Nuclear Energy - if you love your planet

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

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Slide Credits

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- Prof Naidoo (UJ)
- Prof Nicholl (UJ)
- Prof Mulaba (UJ)
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- Dr Bvumbi (NRWDI)
- Dr Maqabuka (IJ)
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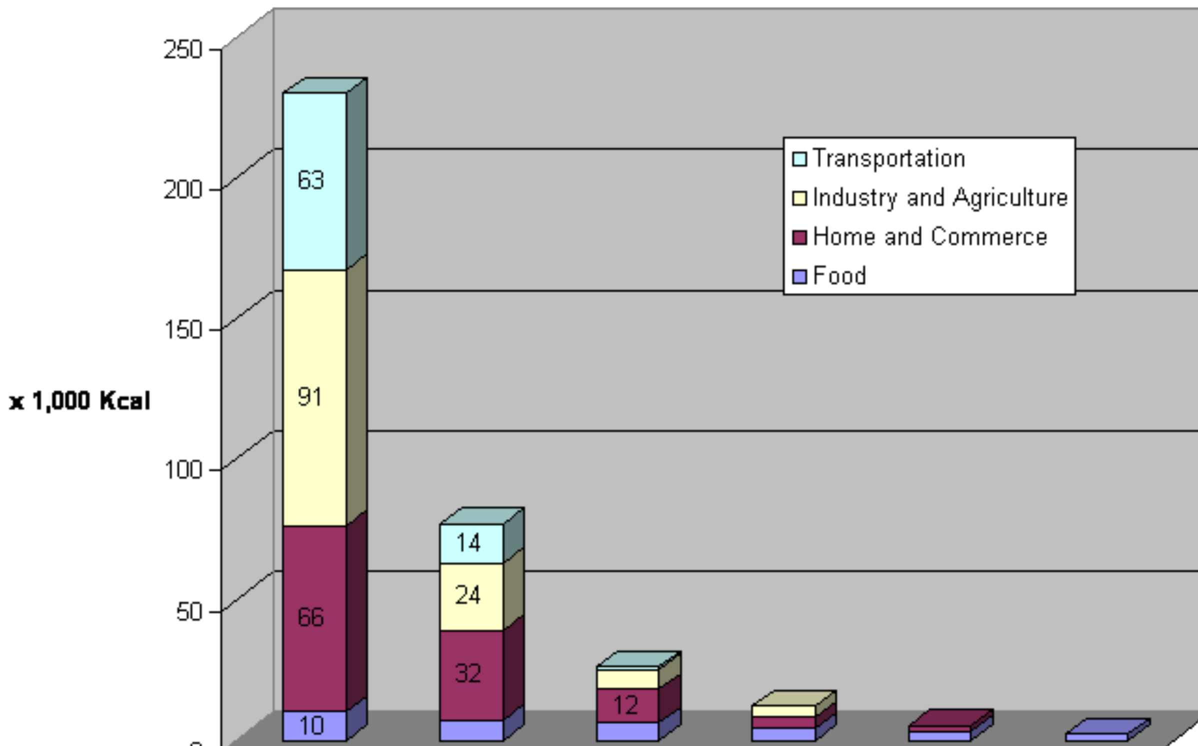
How much energy do we need ?

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”
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

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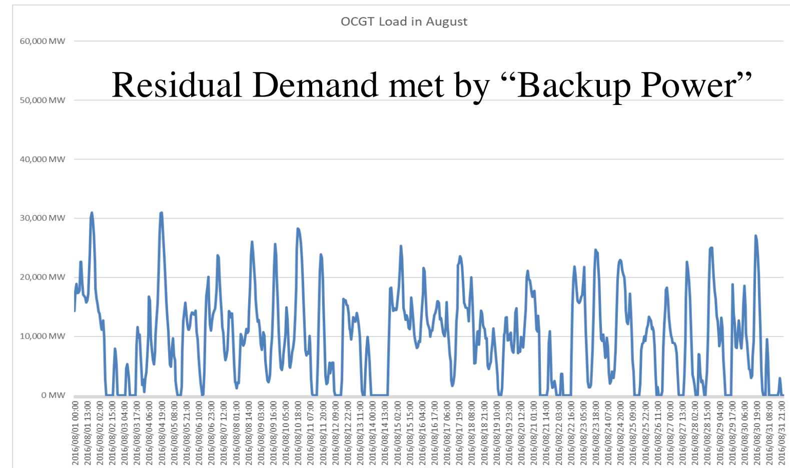
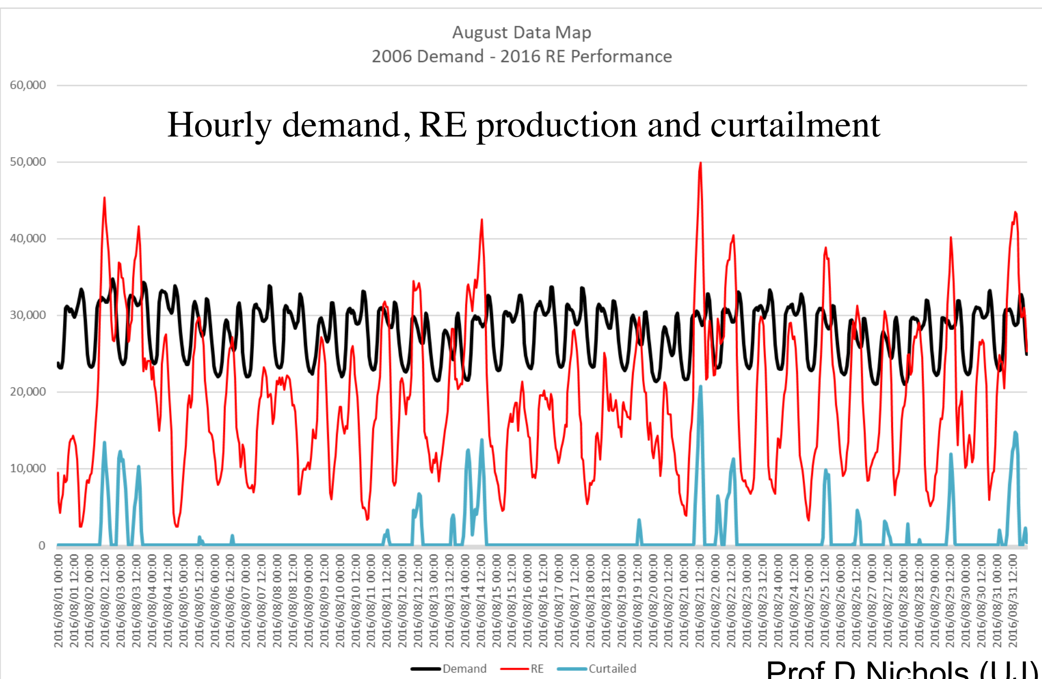
South African model using actual Wind & PV August 2016 profiles (scaled to 45,000MW of wind and 15,000MW of PV) to meet August 2006 demand





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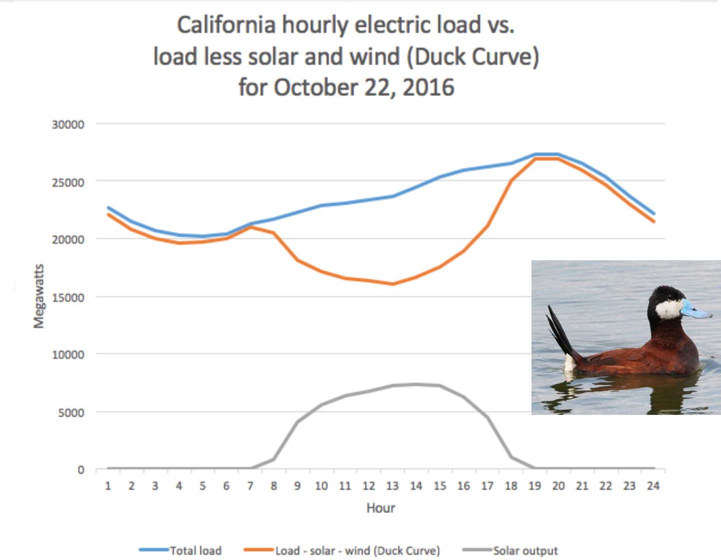

Setting the stage
New beliefs ….
Origins in certain factors

- **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.

Prof D Nichols (UJ)

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 ….

- 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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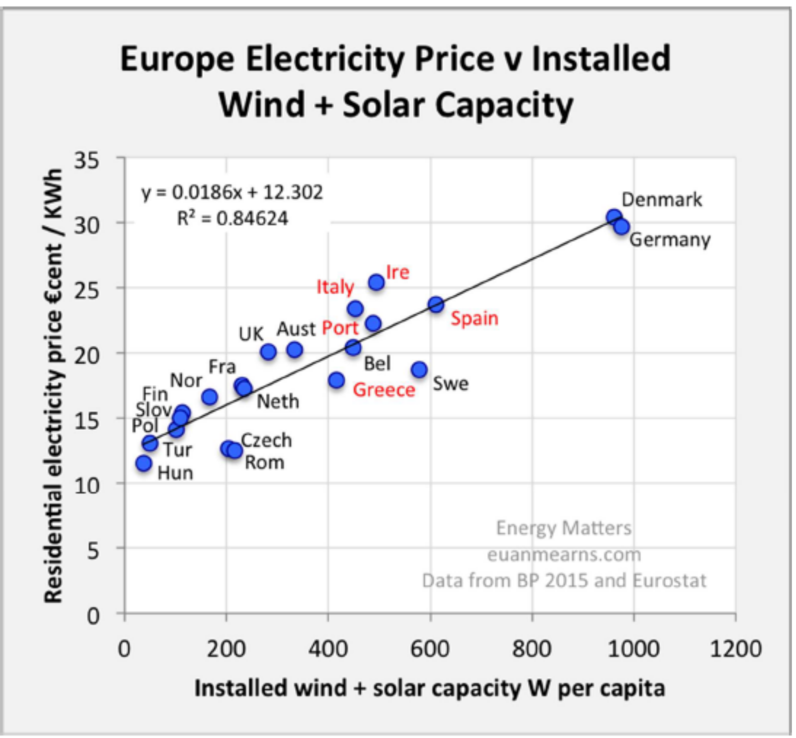
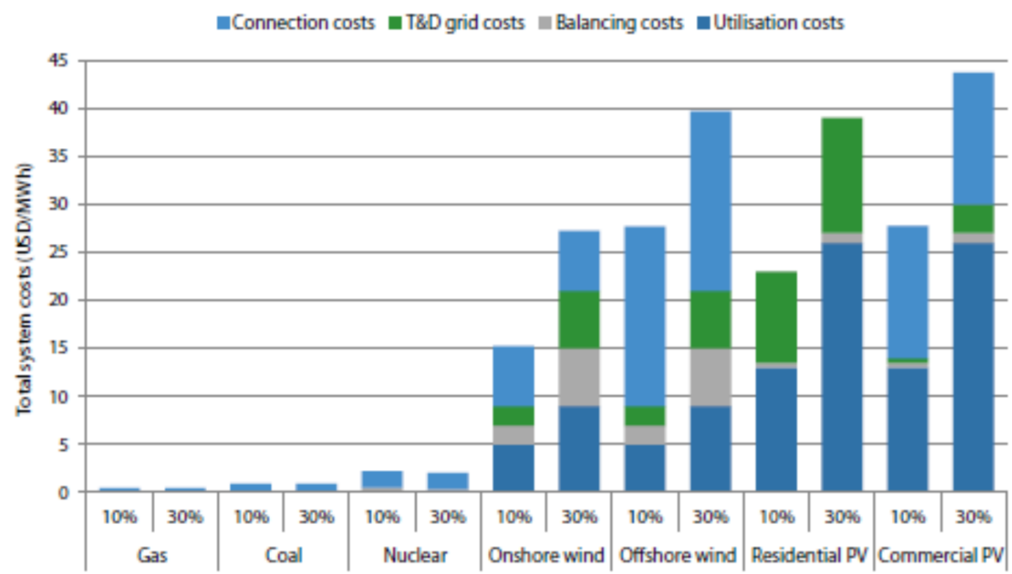


Figure ES.3: **Grid-level system costs of selected generation technologies for shares of 10% and 30% of VRE generation**



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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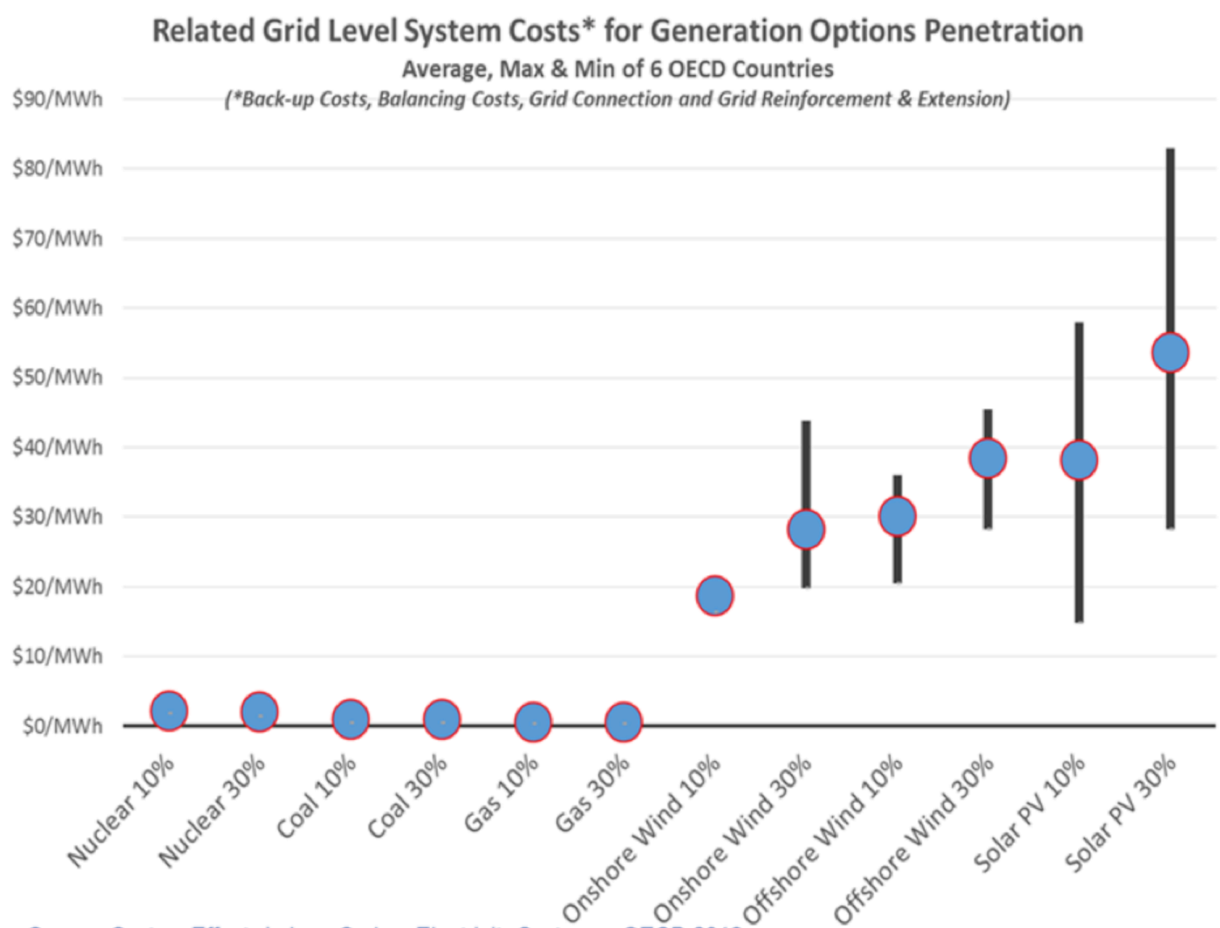
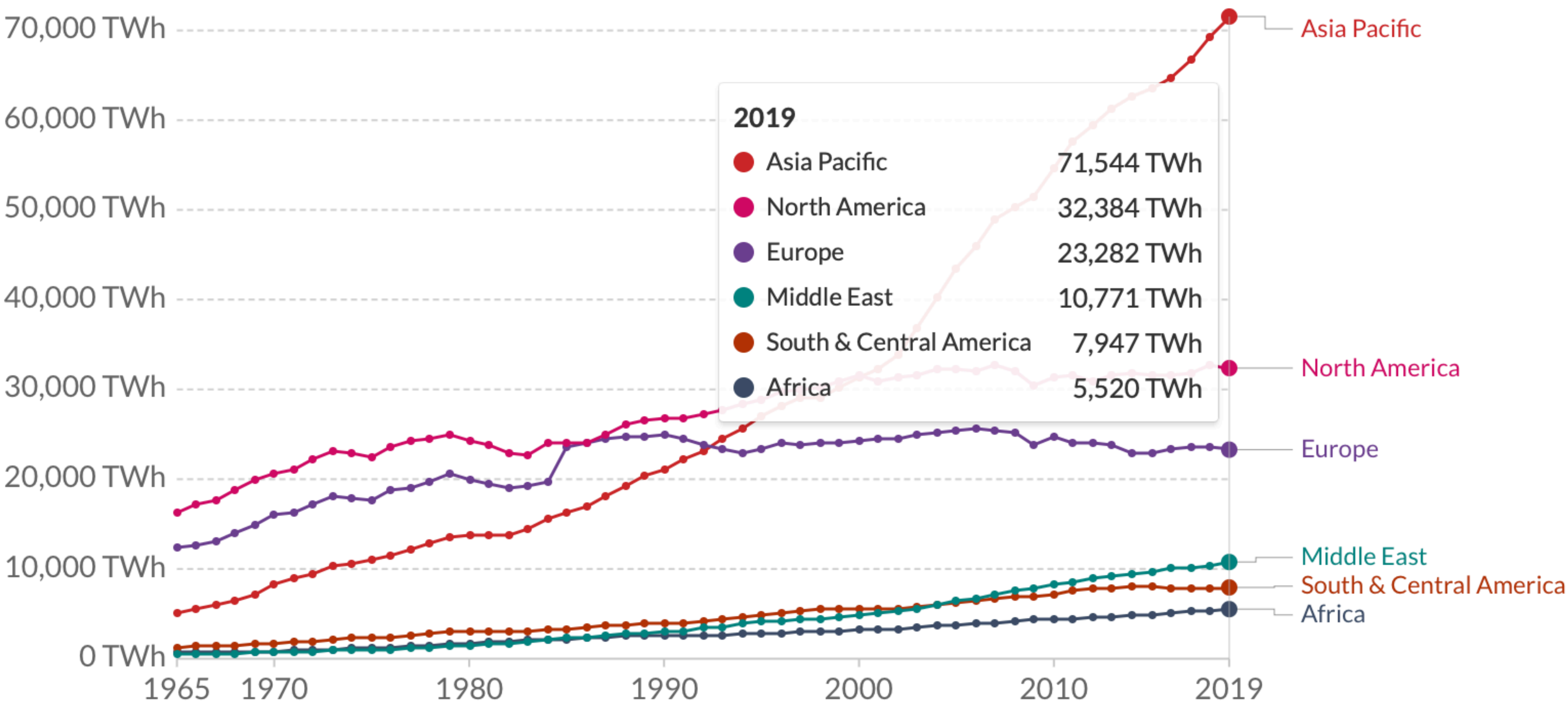


Source: System Effects in Low-Carbon Electricity Systems - OECD 2012

Also add 100% Backup / Storage and shorter lifetime

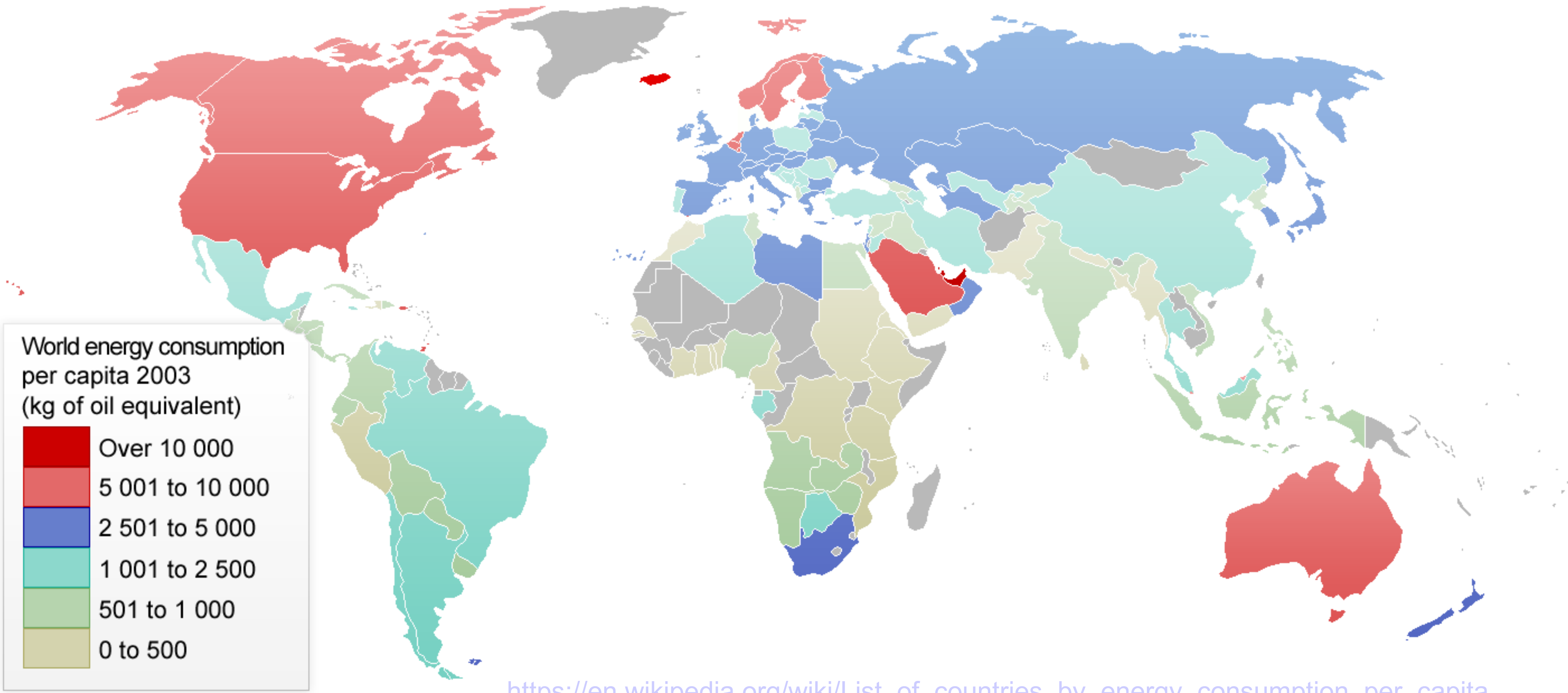
Prof A Cilliers UNW

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

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

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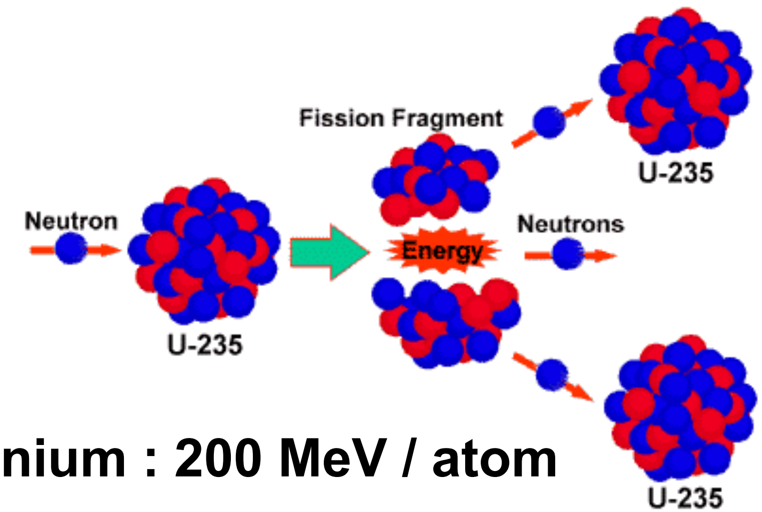
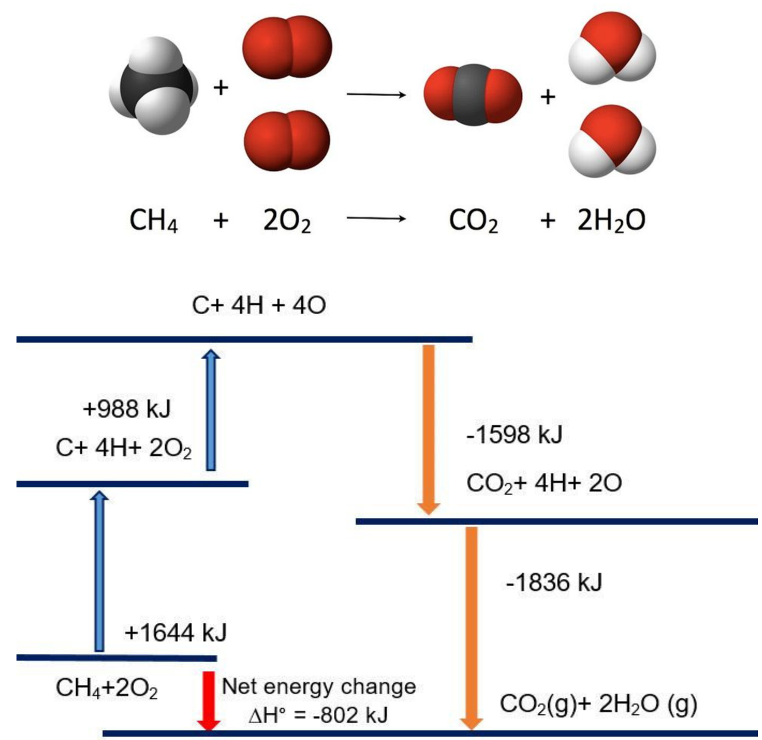


Uranium : 200 MeV / atom

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

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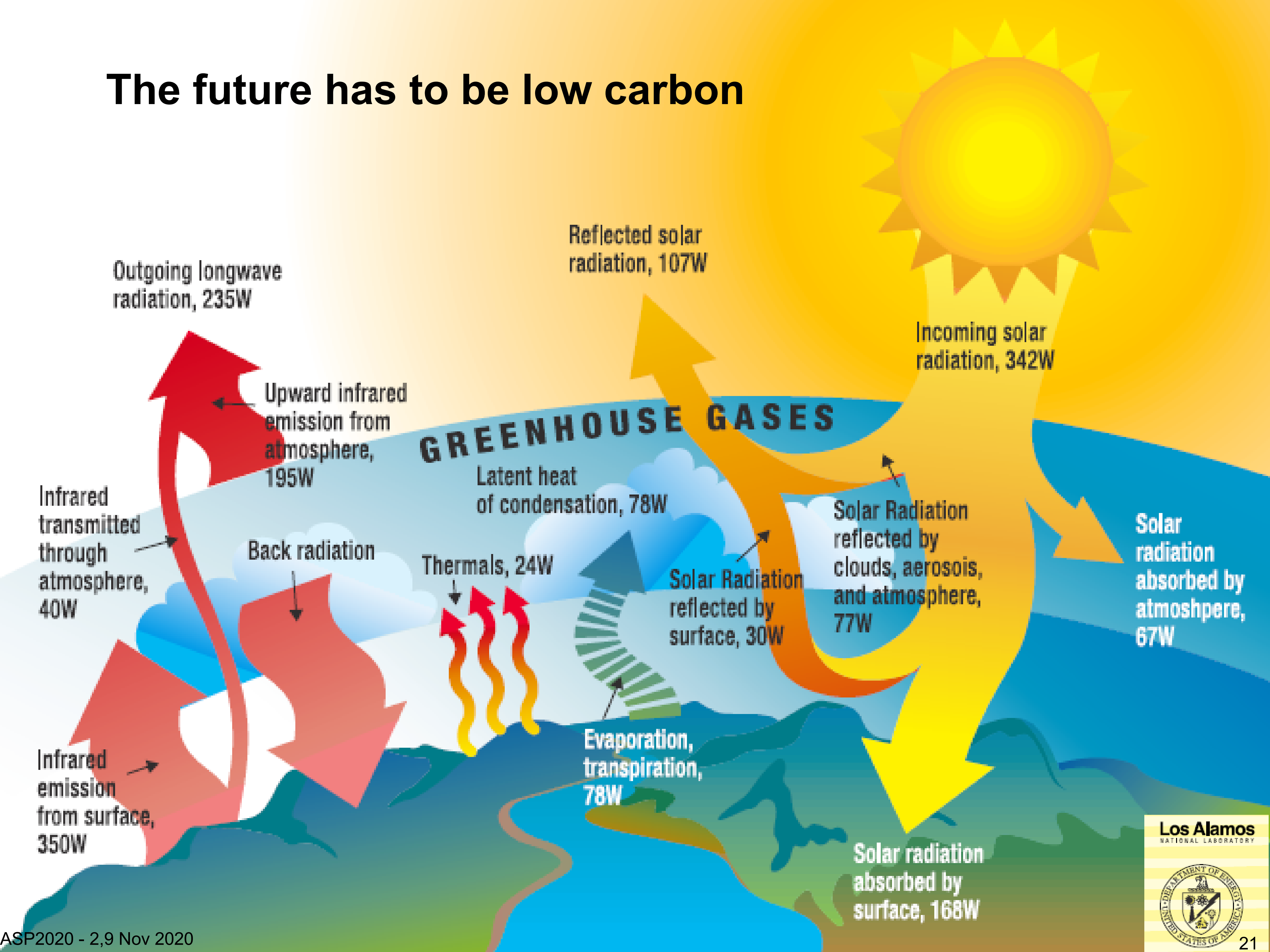
- Coal has
  ~ 1 ppm U and ~3 ppm Th.
- Uranium released into the atmosphere from 1 GW coal fired power station, **25 000 tons / year.**
- **1GW power station**
  - **100** times less activity release.

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

The future has to be low carbon



Low Carbon Modalities

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/km^2

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

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
eia 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

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- **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

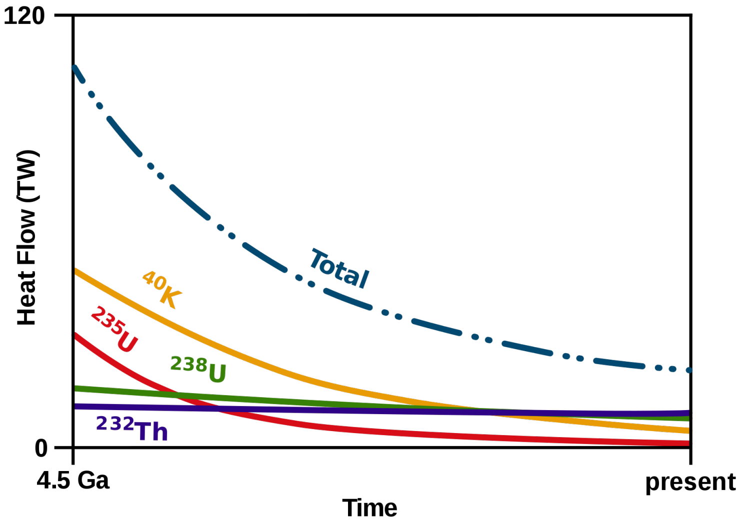
- Nuclear Energy is a 100 year stop-gap
- It is proven safe in a catastrophe and is being further improved
- After 100 years a new technology will emerge

Some nuclear reactors

A natural one
Oklo on Gabon, Africa

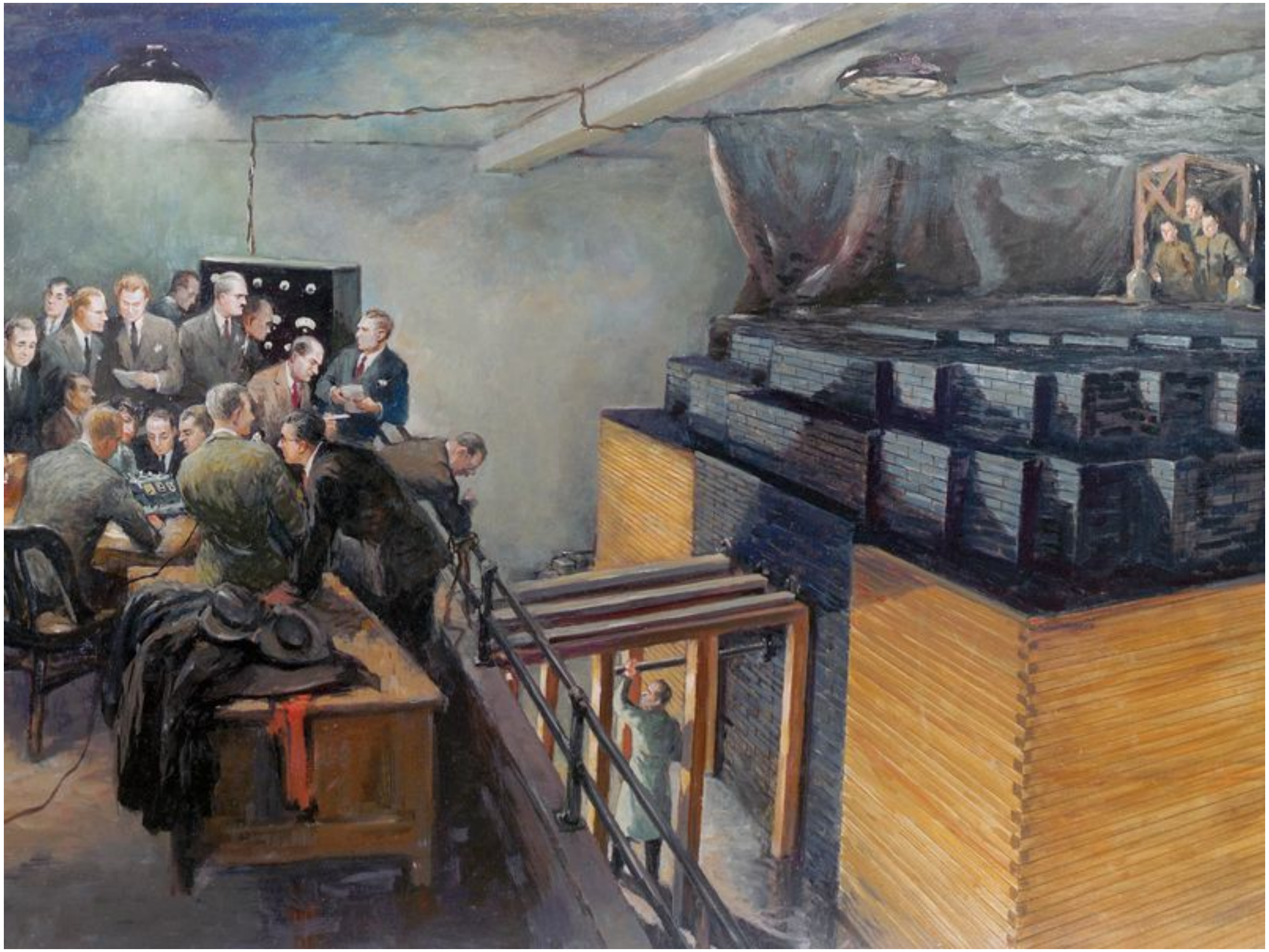
2 billion years ago, intermittent fission for 500 000 years.
Large ore body (50-70% U-oxide, 3% enrichment)
An opportunity to study radio-nuclide transport.

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



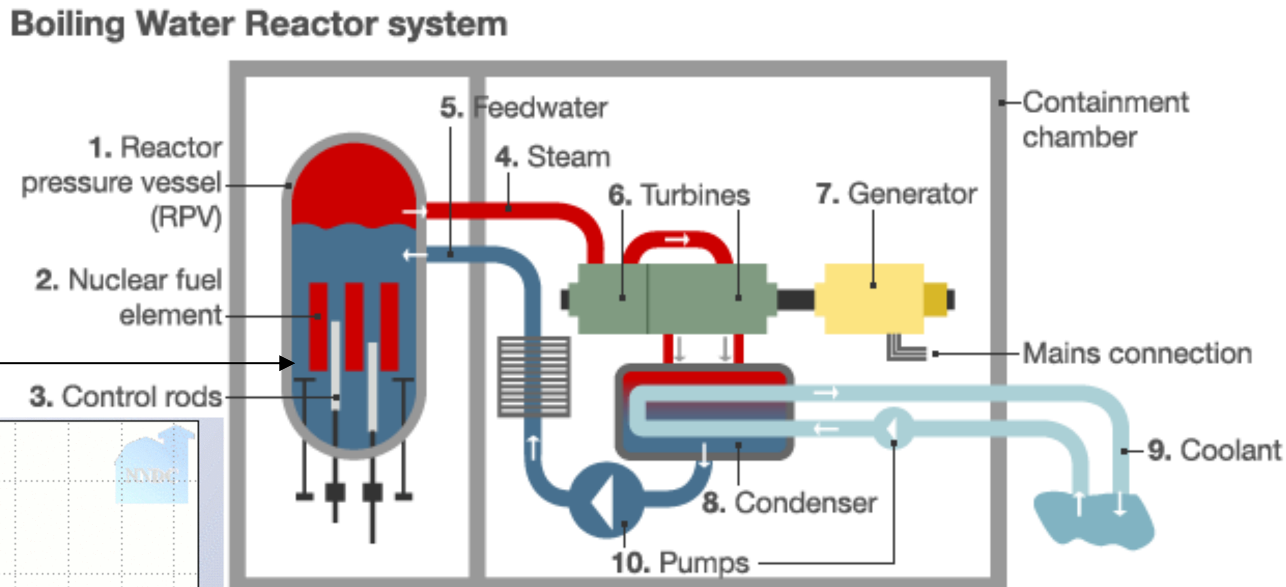
Some nuclear reactors

The first human-made one – 16 Nov 1942
In the University of Chicago’s squash court – Enrico Fermi observing …

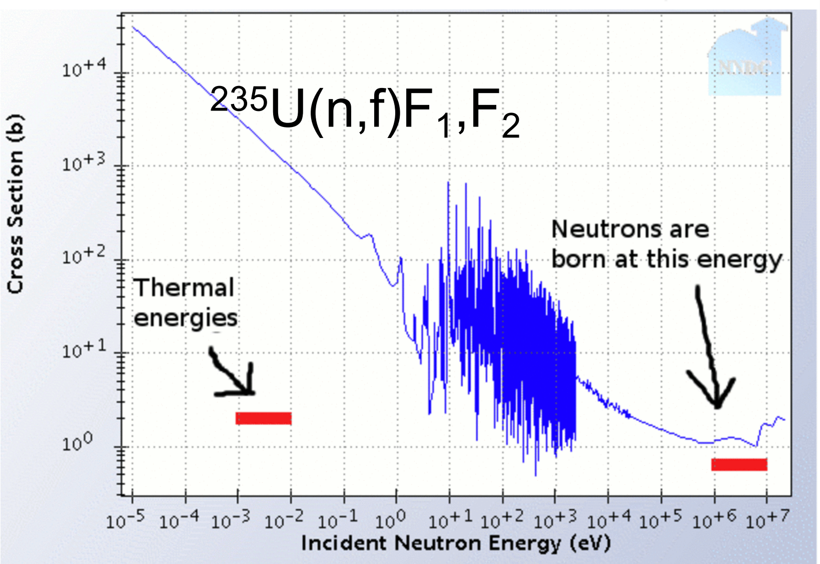


Some nuclear reactors

Typical Boiling Water Reactor (BWR)

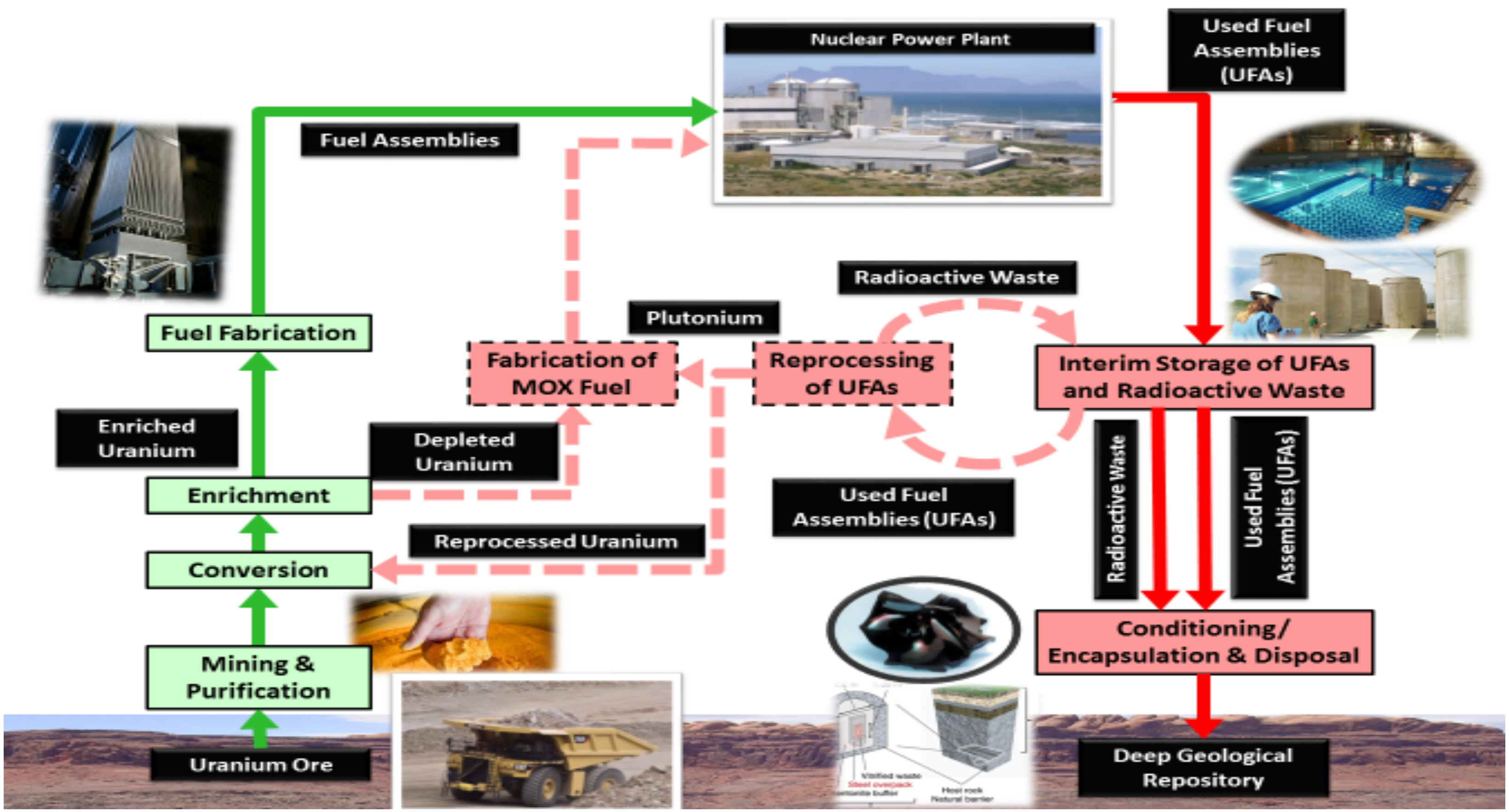


Moderator
slow down n



Nuclear Fuel Cycle

1 GW * 1 yr → 1000kg



Nuclear Fuel Cycle

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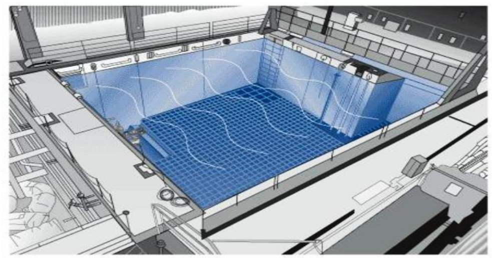
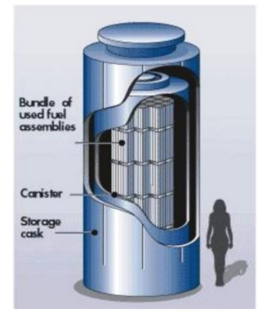
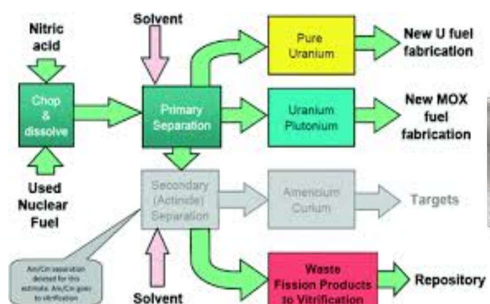
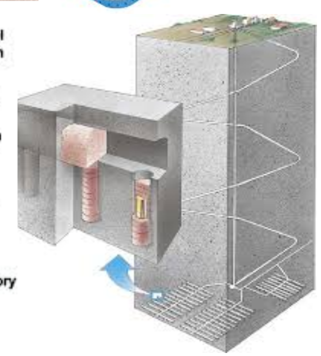
Spent fuel management (SFM) involves

- **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.









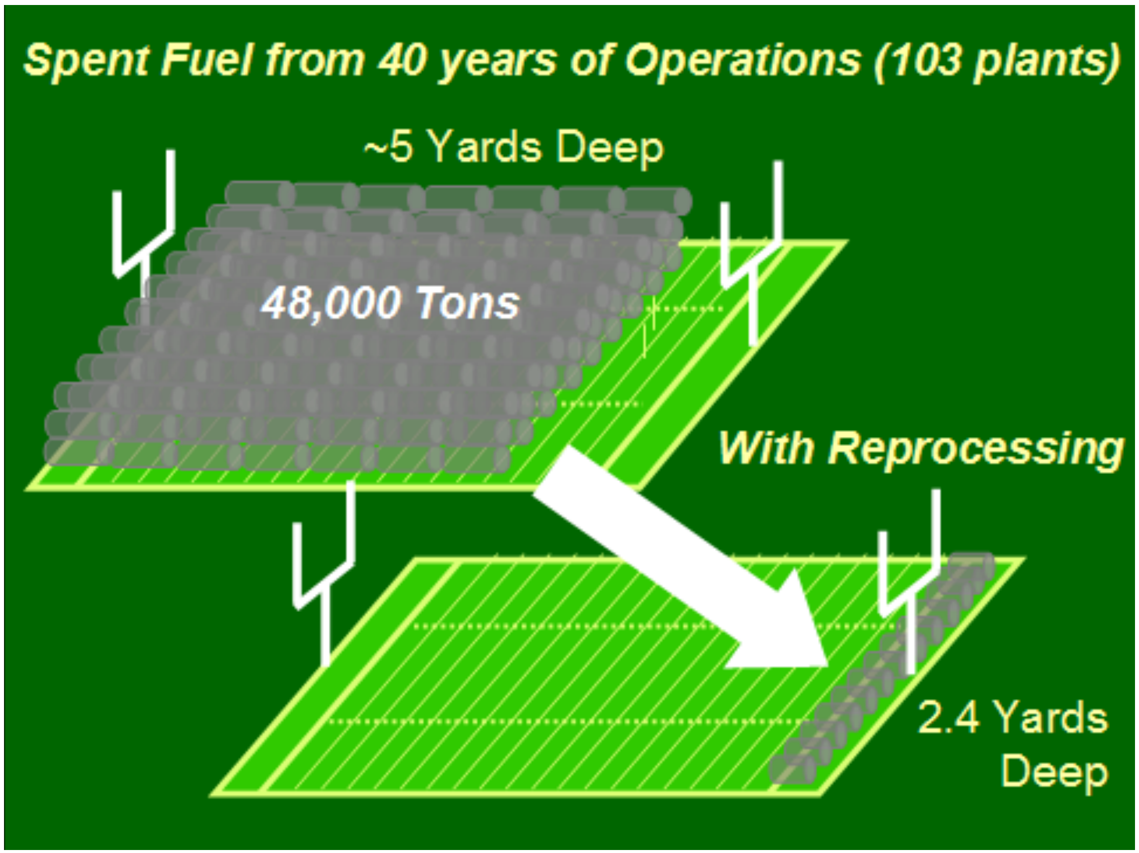
Different strategies or options for SFM are being pursued by different countries:

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

Some countries are implementing combinations of those strategies.

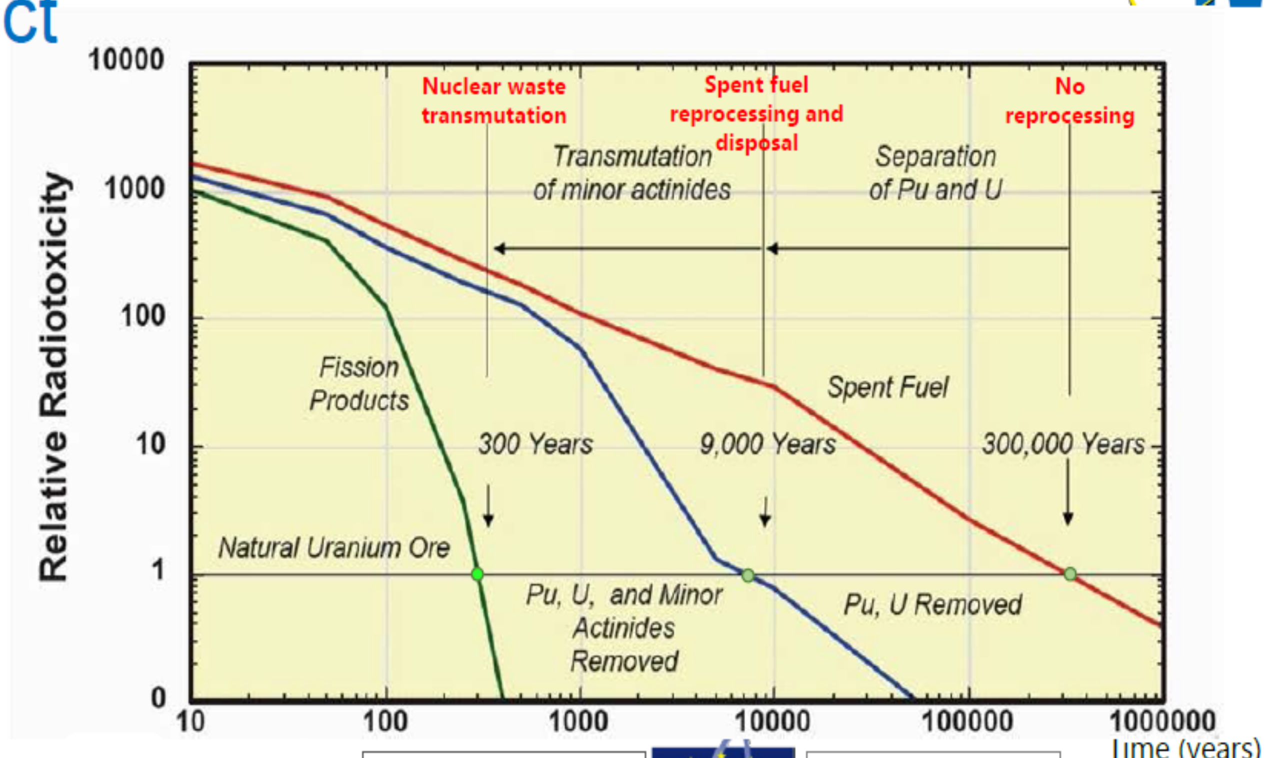
SPENT FUEL CONTAINS VERY LONG-LIVED RADIONUCLIDES, WHICH IS A CHALLENGE SOCIETALLY AND POLITICALLY

Nuclear Fuel Cycle



Nuclear Fuel Cycle

Nuclear waste: transmutation impact



Duration Reduction: 1000x

Volume Reduction: 100x

Dr S Bvumbi (NRWDI)

Nuclear Fuel Cycle
CSIF
Centralised Interim Storage Facility (SA)

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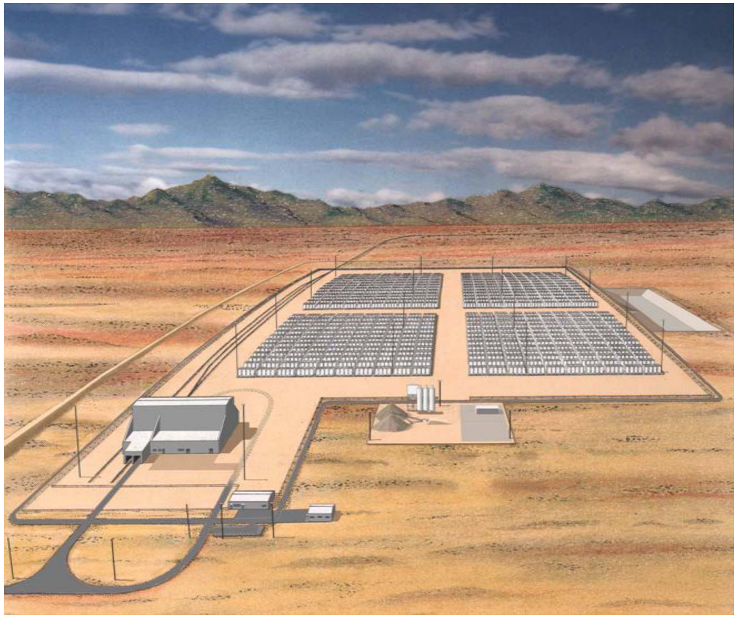
Policy Perspective and Directive

- 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.



Dr S Bvumbi (NRWDI)

Nuclear Fuel Cycle

CSIF

Centralised Interim Storage Facility (SA)

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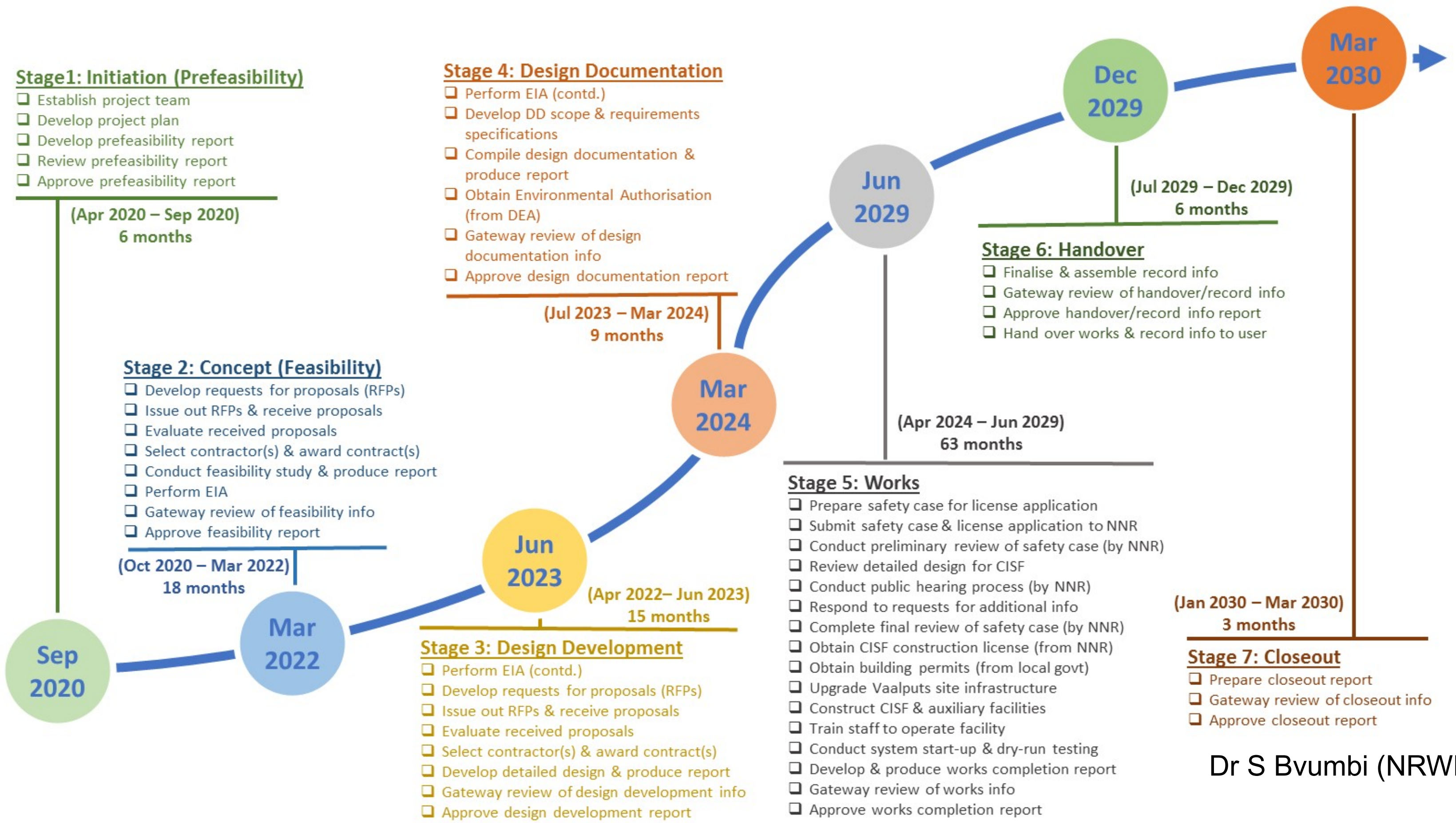


Dr S Bvumbi (NRWDI)

Nuclear Fuel Cycle

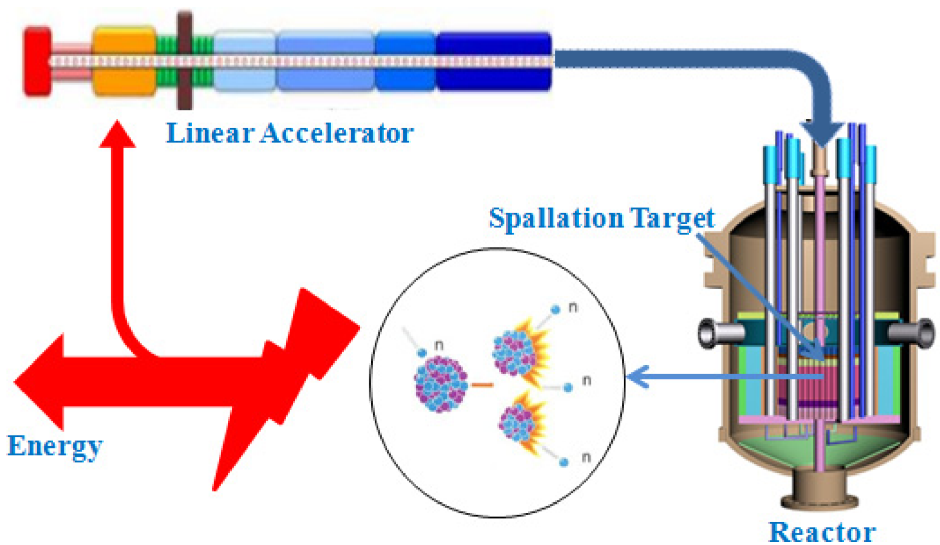
Accelerator Driven Systems

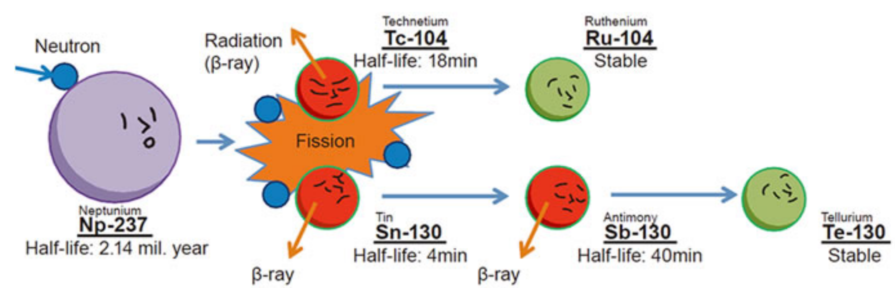
Neutron spallation
Incinerate waste

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

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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

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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