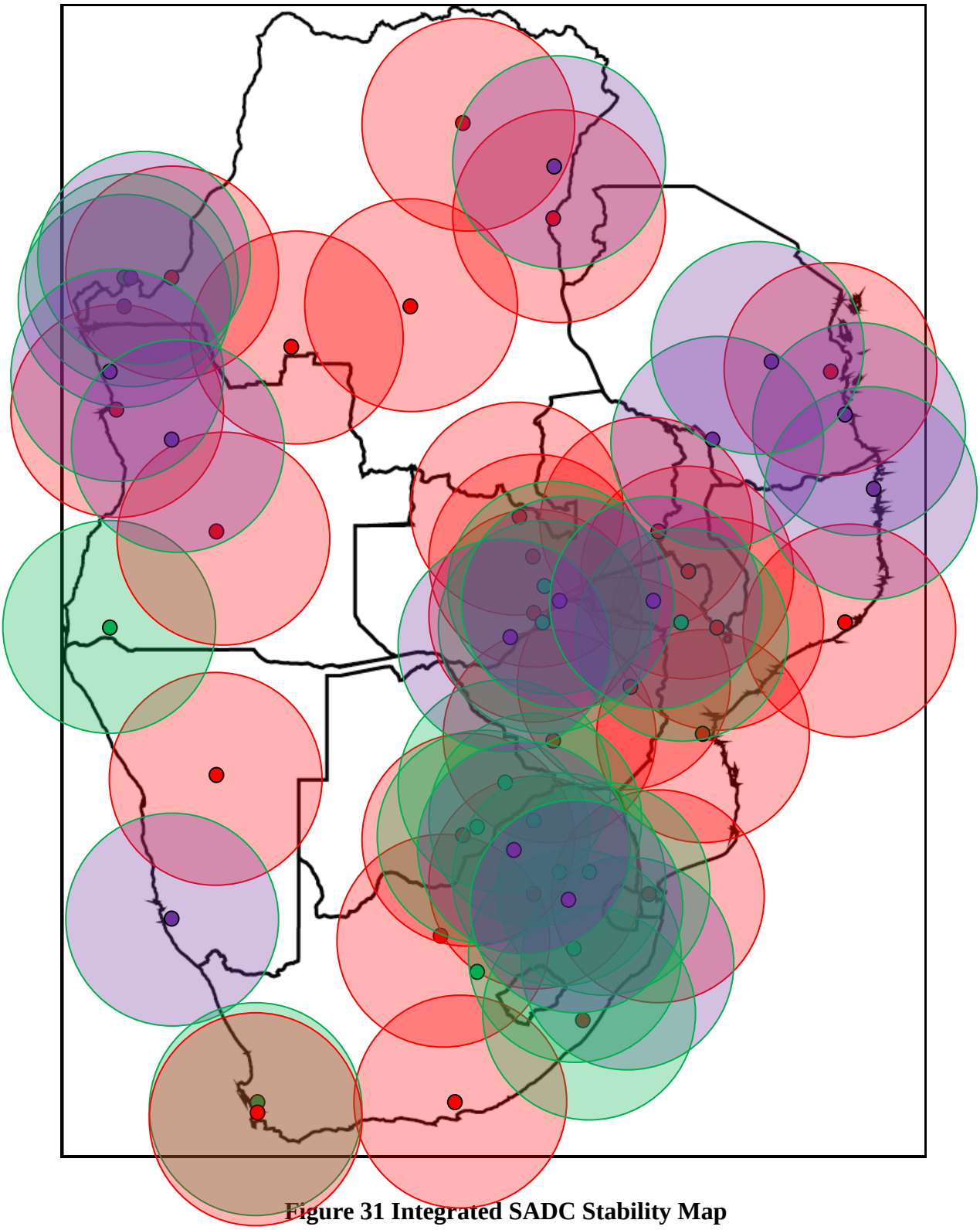


Figure 31 Integrated SADC Stability Map

From the map it can be seen that the desert areas in the north of South Africa and on the boundary between Namibia and Botswana has no large power consumption blocks, nor power generation. This is because of the fact that there is very little natural water and other natural resources in these areas. These areas have in most cases been declared nature conservation areas and are expected to remain under developed. The Square kilometer array development in the Northern Cape Province of South Africa is benefiting from this lack of development in the fact that it needs very low background interference in order to operate optimally.

6.7. Validation

From the density and proximity of the stability circles, Figure 31 shows how the currently well-established economic hubs will ultimately have a strongly integrated electrical grid, which will result in a very stable system. This situation is in line with what is seen in other highly populated and developed regions across the world. Similarly, the model shows how the rural areas will require additional stabilization due to a low density of stability circles. The map allows for a visual representation of these interrelationships and demonstrates the areas where additional stabilization will be required. It can be seen that the patterns of the corridors follow the already established transport corridors, which further supports the results that were produced. From the mapping it is possible to identify the optimum areas where power corridors can be established and allows for improved long term planning.

DISCUSSION

As depicted in Figure 32, one of the pillars of the SADC Regional Development Master Plan is energy and the access to energy (Southern African Development Community, 2012). On this basis the governments in the SADC region have committed to working together to develop an integrated power system which will increase the reliability of the overall system and reduce the cost of ensuring additional reserves.



Figure 32: SADC Infrastructure Vision

The projected energy demands for the region can be weighed up against the availability and the location of power sources. However, grid stability is equally important, as well as redundancy and diversity of supply. This redundancy does not only entail the availability of additional power supplies, but also the possibility of regional weather effects, as well as commodity prices that could impact the availability and cost of some of the generation technologies. Some traditional power generating technologies, like generating power from coal, are falling out of favour, both locally and internationally,

and can no longer be considered as a viable option for future generation. It is essential that the SADC region invests in a diversified power generation technology mix consisting of all the different forms of generation. The region should work towards an integrated grid thereby combining the benefits of the overall investment and minimizing the risks associated with the use of particular technologies.

7.1. Mehodology

The methodologies used for this report made use of three models, the results of each being used as some of the inputs to the next.

The first model made use of a comparison between the population of the SADC region and those of developed and developing countries. This comparison was used to determine the likely amount of energy that the region will require in order to achieve the same level of development as that of countries projected to be on a good path of development. While this method does not produce an exact projection, the answers did compare well with some countries that were considered and with the South African IRP.

The second model considered the limitations of and risks of the different primary energy resources that are available in the region. The availability and risks involved in the use of each of these resources were considered. Limitations were determined to mitigate undue exposure to some of the risks associated with relevant resources. From these considerations the optimum extent of deployment of each of the technologies were considered. This approach demonstrated that nuclear power will inevitably have to be incorporated into the energy mix for the region. The model was validated by the fact that the resultant energy mix was found to be comparable with that being found in other more developed countries and regions.

The third model considered the locality where each of these resources will deployed and where the power will be consumed through the use of stability circles. These circles provide a visual representation of the level of integration of a regional electricity grid that will allow for power to be moved between cities and regions, thereby further reducing risk and allowing for the optimum use of all the different power resources. The model demonstrated where such a grid will ultimately be strongly integrated and where the weak points would be that could benefit from the deployment of nuclear power in order to stabilize the region as a whole. The model is validated by the fact that the density of the stability circles is higher along the currently more developed economic areas and the patterns follow the same routes as the current transport infrastructure.

These models were utilized in order to determine the types of technologies that will be used, the extent to which they should be deployed provided that the risks inherent to each is mitigated and proposes the location of the technologies that will allow for an integrated grid to be established across the region.

7.2. Power Generation Options

Many of the countries in the region have an option to increase the hydro power capacity. However, with the exception of the DRC, this option is limited. Nonetheless, where this option does exist, it is one of the cheapest methods of electricity generation. In addition dams provide benefits for agriculture, provision of potable water and they mitigate seasonal flooding. However, dams do have a significant environmental impact and in some cases could be economically counterproductive. Hydro power plants have an additional benefit in the fact that the generators are not connected to complex turbine systems and can therefore be operated as synchronous condensers, thereby providing substantial angular momentum and voltage stability to large networks. Due to the low commercial risk of hydro power into the future, this study assumed that all the countries in the region will make full use of the hydro power options available to them.

Due to the negative impact of coal power generation on the environment this study concluded that the current coal generation will be retained, but that no new coal generation capacity will be commissioned.

With the world wide use of natural gas as a power source, it is expected that this option will be utilized extensively. Most of the countries in the region have this as an option. It has also been assumed that due to efficiency considerations, this will predominantly entail the use of close circuit gas turbines. In order to mitigate the risks associated with the extensive increases in the generation of CO_2, potential capacity limitations and the potential increase in future gas prices that this option brings, the utilization was limited to 33% installed capacity as a percentage of overall capacity.

Renewable energy is expanding rapidly worldwide. However, the variability of this resource creates big challenges both for availability factor and for on demand dispatching of energy. The lack of synchronous generators further increases the challenges associated with grid stability. The fact that the resource cannot be dispatched on demand could result in the fact that other infrastructure cannot be utilized fully, thereby duplicating investment. The beneficial interrelation between renewable energy and hydro power generation in as far as conserving water was considered. For these reasons the total capacity of renewable power generation was limited to 33% of the overall installed capacity in each country.

Nuclear power has the ability to provide reliable on demand power at very high availability factors. With the exception of the risk of natural disasters, it does not have the limitations related to locality that are applicable to many other resources. It does not generate CO_2 and provide good network stabilization. However, it is expensive to construct, but once in operation it is relatively economical to operate. It does require substantial additional governance structures and produces nuclear waste, in particular spent fuel that has to be stored for a very long time before it is safe. This option was therefore considered as the remainder option.

7.3. Proposed Capacities

When the risk mitigation strategy of limiting the over reliance on any particular source of energy as per this study is implemented, it becomes clear that all the major countries in the region will, to some extent, have to rely on electricity generation from nuclear power. Even South Africa, which currently has an already extensive installed generation capacity, will have to turn to nuclear power generation in the future. The only way that this could be prevented is to increase the investment in natural gas, but that comes with increased CO_2 generation and economic risks.

The proposed spread of energy options provides a good balance between all the different technologies. It provides for the unpredictability of renewables to be compensated for by hydro power and to some extent by natural gas. It is also clear that, although nuclear will have the lowest overall installed capacity, it will ultimately provide the most energy. From Figure 24 it can be seen that this strategy will eventually ensure that more than 60% of the energy produced in SADC will be carbon free.

Should they choose not to import power from other countries Tanzania and Malawi will eventually have to generate the most nuclear power in the region. This is mostly driven by the lack of opportunities for hydro power in those countries. From Figure 25 it can be seen that, had South Africa not previously constructed so many fossil power plants, the situation in South Africa would have been similar. As these fossil plants become obsolete and have to be shut down, nuclear power will become the next feasible option. For the other countries that have some access to hydro power opportunities, it can be seen that the reliance on nuclear would be less. However, since the hydro power opportunities would have been exhausted, the objectives of the region cannot be met without nuclear power. The only alternative would be to install more natural gas. However, as discussed previously, that strategy still leaves a significant carbon footprint and will deplete the current resource earlier.

7.4. Geological Considerations

As per Figure 19, the Great Rift Valley lies to the east of the SADC countries. It extends through the great lakes, through Malawi and Tanzania, into Mozambique. The geological instability of this region makes the construction of large nuclear and hydro power plants expensive and in many cases, for the rivers that follow the routes of the fault lines, the option of hydro power impossible. Although not impossible for nuclear technology, the cost of building nuclear power plants in geologically unstable areas increases the construction cost significantly, making this area not ideally suited for it.

Malawi is a relatively small country and does not have many options for power generation. On the other hand, Malawi also has a large population, making the need for power important. While nuclear power would be able to meet this demand, most of the country is very close to the seismic fault lines which will most probably increase the cost of such plants.

7.5. The Integrated Grid

Since populations are concentrated in cities and considering the international trend of urbanization, the energy demand in and around cities is concentrated. It is therefore important to ensure that the cities and large towns are interconnected as part of the regional grid.

The current SADC integrated transmission grid is very limited. A lot of focus has, in recent years, been placed on improving this situation. As per Figure 5, this has focused primarily on the development of an Eastern-, Central- and Western Corridor, allowing for power to be transferred in a North/South configuration. However, in order for the network to be adequately integrated, it is important to also strengthen the grid in an East/Western configuration. Currently, the only line, outside of South Africa, that can transfer large amounts of power in this direction is in DRC, between Inga and the Copper belt. However, this is a DC line which will in reality not assist in the establishment of a fully integrated synchronized network.

The ability to transfer power in an East/West direction could provide some additional benefits in compensating for the difference in time zones. Figure 33 shows the official time zones used by the different SADC members. The morning and evening peaks in a country is a function of the time zone that such country is situated in. In the morning, when the day starts, power first flows towards the East. As the peak moves westward, power starts flowing into the center of the region and then finally, when the day ends, it flows towards the West. This phenomenon allows for a more distributed power consumption curve. However, it does require a strong integrated grid, with the ability to transfer large amounts of power in an East-West direction.

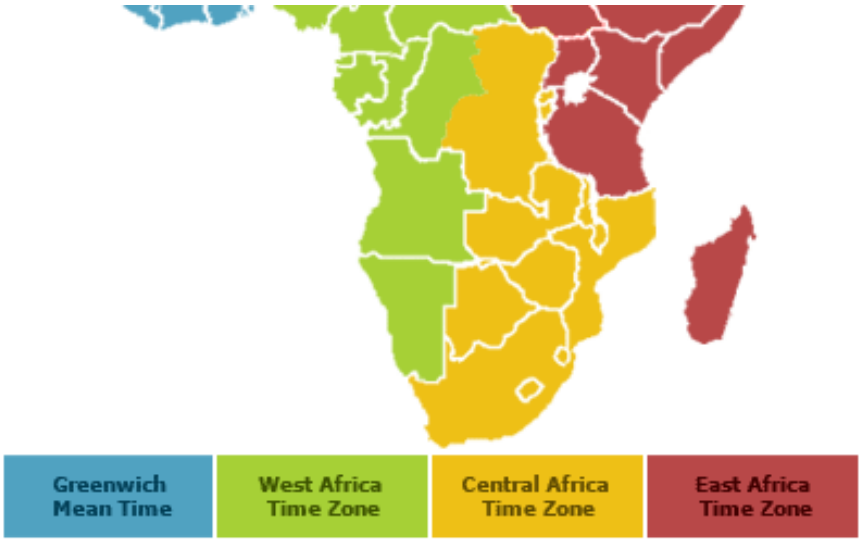


Figure 33 SADC Time Zones

Although there is some benefit in the scattered time zones, most of the countries in the region operate on Central African time, with only Namibia, Angola and Western DRC being later and Tanzania earlier. The benefits are therefore considered to be limited. Getting more countries or parts of countries on an hour before and others on and hour after Central African time might be a great advantage for reducing the power consumption peaks in the region and optimizing the use of solar power.

An additional benefit is the fact that the power from solar generation is accessible to the region over a longer period of time. Such an East West interconnected grid will therefore allow for solar generated power to become available to the Western part of the region earlier and remains available to the Eastern part later.

Although renewable energy can easily be deployed in rural areas, such technologies typically do not rely on heavy rotating components, which are some of the major contributors to providing grid stability in the form of reactive power compensation and through angular momentum. Renewable resources are normally non synchronous technologies, resulting in making the networks less stable, rather than more stable (Katrin, et al., 2017). This study has therefore ignored the contribution of renewable technologies towards their influence on grid stability taking into account of the assumption that none of the countries will install a percentage larger than 1/3rd of the overall in the form of renewables and the fact that the renewable power will be spread relatively evenly across the region. Even with a relatively even distribution of renewable resources, the ideal technology to compensate for the variability of the renewable power is hydro power. While wind generation will be relatively even spread throughout the region, solar generation will peak during midday. As the hydro power plants take over the load at night, the generally spread generation from solar will be moving to the center of the region, but more specifically in the North West, to Inga, requiring a significant reconfiguration of the network.

50% of the hydro capacity in the region will be installed at Inga. If it is assumed that only half of the renewable capacity is solar PV and if this solar PV only generates 50% of its capacity during the middle of the day, it still means that of the 157GW installed renewable capacity, almost 20 GW will be moving to Inga in the evening and away from Inga in the morning.

Further extending renewable power will therefore require an extensive amount of storage ability, the cost of which will be better served by investing this money into generating capacity.

Although large power generation plant can be used for stabilizing integrated grids, it also has to be noted that power is lost to the environment when being transferred. Long lines are therefore less efficient than shorter lines. For this reason it is important to consider the fact that in many cases, constructing the power plant close to the bulk load center improves efficiency. However, when such a plant is off line, power has to be obtained from somewhere else, if the load center is to continue operating. Adequate redundancy therefore has to be built into the generation centers at each location. It is therefore important to take a holistic approach in identifying the optimum locations for generating capacity, especially for those where the plant does not have to be built at or close to the natural fuel resource.

7.6. Proposed Configuration

Having taken all of the analysis and considerations into account, Figure 34, provides a proposed infrastructure layout, for nuclear power plants and an integrated grid, at a conceptual level. The green circles identify areas that are environmentally sensitive, where development should be avoided. All the dark black lines need to be redundant networks that will tolerate single line failures. Some of these corridors follow already established corridors for transporting of goods and services. This infrastructure will support the establishment of the grid and the grid in turn support the further development of the already installed infrastructure as well as the development of new infrastructure in underdeveloped areas. The blue circles identify the positions where nuclear power could supplement the natural resources already present and would provide for a more stable grid as well as optimize the ability to share in the resources of the region.

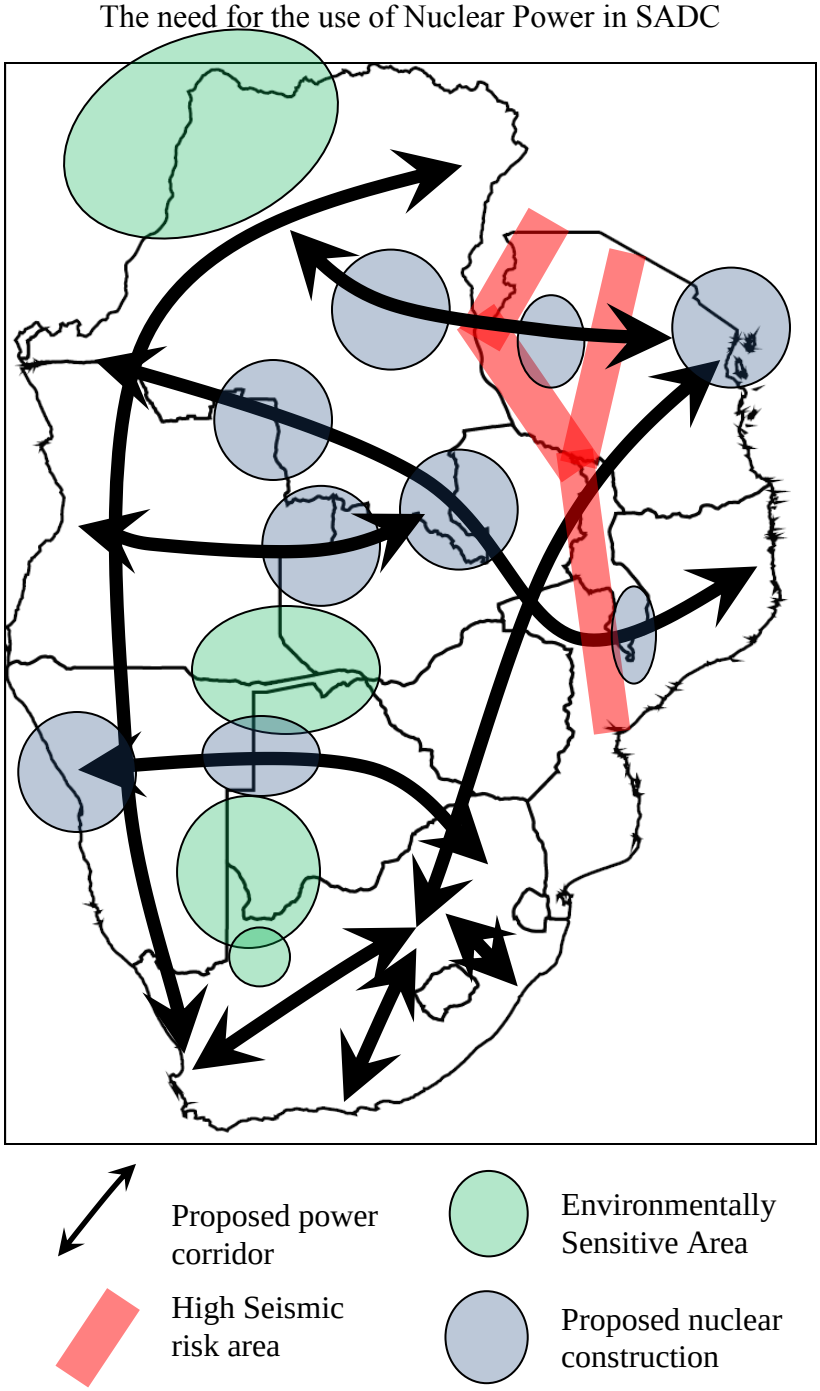


Figure 34 Proposed Network and Nuclear roll-out

In order to facilitate optimal power transfer between Namibia and Botswana, a nuclear power plant between Windhoek and Gaborone, close to the border will assist both countries and the region. Building a nuclear power plant on the coast of Namibia will allow for the region to take benefit from the efficiencies obtained by using the cold water of the Atlantic and will allow for Namibia to contribute to the regional power grid as well as add much needed stability to the Western corridor network.

The Okavango delta is a very sensitive ecosystem and should remain undeveloped. However, north of the Caprivi, it can be seen that the eastern area of Angola and the Western area of Zambia is mostly under developed. As is the case between Botswana and Namibia, integrating the grid between Zambia and the new hydro schemes in Angola will greatly benefit the region. Such integration will require some form of stabilization. This can be achieved by the construction of nuclear power plants, thereby also bringing development to this area.

Northern DRC is an environmentally sensitive region and will most probably not be developed. However, East and especially the southern part of DRC are developing economically. In the East of the country vast amounts of natural gas is available. However, this option does not exist in the south of the country. The south is also were large amounts of minerals, especially coper is mined. Converting the current DC line between Inga and the Copper Belt to AC and constructing a nuclear power plant in the South West of the DRC will allow for the integration of the grid between the center of the continent and the economic hubs within Angola and DRC.

Tanzania has limited power generation. However, this area is experiencing substantial economic growth, which will require large scale power generation. Except for natural gas reserves on the cost, the rest of the country does not have access to reasonable power generating resources. Deploying nuclear power in this area has the challenge of seismic risk. However, there are regions between the fault lines that could be considered for nuclear.

Since most of Malawi is situated in the Rift Valley, it will be difficult to find suitable sites for constructing nuclear power plants. On the other hand, this might not be completely impossible and many nuclear power plants are constructed in seismically sensitive locations. However, it might be cheaper to construct such plants outside of Malawi, if a suitable financial and developmental arrangement can be made with the neighbouring countries. It will nonetheless be beneficial to construct such plants close enough to Malawi in order to minimize line losses, but far enough away from the areas that pose elevated seismic risk. That will cause the corridor to divert slightly east or west around Malawi, placing the potential nuclear power plants in Mozambique, Zambia and in Tanzania.

The study constrains the potential for over investing in one technology to the extent that the risks associated with any particular resource and technology dominates the model. If this approach is used, nuclear power plants will be required. Constructing nuclear power plants in the SADC region will in addition allow for new industries in this generally under developed region, provide essential stabilization of the current corridors and facilitate integration in the East-West direction at various latitudes.

CONCLUSION

8.1. Summary and Conclusions

The study used the current population of the SADC countries as a basis for determining the projected installed capacity that each country and the region will require in order to bring the level of development on par with other successfully developing countries. This model concluded that the overall installed capacity for the region needs to be 282 GW, assuming an availability factor of 70%, compared to the currently installed capacity of 66 GW.

This capacity was used as an initial base line to calculate the installed capacity of different technologies once the energy mix of the region is changed from the current status quo. This was done by identifying the possible energy resources, the technologies that can make use of these, the availability of and the risks associated with each. This information was then used to derive assumptions related to how best to utilize the resources without resulting in an overreliance on any of the resources. The study concluded that, in order to minimize the overall integrated risk, that the use of nuclear power will be necessary. The model produced a breakdown of what the different contributions of each of the technologies will be in the different countries, as well as for the region as a whole. This model concluded that the overall installed capacity will be 348 GW, which is 100 GW more than the 1st model, mostly driven by the lower availability factors of the newer technologies. Of this 76 GW is anticipated to be in nuclear power capacity.

This information was used to construct a mapped model of the SADC region, evaluating where the future grid would be strongly integrated and where it will need additional stabilization. That information was considered against the particular properties of nuclear power, developmental opportunities and the need to develop an integrated regional electricity grid. From this it was concluded what the optimum locations would be for the future construction of nuclear power plants.

Each of the models was considered for validity, mostly by comparing the results with what the situation is in some other countries and regions in the world. The models were found to be generally representative of what the economic, technological and risk considerations have historically produced. The models are therefore considered to be adequate for the purposes of this report.

Considering all the aspects limiting the use and desirability of certain primary fuels, the future risks that will make some fuels less desirable, the impacts of global warming, climate change and associated pricing and availability risks, as well as the objective to construct an integrated grid that will bring more stability and security of supply to the SADC region, it is inevitable that nuclear power will have to play some role in the generation of electricity in the region. The study to determine the necessity of having to make use of nuclear power in the SADC region has therefore demonstrated that the proposed hypothesis: ***"Electricity generation using nuclear power will be required in order to reduce the risks associated with an overreliance on certain sources of power in order to establish a suitable energy mix and stable integrated grid for the SADC region.***" to be valid.

This analysis has demonstrated that:

a. If the resource limitations are considered, and the total installed capacity of any particular fuel is not utilized to the extent where it incurs unnecessary additional risk, there will ultimately be a primary fuel deficit that can only be serviced by another form of power generation like nuclear.

b. If utilized, nuclear power plants will add much needed capacity as well as grid stability in especially remote areas which will greatly assist in stabilizing an integrated electricity network and provide much needed economic activity in such regions.

thereby confirming the original hypothesis.

8.2. Recommendations for Future Work

This research report did not consider the financial comparison between the different technologies. However, many such studies have previously been performed. What has not been adequately researched is the financial quantification of the risk considerations discussed in this report. Such a study might show that in the longer term, investing in some of the resources might be more desirable than others. The economics of operating an integrated grid, especially considering the interrelationships between different technologies will add greatly to the work performed in this study.

The power projection model can be greatly enhanced by adding time and population growth to the considerations. This will inevitably conclude that even more power will be required than what is being considered in this report. The ideal level of deployment of natural gas can be improved by considering the future projections of carbon tax and how that will impact on the cost of the resource. Finally, a mathematical model of the region and the future locations of projected power plants will provide more insights into the stability of a projected electricity grid.

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