Nuclear Energy - if you love your planet

Nexus Group : https://www.nexus.febe.uj.ac.za

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Slide Credits

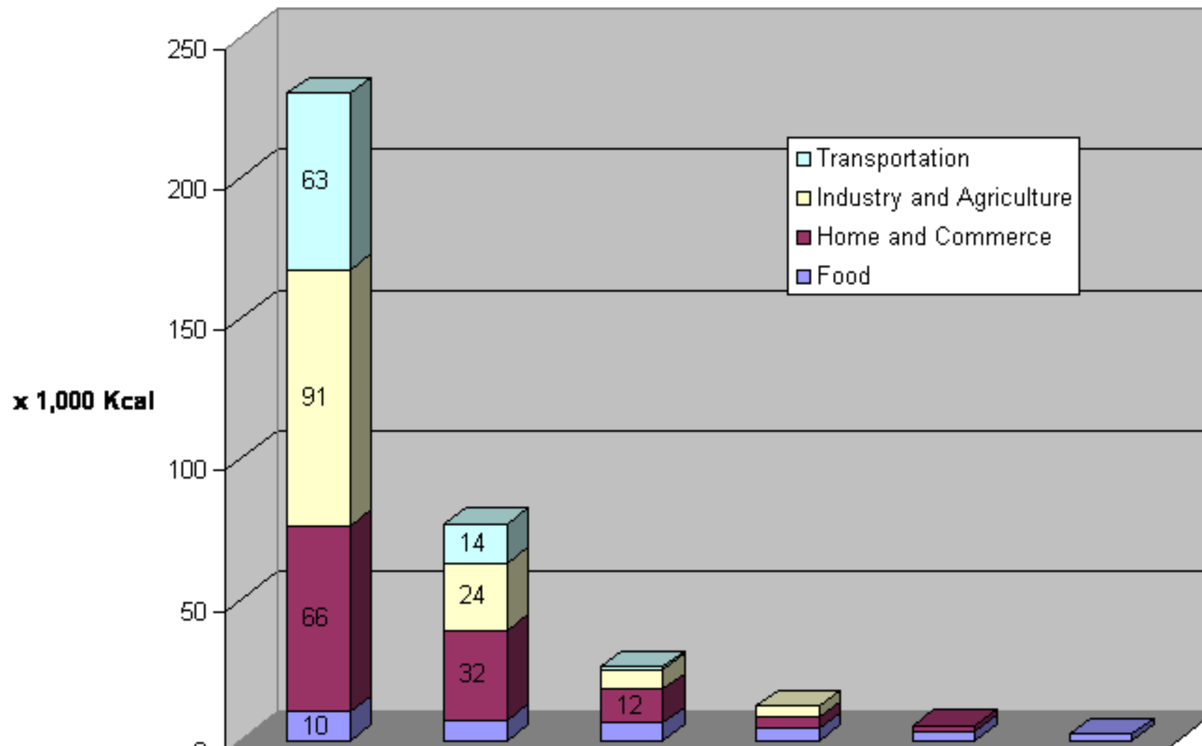
- Prof Connell
- Prof Naidoo (UJ)
- Prof Nicholls (UJ)
- Prof Mulaba (UJ)
- Prof Slabber (UP)
- Dr Bvumbi (NRWDI)
- Dr Maqabuka (IJ)
- Ms Mudau (Necsa)

How much energy do we need ?

What are the energy trends ?

If **Africa** is to become wealthy, it **will need a lot of energy**

Estimated Daily Consumption of Energy per Capita at Different Historical Points Adapted from: E. Cook, "The Flow of Energy in an Industrial Society" Scientific American, 1971 p. 135.



	Technological Man	Industrial Man	Advanced Agricultural Man	Primitive Agricultural Man	Hunting Man	Primitive Man
Transportation	63	14	1			
Industry and Agriculture	91	24	7	4		
Home and Commerce	66	32	12	4	2	
Food	10	7	6	4	3	2

The Vision
Africa becomes a power house

Only South Africa and Egypt have Nuclear Reactors, or are building them, at present. The new era of Nuclear goes beyond electricity generation and introduces process heat. This can be used for desalination and also for powering the hydrogen and synthetic fuels economies. The size of the reactors also now scale from mere kWatts through to GigaWatts. The latter powers and stabilises large grids with clean energy. The midrange Small Modular Reactors or SMRs, can be deployed at city and mine level and for mini grids. The former can power remote outposts. All introduce a new level of safety - walk away safety or be so-called fail safe. They are cost competitive over their 60-80 year lifespan. In these two talks, we will review the physics case, and also discuss the socio-economic context. We can then discuss what the opportunities for Africa are.

Setting the stage
The new and the old

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*The current belief is that the world is moving towards a fully decentralized and deregulated electrical supply system based on small scale, embedded generation technology, (**wind and solar and ….**) in place of the historically centralized and regulated system based on very large generation units linked to customers by a large transmission system (**THE GRID**).*

This has led to extensive changes in the previous regulations with support to small newcomers to the system and the "economic death spiral" of the historical large vertically integrated utilities.

*If this is truly the way of **the future** then why is there concern of the economic viability of the "supplier of last resort"? Surely the old utilities will go the same way of other industries overtaken by technology, such as the copper wire based fixed line telephones.*

Or is the current belief in the new model for electricity supply a mirage?" ….

Prof D Nichols (UJ) and Chair Necsa Board, formerly CNO ESKOM

Setting the stage
Key Questions to answer

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or ……The Emperors New Clothes

1. What is the current belief in the “new grid”?
2. What is the current belief in the “old grid”?
3. So why does the “new grid” need the “old grid”?
4. What factors are these beliefs based on?
5. What evidence are these beliefs based on?
6. Why don’t the models reflect the evidence?
7. What are the key assumptions in the “new grid” that
8. What are the impacts of these assumptions being wrong?
9. Why is this paradigm supported?

Cartoon by **Peter Brookes**.

Prof D Nichols (UJ) and Chair Necsa Board, formerly CNO ESKOM

Setting the stage
Current beliefs

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The New Grid

- Distributed
- Deregulated
- Based on Wind, Solar and Batteries
- Environmentally Friendly and Low Carbon
- Flexible
- Low cost and Fair to Society

The Old Grid

- Bureaucratic State Control
- Inefficient
- Expensive
- Polluting
- Inflexible

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Setting the stage

…. but ….. Some new terminology

Variability, Intermittency, Dispatchablility

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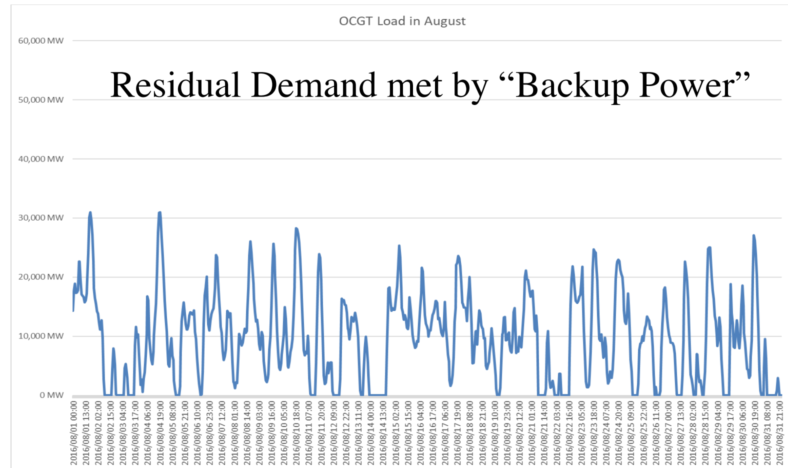
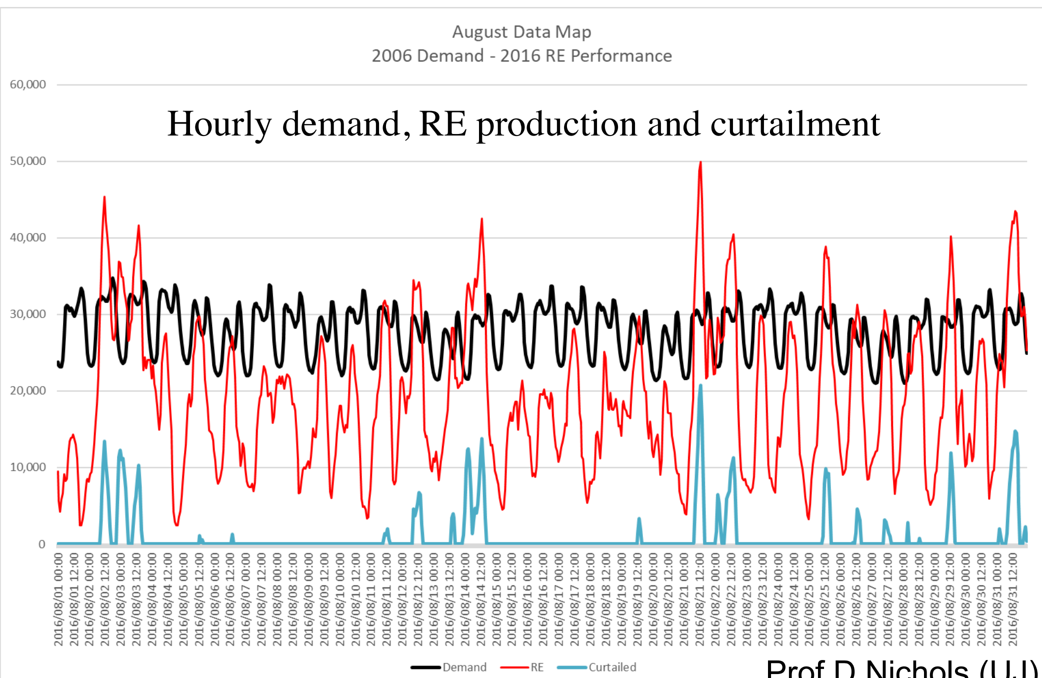
South African model using actual Wind & PV August 2016 profiles (scaled to 45,000MW of wind and 15,000MW of PV) to meet August 2006 demand





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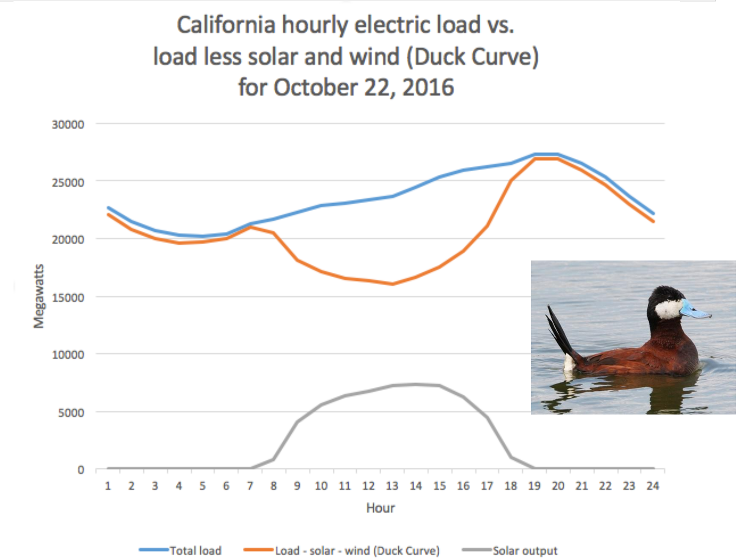

Setting the stage
New beliefs ….
Origins in certain factors

- **Inherent inefficiency of central planning** vs. deregulated free market.
- The **ability of the renewable energy sources**, linked to low cost energy storage systems to meet all loads and grid stability requirements.
- The **acceptability of "dynamic load management"** by society.
- The **ability of the de-regulated market forces** to take long term commercial risks related to future demand.

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Setting the stage

New beliefs ….

Evidence …..

- Rapid roll out of Renewable Energy in many countries.
  - state support and subsidies?
  - Sovereign Guarantee
- Low Levelised Cost of Energy (LCOE) for new RE plants.
  - cost of ancillary services and backup?
- Cost benefit of PV on homes.
  - non-cost reflective tariff structure?
  - cost = Generation + Transmission + Distribution
- Rapid evolution of digital technology.
  - demand/supply sensing, big data, AI, Intelligent Grid,
  - fast switching, dual circuit households (dirty-clean)

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Setting the stage
New beliefs ….
Why this is suspect ….

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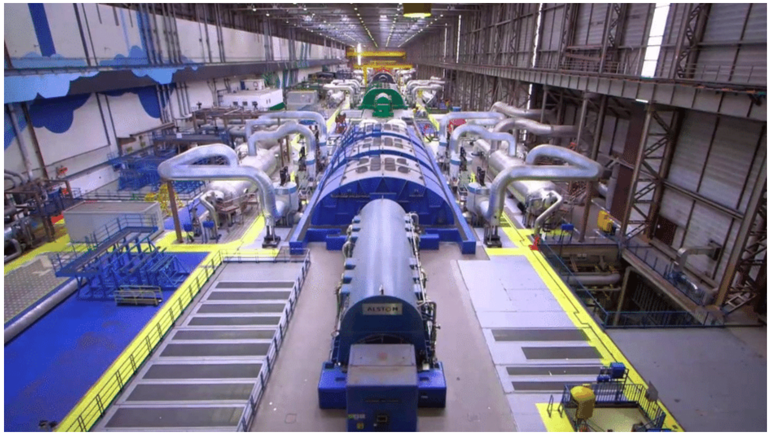
- Models developed for dispatchable, synchronous machines.
  - all historic machines had this characteristic
- Ignores grid expansion/connection costs.
  - largely included in direct plant costs
- Ignores grid stability issues.
  - rotating machines with droop control
- Assumes low cost energy equates to low cost electrical supply.
  - transmission costs added ~15% to power plant costs



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https://www.researchgate.net/

Setting the stage

Which assumptions are challenged ….
Why this is suspect ….

- Low-cost electrical storage.
  - lead acid batteries (1859)? pumped storage?
- Can we store many Giga Watts for 6 hours ?
  - this is called a bomb
  - 2GW * 6 hours → 10 Kilotons of TNT : 1% of Hiroshima
- Load management acceptability.
  - geyser control, space heating, load shedding?
- Risk taking without guarantees.
  – IPP policy impact …. Utilities are not happy
- Grid stability & management.
  – weather, time scales of seconds, minutes, hours, days
- Can it scale to take 3rd world → 1st world.
  – think Terra Watts

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Setting the stage

Consequence if new thinking is wrong….

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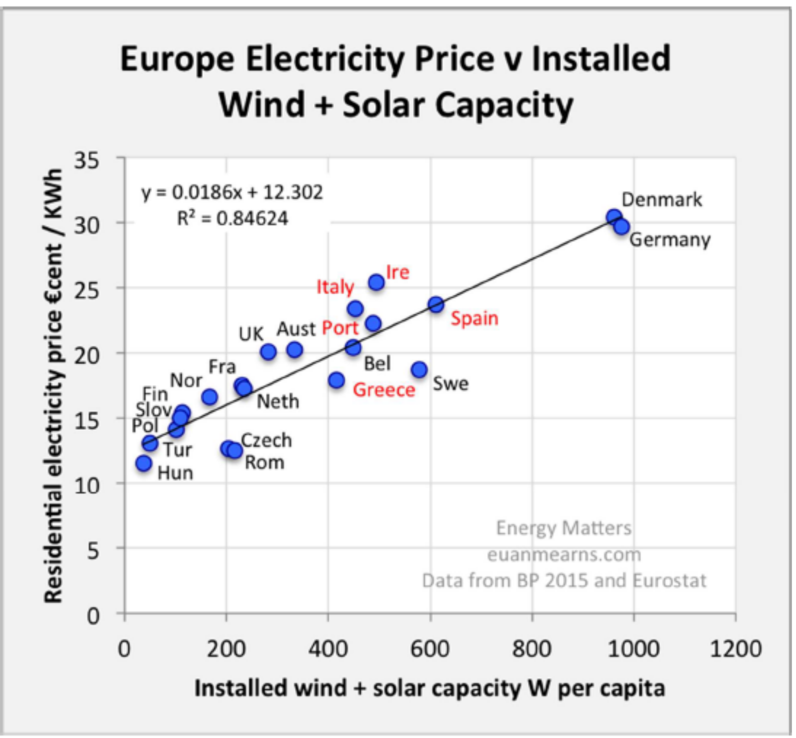

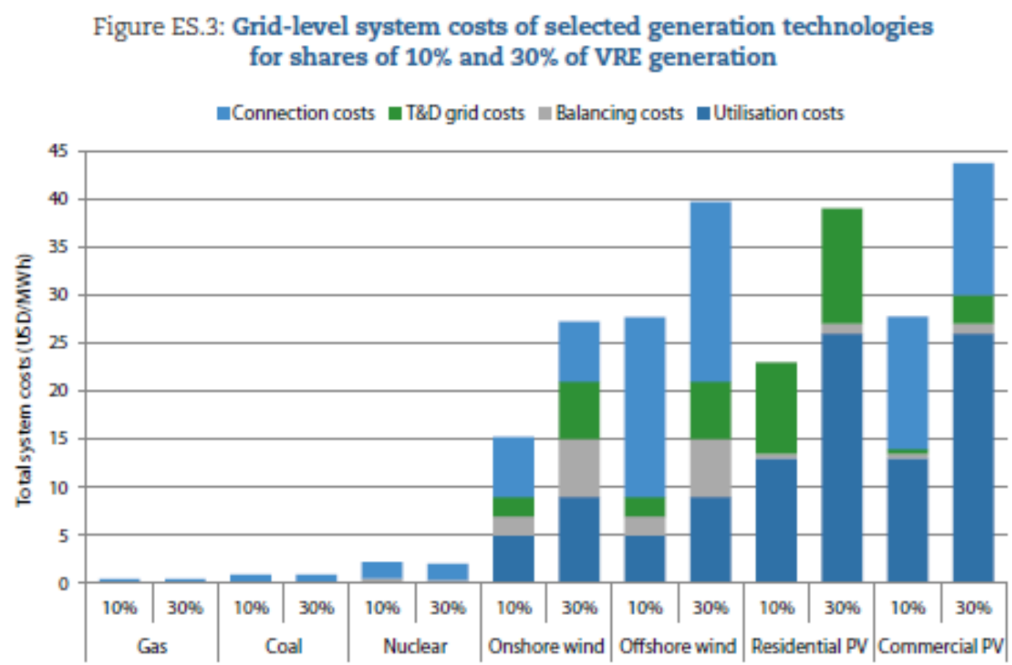

THE FULL COSTS OF ELECTRICITY PROVISION, NEA No. 7298, © OECD 2018

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Setting the stage

Consequence if new thinking is wrong….

Part of the hidden cost of renewables

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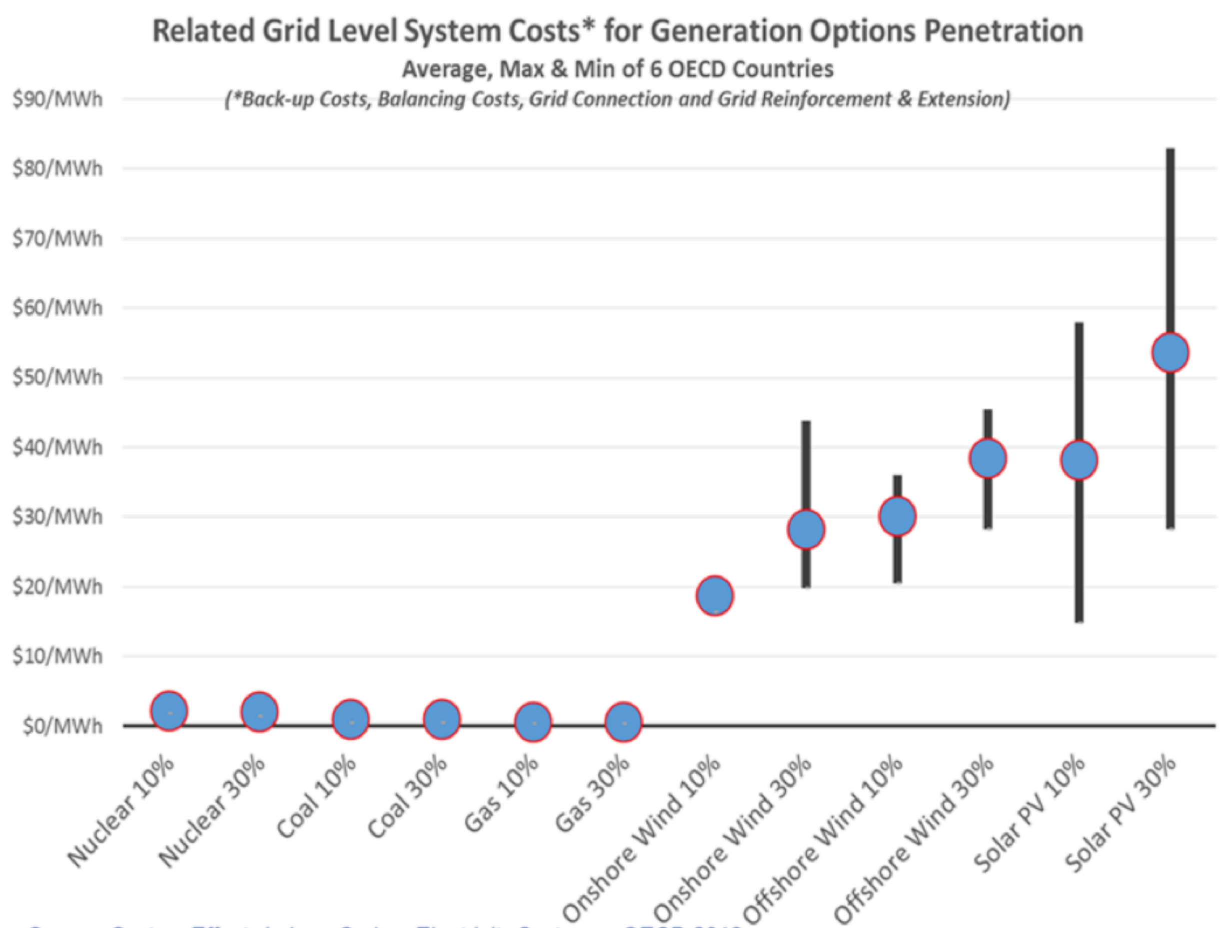
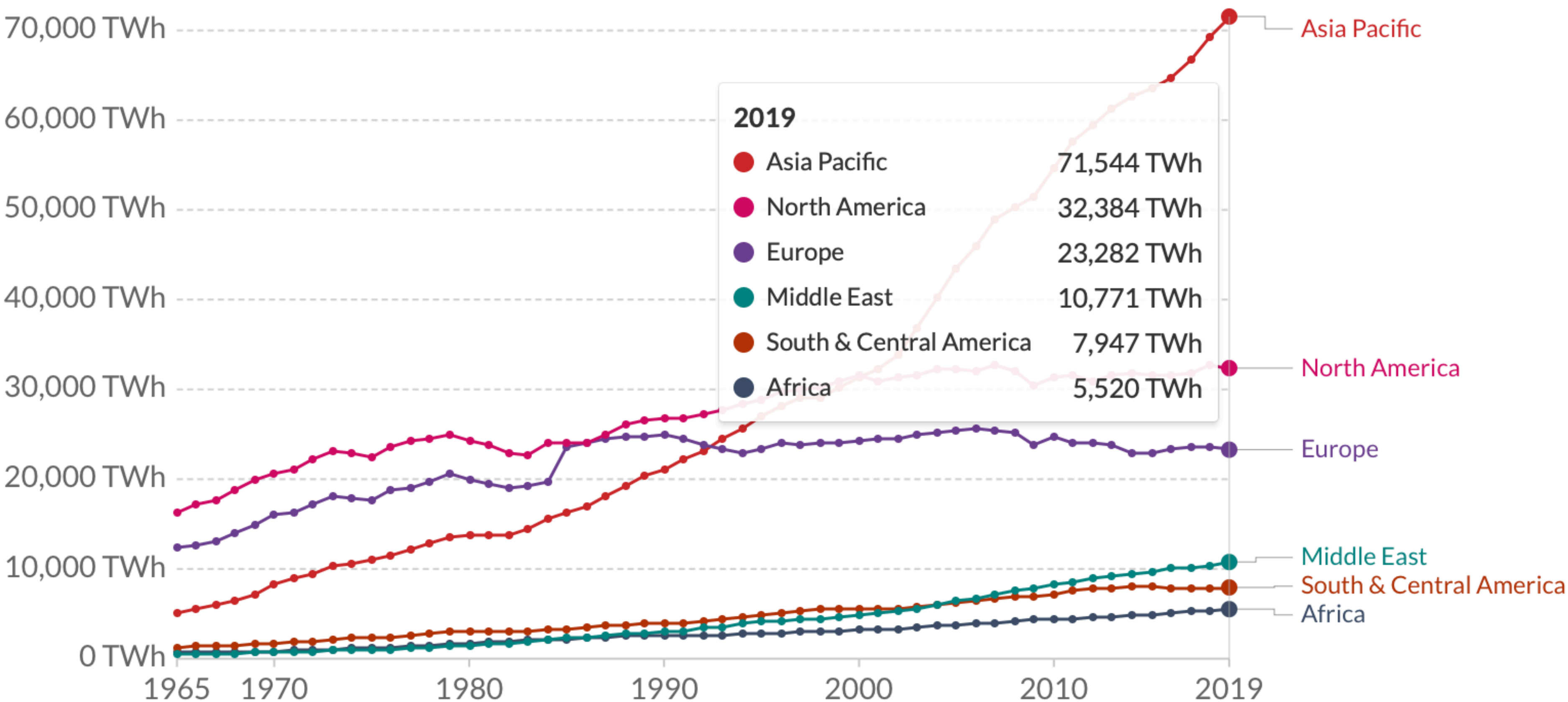


Also add 100% Backup / Storage and shorter lifetime

Source: System Effects in Low-Carbon Electricity Systems - OECD 2012

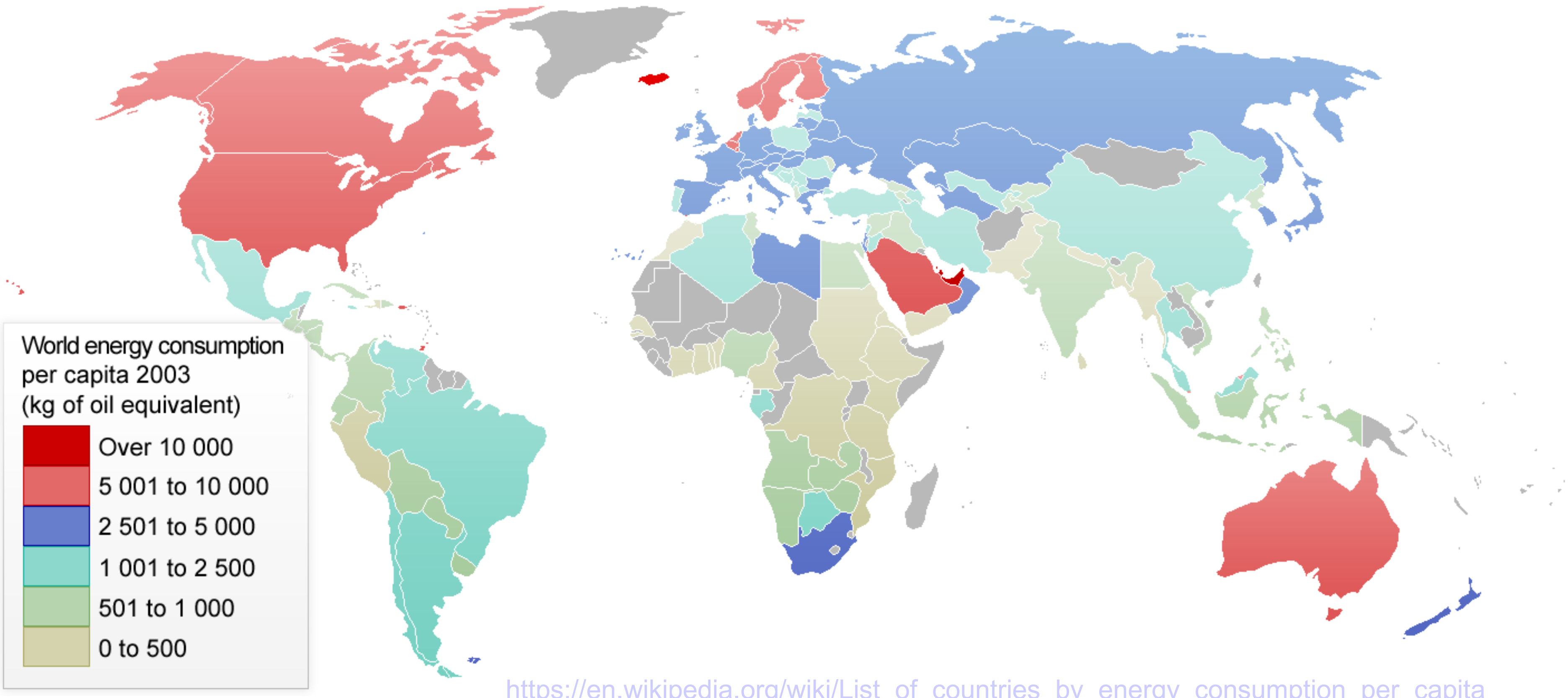
Prof A Cilliers UNW

Energy by region



https://ourworldindata.org/energy

Energy / capita by region



https://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita

Energy / capita by region

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Electrical generation capacity

Africa :170 GW Population 1.35 billion
USA : 1100 GW Population 0.331 billion

Wealthy advanced Africa needs 3400 GW.

Africa needs 20 times more power.

One can argue about efficiency and savings … that's about a %
Its inescapable that an advanced economy needs a lot of energy
One needs to think … SCALE ….

https://ourworldindata.org/energy

Energy requirements

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Let us look at the options ……

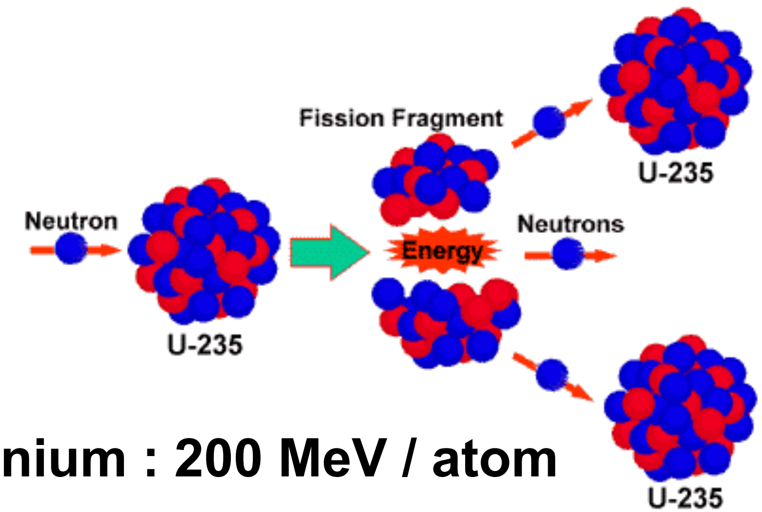
But think about **Terra Watts …… not Watts !**

(10^{12})

Scale all issues

1. Consumption of **natural resources**
2. Availability of natural resources
3. **Safety** at scale
4. **Environment**, sustainability at scale
5. Power must be there the instant you press the switch
   - This is called **dispatchable power**
6. **Storage** …… Can you store Terra Watts ?
   - Make only as much as you need, when you need it

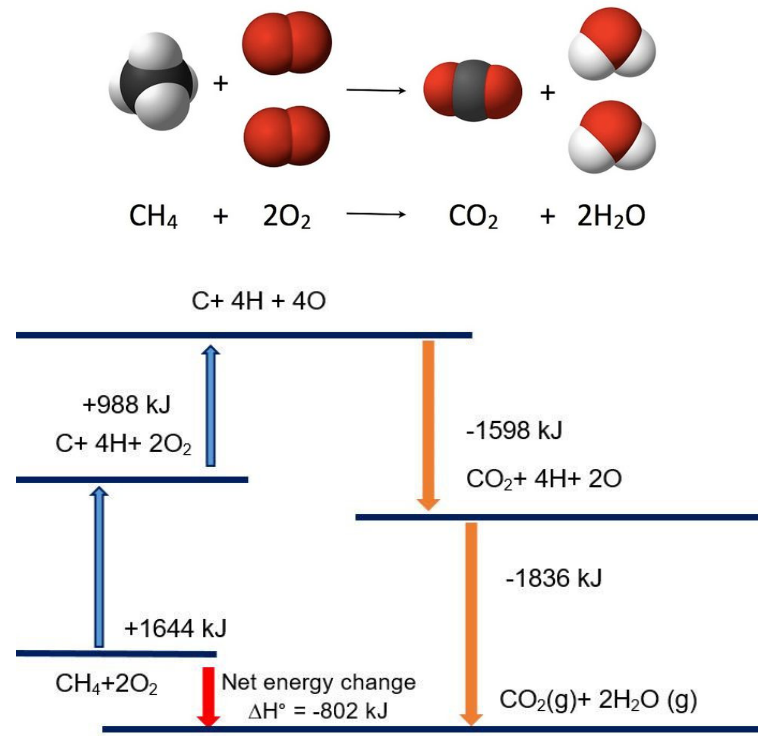
Energy / atom
compare the nucleus to the electron
a multiplier of 10^7 - 10^8



Uranium : 200 MeV / atom

Coal : 4 eV / atom

Oil : 7 eV / atom



Methane : 8.4 eV / atom

https://arrowhead.instructure.com/courses/4231/

https://www.researchgate.net/

Energy comparison - again

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(10g of 10% enriched uranium)

5.76 tons of coal

1.5 to 2.5 tons of ash

21 tons of CO^2

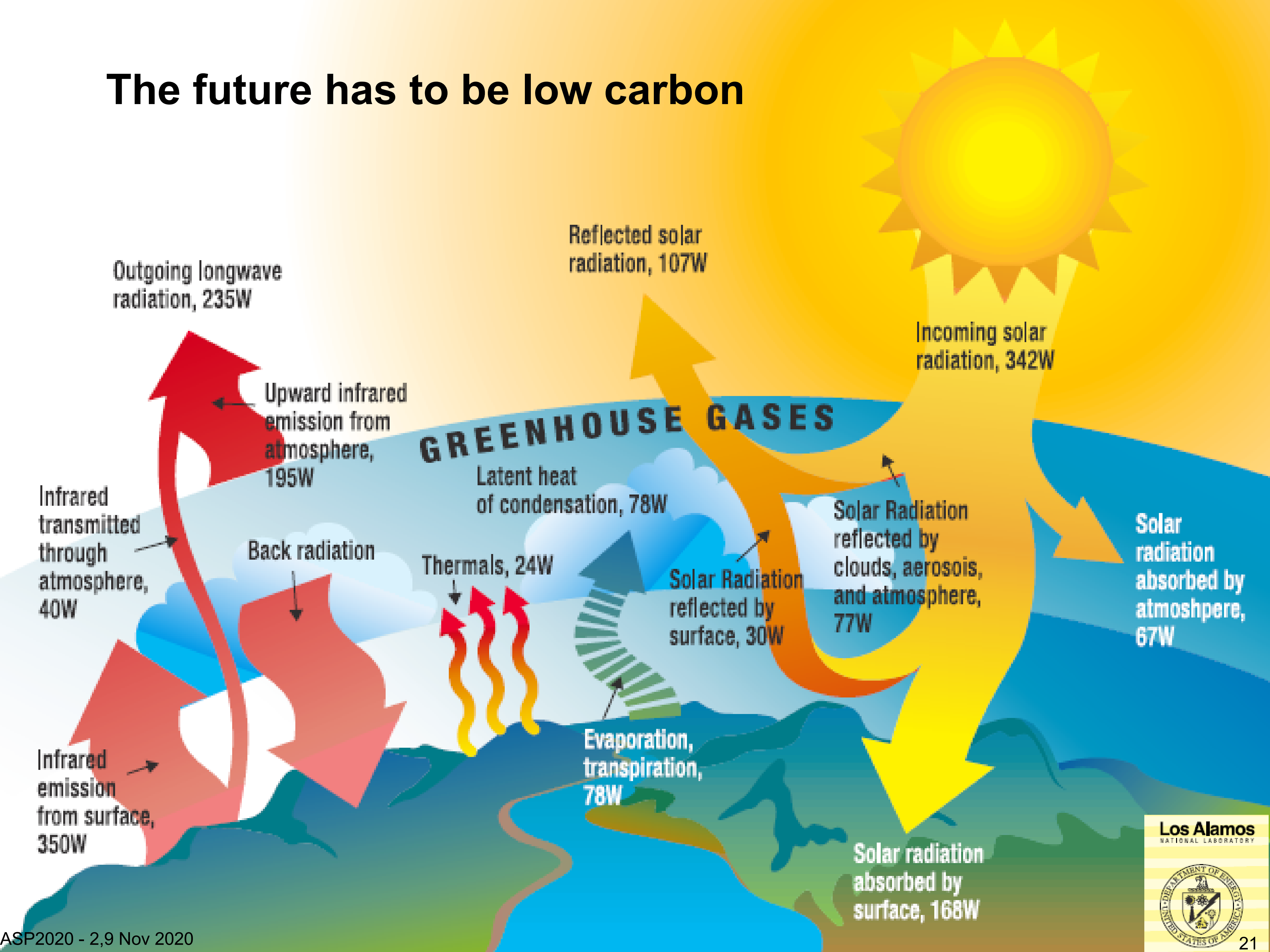
Radiation also from Coal Fired Power Stations

- **Coal has ~ 1 ppm U and ~3 ppm Th.**
- **Uranium released into the atmosphere from 1 GW coal fired power station, 25 000 tons / year.**

- **1GW power station**
  - 100 times less activity release.

Oak Ridge Nat Lab Review Vol. 26, No. 3&4, 1993

The future has to be low carbon



Los Alamos NATIONAL LABORATORY

Low Carbon Modalities

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Hydro

- Need a river
- Capacity Factor 40%

Wind and Solar.

- Variable, intermittent, need 100% backup / storage
- Very diffuse source, need lots of plant to harvest it
- Need a “copper plate” grid for handover
- Lifetime 25 years
- Capacity Factor 40%, 30%

Nuclear

- Dense form of energy – 10^8 power density (atomic) . chemistry
- Flexible location and sizes
- Lifetime 60-80 years
- Capacity Factor 90%

How big are the biggest ?
Hydro

3 Gorges Dam, China Yangtze River, 22.5 GW   1084 km^2
20 MW/km^2

https://www.geoengineer.org/news/chinas-three-gorges-dam-under-flood-pressure

How big are the biggest ?
Solar

Bhadla solar park, 2.25GW Jodhpur district of Rajasthan, India. 60 km^2
40 MW / km^2

https://www.nsenergybusiness.com/projects/bhadla-solar-park-rajasthan/

How big are the biggest ?
Wind

Jiuquan Wind Power Base, China, planned 20GW
10 MW/km²

https://www.power-technology.com/features/feature-biggest-wind-farms-in-the-world-texas/

How big are the biggest ? Nuclear

Koeberg, outside Capetown, 2 GW

https://www.power-technology.com/features/feature-biggest-wind-farms-in-the-world-texas/

Summary of space requirements

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Considering 1 GW of production

Method	Requirement/ Description	Land Area (sq. miles)
Photovoltaic	100 km^2 @ 10% efficiency	40
Wind	3,000 Wind Turbines @ 1 MW ea.	40-70
Biogas	60,000,000 pigs or 800,000,000 chickens	??
	6,200 km^2 of sugar beets	2,400
Bioalcohol	7,400 km^2 of potatoes	2,800
	16,100 km^2 of corn	6,200
	272,000 km^2 of wheat	104,000
Bio-oil	24,000 km^2 of rapseed	9,000
Biomass	30,000 km^2 of wood	12,000
Nuclear	<1 km^2	1/3

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What does electricity cost ?

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LCOE – Levelised Cost of Electricity

Strong dependency on cost of capital and recovery period

Highly contested – the basic message is the costs are rather similar.

Cost of variability, distribution, lifetime, scalability …….

Independent Statistics & Analysis U.S. Energy Information Administration

Plant type	US average LCOE for plants entering service in 2019 ($/MWh)				
	Capacity factor (%)	Levelised capital cost	Fixed O&M cost	Variable O&M cost	Total system LCOE
Coal(Conventional)	85	60.0	4.2	30.3	95.6
Coal (Combined cycle)	87	14.3	1.7	49.1	66.3
Wind	35	64.1	13	0.0	80.3
Hydro	53	72.0	4.1	6.4	84.5
Solar PV	25	114.5	11.4	0.0	130.0
Nuclear (advanced)	90	71.4	11.8	11.8	96.1

Prof J Slabber (UP)

Let us Re-examine nuclear

The "Three Nuclear Nightmares"

But physics, engineering and technology takes these all away

- **Proliferation** is easy to monitor and design away
  - Tell-tale signs

    Modification of plant.

    Change in isotopic content of fuel rods, other in-core indicators.

    Leakage of minute but detectable finger-print species into the environment.
- **Waste** as a resource
  - It is rather trivial in volume compared to medical and industrial waste.
  - A plant has its lifetime of waste (60-80 years) typically stored unprocessed on site.
  - With processing, volume reduction.
  - Storage technologies exist – accessible storage.
  - A solid waste is preferable.
  - It is ultimately a resource, new technologies will allow it to be mined for energy and for rare materials, and to be quieted → The energy amplifier
- **Accidents**, the risk can be made sufficiently low
  - Nuclear is safer by factor >100 for full cycle when audited

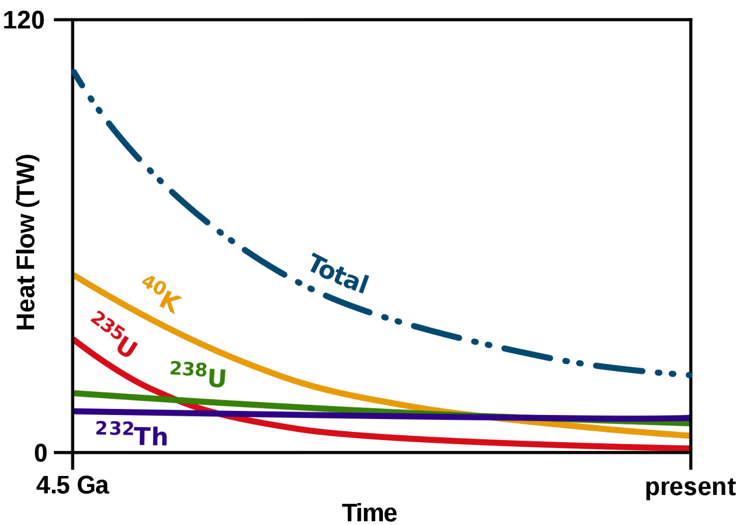
- Nuclear Energy is a 100 year stop-gap
- It is proven safe in a catastrophe and is being further improved
- After 100 years a new technology will emerge

Some nuclear reactors

A natural one
Oklo on Gabon, Africa

2 billion years ago, intermittent fission for 500 000 years.
Large ore body (50-70% U-oxide, 3% enrichment)
An opportunity to study radio-nuclide transport.

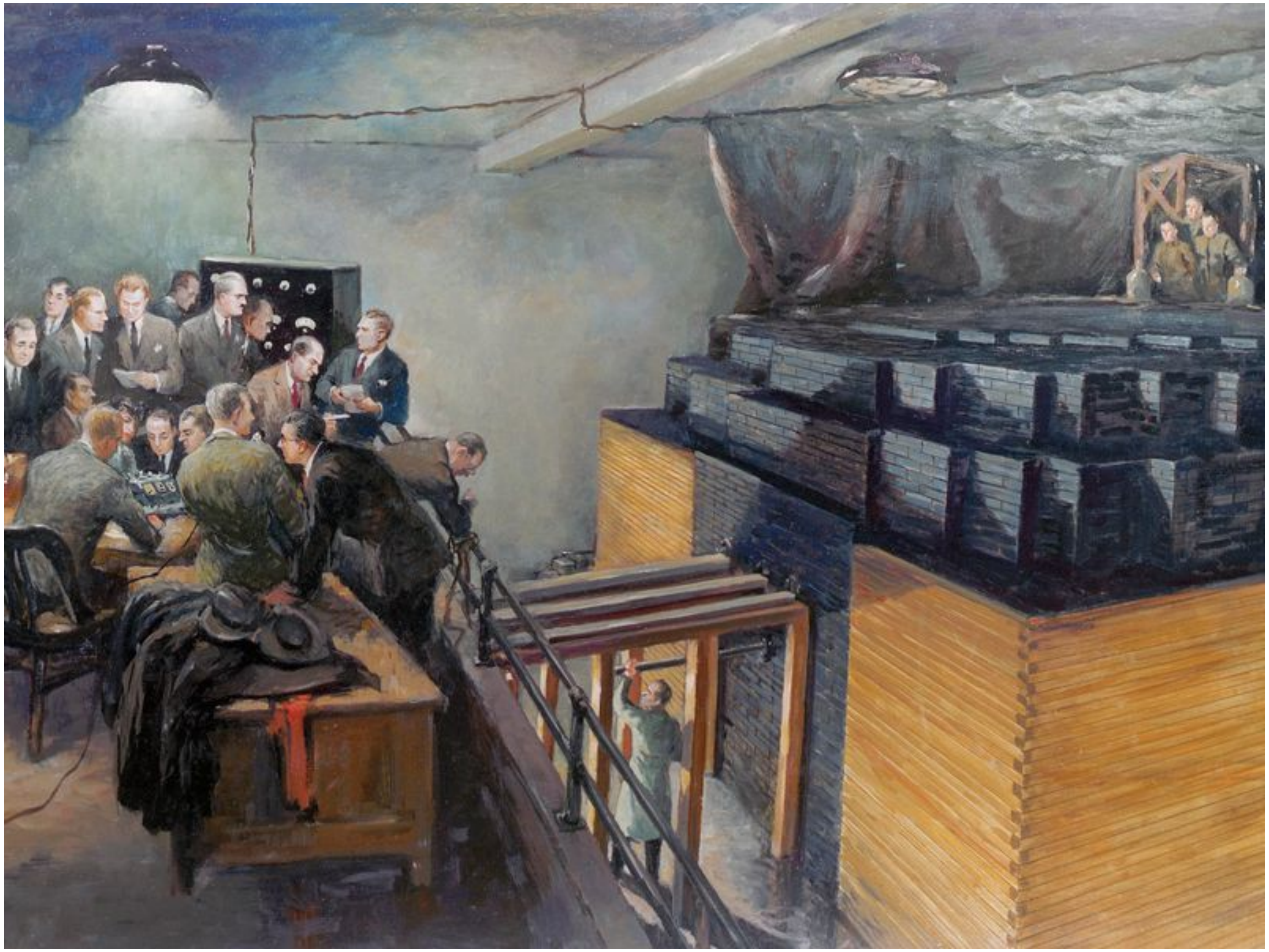
$t_{1/2}(^{235}U)$ ~ 713 million years
$t_{1/2}(^{238}U)$ ~ 4150 million years



Some nuclear reactors

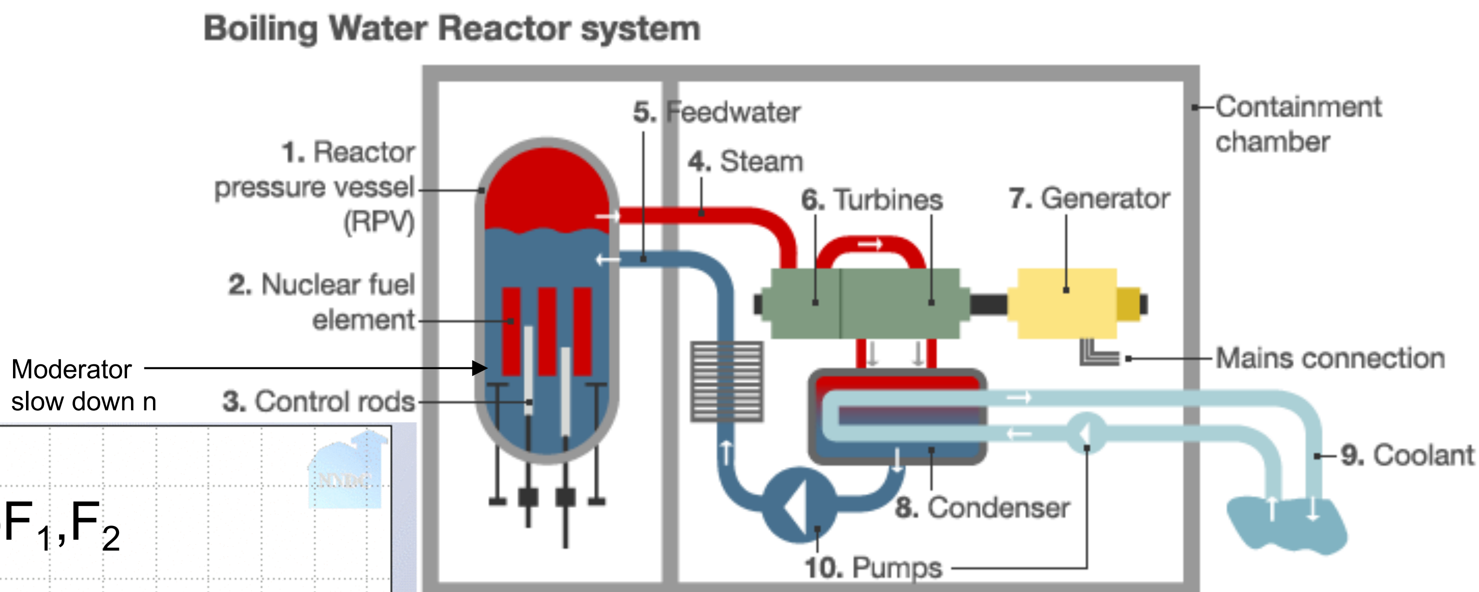
The first human-made one – 16 Nov 1942

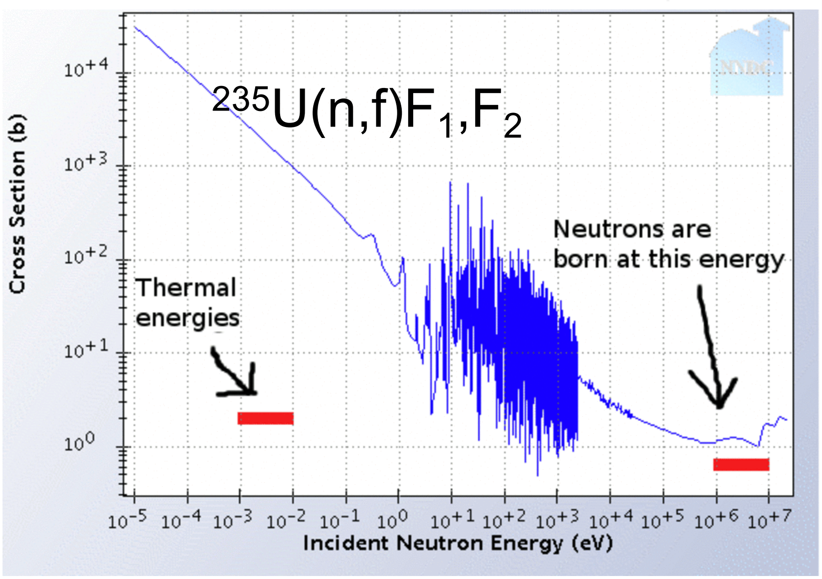
In the University of Chicago's squash court – Enrico Fermi observing …



Some nuclear reactors

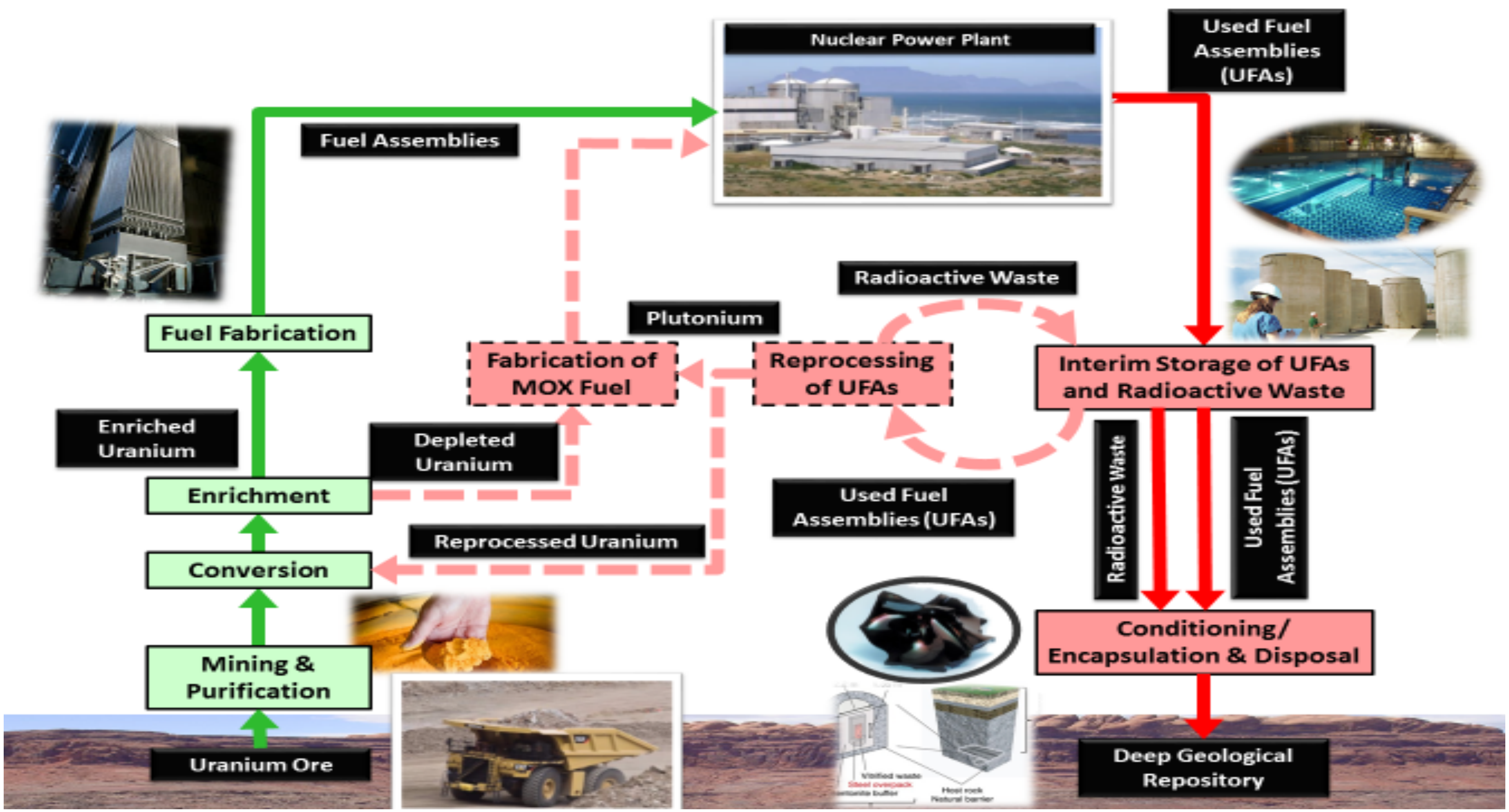
Typical Boiling Water Reactor (BWR)





Nuclear Fuel Cycle

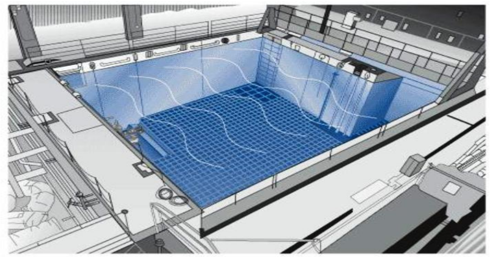
1 GW * 1 yr → 1000kg

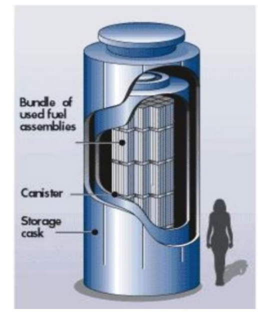


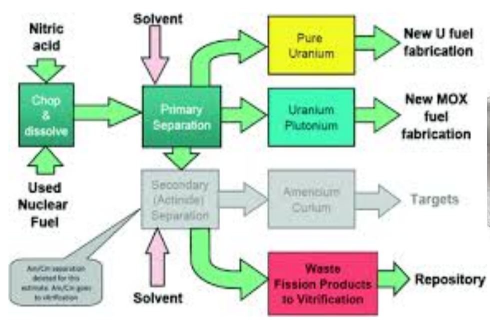
Nuclear Fuel Cycle

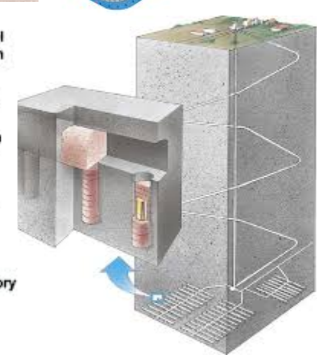
Spent fuel management (SFM) involves

- **On-site storage** – safely stored on reactor site in spent fuel pools and dry storage casks for many years.
- **Off-site consolidated storage** – safely stored away from reactor site in wet or dry centralised interim storage facilities (CISF) for decades (e.g. Sweden, Switzerland, Germany).
- **Reprocessing** – used today in France, India, Russia, the UK (ceasing this year), and is planned in China and Japan. A number of other countries have reprocessed and recycled in the past.
- **Disposal in deep geologic repositories (DGR)** – required even if reprocessing is in use. (Finland is poised to be the first to construct a DGR.)
- **Transportation** – in transport casks, by road, rail and/or sea, between facilities.









Different strategies or options for SFM are being pursued by different countries:

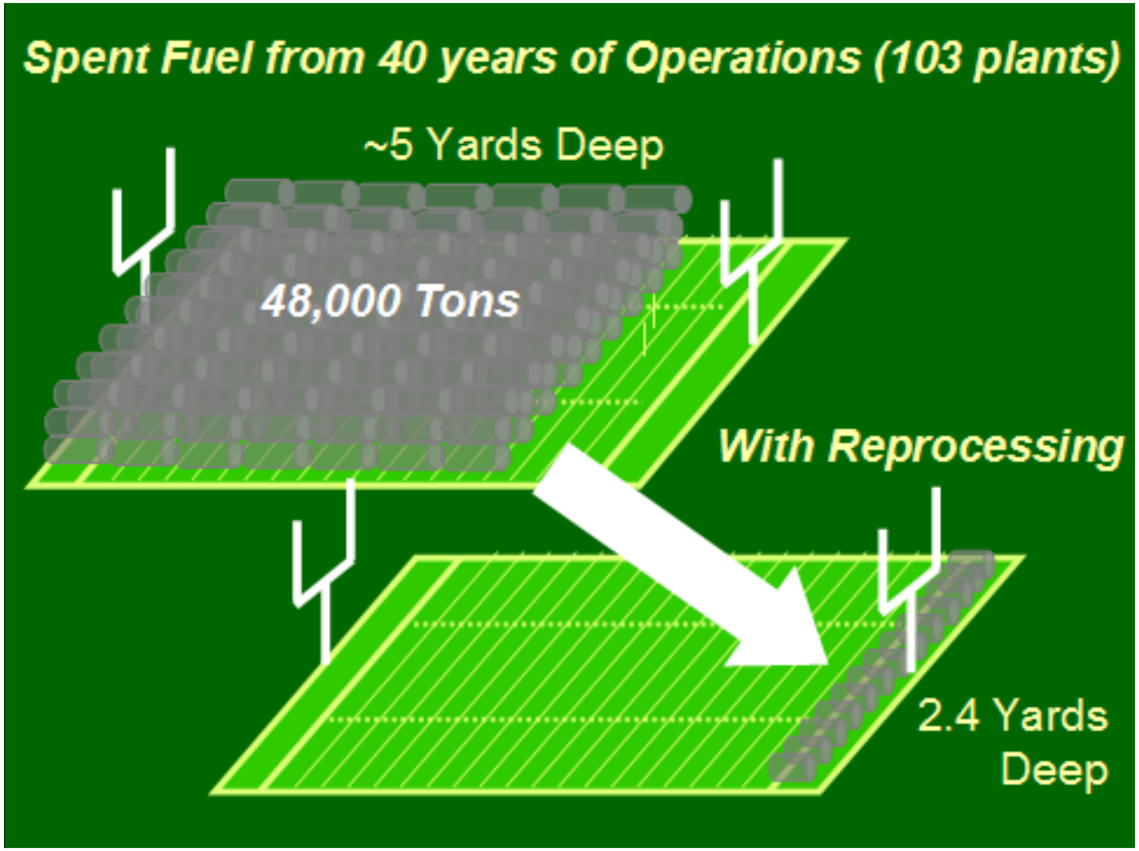
- Reprocessing & recycling
- Direct disposal
- Postponement of decision while actively evaluating the strategies.

Some countries are implementing combinations of those strategies.

SPENT FUEL CONTAINS VERY LONG-LIVED RADIONUCLIDES, WHICH IS A CHALLENGE SOCIETALLY AND POLITICALLY

Dr S Bvumbi (NRWDI)

Nuclear Fuel Cycle



Nuclear Fuel Cycle

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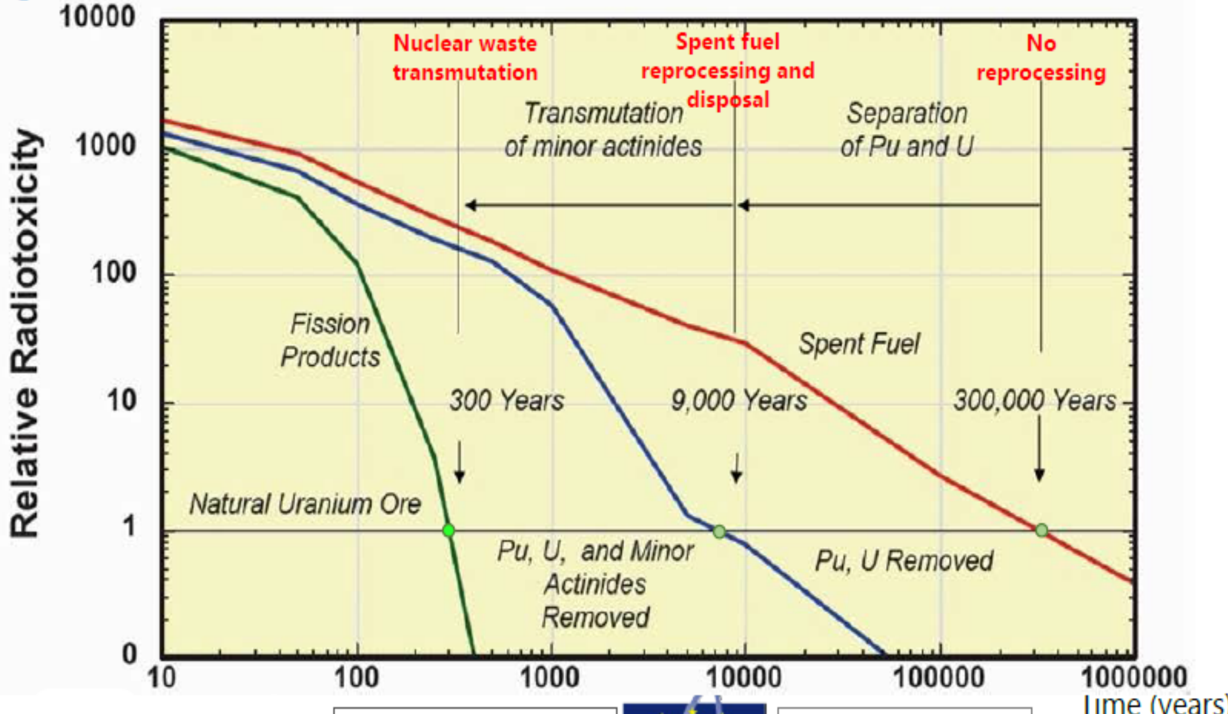
Nuclear waste: transmutation impact

GEN IV International Forum



Duration Reduction: 1000x

MYRRHA

Volume Reduction: 100x

Dr S Bvumbi (NRWDI)

Nuclear Fuel Cycle
CSIF
Centralised Interim Storage Facility (SA)

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Policy Perspective and Directive

•The CISF project locates itself within the spent fuel and radioactive waste management programme that is based on the Radioactive Waste Management Policy and Strategy for the Republic of South Africa of 2005 ("the Policy").

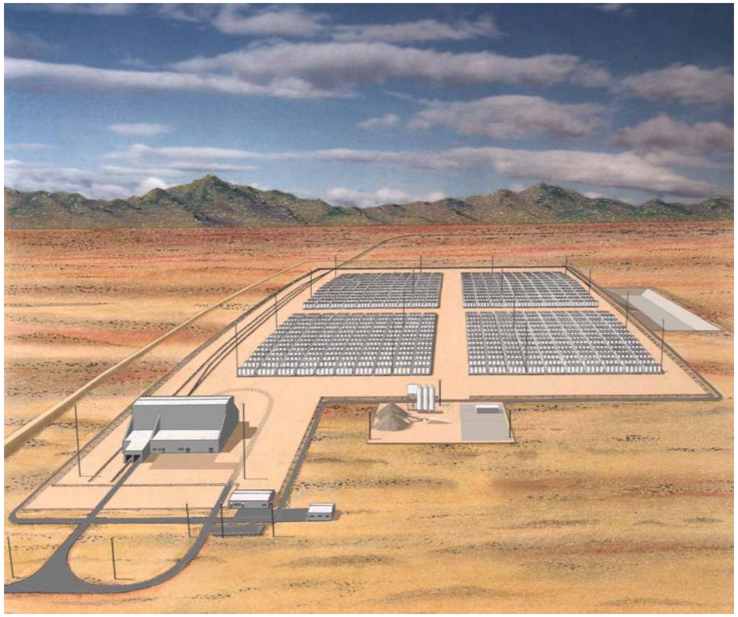
•According to the Policy, the storage of spent fuel on the reactor sites is finite and its practice unsustainable in the long term.

•The Policy, therefore, provides for the Government to ensure that investigations are conducted within set timeframes to consider the various options for safe management of spent fuel in South Africa.

•Included in the options for investigation is a "long-term aboveground storage on an off-site facility licensed for this purpose", which refers to the proposed CISF, with due caution that "storing aboveground indefinitely may result in an undue burden on future generations."

•As such, the Policy forms a basis for establishing the CISF for continued storage of spent fuel from the country's nuclear reactors.

•In 2019, NRWDI obtained Ministerial authorisation to develop and execute the CISF project.



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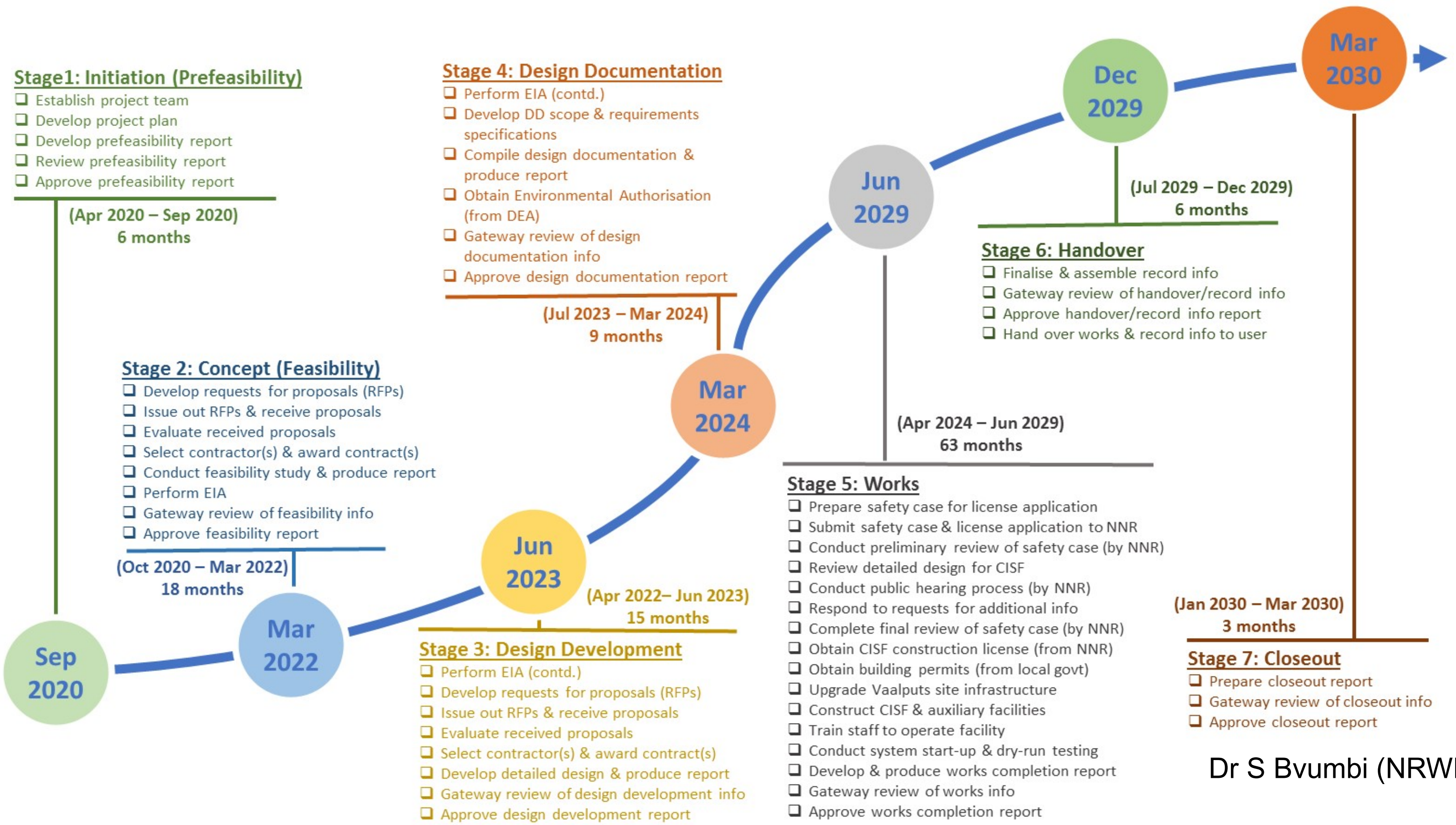
Nuclear Fuel Cycle

CSIF

Centralised Interim Storage Facility (SA)

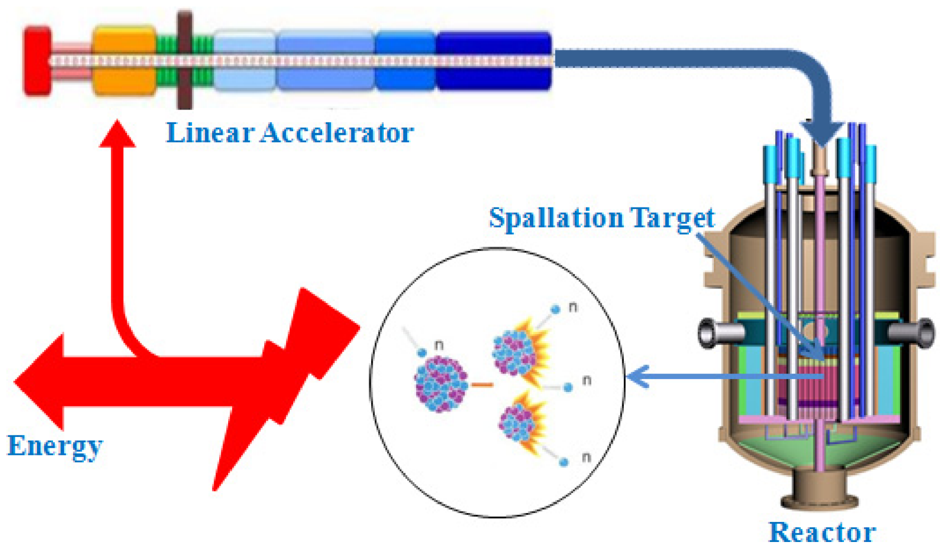


Dr S Bvumbi (NRWDI)

Nuclear Fuel Cycle

Accelerator Driven Systems

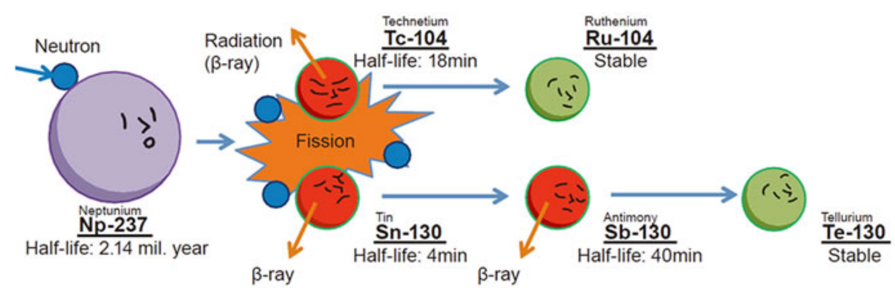
Neutron spallation
Incinerate waste



Tc-99 (τ ~ 213,000 years)
I-129 (τ ~ 16 million years).

Tc-99 + n → **Tc-100** (short lived)
I-129 + n → **I-130** (short lived)

Tc-100 → **Ru-100** + β (stable)
I-130 → **Xe-130** + β (stable)



Nuclear Fuel Cycle

Solution for Africa

Complexity of processing and storage
Regulatory Issues

Regional / Pan-African Consortia

1. Economically no African country can afford to establish a repository on its own
2. Shared processing / repository
3. Lower the barrier to entry per country.
4. Enable entry from installation of only SMR technology at few hundred MW → Conventional PWRs with n GW level units
5. Youth engagement - waste management projects

Nuclear Energy in the mix …
… can it power Africa sustainably

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- **Part 2**
  - Large Reactors ~ 1GW, Gen 3+, Gen IV
  - SMRs 50 – 300 MW
  - Micro reactors 1-10 MW
  - Passive safety
  - Fuel every 10 years, or once per 80 years

  - Process heat
    - Desalination
    - Synthetic fuel carriers
      - Hydrogen Economy
      - Liquid synthetic fuel

Nuclear Energy in the mix …
… can it power Africa sustainably

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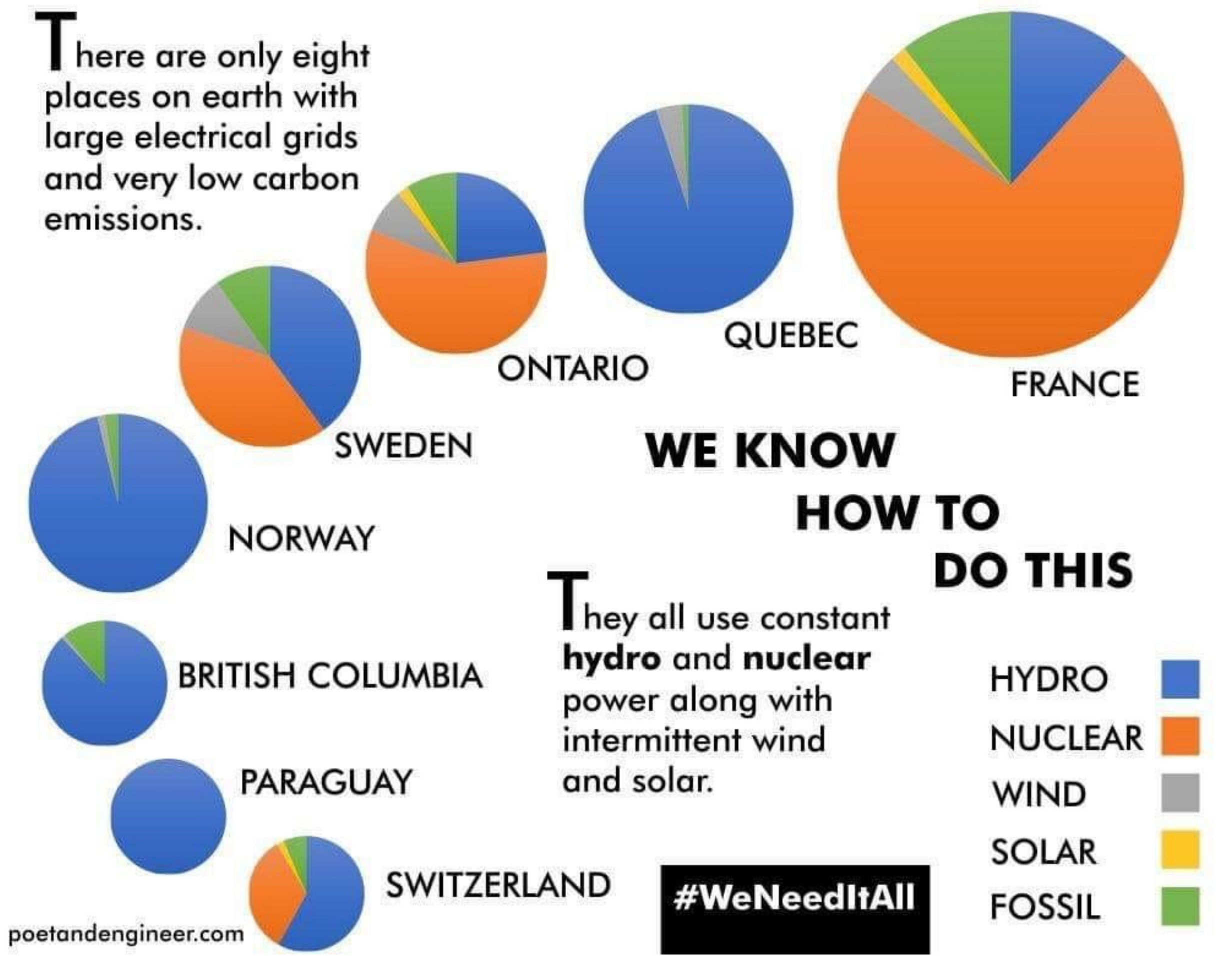
- **Take home message** : renewables are nice, but ……
  - They are ot dispatchable
  - One needs 100% back-up
  - There is a very strong reliance on the grid
  - They harvest a diffuse resource
  - Wealthy Africa needs 3400 GW (scale to USA or China)
    Renewables require enormous plant
  - **Renewables have their place but its not baseload generation**

- **Carbon free dispatchable alternatives**
  - **Hydro**
  - **Nuclear**
  - **Other**

Nuclear Energy in the mix …
How to be green



Nuclear Energy in the mix …
African Hydro ……

Grand Inga Hydro Power Project

- World's most potent Hydropower project ?
- **Inga Falls** (rapids) where the Congo river drops 96 m over the course of 15 km (150 km from the river mouth)
- 39 GW, $80b, grid to Africa $10b
- Still mythical due to concerns of security of supply
- **39 GW << 3400 GW !**

Nuclear Energy in the mix …
Lets look at Egypt

Large Reactors ~ 1GW, Gen 3+, Gen IV

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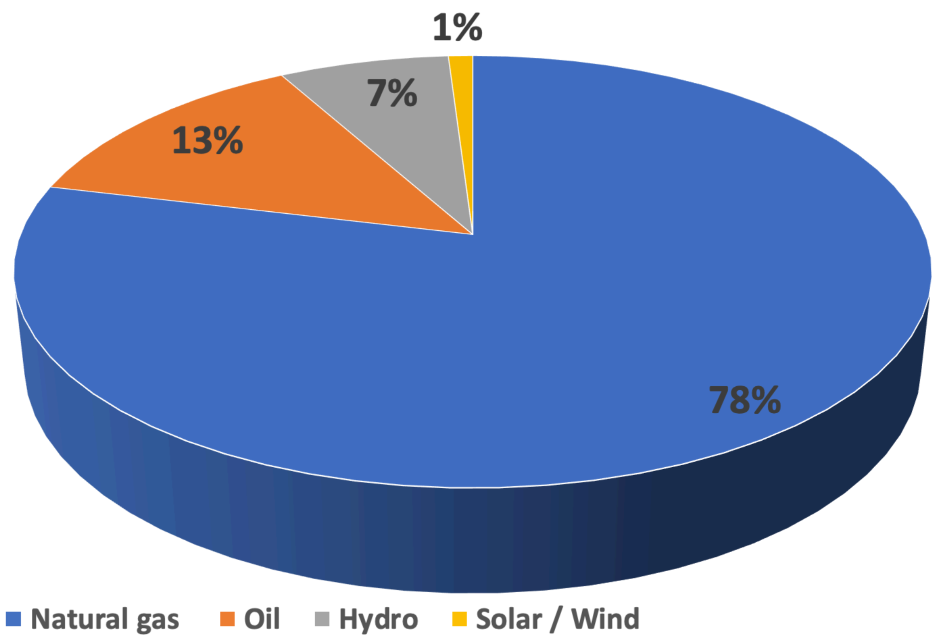
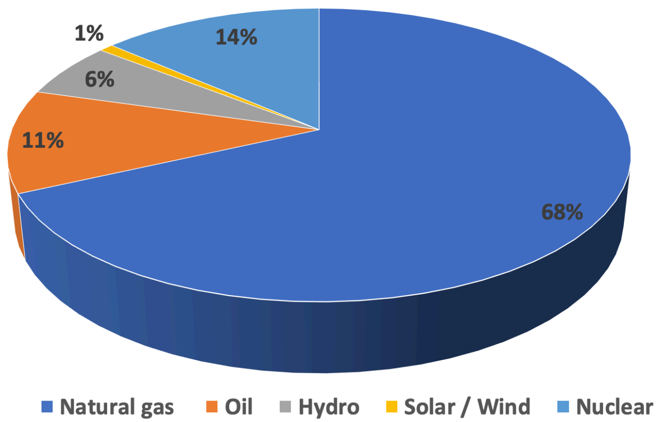
Egypt has 31 GWe in 2019

+ 4.8 GWe Nuclear from 2026





Nuclear Energy in the mix …
El Dabaa

- 1955/6 Egyptian Atomic Energy Authority (EAEA)
- 2015 Egypt – Russia sign agreement re Nuclear Power
  - $60 billion life cycle cost. Reactors costing $29 billion
  - Completion by 2026-2027.
  - VVER 1200 x 4 = 4.8 GW : Gen 3+ warm-water modification.
  - El Dabaa 100 km west of Alexandria
- Desalination 170,000m^3/d facility = ¼ of Capetown
  - Uses 1% of the output
  - Multiple Effect Distillation (MED). In each stage, the feedwater is heated by steam in tubes. Some of the water evaporates, and this steam flows into the tubes of the next stage, heating and evaporating more water. Each stage essentially reuses the energy from the previous
- SA and Egypt will be the only two countries in Africa with Nuclear Power

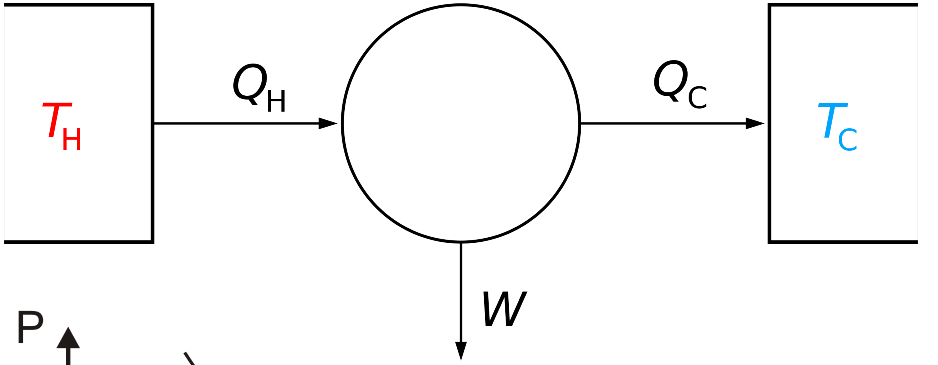
Nuclear Energy in the mix …
El Dabaa

Wikipedia

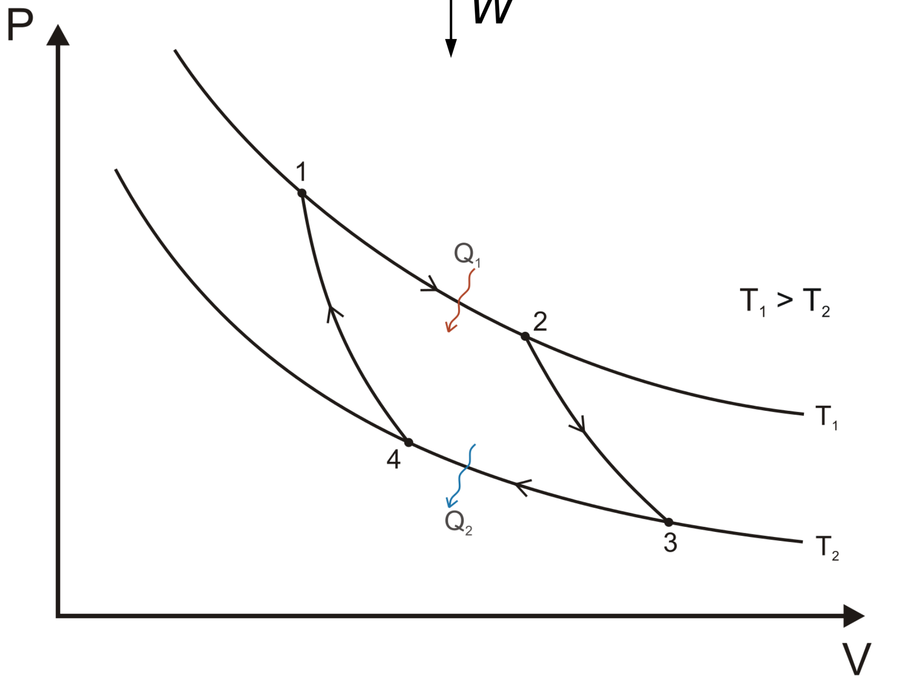
https://www.facebook.com/photo.php?fbid=2276689379056237&set=a.169931563065373&type=3&theat

Nuclear Energy in the mix …
Process heat

- **Process heat**
- Reduce electrical efficiency
- Exhaust temperature higher
- Also have desalination
- Overall energy usage better



$$\eta_{\mathrm{I}} = \frac{W}{Q_{\mathrm{H}}} = 1 - \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}$$



Nuclear Energy in the mix …
Grid Limitations

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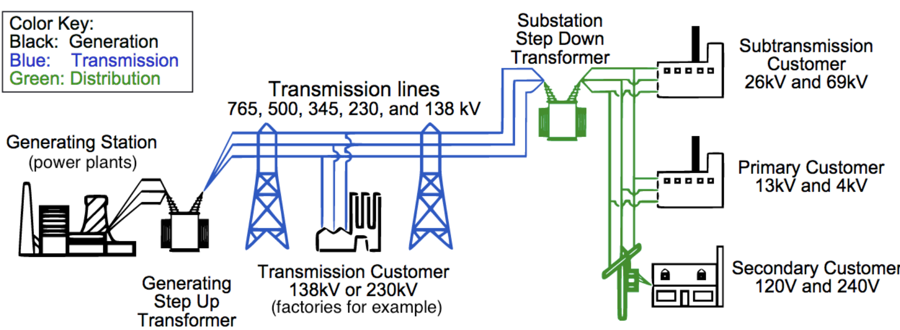
- **National grids**
- **Mini grids**
- **Micro grids**

- **Source < Connected Load / 10**
  - Avoid stability issues
  - Can't place 1 GW just anywhere !

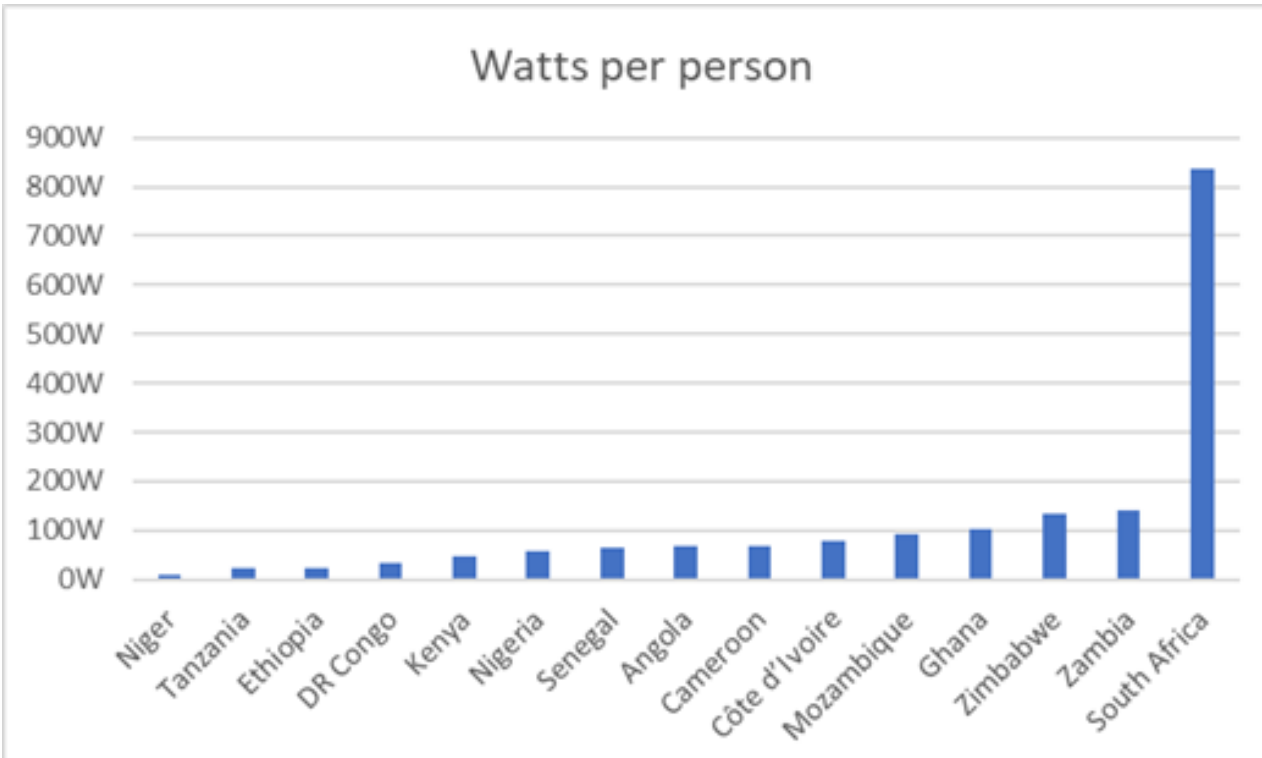


Source: (AEEP, 2016)

Nuclear Energy in the mix …
Overview ….

- The size of nuclear power reactors have grown in size since the 1960s.
- The range of size of current commercial reactors is from 600MW to 1750MW.
- Small Modular Reactors are a new development of units of 50MW - 300MW.
- Only South Africa and Egypt have (or are building) nuclear power reactors at present

Nuclear Energy in the mix …
Most African countries are short of electricity



Sustainability implications of electricity outages in sub-Saharan Africa, DeVynne Farquharson, Engineering and Public Policy, Carnegie Mellon.

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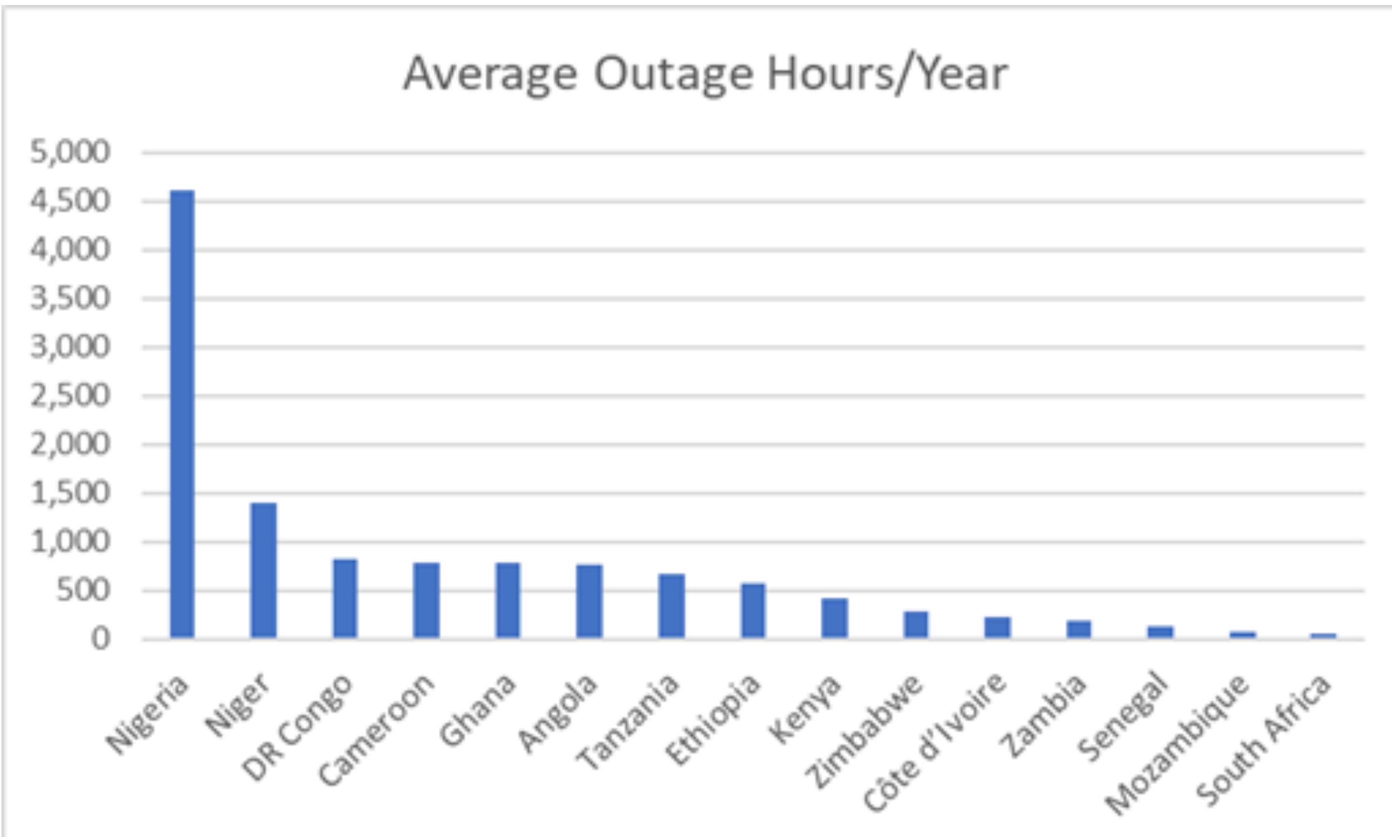
Nuclear Energy in the mix …
Current African power is unreliable



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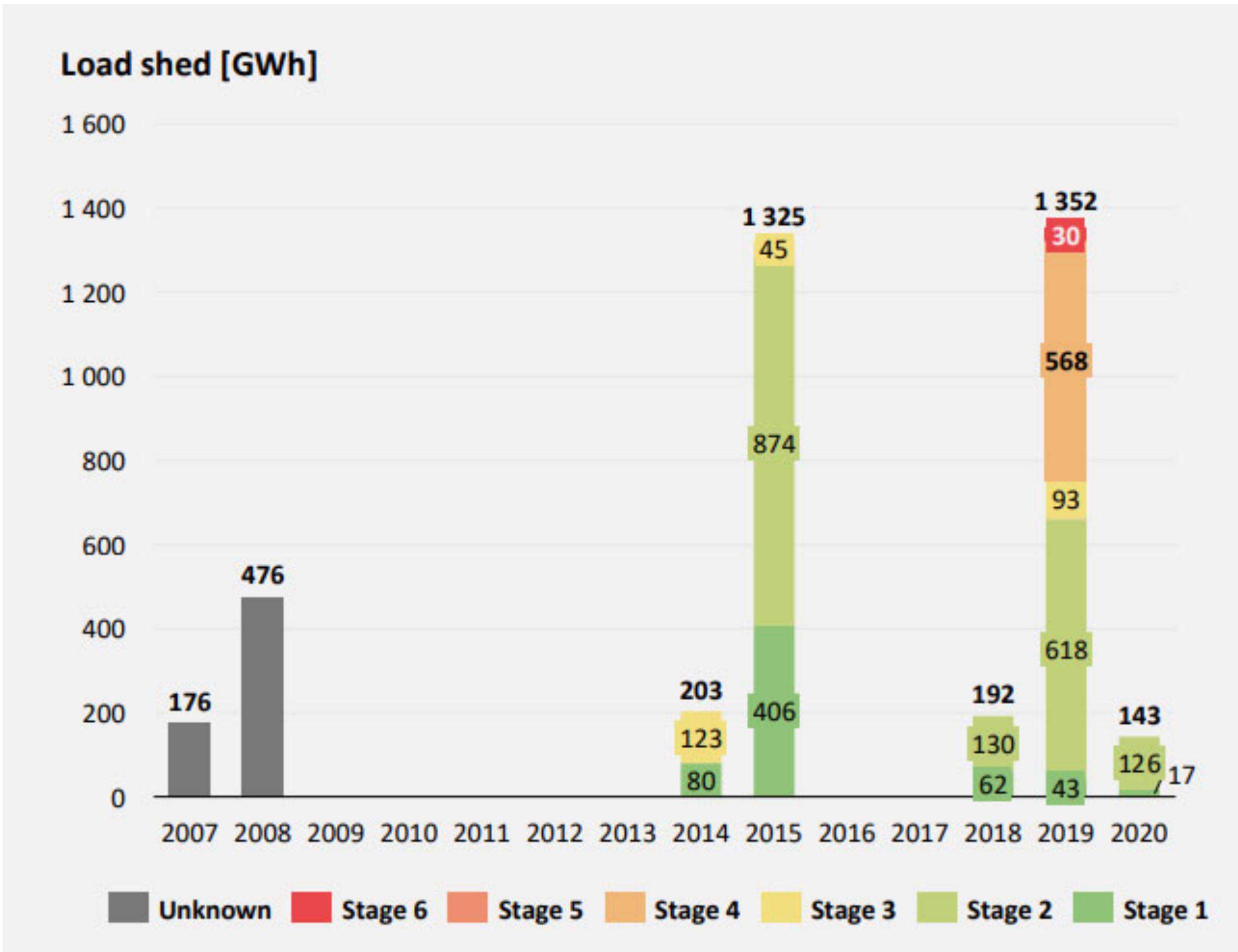
Nuclear Energy in the mix …
In SA – ESKOM load shedding history



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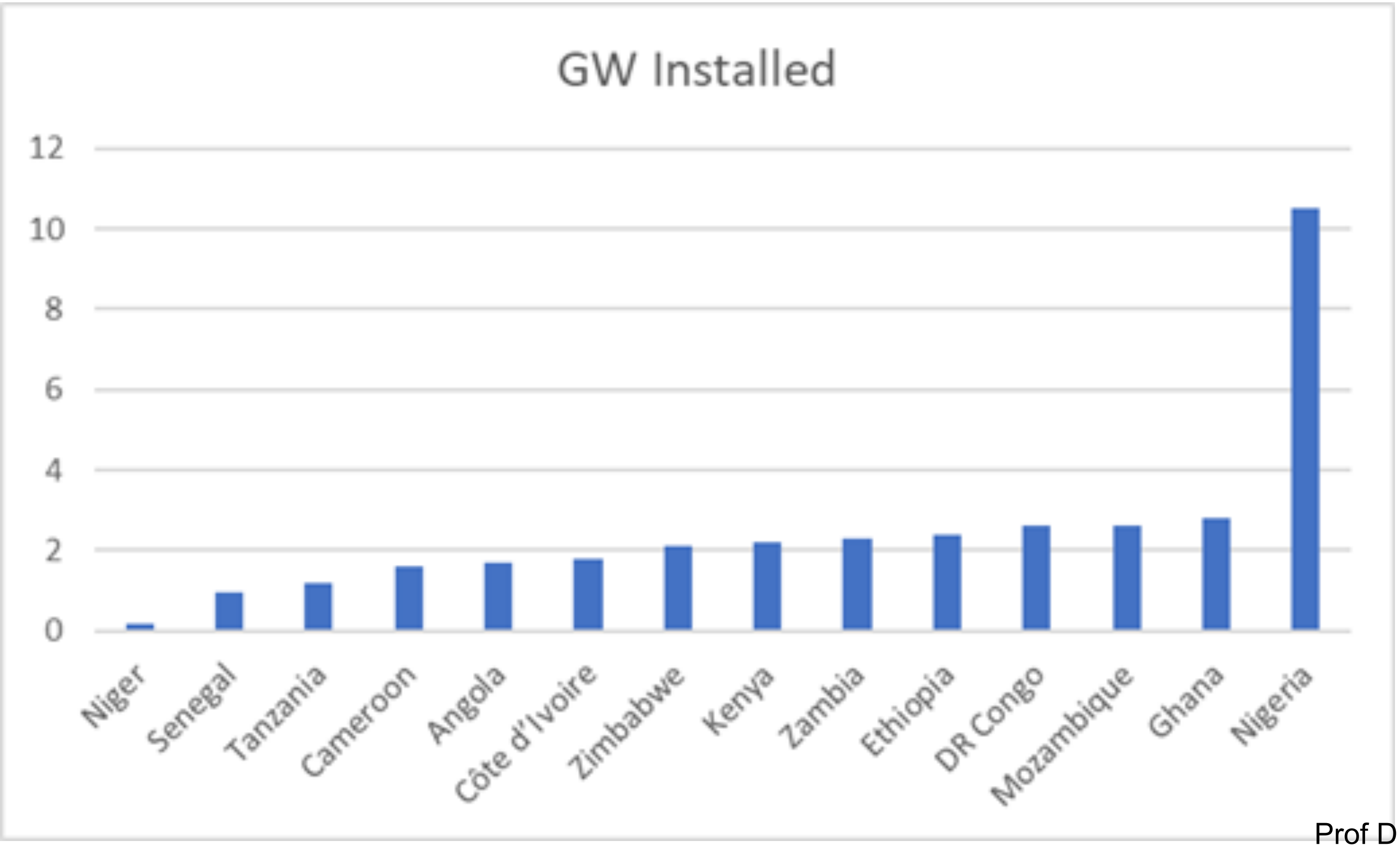
Nuclear Energy in the mix …
National Grid size limits large units



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Nuclear Energy in the mix …
The Impact of SMR Technology

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- The deployment of Small Modular Reactors (SMRs) promises to break the historical cycle of ever larger nuclear power station designs with greater cost over runs and delays.
- Current large reactor designs are all based upon existing, deployed technology, and increasingly that is the classic Pressurised Water Reactor. This is shown in the AP1000, EPR, Hualong One, APR1400, VVER-1200, CAP1400, etc.
- All the SMR designs currently proposed move away from the PWR technology and use, in many cases, technology demonstrated in the 1960s but never full commercialised .

Nuclear Energy in the mix …
Desalination Technology Issues

- There are two principal families of desalination technology.
  - Reverse Osmosis (RO)
  - Thermal Desalination
- While RO plants benefit from warm raw water supply (up to some 40°C) the primary energy input is the high pressure pumping of the water through the membranes.
- Thermal processes (MED, MVC and MSF) rely on converting the liquid water into steam, and therefore the primary energy input is heat, around 100°C).
- Therefore the key question in applying SMRs to Desalination Plants is whether it is better to extract heat energy for Thermal Desal, with the prospect of losing overall efficiency, or using electricity directly for RO.

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Nuclear Energy in the mix …
Impact of Desalination on Power Conversion

- A normal Rankine cycle steam plant will get higher thermal efficiency the lower the heat sink temperature (T_{cold} - e.g. the sea)
- The impact of removing “low temperature” steam from a Rankine cycle plant on efficiency is greater if the T_{hot} of the system is lower.
- A direct cycle Brayton gas turbine plant (e.g. PBMR 400) would reject heat at over 100°C without any efficiency loss.

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Nuclear Energy in the mix …
Impact of potential SMR Technology - I

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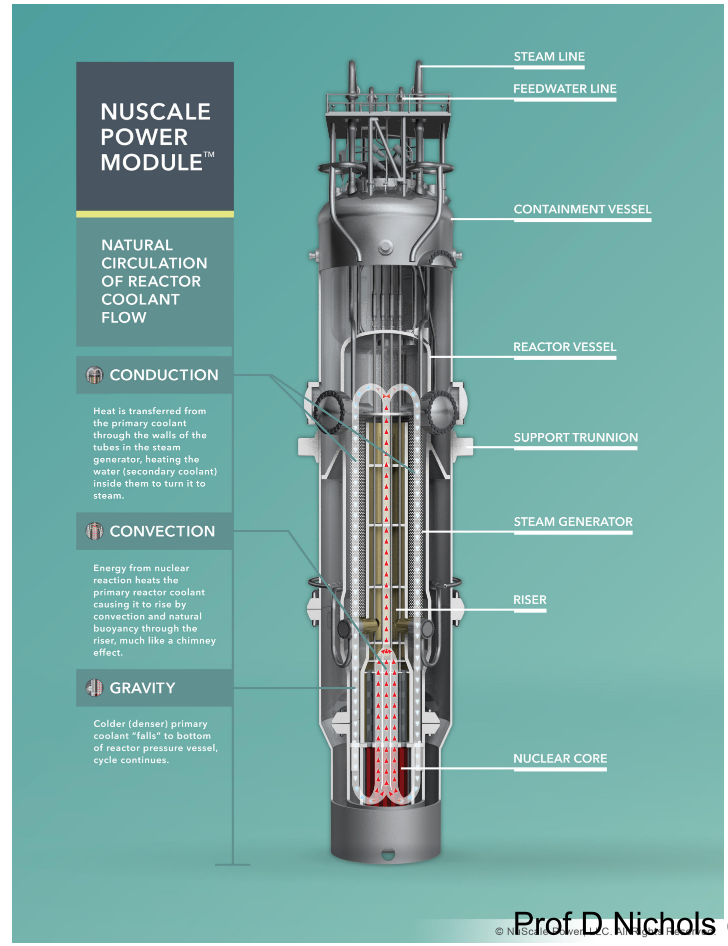
- Integral Light Water Reactors (e.g. NuScale)
  - Technology largely based upon PWR & BWR
  - Rankine Cycle with net efficiency about 28%
  - Significant Impact on efficiency if steam taken for Thermal Desalination
  - Lends itself to Reverse Osmosis technology



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Nuclear Energy in the mix …
Impact of potential SMR Technology - II

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- Alternative Technologies using Rankine Cycle
  - These are technologies using higher temperature coolant that LWR (helium, sodium, lead, molten salt etc)
  - Technology largely based on experience of "prototype" reactors from 1960s and 1970s.
  - High temperature coolants leads to steam conditions similar to advanced fossil plant, with efficiency of about 40%.
  - This would mean a more limited impact of thermal desalination on efficiency

HTR-PM – Chinese HTGR with Rankine steam cycle, 567°C steam and 40% efficiency

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Nuclear Energy in the mix … HTGRs

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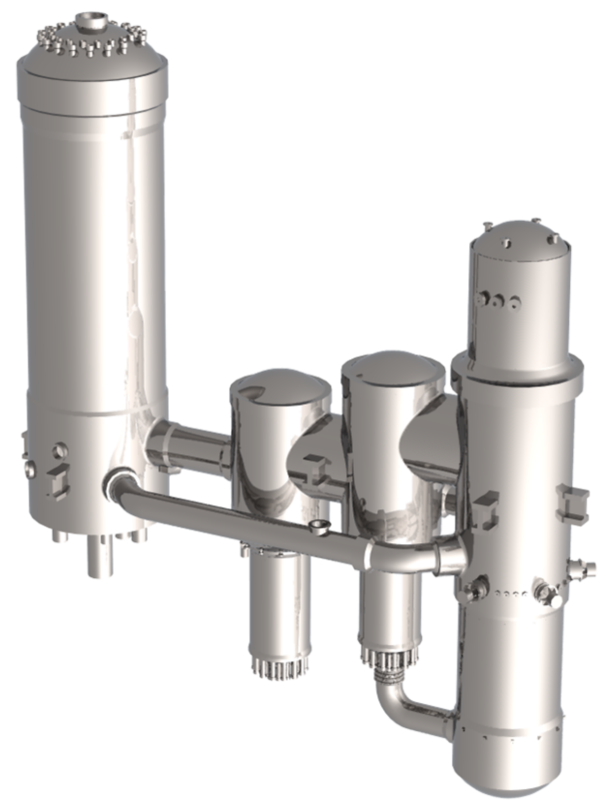
- Direct Cycle Gas Cooled Reactor
  - Technology a meld of combustion gas turbine and 1980s HTGR technology.
  - Uses the Brayton cycle with a primary circuit reject heat of about 120^{o}C.
  - Overall thermal efficiency 40%-50%
  - Could provide thermal energy to Thermal Desalination plant with no loss of plant efficiency.



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Nuclear Energy in the mix …
Key requirements for SMRs in Africa

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50-200MW size

Standardized design with short construction period

Simplified regulation, probably on a regional basis

Competitive economics (US$c5/kWh to US$c14/kWh)

Political Acceptance

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Nuclear Energy in the mix …
Example from South Africa now

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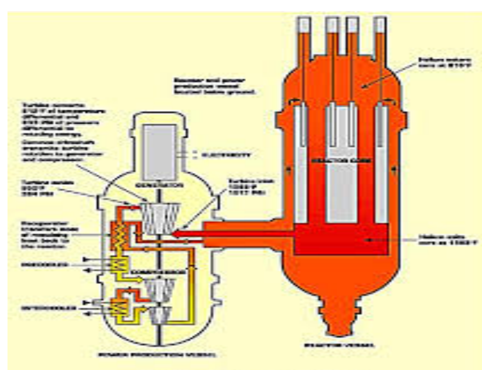
Emerging Market Opportunities : 2500 MW RFI

Issued by the Ministry of Mineral Resources and Energy

- Large PWR CAP Design – Brownfield Units 3 and 4 at Koeberg
- A collection of 300 – 600 MW of SMR's
    - China – SNPTC 300 MW;
    - USA – NuScale 600 MW)



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Nuclear Energy in the mix …

- **Emerging Market Opportunities**

  Repurposing of the Old Thermal Coal Power Stations
  Eskom Call for Expression of Interest for Komati, Camden and Grootvlei

- Paris Agreement : Coal is Out

  Eskom Thermal Power Stations :
- Mechanical Plant has Aged : Boiler Tube Leaks
- Electrical Plant can go on for another “100 years”
- Add : SMR as Heat Source;
- Add Steam Generator;
- Continue Base Load Power Station Operations

Nuclear Energy in the mix …
SMR → AHTR

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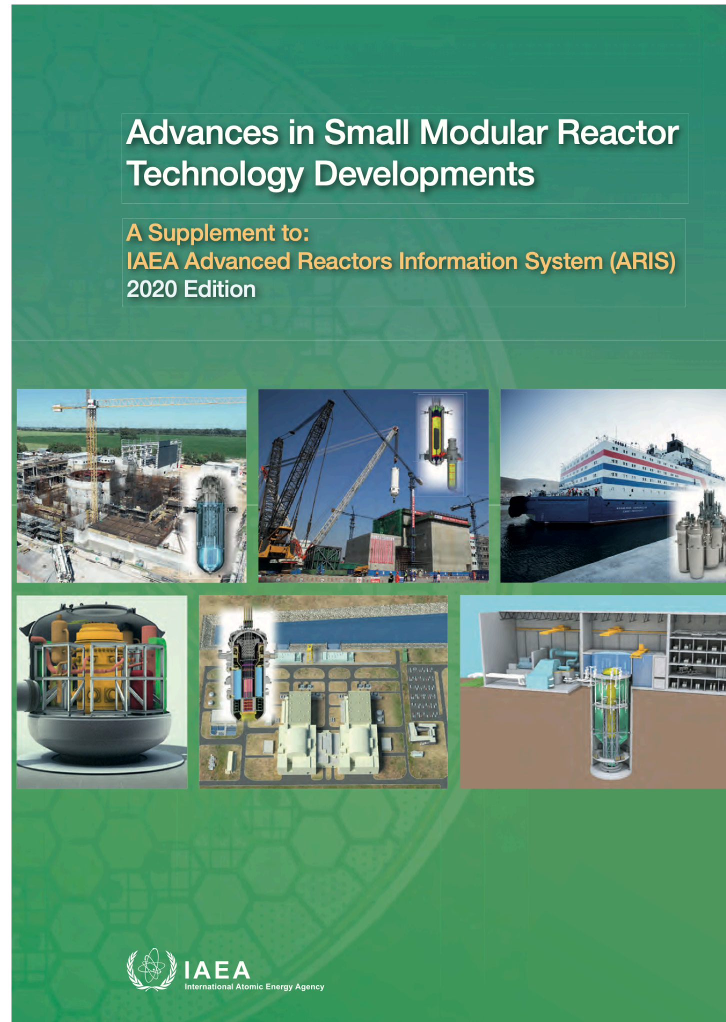
3 design projects from SA in this book

Discuss the AHTR

- Design a nuclear reactor for the grid demands of the future.
- Plant should fit various size grids.
- Flexible to follow load changes.
- Adaptable to various demand side requirements.
- Simplified construction and maintenance.
- Safe without engineered safety systems.
- Economic – maximise efficiency, reduce costs.
- Renewable energy claim 4c US per kWh
- Nuclear today at 8c US per kWh
- Designed with the UN sustainable development goals in mind –
  - Good health and well being; clean water and sanitation; decent work and economic growth; industry, innovation and infrastructure; sustainable cities and communities; responsible consumption and production.

Prof A Cilliers



Nuclear Energy in the mix …
SMR → AHTR

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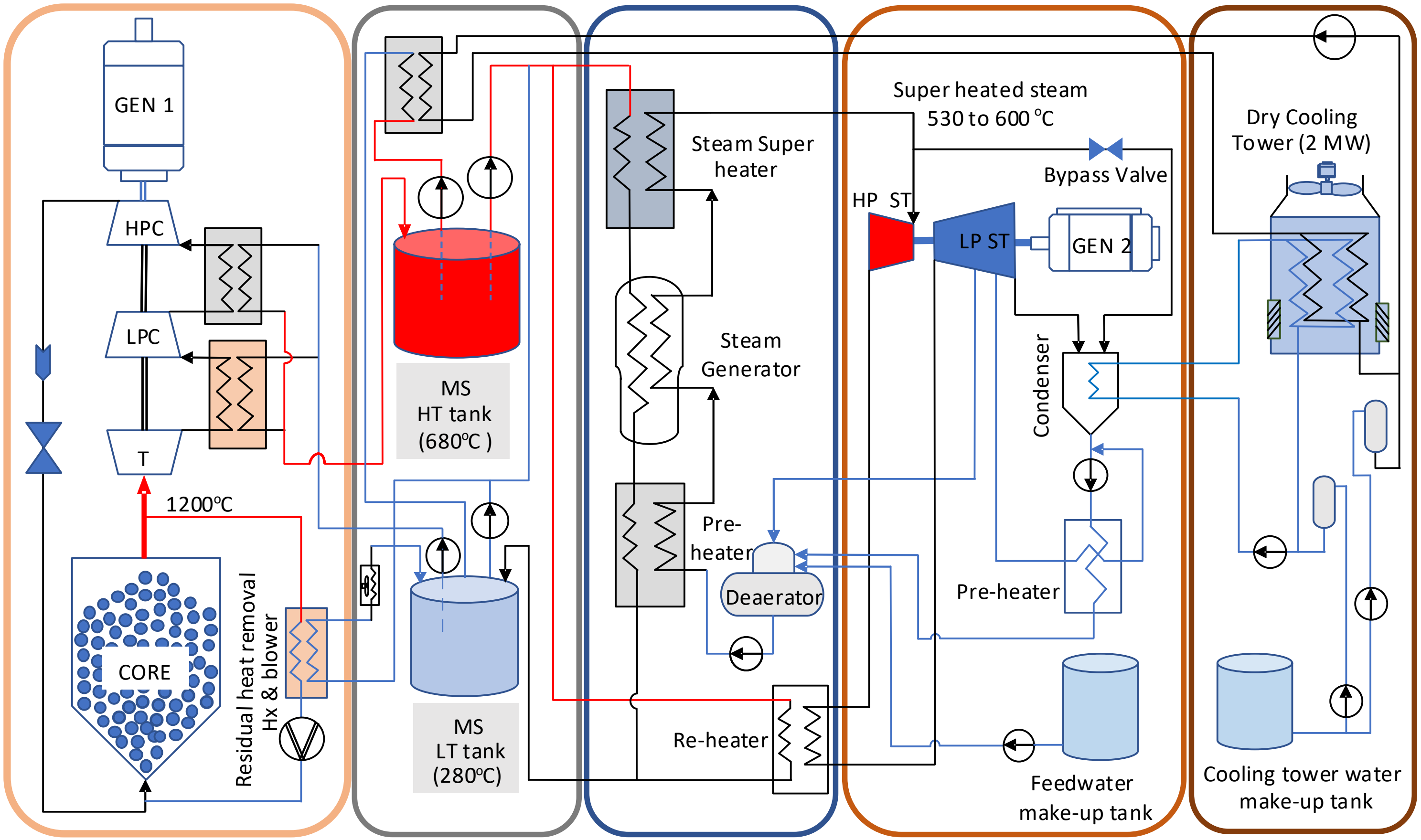
Process plant of AHTR-100



PRIMARY POWER SYSTEM (PPS)
(Reactor & Helium TCGS)

ENERY STORAGE SYSTEM (ESS)
(Battery)

ENERGY TRANSFER SYSTEM (ETS)
(Heat exchangers)

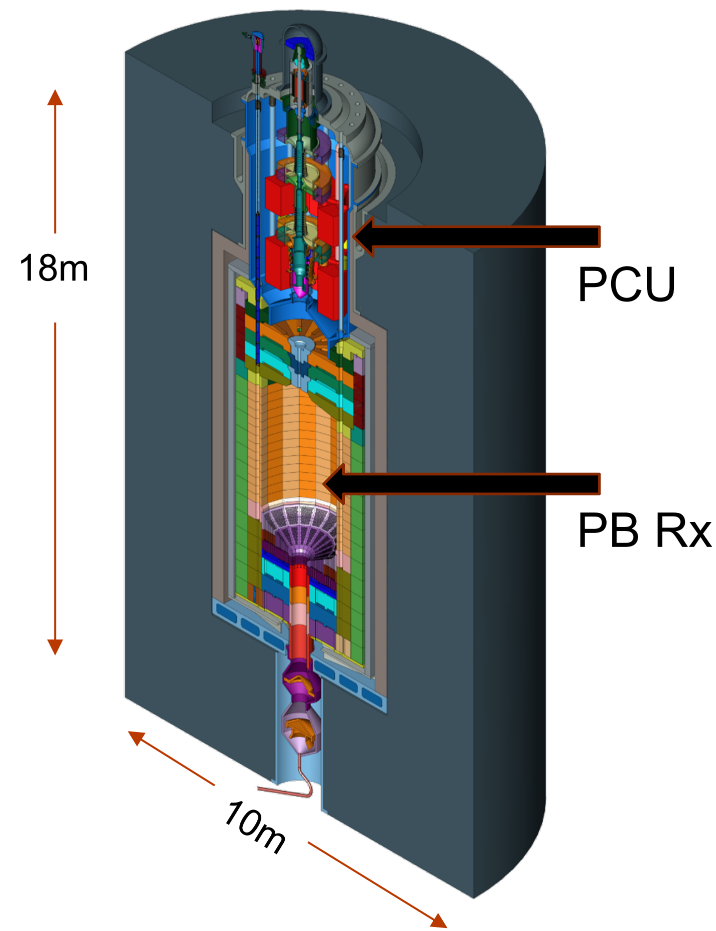
SECONDARY POWER SYSTEM (SPS)
(Steam TGS)

CYCLE COOLING SYSTEM (CCS)
(Heat rejection)

Nuclear Energy in the mix …
SMR → AHTR

PCPV with Power Conversion Unit (GT & Hx) above the Pebble Bed Reactor Core

- Pebble Bed Reactor – Proven concept, simple core, limited dynamic requirements, no load following with reactor.
- No active safety systems – reduce costs
- Combined cycle – use of He turbine to provide plant base-load, bottoming HX-combination to provide secondary circuit load following.
- Almost double efficiency.
- Heat storage in secondary circuit for plant flexibility.
- Heat storage allows nominal 66% load following without change in reactor power. (Plant maintains full power output on average – ideal for base and peak supply). Can be expanded.
- Modular for adapting to different grid demands.



Nuclear Energy in the mix …
SMR → AHTR

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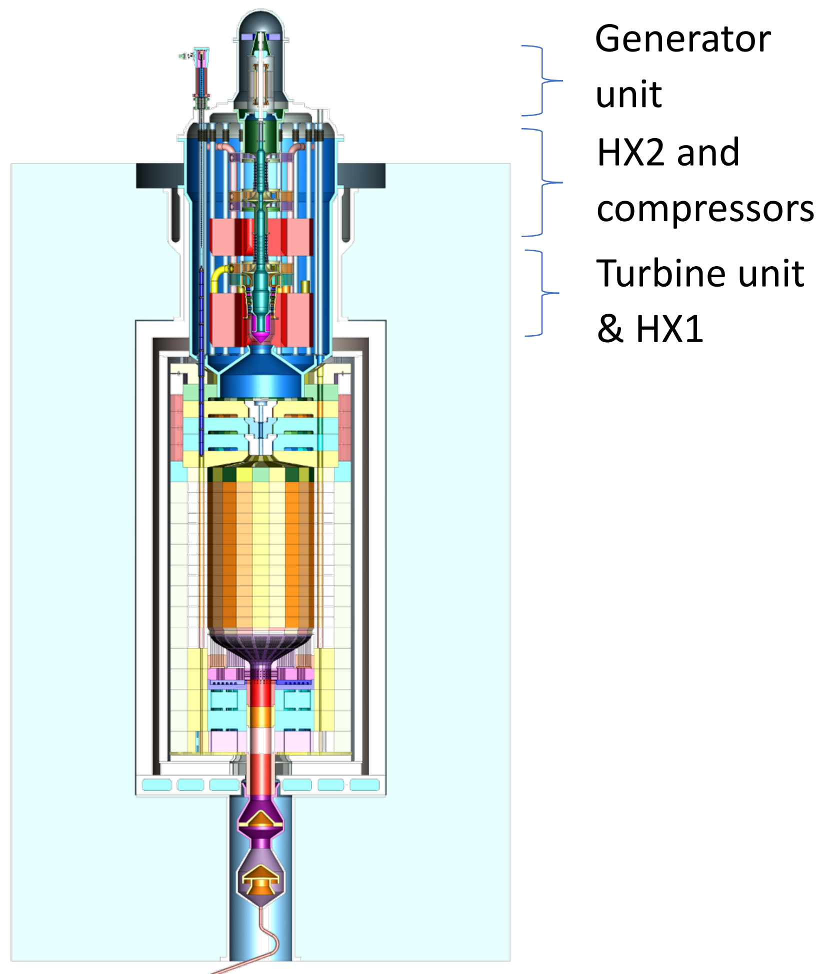
Turbine, compressor and Hx

- He up flow allows deep burn-up with once-through fuel cycle.
- Modular power conversion unit, allows 5 day maintenance outage.
- Online refuelling – no refuelling outage.
- Projected cost <2.5c US per KWh.
- Ideally suited for heat applications – Desalination, Hydrogen production, supports reducing carbon emissions in the fossil fuel industry.



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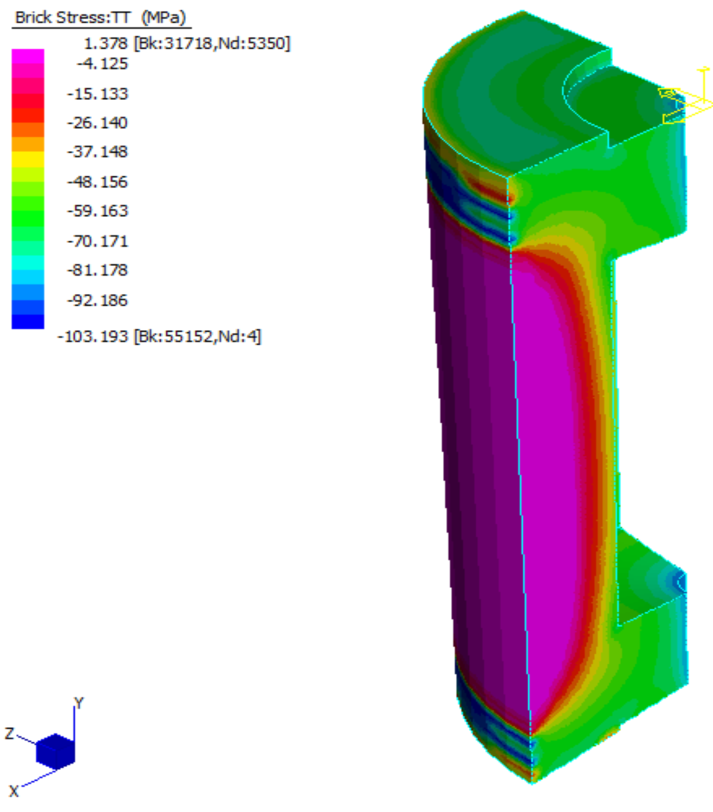
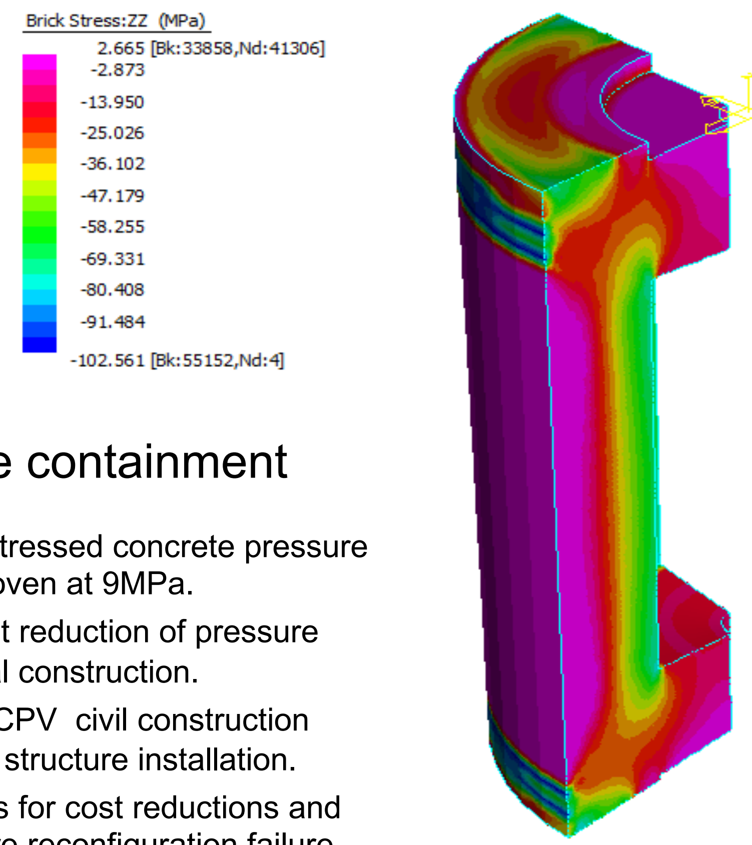
Nuclear Energy in the mix …
SMR → AHTR

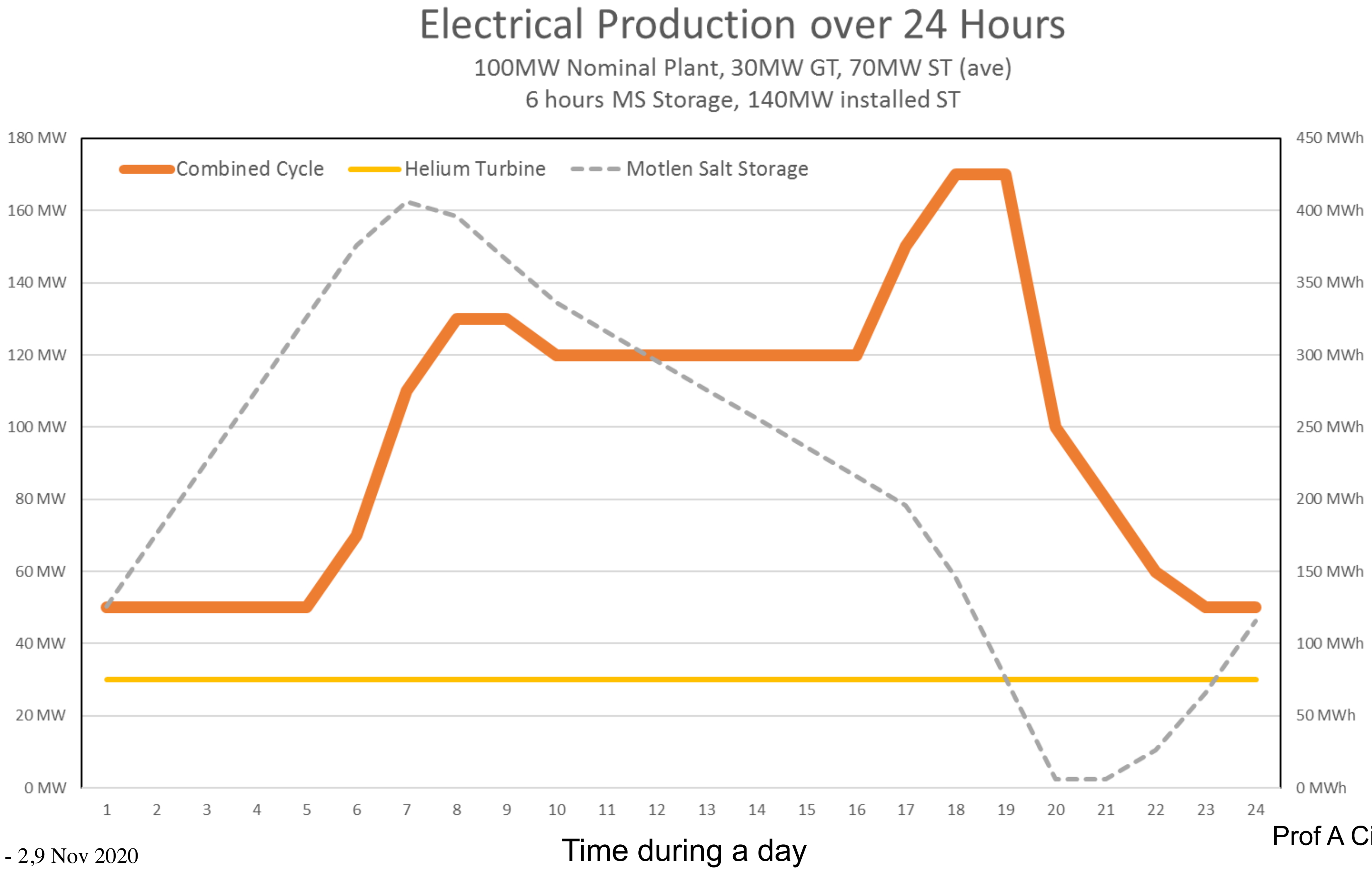




Concrete containment

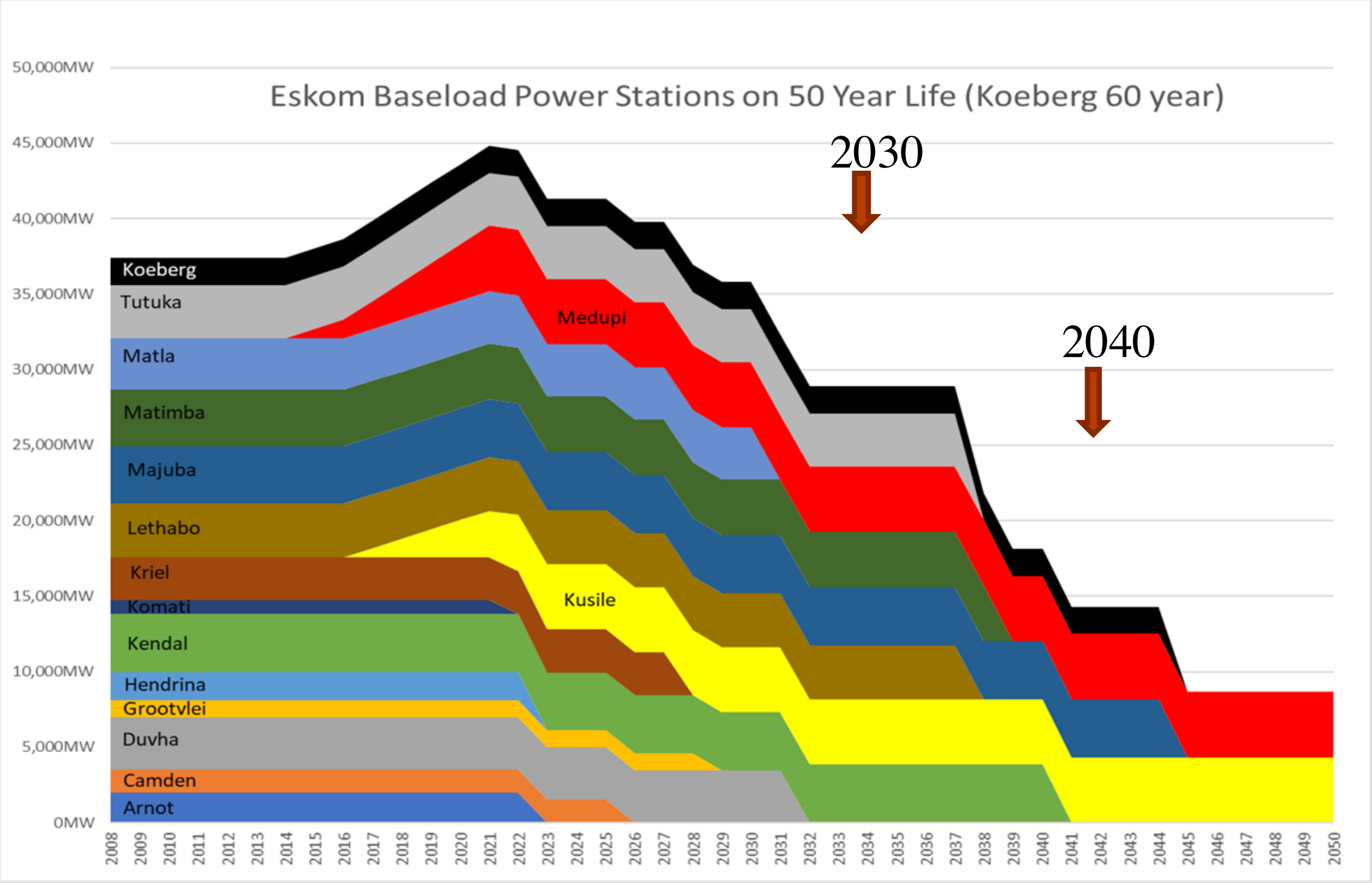
- Use of pre-stressed concrete pressure vessel at proven at 9MPa.
- Factor 5 cost reduction of pressure vessel - local construction.
- Complete PCPV civil construction before core structure installation.
- PCPV allows for cost reductions and removes core reconfiguration failure mode.

Nuclear Energy in the mix …
SMR → AHTR



Nuclear Energy in the mix …

- In SA, Eskom's current baseload fleet will be phased out by the end of the 2030s
- Their replacement as dispatchable, baseload plant is vital to maintain the current SA industrial economy.



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Nuclear Energy in the mix …
Kilopower from NASA

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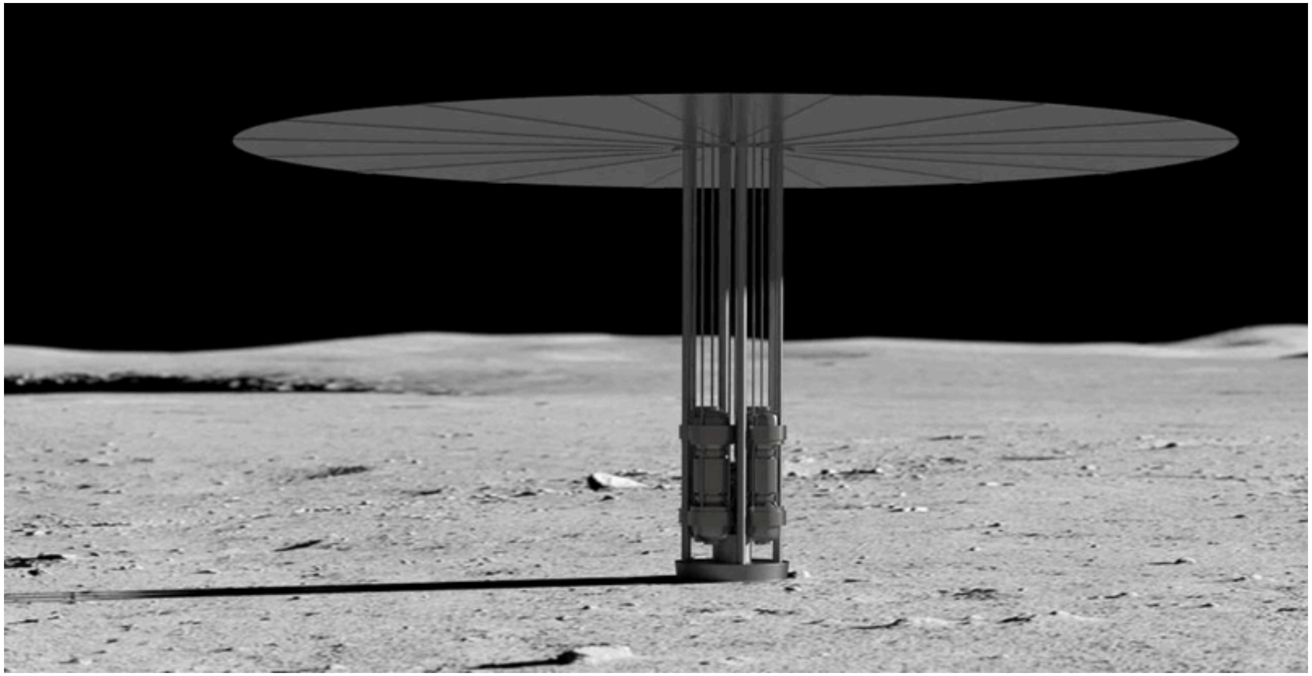
- NASA has developed a 10 kW small modular nuclear reactor, coupled with a Stirling engine, to meet the power demand requirements for space applications.
- KRUSTY – Kilopower Reactor Using Stirling technology



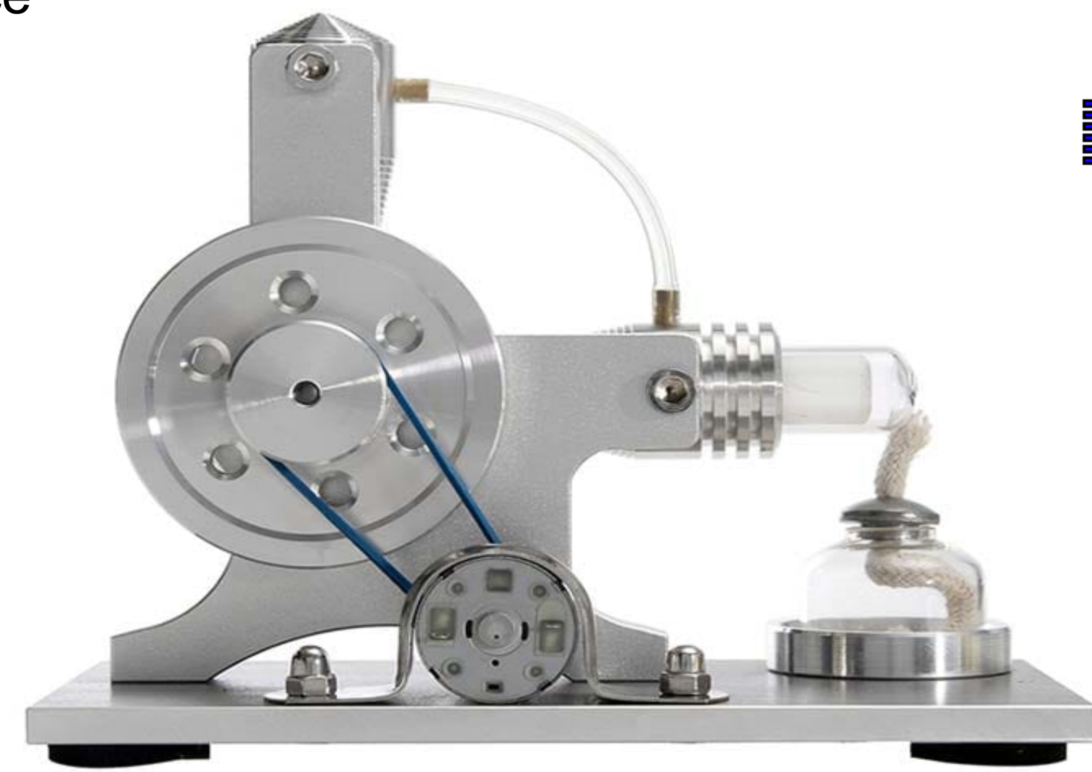
Nuclear Energy in the mix … Design Specification of NASA's Kilopower Reactor

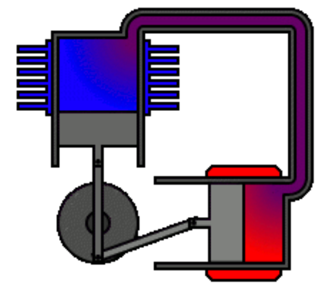
Title	Description
Reactor Type	Stirling Engine
Fuel	Uranium 235
Fuel State	Solid – Cast Cylinder
Primary Control Method	Boron Carbide Control Rod
Neutron Reflector	Beryllium Oxideradial Reflector
Primary Coolant	Sodium Heat Pipes
Power (Thermal)	4.3- 43.3 kW
Power (Electric)	1.0 – 10.0 kW

- This design has opportunity to promote the commercial market development of small-distributed power generators for use by individual customers, micro and nano grids. The constant energy source is available 24/7 for a about a decade (lifetime core).
- A spent unit is exchanged. Specialist workshops perform maintenance.

Nuclear Energy in the mix …
The Stirling engine

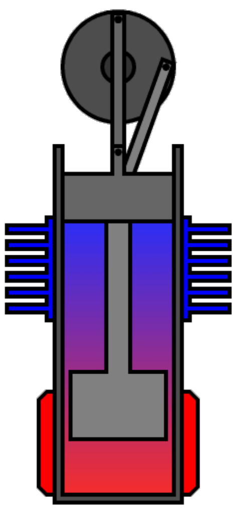
- Conversion of heat to kinetic energy via the cyclic expansion and compression of a working fluid due a regional temperature difference

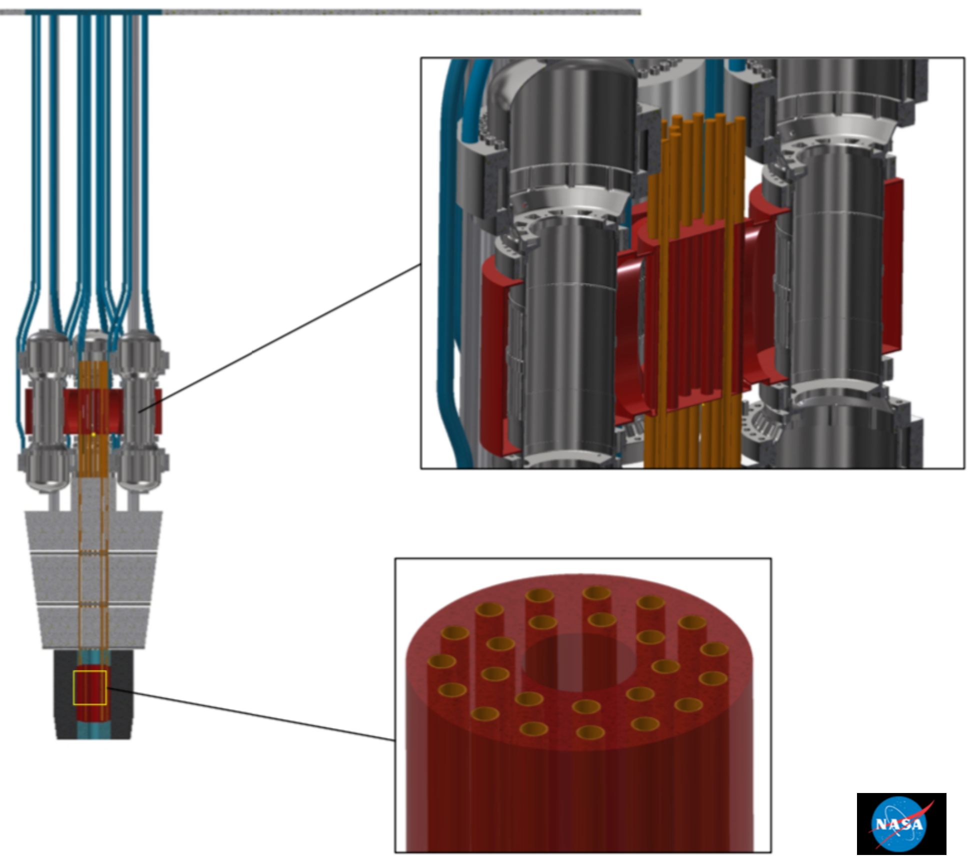




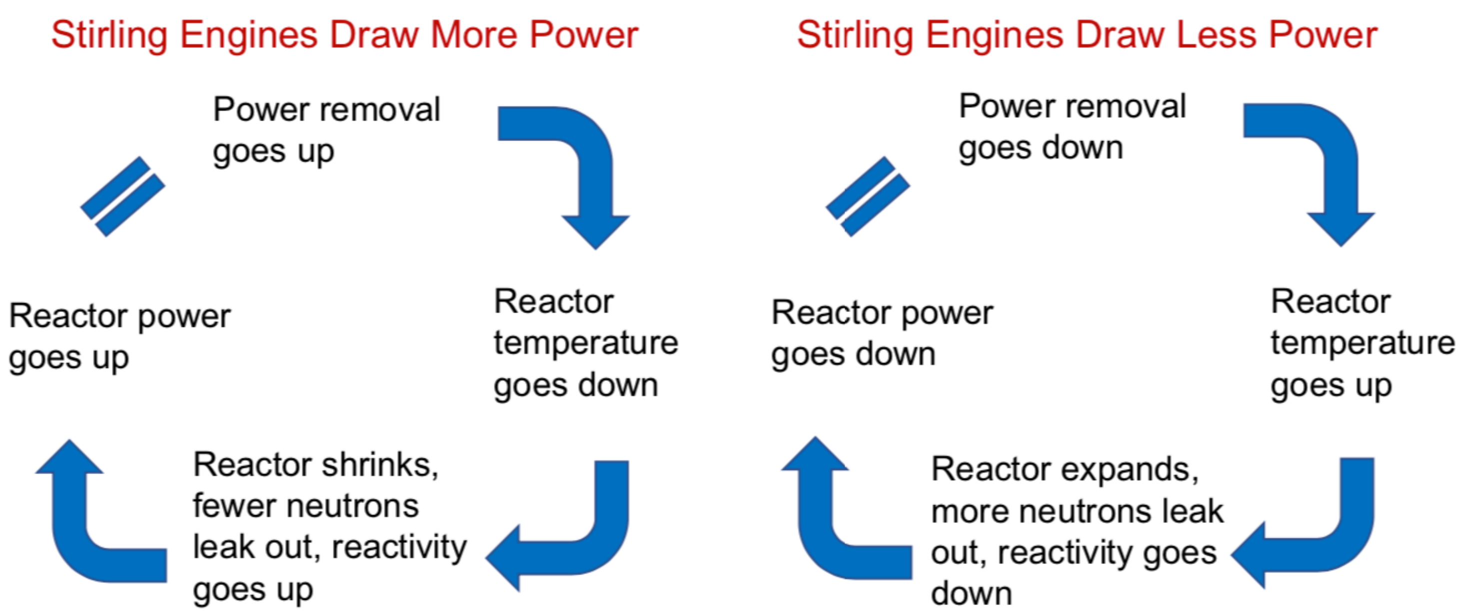
WIKIPEDIA
The Free Encyclopedia

Nuclear Energy in the mix …
Understanding Krusty

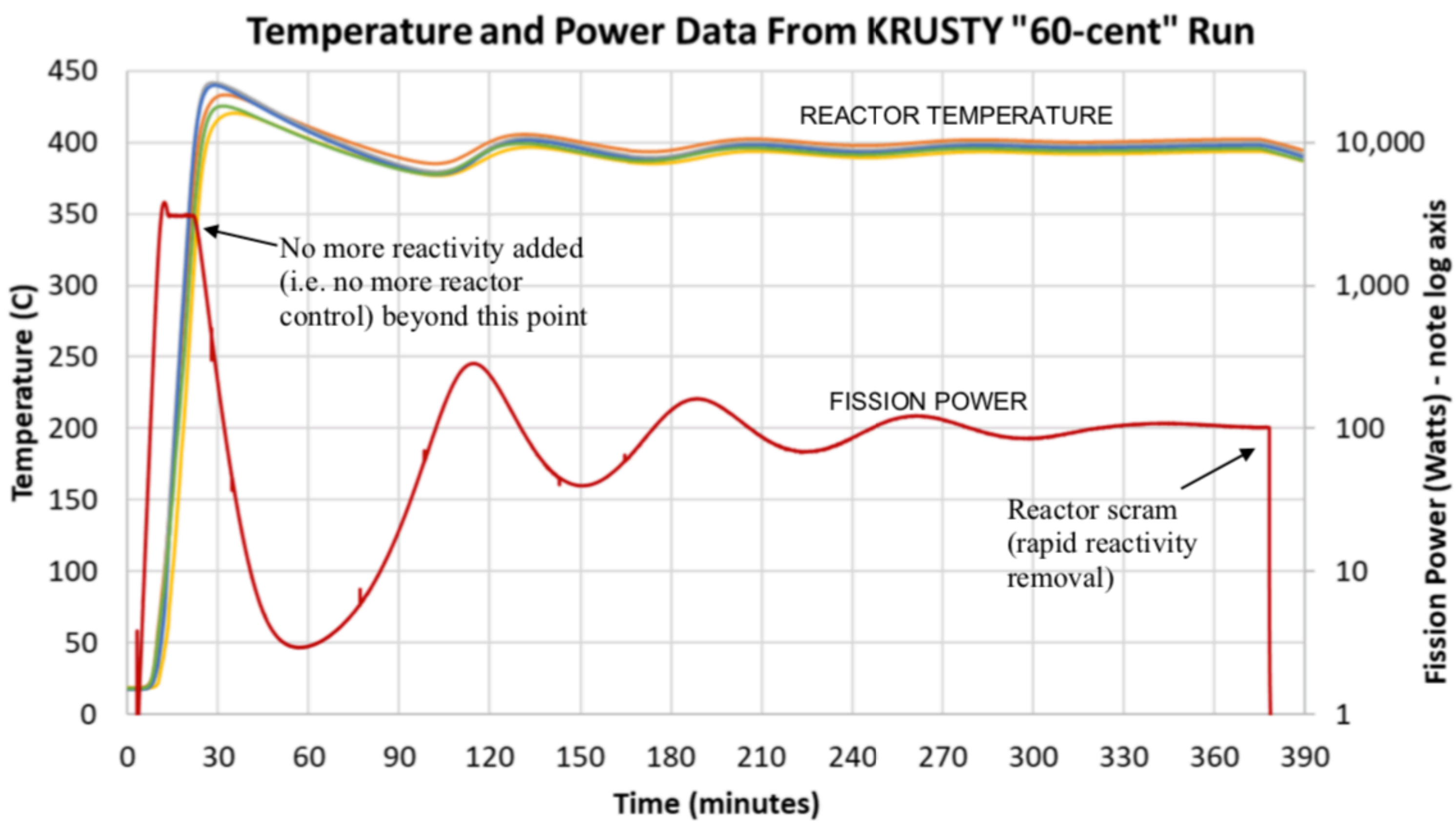




Nuclear Energy in the mix …
Krusty – Intrinsic safety and stability



Nuclear Energy in the mix …
Krusty – Warm Criticals test



Nuclear Energy in the mix …
Lrusty – Full Power test

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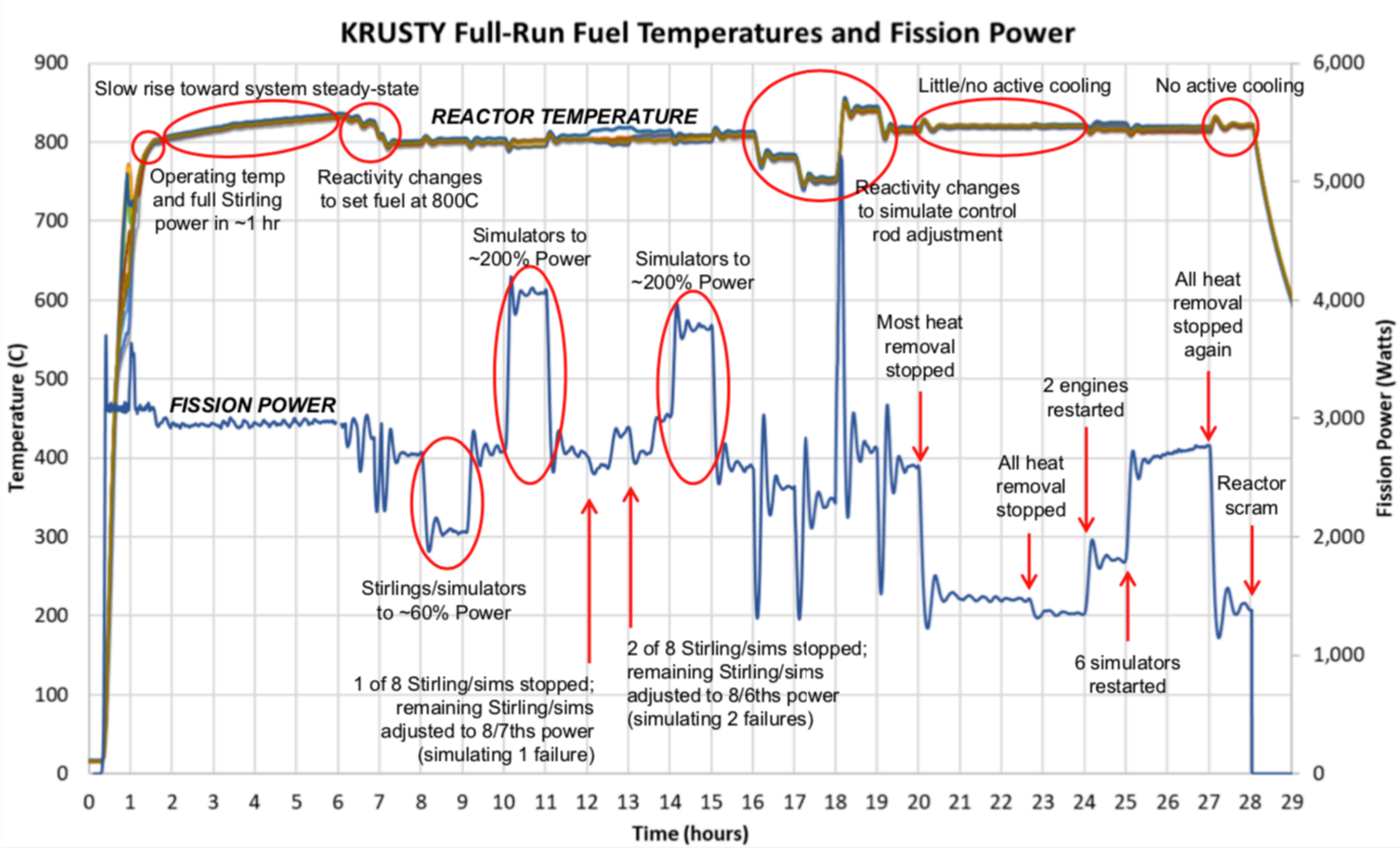

Nuclear Energy in the mix …
Kilopower Safety discussion

- Safety discussion
  – Proliferation, - Meltdown, - Waste

Nuclear Energy in the mix …
Kilopower conclusions

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- Nuclear energy can deliver continuous electricity supply for about a decade.
- Passive heat transfer using pipes filled with liquid sodium holds the key to making small amounts of electricity for use in stand-alone applications or for nano and micro grid distribution.
- The stand-alone applications could be a simple domestic installation or a mission critical installation.
- The nuclear powered solution is available in laboratory.
- The migration of the technology to the commercial markets will occur in the next decade.
- Possibly accelerated by global warming and climate change.
- Economics and criticality of application will determine the pace of commercialization.

Nuclear Energy in the mix …
Process Heat Applications
Climate Control and Terraforming

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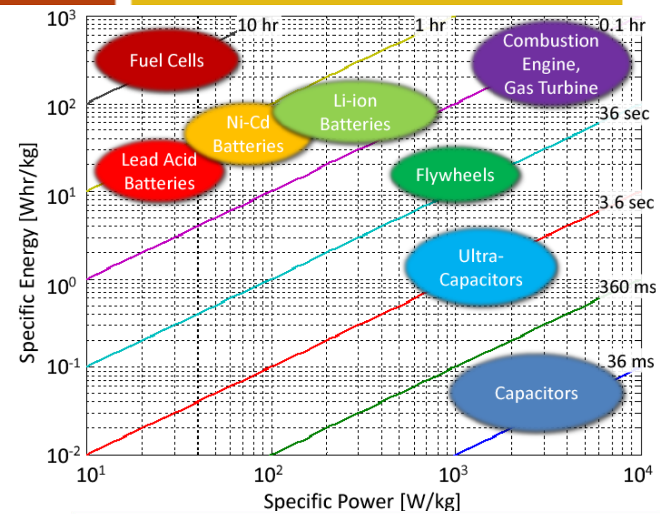
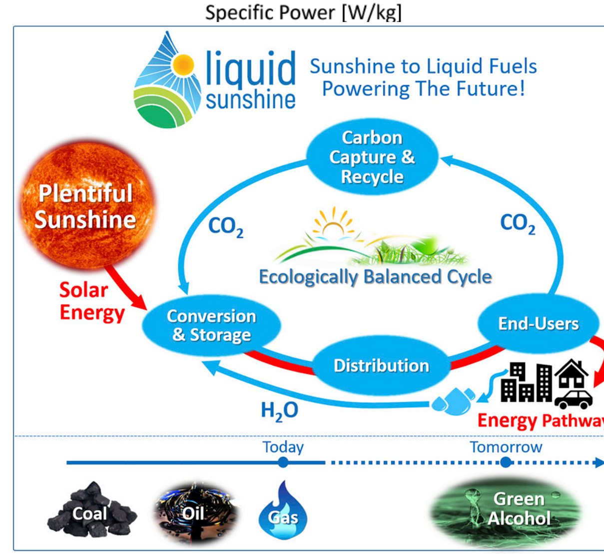
- Desalination
  - Use waste heat
- Hydrogen Economy
  - High temperature chemistry
  - Water splitting
  - Recover H
  - Fuel cell technology

  https://ecal.berkeley.edu/pubs/VPPC10-MEx99-FINAL.pdf
- Liquid synthetic fuel energy carrier
  - CO_2 sequestration for C
  - Water for H
  - Produce hydrocarbons

  https://doi.org/10.1016/j.joule.2018.08.016





Nuclear Energy in the mix …
The Water Grid

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Analogy:

- Electrical Grid

- Water Grid

If you have enough energy, you also have enough water

Nuclear Energy in the mix …

Yes … a sustainable and viable Africa

Thank you