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Deteriorating Synchronous Generation and the Future of the South African National Grid

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SUMMARY

South Africa's thermal coal power stations are challenged by breakdowns. The forecast is that the electricity supply availability will continue to deteriorate into the future. The paper examines the performance of South Africa's thermal coal fleet of power stations, the use of load shedding and emergency generation of diesel, and the support from complimentary supplies of base load nuclear and intermittent renewables of solar and wind. Given the magnitude and scale of loss of baseload thermal coal generation, presently in the 10 to 20 GW range, the paper questions the future of the national grid, the dynamic link that synchronously couples sources to loads. South Africa's collection of large synchronous generators requires substantial heat energy to mechanical torque conversion to drive the rotor of the generator. For the long run, given the tightening global climate change limits for carbon based fossil fuels, should South Africa consider domestic nuclear and or hydrogen from renewable energy resources as a clean energy heat source of equivalent magnitude? Given growing insecurity in national energy supplies, a concern is the permanent loss of valuable synchronous machine assets to scrap value. The Duvha Thermal Power Station Unit 3, a 600 MW synchronous generator, stranded since 2013, is testimony.

KEYWORDS

Energy Availability, Load Shedding, National Grid Resilience, Clean Energy

1. INTRODUCTION

South Africa operates an interconnected power system. All the power station generators are synchronised and effectively operate as a single power source for the

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whole system. High voltage transmission lines interconnect power stations to form the national grid. The nominal voltage of the South African national grid is 400 kV; embedded with circuits at 765kV for longer distance bulk power transfers and 275kV for bulk power distribution to regional, municipal or large, energy intensive industrial and mining customers.

A pooled power system consists of many synchronous machines operating in parallel and feeding electrical energy onto an infinite bus-bar; a virtual node where the system voltage and frequency is constant. A first observation of an interconnected power system is that all the components of the system affect each other and this determines the overall functioning of the total power system. When adequate generation (scheduled and emergency) is not available, to maintain the infinite bus-bar requirement of constant frequency, system operations sheds load. Load shedding is a controlled action to ensure that the synchronism of the power system remains within the designed tolerances of stability; in cases when demand exceeds the available supply, demand is reduced.

Since 2007, South Africa has experienced load shedding. For the present day, the South African power system is moving progressively deeper into the use of load shedding as a system management tool. The sustained loss of large magnitude of synchronous generation opens new questions on the increasing costs and decreasing quality of supply delivered to customers, the integrity of the electrical strength of the power system and the future of the national grid and its supply resources.

In the global context of the energy revolution as driven by climate change, the United Nations target in 2050 is for zero use of carbon fossil fuels of thermal coal, oil and gas for heat energy. All fossil resources must remain firmly in the ground and will not be available for combustion.

South Africa's main source of electricity is the mechanical form ; sourced indirectly and primarily from thermal coal heat energy that converts to electricity in the air gap of synchronous generators. South Africa has a vast collection of large synchronous generators. The range extends from 200 to 980 MW with the majority of machines at 600 MW. The equivalent heat energy to power the rotors of the machines can be sourced from nuclear and or hydrogen as derived from renewable energy resources, described as green hydrogen. The clean heat sourced from domestic nuclear and or green hydrogen will have the strength to power the existing national assets of synchronous machines, national grid substations and the national grid.

The study adopts a mixed method methodology of literature review and data analysis. Literature review briefly explores relevant electrical theory and the state of the global energy revolution. This is followed by data collection of South African power station performance, a first pass analysis of national grid security and discussion of results.

The data set is collected from published audited reports and is employed to construct the theme that the performance of South Africa's thermal power stations is deteriorating. The paper concludes with recommendations to develop long run clean

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energy solutions to power up the potentially stranded national assets of synchronous machines, national grid substations and the national grid.

2. LITERATURE REVIEW

2.1 Power System Strength

In steady state mode, the alternating current power system continuously adjusts to maintain the virtual node of an infinite bus bar where the system voltage and frequency is constant. The mechanical power input to the machines is managed to maintain the constant frequency of the infinite bus-bar; relying on automatic governor controls, reduced machine loading when frequency rises under light demand periods and increased machine loading when frequency drops under heavy demands periods. Real time system operations manages the system voltage of the infinite bus-bar ; by excitation control, machine reactive power management, the use of tap change control of the interconnecting power transformers, static var compensators and switched shunt capacitors.

Kunder et al in their definition and classification of power system stability noted that stability is a real time state of equilibrium between opposing forces [1]. Depending on the power system status and the form of a disturbance, different set of opposing forces may experience sustained imbalance and different forms of instability. They grouped power system stability into three categories ; rotor angle stability, frequency stability and voltage stability. These are time varying inputs to the greater chapter on security and reliability of supply. A reliable power system is a secure power system that is stable under contingencies.

The performance of connected plant and equipment is influenced by the fault level or electrical strength at the point of common coupling. EPRI's Handbook defines electrical strength in terms of its three phase fault MVA, short circuit capacity (SCC) [2].

$$SCC = \sqrt{3}\ x\ Nominal\ Line\ to\ Line\ Voltage\ x\ 3\ Phase\ short\ circuit\ current.$$

As example, high voltage direct current (HVDC) power electronics connected to an alternating current power system is real time influenced by the closed loop interaction between the DC and AC circuits. The Thevenin equivalent impedance at the point of common coupling determines the degree of closed loop interaction. The higher the system impedance, the weaker the system. HVDC designers use a figure of merit for the AC system strength relative to the HVDC system rating ; called the short circuit ratio. Typical figure of merits are SCR of 5.0 and 2.5 respectively for strong and weak AC power systems [3].

$$SCR = SCC\ MVA/(HVDC\ Power\ Capacity\ in\ MW)$$
$$SCR\ > 5.0\ strong\ AC\ power\ system$$

$$SCR\ < 2.5\ weak\ AC\ power\ system$$

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2.2 State of art in global energy revolution

In November of 2021, the United Nations COP 26 congress will be held in the United Kingdom. As co-host with Italy, the UK has tabled the aspiration that by 2024, all thermal coal power generation will cease even in the era of doubling of demand from the present day of 300 TWh today to 610 TWh in 2050 [4]. The UK has migrated from 500 gCO_2/kWh in 2012 to 200 gCO_2/kWh in 2020 and plans for net zero in 2050. The net zero plan of the UK resolves to increase variable renewables to 80% of generation by 2050 ; 60% of generation by 2030, 70% by 2035, and 80% by 2050. Offshore wind will provide 265 TWh of generation in 2035 and 430 TWh in 2050. Solar generation will increase from 10 TWh in 2019 to 60 TWh in 2035 and 85 TWh in 2050. On average, 3 GW of wind and solar new capacity will be built each year. Energy storage to absorb the variability from renewables will primarily come from hydrogen. From 2030 onwards, a new hydrogen economy will develop to a scale that will be comparable to the existing electricity usage by 2050. Hydrogen is planned to displace natural gas and to reuse the existing natural gas infrastructure. For the planning horizon to 2050, the UK retains their existing pumped storage and nuclear generation contribution to the national grid. Nuclear will continue to provide its constant supply of 10GW of electricity ; some existing plant will retire in the 2020's but new nuclear new build will compensate and hold constant the baseload electricity generation. Opportunity for new pumped storage exists and will be explored.

2.3 The electrical strength of variable renewable energy converter dominated power systems

Urdal et al, at National Grid UK are challenged by increasing non synchronous generation from variable renewable energy ; all connected as power electronic converters to the national grid [5]. The standing questions are what determines the electrical strength in the absence of synchronous machines ?; what is adequate for system stability ? ; and if variable renewable energy generation is constrained, what are the implications ? Their best answer is for closer collaboration across the industry value chain to determine the optimum missing solutions to the emerging challenges ; noting that power system stability will in future be determined by the remaining synchronous machines, the grid code compliance and improvements in power electronic converter technology.

Their study made reference to the electrical strength of the national grid ; the higher the impedance at the point of common coupling, the weaker the power system. For a weaker power system, the greater will be the issues of voltage variation and quality of supply, on protection system performance especially older schemes, on synchronising electromagnetic torque and rotor stability and on power electronic closed loop controls of variable renewable energy generation and line commutated HVDC schemes.

In the long run, a mix of real time and regulated solutions in energy, capacity and ancillary services, that could emulate the typical synchronous generation performance, will be the most likely outcome for a reliable, secure and stable power system.

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3. DATA COLLECTION AND CONSTRUCT OF THE THEME: PERFORMANCE OF SOUTH AFRICAN SYNCHRONOUS GENERATION IS DETERIORATING

3.1 The supply and demand for electrical energy as recorded on the South African National Grid

For FY2020, the recorded supply and demand for electrical energy on the South African National Grid is provided in table 3.1 [6].

Table 3.1: Supply and Demand for Electrical Energy

Supply of Electricity (231 356 GWh)		Demand for Electricity (231 356 GWh)	
Eskom Power Stations	214 968	Customer Sales	190 446
IPP's	11 958	SAPP Exports	15 189
SAPP Imports	8 568	Technical Losses	23 457

The bulk of South Africa's electrical energy is provided by the synchronous generators of the Eskom Power Stations (92,9%). Technical losses, including theft of electricity and accounting errors constitutes 10,13% of the national grid energy, almost double of that supplied by the independent power producers (5,16%). The data clearly shows that the South African National Grid and all the national and regional customers are completely dependent on the performance of the Eskom Power Stations.

3.2 Breakdown of the production of electricity from the Eskom Power Stations

In FY2020, thirty power stations of 45 117 MW nominal capacity produced the 214 968 GWh of electrical energy [6]. Table 3.2 shows the energy delivered by the different energy resources of the Eskom fleet.

Table 3.2: 2020 Profile of the Eskom Power Station Energy Sent Out

Energy Resource	Nominal Capacity MW	Energy Produced GWh
Thermal Coal	37 424	194 357
Nuclear	1 860	13 252
Pumped Storage	2 724	5 060
Hydro	600	688
OCGT's	2 409	1 328
Self Dispatching Wind	100	283

3.3 Total and unit costs of the energy resource mix on the national grid

Thermal coal produced electrical energy dominates and powers the South African National Grid. The dominance is historical, driven by South Africa's abundance of the natural thermal coal resource. South Africa's coal reserves are estimated at 53 billion tonnes, with potential for another 200 years of service to the national economy [7].

Thermal coal's attribute of providing the lower cost bulk electrical energy affords resilience against other energy resources. Table 3.3 demonstrates the economic

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strength that emanates from longer term production assets coupled with lower primary energy costs [8]. Thermal coal, nuclear and SAPP imports, primarily the hydro electric infeed from Cahora Bassa, are the long run lower cost energy from aged and depreciated assets whilst renewable IPP's refects total energy costs inclusive of new and limited term power purchase contracted production assets. OCGT's reflects both expensive primary fuel and recoveries for new production assets.

Table 3.3: 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
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

Table 3.4 shows that the annual unit costs expressed as R/MWh remains fairly consistent for each of the energy resources as currently dispatched [6].

Table 3.4: Annual R/MWh for Each Energy Resource Currently Dispatched

Energy Resource	FY 2020	FY 2019
Thermal Coal	397	339
Nuclear	100	103
OCGT	3231	3128
Total IPP Costs	2347	2200
SAPP Imports	550	509

3.4 The national grid energy availability factor

The 2020 integrated report of Eskom [6] records that the energy availability factor of the total system generation was 66,64%, dropping from the 2019 level of 69,95%. There were 46 days of national load shedding. A stage 6 incident was recorded on 9 December 2019. Emergency OCGT's were frequently used during the year. The recorded cost was R7.5 billion.

The loss in energy availability factor was mainly due to worsening thermal coal plant performance. Table 3.5 shows the coal plant energy availability and energy utilisation factors for the last five years.

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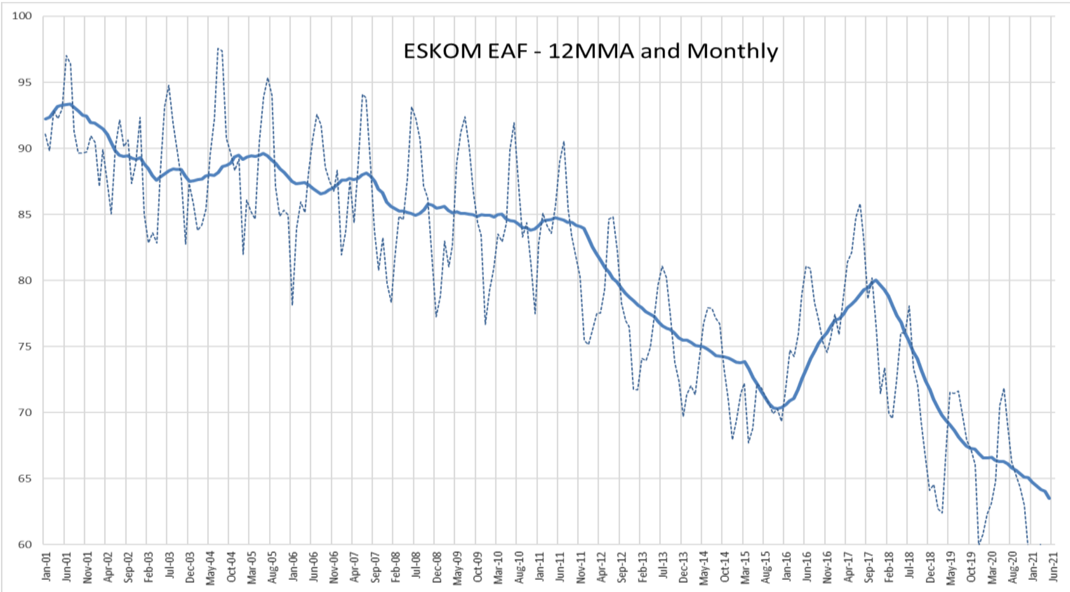
Table 3.5: Thermal Coal Plant Performance for 2015 to 2020

	2015	2016	2017	2018	2019	2020
% EAF	70	68	75	75	69,95	66,64
% EUF	93	93	83	81	90	93

3.5 Performance of Eskom Generation

At the turn of the century, Eskom generation was celebrated as a top performing global power utility. The benchmark was set at 90 :7 :3 for EAF : PCLF : UCLF. In 2007, the first event of national load shedding was recorded. Since 2010, the generation performance has been in steady decline. A concerted effort was made to restore performance in the period 2014 to 2018, but post 2018, the decline in performance accelerated. Graph 3.1 captures the long run performance from 2001 to date [9].



Graph 3.1: National grid energy availability factor from 2001 to Date

Table 3.6 presents the accelerated decline in performance since the best ever recorded performance of 83,2% in September 2017 [6].

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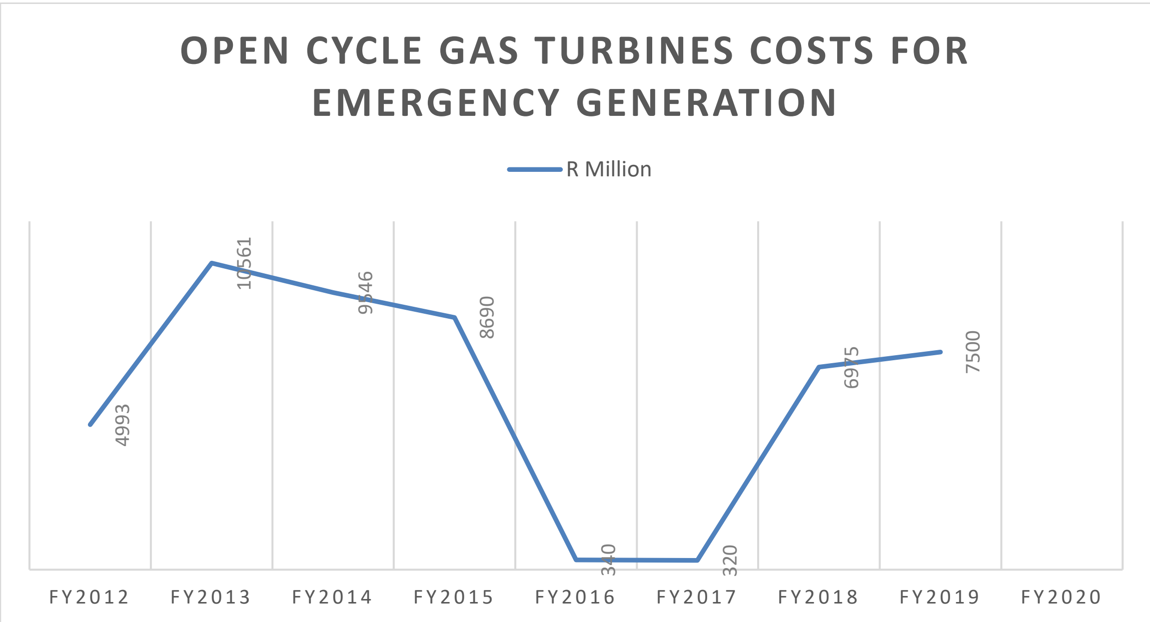
Table 3.6: The accelerated decline in energy availability factor since September 2017

	2019 Annual Results ending 31 March 2020	Interim Results for 6 months ended September 2019	2018 Annual Results ending 31 March 2019	2017 Annual Results ending 31 March 2018	Interim Results for 6 months ended September 2017
% National Generation Energy Availability Factor	66.64%	67.86%	70%	78%	83.2%
Load Shedding Days	46 days (Stage 6 Incident on 9/12/2019)	19 days	30 days	0	0

The decline in scheduled generation performance is accompanied by a simultaneous increase in the emergency generation performance, as shown in graph 3.2.



Graph 3.2: OCGT Costs for Emergency Generation

R320m and R340m reported for FY Ending March 2018 and March 2017 respectively is for diesel storage and demurrage costs incurred as a result of not using OCGT emergency generation. Table 3.7 presents the recent use of Eskom and IPP OCGT's, noting that both resources are employed extensively.

Table 3.7: Emergency OCGT usage for two six month periods

	FY 2020 – 6 Months ending September 2020			FY2019 – 6 Months ending September 2019		
	Cost Rm	**Energy Sent Out GWh**	**Unit Cost R/MWh**	**Cost Rm**	**Energy Sent Out GWh**	**Unit Cost R/MWh**
Eskom OCGT's	1 391	496	2 811	1 100	331	3 327
IPP OCGT's	1 259	291	3 648	926	169	4 389

4.0 DISCUSSION

4.1 The fragile South African national grid

Table 3.8 presents the weekly and daily national grid operating reserve margin data for weeks 19 to 24 of 2021 [10]. The operating reserve margins for weeks 19 to 23 were completely eroded. National load shedding was almost a daily occurrence involving stages 1 (1000 MW), 2 (2000 MW), 3 (3000 MW) and 4 (4000MW). In week 24, the operating reserve margin improves with consequential no national load shedding.

Table 3.8: The national grid operating reserve margin expressed as a percentage of available capacity to real time demand.

Day of the Week	Week 19 of 2021	Week 20 of 2021	Week 21 of 2021	Week 22 of 2021	Week 23 of 2021	Week 24 of 2021
Monday	2,7	1,5	4,0	-0,4	3,2	***7,0***
Tuesday	9,1	3,6	1,8	5,5	1,5	***6,2***
Wednesday	10,5	8,1	2,3	5,9	1,5	***13,2***
Thursday	7,3	11,7	9,2	-1,3	2,7	***9,6***
Friday	14,1	9,4	11,3	4,9	11,9	***13,3***
Saturday	9,8	9,4	5,4	5,0	2,3	***12,6***
Sunday	1,8	10,6	2,7	4,4	3,4	***21,9***

Given the one assumption that thermal coal production would hold to its consistent poor performance, this small sample of data shows the fragility of the national grid and its dependency on the status of national electricity production, particularly at the Koeberg Nuclear Power Station. In weeks 19 to 23, only one Koeberg generator was in service. On the Monday of week 24, the second generator returned to service. The available capacity included all resources of non commercial and self dispatching renewable energy production.

The dependency on the operating status of Koeberg has two major concerns ; in the immediate short term, all six steam generators will require outages for scheduled replacement and for the longer term ; in 2024, Koeberg will complete four decades of continuous production and will need to be relicensed and technically prepared to continue working for another two decades.

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4.2 South Africa's Acceleration to Decarbonise Electricity Generation

The deterioration in performance supports South Africa's journey towards downsizing on thermal coal electricity production. As power station plant and equipment fails, a reluctance could exist to defer additional resources for performance enhancement.

Assuming that all carbon fossil fuels usage must cease by 2050, South Africa should be accelerating the uptake of renewable energy generation as promoted in the National Integrated Resource Plan of 2019. The Independent Power Producer Renewable Energy Programme, driven by power purchase agreements, have reached their ceiling in terms of national fiscal guarantees. Without national guarantee, there will be no bankability of investments. The alternative option is for a market based approach. The present day efforts to accelerate the unbundling of the one hundred year vertically integrated company into its constituent parts of Generation, Transmission and Distribution is noted. An independent Transmission could deliver the required services of an independent system and market operator.

5. CONCLUSION

The deterioration in South Africa's synchronous generation performance has commenced. This is evident from the data that since 2018, the deterioration in performance appears sustained. The present day outcome is increased usage of emergency generation and increased incidents of national load shedding.

A first recommendation is for South Africa to secure its thermal coal synchronous generation performance. In parallel, the country must source new renewable energy investments and secure its nuclear energy strength. A new presence in the hydrogen economy will be an advantage. As part contribution to just transition, hydrogen from coal should be introduced to recover the stranded 600 MW synchronous generator at its Duvha Thermal Coal Power Station. With progress, coal can be replaced by renewable energy as the primary source of hydrogen.

The clean energy potential of nuclear and hydrogen will define South Africa's path to net zero carbon emissions by 2050. Uranium and hydrogen co-exist in the same stable of an energy economy that is powered by science, technology, engineering and mathematics. Both elements require a knowledge driven effort. South Africa has the main ingredient for such an uptake ; a population dominated by youth; all available, energised and schooled at the many world class South African academic and research institutions. Uranium and hydrogen will deliver the equilibrium amongst opposing forces of stability. Potentially stranded assets will be recalled to national advantage. National grid stability will be assured. Global climate change committment will be assured. Existing jobs will be secured. Both elements go the extra step in creating new work opportunity for individuals and for industry. Individuals will be urged onto higher degree qualifications. Industry will be thrust into the era of advanced and smart manufacturing. Reflecting on China's economic renaissance, national economic growth will shift into double digit performance. By virtue of its natural abundance of renewable energy and mineral resources, South Africa 2050 can become a net energy exporter.

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