The Development of Small Modular Reactors for Emerging Nuclear Countries in Africa

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Outline

- Status of the African Power Sector
- The Nuclear Option for Africa
- Small Modular Reactors
- The MYRRHA Project
- Towards a Sustainable Fast Lead-Cooled SMR
- Conclusions

Status of the African Power Sector

- Electricity deficit is a very serious issue in Africa, particularly in sub-Saharan countries.
  - It affects education, health and businesses, being one of the main reasons preventing the economic development of the continent.
  - Causes of this power crisis include:
    - Insufficient investment
    - Lack of diversification
    - Droughts
    - Oil price hikes
    - Conflict damaged infrastructure
    - Lack of maintenance skills

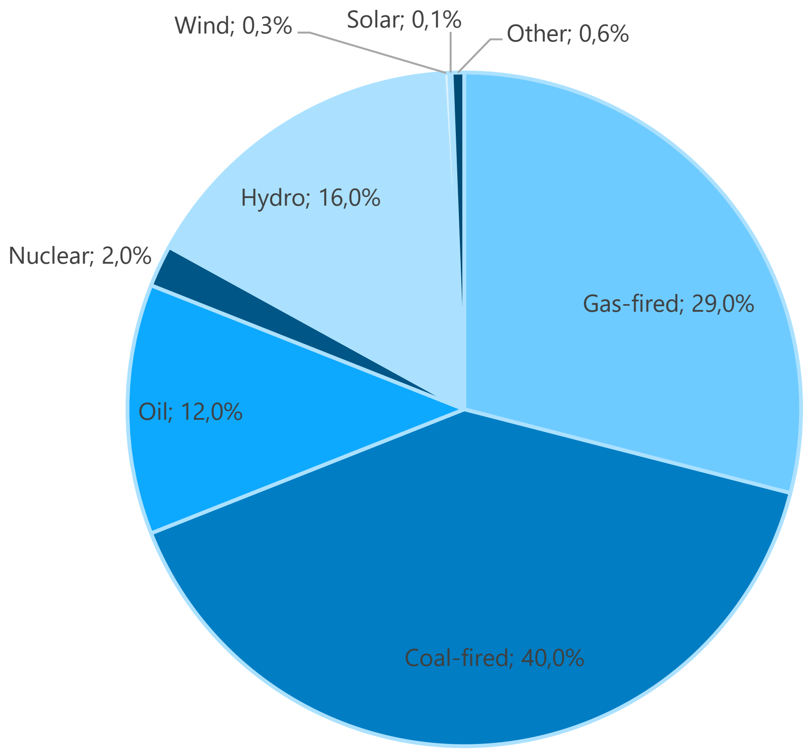
Status of the African Power Sector

- Fossil fuel-based power generation is the single largest source of electricity generation in Africa.
- Coal oil and gas account for more than 80% generation.
- Africa's untapped resources:

Source	Potential
Uranium	>1,000,000 t
Wind	~1,000 GW
Solar	~ 220 W/m^2 *

*Annual median irradiance for South Africa

African Energy Sources (Kessides, 2014)



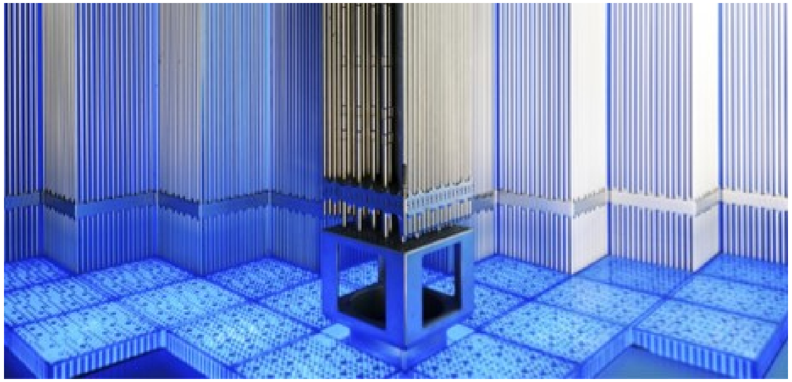
The Nuclear Option for Africa

- According to the International Energy Agency (2013), Africa will require 250 GW of new generation capacity by 2035.
- The right energy mix is a multi-variable problem (small, local production in rural areas vs. GW level solutions for urban areas).
- Options:
  - **Hydro**. Significant potential, but location of hydro resources and demand poorly matched and might be disruptive for environment.
  - **Other renewables**. Significant potential, but need for reserve of dispatchable energy so that operators can maintain network grid reliability. Potential sites far from load centres.
  - **Fossile-fired**. Good for baseload capacity, less vulnerable to supply disruptions and price shocks (coal), but high CO_2 emissions.

What about nuclear?

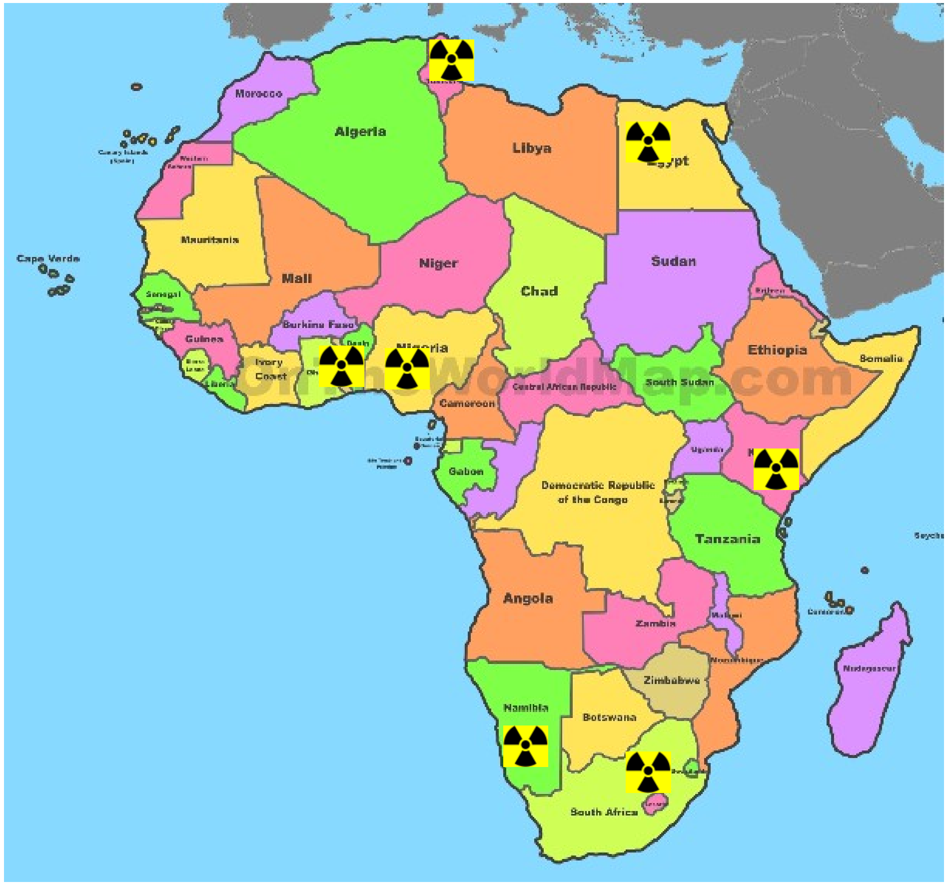
The Nuclear Option for Africa

- Nuclear energy presents the following advantages:
  - Reduced reliance on fossil fuels means less greenhouse emissions.
  - Efficiency: more energy produced per unit of fuel.
  - Reliable baseload capacity.
  - Provides stable and competitive energy prices.
  - Proven technology.
  - Large return of experience on plant safety.



The Nuclear Option for Africa

- Challenges include:
  - Large reactors will pose severe challenges on electricity networks.
  - It requires legal policies and regulatory frameworks
  - It requires technical capability and the availability of trained personnel.



Many countries in Africa are well advanced in resolving these challenges and getting ready for the nuclear option

The Nuclear Option for Africa

- Role of the Forum of Nuclear Regulatory Bodies in Africa (FNRBA)
  - The FNRBA provides an efficient and effective regional network advancing excellence in regulatory systems for radiation protection, nuclear safety and security in Africa. It does so by:
    - Creating awareness amongst policy makers.
    - Ensuring understanding, development, promotion and implementation of high standards of radiation protection, nuclear safety and security.
    - Implementing capacity building activities at regional and national level.
    - Promoting the harmonization of regulatory frameworks across different countries.

- The FNRBA is organized in different Thematic Working Groups covering legislation and regulation, radiation safety, regulatory frameworks, education and training, waste management, transport safety and emergency planning and response.

The Nuclear Option for Africa

- How ready is a country for nuclear power?
  - A study performed for the IAEA* identified 22 indicators to assist member states to make an assessment of their readiness for nuclear.

Demand and Energy	Financial and Economic	Physical and Legal Infrastructure	Carbon Reduction Incentives
Gross Domestic Product Growth Rate	Gross Domestic Product (PPP)	Total Installed Electric Capacity	Carbon Dioxide Emissions Per Capita
Growth Rate Primary Energy Consumption	Per Capita GDP (PPP)	Infrastructure Index	Fossil Fuel Energy Consumption (% of Total)
Per Capita Energy Consumption	International Trade (% of GDP)	Ease of Doing Business Index	Oil, Gas, Coal (% of Electric Capacity)
Percent Rural Population	Foreign Direct Investment, Net Inflow (% of GDP)	Rule of Law Index	Energy Imports (% Total Energy Use)
Desalination Capacity	Credit Rating / External Debt Stock	Political Stability and Absence of Violence Index	Uranium Resources
District Heating Demand			
Energy Intensive Industries			

* Solan, D., Small Modular Reactor Deployment Indicator Study Assessing Member State Readiness for the Deployment of Small and Medium-Sized Reactors , Center for Advanced Energy Studies, Boise State University, 2015.

The Nuclear Option for Africa

- The assessment is largely to be different whether the country is trying to assess its readiness adopting SMR or large nuclear.
- Data needs to be gathered from local and regional governments to ask questions around matters such as:
  - Is the goal coping with increasing demand or to develop remote areas?
  - What are the characteristics of the existing grid?
  - Is decarbonisation important in the strategy?
  - Are off-grid applications important? Heat production? Desalination?
  - What are the characteristics and natural resources of the country?
- Depending on the answer to these questions a country will score differently against different criteria and the final score might indicate that, whereas a country might not be ready for large nuclear, it might well be for SMR.

The Nuclear Option for Africa

- Challenges faced by Large Reactors searching for Capital Investment:
  - Large up-front investment escalation (France, Finland). Flamanville and Olkiluoto are three times over budget.
  - EPR investment plans in UK illustrate funding size challenge. Chinese investment needed for financing: which country can still finance LRs?
  - Financial distress / (near)-bankruptcy. Areva in financial distress caused (primarily) by Flamanville and Olkiluoto cost overruns, French Government stepped in to save the company. Westinghouse filed for Chapter 11 protection on March 29th 2017, caused (primarily) by cost overrun of 4 AP-1000 reactors in the USA

Increased uncertainty around Large Reactors in USA and Europe, given poor track record on Economic requirements (affordability + predictability). Likely same problems in Africa.

Small Modular Reactors (thermal/fast)

Size criterion:

- Small Reactor: up to 300 MWe
- Medium sized Reactor : 300-700 MWe
- LR: large Reactor: > 700 MWe

Modularity criterion: 2 aspects

- Possibility to **group** individual reactors to form a large nuclear plant
- Use of **pre-fabricated modules** assembled on-site), possibly entire reactors **factory-fabricated**

Benefits	Description
Economics	
CapEx	▪ Lower capital investment → lower risk
Factory-production	▪ Factory manufacturing → planning control ▪ Economies of volume
Climate and Safety benefits	
Sustainability	▪ Spent fuel reduction (half-live/1000) ▪ Increased fuel resource utilisation (50x)
Passive cooling	▪ Lower power → safer by passive design
Proliferation-resistant	▪ Long refuelling time→ more proliferation resistent
Modularity	▪ Deployment in series increases safety controls
Other benefits	
Grid integration	▪ Easier to integrate in distributed electricity market (flexibility), easier load following
Stable load	▪ No volatility: stable predictable base load
New markets	▪ E.g. isolated sites, emerging countries,...

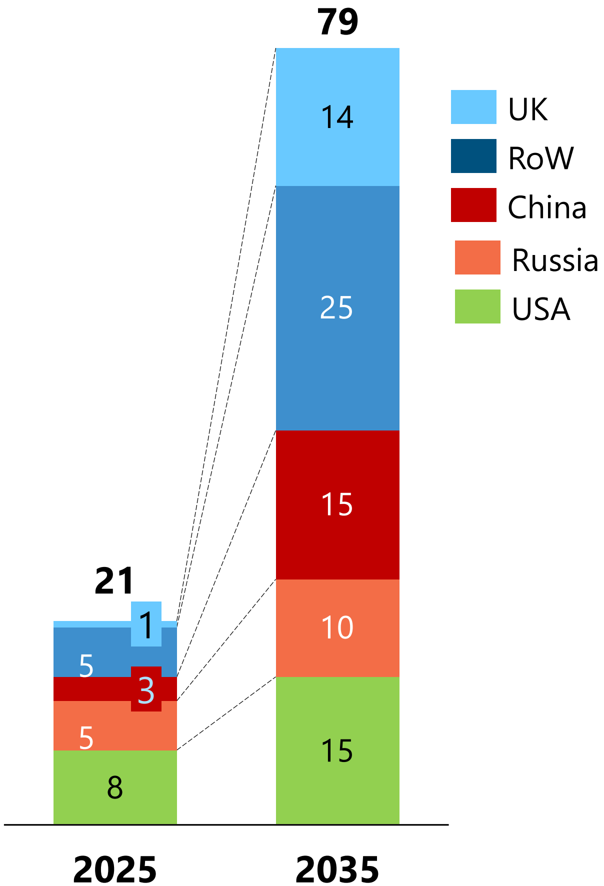
* SMR = Small Modular Reactor
LFR = Lead Fast Reactor

Small Modular Reactors

- How do SMR achieve smaller capital costs?
  - In the long term:
    1. Higher pace and volume of reactor production compared to large nuclear.
    2. Learning from a greater proportion of factory build components.
  - At project level:
    - Reduced initial investment.
    - Earlier Return of investment.
    - Harmonised licensing requirements.
    - Factory controlled activities.

Higher confidence → **Lower financing costs**

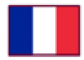
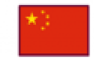
Global market potential in GWe (NNL 2014)



*Source: Scenario B of NNL study, assuming SMR technology is cost-competitive with large nuclear power plants across a global range of sites. Market potential excludes de-salination and co-generation. **Assuming 100MWe average size per unit Source: "Small Modular Reactors (SMR) Feasibility Study", National Nuclear Laboratory (UK), December 2014*

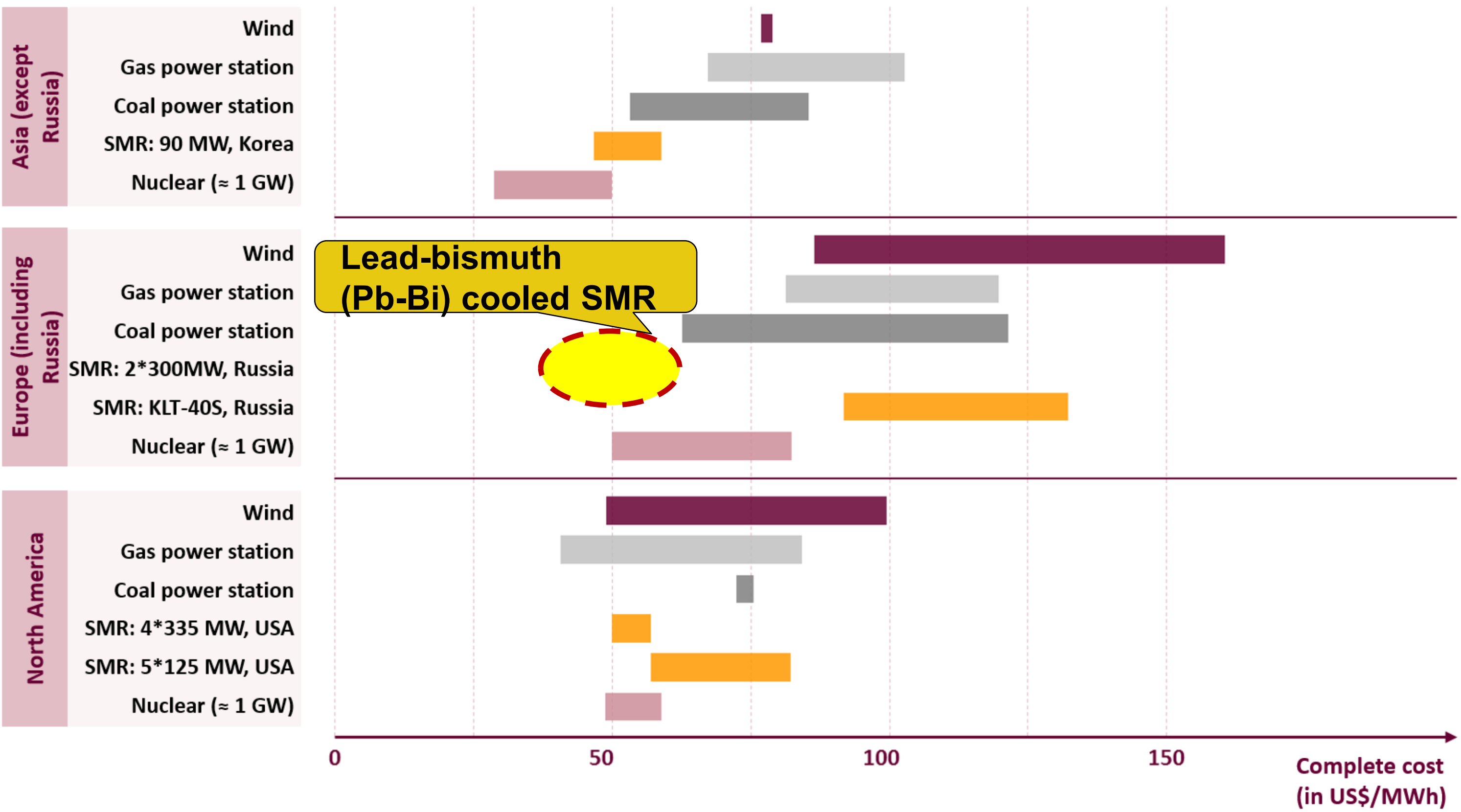
Small Modular Reactors

- Examples of SMR market designs

New designs		KLT-40S	FlexBlue	mPower	NuScale	SVBR-100	SMART	CNP-300
								
	Firm(s)	• OKBM (Rossatom) *CNNC agreement*	• DCNS *partnerships with AREVA, EDF, CEA*	• Babcock & Wilcox	• NuScale Power	• AKME Engineering	• KAERI	• CNNC
	Technology	• Pressurized Water Reactor (PWR)	• PWR	• PWR	• PWR	• Pb-Bi-cooled reactor	• PWR	• PWR
	Power	• 2 x 32 MWe	• 1 x 160 MWe	• 2 x 180 MWe	• 12 x 45 MWe	• n x 100 MWe	• 1 x 100 MWe	• 1 x 325 MWe
	Specificities	• « Floating » mobile power station	• Mobile underwater power station	• DoE subsidy laureate	• DoE subsidy laureate • Modulating power	• Modulating power • Reloading every 7-8 years	• Easily adaptable to desalinization	• II+ generation reactor
	Progress	• Licence obtained • Under construction	• Preliminary design studies	• Detailed design • Pre-certification	• Detailed design • Pre-certification	• Detailed design • Certification in progress	• Licence obtained	• Operating
	Target markets	• Coastal sites with temporary or lasting needs	• Coastal sites with temporary or lasting needs	• Electricity production, cogeneration	• Electricity production, cogeneration	• Electricity production	• Electricity production, cogeneration, desalinization	• Electricity production

Small Modular Reactors

- Affordable Electricity



LCOE = Levelized Cost of Electricity = uniform standardized measure to compare electricity costs from different power sources. LCOE includes initial capital cost, discount rate, as well as the costs of continuous operation, fuel, and maintenance. LCOE excludes grid and distribution costs.

Source: OECD / NEA Study on the Economics and Market of Small Modular Reactors, Alexey Lokhov, Ron Cameron, Vladislav Sozoniuk (2013) at 6th INPRO (Vienna)

Small Modular Reactors

- Small Modular Reactors are not new.
- Africa can benefit from the significant international effort being made internationally to enable the deployment of SMR.
- There is a strong push to harmonize the regulatory framework for SMR which will increase security and reduce cost.
- International institutions like IAEA and OECD are fully behind these efforts.

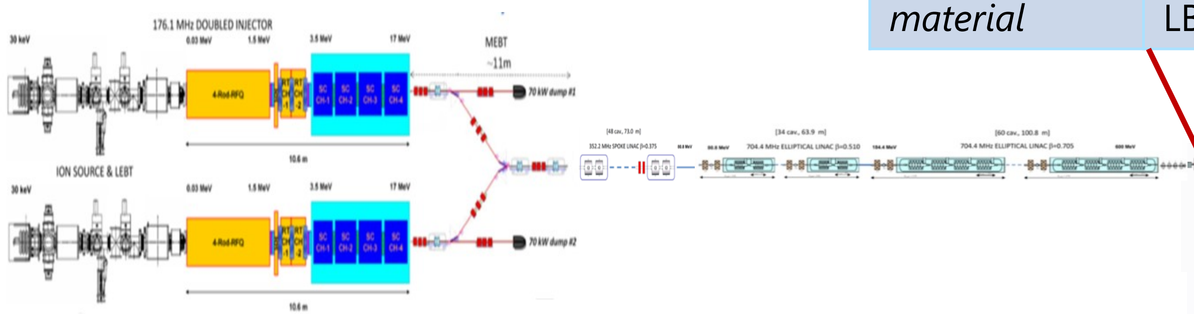
The MYRRHA Project

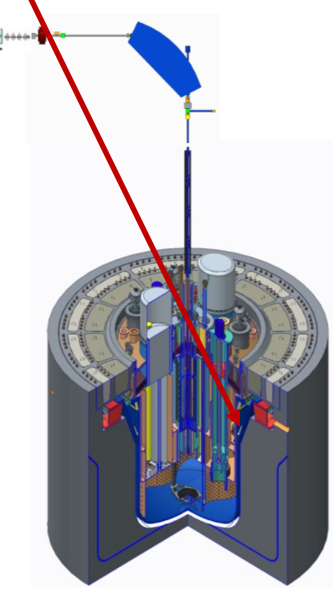
Construction of an Accelerator-Driven System (ADS) consisting of

Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA

Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)

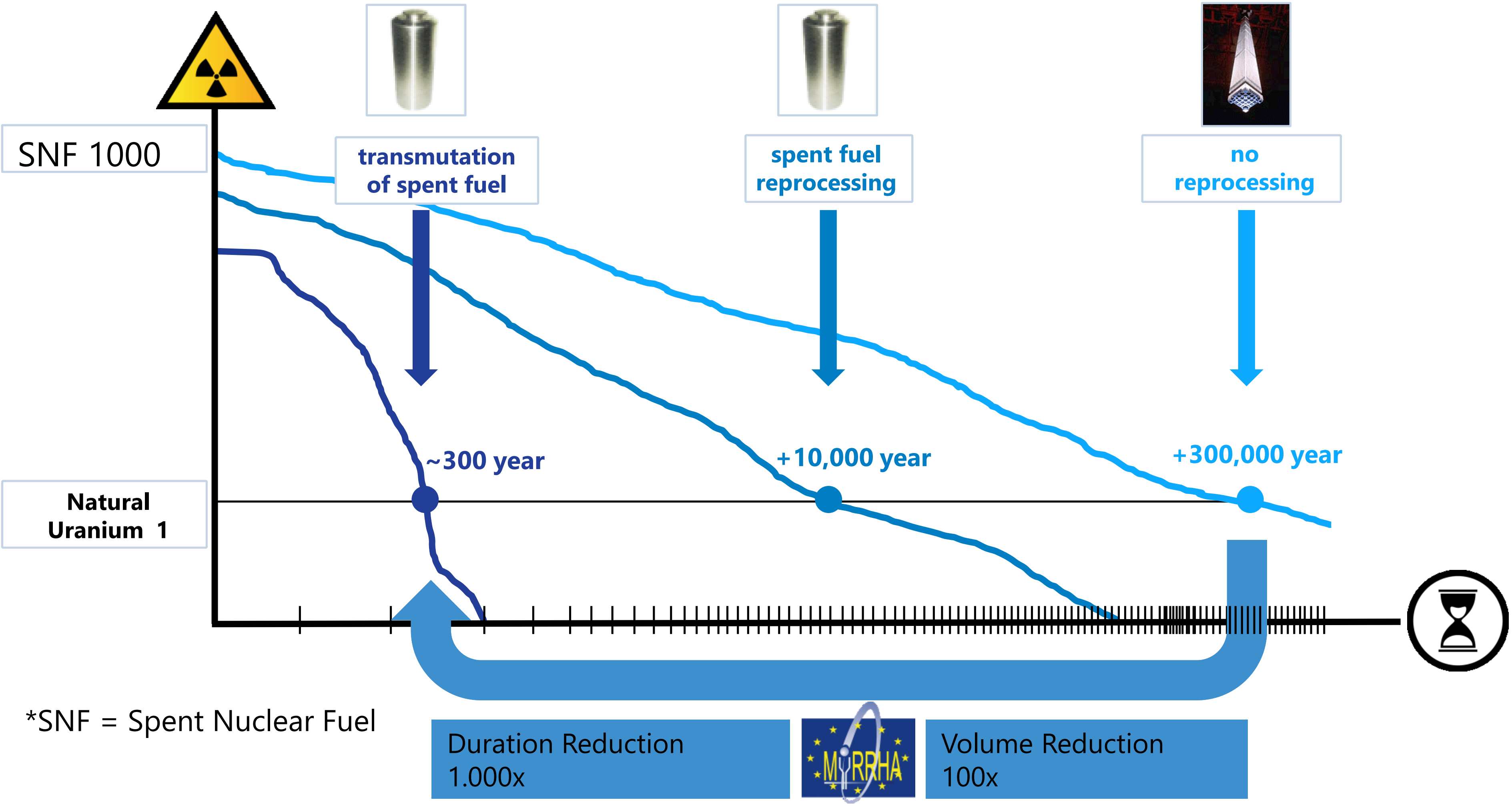
- A 600 MeV – 2,5 mA to 4,0 mA proton linear accelerator
- A spallation target/source
- A lead-Bismuth Eutectic (LBE) cooled reactor able to operate in subcritical & critical mode





Reactor	
power	65 to 100 MW_{th}
k_{eff}	0,95
spectrum	fast
coolant	LBE

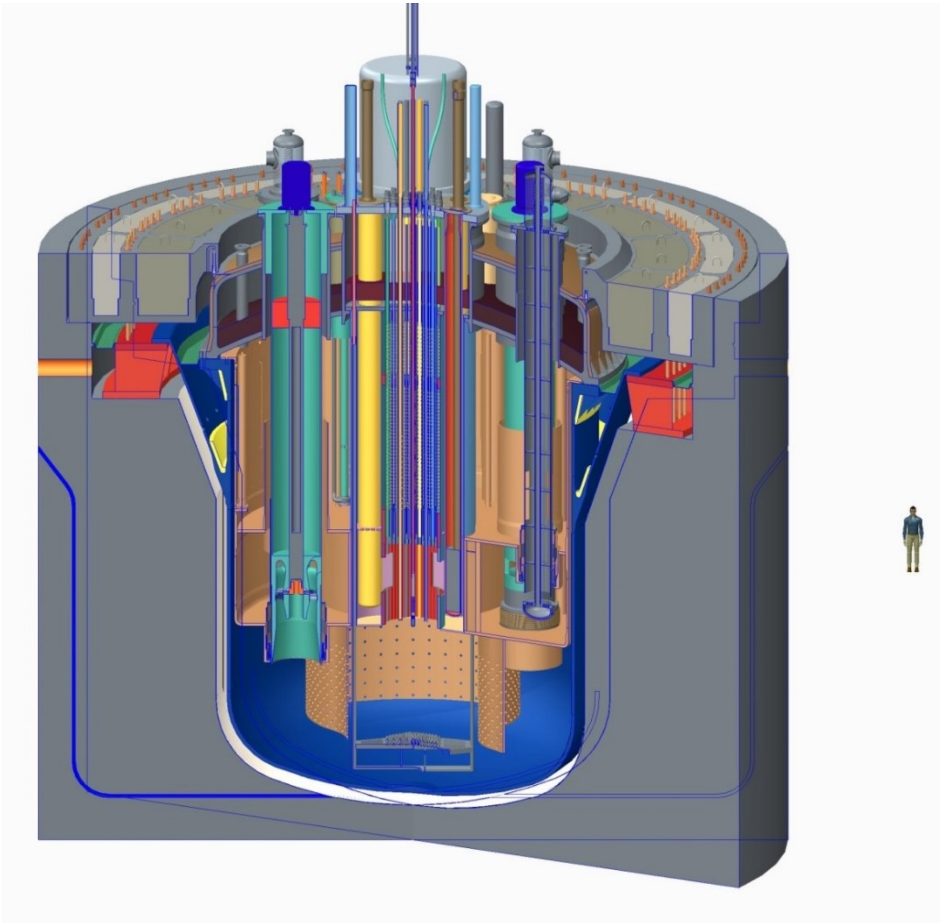
The MYRRHA Project



*SNF = Spent Nuclear Fuel

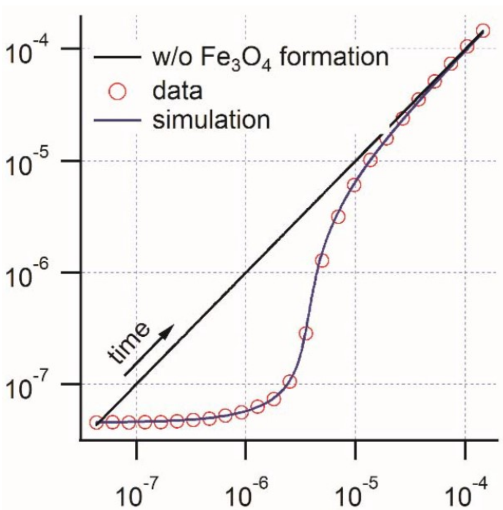
The MYRRHA Project

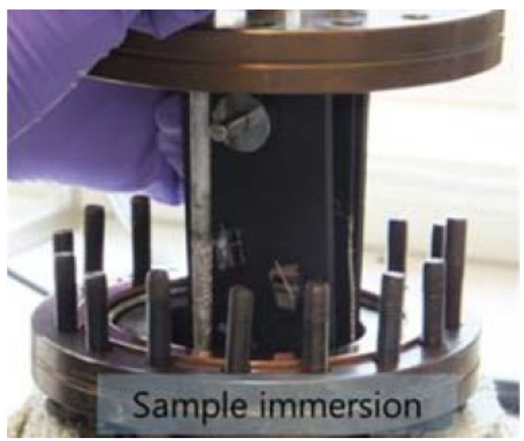
- Reactor layout
  - Vessel
  - Cover
  - Core barrel and Multi-functional plugs
  - Above Core Structure
  - Cradle, Core Restraint System, beam line and window target
  - Mo-irradiation units, control rods and safety rods
  - Primary Heat Exchangers
  - Primary Pumps
  - In-Vessel Fuel Handling Machines, Fuel Transfer Devices, Failed Fuel Detection Devices, Extraction Pumps
  - Diaphragm and support structure
  - Reactor pit, Reactor Vessel Auxiliary Cooling System



The MYRRHA Project

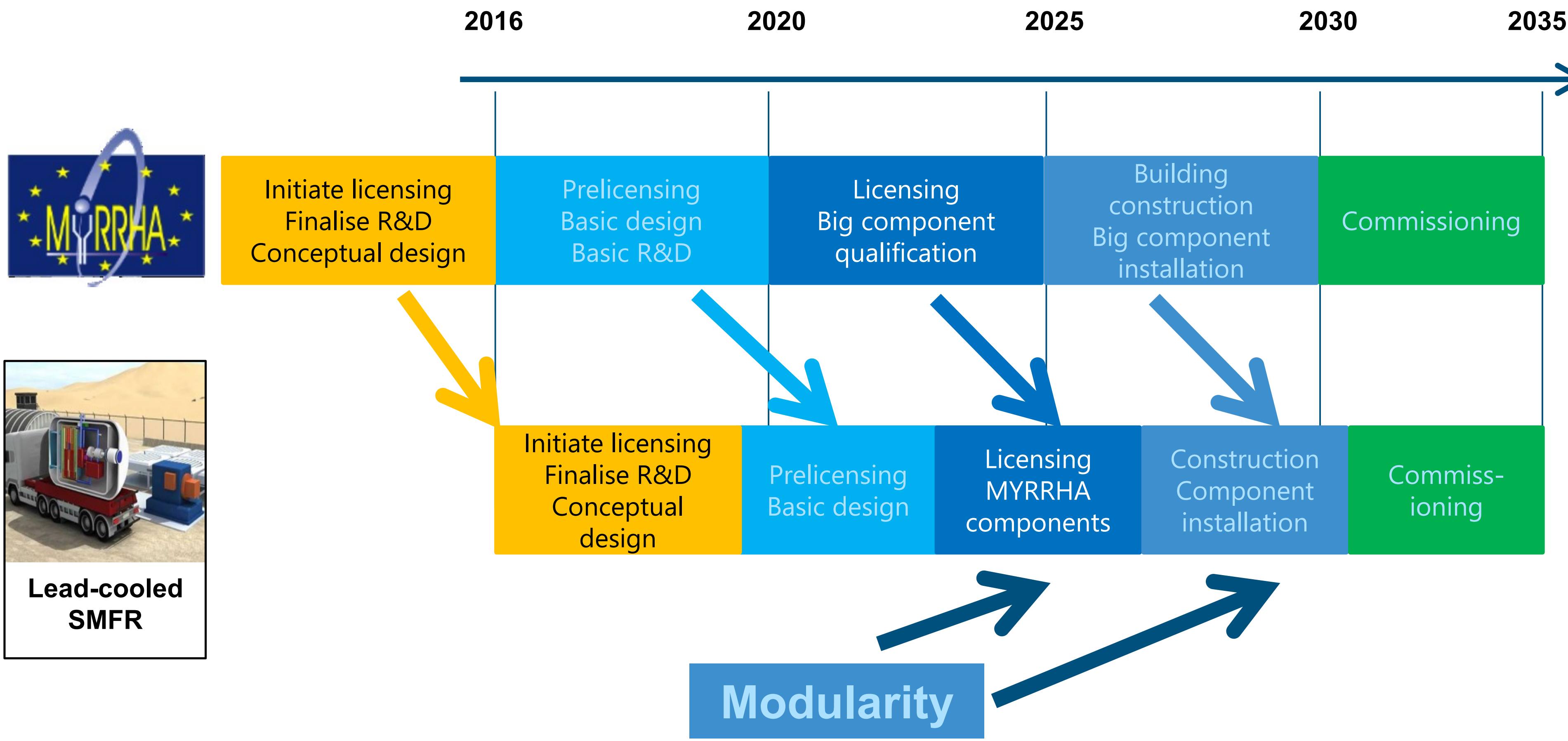
- The MYRRHA project is developing HLM technology @SCK-CEN site and through (inter-)national partnerships:
  - HLM zero-power reactor
  - Materials corrosion R&D
  - HLM chemistry control R&D
  - Reactor components testing facilities
  - Thermo-hydraulics test facilities





Towards a Sustainable Fast Lead-Cooled SMR

- Maximise technology transfer from MYRRHA to lead-cooled SMFR to benefit from development of MYRRHA and satisfy time window



Conclusions

- **<u>Energy mix projected to be a combination of:</u>**
  - Fossile-fired plants will remain, but share will need to decrease
  - Renewables (intermittent) will increase
  - Nuclear energy: carbon free non-intermittent base-load can contribute in the mix
- **<u>Large nuclear reactors:</u>** large investment costs & important schedule delays:
  - Move from Economy of scale → Economy of series
  - → Small Modular Reactors
- **<u>Fast (lead-based) SMR:</u>** less waste, better resource use, more passive safety

Opportunity for the African continent to demonstrate to the world the potential of SMR in terms of clean, guaranteed and affordable electricity for economic development

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