Probus Club of Sydney

Nuclear Power - Australia's Answer to Climate Change?

Should nuclear power be part of Australia's 2050 clean energy commitments?

Martin Thomas

3 December 2019

Outline of my talk

1. Nuclear power – the big picture worldwide
2. Australia's proud nuclear energy story to date – and where does Australia's electricity come from now?
3. What are the big questions for Australians if we choose to include nuclear in the electricity generation portfolio?
    1. *How safe is it?*
    2. *The wastes – can we dispose of them?*
    3. *What nuclear technologies could Australia use?*
    4. *What are the comparative economics of nuclear versus other technologies?*
    5. *And what is its impact on the environment?*
4. So - finally – where can we go to from here – and should we even make that journey?

That of course will be up to you – the people!

And, if we have time, what could future technologies promise? And what are they?

1. **Generation IV reactors** – what are they and what can they do?
2. **Thorium fuel** – the pros and cons – does it have a future?
3. **Nuclear fusion** – is near infinite carbon free energy for our world really a possibility?

First - the big picture

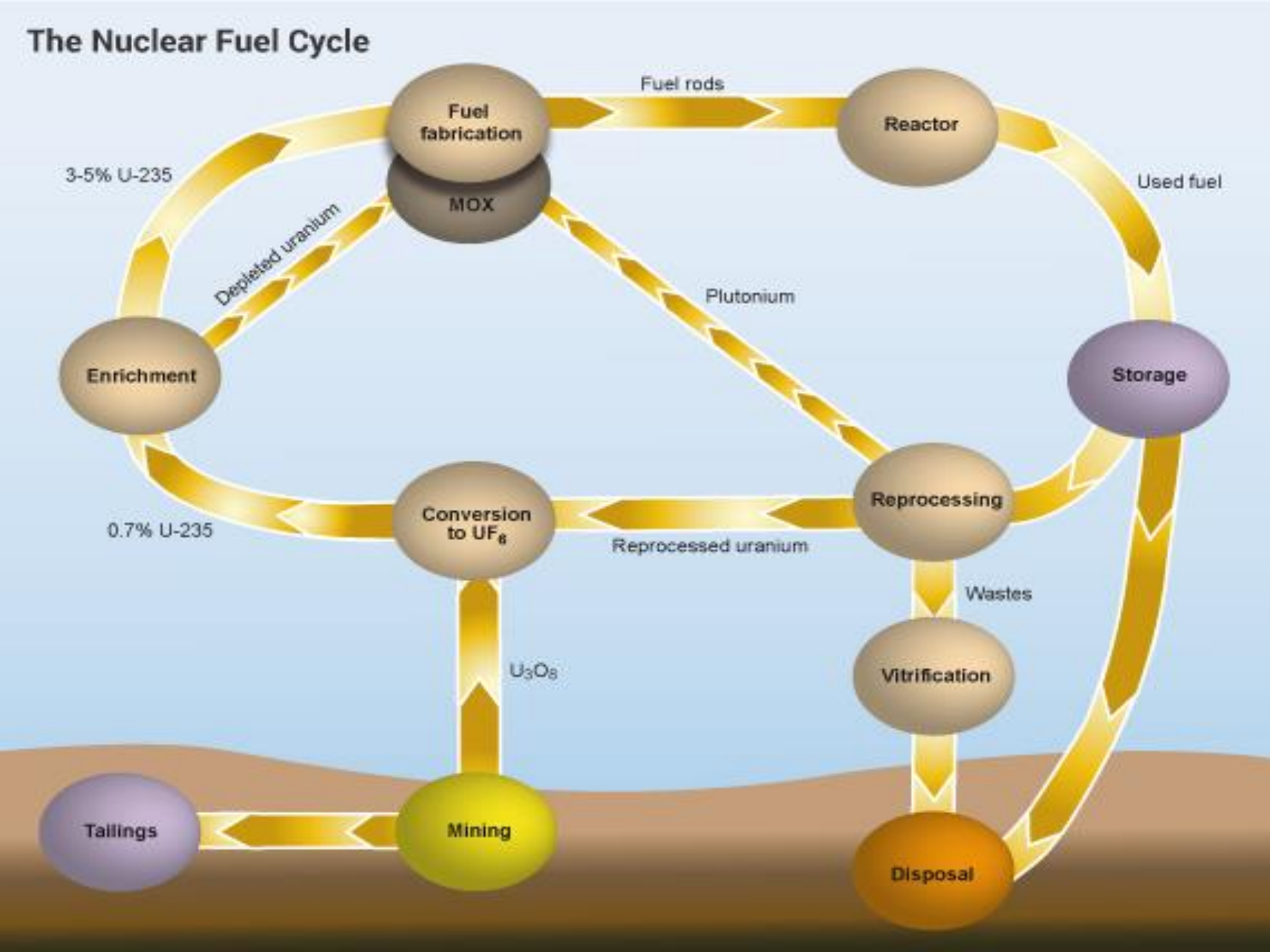
The world nuclear power industry – some facts:

In November 2019 there were:

- **443 reactors operable in 30 nations generating just over 10% of world's electricity**
- **395 GW is installed - over 8 times Australia's ~ 50 GW!**
- **55 reactors under construction, 110 planned and another 330 proposed operational by 2030!**

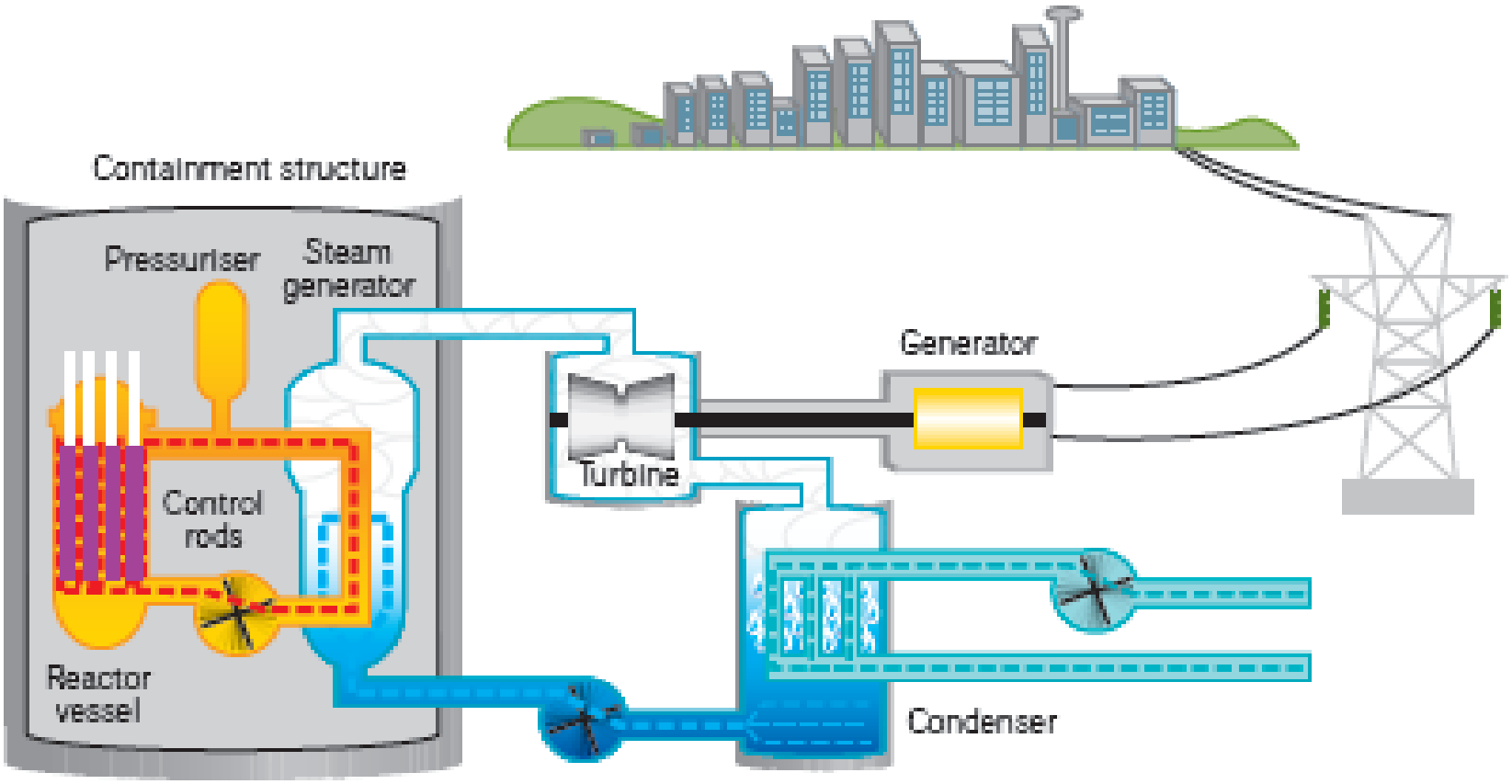
Nuclear remains a significant source of clean electricity!

Source: World Nuclear Association (WNA) website http://www.world-nuclear.org/info/Facts-Figures/


The Nuclear Fuel Cycle
Fuel fabrication
Fuel rods
Reactor
MOX
3-5% U-235
Used fuel
Depleted uranium
Plutonium
Enrichment
Storage
Conversion to UF_6
Reprocessing
0.7% U-235
Reprocessed uranium
Wastes
U_3O_8
Vitrification
Tailings
Mining
Disposal

Typical conventional nuclear power station

Figure 1.2 Schematic of a pressurised water reactor



Source: United States Nuclear Regulatory Commission (NRC)[21]

Nuclear Energy – Australia's proud history - some key dates

- **1953-1987 - Australian Atomic Energy Commission (AAEC)**
- **1958-2007 - High Flux Australian Reactor (HIFAR)**
- **1963-2008 - Centrifuge and laser enrichment developed in Australia – then abandoned – why?**
- **1969-1971 - Jervis Bay 500MW nuclear power station – commitment to abandonment – why?**
- **1978 - Synroc for waste encapsulation – where next?**
- **1970-1984 - Nuclear science and engineering courses at UNSW – abandoned – why?**
- **Australia, back then, was among the world leaders and was ready for nuclear power. We had a 'seat at the table'. Why did we forego that enviable position? And where are we today?**

Nuclear Energy – Australia's proud history - more key dates

- 1987 – Australian Nuclear Science and Technology Organisation (ANSTO) established – replacing the AAEC
- 1989 – Australian Synchrotron project conceived and built
- 2006 – Uranium Mining, Processing and Nuclear Energy Review (UMPNER) – aka the Switkowski Report
- 2007 – Open Pool Australian Lightwater research reactor (OPAL) commissioned – HIFAR heritage listed
- 2010 - Nuclear engineering re-established at UNSW and ANU
- 2016 – Australia joins International Thermonuclear Experimental Reactor (ITER) fusion project as technical partner
- 2016 – South Australia's Nuclear Fuel Cycle Royal Commission
- 2017 – Australia joins International Generation IV Forum (GIF)
- 2019 – Federal and NSW Inquiries into repealing legal impediments

Australia's nuclear legacy – the lucky country's contribution

- Australia has just 0.3% of the world's population, but around 30% of the world's economic uranium reserves
- But only 10% of the world uranium market
- Has Australia made best use of its legacy? Or simply followed the second servant in the biblical parable of the talents – acceptance with unduly modest exploitation?
- I believe we have willfully squandered our legacy!
- Australia is today the world's third largest supplier of uranium fuel, exporting some 7,500 tpa of concentrate (yellowcake) for enrichment to nuclear reactors worldwide
- Are we therefore hypocritical to deny nuclear power to Australians?

Australia's nuclear legacy – the luck continues!

- **The energy content of the uranium we export (in terms of generated electricity via today's GII and GIII reactors) is about the same as that of all Australia's thermal coal exports and the near equivalent all of the electricity generated in Australia!**
- **It contributes far more to clean energy worldwide than our current investment in renewables, attractive as they are**
- **So called fast neutron GIV reactors open the prospect of improving that clean energy recovery by 60 times or more.**
- **Uranium is plentiful and cheap - it will not 'run out'**
- **Thorium, still to be commercialised, likewise offers eons of clean safe power and heat**
- **Our nation is amazingly fortunate; would that we had the wisdom to better exploit our inheritance for our own people!**

Yet more of the proud Australian nuclear science story!

- **Australia today has one of the world's finest nuclear research centres – the Australian Nuclear Science & Technology Organisation (ANSTO)**
- **Australia is a world leader in supply of medical radiopharmaceuticals – moving from meeting 3-5% of world demand up to 30-35% from ANSTO's OPAL research reactor and the recently commissioned ANSTO Nuclear Medicine (ANM) facility at Lucas Heights**
- **And ANSTO is now building the new Synroc Waste facility at Lucas Heights – at long last Synroc has come of age!**

But still nuclear power remains illegal in Australia!

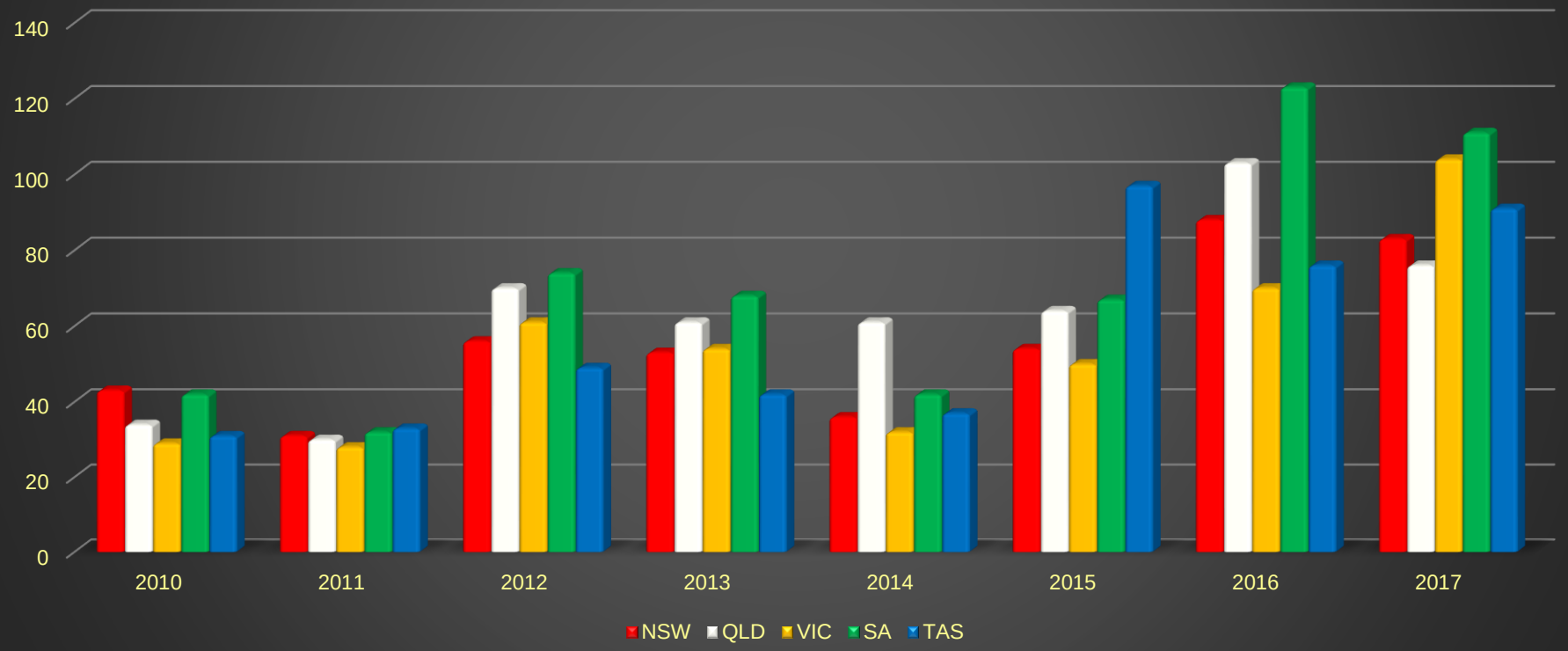
- **Australia is the only top 20 OECD nation where nuclear power is illegal.**
- **Commonwealth prohibitions are the Environment Protection and Biodiversity Conservation (EPBC) Act 1999 and the Australian Radiation Protection and Nuclear Safety (ARPANS) Act 1998**
- **New South Wales, Victoria and Queensland also have long outdated acts prohibiting nuclear power.**
- **These bans have no supporting logic; they must be repealed to let nuclear energy compete on its merits!**
- **Current Commonwealth and NSW Government inquiries are rightly examining the case for their repeal.**

Where did our National Electricity Market (NEM) electricity come from in 2016/17? Are variable renewables really providing cheap reliable power? What will happen when the coal stations retire?

2017	Coal (black and brown)	Gas	Hydro	Wind	Solar	Other	Total
Energy TWh	150.9	17.6	15.5	10.6	0.6	1.3	196
Market share %	77%	9%	8%	5%	0.3%	0.7%	100%

Note: Figures for solar exclude private rooftop installations which can deliver up to 5% of NEM demand.
Source: AEMO website https://www.aemo.com.au/

AUSTRALIAN NATIONAL ELECTRICITY MARKET
AVERAGE SPOT PRICES



	2010	2011	2012	2013	2014	2015	2016	2017
NSW	43	31	56	53	36	54	88	83
QLD	34	30	70	61	61	64	103	76
VIC	29	28	61	54	32	50	70	104
SA	42	32	74	68	42	67	123	111
TAS	31	33	49	42	37	97	76	91

3 - The big questions for nuclear – first let's look at safety

- Do we live in a risk-free world?
- How many people has nuclear power killed?
- How does nuclear power rank for safety with all other generation technologies?
- Will nuclear power get any safer?

What does history tell us?

Do we live in a risk free world?

The slide following shows just one short week in August 2012!

BOAT SINKS IN MOSCOW, KILLING NINE

Cheers, then screams as plane breaks up

Chinese bullet train crashed into another high-speed train that had stalled after being struck by lightning – 39 dead, 191 injured

Anders Breivik massacres 77

World wide nuclear industry deaths over 2,500 weeks?

Three Mile Island (1979) – 0 Chernobyl (1986) - 50 Fukushima (2011) - 0

And there's more!

Russian Hydroelectric Dam Disaster 76 Dead - 2009

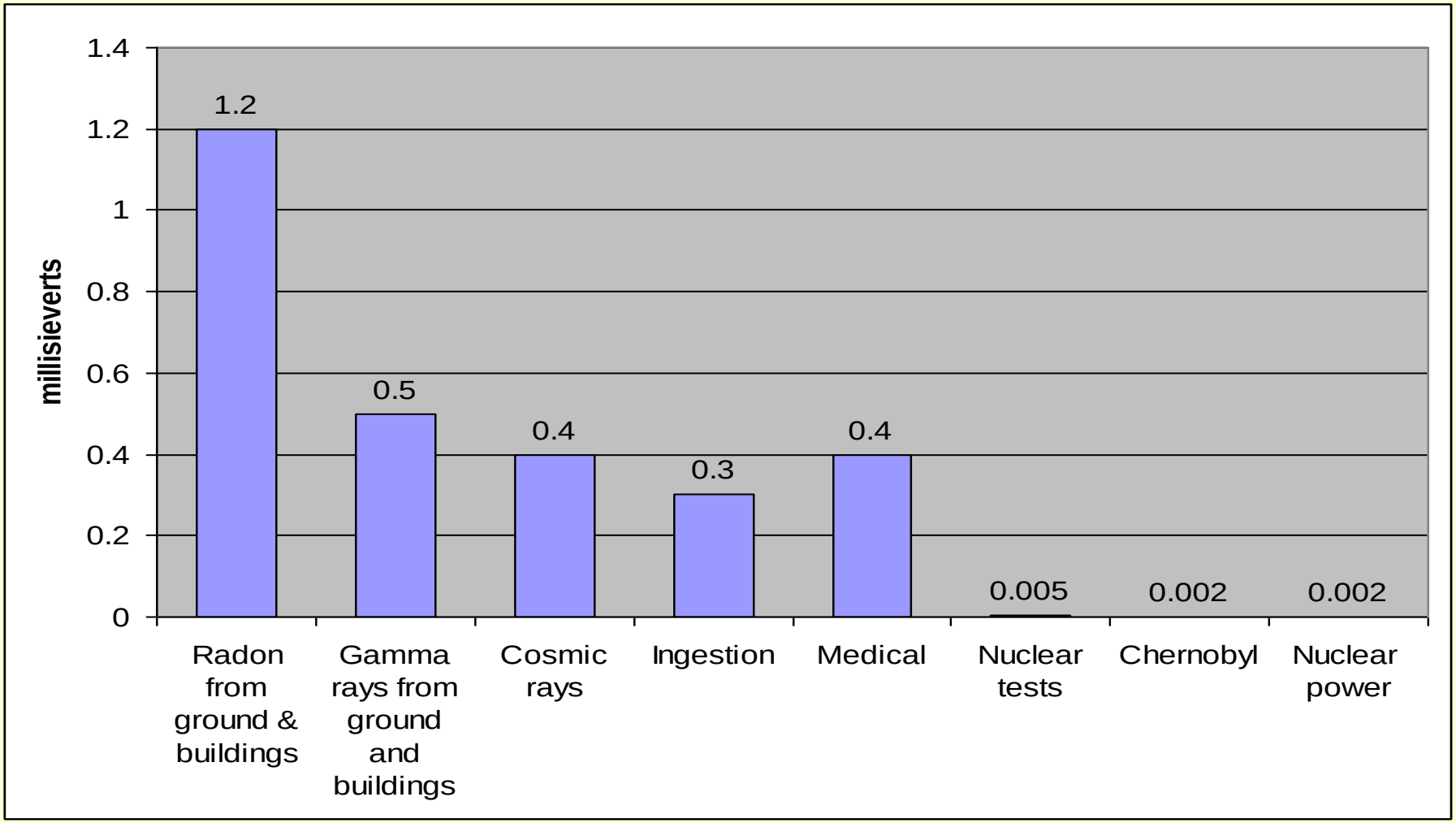
SEVEN DIE IN INDIAN TRAIN ACCIDENT

Banqiao Dam – China - 1975
Worst dam disaster in history
Eventual lives lost ~ 100,000

What about nuclear radiation?

Australian Government
Department of the Prime Minister and Cabinet
Uranium Mining, Processing and Nuclear Energy Review

International Commission on Radiological Protection (IRCP) limit is 1 millisieverts pa above natural background



The contribution from nuclear power is minute!

And how about nuclear power plant safety?

- **Radiation dose return Sydney-London flight greater than living near nuclear power plant for 60 years – but still minimal. Pilots and flight crew don't die of radiation!**

- **Modern reactors, like cars, have dramatically improved safety and operator training post TMI (1979) and inherently unsafe Chernobyl (1986) – 40 and 33 years ago!** *Fukushima (2011) shut down safely, despite the devastating tsunami which killed over 18,000.*

- **Enormous improvements made – Gen III+ and emerging Small Modular Reactors (SMRs) are inherently safe**

So how many people has nuclear power killed?

World wide nuclear industry deaths over 2,500 weeks (over 50 years!)

Three Mile Island (1979)	**0**
Chernobyl (1986)	**~50 to 60**
Fukushima (2011)	**0 or possibly 1**

How does nuclear compare with energy sector safety as a whole? (1996-2000)

Technology	Fatalities	Per GWe/year
Coal	25,107	0.876
Oil	20,283	0.436
Coal (exc China)	7,090	0.690
Natural gas	1,978	0.093
Hydro (inc Banqiao)	29,938	4.265
Hydro (exc Banqiao)	3,938	0.561
Nuclear reactors	31	0.006

Nuclear by comparison is exceptionally safe!

Source: UMPNER Report 2006 – Table 6.1

What about high level nuclear waste (HLW) – the dangerous stuff!

- What volumes are we talking about?
- How do they compare with other generation technology wastes?
- How dangerous is HLW?
- Does HLW have any other uses?
- And finally - how do we dispose of it safely?

Volumes - a typical fuel pellet

Figure 3.7 Fuel pellet

Source: Cameco

And what is that pellet equivalent to?

1 similar spent fuel (HLW) pellet

1 tonne of coal

3 barrels of oil (that's 360 litres!)

3 tonnes CO_2, and

17,000 cubic feet of natural gas!

Uranium is exceptionally concentrated energy!!

More interesting equivalents

1 golf ball of uranium (or thorium) in a Generation IV reactor could provide a lifetime's energy use for a typical Australian - all electricity, transport and food production - yielding the same quantity of spent fuel with near-zero emissions of any sort!

3,200 tonnes of coal (about a 16m cube) will do the same, but with over 11,000 tonnes of CO_2 and much toxic mildly radioactive ash and unhealthy particulates.

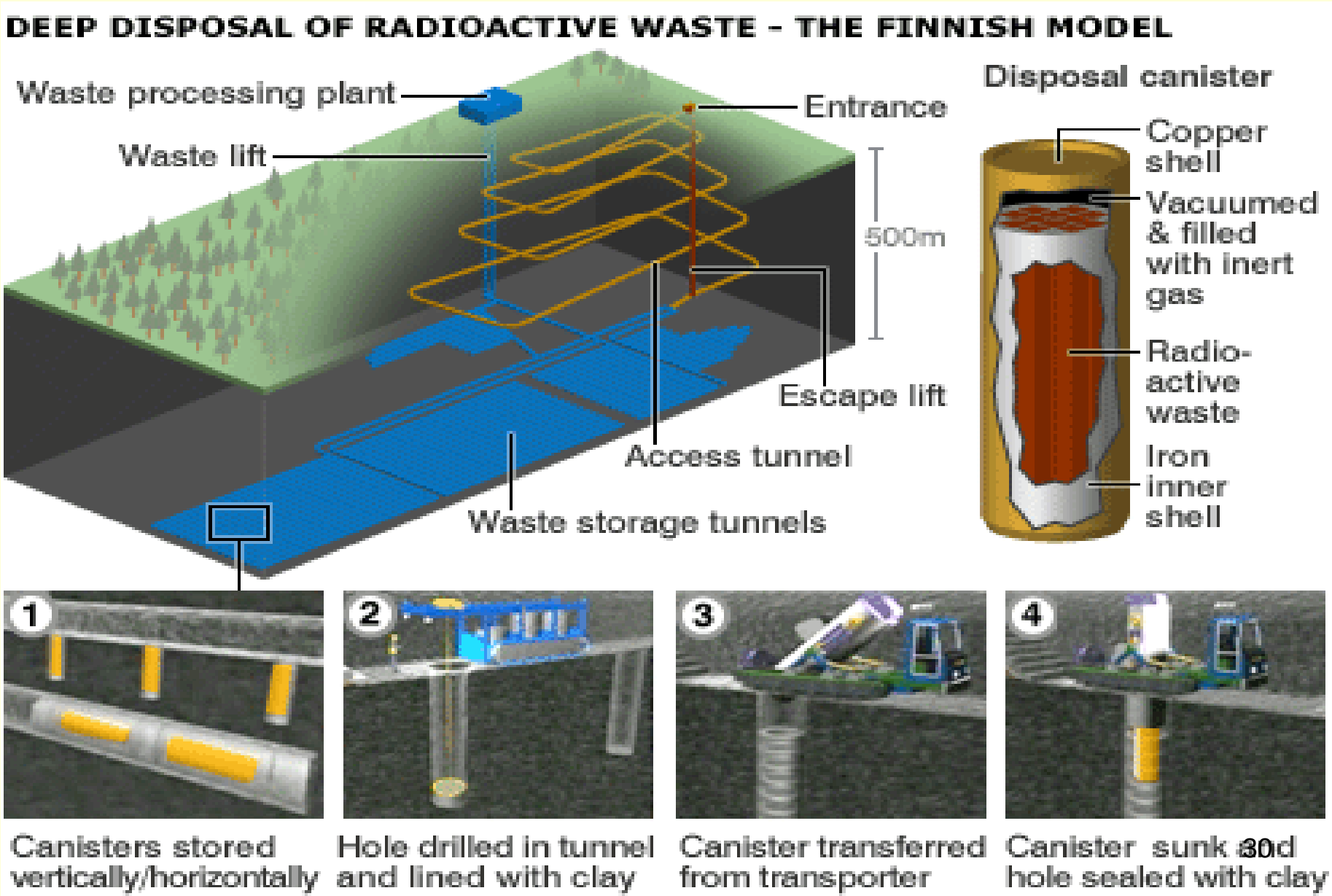
So let's take a quick look at high level (dangerous!!) waste (HLW) disposal options

but first – what is HLW?

Reprocessing spent fuel and high-level waste (HLW) disposal

- Medium term HLW disposal in cooling ponds - heat and radioactivity decays
- Reprocessing HLW to retrieve uranium and plutonium - highly complex – unattractive for Australia
- Long term deep HLW disposal - mature long before Australian need – earliest 2050
- Much of Australia ideal for long term deep (>500m) geological HLW disposal
- HLW volumes small – around one ensuite bathroom per 1000MW reactor year if fuel reprocessed – cf 7 million tonnes of CO_2 for coal

Option 1 - Deep HLW disposal - Finland



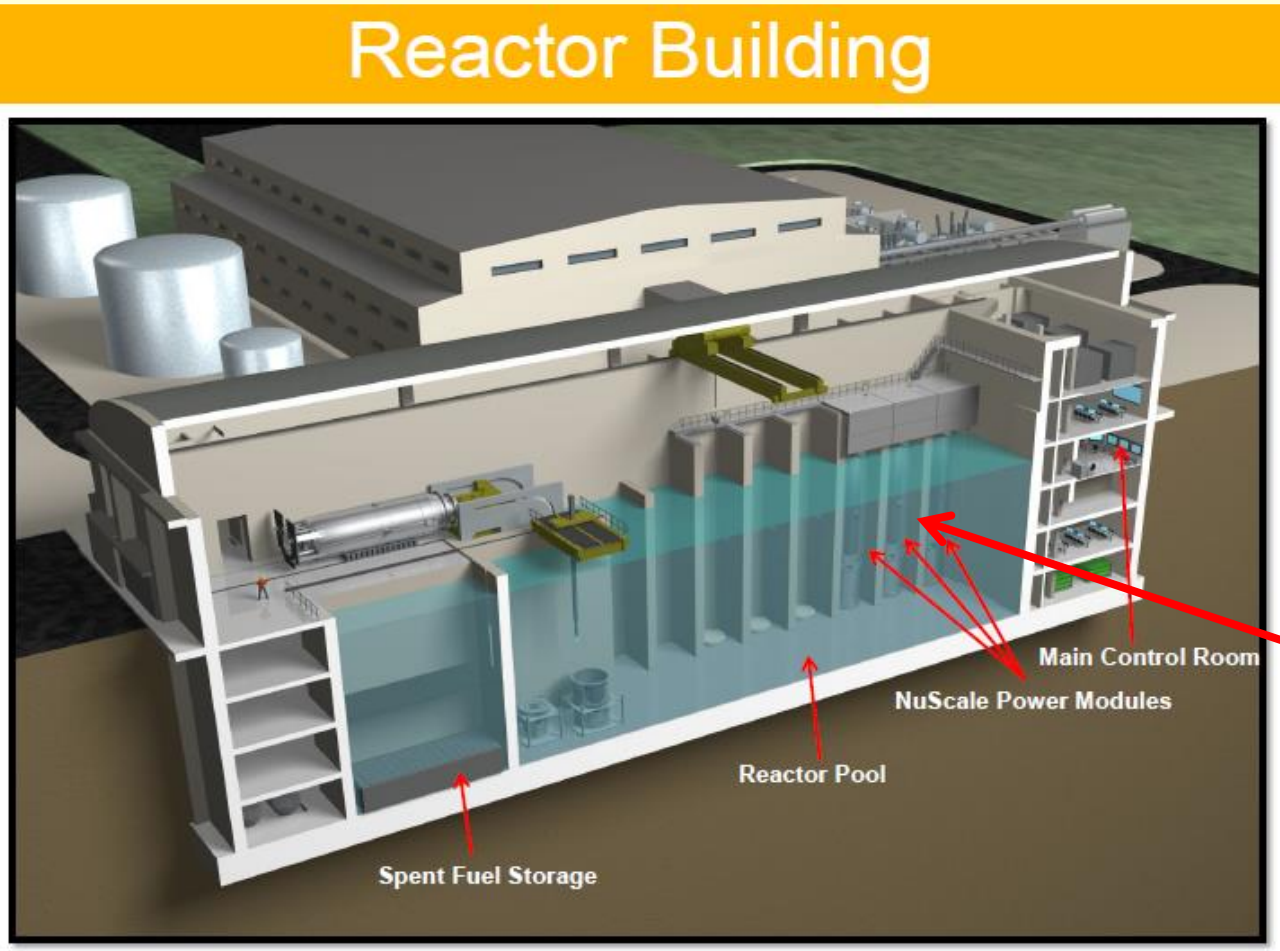
Option 2 - Dry cask HLW disposal – South Korea

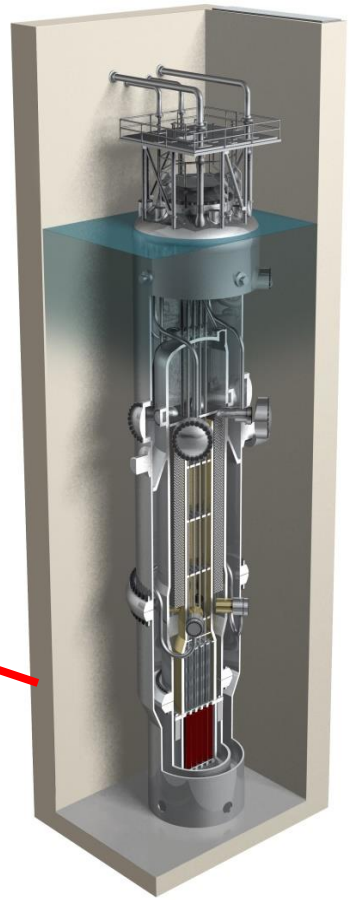
What nuclear fuel cycle technologies could be relevant to Australia?

- **Uranium mining and export?** Absolutely! Build on strength.
- **Conversion, enrichment and fuel fabrication?** Not now. Australia has missed the opportunity boat.
- **Generation III+ reactors?** Now well proven. At >1,000MWe the AP1000 would be ideal for replacing Australia's ageing coal fired stations - (think Hazelwood @ 1,600MW and Liddell @ 2,000MW) - while providing for Australia's future load growth and robust system security (Finkel).
- **Small Modular Reactors (10-300MWe)?** Certainly! Both off-grid (eg remote towns and mines) and on-grid for modular growth on NEM.
- **Gen IV Integrated Fast Reactor (IFR)?** The future! It will 'burn' HLW.
- **HLW disposal or storage?** No reason why not. HLW is needed for IFR.

So let's have a quick look at HLW technologies ….

SMRs - NuScale Power (USA) 60 MWe modules



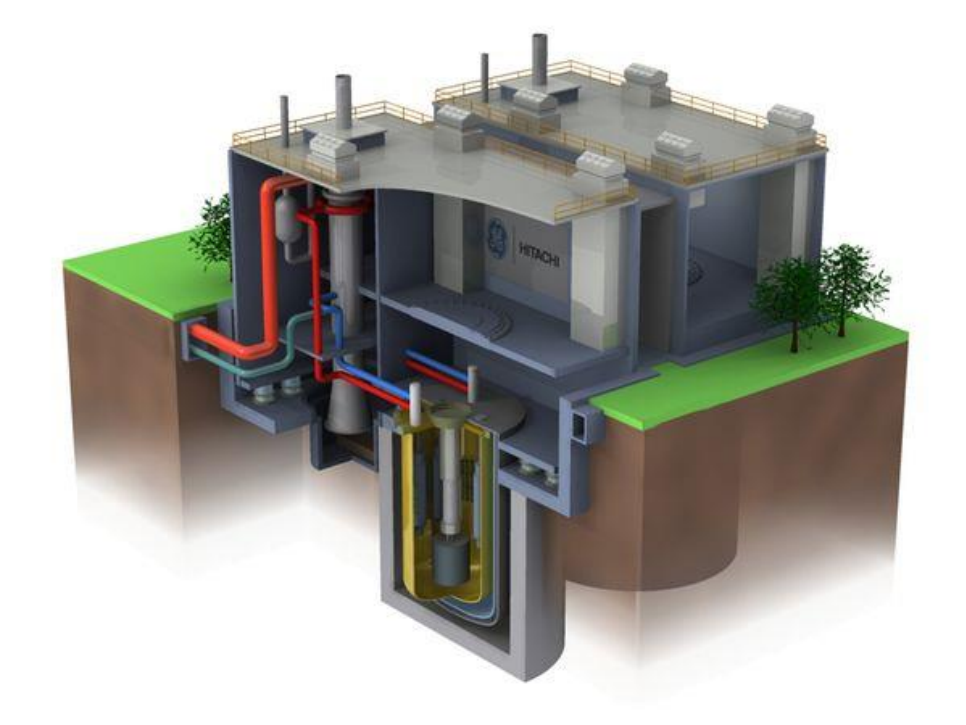


Up to twelve x 60MWe modules = 720MWe. Natural circulation, reactor underground. Passive safety systems – cooled indefinitely without attention – "indefinite coping time" - 18 hectare site – can use dry cooling

Source: NuScale Power

Slide by courtesy of Mr Tony Irwin

Generation IV Integral Fast Reactor (IFR) which 'burns' HLW as fuel while extracting 60 times more energy from uranium than current Gen III reactors!



GE Hitachi S-PRISM 311 MWe IFR module

"Study finds waste-fuelled reactor feasible for UK"

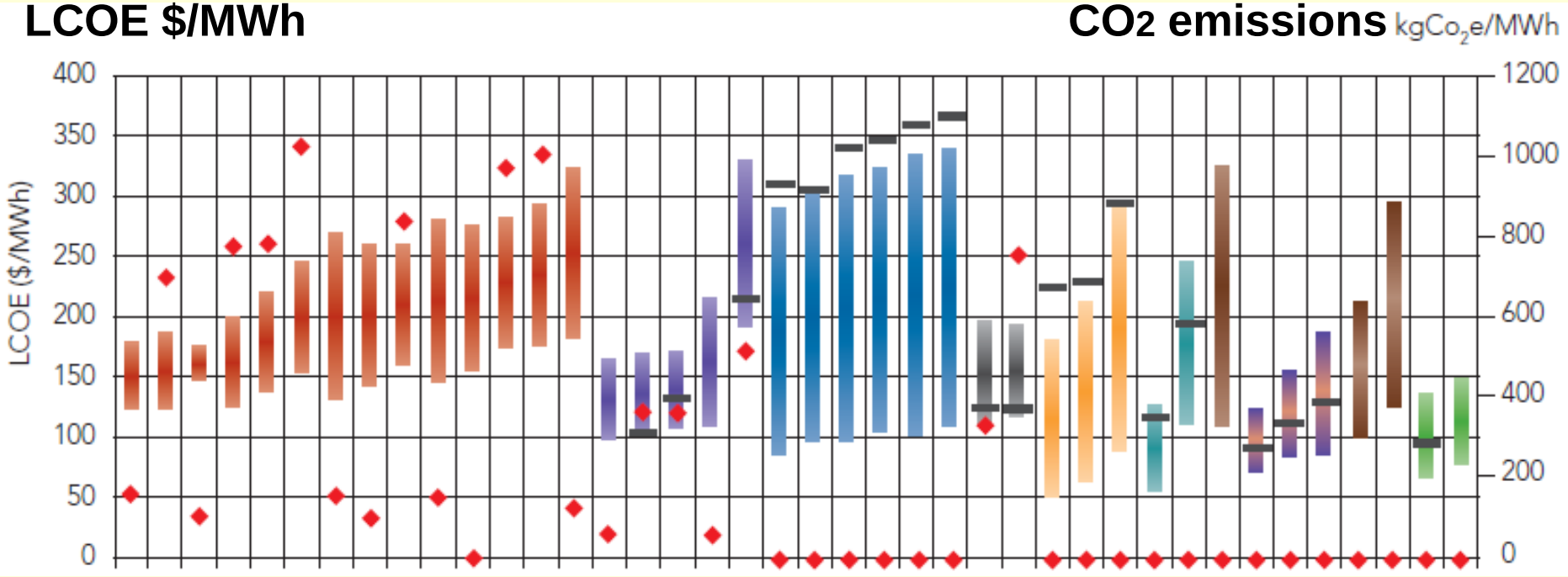
***The report includes a vote of confidence by analysts DBD Ltd, which says that in terms of fuel fabrication, reactor operation, and fuel storage, there are "no fundamental impediments" to licenceability in the UK*.**

July 2012

What are the economics of nuclear power – versus other technologies?

- **Nuclear power, like coal, offers high capacity factors (85-95%) and long plant life (~60+ years) for low cost baseload generation**
- **Variable renewable energy (VRE) technologies, being time and weather dependent, have low capacity factors (from 10-40%) – so need back up and/or storage for 'firming'**
- **Power cost at plant output is expressed at plant boundary as Levelised Cost of Electricity (LCOE) in units of $/MWh.**
- **LCOE includes capital, financing and depreciation, plant life, fuel cost, operation and maintenance and waste disposal, but excludes insurance and decommissioning**
- **But excludes system costs – ie transmission, storage and back up – SLCOEs are typically 40% higher**

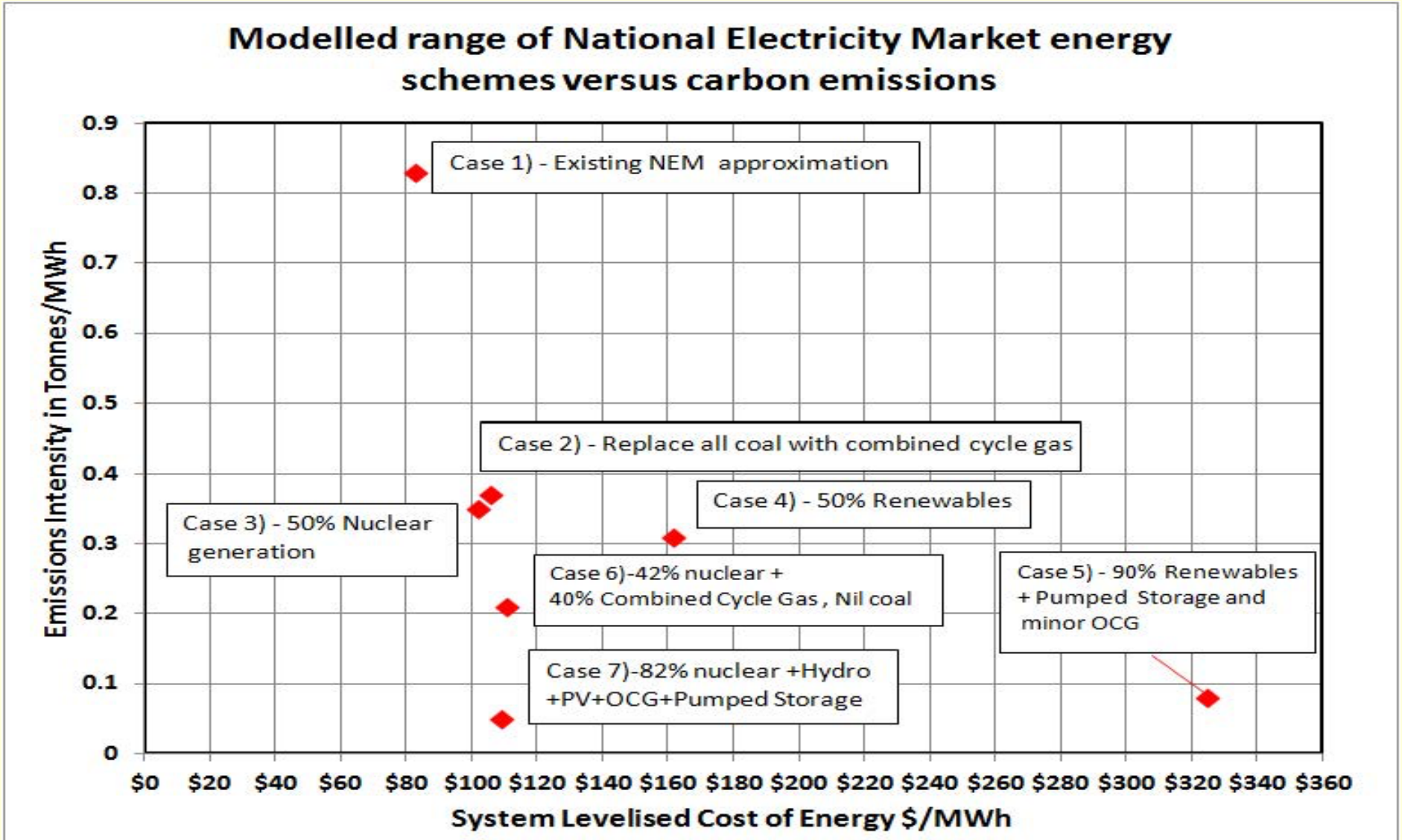
Australian Energy Technology Assessment
Projected technology LCOE ranges (2030)



Red diamonds = emissions intensity kg CO_2/MWh Black bars = LCOE mid-point

Comparison of alternative generation plant mixes – whole of system costs (SLCOE)

By courtesy of Dr Robert Barr AM – EPC Electric Power Consulting Pty Ltd



IEA Electricity Costs Report 2015 – LCOE

Generation technology	Median capacity (MW)	LCOE minimum ($US/MWh)	LCOE Maximum ($US/MWh)
Coal	**772**	83	119
Gas - CCGT	**475**	71	143
Nuclear	**1,250**	51	136
Hydro - Large	**50**	Not given	Not given
Geothermal	**27**	*~125*	*~155*
Biomass	**10**	Not given	Not given
Wind - Onshore	**14**	52	223
Wind - Offshore	**223**	167	327
Solar PV - Residential	**0.005**	162	374
Solar PV - Commercial	**0.14**	121	230
Solar PV - Large (ground)	**4**	103	290
Solar thermal – With storage	**146**	215	315

Given those economics, let's look at the environmental consequences of nuclear energy

First let us see what CSIRO's *eFuture* model predicts for 2030 and 2050:

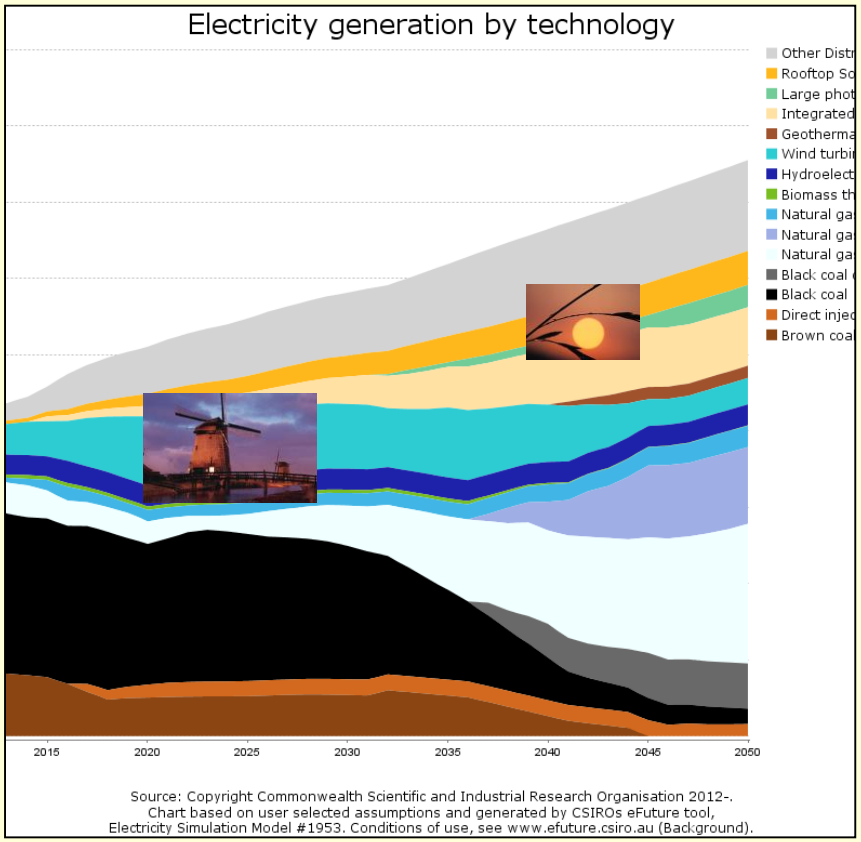
1 - Without nuclear, and

2 - With nuclear

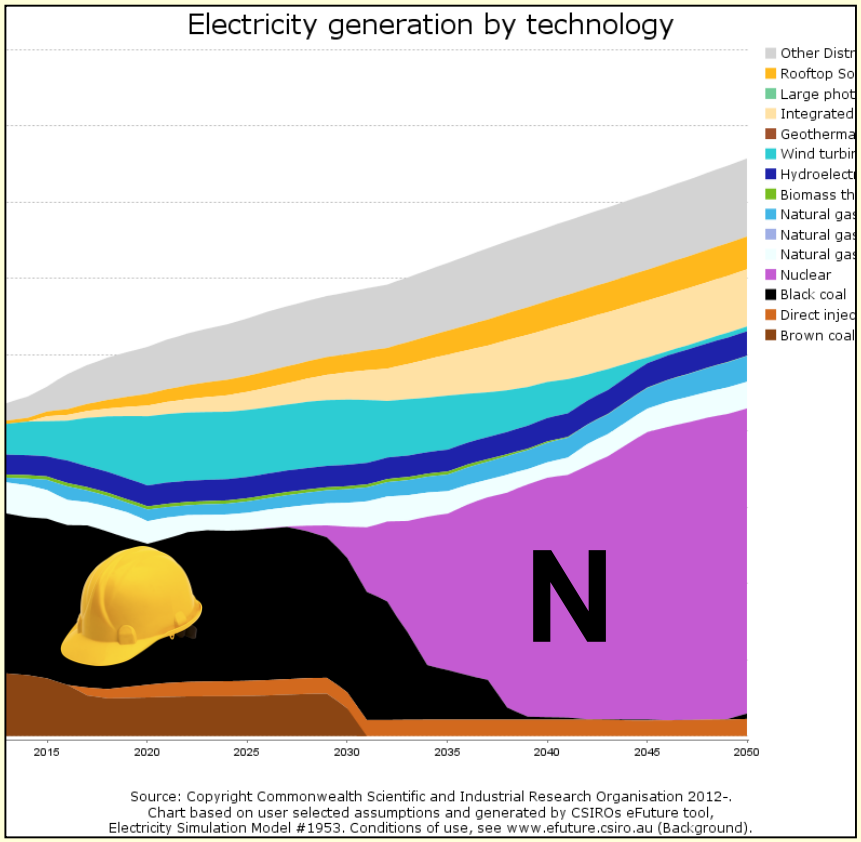
Prepare to be surprised!

Electricity generation by technology

No nuclear

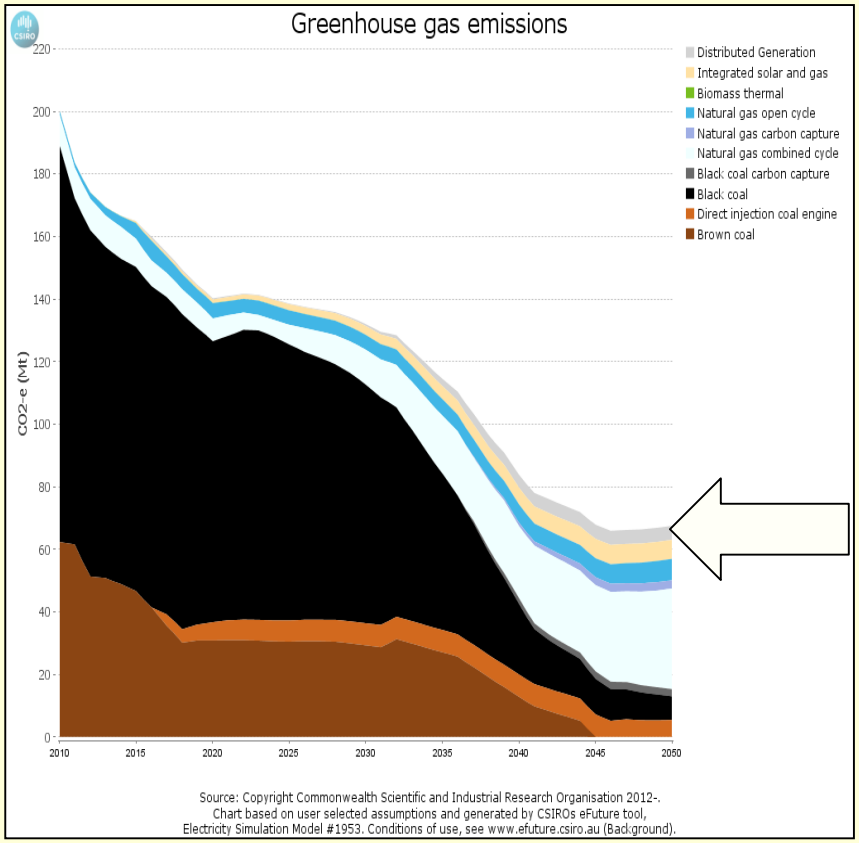


With nuclear (N)

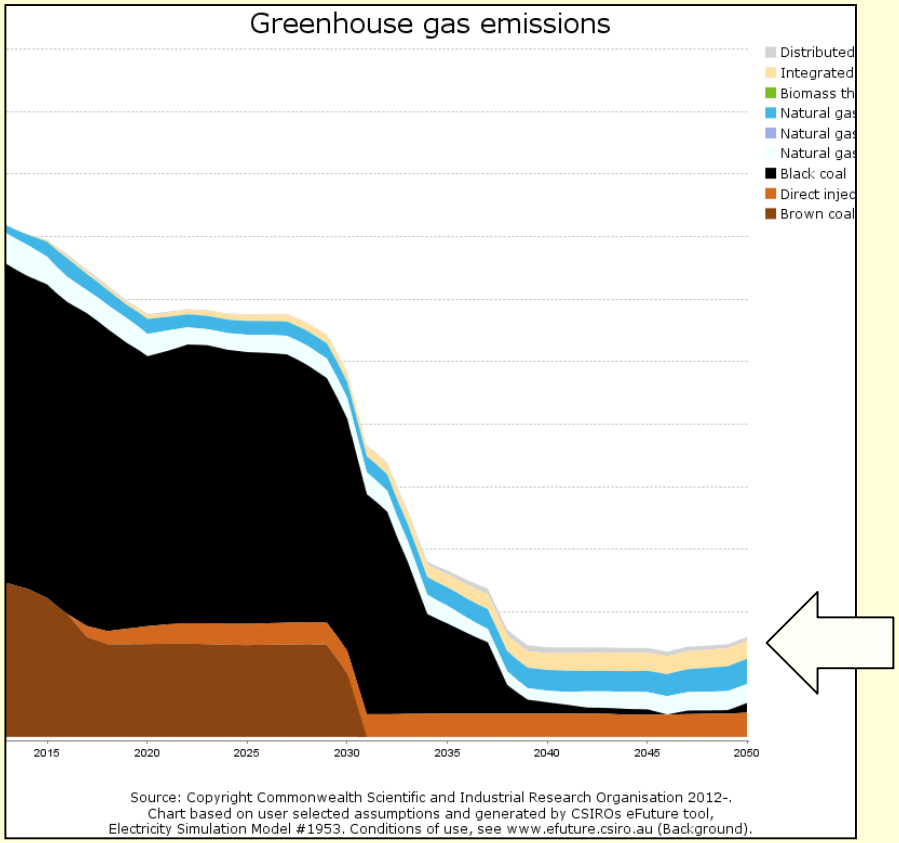


Greenhouse gas emissions

No nuclear

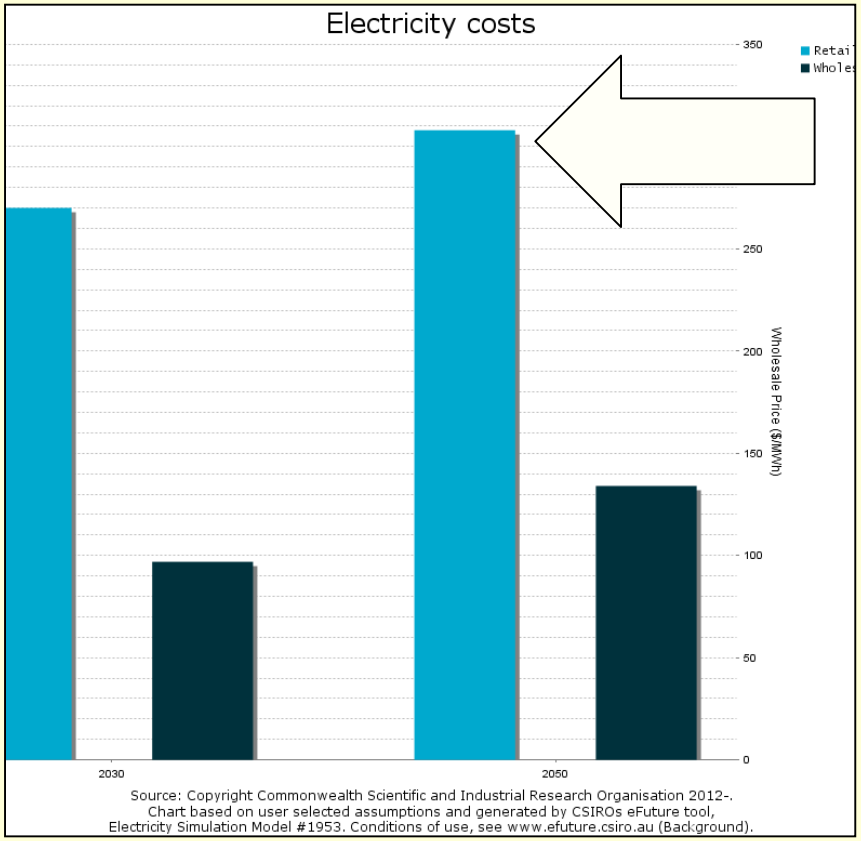


With nuclear

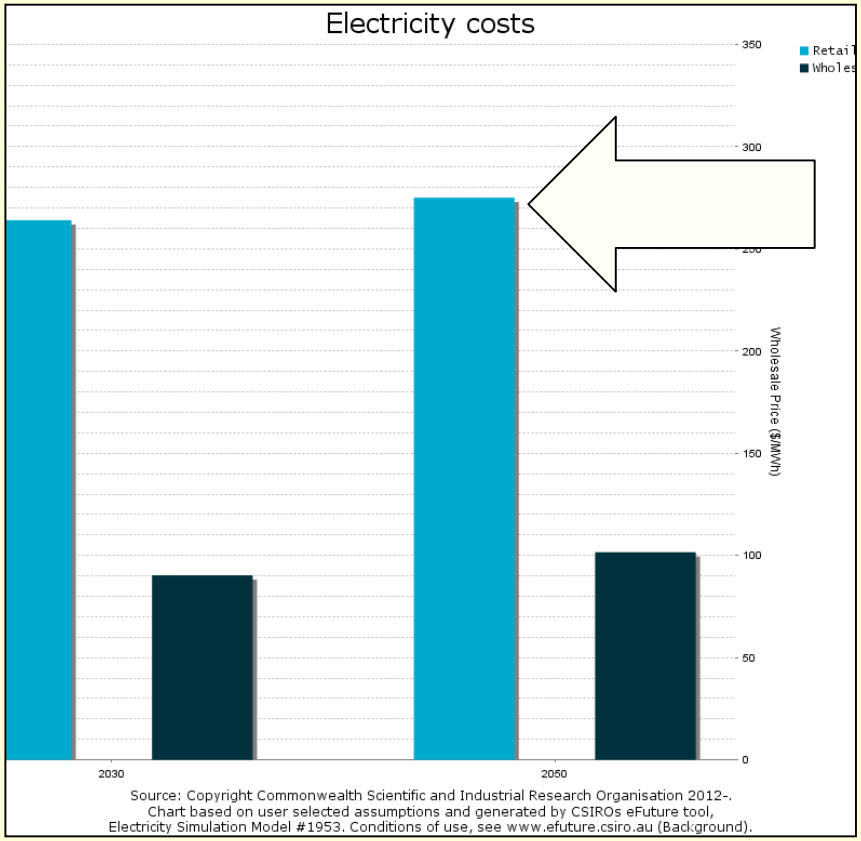


Electricity costs

No nuclear



With nuclear



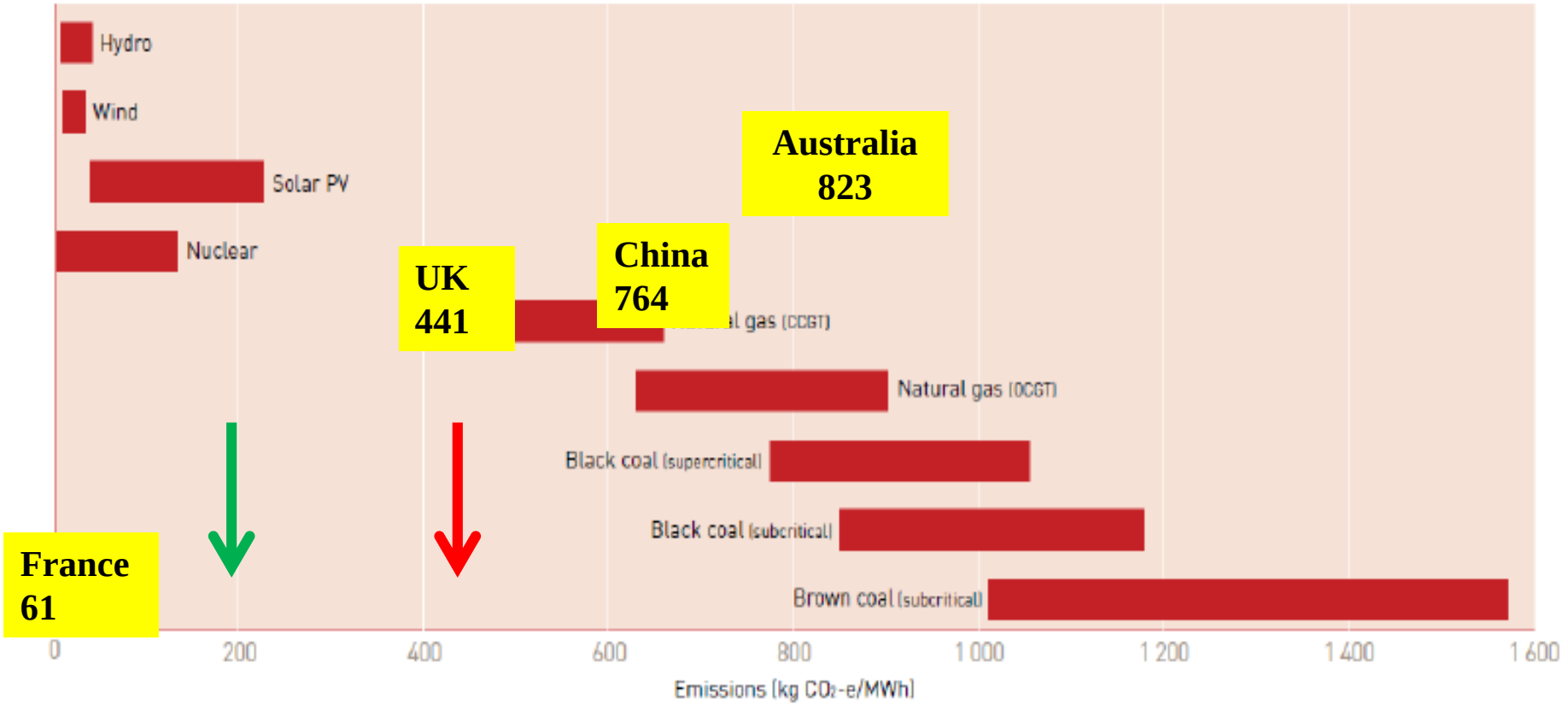
So how does Australia compare with the rest of the world for emissions?

And how do nuclear technologies compare with its alternatives?

Let's have a look!

Lifecycle GHG Emissions from Electricity Generation

kg CO_2 –e emitted per unit of electricity generated (MWh)



Notes: CCGT, combined cycle gas turbine; OCGT, open cycle gas turbine; PV, photovoltaic.
The figure shows the estimated range of emissions for each technology and highlights the most likely emissions value. It includes emissions from power station construction and the extraction of fuel sources.

Source: Australian Energy Regulator, 2009, 'State of the Energy Market'.

Source country figures: IEA 2013 CO2 Emissions from Electricity Generation (latest year data 2011) Slide provided by courtesy of Mr Tony Irwin

4 - Where might Australia go from here?

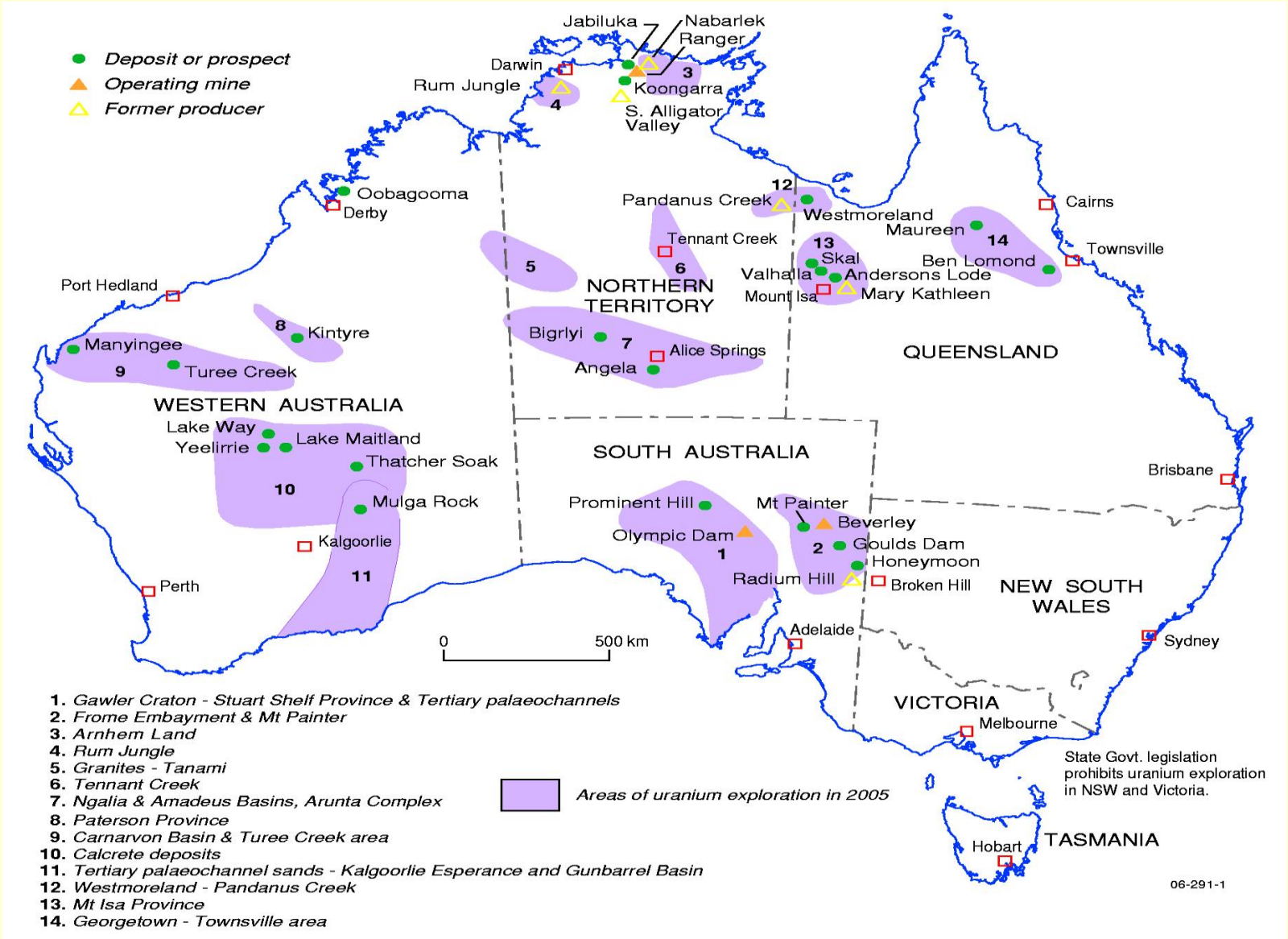
As a starting point let us see where we are now

Australia in the Nuclear Fuel Cycle today

- Uranium - part of Australia's mining heritage. Three mines today – Ranger (NT), Beverley (SA) and Olympic Dam (SA) – with more planned as market recovers.
- Australia's uranium reserves - world's largest.
- In 2009 Australia exported over 9,700 tonnes (over A$ 1.1 billion); today exports are only 7,500 tonnes per annum
- Australia is now the third largest producer after Kazakhstan (~18kta) and Canada (~10kta)
- But – Australia is the only G20 country not using nuclear power! With climate change concerns and fast rising electricity costs, nuclear power is an economic imperative – if policy to reduce CO2 by 80% by 2050 has any meaning!

Uranium deposits are widespread

Australian Government
Department of the Prime Minister and Cabinet
Uranium Mining, Processing and Nuclear Energy Review



Ranger uranium mine

Figure 7.10 Ranger uranium mine, Northern Territory

Source: Skyscans/Energy Resources of Australia Ltd

U_3O_8 (Yellowcake) export

Figure 2.8 Drums of U_3O_8 being loaded into a shipping container for transport

Source: Heathgate Resources

Nuclear power plant credentials

- **Land** – comparable coal PS without chimneys, mine or ash dam. Typical nuclear PS generates ~ 1,000W/m^2, cf concentrated solar ~ 15W/m^2 and offshore wind ~ 3W/m^2.
- **Water** – 20% more than coal – but can use once-through sea/estuary water, evap cooling towers or radiator cooling
- **Air pollution** – >10 times less than coal – no CO2 or particulates
- **Solid waste** – dramatically below coal - radioactivity and toxics contained
- **Access** – as for coal less need for mine proximity
- **Skills** – as for coal plus additional reactor skills
- **Safety** – safest of all generation technologies
- **Location** – anywhere near grid, especially SMRs

So what is the likely future for Australian power generation?

- **Coal, still supplying over 70%, will decline as ageing plants retire**
- **Gas, around 10-15% of annual electricity and rising, will meet peaks. Prices increase from $7/GJ to $12/GJ with strong LNG export market, with community resistance to using the gas under our feet!**
- **Hydro at ~ 8% will remain stable but is topographically limited, although hydro pumped storage will increase (eg Snowy 2.0)**
- **Variable renewables (solar and wind) currently supply around 9%. Both grow strongly but are unsuited for baseload due to low capacity factor, need for storage and non-dispatchability. Pumped storage and batteries, both costly, will add to future portfolios.**
- **Nuclear, dispatchable with high capacity factor, long life and low emissions (CO2 and particulates) is a serious 24/7 option for Australia's future generation to replace coal. It must be considered!**

But Australian infrastructure is on the cliff edge!

"Australia is facing a potential monumental infrastructure disaster as the politicians dither with long-term carbon questions and undertake speculative research on coal technologies.

"Unless someone starts actually making hard decisions now, fasten your safety belts for a very large rise in power prices in the eastern states, which will flow into inflation and interest rates."

COMMENTARY **ROBERT GOTTLIEBSEN 15 Jul 2009**

I leave my closing comments to the Immortal Bard

"There is a tide in the affairs of men.
Which, taken at the flood, leads on to fortune;
Omitted, all the voyage of their life
Is bound in shallows and in miseries.
On such a full sea are we now afloat,
And we must take the current when it serves,
Or lose our ventures."

William Shakespeare *Julius Caesar*

Thank-you!

So what choices would you make?

Generation IV reactors – what are they and what can they do?

- Three fast reactors and three thermal reactors are being developed within the Gen IV Forum (GIF)
- Fast neutron (or breeder) reactors can extract > 60 times more energy from uranium fuel and can 'burn' most of the HLW (actinides) from Gen III reactors. Concept designs are technically proven
- High temperature reactors are passively safe. They generate very high temp process heat, producing low cost power – and are suited to thorium fuel
- Importantly - Australia has recently joined the GIF!

Thorium fuel – for and against – does it have a future?

- **For -** Thorium fuel is 3 times more abundant and easily mined than uranium, does not require enrichment, has far less wastes with lower radiation and reduced waste storage. It is unsuited for nuclear weapons, thus cleaner and safer. A 1965 USA prototype thorium reactor operated successfully and safely for many years. Canada is undertaking a 25MW project in Indonesia; R&D is growing worldwide.

- **Against –** USA's thorium reactor research was discontinued in 1973 on grounds that uranium breeder reactors were more efficient – and the USA needed plutonium! So thorium reactor technical and market development lags that of advanced uranium reactors – just as more efficient electric vehicles lag petrol cars – but their time will come!

Nuclear fusion – is near infinite carbon free energy for our world a real possibility?

- Fusion power is the generation of energy by nuclear fusion; ie the fusing together under pressure of two lighter neutrons to form a single heavier one, giving off heat (the opposite of fission!)
- Massive magnetic confinement is required in a 'tokomak' for fusion to occur - replicating the energy sources of stars including our sun.
- Although tokomak fusion has been achieved, energy delivered is still well below energy consumed for the supercooled magnets.
- The International Thermonuclear Experimental Reactor (ITER) being built at Cadarache, France is a demonstration project aimed to produce 500MW for 1,000 seconds, needing only 50MW to operate.
- The benefits? Plentiful cheap fuel (deuterium and tritium) available, no CO2, minimal radioactivity and minimal environmental impact. But still at least 50 years before delivery of commercial power!