Application of Small Modular Reactors in Sub Saharan Africa

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Abstract

United Nations Sustainable Development Agenda 2030 calls for access to affordable, reliable, sustainable and modern energy for all. Sub Saharan Africa has an abundance of natural renewable energies as in solar and large scale hydroelectric resources. These resources remain untapped due to the general absence of a synchronous and interconnected electrical power system. For the present day, off grid individual load solutions permeate the region and the continental lag remains in the industrial and postindustrial economies. Without dispatchable and economic electricity, sub-Saharan Africa will be stranded and her millions of inhabitants will be destined to poverty. A clean energy resource to power up national and regional economies and to harness the continents massive renewable energy potential is nuclear energy. The paper discusses the issues which have limited the current nuclear technologies from being deployed and why the prospect of modern Small Modular Reactors to meet this need would seem appropriate. The paper recommends a charter for the large scale introduction of nuclear technology to Sub Saharan Africa; incorporating policy, regulatory practices, design standards and people development.

Keywords
Sustainable Development, Small Modular Reactors, Dispatchable Synchronous Generation, Nuclear Policy, Regulation and Practices.

1. Introduction
United Nations Sustainable Development Agenda 2030 calls for access to affordable, reliable, sustainable and modern energy for all. Agenda 2030 further defines the key expectations as follows:

> “7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology; and
> 7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States and landlocked developing countries, in accordance with their respective programmes of support.”

Sub-Saharan Africa, with the exception of South Africa, comprises a collection of least developed countries and landlocked developing countries. Given an abundance of renewable energy as in sunshine and concentrated large scale hydro potential as in the proposed Inga Complex on the Congo River, Sub Saharan Africa lacks the classic synchronous power supply system to harness the vast potential renewable energy resources. Thus, for the present day, Sub-Saharan Africa remains part of the dark continent. Renewable energy solutions are mostly of off grid design to individual loads. The region deeply lacks affordable bulk electricity supply to power up industrial and post industrial economies. The millions of inhabitants are stranded in the informal agricultural economy and destined to poverty. Figure 1 illustrates the challenge and provides the installed capacity as "Watts per person" in the population for 14 major Sub-Saharan countries. This is compared to the South Africa.

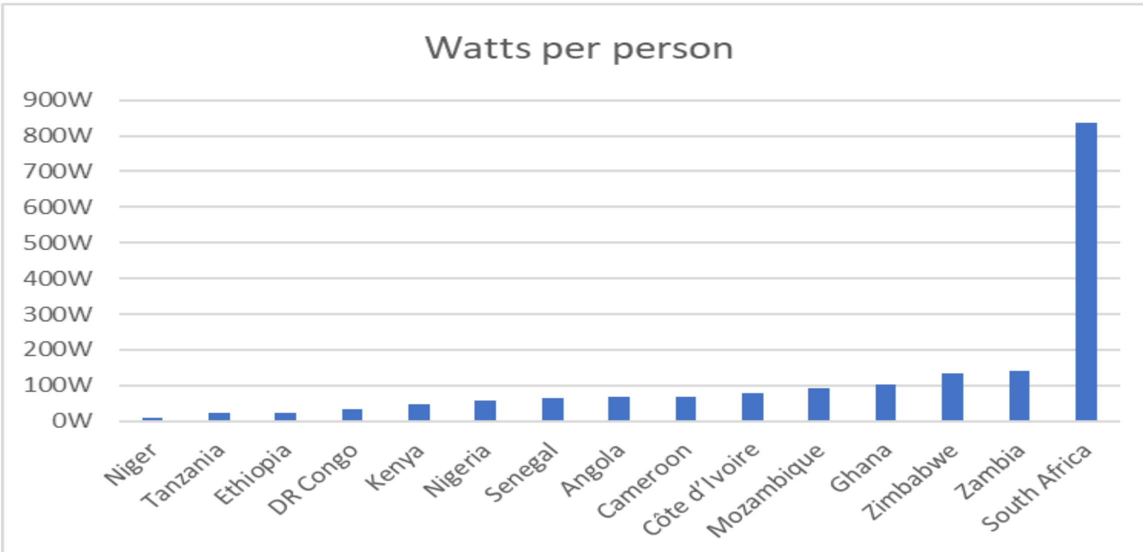

Figure 1 : Watts per Person in Sub Saharan Countries as Compared to Industrialized South Africa

In most of these countries the power supply comes from either small hydro or diesel generators. This leads to an extreme cost distortion. For example in Zambia the grid cost of electricity is US$6c/kWh but the estimate of the diesel generator power is US$c53/kWh. Figure 2 illustrates the average hours of grid outage per year shows the potential impact of electrical shortages on any prospect of industrial led growth.

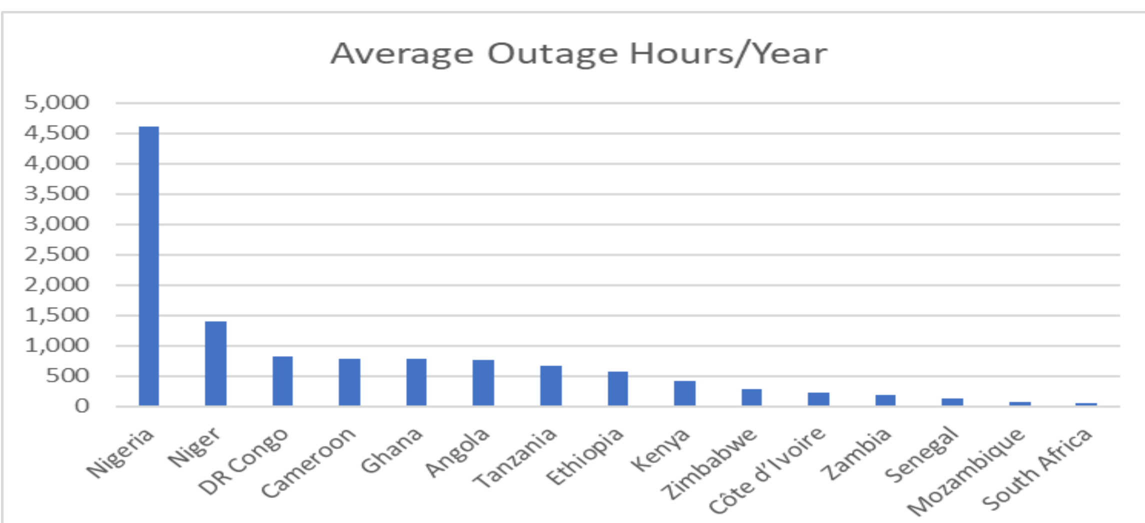

Figure 2 : Average Outage Hours per Year for Sub Saharan Countries

The South African data (50 hours per year), linked to South Africa's anemic growth since the grid capacity was first constrained in 2006/7, shows that without much more cost effective generation plant there is little hope for industrial growth in the region. The need for such generation plant to be low carbon leads to the constraint that coal and natural gas[1] installations will be challenging to environmentally justify and fund. The clear politically supported option is to install renewable energy sources (wind and PV) and while the energy cost per kWh of these sources is very competitive their correlated intermittency (e.g. the sun goes down at the same time in the 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. Clearly hydro plant is an excellent solution, if the national geography and weather supports it, but this is not the case in many countries.

2. The Limitation of Traditional Nuclear Technology as in Pressurized Water Reactors

Many countries in Africa have talked about installing nuclear power stations but only two have actually undertaken and committed to nuclear power. South Africa has the 2 x 930MW units at the Koeberg nuclear power station and Egypt has the signed contract for the 2 x 1200MW units at El Dabaa nuclear plant. South Africa has plans for additional nuclear post 2030 (DMRE IRP 2019). 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. With the exception of 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%. As can be seen from Figure 3, only 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.

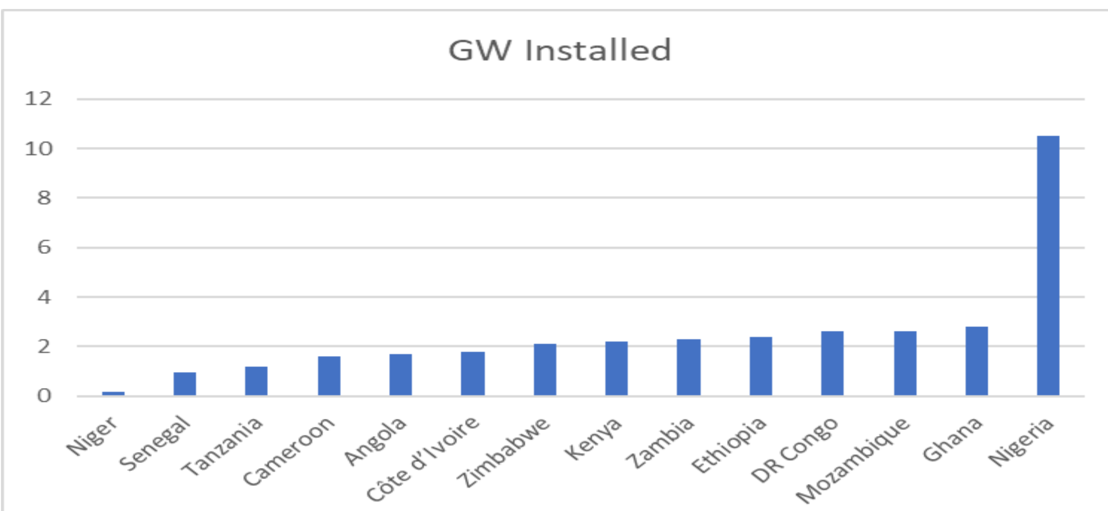

Figure 3 : Installed National Grid Capacities of Sub Saharan Countries

[1] The often quoted "low carbon impact" of natural gas generation is based on the combustion products and thermal efficiency of CCGT plant compared to classic coal plants. It ignores the methane leakage in the gas extraction and supply system which, if leakage is equivalent to the claimed US industry leakage of 3.3%, makes natural gas based electricity production similar to coal in greenhouse gas impact (methane is 84 times more potent than carbon dioxide but has a shorter residence time in the atmosphere.

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, way too big for most African grids.

3. The Potential of Small Modular Reactors for Sub Saharan Africa

Starting with innovative designs in the 1990s a new class of reactors, the so called "Small Modular Reactors" or SMRs, was being designed with power outputs from about 50MW to 300MW. These designs are not just smaller versions of the current power reactors but are, in most cases, designs based on technologies which had been analyzed and, in many case tested, in the 1950s and 1960s, but had not yet become commercial successes. In all these cases the approach was to look for a technology that did not need external "safety systems" but were close to "inherently safe" designs. What this meant was that whatever failed or whatever human error the operator made there should not be a significant release of radiation.

The choice of a small size enabled passive cooling and this allowed such inherently safe designs to be developed. It is important to emphasize that the enhanced safety is not simply a stricter implementation of standards, but a completely new design philosophy, leading to a distinct categorization as a new generation of reactor, the so called Gen IV. Any failure condition should result in a safe, passively cooled, contained, shutdown of the fission process, and the process must be also proliferation resistant and the spent fuel (not the waste) should be essentially safe as well. All this is achieved by arrangement of the various physics phenomena in a carefully crafted engineered solution, so that failure in a safe state is a natural consequence, rather than the result of an operator intervention. The cost issue is addressed by creating economies of scale by serial construction, not by large unit size. This move from "bespoke" designs with each plant having its own, unique, safety analysis to a "standardized serial" design with every plant having the same analysis (like modern airliners) along with standardized operating procedures, maintenance routines etc., will be the key to the success of the SMR future. As can be seen from figure 3, the ideal unit size for deployment would be in the order of 100MW - 200MW; as modular units.

To commence the investment, the first dispatchable generation nodes will be the existing municipal utilities. Small modular nuclear reactors as municipal power stations can contribute to the increasing energy demand and the changing energy mix of the large urban cities (Naidoo et al 2019). 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. 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 should be encouraged given a synchronous grid connected power system. In addition, the heat source will be available to serve the traditional municipal utility sectors of water, sanitation and transport plus provide opportunity sales as steam energy for embedded municipal commercial industries such as from the paper, pulp, food production, packaging and apparel sectors. 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. Collectively, the revenue flows will enhance the business case.

Other potential bankable sites for SMR's would be energy intensive mining and industrial nodes. Sub-Saharan Africa is endowed with mineral resources. The mines and their communities are generally located in remote sites away from the municipal nodes. Given the absence of power delivery circuits of transmission, distribution and reticulation, an option would be engineer stand-alone micro or mini grids. The British Institute of Engineering Technology had reported on NASA's development a 10 kW small modular nuclear reactor, coupled with a stirling engine, to meet the power demand requirements for the MARS spacecraft. The constant energy source is available 24/7 for a period of a decade or two. When the source is depleted, the unit is exchanged for another whilst maintenance and spent fuel recovery is conducted in specialist workshops and environments. Naidoo et al (2019) reviewed the technical merits of the opportunity and proposed a functional design for a small modular nuclear reactor working in association with a stirling engine for electricity generation. Being a heat source, the waste heat is available for other applications such as steam generation, water purification and sanitation disposal. The customized plant will supply individual needs and requirements as in mining, industrial, residential, commercial, and agricultural customers; plus specialist applications such as power supply for other the generally remotely located mobile cellular base stations and water pump stations.

3.1 High Temperature Gas-cooled Reactors (HTGRs)

While there are many different technologies being proposed for SMRs at present the technology with the most short-term potential is that of High Temperature Gas-cooled Reactors (HTGR). This is because of the non-water-based technologies proposed this as the option with the greatest safety margins and most real operating experience.

HTGRs are helium cooled, graphite moderated reactors with "coated particle" fuel (the TRISO technology). This was heavily developed in the 1960s-1980s, with Germany and USA each constructing two power stations, one of which ran for over 20 years. UK, Japan and China have also built HTGR research reactors and China is about to commission its first 210MW commercial sized unit. What makes HTGRs different to current water based reactors is the very high helium coolant operating temperature (by current experience, up to 950ºC) and a safety approach that if all the coolant is lost and no safety systems function then there is no fuel failure, even with no operator intervention - ever. The high operating temperature allows higher efficiency than current designs (either direct cycle or a steam cycle at ~570ºC, cf ~275ºC in a PWR). The safety features remove the need for any public emergency planning (such as evacuation) and related staff costs and also regulation related costs.

This safety advantage of HTGRs was not seen in the 1960s and 1970s when they were being developed to compete with large (1000MW) PWRs and BWRs. Prior to the nuclear accident at Three Mile Island PWR reactor in 1979, all the developers in US and Germany were driving for a very large HTGR (500MW-1000MW) and the loss of the safety features was not seen as an issue. These large HTGR design's tended to have some safety systems, albeit less than PWRs. It was only after TMI that safety became such a priority and the related costs rose exponentially in the industry. It was then realized that if HTGRs were designed to allow the unpressurised loss of heat, such that the TRISO fuel temperature would not exceed the point of radioactive release at any time, an "inherently safe" design could be created. This limited the size of the core of the reactor but the gain in safety margins more than compensated. This has been phrased as "walk away safety". Operating the core at a higher temperature also allowed a natural temperature ceiling to build into the fission process. As the core temperature increases, the probability of neutron absorption reactions occurring can be arranged to increase relative to fission reactions, by careful design. This means that if the reactor gets too hot, it will consume its own neutron population with non-fission neutron absorption processes. It will shut itself down. Such a feature is termed a strong negative temperature coefficient of reactivity. Combining this feature with resilient fuel is a very powerful safety combination.

3.2 Preparing Sub Saharan Africa for HTGR Small Modular Reactors

If this HTGR based SMR is a credible solution for Sub Saharan Africa, what are the prerequisites?

a. A Standard Design

There are several HTGR projects in the world, such as the X-energy project in the USA (75MW) or the HTR-PM in China (210MW twin unit) and others. Given the resource constraints in Africa, it is probable that only one design would become the continental standard. Given the acceptance of an "African Union" regulation this would call for standardization on all aspects of the design, construction, operation and regulation.

b. Competitive Economics

There is a wide range of electricity prices across Africa but this does not necessarily reflect the actual costs of new generation plant. The effective cost of electricity from the SMRs would be based on two key variables, being the installed costs ($/kWe) and the Net Discount Rate. If the capital costs are of a similar range to the current large reactors ($3500/kWe-$6000/kWe) and the discount rate in the range of that assumed by the OECD/NEA for such projects (3% - 10%) this would lead to a wide range of potential power costs of US$c5/kWh to US$c14/kWh. The key to low costs, as with other such projects, would the reducing of overheads and standardization. The estimated installed capacity required to close the Sub Saharan power deficit is 68GW. This would be some 700 HTGR modules, or $350bn of investment.

c. Regulatory and Licensing

SMR is a type of nuclear reactor that has an inherently different fuel supply and power extraction design as compared to the conventional large scale, pressurized or boiling water reactors. SMRs provides modular construction, scalable size and flexible operation in addition to conventional advantages of nuclear power production. The conventional safety standards and related licensing regulation makes nuclear technology for power generation more expensive than other energy resources. The high fixed overhead costs causes the power generation plants to become larger such that the safety and regulatory burden per unit cost of power generated, is lower. Today, the market boasts very large units (up to 1750MW) with multiple units on a common site. This causes the current technology to be suitable for large grid deployment such as that of large national or regional power grids. Coupled with the call on standard designs, Naidoo et al (2019) discusses the emerging global practice to develop a number of different classes of nuclear power plant regulations for the different types of nuclear power plants. This approach would make practical and affordable the regulatory requirements for the licensing and operations of small modular nuclear reactors.

d. Human Resource Development

Nuclear energy is an extremely dense form of energy that requires enormous and disciplined investment in people development. The rewards are equally extreme; long term employability and sustainability of jobs and a better quality of life for all.

Let us recall that the Sun is the sole source of all energy. All the energy received converts from one form to another; energy is neither created nor destroyed. The best representation of the energy carriers are the elements of the periodic table; for example, coal, oil and gas constitutes the carbon element. In the case of nuclear energy, uranium is the element. Energy storage sustains and the dense fuel can be packaged for use in future time. To manage and utilize the density of the natural fuel, people development is a necessary requirement. Specialist and disciplined scientists, engineers and technologists are required. In the era of the 4th Industrial Revolution, open source software and specialized physical and mathematical tools are available to realize the goal of large scale people development for the emerging nuclear economy. Naidoo et al (2019) presents the results of an undergraduate dissertation in Mechanical Engineering Science. The paper demonstrated the development of the simulation model of a single simplified high temperature gas cooled reactor fuel element surrounded with a helium coolant. The study of the behavior of the neutron economy of the simulated reactor showed the inherent safety of the fuel pebbles. The study confirms that with the aid of computational simulations, engineers can promote strenuous testing of reactor and fuel designs to ensure the safety and sustainability of the plant. Small modular nuclear reactors are capable of having a radioactivity risk load of less than that which currently prevails in the local community hospitals.

4. Conclusion and Recommendations

For the past 250 years, three industrial revolutions greatly increased wealth, health and welfare for most, except Africa. In the present day, the 4th Industrial Revolution is underway and the global community is experiencing dramatic changes in the world of work. Sub Saharan Africa must ensure that it is an active participant in this revolution and accumulates the gains. Modern and clean energy for all is the requirement. Small modular reactors has the potential to leverage Sub Saharan Africa out of poverty and onto a sustainable path of prosperity. To commence the investments in SMR's, the following is a set of first recommendations:

4.1 Policy Issues to be Resolved

As an example the nuclear safety authority in South Africa, with one nuclear plant, has about 190 staff, most of whom are highly qualified technical employees. As the staffing of an SMR would be aimed to be well below 200 this shows the national regulatory overhead would have to be managed very differently than as for a current nuclear plant. The logical approach would be to establish an "African Union" based nuclear regulation system for such SMRs as they are deployed. This would clearly lead to a completely standardized set of designs which would then be operated to the same standard across the continent. While this is a radical approach in the nuclear industry it is exactly the model applied in the airline industry, which in many ways has a much greater safety challenge than the nuclear industry.

The nuclear industry was initially developed in large, industrialized countries (USA, USSR, UK, France etc.) and the national objectives of these countries led to purely nationalistic management of the key infrastructural and policy issues. This approach has been carried forward to the overall approach adopted by the international community, specifically the IAEA and other bodies and treaties.

If one is to deploy SMRs on a limited scale (initially a few units per country) it is difficult to imagine the economics of the country supporting an independent regulator with a "stand-alone" technical licensing ability, a national spent fuel repository etc. The need to review these issues and possible approaches is discussed below.

4.2 Nuclear Regulation

Unlike other international high technology industries (such as airliners) the current view is that each country has its own licensing processes, rules and regulation with an authority resourced to undertake a complete national review of the design, construction, operating rules etc. This allows a national authority to independently certify the safety of the nuclear operation.

This may seem reasonable at face value but it should be compared to another international industry – aerospace. If each country required the local regulator to independently, from first principles, certify the design and operating status of each airliner (e.g. Boeing 747) before it could operate in the country it would stop international air travel almost completely. The approach taken by the aerospace industry is to have (essentially) automatic acceptance by all countries of certification given by the recognized authority in the country of design (e.g. FAA - Federal Aviation Administration in the USA or JAA - Joint Aviation Authority in Europe). For the SMRs to be deployed effectively in Africa in the way discussed above there would need to be some treaty agreement between the various countries (probably under the AU) to establish a common licensing regime (in many ways similar to the European JAA) for standardized nuclear plant designs. This would require a very rigorous, common, approach to operation and maintenance, in the same way that, for example, all Boeing 747s have an approve maintenance regime, through certified companies etc. While this may seem eminently sensible it is a dramatic change from the current practice of requiring comprehensive national competency. It means that some foreign organization can dictate the functioning of the local nuclear power station. When the US FAA withdrew the Boeing 737-Max airworthiness it stopped all Boeing 737-Max flying in the world. No one suggested that the South African airlines could ignore the FAA decision.

4.3 Design Authority

If one accepts, like the airline industry, a centralized "African Regulator" over all the countries then the other issue it resolves is the "Design Authority" requirement. At present the nuclear license is issued to the operator by the national authorities and is specific for the installation of the operator. The operator is therefore required to have a full technical understanding of the plant and all submissions to the national regulator are made by the operator, even though there may be a lot of backroom work done by the OEM. Even in the US, with the Design Certification process by the OEM, the submission of the license application is by the operator and he is required to have a full understanding of the design of the installation. This is as if one was required to have a full design understanding of one's car when one got a driving license. If one had to be able to justify the safety of your car before one could drive it (such as the design of the brakes and the stress calculations under emergency braking?) nobody would have a car.

In the current nuclear industry, therefore, the license for the operator includes a first principle analysis on the specific design, operated and maintained by the operator. The operator is therefore the Design Authority for the installation. The operator cannot contract that out to the original OEM and must maintain the full competency to analyze all aspects of the plant.

This clearly is not tenable for SMRs deployed on a limited basis in a specific country. In the same way as with airliners it requires the Design Authority to be the OEM, as with airliners and cars. As with those technologies, of course, the OEM disavows the design if it is not maintained according to the laid down requirements or it is modified from the specification (one's warrantee on a car is voided if you modify it!)

4.4 Nuclear Liability

One of the issues that flow from the Nuclear Regulation proposal above is the issue of accident liability. In the current situation the operator of a nuclear facility has "Strict Liability" in virtually all countries. This means that if there is an event causing nuclear damage to external parties (e.g. a radioactive release causing cancers in local population) then the only party liable for the damages is the licensed operator, and the operator has no defense from liability if damage is proved. This is very different from other industries. If an airliner crashes, for example, the victims can sue whoever is seen to be at fault – airline, manufacturer, maintenance company etc., and the legal defense can be that they were not negligent.

In a nuclear liability situation there is no such defense, if there is nuclear damage emanating from an event at a nuclear installation then the licensed operating company is liable for the damages. This works in theory because the licensed operator is accountable for all aspects of design, manufacture, operation, maintenance etc. If one is moving closer to the model of the airline industry this would have to be adjusted to include the OEM (who would now be the Design Authority) as also liable if the event was caused when the operator was obeying all the OEMs requirements (in terms of modifications, operations, maintenance etc.).

This approach would only be credible where the inherent design of the plant lead to confidence that the maximum nuclear damage it could cause was sensibly insurable. This would lead to a premium of plant safety features such as the HTGRs with TRISO fuel demonstrate.

4.5 Decommissioning Provision

Another key issue for deployment of SMRs in Africa would be the acceptability of the decommissioning funds. While there are many different approaches to this in the current world nuclear industries it would be most straight forward for the establishment of individual decommissioning funds for each nuclear installation, funded over its operating life. This could be modelled on the US practice where the fund is a legally separate item which is therefore not, as in some situations, a provision on the balance sheet of the operating company. It might even be appropriate for the decommissioning fund to be fully funded at plant start up, with investment returns on the fund that are greater than inflation being returned to the operating company as income.

4.6 Waste and Spent Fuel Management

The current international approach for the management of nuclear waste and spent fuel is that it is a purely national responsibility and it is not allowed to "export" (or "import") nuclear waste for final disposal. This approach was largely put in place to avoid third world countries becoming "dumping grounds" for first world waste. It is reasonable approach for countries with a substantial nuclear program but may be an economic challenge for countries with a very small program. For low and intermediate waste it may be reasonable to establish a near surface disposal site on a country by country basis, as the overhead costs are not severe and the facility may only be required at plant decommissioning. The issue of a final repository for Spent Fuel is, however, much more challenging. There is a very large fixed cost for establishing the repository facilities which are considerable and which would distort the economics substantially. Given that the SMR design should aim to store all the spent fuel from its operating life on the site this issue would only be needed at end of plant life but must be included in the costing model from the beginning. A high-level repository establishment can be in the region of $2bn (the establishment cost of the US Waste Isolation Pilot Plant (WIPP) in the 1990s). In the context of the overall WIPP lifetime costs of some $20bn including operations this is reasonable, but to support a nuclear reactor plant that may have a capital cost of $1.5bn (say 300MW at $5000/kWe) it is clearly unacceptable. It therefore would become important to accept a regional Spent Fuel Disposal facility. It may be logical to consider the future South African spent fuel disposal site which is already included in Koeberg's spent fuel provisions. The policy on the final disposal of Spent Fuel as well as the low and intermediate waste needs to be included at the beginning of the projects and it would seem logical to approach this on a regional basis.

The work ahead is vast, detailed and complex. Nuclear energy will require a substantial investment in human resources. Science, Technology, Engineering and Mathematics (STEM) would need to be cultivated in the early years of primary and secondary schooling; to be followed through with undergraduate and postgraduate qualifications across a multitude of faculties and national research laboratories. The wealth of nuclear energy vests with its people; society will be the beneficiary.

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Biographies

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