Nuclear and its Role in a Carbon Constrained World

1. What is Nuclear Energy and Who's got it?
2. Nuclear Energy as a Low Carbon Energy Source
3. Current Practice with Generation 2 and 3 Reactors

   Near future with Small Modular Reactors - NuScale
4. Dealing with Used Fuel and Gen IV reactors
5. A solution to Australia's energy security and emissions reductions

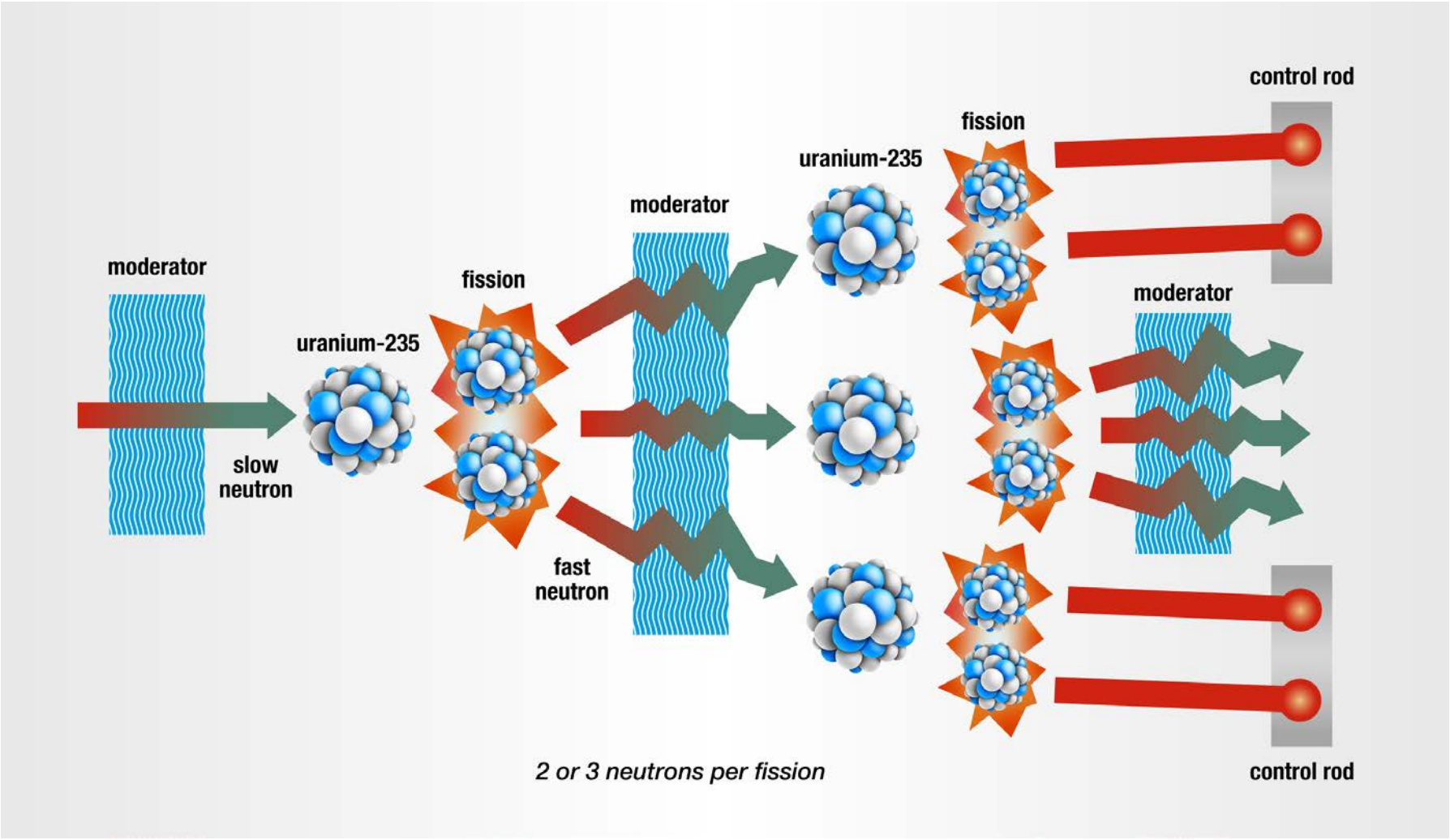
1. What is Nuclear Energy and Who's Got It?

Very high Power intensity for Nuclear Reactors

A 1000 MW(e) plant requires the following number of tonnes (t) of fuel annually:

- **2,600,000 t coal: 813 trains (3200 t each)**
- **2,000,000 t oil: 10 super tankers**
- **30 t uranium: reactor core (10 cubic metres)**

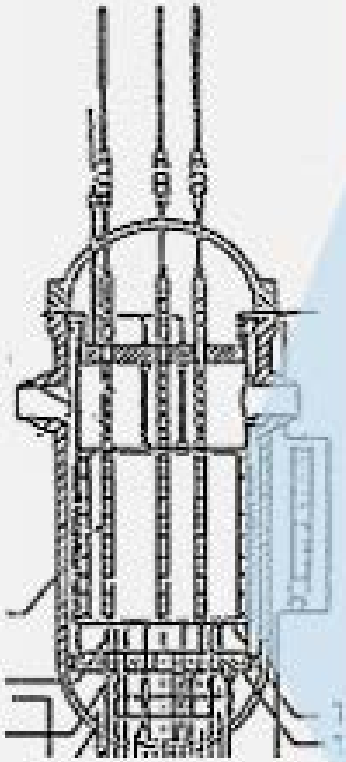
236.053 amu in → 235.867 amu out
0.186 x C^2= 172.57 MeV + 26 MeV delayed



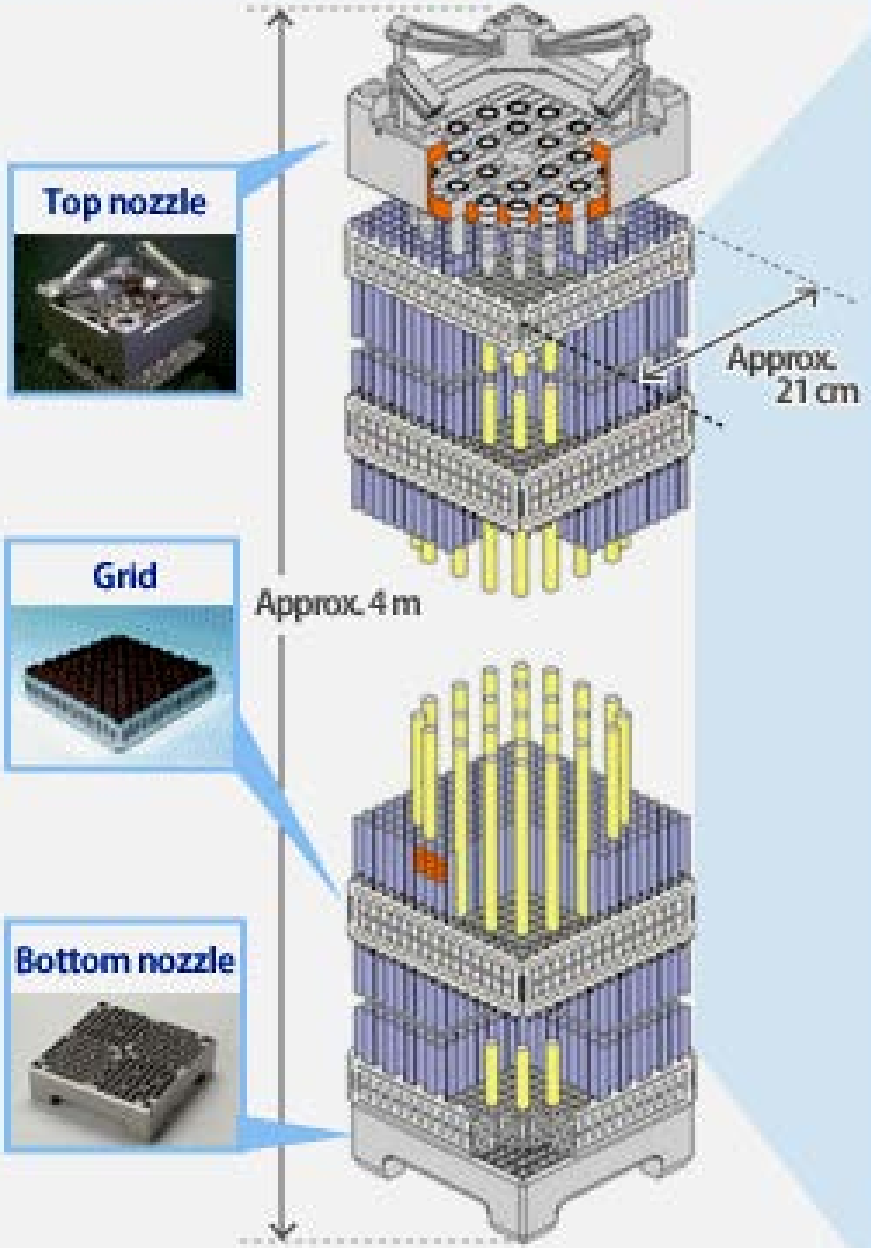
e.g. 1n+ ^{235}U→ ^{137}Cs+ ^{96}Rb+ 3neutrons

The 264 fuel rods are bundled with grids, and the fuel assembly is equipped with top and bottom nozzles. ▶

Pressurized water reactor (PWR)



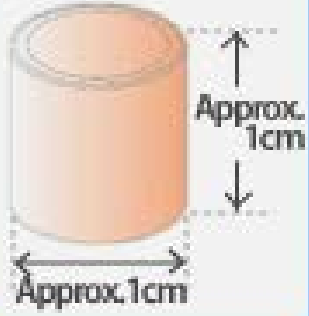
Fuel Assembly (17 x 17 type)



Fuel Rod

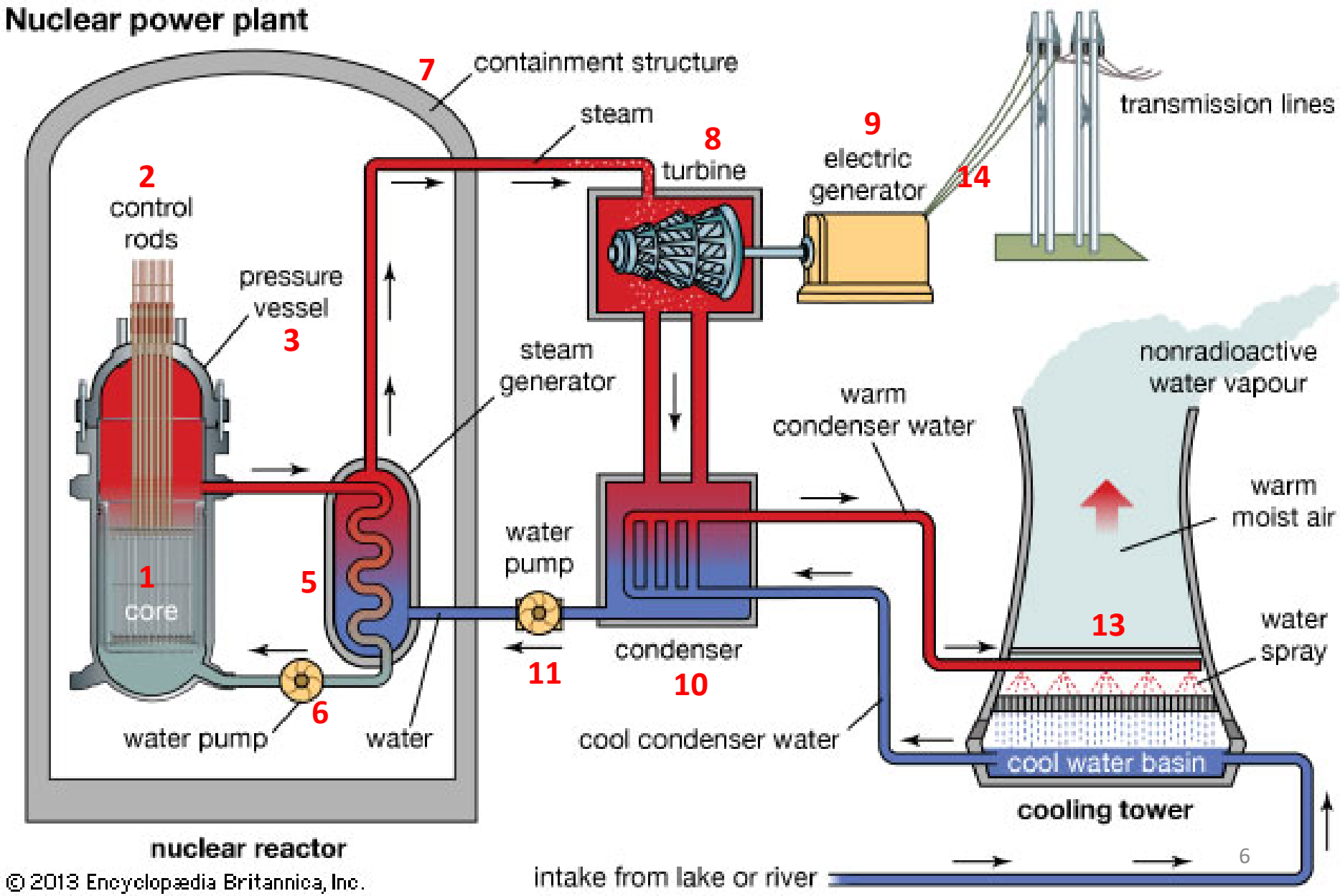
◀ A cladding tube contains about 400 pellets with both ends plugged. Those pellets are fixed with springs.

Pellet

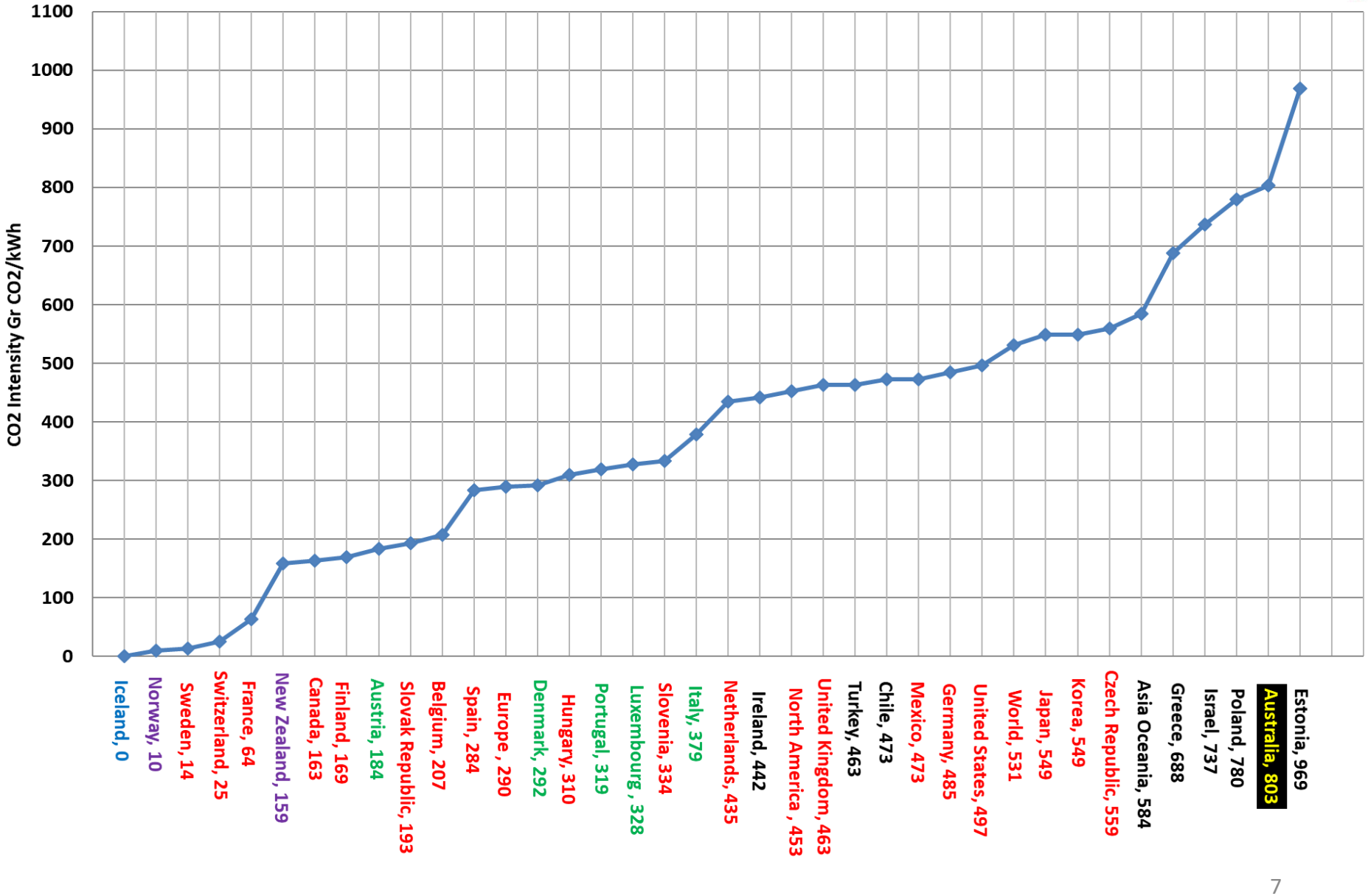


▲ Uranium powder is baked into the pellet form in a cylindrical shape. About five grams of the pellet can produce electricity that could support a normal household life for six months.

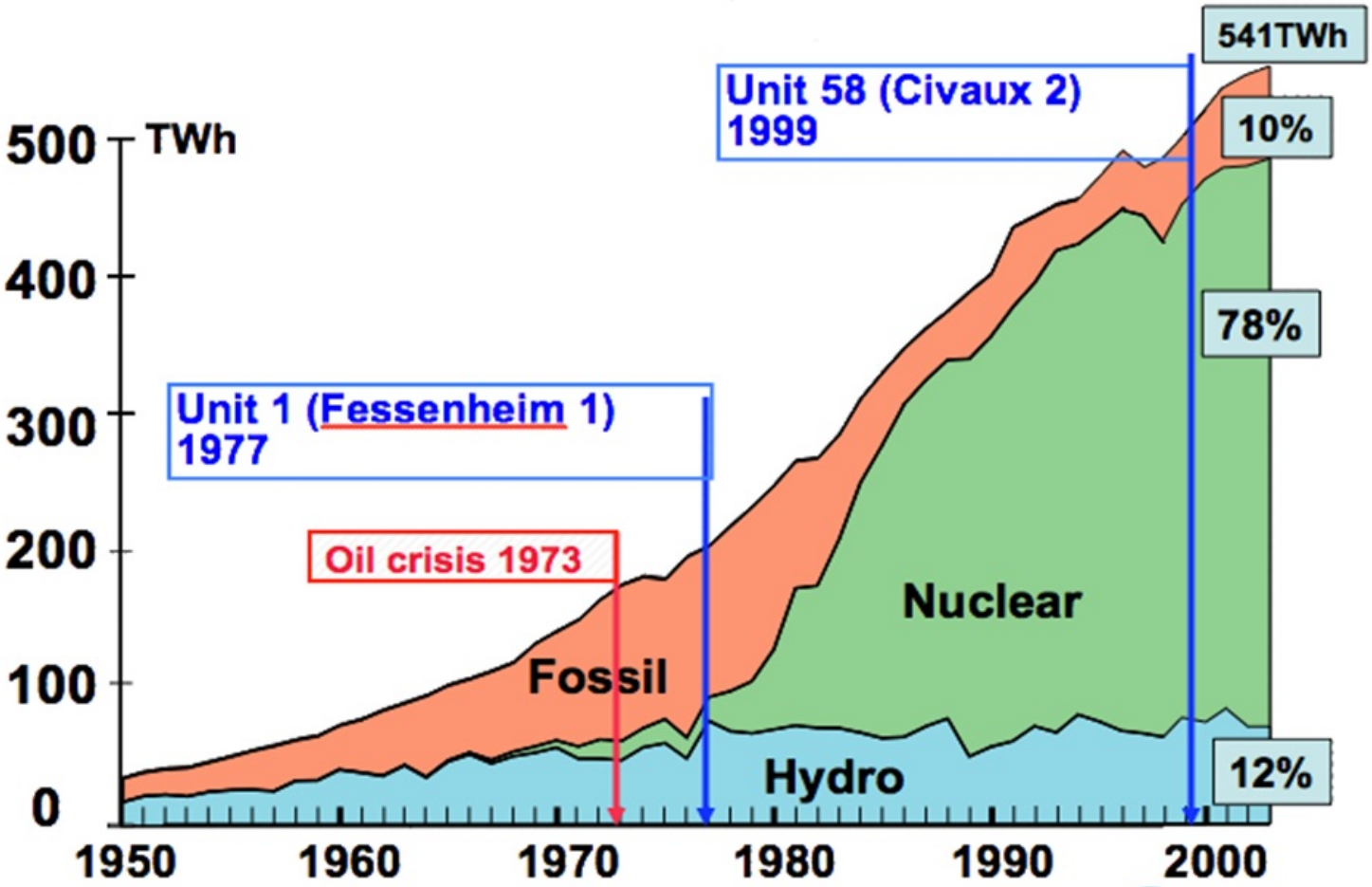
Fission Power Reactor - PWR



CO2 Intensity of Electricity Production OECD 2011 to 2013

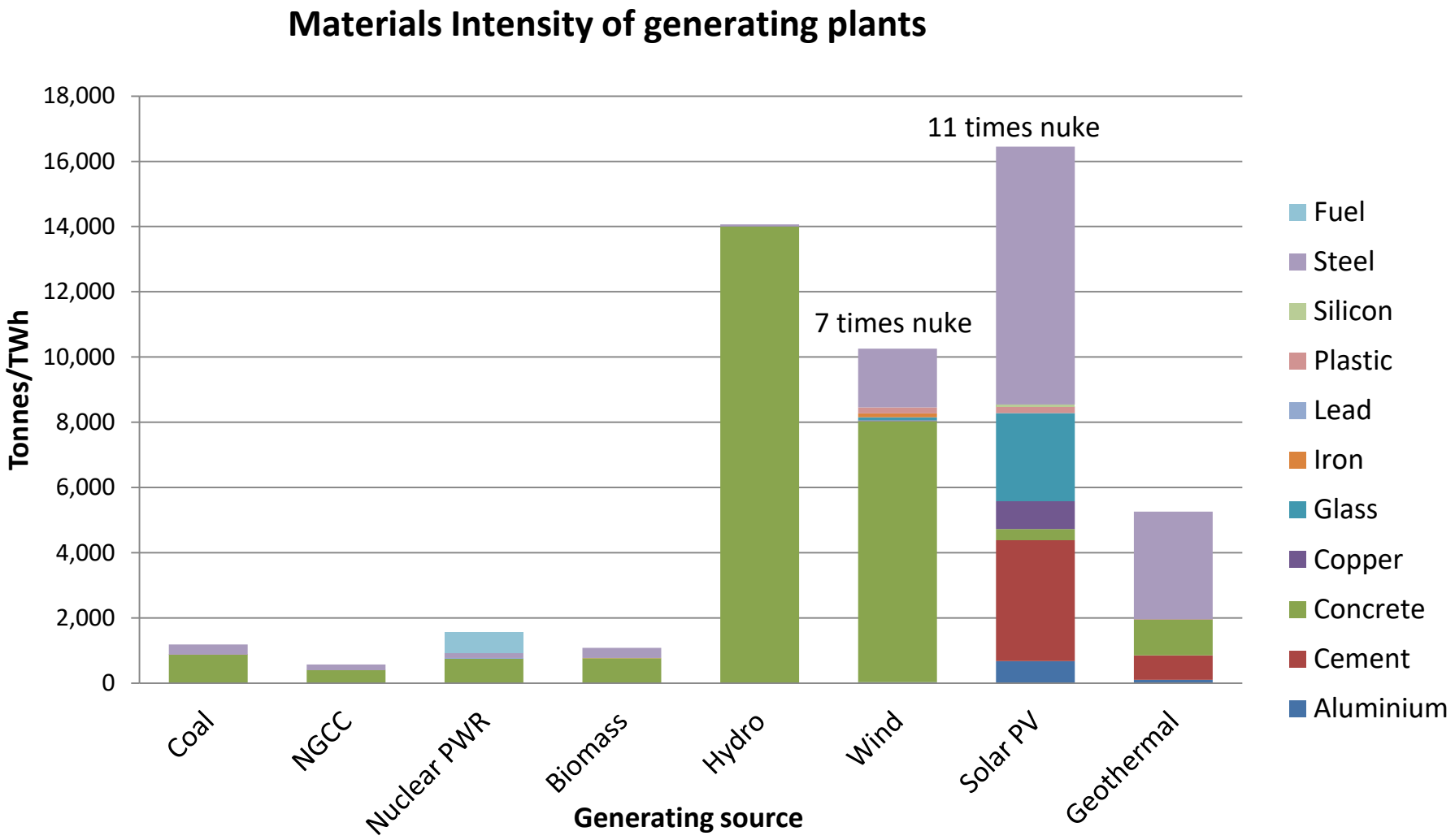


French nuclear programme.
58 nuclear power plants in 22 years



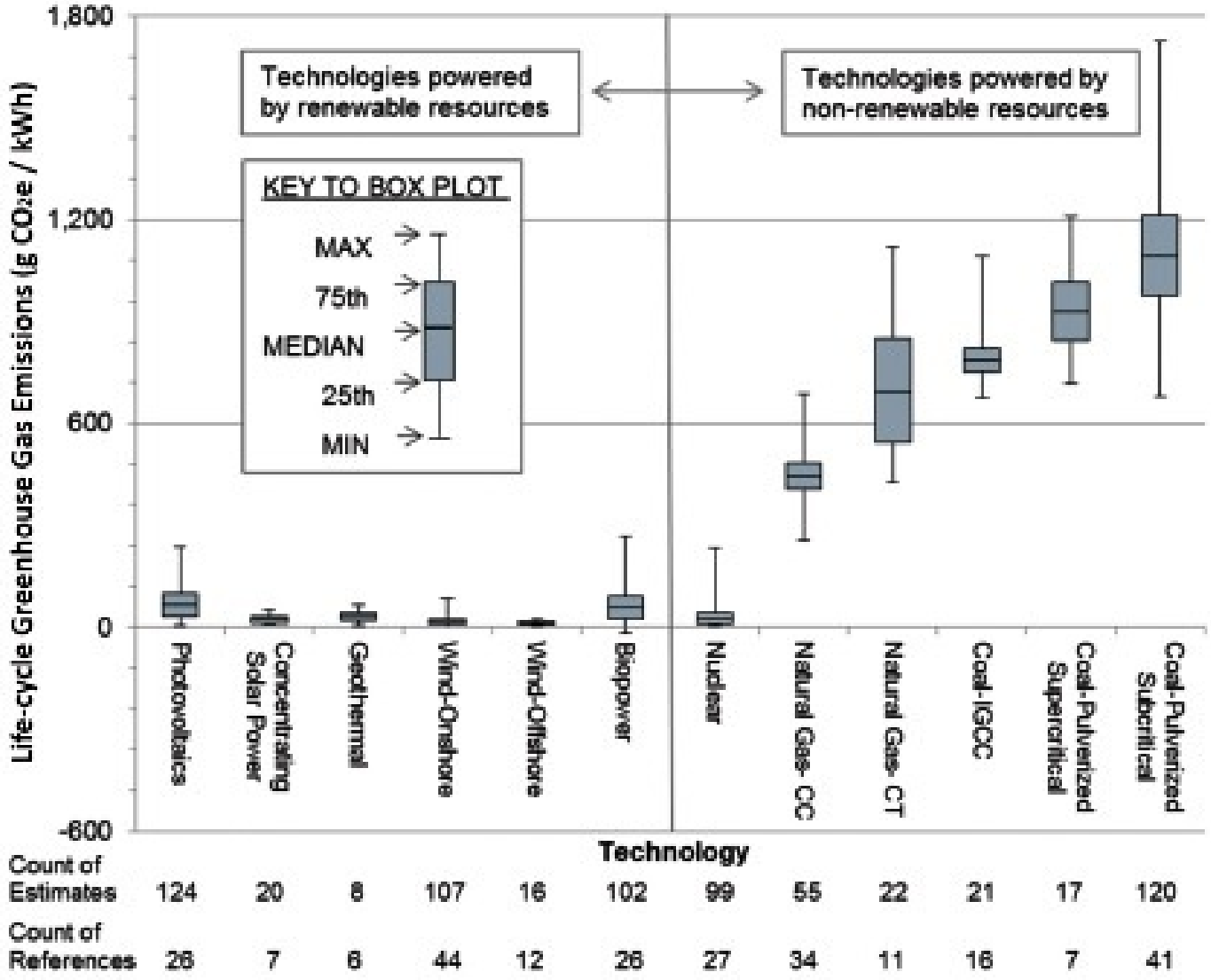
2. Nuclear Energy as a Low Carbon Electricity Source

What does renewable really mean?



Data from IAEA 2010
Electricity generation and health
Anil Markandya, Paul Wilkinson, Lancet 2007; 370: 979–90

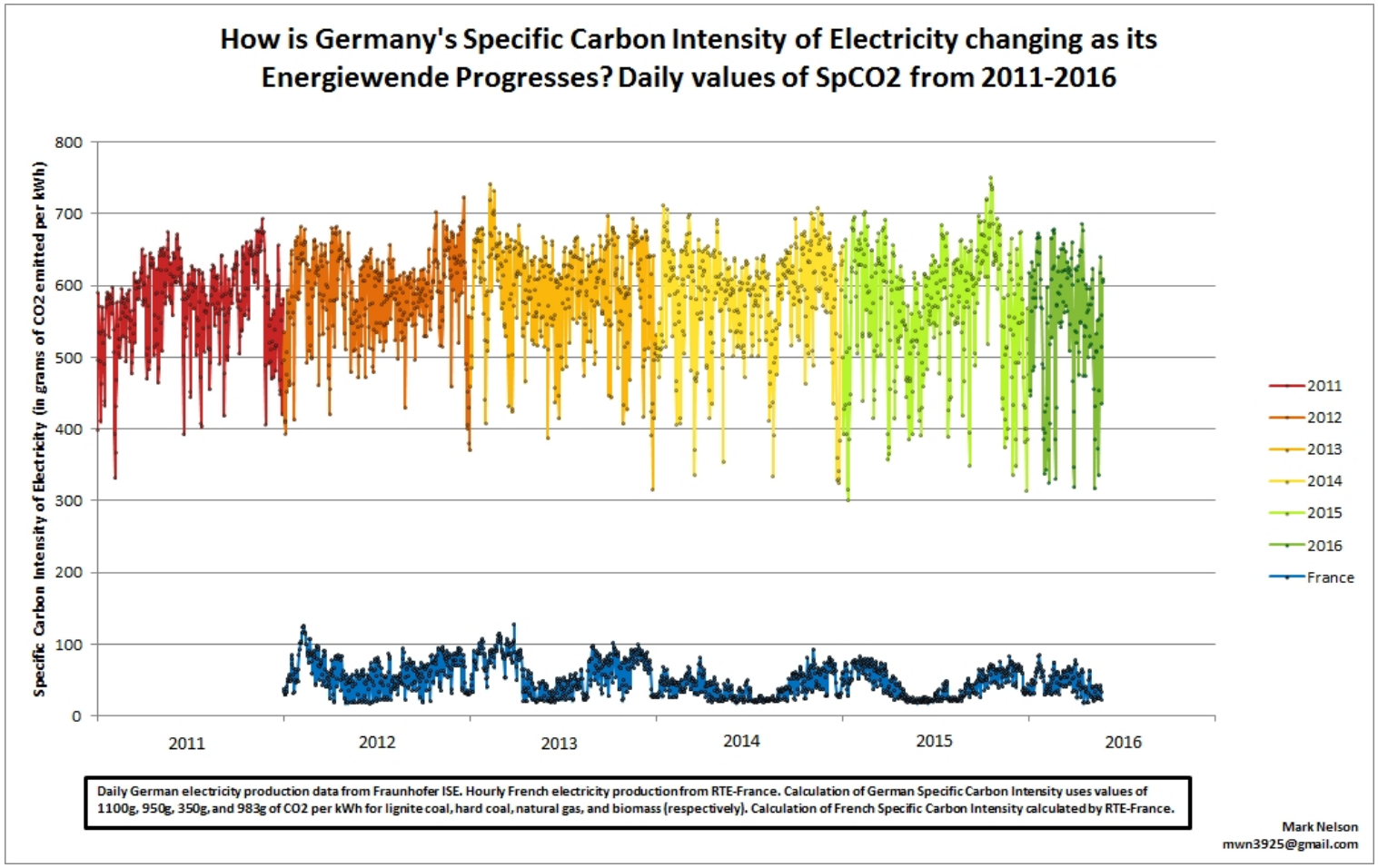
Figure 10.2 Illustrative Comparison of Life-Cycle GHG Emissions of Various Electricity Generation Technologies[2]



Note: Reference has "harmonized" original data to correct for differences in a number of input assumptions, resulting in reduced variance. "Count of estimates" refers to the number of separate sources of data. "Count of references" refers to the number of separate studies used to provide data. Key: CC = combined cycle; CT = combustion turbine; and IGCC = integrated gasification combined cycle.

An Assessment of Energy Technologies and Research Opportunities, Quadrennial Technology Review (QTR), 2015, US DOE

German vs French Emissions

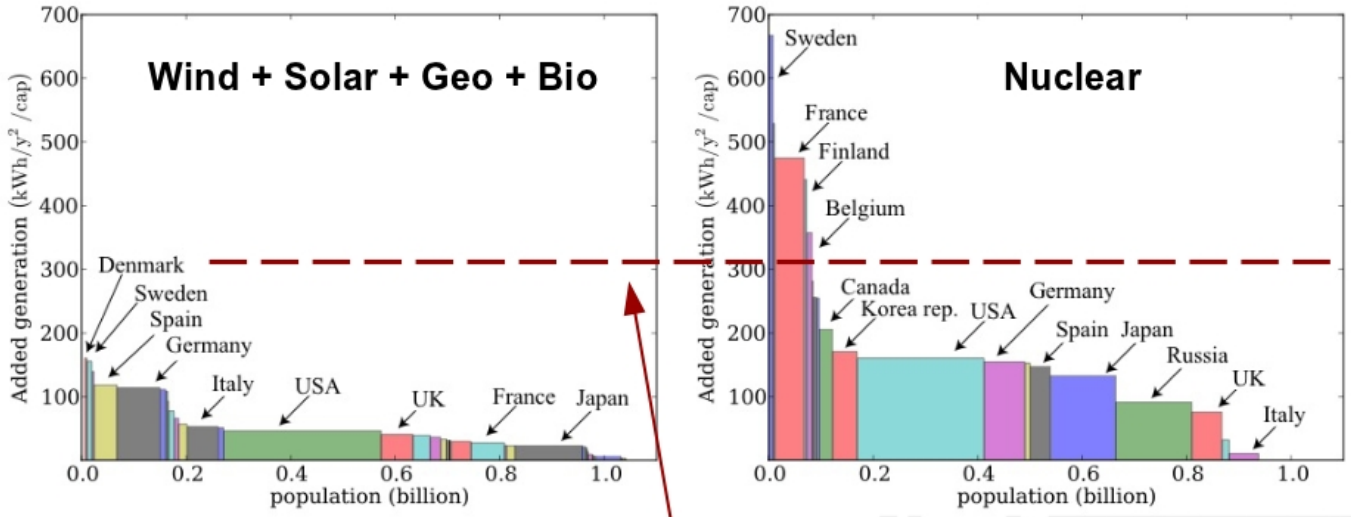


Angela Merkel, 22 January 2019 : " When we participate in conferences on the climate, Emmanuel Macron has a small advantage over me because he has so many nuclear power plants that he emits very little CO2 "

Nuclear Power has proven to be Humanity's Fastest Tool for Decarbonisation

How fast is fast enough?

Fastest added generation of electricity per person and year



analys.se

Required rate for 2 degree target

Source: World Bank & BP Statistical Review, picture by Carl Hellesen

3. Current Practice
Generation 2 and 3 Reactors

Evolution of Reactors

Generation I

Big Rock Point, GE BWR

Early prototypes

- **Calder Hall** (GCR)
- **Douglas Point** (PHWR/CANDU)
- **Dresden-1** (BWR)
- **Fermi-1** (SFR)
- **Kola 1-2** (PWR/VVER)
- **Peach Bottom 1** (HTGR)
- **Shippingport** (PWR)

Generation II

Diablo Canyon, Westinghouse PWR

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville 1-2** (PWR)
- **Fukushima II 1-4** (BWR)
- **Grand Gulf** (BWR)
- **Kalinin** (PWR/VVER)
- **Kursk 1-4** (LWGR/RBMK)
- **Palo Verde** (PWR)

Generation III / III+

Kashiwazaki, GE ABWR

Olkiluoto 3 AREVA PWR

Evolutionary designs

- **ABWR** (GE-Hitachi; Toshiba BWR)
- **ACR 1000** (AECL CANDU PHWR)
- **AP1000** (Westinghouse-Toshiba PWR)
- **APR-1400** (KHNP PWR)
- **APWR** (Mitsubishi PWR)
- **Atmea-1** (Areva NP -Mitsubishi PWR)
- **CANDU 6** (AECL PHWR)
- **EPR** (AREVA NP PWR)
- **ESBWR** (GE-Hitachi BWR)
- **Small Modular Reactors**
  - B&W mPower PWR
  - CNEA CAREM PWR
  - India DAE AHWR
  - KAERI SMART PWR
  - NuScale PWR
  - OKBM KLT-405 PWR
- **VVER-1200** (Gidropress PWR)

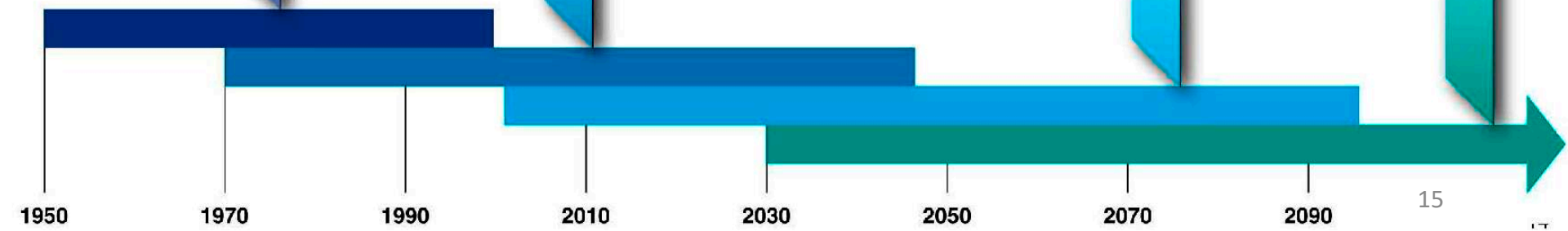
Generation IV

Safe
Secure
Sustainable
Competitive
Versatile

Arriving ~ 2030

Innovative designs

- **GFR** gas-cooled fast reactor
- **LFR** lead-cooled fast reactor
- **MSR** molten salt reactor
- **SFR** sodium-cooled fast reactor
- **SCWR** supercritical water-cooled reactor
- **VHTR** very high temperature reactor



Shin Kori Units 1 and 2

near Busan in South Korea

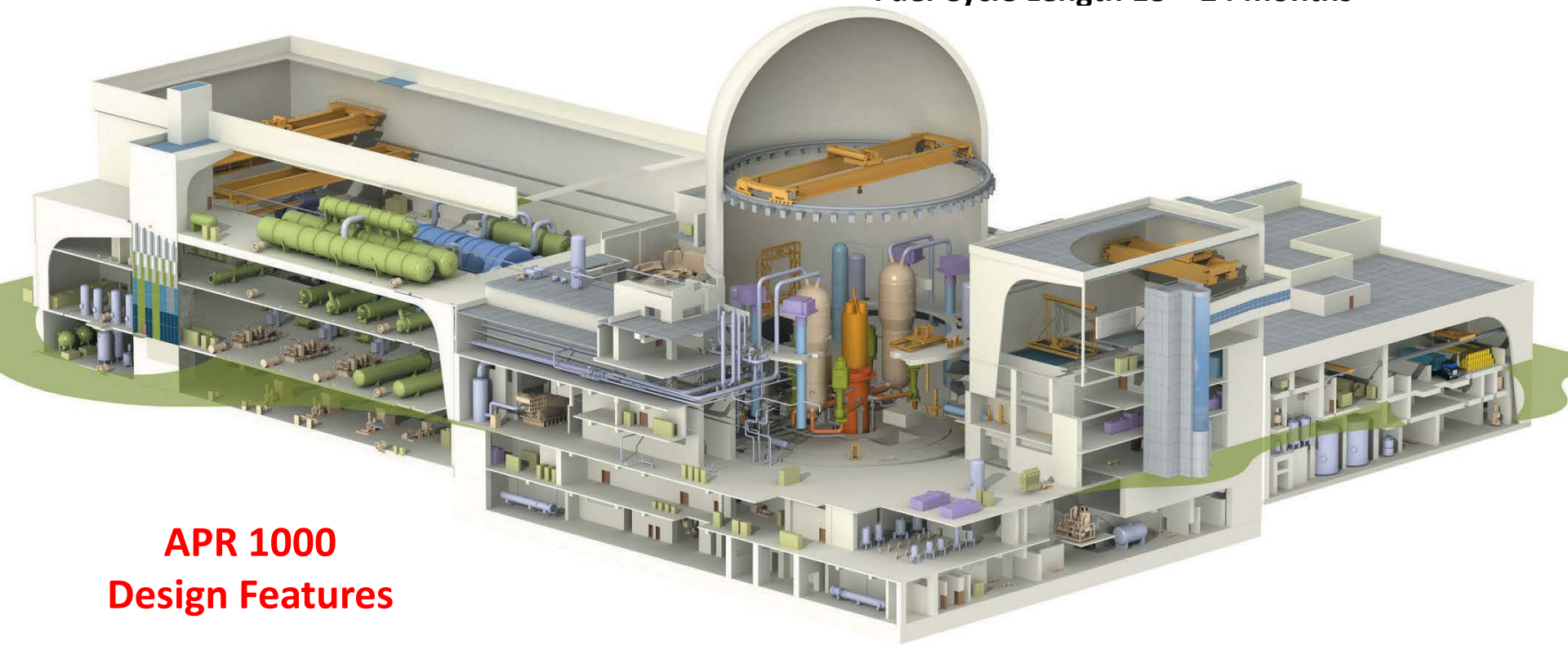
2 x 997MW OPR1000 Nuclear Power Plants

General Plant Data

Electrical Power Output
Gross/Net 1,050 / 1,000 MWe
Thermal Power 2,815 MWth
Design Lifetime 60 years
Seismic Design Basis SSE 0.3g

Reactor Core

Active Core Length 3,810mm
Equivalent Core Diameter 3,120mm
Average Linear Heat Rate 17.26 kW/m
Number of Fuel Assemblies 177, 16 x16 array
Number of Control Element Assemblies 73
Fuel Cycle Length 18 – 24 months



APR 1000
Design Features

Turbine

Number 1 High Pressure and 3 Low pressure
Type 6 Flow, Tandem Compound
Speed 1,800 rpm

Reactor Coolant System

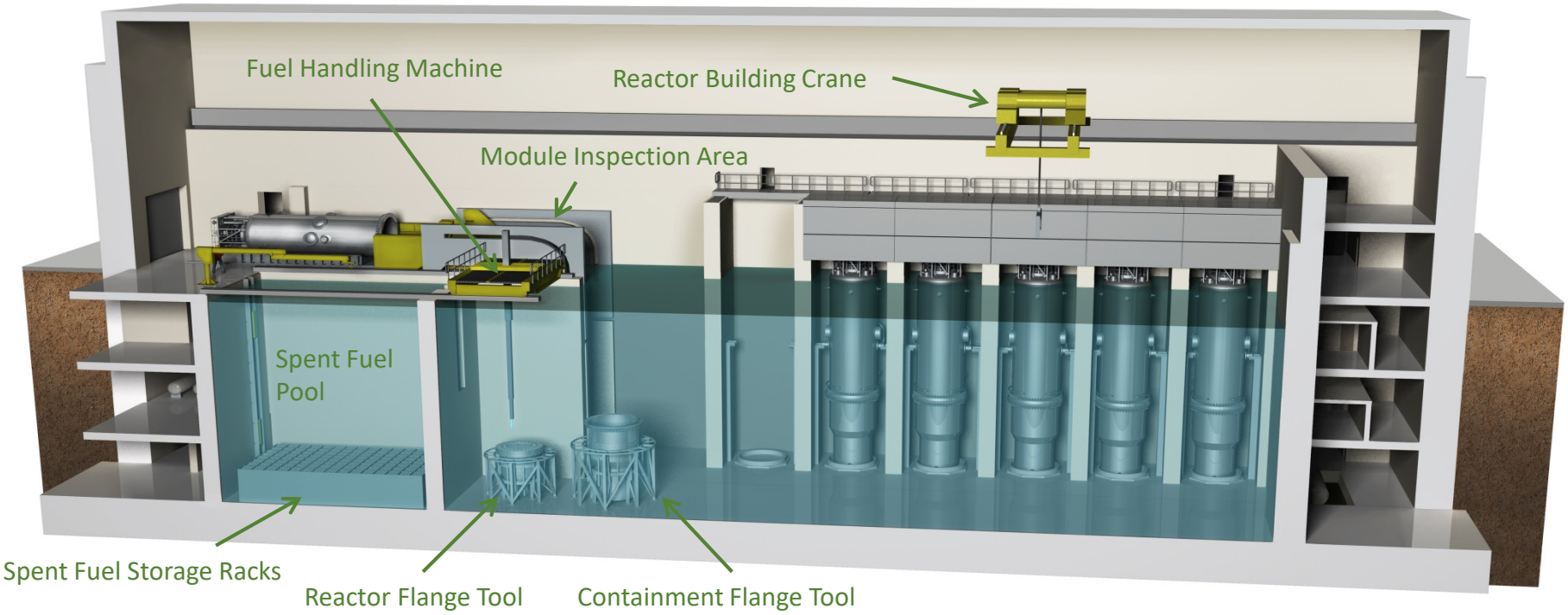
Number of Coolant Loops 2
Operating Pressure 15.52 mpa
Coolant Inlet Temperature 296 C
Coolant Outlet Temperature 327 C

Near future

Small Modular Reactors

NuScale

Reactor Building

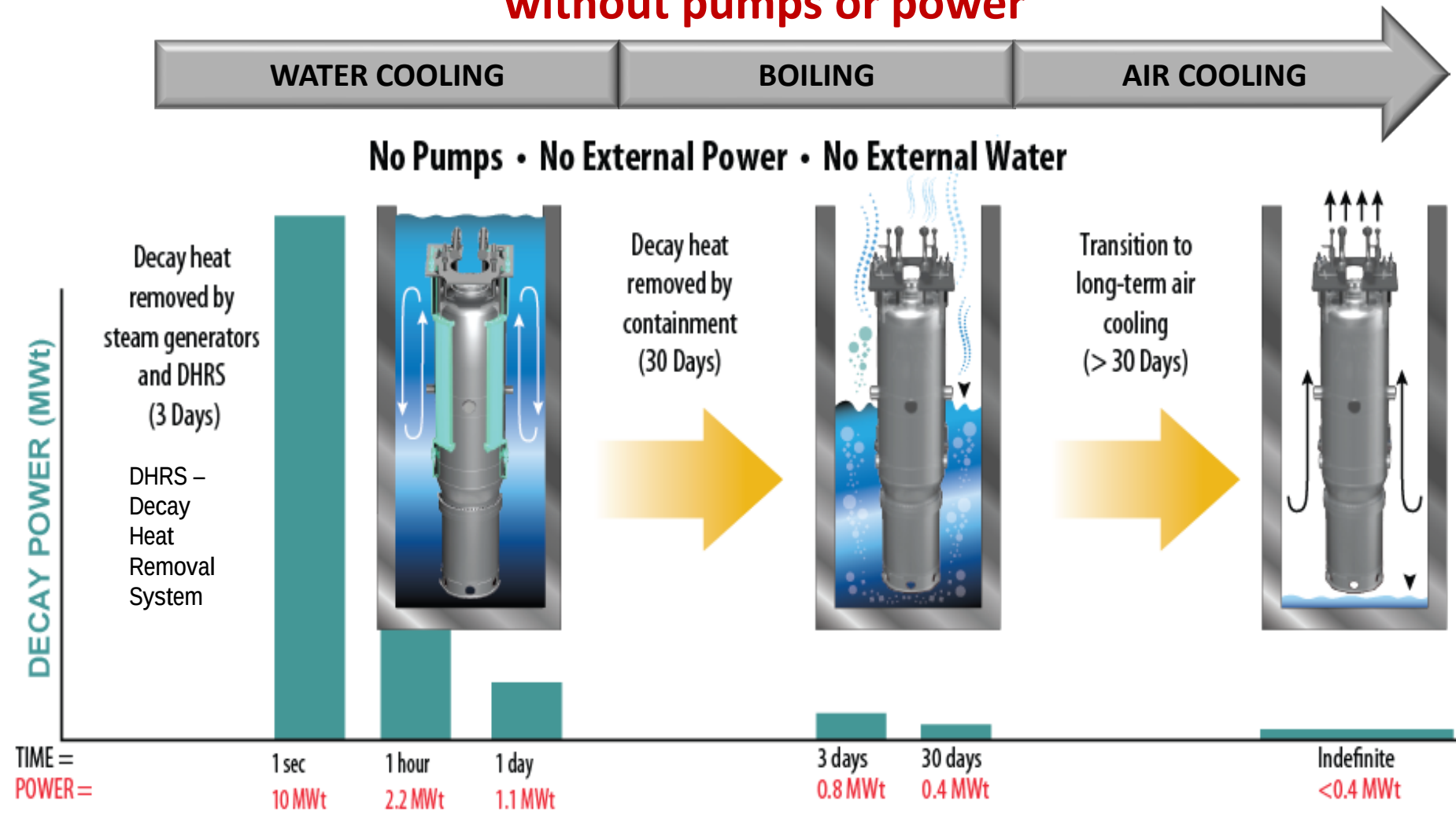


- **Spent fuel pool has capacity to store:**
  - **10 years of spent fuel**
- **Spent fuel storage racks**
  - **Seismic Category I**
  - **high density design**
  - **neutron absorber material for criticality control**

- **Module assembly equipment**
  - **reactor module assembly/disassembly**
  - **refueling core**
  - **loading dry storage cask**

Stable Long-Term Cooling Under all Conditions

Reactor and nuclear fuel cooled indefinitely without pumps or power

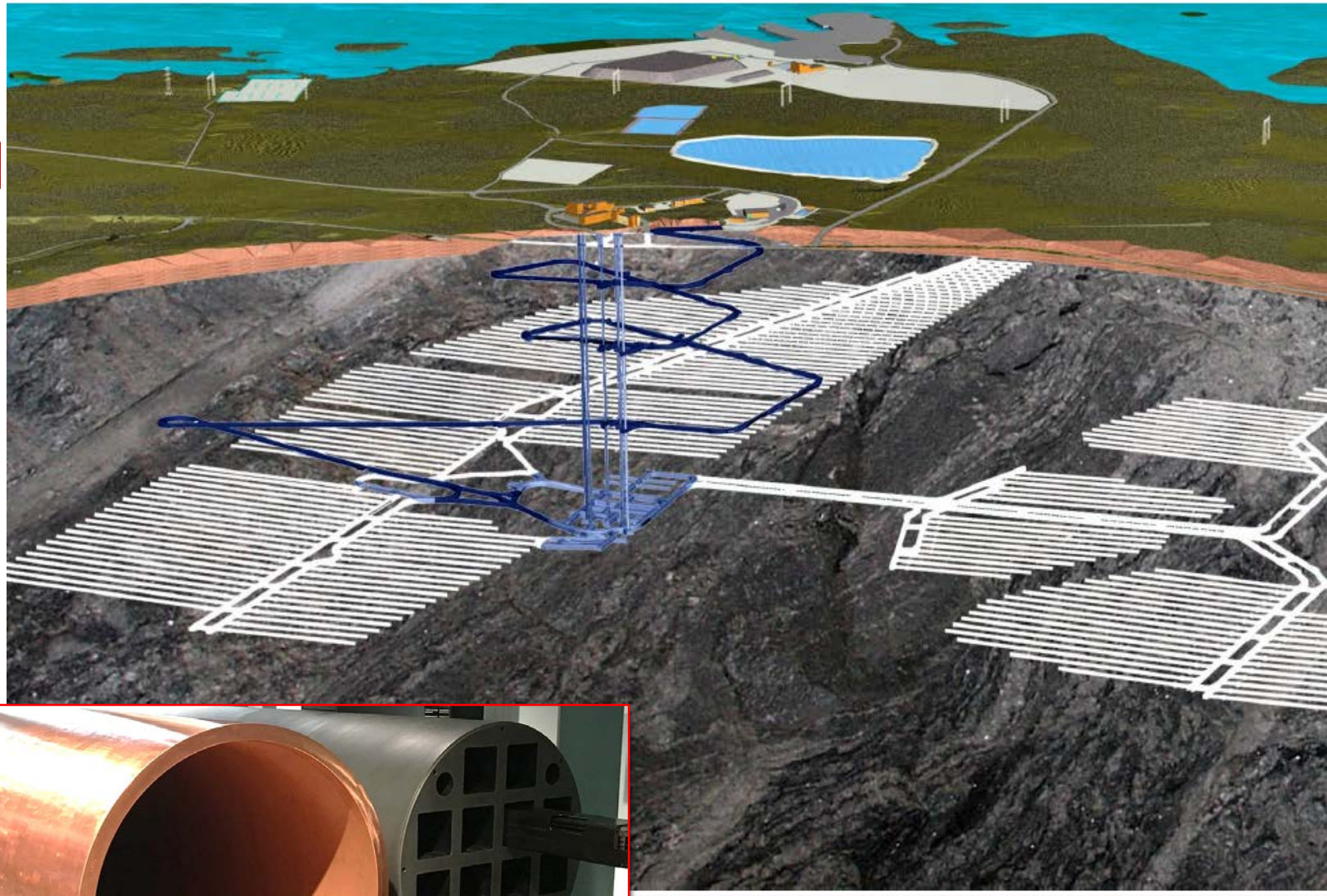


** Based on conservative calculations assuming all 12 modules in simultaneous upset conditions and reduced pool water inventory*

4. Dealing with used fuel and Gen IV reactors

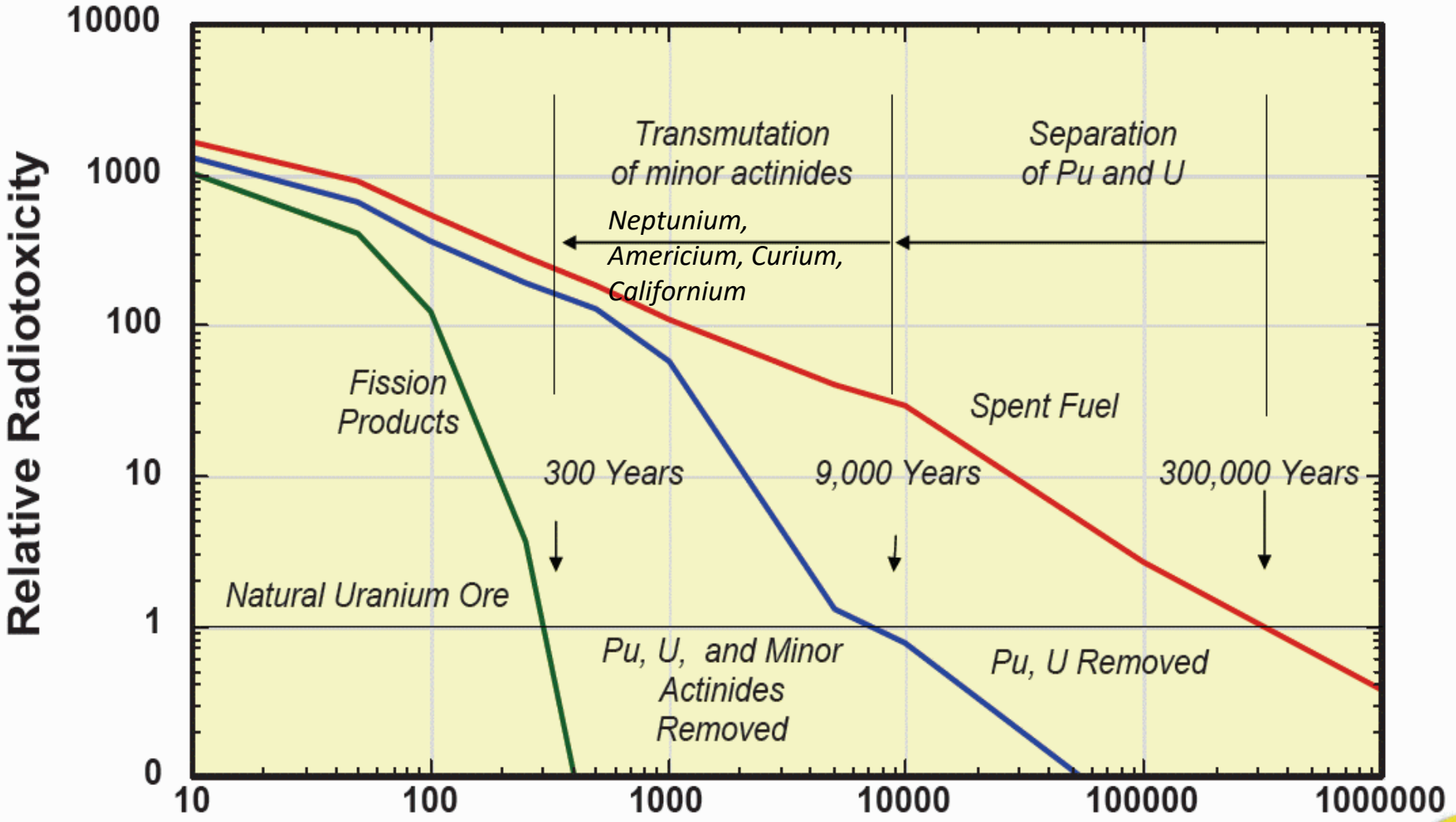
Disposal facility above and under ground

Deep disposal in granite 500m down



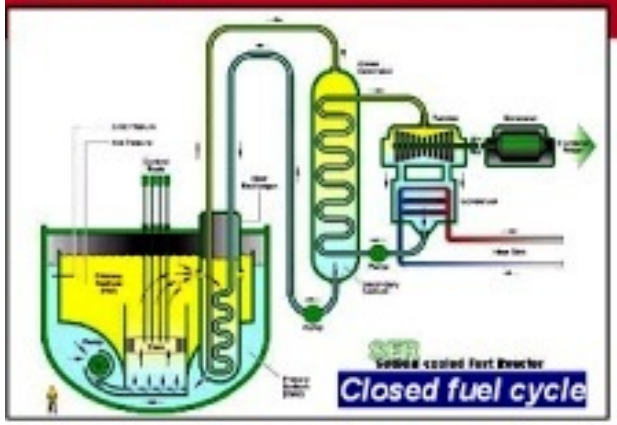
Nuclear for CLIMATE AUSTRALIA

Actinide partitioning and Transmutation

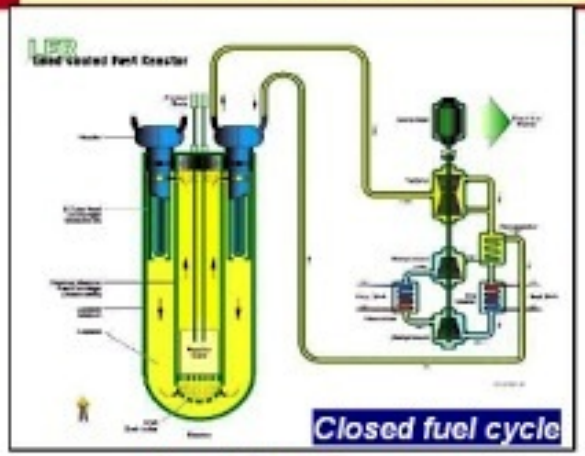


GEN-IV INTERNATIONAL FORUM: 6 SYSTEMS FOR R&D

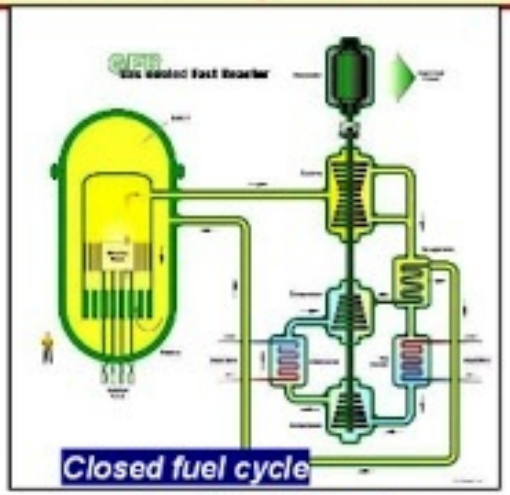
GIF Selection of six Nuclear Systems



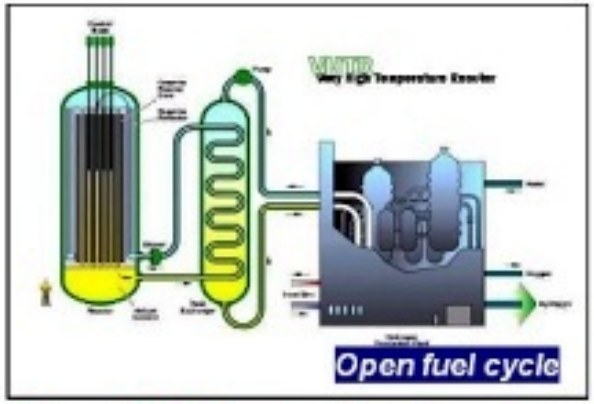
Sodium Fast Reactor



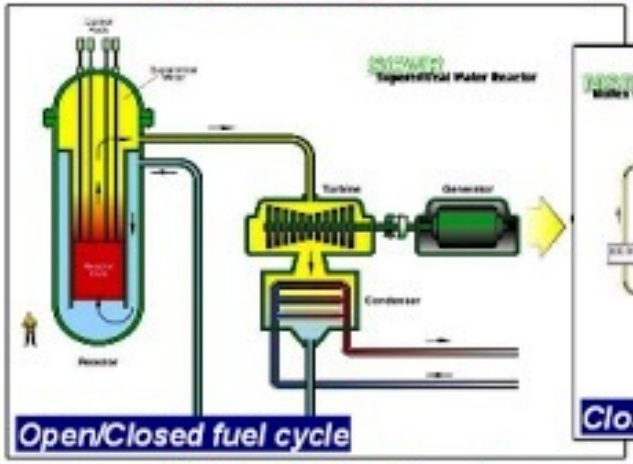
Lead Fast Reactor



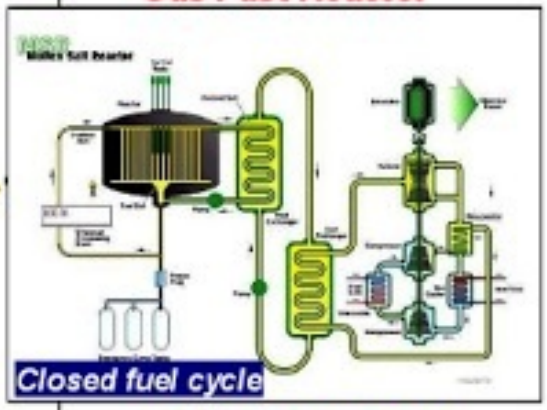
Gas Fast Reactor



Very High Temperature Reactor



Super Critical Water Reactor



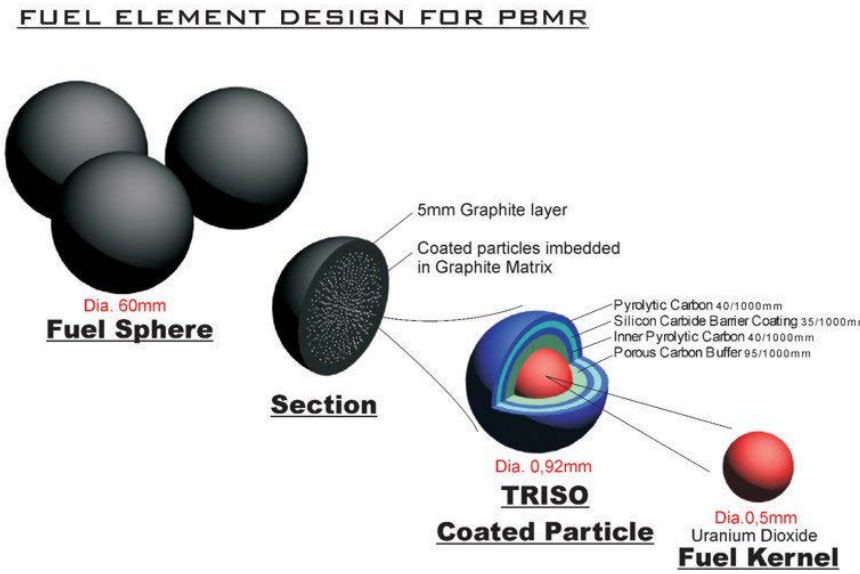
Molten Salt Reactor

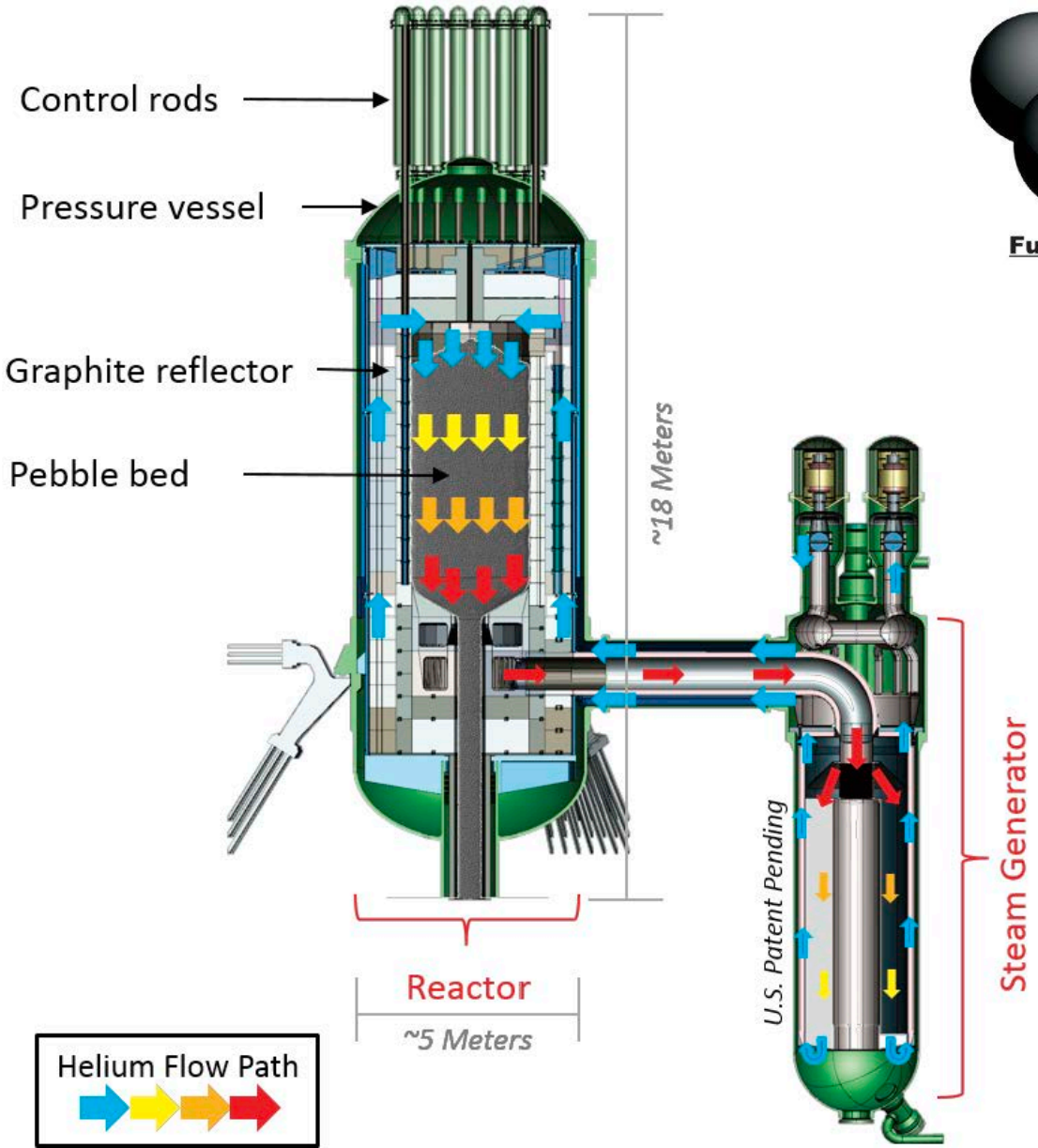
Recognition of the major potential of fast neutron systems with closed fuel cycle for breeding (fissile re-generation) and waste minimization *(minor actinide burning)*

BN800 - Fast Breeder/Burner Reactor

Power (thermal)	2100 MW_{th}
Power (electric)	789 MW_e net, 885 MW_e gross

High Temperature Gas Cooled reactors – Pebble Bed





HTR-PM

2 units at Shidao Bay NPP in China

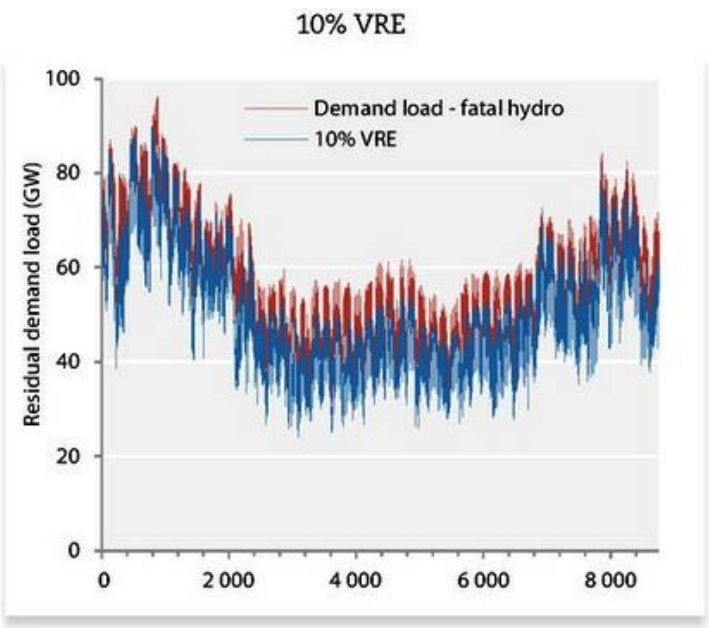
Pebble Bed Reactor

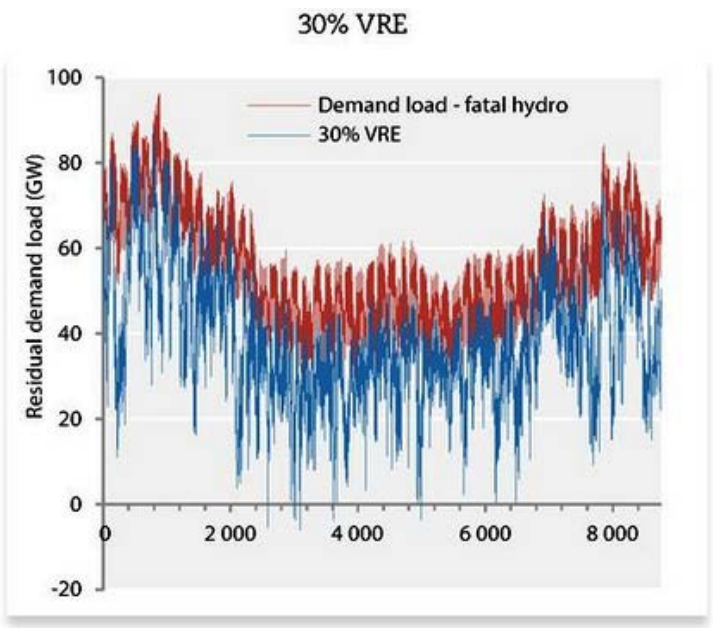
110 MWe output per unit

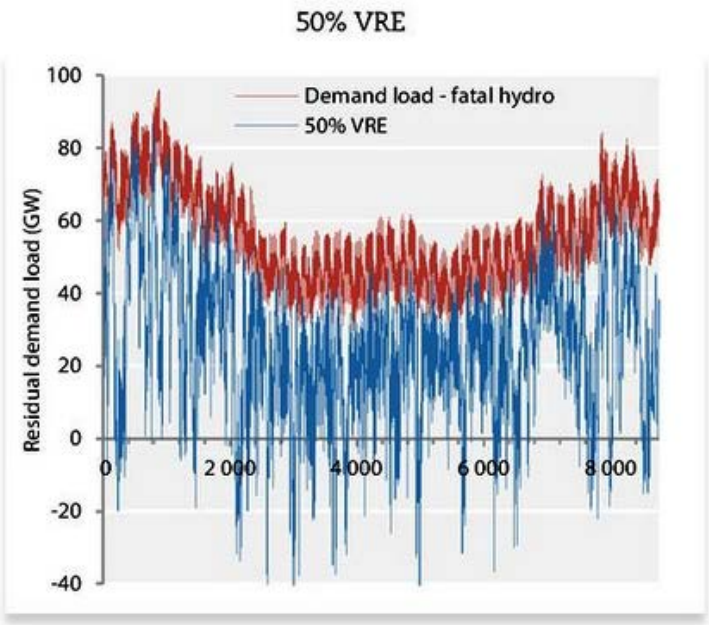
Low power density, Meltdown proof

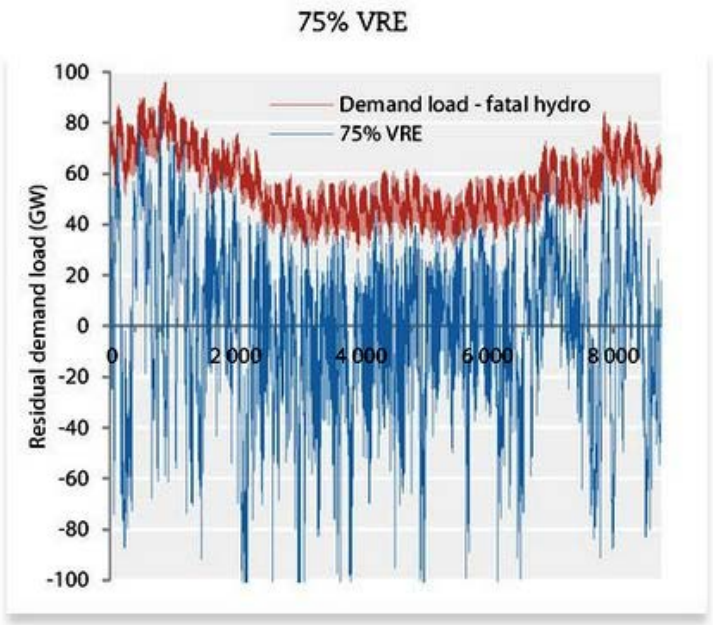
Self limiting reactor with no emergency core cooling required

5. A solution to Australia's energy security and emissions reductions







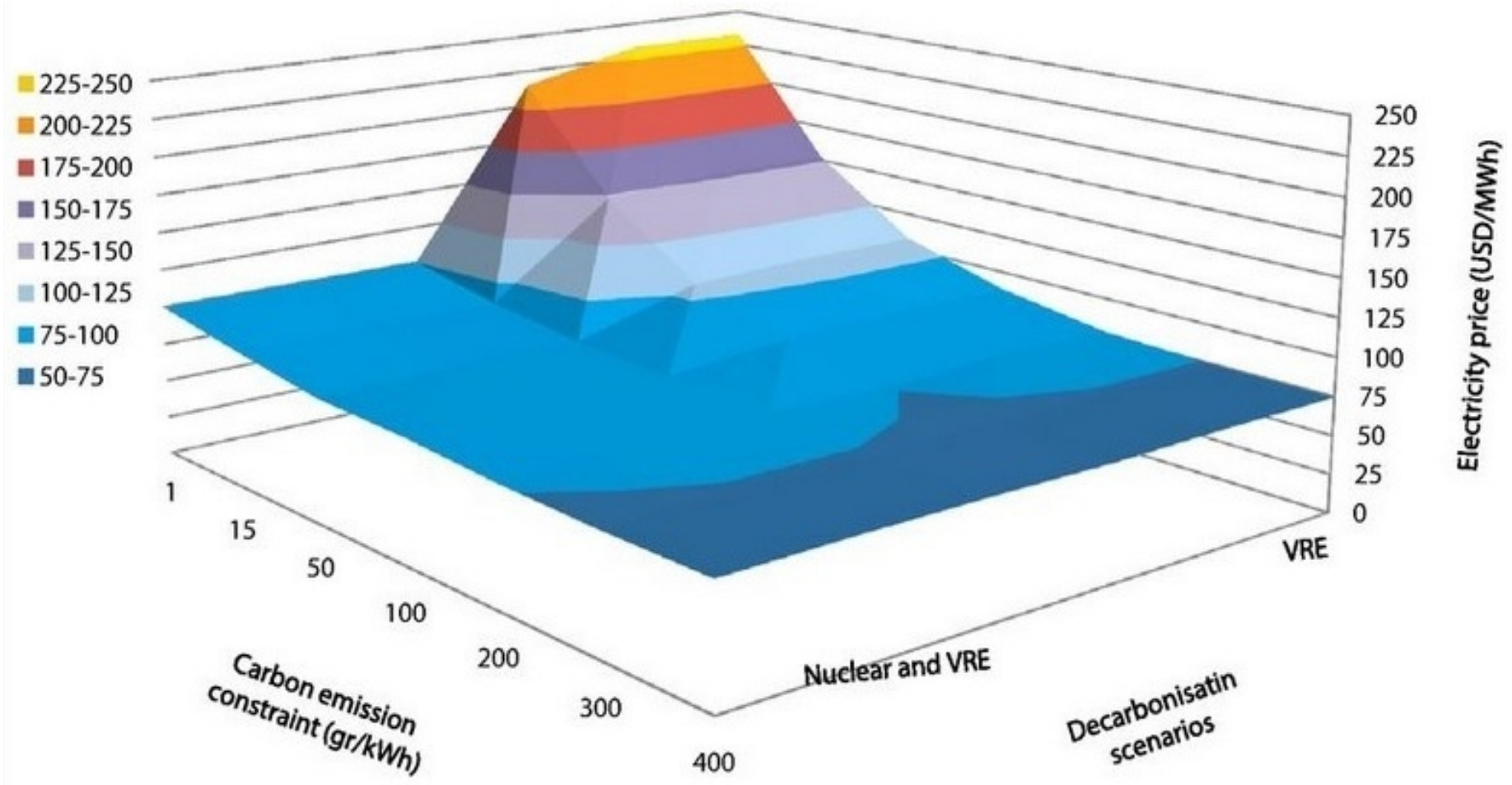


Note that the figures have a different vertical scale.

Figure 23. Comparison of the residual load at different VRE generation shares.

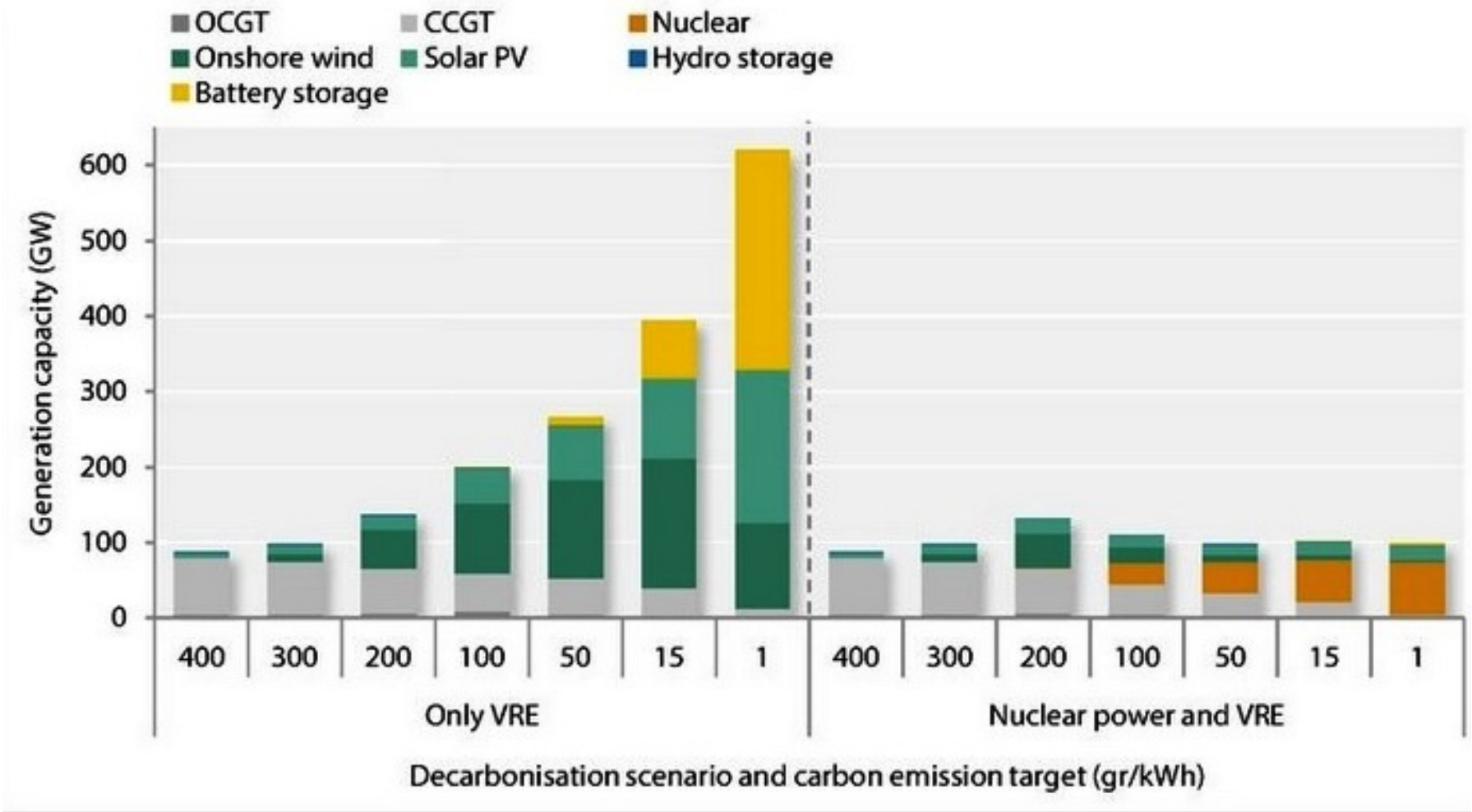
Impact on Capacity Factors

Figure 15. Average price of electricity as a function of pathways and emissions intensity targets - *Electric Reliability Council of Texas (ERCOT)*



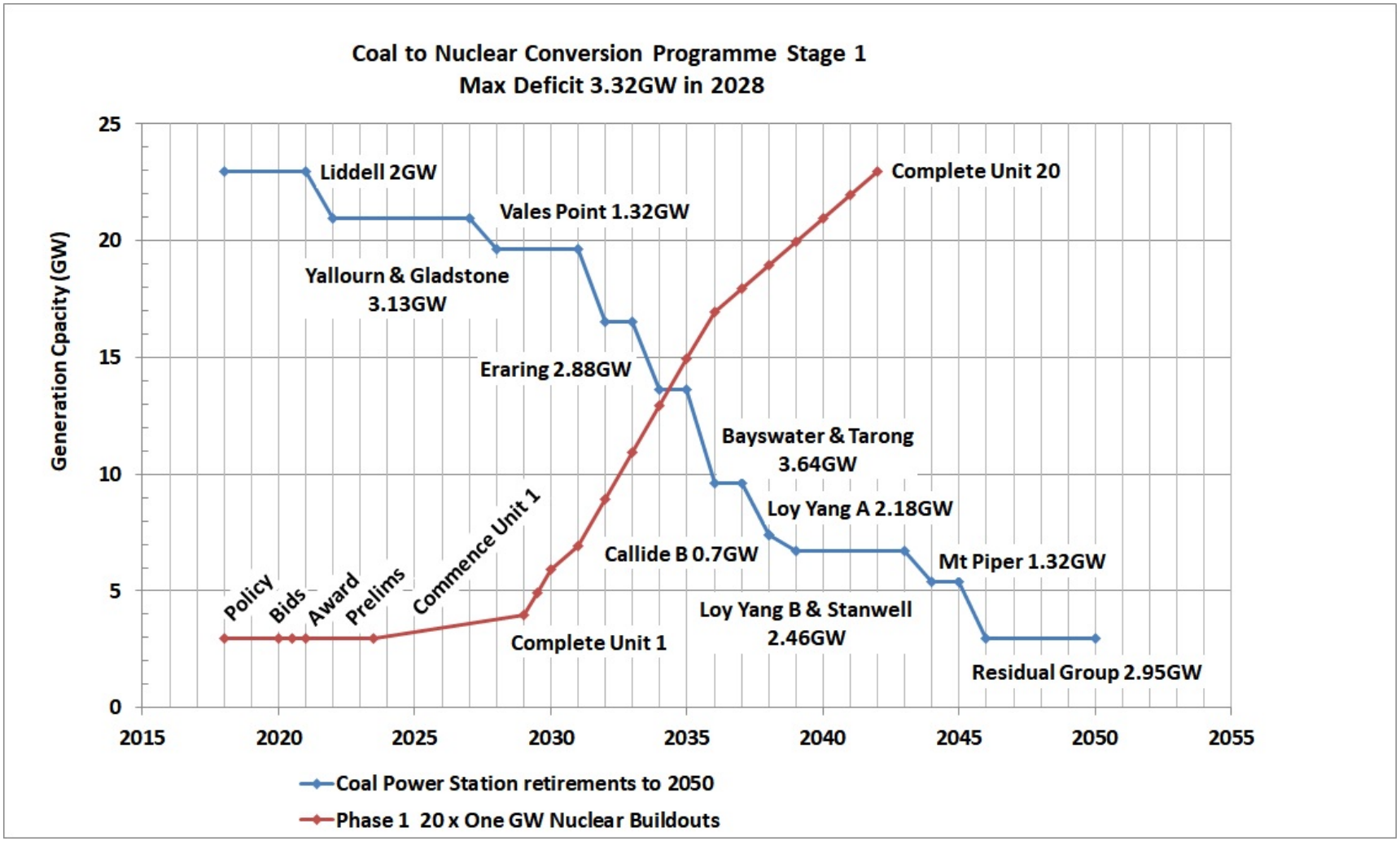
Source: Based on Sepulveda, 2016.

Figure 17. Optimal capacity mix for two main pathways as a function of the carbon target - *ERCOT*



Source: Based on Sepulveda, 2016.

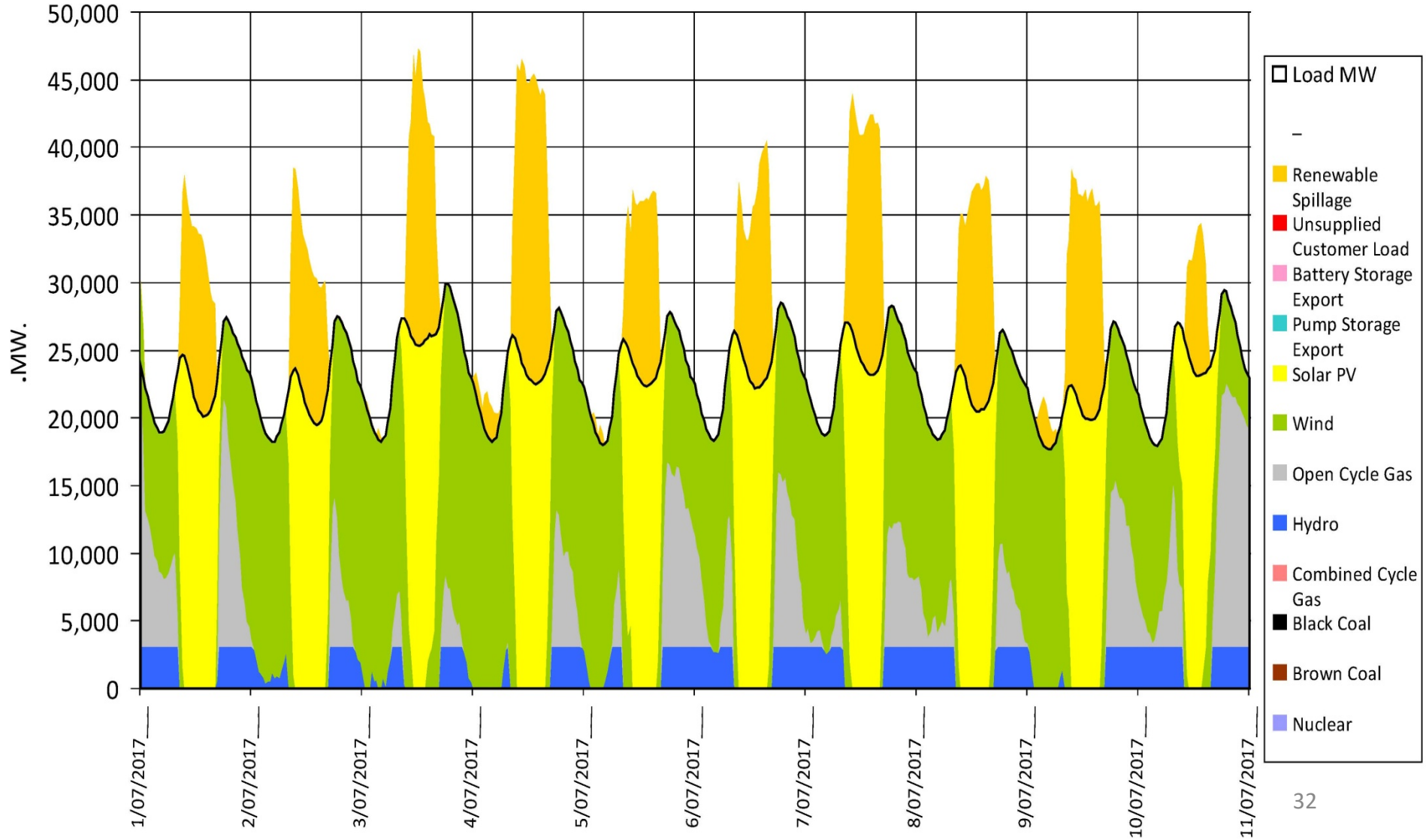
Nuclear Replaces Coal with 20 Nuclear Power Plants



Renewables – 82% NEM Energy

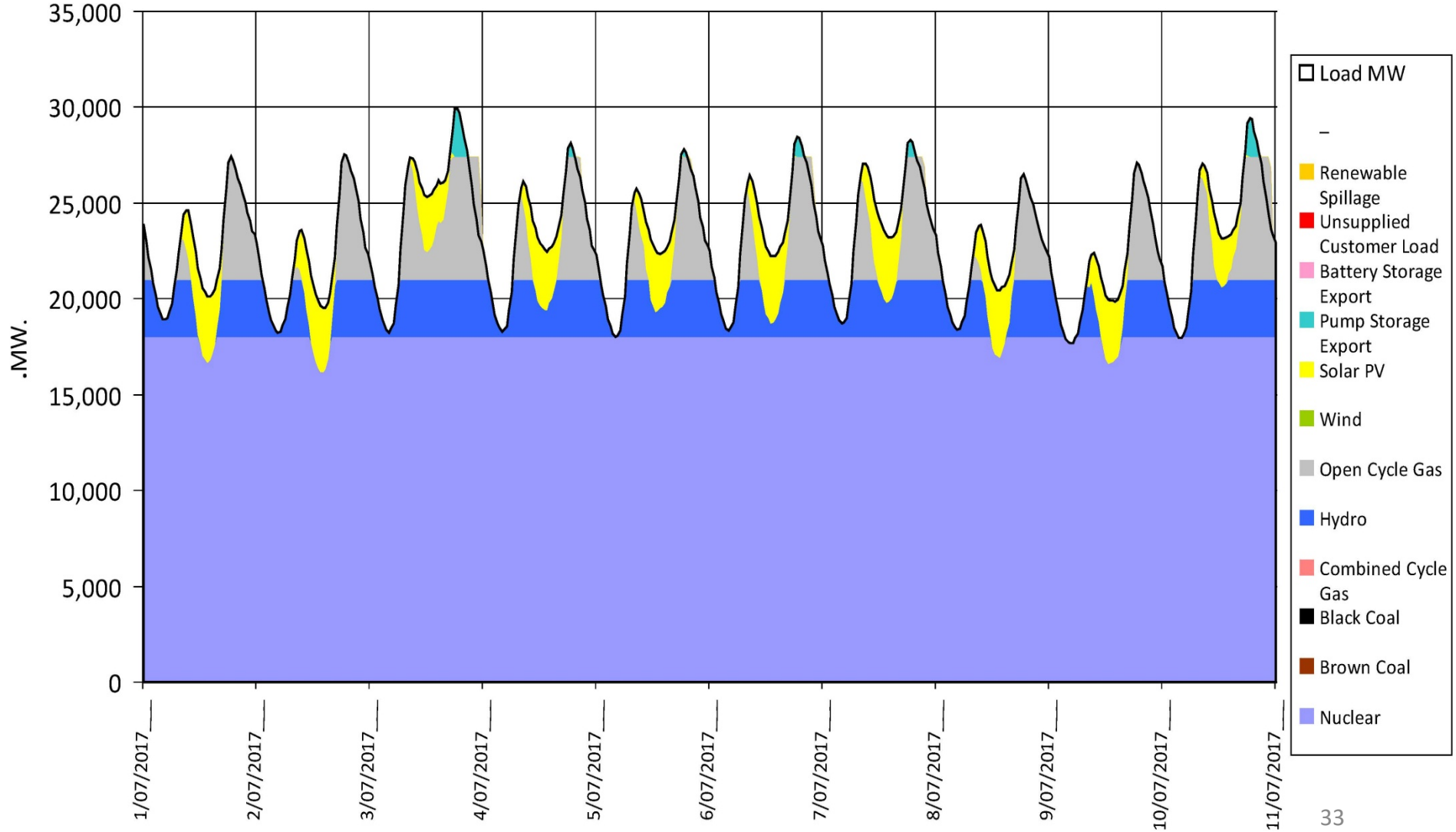
45GW Solar PV, 20GW OCG, 3GW Hydro, 37GW Wind

5GW Pumped Storage for 2 days = 240,000MWh , 130gr CO2/kWh

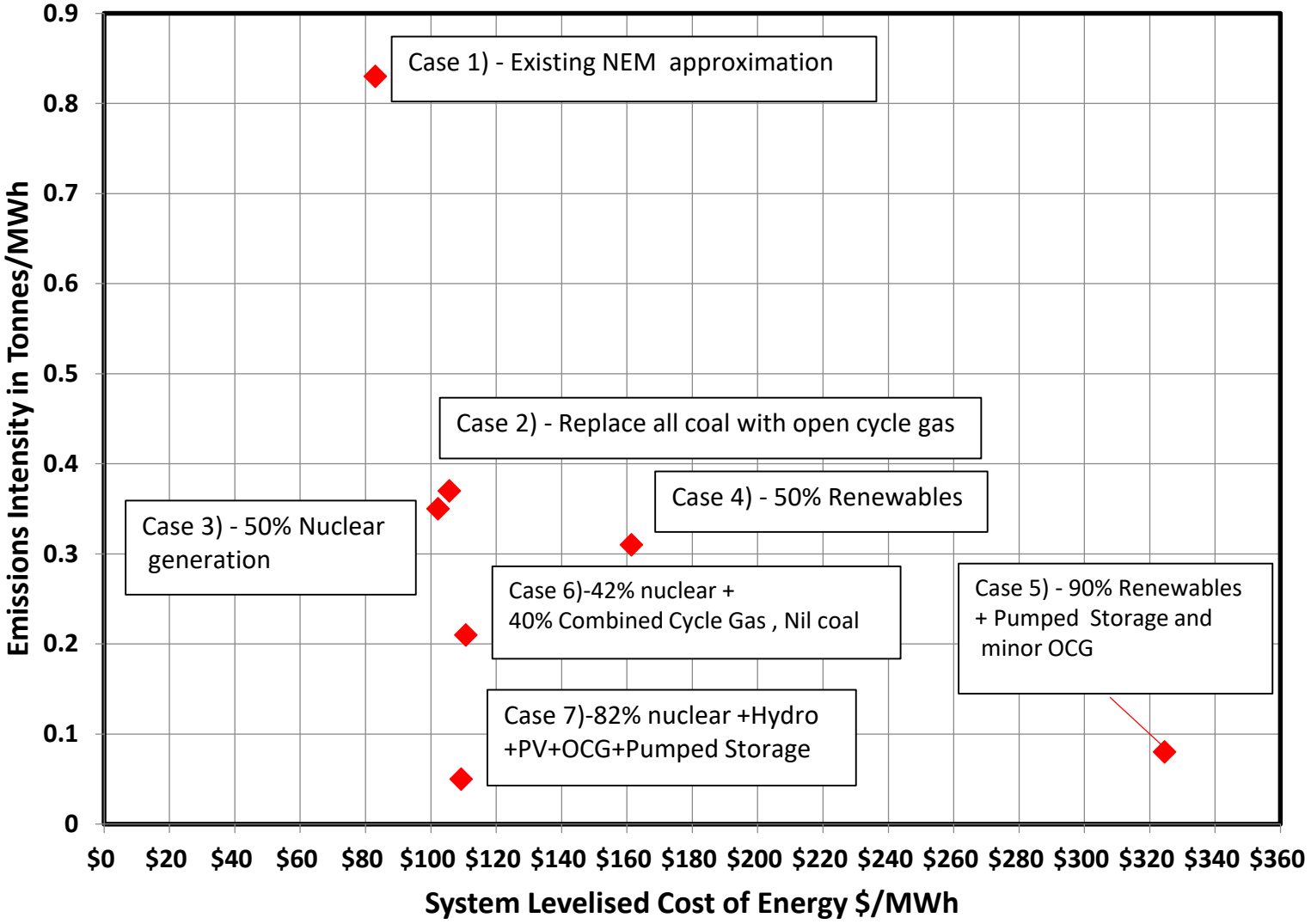


Nuclear – 82% NEM Energy

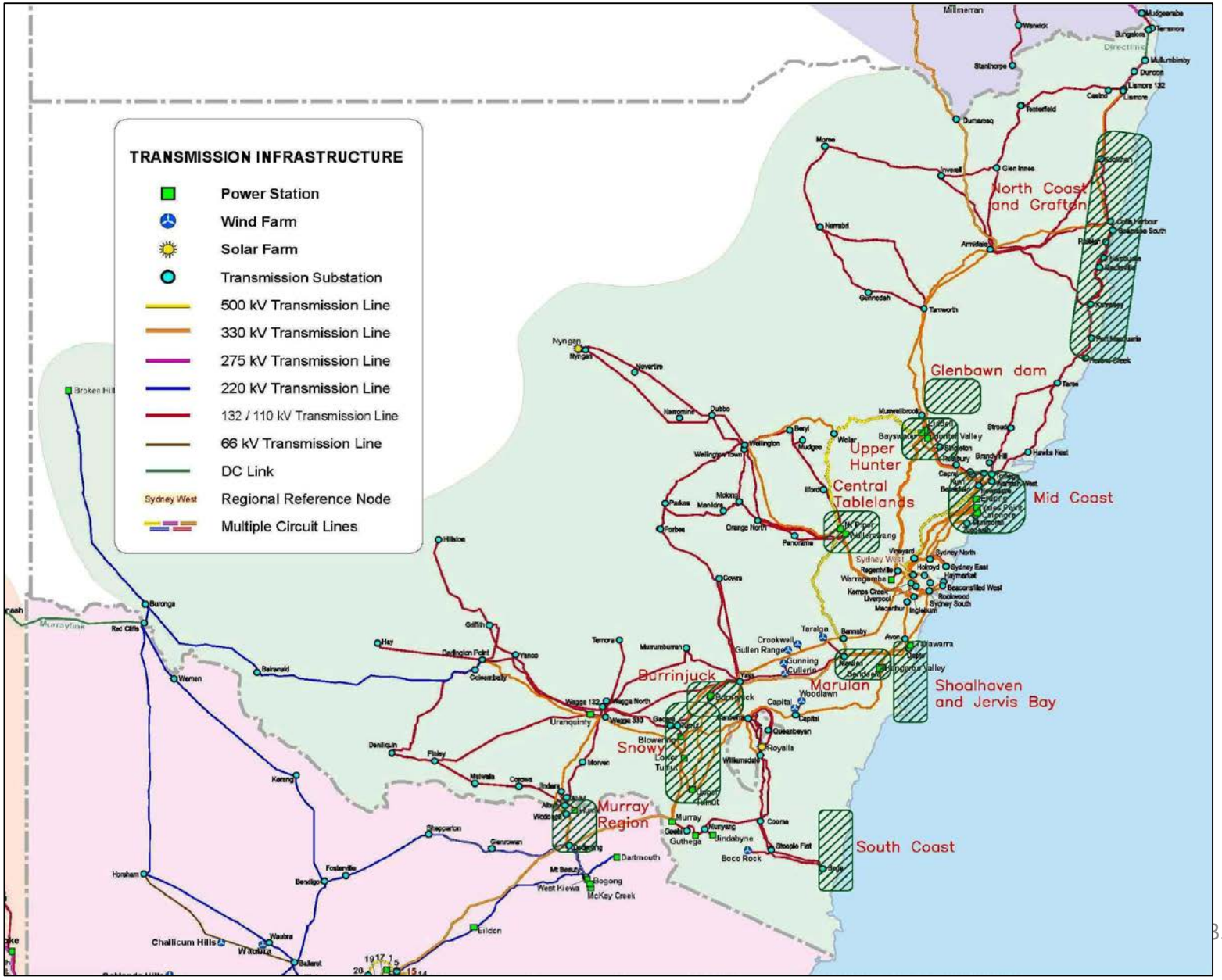
4GW Solar PV, 6.5GW OCG, 3GW Hydro, 20GW Nuclear,
5GW Pumped Storage for 2 days = 240,000MWh 50 gr CO2/kWh



Modeled range of National Electricity Market energy schemes versus carbon emissions



NSW/ACT Regions of Interest



Nuclear for CLIMATE AUSTRALIA

https://nuclearforclimate.com.au/

The Australian Nuclear Association
http://www.nuclearaustralia.org.au/

Fukushima Province Radiation

Measurements I took in 2017