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Applicability of Small Modular Reactors in Sub Saharan Africa

D. NICHOLLS [1] [3], P. NAIDOO [1] [3], S. H. CONNELL [1] [3], J. SLABBER [2] [3]
University of Johannesburg [1], University of Pretoria[2]
SAIEE Nuclear Chapter [3]
South Africa

SUMMARY

In the global era of the 4th industrial revolution, Africa remains a dark continent. Sub Saharan Africa is the largest area in the current world without adequate electricity resources to power national economies. The ability to increase the electrical energy supply is constrained by the need for low carbon generation and the very limited size of the current grids. While renewable energy may be seen as potential approach this is constrained by the need for either bulk electricity storage of backup dispatchable generation. While this problem could be addressed by nuclear power this has only been applied in South Africa to date. It has been possible in South Africa because of the large, integrated grid which allows for the installation of 1000MWe class units. The other national grids in Sub Saharan Africa are far too small to accept such large units due to stability concerns. In the last 15 years there has been the development of Small Modular Reactors (SMR) in the range of 5 - 300MWe which would be able to be included in virtually all the national grids in the region. While the actual deployment of SMRs is only just starting in the world (with units under construction in China, Russia and Argentina) the technology is commercially available to provide dispatchable, economic electricity for each of the countries in Sub Saharan Africa. This paper briefly unpacks the understanding of costs to promote a nuclear investment.

KEYWORDS

Energy Poverty, Energy Mix, Reactor Costs, Emergency Generation, Intermittent Renewables.

nicholdr@iburst.co.za

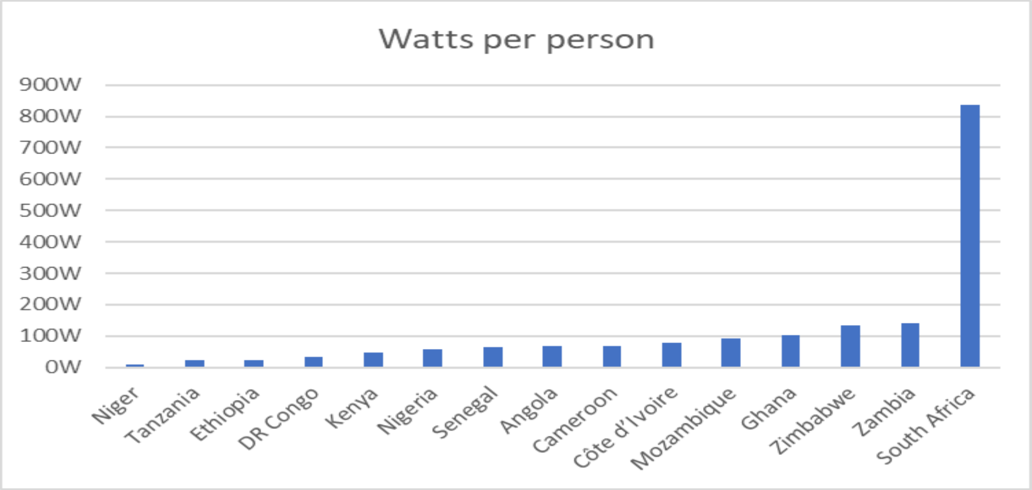
1. INTRODUCTION

Energy poverty dominates Africa. Africa has abundance of natural and renewable resources but remains in poverty. A first understanding of the energy poverty will help to set the framework for the conversation on developing energy capability, as in grid electrification, domestically.

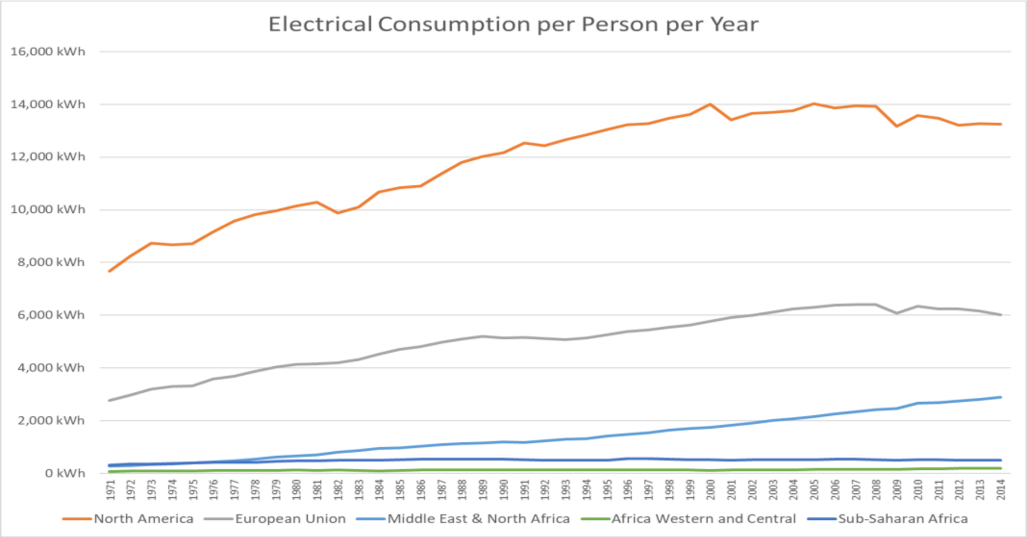
1.1 Status and Issues of the Sub Saharan Africa Electricity Supply

Sub-Saharan Africa, with the exception of South Africa, is the last substantial portion of the world that lacks bulk electricity supply. The installed capacity per person per country for the major economies of sub-Saharan Africa is given in graph 1 [1]. Relative to South Africa, the data conveys the message of energy poverty. Graph 2 presents the energy poverty profile of Sub-Saharan Africa relative to that of global peers [2].

Graph 1 : Installed Capacity in Watts Per Person for Sub Saharan Countries



Graph 2 : Sub Saharan Energy Poverty Relative to Global Peers

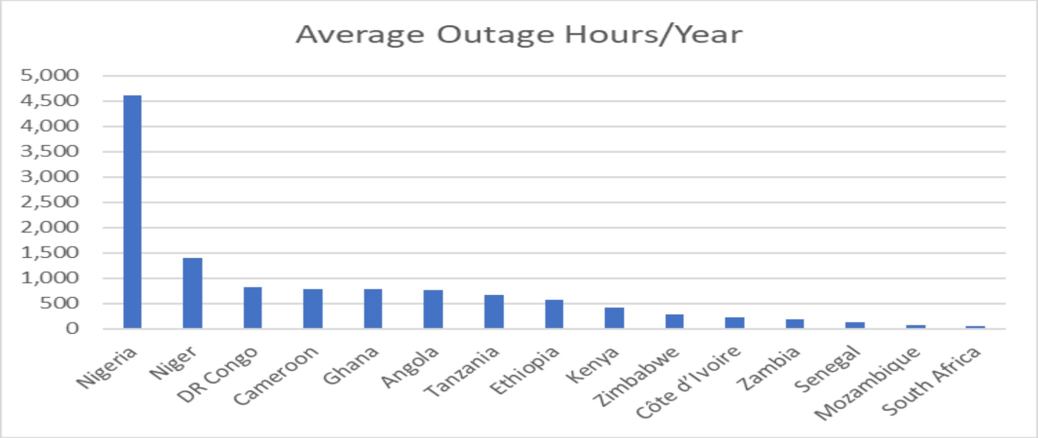


nicholdr@iburst.co.za

Except for South Africa, many of customers of Sub Saharan countries are powered by liquid fuel (diesel or petrol) generators. Where available, these are complimented by grid based small hydro power stations. However, mixing grid hydro with liquid fuel powered generation leads to extreme cost distortion. For example, in Zambia the grid cost of electricity is US$6c/kWh but the estimate of the customer diesel generator power is US$c53/kWh.

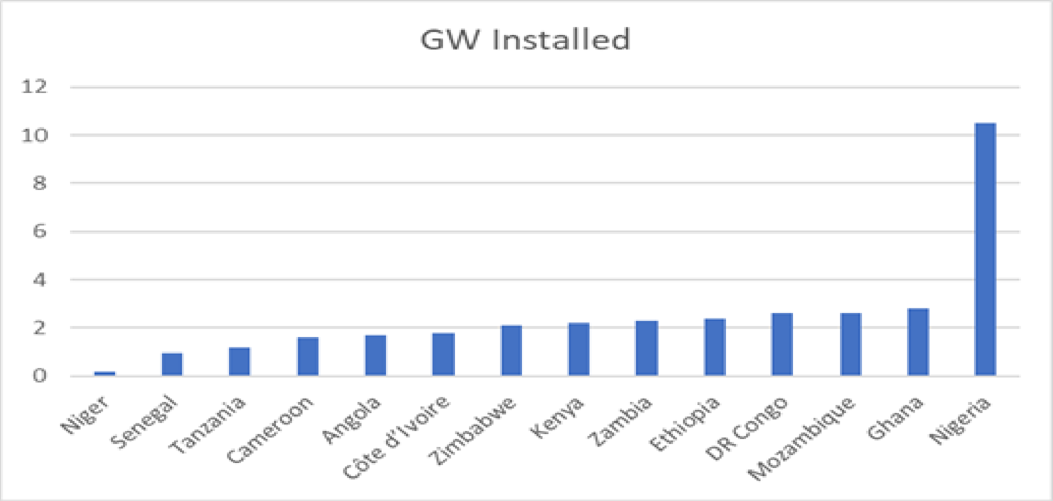
The full impact of having no dispatchable and cost effective generation resources is given in graph 3; the average energy unavailability per country [1]. The unavailability of dispatchable energy as in electricity accounts for the lack of industrial and manufacturing activities. This explains the lack of jobs and supports the theory of continuous energy poverty for all.

Graph 3 : Average Outage Hours/Year Per Sub Saharan Economy



Graph 4 shows the installed generation capacity per country [1]. Excluding South Africa and Nigeria, many of the countries will have opportunity to power up 2000MW of electricity for the national economy.

Graph 4 : Installed Existing Generation Capacity per Country



1.2 The Potential Energy Mix for an Industrialized Sub Saharan Africa

1.21 Fossil Fuels of Coal, Oil and Gas

Given a general abundance of natural resources, the constraint will be bankability of projects and developments. The national and international financial institutions are not supporting the use of fossil fuels. This emanates from the global call of the United Nations for all countries to embark on a path to net zero carbon emissions by 2050.

1.22 Renewable Energy Resources of Solar and Wind

The global trend is to install renewable energy sources of wind and solar photovoltaic. The energy cost per kWh of these sources is competitive. Their correlated intermittency (e.g. the sun goes down at the same time across the entire country – adding more PV does not do anything to increase night production) makes it essentially impossible to build any national stable grid purely on these sources.

1.23 Hydro

Clearly hydro plant is an excellent solution. This depends on the national geography and weather. In general, if available, the small scale is tapped and the larger scales are so large that the extensive capital and transmission systems become the next hurdle.

1.24 Nuclear

The current grid size for most sub-Saharan grids is about 2000MW. This would indicate that the ideal unit size for deployment would be in the order of 100MW - 200MW. Small modular reactor technology could deliver an economic renaissance for an industrialized country and region.

1.3 Towards an Integrated Resource Plan for Sub Saharan Africa

Renewables of solar and wind, hydro and nuclear will be the constituent primary contributors to an integrated resource plan for Sub Saharan Africa. Such a plan will be consistent with that being adopted by both the developed and developing countries. In the case of the United Kingdom, their sixth carbon budget, as legislated, commits to full decarbonization by 2050 [3]. The UK will cease all coal fired power generation by 2024. The baseload generation will be replaced by renewables, in particular off shore wind. The intermittent renewables will be supported by baseload nuclear. They plan to retain their present 10GW capability by replacing aged power units with new build. In the case of South Africa, the integrated resource plan of 2019, retains the existing nuclear power station for another two decades; in 2024, Koeberg will have completed four decades of continuous base load electricity supply to the South African economy [4]. The plan goes forward and makes allowance for new nuclear beyond 2030 at a pace and scale that will be affordable to national treasury.

Accepting that Sub Saharan Africa will be dominated by a renewables mix of solar, wind and hydro, space will exist for nuclear as a clean energy resource as a base load bulk electricity supply to the national grid.

Unpacking nuclear for national application, three key themes emerge is policy conversations. These are the high capital cost of building a nuclear power plant, the safety of nuclear to operators and the greater environment and the management of low and intermediate waste and spent fuel. This paper unpacks briefly the theme of high capital costs of nuclear in the context of small modular reactors. Follow through papers will take a deep dive into the issues of safety and waste management.

2.0 LITERATURE REVIEW

2.1 Small Modular Reactors

The early nuclear reactors (before the late 1960s) were small by today's standards, with the first commercial Pressurised Water Reactor (Shippingport in the USA) being some 80MW and the first Gas Cooled Reactor (Calder Hall in UK) had four units, each of 60MWe.

In the 1990s the International Atomic Energy Agency had a classification of reactor sizes that did not consider any reactor design of less than 600MWe as commercial. The first major project to challenge this approach was the Pebble Bed Modular Reactor (PBMR) project by Eskom from 1995. This project proposed that the small 100MWe class PBMRs would be built in clusters of up to 8 reactors, hence "modular" approach. While the PBMR project itself was placed in care and maintenance in 2010 it can be seen as the precursor to the range of Small Modular Reactors (SMR).

An SMR can be seen as a reactor with an electrical output of between 5MWe and 300MWe. The approach taken to achieve economic performance is to have a totally standardized design and construction with inherent safety by simplified design approach. The standardized design and small size is to allow mass production with a very large fraction of factory (vs. site) construction. This standardization, linked to the inherent safety approach, also avoids the very high cost of bespoke engineering, training, safety analysis in current nuclear projects.

The technologies being proposed for the SMRs is much more diverse than the current offerings in the market for large nuclear reactors (virtually all Pressurised Water Reactors). To achieve the inherent safety required of these designs the technologies that were developed in the 1960s and 1970s, but never fully commercialized, have been reconsidered. These include High Temperature Reactors, Molten Salt Reactors and Liquid Metal Reactors as well as simplified water-cooled reactors. These technologies had all been shown to be technical feasible and have the ability to achieve required safety levels, but did not scale to the large sizes seen to be important in the development of current generation reactors.

The International Atomic Energy Agency lists and describes 72 different SMR designs under consideration/development in the world [5]. The status of these designs varies from actual construction to conceptual studies. The key issue is the degree to which these designs could be seen as viable in the short to medium term for deployment. For this reason is logical to look at those that are actually in construction and therefore do have a detail design and a degree of safety authority approval.

The designs at the construction stage are listed in table 1.

Design	**Country**	**Type**	**Status**	**Power**
ACP100	China	Water Cooled	Construction started 2021	125 MWe
Brest-300	Russia	Lead Cooled	Construction Started 2021	300 MWe
Carem-25	Argentina	Water Cooled	In Construction	32 MWe
HTR-PM	China	Gas Cooled	Ready for Fuel Loading	210 MWe
KLT-40s	Russia	Water Cooled	In Operation	35 MWe

Table 1: SMR's Under Construction

There are many projects at an advanced stage of development and could be considered as ready for construction, including the NuScale (60MWe, USA), SMART (107MWe, S. Korea),VK-300 (355MWe, Russia), BWRX-300 (280MWe, USA/Japan), RITM200 (53MWe, Russia), Xe-100 (83MWe, USA), 4S (10MWe, Japan) and the SVBR (100MWe, Russia).

2.2 Reflecting on the Large Reactors of South Africa and Egypt

Many countries in Africa have talked about installing nuclear power stations but only two have actually undertaken it or committed to it, South Africa with the 2 x 930MW Koeberg nuclear power station and Egypt with the signed contract for the 4 x 1200MW El Dabaa nuclear plant. The reason for this is clear in the size of the grids relative to the size of the nuclear units. South Africa has a current integrated grid load of some 35GW today and was some 20GW when the Koeberg units were completed. Egypt has a grid load of some 40GW and growing at 6% per year. Clearly these grids can support the large (~1GW) classic nuclear units. The except for South Africa the rest of the sub-Saharan grids would not support such unit sizes. The standard approximation is that for the purpose of grid stability and management no single unit should exceed 10% of the installed grid, with ideally no more than 5%. Nigeria comes close to this criterion for a 1GW nuclear unit. All the other grids are far too small to support such units and while cross border grids could address some of this concern the political and geographical issues would tend to limit this potential.

This issue raises the question as to why nuclear units sizes are so large. This is based on the economics of the large industrial countries that first adopted nuclear power (e.g. USA, France, Russia, Germany etc.) and the specific technology chosen. These countries had large grids that put no real limit on unit sizes and chose to use a water cooled design (PWR and BWR) with the related safety issues resolved by the inclusion of major safety systems, such as safety injection, containment spray and auxiliary feed systems, all supported by high integrity electrical power supplies, using emergency diesel generators etc. This approach to nuclear safety, linked to the tendency for each plant to be bespoke, led to an increasingly expensive involvement in the nuclear programs by the nuclear regulators and therefore a drive to create bigger and bigger units to maximize the output and reduce specific costs per MW. The early PWRs in the 1960s were about 400MW, rising to 900MW and then to 1400MW from the 1970s & 1980s with the most modern designs (EPRs) being 1750MW. This growth has been slowed in most of the PWR designs, with 1200-1400MW being the current power of most designs. They are still, however, too big for most African grids.

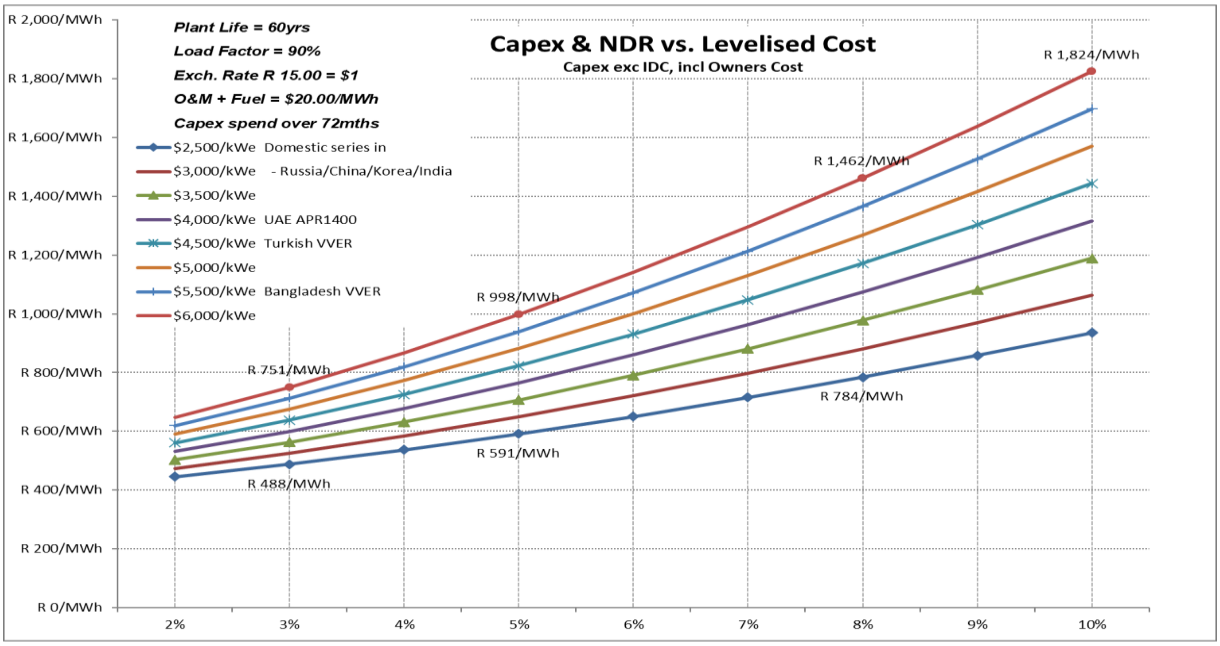
3.0 FIRST PASS COST ANALYSIS FOR MEETING DEMAND WITH SMR'S

The cost of production for a nuclear plant is dominated by the capital cost of the plant and the cost of capital. If the plant is run as a pure baseload plant and operating, maintenance and fuel cost is assumed to be $20/MWh with a 60 year life then Graph 5, current costs for nuclear reactors being built, applies. The data could be used for a large or small reactor.

If the SMR achieves the economies of volume production linked to the lower overheads offered by inherent safety then there is no logical reason for SMR to meet large reactor costs. As discussed above the expectation by the vendors of the capital costs of serial production on SMRs should be at $2500/kWe or below $3000/kWe which is being achieved by the units being built in Russia, China, Korea and India.

Given this approach one can model the cost of a nuclear solution (using serial production SMRs). Table 2 presents the cost of electrical energy as based on the cost of capital.

Graph 5 : Current Costs for Nuclear Reactors Under Construction



nicholdr@iburst.co.za

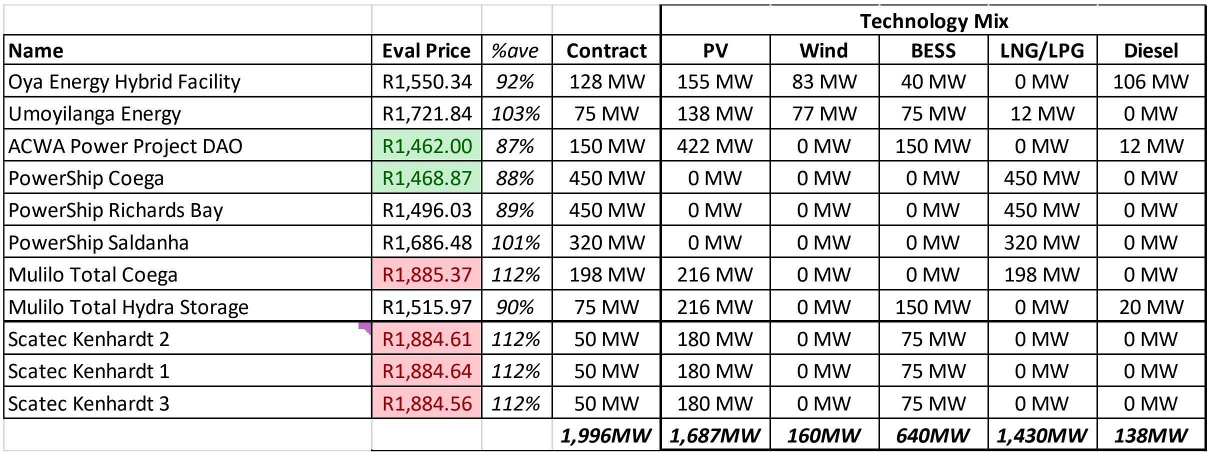
	Net Discount Rate		
Capex	**8,0%**	**5,0%**	**3,0%**
$6000/kWe	R1462/MWh	R998/MWh	R751R/MWh
$2500/kWe	R784/MWh	R591/MWh	R488/MWh

Table 2 : Costs of Electrical Energy as Influenced by Cost of Capital

As can be seen the impact of the capital costs is less important than the net discount rate (NDR) being applied. If the NDR relates to the actual cost of capital on the market (e.g. Export Credit Agency rates under OECD rules of about some 2% real) then nuclear is extremely competitive in the current electricity market.

3.1 Comparison of First Pass SMR Costs with 2021 Published Data on South Africa's Emergency Power Purchase Procurement Bids

The bid evaluation results of the South African Risk Mitigation Independent Power Producers Program (RMIPPP) is given in table 3 [6]. This project was to obtain dispatchable plant that could meet South African national grid requirements for guaranteed production from 05:00 to 21:30 on a daily basis.



				Technology Mix				
Name	**Eval Price**	*%ave*	**Contract**	**PV**	**Wind**	**BESS**	**LNG/LPG**	**Diesel**
Oya Energy Hybrid Facility	R1,550.34	*92%*	128 MW	155 MW	83 MW	40 MW	0 MW	106 MW
Umoyilanga Energy	R1,721.84	*103%*	75 MW	138 MW	77 MW	75 MW	12 MW	0 MW
ACWA Power Project DAO	R1,462.00	*87%*	150 MW	422 MW	0 MW	150 MW	0 MW	12 MW
PowerShip Coega	R1,468.87	*88%*	450 MW	0 MW	0 MW	0 MW	450 MW	0 MW
PowerShip Richards Bay	R1,496.03	*89%*	450 MW	0 MW	0 MW	0 MW	450 MW	0 MW
PowerShip Saldanha	R1,686.48	*101%*	320 MW	0 MW	0 MW	0 MW	320 MW	0 MW
Mulilo Total Coega	R1,885.37	*112%*	198 MW	216 MW	0 MW	0 MW	198 MW	0 MW
Mulilo Total Hydra Storage	R1,515.97	*90%*	75 MW	216 MW	0 MW	150 MW	0 MW	20 MW
Scatec Kenhardt 2	R1,884.61	*112%*	50 MW	180 MW	0 MW	75 MW	0 MW	0 MW
Scatec Kenhardt 1	R1,884.64	*112%*	50 MW	180 MW	0 MW	75 MW	0 MW	0 MW
Scatec Kenhardt 3	R1,884.56	*112%*	50 MW	180 MW	0 MW	75 MW	0 MW	0 MW
			1,996MW	***1,687MW***	***160MW***	***640MW***	***1,430MW***	***138MW***

Table 3 : Published Evaluation Prices for the RSA Emergency Power Procurement

Compared to that for SMR's as given in Table 2, the competitive gap is evident. Fossil fuel has short term, lower density energy characteristics as compared to the longer term, higher energy density characteristics of nuclear.

Nuclear is clearly a balance sheet entry, a bankable investment. Returns are enjoyed into time as lower and affordable tariffs. Fossil gas is an income statement entry. Returns are generally negative. The direct impact will be on cost of sales, placing a continuous upward pressure on customer tariffs. This unique strength of nuclear, the correlation of a longer term bankable investment with the associated outcome of longer term delivery in lower customer tariffs is recommended for further study.

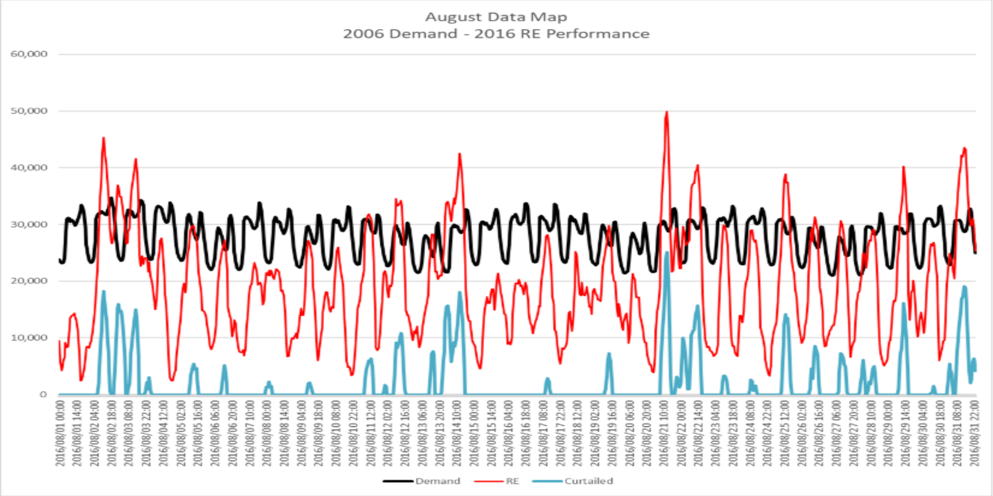
nicholdr@iburst.co.za

3.2 Comparison of First Pass SMR Costs with Renewables using Natural Gas as Back Up Generation

Present day global trends is for renewable energy options (PV and Wind) backed up by natural gas powered generation system to yield a lower carbon outcome. Most of the global countries have natural gas and harvesting technologies as a low cost, domestic resource. In the case of South Africa, given natural free energy resources, both the natural gas and the harvesting technologies of wind and solar PV will be a foreign exchange import.

However, technically, a comparison is made of the wind and PV as dispatched on the South African system in August 2016 versus the unconstrained national grid demand of August 2006. The decade later comparison is made when all the national grid power stations were unconstrained, noting that South Africa's first incident of load shedding occurred in 2007. The graphs were sourced from the published reports of Eskom System Operations.

Graph 6 : 2016 RE Production vs 2006 Unconstrained Demand



The intermittent characteristic of renewable energy generation is evident. The national grid will require back up generation. Table 4 provides the present day of costs of energy delivered to the South African national grid by the mix of energy resources [7].

Table 4 : Energy Resource Total and Unit Costs for South African Electricity Production

Energy Resource	September 2020			September 2019		
	Cost Rm	Energy Sent Out GWh	Unit Cost R/MWh	Cost Rm	Energy Sent Out GWh	Unit Cost R/MWh
Thermal Coal Excluding Pre Commissiong Energy from Medupi and Kusile	36 227	94 047	385	36 026	98 037	367

nicholdr@iburst.co.za

Nuclear	461	4 374	105	732	7 564	97
OCGT's	1 391	496	2 811	1 100	331	3 327
Renewables IPP's	12 456	5 551	2 244	11 241	5 220	2 153
OCGT IPP's	1 259	291	3 648	926	169	4 389
SAPP Imports	2 524	4 474	564	1 993	3 703	538

The total real costs as seen by both the national utility and end customers for both renewable energy and open cycle gas turbines are in the upper range of the scale of costs. This scenario will only have one outcome for customers, an economy that will be driven by continuously increasing annual electricity tariffs.

4.0 CONCLUSION

The first pass cost analysis demonstrates that small modular reactor technology will constitute an affordable fit to the integrated resource plan of countries in Sub Saharan Africa. The constraint of large nuclear is lifted by the advent of commercial SMR's of sixty year economic potential. The sixty year life span has deep bankability for continuous and affordable electrical energy for national economic development. This start towards national economic renaissance can be delivered by foreign direct investment from both original equipment manufacturers and the United Nations led clean energy development financing mechanisms.

The other key issue with SMRs is their availability and refueling regimes. The classic PWR/LWR is required to shut down every 18 months for about 30 days to refuel. The different technologies of SMRs offer a wide range of alternatives. Pebble Bed High Temperature reactors are refueled on load, some of the water based reactors have refueling cycles of up to 5 years and some of the very small reactors are offering up to 20 years between core changes. In general the target availability of the SMR designs are normally at, or above, 95%. Clearly any planning for SMRs must consider the availability and maintenance cycle.

Nuclear, aside from the uranium ore and the materials that constitute the reactor, it is all about science, technology, engineering and mathematics. This attribute vests with and extracts the value from people resources. The nation's scholars will need to be trained and skilled in all four portfolios. This opportunity opens up a new door to quality jobs for all in an advanced industrial environment. South Africa's nuclear investment supported and continues to support just over 2000 direct full time jobs for the approximately 2000 MW delivered by the Koeberg Nuclear Power Station.

In follow through papers, the research team will explore and quantify the remaining two themes of safety and environmental impact of waste. In brief, assurance is by design supported by regulatory policy and practices. Since the discovery of nuclear sciences, assurances have matured to levels of total confidence; in risk assessment, risk management, accident containment and residual radioactivity post application. This

nicholdr@iburst.co.za

applies equally to nuclear medicine as it is to nuclear energy. Nuclear medicine is increasing in societal applications both for personal and public health.

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nicholdr@iburst.co.za