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DEVELOPMENT OF SMALL MODULAR NUCLEAR REACTORS AS MUNICIPAL POWER STATIONS

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SUMMARY

Small modular nuclear reactors as municipal power stations can contribute to the increasing energy demand and the changing energy mix of large urban cities. Urban population growth, driven primarily from migration into the city, is increasing energy demand and placing strain on existing service delivery infrastructure. Rooftop solar photovoltaic systems are increasing in application and is leading the change in the energy mix of large urban cities. Climate change and global warming will accelerate the energy impact on cities. The expectation is for the major cities of the world to provide new leadership on sustainable, resilient and clean energy resources to serve the growing municipal customer and utility services.

Small modular reactor (SMR) technology is nuclear energy powered. SMR technology is effectively a zero emission, clean, constant and continuous heat source. The heat source will be available for application for a long period of time, as in decades. The long period of availability will lower the marginal unit cost of energy. Lower energy prices will make the technology economic and affordable. The downside of the technology will be the continued radioactivity of the spent fuel. Existing nuclear regulatory policies of waste disposal and management practices exists to manage spent fuel.

The heat source will be available to serve the traditional municipal utility sectors of electricity, water, sanitation and transport. In addition, opportunity sales as steam energy for embedded municipal commercial industries such as from the paper, pulp, food production, packaging and apparel sectors will enhance the business case. An emerging new opportunity for the heat source is that of hydrogen production to power the fuel cells of the next generation of electric mobility.

KEYWORDS
Municipal Utility Services, Small Modular Reactors (SMR), Pressurized Water Reactors (PWR), Uranium Economy, Hydrogen Economy

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1 INTRODUCTION

Renewable energy resources such as solar and wind will make deep penetration into the existing energy mix of municipal power supply grids. South Africa's recent Renewable Energy Independent Power Producer Programme invested approximately R200billion for a power supply having an average load factor of 30%. Engineering, procurement and construction costs accounted for 75% of the investment, whilst project preparation costs consumed the balance of 25% [1]. Going forward, the latest Integrated Resource Plan calls for more investments in renewable energy, notably onshore wind and solar photovoltaic, estimated at present day value of R400billion. For power distribution grids, in a carbon-constrained scenario, one of the key issues is the provision of dispatchable back-up power to a system dominated by intermittent renewable energy resources such as solar and wind. Presently, batteries, fuel cells, gas and diesel powered generators are available. The menu of dispatchable back up power has boundary conditions of capacity, operating costs and environmental impact. An opportunity exists to introduce nuclear energy as in small modular reactors to provide the dispatchable back up power. The key business case parameters will be life of plant and average load factors; renewable energy has commercial life of 20 years @ 30% average load factor whilst SMR will have commercial life of 60 years @ 100% average load factor.

The small nuclear powered reactors have emerged from the military era as small nuclear power plants for naval vessels and are now under consideration as a zero carbon emission technology for merchant vessels [2]. The power plant for vessels, which are as small as 15MW, can ramp load at very high rates (technical core limits being in the order of 1% to 100% in one minute). They can operate stably at very low power levels (below 10% power). Similarly, modern small modular reactors are being developed in the world and the size ranges from below 5MW to 300MW. They all promise much simpler design and have far simpler and designed (inherent) nuclear safety systems. There exists zero emissions from operations, their footprint is limited and existing regulatory practices will manage licensing and operations. Small nuclear powered reactors offer new boundary conditions for the secure, safe and economic operation of distributed power supply grids. Designs are modular and compact in structure, they are capable of rapid load following, are carbon emission free, are capacity flexible to municipal needs and requirements, have long-term capability of energy availability, to yield assured security of supply, low fuel operating costs and lower marginal unit cost of energy.

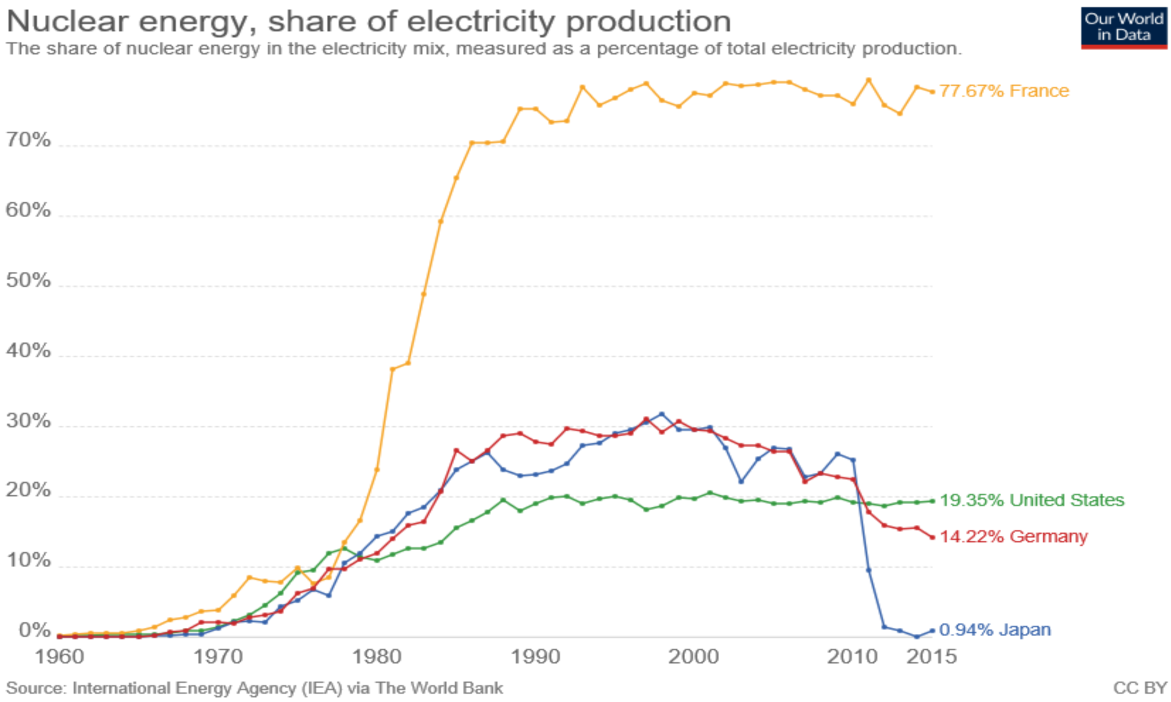
To strengthen the business case, the heat source is available for commercial and industrial processes that requires steam, for example, the paper, pulp, food packaging and apparel industries. In the case of municipal utility operations, the heat source is available for use in reverse osmosis technologies that can recover fresh water from wastewater resources such as municipal sanitation. The opportunity sales is available for wastewater from industrial and mining operations. In the case of coastal municipalities, seawater desalination is a possibility. In cold climates, municipal heating systems is another possibility. The heat source constitutes monetary value as an additional revenue for municipal operations. Another emerging new economy is that of the hydrogen economy. Electric mobility will gather momentum in the decade ahead. Fuel cells and hydrogen energy will be spur on the new economy. Hydrogen from water, plus a separate oxygen economy implies that large quantities of heat energy will be required.

The two likely sources for the large quantities of heat energy will be nuclear and solar. Solar, naturally renewable, is the preferred choice. Solar has the downside of time dependency of energy delivery. Nuclear, independent of time, has the downside of potential environment impact from spent fuel radiation. A summary of the international trends in nuclear energy will support the discussion going forward.

2 INTERNATIONAL TRENDS IN NUCLEAR ENERGY

Physics Today, a publication of the American Institute of Physics, reports in its December 2018 issue that cheap natural gas (from the shale gas boom) and the large increase in renewable energy from wind energy resources is accelerating the decline of the US commercial nuclear industry [3]. The decline is irreversible. The era of large commercial nuclear reactors in America will end. Graph1 shows the share of nuclear energy production for the United States as compared to France, Germany and Japan; noting that the latter two countries are in sunset mode following the Fukushima incident.

Graph 1: Nuclear Energy Share of Electricity Production



In the US, 98 reactors continue to operate and supplies 19,35% of the national electricity [3]. The large reactors have lost economic relevance in the wholesale competitive markets. The competitive market price discovery mechanism allows the cheaper energy resources to set the price paid to all generators. Nuclear operates at full capacity and unity load factor. They remain on and just accept the price as set by the others market participants and become price takers. The competitive market mechanism is working to the advantage of buyers (customers); the most efficient and economic resource is dispatched. The era of large nuclear power plants in the US, possibly Germany and Japan, will end. Arguments of reliability, resilience and carbon free emission credits are academic.

In the case of Russia and China, possibly India, Korea and the Middle East, large nuclear power plants are experiencing a sunrise industry. Russia has 53 reactors on its domestic book and internationally, 50 reactors in 19 countries [3]. China has 220 new reactors on its domestic book and internationally, 20 reactors in 12 countries [3]. Russia and China have state owned enterprises that builds, owns and operates the nuclear reactors. State owned transmission and distribution system operators manage the power delivery to end customers. The case of China has particular interest in that the Chinese employ all technologies; coal, nuclear, hydro, renewables and are exploring hydrogen for the emerging generation of electric vehicles. Their monopoly market model of the last two decades helped move millions of their people from poverty to prosperity.

Thus, in general, the market model determines the participants. Inefficiencies exists in both society and market models. Competitive markets manage the inefficiencies in real time whilst monopoly and regulated markets absorb the inefficiencies in time. The longer the time term, the lower the impact of and the greater the smoothing of the model inefficiencies. The competitive markets that displaced the large reactors on economic grounds of high costs is encouraging the growth and development of smaller modular nuclear reactors. Many US companies are pursuing this option and expect new commercial interest in the period 2020 to 2025. The modular reactors are in the capacity range of 100 MW and less; with micro and nano reactors in the range of MW's to kW. The intent is to factory build the reactors, deliver to site and return same to the factory for refueling and maintenance. Historically, all of the commercial nuclear reactors descended from naval reactors and the small modular reactor design continues the legacy.

3 THE ENIVIRONMENT FOR MUNICIPAL POWER STATIONS

3.1 Increasing Urbanization and The Need to Converge the Municipal Services of Electricity, Water and Waste for Sustainable Development

Presently, 55% of the world's population live in urban areas. The United Nations projects that this number will increase to 68% by 2050 [4]. By 2030, the world will have 43 megacities with over 10 million inhabitants. Table 1 lists the populations of a few megacities of the world in comparison to South Africa's top six cities.

Table 1 : Population of a Few Megacities in Comparison to South Africa's Top Six Cities

World MegaCity	Population Millions	South Africa MegaCity	Population
Tokyo	37	City of Johannesburg	4,435
Shanghai	26	City of Cape Town	3,74
Mexico City	22	Ethekweni	3,442
Sao Paulo	22	Ekurhuleni	3,178
Cairo	20	City of Tshwane	2,921

Mumbai	20	Nelson Mandela Bay	1,152
Beijing	20	Buffalo City	0,755
Dhaka	20	Mangaung	0,747

Tokyo has a demand of 70 GW compared to the City of Johannesburg of 3 GW. Both the cities are fossil fuel powered and will need to start changing as per the challenge of climate change and global warming. In addition to that of climate change and global warming, urbanization will intensify and stress the municipal service delivery of electricity, water and waste.

Sustainable urbanization is key to successful development. The implementation of the 2030 United Nations Agenda for Sustainable Development calls for a new framework of urban development. The future focus will shift to the nexus of energy, water, waste, sanitation and transportation. The common denominator in the nexus of services is heat energy. An abundance of heat, safe and continuous, has the potential to serve each of the sectors of energy, water, waste, sanitation and transportation and can go further to deliver quality jobs and a clean and healthy environment; all leading to an uplift of municipal economic growth and development.

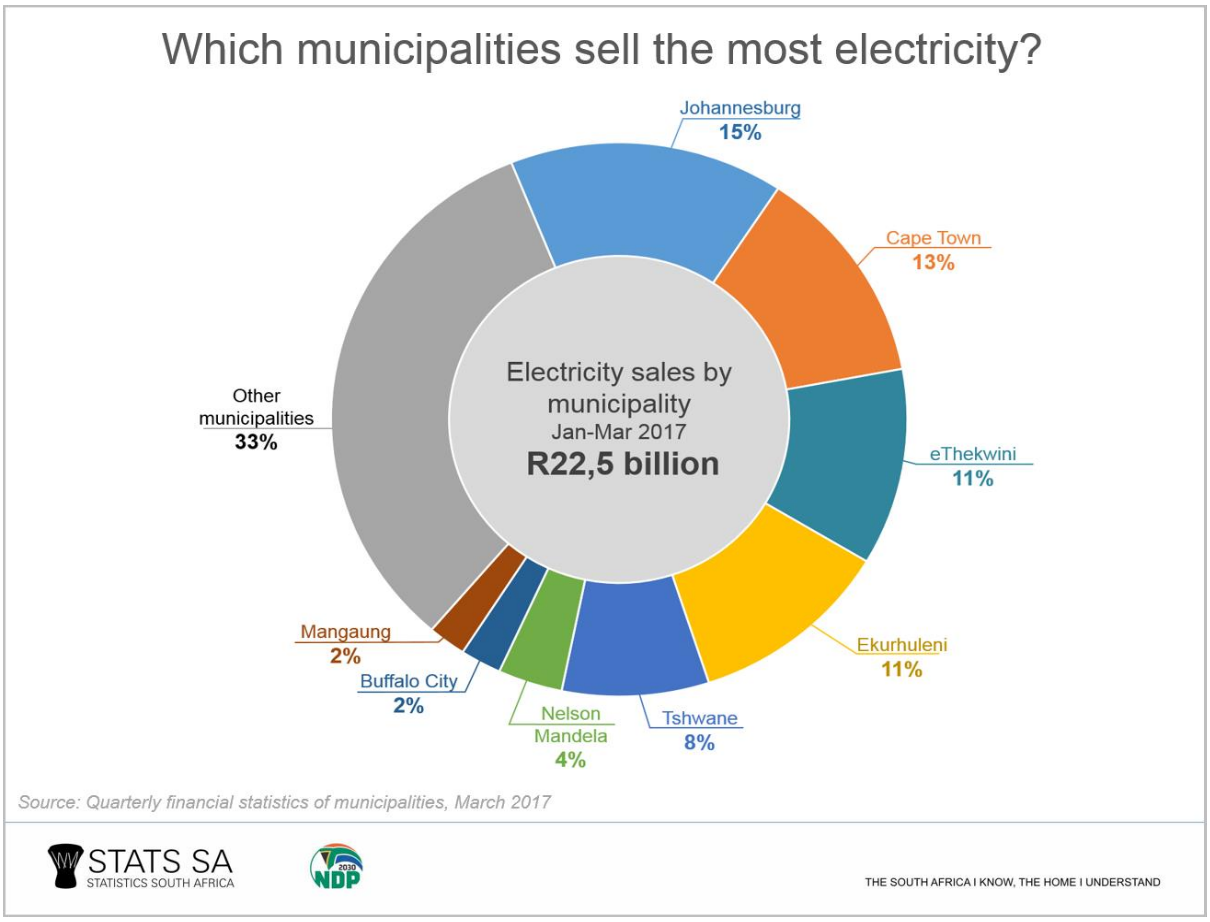
3.2 Cash Flows of Municipal Electricity Sales for New Investment in Municipal Power Stations

The question city leaders will need to answer; how do we get the financial resources to develop municipal power stations? Stats South Africa has an answer:

"Trading electricity is big business for local government, according to Stats SA's. The March 2017 quarterly financial statistics report on municipalities records that South Africa's 257 municipalities earned just over a quarter of their total income (R22, 5 billion) from selling power in the first quarter of 2017. With R15, 7 billion spent to purchase the electricity from Eskom, municipalities were left with a R7 billion surplus, representing precious additional money that can be used to fund municipal investments and activities." [5].

Graph 3, extracted from Stats SA quarterly financial statistics report for municipalities, dated March 2017, shows the municipal electricity sales for the first quarter of 2017 [5]. Eskom's Integrated Report for 2018 [6], records that of the 212,190 GWh total energy sales, 41% was purchased by the municipalities; representing R71,75 billion of Eskom's total annual revenue of R175 billion. Four municipalities, Johannesburg, Cape Town, Ethekweni and Ekurhuleni comprises 50% of the total R71,75 billion annual municipal revenue to Eskom. These municipalities typically represents a captive market for investment in small modular reactor nuclear powered municipal power stations. The municipal environment presents itself as a friendly environment for small modular nuclear reactors; a right fit in terms of size, capacity, affordability and safety.

Graph 3: Municipal Electricity Sales Profile



The International Atomic Energy Agency (IAEA) reports on the advanced development of small modular reactors [7]. For example, in the United States of America, new competitive market models for the trading of electricity has encouraged the growth and development of small modular nuclear powered distributed generation. IAEA has reported on two new developments at MPower USA and at NuScale USA [7]. In terms of an actual demonstration plant, IAEA reports on the work in progress in China [7]. These examples demonstrate the readiness of the technology and of the regulatory environment to accept the new small reactor modular technology as part of the energy mix of municipalities.

3.2 The MPower USA SMR Example

The plant is of passive safety design and is a pressurised water reactor with nominal output of 195 MW(e) per module [7]. A twin pack module will deliver 390 MW (e) of capacity. Tennessee Valley Authority (TVA) has announced its intention to build two or more SMR modules at its Clinch River site in Roane County. The timing is around 2025. Table 2 presents the high level technical parameters for the mPower design.

Table 2: High Level Technical Parameters of the mPower Design

Parameter	Specification	Comment
Reactor Type	PWR	PWR = Pressurised Water Reactor; Mature Technology as employed in the large nuclear reactors
Coolant/Moderator	Light Water/Light Water	
Thermal Output MWt	575	In addition to electricity generation, the heat source is available for other applications such as water reclamation from sanitation etc.
Electrical Output MWe	195	
Primary Circulation	Forced Circulation	These specifications are similar to that existing at the Koeberg Nuclear Power Station located in the Western Cape. There will be an abundance of local skills for managing, operating and maintaining the new investment.
Core Inlet Pressure (MPa)	14.8	
Core inlet/outlet temperatures (o C)	290.5/318.9	
Fuel Type/Assembly Array	UO 2 pellet/ 17 x 17 square	
Number of fuel assemblies	69	
Fuel enrichment (%)	< 5.0	
Fuel burnup (GWd/t)	<40	
Fuel cycle (months)	24	
Main reactivity control mechanism	Control Rod Drive Mechanisms	
Design life (years)	60	

3.3 The NuScale USA SMR Example

For the NuScale design, each module is engineered to deliver 50 MWe [7]. The plan is to scale up to twelve units for a total site capacity of 600 MWe. Utah Associated Municipal Power Systems has ordered their first unit for 2026 commercial operation. The planned site is Idaho, USA. Table 3 presents the high level technical specification for the NuScale design.

The passive safety design promotes close location of the power plant with other activities of the municipality. Effectively, the power plant can be located within the municipal area of supply. This will result in short power delivery routes to customers.

Table 3: High Level Technical Parameters of the NuScale Design

Parameter	Specification	Comment
Reactor Type	PWR	The emerging picture of SMR's is one of standard design having passive safety systems; the fuel assembly is held constant
Coolant/Moderator	Light Water/Light Water	
Thermal Output MWt	160	
Electrical Output MWe	50	
Primary Circulation	Natural Circulation	
Core Inlet Pressure (MPa)	12.8	

<table>
<tr><td>Core inlet/outlet temperatures (^{o}C)</td><td>258/314</td><td rowspan="8">for the many types of designs and the rated capacity is determined by the number of fuel assemblies deployed.

The modular concept promotes factory shop manufacturing of reactors and balance of plant</td></tr>
<tr><td>Fuel Type/Assembly Array</td><td>UO_2 pellet/ 17 x 17 square</td></tr>
<tr><td>Number of fuel assemblies</td><td>37</td></tr>
<tr><td>Fuel enrichment (%)</td><td>< 4.95</td></tr>
<tr><td>Fuel burnup (GWd/t)</td><td>>30</td></tr>
<tr><td>Fuel cycle (months)</td><td>24</td></tr>
<tr><td>Main reactivity control mechanism</td><td>Control Rod Drive Mechanisms</td></tr>
<tr><td>Design life (years)</td><td>60</td></tr>
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3.4 The Chinese High Temperature Gas Cooled Reactor SMR Example

The Chinese have prepared a conceptual design for a 200, 600 or 1000 MWe multi-module high temperature gas cooled reactor nuclear power plant [7]. For the 600 MWe design, the power plant consists of six reactor modules that couple to one steam turbine. The reactor module is the same design as their demonstration plant that will go commercial in 2019. Each reactor module retains its independent, passive safety systems. The footprint of the high temperature multi-module plant is similar to that of the NuScale PWR plant. The customers will shortly have choice in terms of reactor technology; high temperature gas cooled versus pressurised water-cooled designs.

4 CONCLUSION

IAEA has reported on the global effort to develop and commercialise small modular nuclear reactors, having by design, inherent passive safety features [7]. The intense research and development work is in the final stages of warp up, the first commercial demonstration units will commence duty and in the period towards 2030, we expect many more units to go into commercial service. The list of countries engaged in promoting SMR development is vast and global, including South Africa.

In positioning Africa, South Africa and the University of Johannesburg, the Department of Mechanical Engineering Science has aspiration to grow and strengthen its presence in the field of both natural renewable energy resources such as solar, wind and water plus that of the stored energy resources such as carbon, uranium and hydrogen. Each of the renewable and stored energy resources have boundary conditions for application.

For the case of SMR nuclear powered technology, the reactors have the advantage of flexibility in application for a wide range of user and applications, namely,

a. For application in smart and micro grids;
b. As decentralised bulk power generation for the many distributed load centres scattered across continental Africa;
c. To promote the nexus of energy, water, waste and food security; and
d. To complement the intermittent power supplies of the growing renewable energy market.

The net benefit of SMR's lies in the modularity, multiple duty application and "just in time" financing. Thus, an emphasis going forward is that one should invest in "informed buying of technology" rather than "research and development of technology". Informed buying of the technology from international vendors refers to having the knowledge, skills and expertise to specify the technology and to evaluate the delivery of the technology against the specification. The range of the specifications will span design, engineering, operations, maintenance and decommissioning of the assets, inclusive of the primary and spent fuel, safety and environmental regulatory compliances.

South Africa and Africa have a unique position in the service delivery sector. Traditional solutions have lagged and what is required is a leapfrog effort in terms of providing service delivery to the growing population. The new generation SMR is equivalent to that of cellular communications. There is no need for large-scale investments in "wire connected solutions". This attribute afforded rapid growth in mobile technology acceptance right across continental Africa. The most remote part of Africa has access to mobile cellular technology. Coupled with informed buying, SMR's are poised to make a deep penetration into providing service delivery to the growing population of Africa. Small modular reactor technology, nuclear powered and configured as a heat source for multiple municipal and customer services is emerging as a choice in the energy mix of the South African municipalities such as Johannesburg, Cape Town, Ethekweni and Ekurhuleni; typical capacity sizes will be in the order of 200, 600 or 1000 MW; having modular ratings of 50, 100 or 200 MW.

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