

Hydrogen and Nuclear Energy

An unlikely marriage?

Probus Club of East Wahroonga

25 July 2022

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Presentation outline

1. What is hydrogen? How does it occur in nature? What are its properties?
2. How is hydrogen made and stored? What are the manufacturing pathways?
 1. What is gasification and reforming?
 2. What is electrolysis?
3. What is hydrogen used for? Does it burn? Is it safe?
4. What are the Australian Government's policies and strategies for hydrogen?
5. What are Australia's large scale aspirational uses of hydrogen, and what projects are planned for Australia?
6. Importantly - is there a role for nuclear energy in the hydrogen story?
7. And lastly - what are the economics of hydrogen use at scale?

First - what is hydrogen and how does it occur?

- Hydrogen is the lightest of all chemical elements,
- With symbol H and atomic number 1, but
- Being diatomic its formula is H_2 .
- At standard temp and pressure (STP) it is a colourless odourless gas,
- Non-toxic but highly combustible.
- Most hydrogen on earth exists in combined molecular forms like:
 - water (H_2O)
 - organic compounds (eg natural gas (CH_4), and
 - synthetic nitrogenous fertilisers using ammonia (NH_3)
- It is the most abundant chemical substance in the universe:
 - constituting roughly 75% of all known matter, with
 - stars like our sun consisting mainly of hydrogen in the plasma state.

And what are hydrogen's most relevant attributes?

The gravimetric energy density of H_2 is pretty good, though nowhere near as good as uranium! *(See the yellow golf ball!)*

The volumetric energy density is poor; very many times worse than uranium

H_2 is highly flammable, and indeed explosive, and hard to store in its natural uncombined form.

So is H_2 the much-hyped pathway to the goal of **Net Zero Emissions (NZE) by 2050** and a great new industry for Australia?

Let us see!

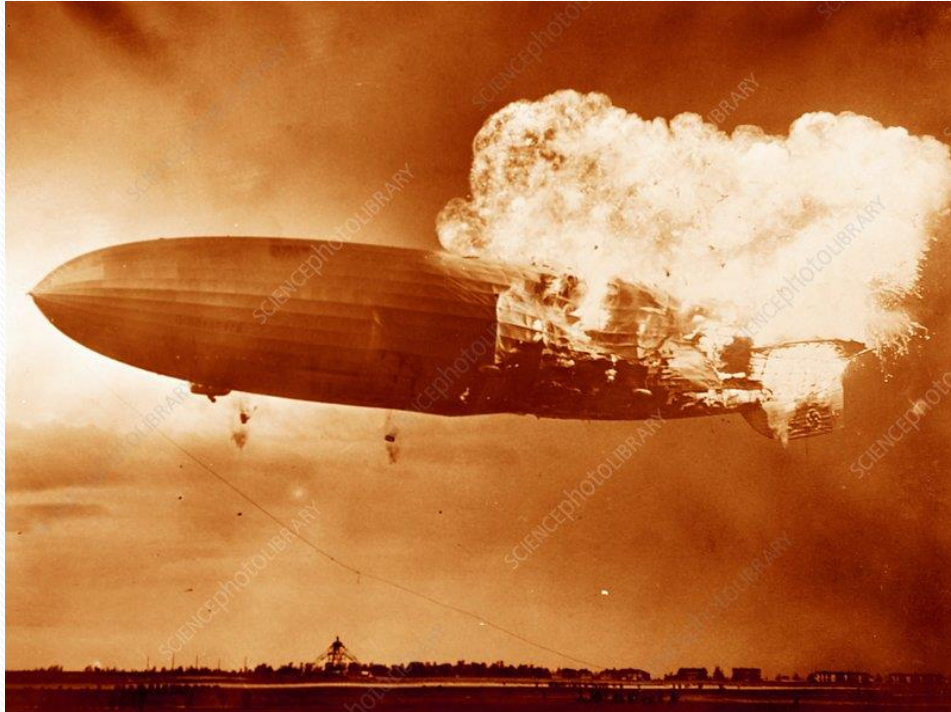
The colours of hydrogen – what do they mean? (from least to most costly)

- Black – steam reforming of natural gas (CH_4) using fossil fuels (coal, oil, gas) without carbon capture and storage (CCS)
- Blue - Steam reforming of natural gas (CH_4) using fossil fuels (coal, oil, gas) with carbon capture and storage (CCS) – but only 9-12% less polluting than Black
- Green – Electrolysis using renewable electricity from wind and solar electricity

and then there's my favourite ... pink!

- Pink – Electrolysis using nuclear power (or nuclear heat)

**But first - is hydrogen safe? Does it burn?
Can it explode? Well yes it certainly can!**



The German airship Hindenburg is famous for the disaster of 6th May 1937, when it caught fire and was destroyed attempting to dock at Lakehurst, New Jersey.

Of 97 crew and passengers 35 were killed as well as one ground crew. The airship was filled with **hydrogen, a highly flammable gas.**

The disaster well marked the end of the hydrogen filled airship era!

How is hydrogen made?

1 - Steam Methane Reforming
using natural gas

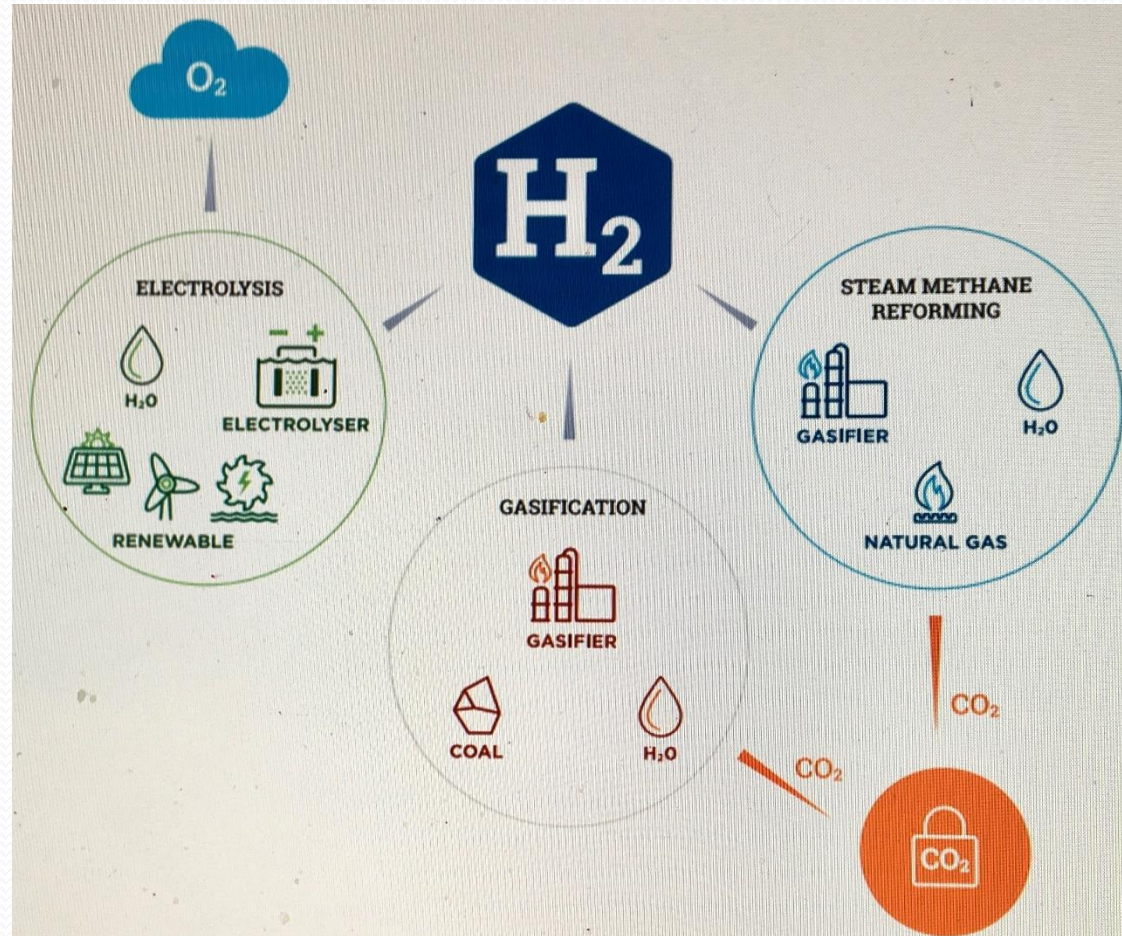
2 - Gasification using coal for
heat and methane production
(*but could use nuclear heat!*)

Author's italics!

3 - Electrolysis using
renewable electricity (*but
could use nuclear electricity!*)

Author's italics!

Source: Australia's National Hydrogen Strategy



How is hydrogen made?

Direct Current Electrolysers

The global capacity of electrolysers has doubled over 5 years to reach just over 300MW by 2021 (mainly in Europe, but Australia is very ambitious).

World electrolyser H₂ production is projected to reach 8Mt/a by 2030. But 80Mt/a is needed by 2050 to meet NZE 2050 targets- with massive attendant growth in power generation.

This offers a massive role for VRE, battery and HV transmission investment.

Or, better, an opening for SMRs? *I think the latter!*

So what is hydrogen used for today?

Hydrogen has numerous uses and applications – some unavoidable and in wide commercial use today; others emerging and prospective; while some are very highly speculative and assuredly uncompetitive!

At the end of the talk, when we look at economics, we will examine the Liebreich **Hydrogen Ladder** to form and try to rank hydrogen's applications in some order of reality from 'unavoidable' to 'possible' to 'uncompetitive'.

The uses of hydrogen - commercial, prospective and speculative - include the following, in declining order:

- Nitrogenous fertilisers, oil refining (hydrocracking) and petrochemicals (account for ~2% of global emissions, with no known alternatives).
- Transport and industry – including shipping**, off-road heavy vehicles, remote heavy mining trucks, remote trains, chemical feedstock – and possibly medium haul aviation**.
- More transport – including long distance trucks and coaches, rural trains and possibly light aviation.
- High temperature industrial heat, commercial heating, mid and low temperature heating and domestic heating.
- Metro trains and buses, hydrogen fuel cell cars, and
- Power system generation and balancing.

** H₂ from NH₃

What is Australia's National Hydrogen Strategy?

*Australia's Technology Investment Roadmap:
Low Emissions Technology Statement 2021*

identifies H₂ as one of its six **'Priority Technologies'**

So where does it fit into Net Zero Emissions?

Note: *Australia's Technology Investment Roadmap: Low Emissions Technology Statement 2021* does not include nuclear energy as a priority technology. See next slide!

Australia's Technology Investment Roadmap: Low Emissions Technology Statement 2021 - **six priority technologies are:**



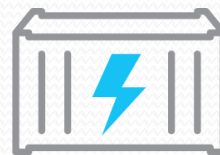
Clean hydrogen

Goal - production @
<\$2/kg



Ultra-low-cost solar

Goal - electricity @
\$15/MWh



Energy storage

Goal - storage cost @
<\$100/MWh



Low emission materials

Goals - steel @ <\$700/tonne
& aluminium @ <\$2,200/tonne



Carbon capture and storage

Goal - CO2 storage @
<20/tonne



Soil carbon

Goal - measurement @
<\$3/hectare/annum



So what are the potential uses for Australian hydrogen?

- 1 - Chemical feedstock (nitrogenous fertilisers - via NH_3)
- 2 - Exports (potentially significant)
- 3 - Heat (space heating and industrial processes)
- 4 - Transport (trucks, buses, trains, ships, ... and planes?)
- 5 - Electricity generation (via gas turbines)



**Let us now look at some projects we
Australians, both Government and
private sector, exist now or are
projected**

Incitec Fertilisers, Kooragang Island, Newcastle



This long-established plant is fed by natural gas (CH_4) to make ammonia (NH_3) based nitrogenous fertilisers.

If H_2 is added to the CH_4 feedstock it would enhance H_2 content and reduce carbon CO_2 waste to the atmosphere.



But making fertilisers (MAP and DAP) isn't quite that simple! Firstly – what are MAP and DAP fertilisers – and secondly, let's have a look at the supply chain

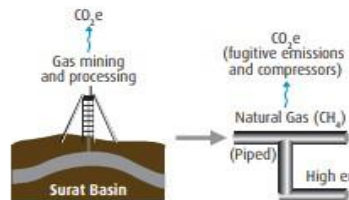
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What are MAP and DAP fertilisers?

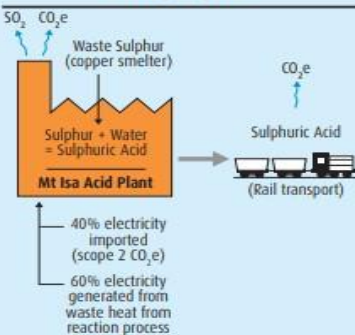
MAP and DAP are made by ammoniating phosphoric acid. The ratio of ammonia (NH_3) to phosphoric acid (H_3PO_4) determines which product, **monoammonium phosphate (MAP) or diammonium phosphate (DAP)**, is produced. Here are the formulae:

- Monammonium phosphate: $\text{NH}_3 + \text{H}_3\text{PO}_4 \rightarrow \text{NH}_4\text{H}_2\text{PO}_4$
- Diammonium phosphate: $2\text{NH}_3 + \text{H}_3\text{PO}_4 \rightarrow (\text{NH}_4)_2\text{HPO}_4$

Producing MAP and DAP Ammonia Based Fertilisers (Phosphate Hill Process)



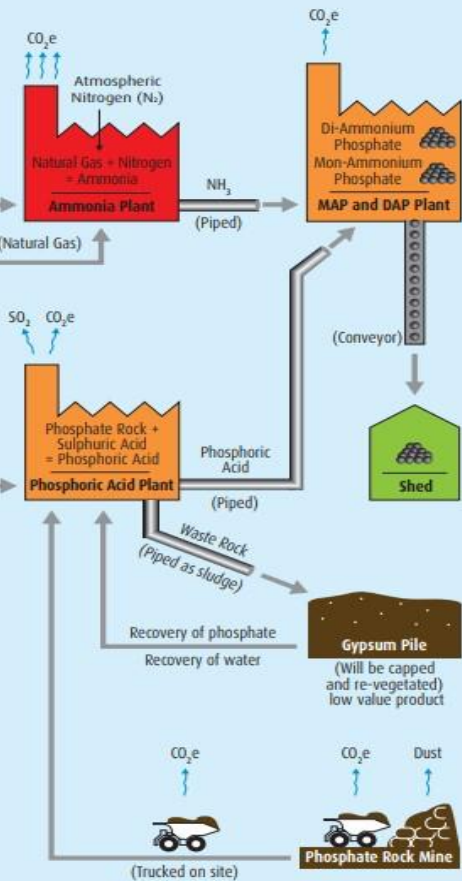
MT ISA SITE



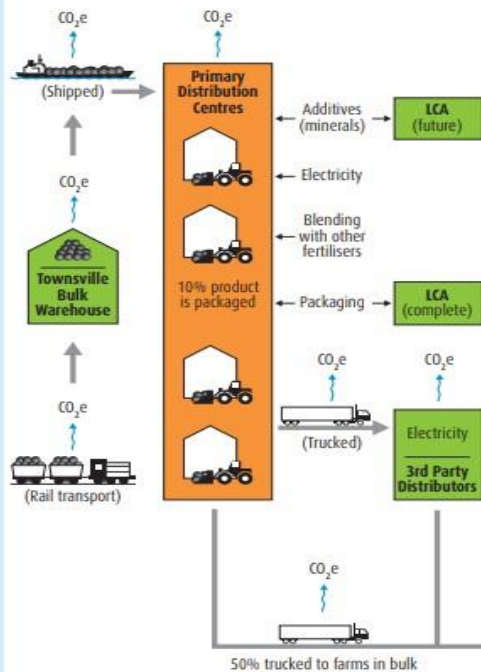
Energy use and emissions

Very high Medium Low

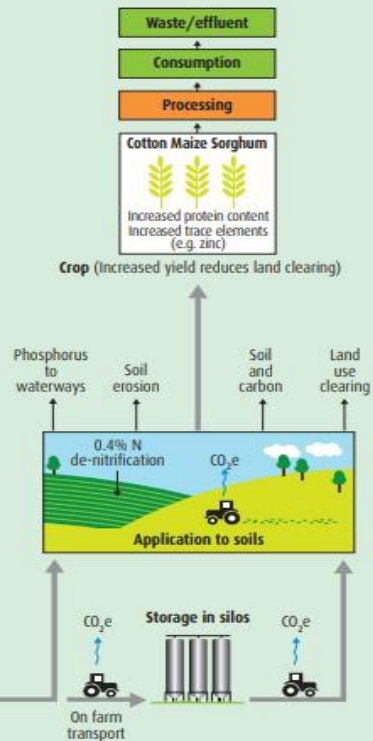
PHOSPHATE HILL SITE



DISTRIBUTION



USE AT FARM





Making fertilisers is a major use for hydrogen. Let us now look at more prospective uses and projects in hand to demonstrate proof of concept. There are several.

Jemena Western Sydney Green Gas (WSGGP) Project



Jemena Western Sydney Green Gas (WSGGP) Project



South Australia - \$750M hydrogen electrolyser proposal



Port Pirie

Proposal for world's largest hydrogen electrolyser, adjacent Nyrstar lead smelter.

Construction 2023?

Creates 150-300 new jobs.

Purpose? NH_3 export and local heavy transport fuel, with O_2 used in lead smelter.

Fortescue Future Industries (FFI) - Gibson Island Ammonia Plant



FFI plans to convert Incitec Pivot's Gibson Island plant to hydrogen from renewable energy, replacing increasingly costly gas.

The plant would consume 50kt/a of renewable (**aka GREEN**) H_2 to produce 300kt/a of NH_3 , using an onsite electrolysis plant, driven by 1,000MW of wind and solar.

Incitec had planned to shut down Gibson Island as its gas was getting too expensive.

Could Twiggy's **GREEN H_2** offer a new lifeline?

Woodside Petroleum H2Perth Project



A conceptual image of H2Perth.

The plant is to be fed by natural gas (CH_4) to make ammonia (NH_3) and water (H_2O) by electrolysis, using **GREEN** electricity!

Fortescue Future Industries mine truck project

*“**Green** hydrogen is the reality and truth of employment!” says Twiggy.*

The 2,000kW diesel engine of a huge 240t payload mine truck has been replaced by a 180kW hydrogen fuel cell and a 300kWh battery hybrid power unit.

It is almost silent (*“The sound of the future”* eulogises Twiggy!)

For remote mining trucks, I think Twiggy could be right!



Cars? The Hyundai hydrogen car



And another hydrogen car – the Toyota Mirai



And there's even a concept hydrogen ute!



**But will it ever make
it to the market?**

We'll see!

Are hydrogen cars widespread? Certainly not yet!

Alan Finkel filling his
Toyota Mirae with
hydrogen

but ...

it's from the only H₂
filling station in
Australia (in Canberra
of course!)

Source *The Australian* EV supplement



Former chief scientist Alan
Finkel charges his new
hydrogen-powered electric car.

Hydrogen trucks - Hyzon Motors (USA) to deliver five ultra heavy (140t) hydrogen trucks to Sun Metals zinc plant in Townsville



Courtesy Dr Alan Finkel

Hydrogen trains - Alstom CORADIA iLINT

Austria
Italy
Netherlands
France
Germany

1,000 km range



Courtesy Dr Alan Finkel



**What role if any could
nuclear energy play in the
hydrogen story?**

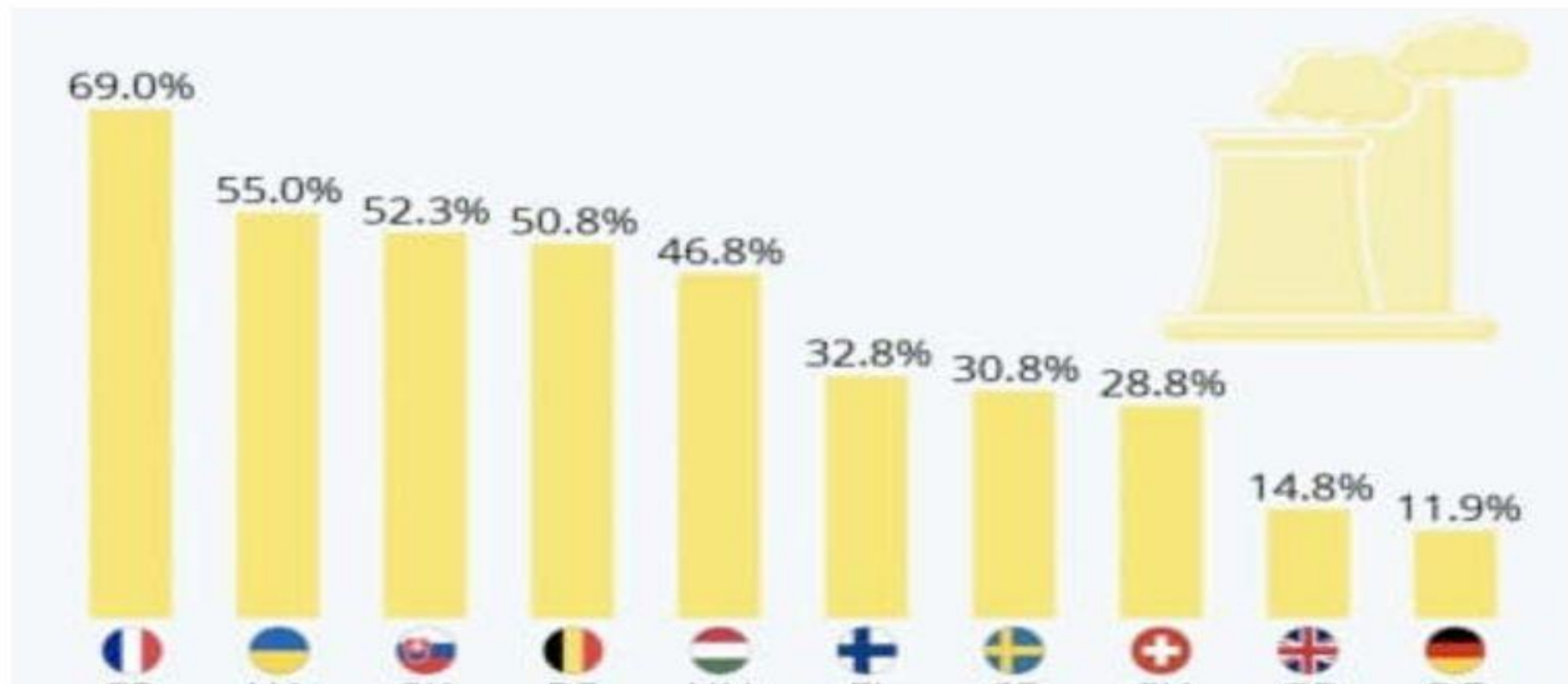
Let us see!

Firstly – there is a mature nuclear energy industry worldwide

- Over 50 reactors under construction - over **60GWe** (more than Australia's total generating capacity!) - in Bangladesh, Belarus, Brazil, China (18GWe), India (4GWe), S Korea (5GWe), Russia, Turkey, Ukraine, UAE (4GWe), UK (3GWe) and the USA,
- Over 100 reactors planned – over **100GWe**,
- And 300 reactors proposed – over **350GWe**!
- Australia? **One** operational research reactor (OPAL), no power reactors under construction, planned or proposed; not even a **Priority Project** in the Technology Investment Roadmap for NZE 2050. Currently *proven technology SMRs* are listed in the TIR as an **Emerging Technology**, along with *low emissions aircraft* and *solar thermal*. Meantime Australia monitors overseas SMR development, maintains a 'watching brief' and keeps nuclear power illegal – while selling uranium into a buoyant market!
- Is Australia hypocritical? Politically blind? Or just foolish?

Countries reliant on nuclear power

Nuclear power's share of total electricity in 2021



The most promising nuclear power generation options for Australia appear to be Small Modular Reactors (SMRs) which:

- ✓ are factory built and tested before despatch,
- ✓ are readily transportable by road, rail and ship,
- ✓ are intrinsically ultra safe,
- ✓ can be air cooled where water is scarce,
- ✓ are modularised for progressive delivery and deployment, and
- ✓ are ideal for location at retired coal power station sites.

Most importantly SMRs can produce both electricity and heat, both 365/24/7 reliable inputs for hydrogen production.

Unlike solar PV and wind (VREs) which can only produce intermittent electricity and no heat!

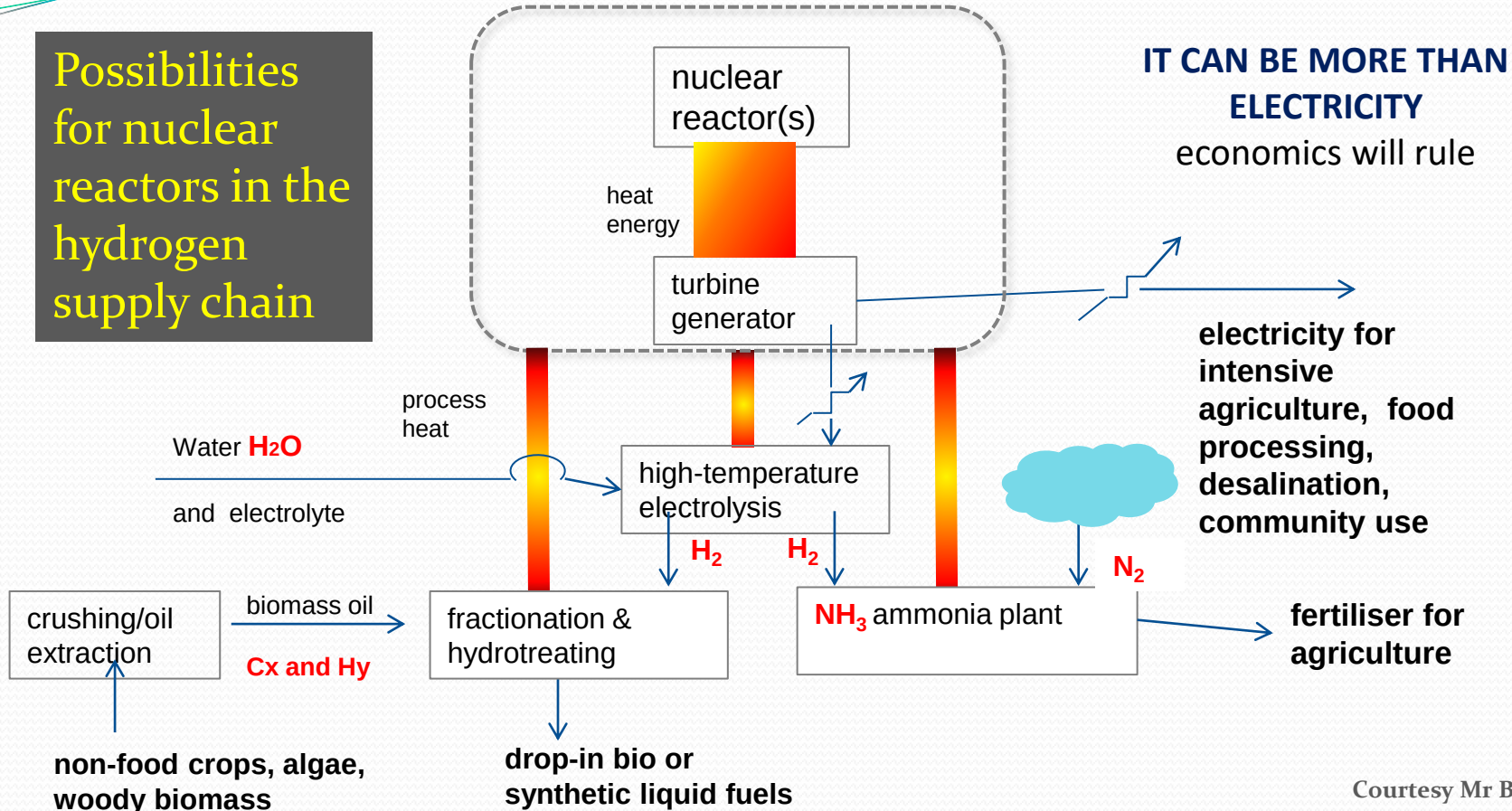
Candidate Generation IV reactors and their key features (1)

- **Very high temperature reactor (VHTR)**
 - Helium or molten salt coolant – very high outlet temperature (1,000 degrees C)
 - block or pebble bed fuel – good for industrial process heat or hydrogen production – strong Chinese interest
- **Molten salt reactor (MSR)**
 - Fuel and primary coolant are a complex molten salt mixture – can be thermal or fast – low waste – many designs – potentially the greatest inherent safety of all six reactor types
- **Supercritical water-cooled reactor (SCWR)**
 - Essentially light water reactors (LWRs) operating at higher temperatures – hence high thermal efficiency (45%) – aimed at generating low-cost electricity with simplified plant – strong commercial interest worldwide

Candidate Generation IV reactors and their key features (2)

- **Gas-cooled fast reactor (GFR)**
 - Helium cooled – high outlet temp 850 degrees C – uses direct Brayton cycle gas turbine for high efficiency – strong European interest
- **Sodium-cooled fast reactor (SFR)**
 - Proven in Russia at 800MWe – strong Indian interest – also USA – GE-Hitachi PRISM Integral Fast Reactor – burns spent fuel (aka HLW)
- **Lead-cooled fast reactor (LFR)**
 - Lead bismuth eutectic (LBE) coolant – long refueling intervals – high outlet temp up to 800 degrees C – suitable for hydrogen production

Possibilities for nuclear reactors in the hydrogen supply chain

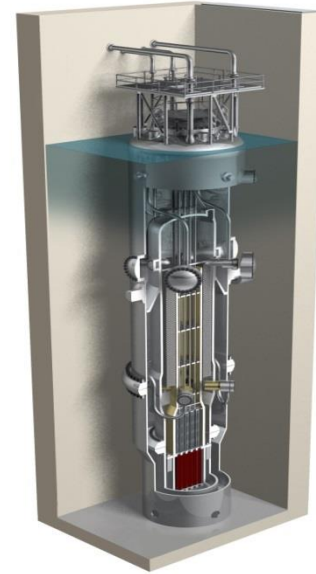
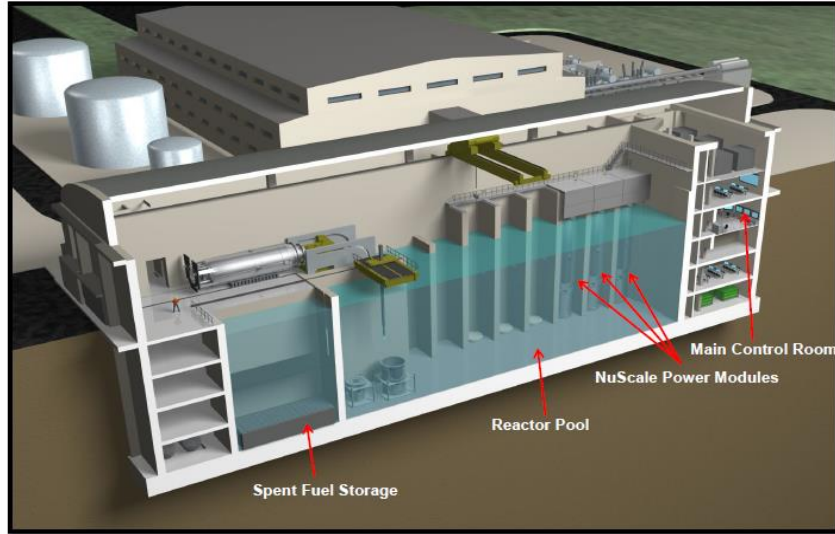


Possible small nuclear reactors (SMRs) for Australia

- Most probably Australia's entry point to nuclear power generation will be via Small Modular Reactors (SMRs)
- At this stage possible candidates include:
 - The NuScale 12 x 77MWe modules – totalling 884MWe,
 - The GE-Hitachi BWRX 300MW x 2 modules – totalling 600MWe,
 - The Rolls Royce 1 x 470MWe module – totalling 470MWe and, as a long shot
 - The GE-Hitachi Integrated Fast Reactor – just wait!
- Or none at all if we continue to sit on our hands!

SMRs - NuScale Power (USA) - 12 x 77MWe modules

Reactor Building



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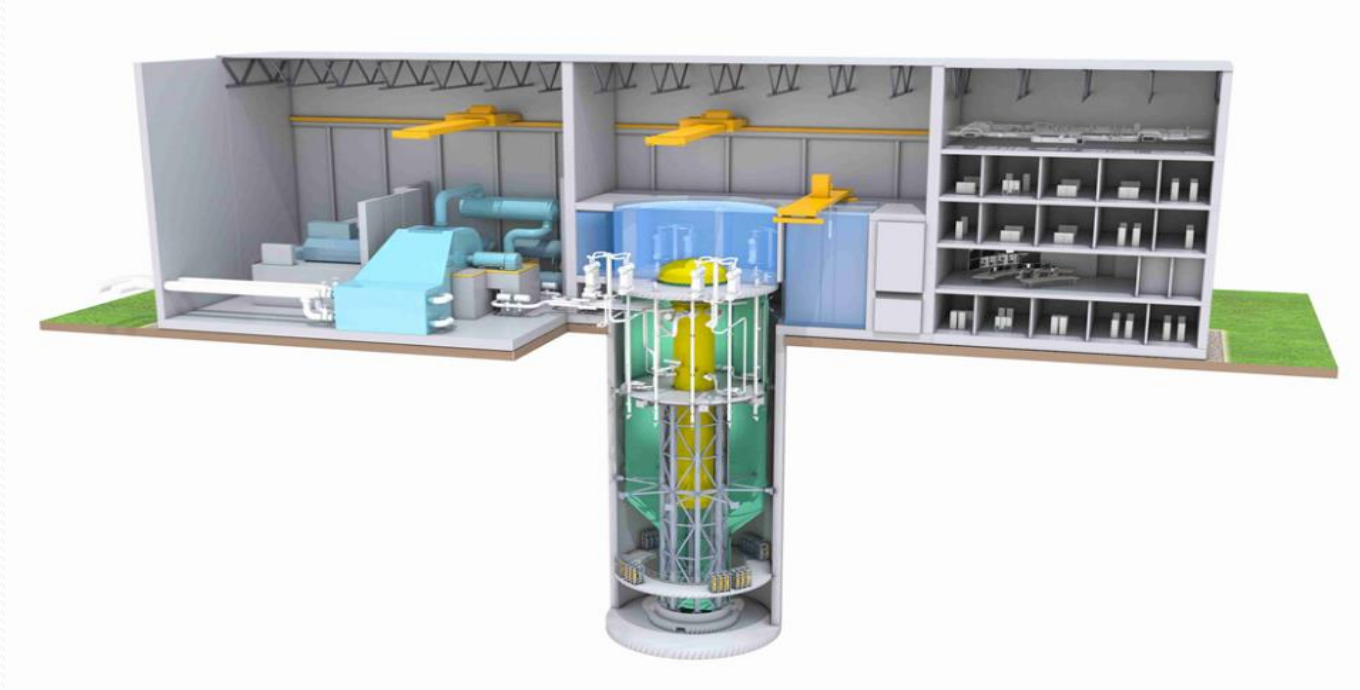
Up to twelve x 77MWe modules = 884MWe. Natural circulation, underground reactor. Passive safety systems – cooled indefinitely without attention with indefinite coping time. 18 hectare site – can use dry cooling.

SMRs - NuScale Power (USA)

12 x 77MWe modules – Site layout



SMRs – GE-Hitachi BWRX 300MWe Module



GE-Hitachi BWRX 300MWe boiling water nuclear power plant
US\$2,500/kWe - allow \$A4,580/kWe

SMRs – GE-Hitachi BWRX 300

2 x 300 MWe modules – View 1



Courtesy Mr Robert Parker

Source GE-Hitachi

SMRs – GE-Hitachi BWRX 300

2 x 300 MWe modules – View 2



Courtesy Mr Barry Murphy

Source GE-Hitachi

SMRs – Rolls-Royce 470 MWe Module



Source Rolls Royce

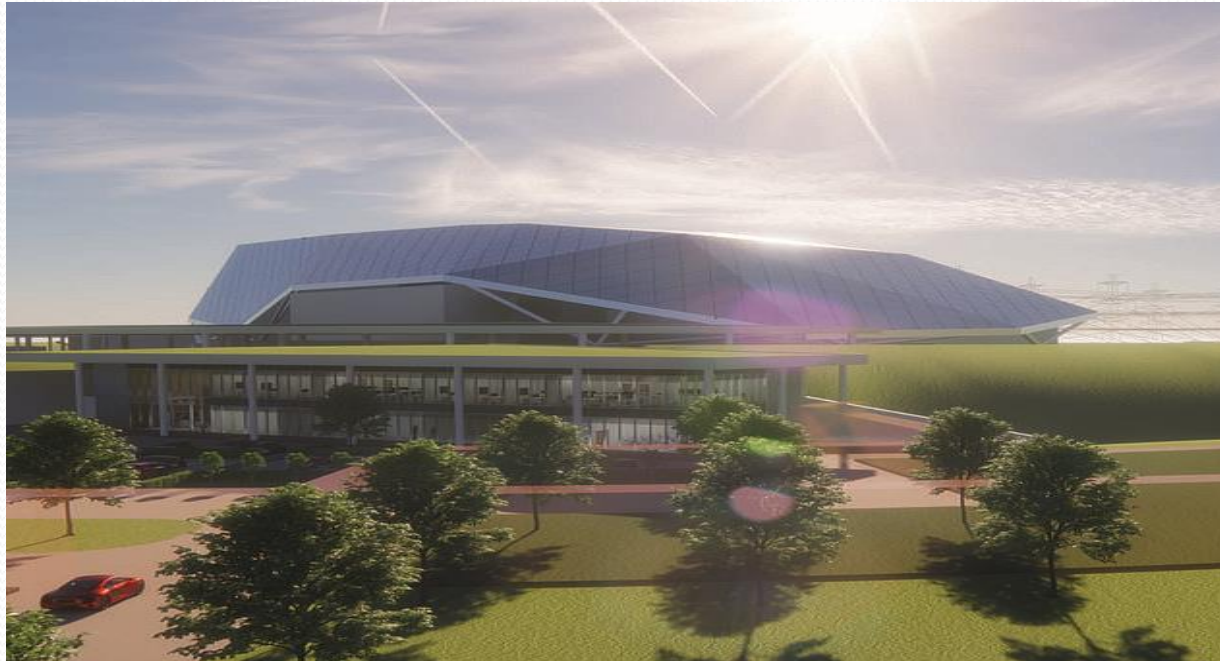
SMRs – Rolls-Royce 470 MWe Module

Site layout – View 1



SMRs – Rolls-Royce 470 MWe Module

Site Layout – View 2

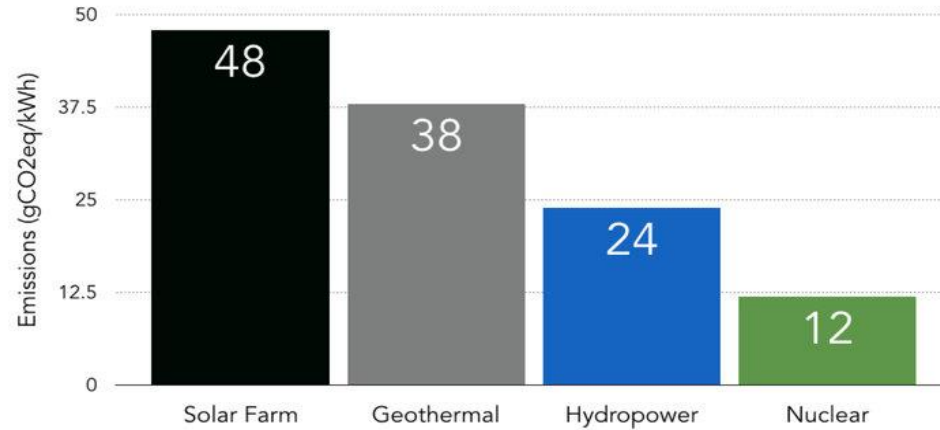


The switch from an 'armadillo'-shaped building to one with a 'faceted' top allowing the roof to wrap around the inner workings made it more efficient.

Courtesy Mr Barry Murphy Source Rolls Royce

Relative renewable sources of pollution

Nuclear produces four times less carbon pollution than solar farms



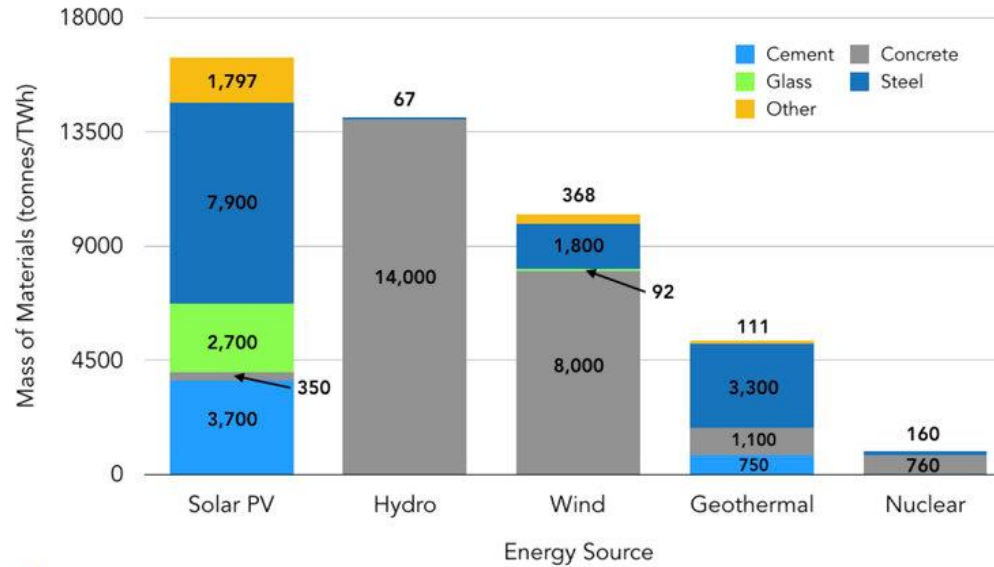
Source: Intergovernmental Panel on Climate Change (IPCC) 2014

Annex III Table A III.2 :: Schlömer S., T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, and R. Wiser, 2014. "Annex III: Technology-specific cost and performance parameters." In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.



Relative raw material requirements

Materials throughput by type of energy source



Relative Land Requirements

Needs 400 times more land for wind
than nuclear



Source: Comparison between Diablo Canyon Nuclear Plant and Alta Wind Energy Center. In 2017, Diablo Canyon produced 17.90 TWh of electricity on an approximate land area of .84 square kilometers. In 2017, Alta produced 3.18 TWh of electricity on an approximate land area of 60.4 square kilometers. Generation data from Energy Information Agency.

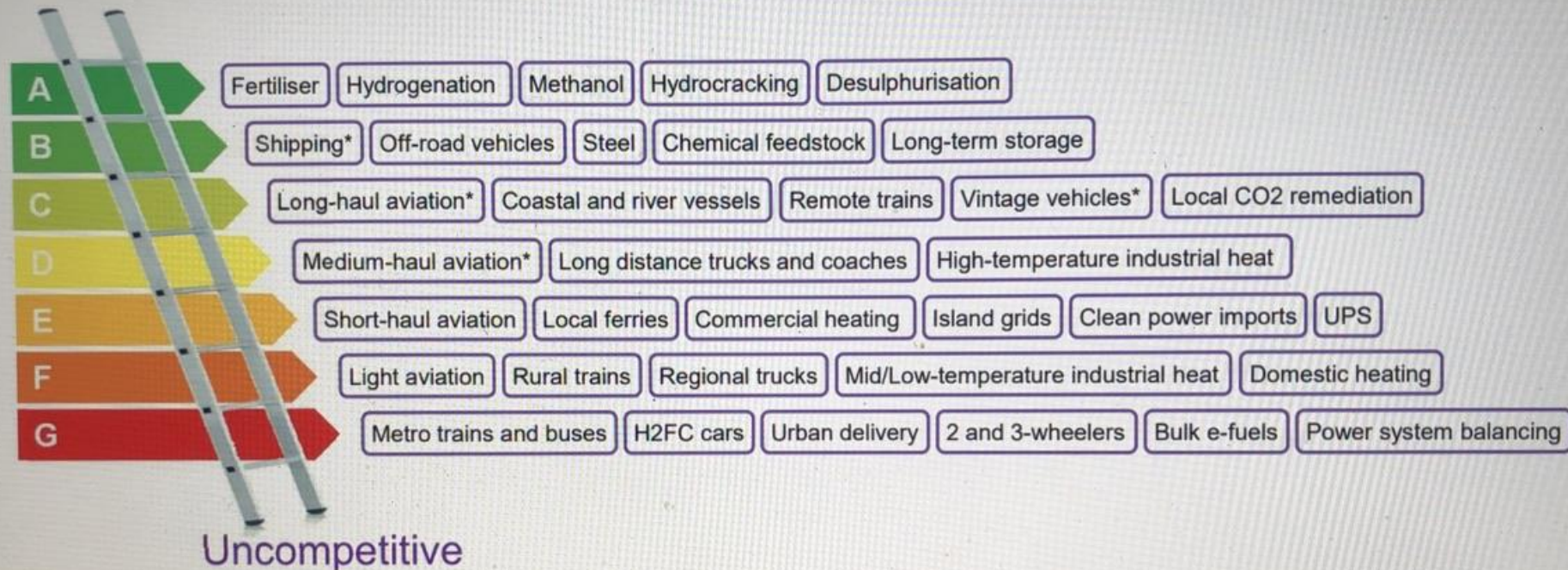


To wrap up the hydrogen economics for this highly simplified presentation, let us now look at the well researched and peer reviewed predictions of *Michael Liebreich* and his hugely innovative

Hydrogen Ladder

Clean Hydrogen Ladder

Unavoidable

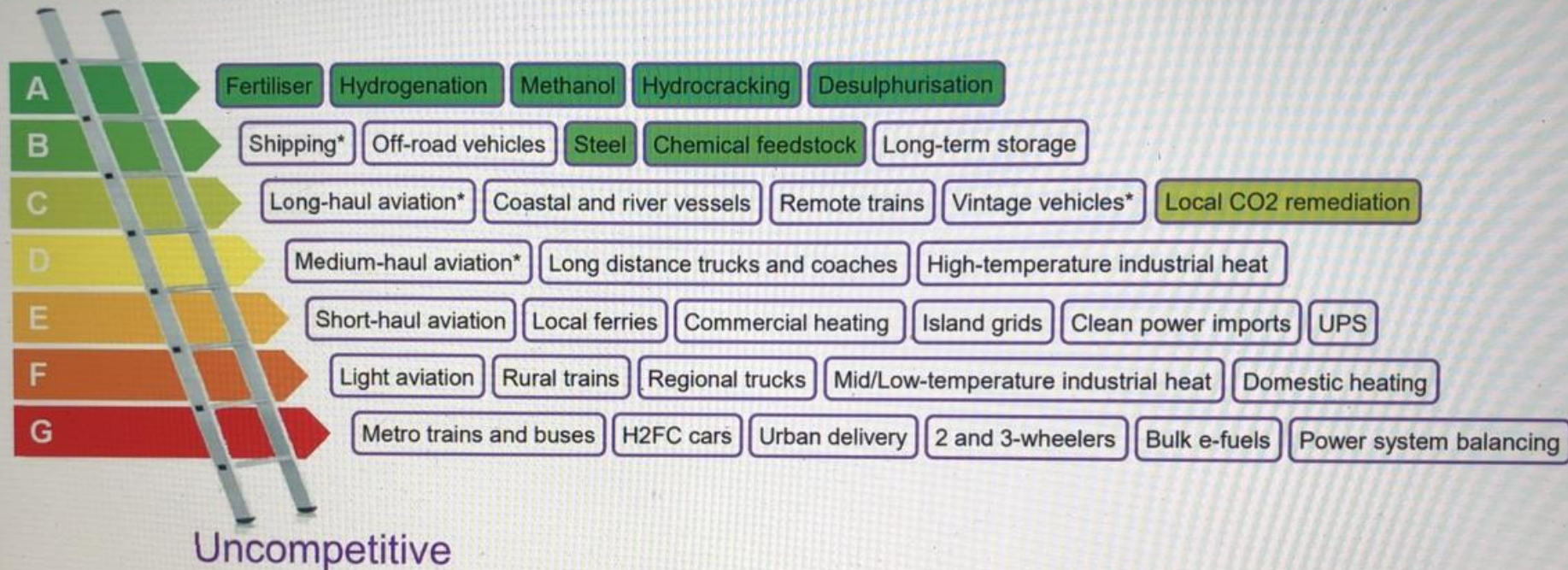


* Via ammonia or e-fuel rather than H2 gas or liquid

Source: Liebreich Associates (concept credit: Adrian Hiel/Energy Cities)

Clean Hydrogen Ladder: Chemicals & processes

Unavoidable



* Via ammonia or e-fuel rather than H2 gas or liquid

Source: Liebreich Associates (concept credit: Adrian Hiel/Energy Cities)

So what are my personal conclusions on the future for hydrogen?

I have drawn these personal conclusions on much research and wide reading. Given that economics should dictate how best to use scarce resources I remain a **Doubting Thomas** on the massive economic future for H₂ so optimistically projected by so many.

Maybe *Australia's National Hydrogen Strategy* and the supporting *Technology Investment Roadmap: Low Emissions Technology Statement 2021* will achieve the huge cost reductions it targets; maybe also Australia's long delayed acceptance of the heat and power available from nuclear energy could change my views.

So I will close by showing you where Michael Liebrich (and therefore I) believe are the most likely energy choices for all those tasks we have identified.

Clean Hydrogen Ladder: Competing technologies

Unavoidable

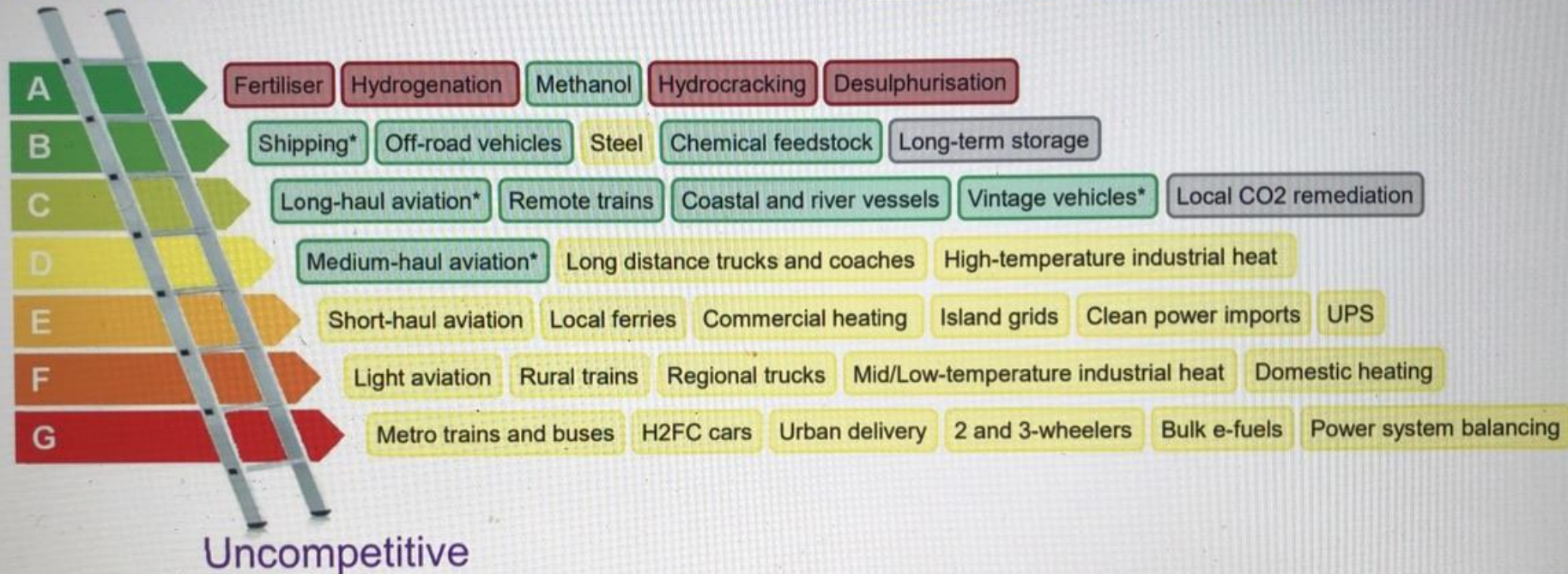
Key:

No real alternative

Electricity/batteries

Biomass/biogas

Other



* Via ammonia or e-fuel rather than H2 gas or liquid

Source: Liebreich Associates (concept credits: Adrian Hiel/Energy Cities & Paul Martin)

My personal conclusions (1) ... on making H₂ greener

Black H₂, made from coal or natural gas, is still the cheapest universal means of production and, short of a punitive carbon tax, will remain so.

Replacing Black H₂ with **Green H₂** is the priority, but today there is none because it is completely unaffordable - without massive subsidies.

Blue H₂, with CCS, is very little greener and costs a multiple of Black H₂.

Green H₂ will cost a yet greater multiple of **Blue H₂**.

Good luck to Fortescue Future Industries! They will need, and probably get, substantial subsidies to make sure that *Australia's National Hydrogen Strategy* is made to work. That will be a political decision, not an economic choice!

My personal conclusions (2) ... on the industrial uses of H₂

Today's primary world use (98.5%) of all H₂ is for nitrogenous fertiliser manufacture. This will continue so long as we need to feed the world.

The second primary use is in oil refining (hydrocracking) to make 'light' petrol from 'heavy' (ie carbon rich) crude oil.

All other uses are still relatively minor (eg cars, trucks, trains, etc).

My personal conclusions (3)

... on H₂ transport via cars, trucks and trains

Cars? H₂ cars will never cut it economically. 43,000 are on the road worldwide but still well below 11 million *Battery Electric Vehicles* (like the one I have just ordered – a Tesla 3!) BEVs are technically far simpler, getting cheaper (nearly competitive with petrol), are much easier and cheaper to recharge than petrol and diesel – and wonderful to drive!

Trucks? For short haul (up to 500km/day) BEVs are better. However off-road off-electricity system trucks (eg bulk haulage at remote mines) look far more promising. See FFI Mine Truck project. Also the Australian Hydrogen Council aims to create an eastern seaboard route – with a \$20M subsidy.

Trains? Possible for long haul bulk carrier trains (eg coal and iron ore) in remote regions. Otherwise electricity is proven, direct and more economic today.

My personal conclusions (4)

... power generation and system balancing?

Power generation? Very unlikely! Why convert variable renewable energy (VRE) into hard to store hydrogen via costly low capacity factor electrolyzers for reconversion back to electricity in a (PEM) cell?

Losses? Along the H₂ pathway the losses will be huge. Better to store intermittent VRE electricity in pumped storage or possibly very expensive, limited life, rare earth resource hungry, hard to dispose of energy consuming batteries.

Nuclear energy? Direct power from 365/24/7 load following small modular reactors (SMRs) seems a far more attractive and economic pathway!

My personal conclusions (5)

... energy storage in gas systems?

Energy storage and transmission? Up to 20% H₂ can be mixed in natural gas pipelines to displace CH₄ if the economics so dictate. The mixed gases can be combusted in most natural gas appliances and gas turbines.

Storage for transport can be as ammonia (NH₃) for bulk shipping or, very expensively, as high-pressure gas.

Pipeline transmission of H₂ is possible, and may be used, but pumping costs to transmit the equivalent amount of energy are far higher than comparable electricity transmission costs. Nuclear power via SMRs sited at retiring coal power station sites, re-using existing infrastructure and trained labour force, appears to offer more economic merit.

My personal conclusions (6)

... what are Australia's policy drivers?

Policy drivers:

- 1 - Climate change - **Green H₂** can help decarbonise (*but remember the costs!*)
- 2 - Contribute to other policy objectives (eg energy security, air pollution, economic development, international energy exchanges (*of wind and sunshine, not uranium!*), infrastructure development and more.
- 3 - Ensure more rapid growth of VREs (*but no reference to nuclear energy – why?*)
- 4 - Benefit from previous government support programs (*ie yet more subsidies!*).

My personal conclusions (7)

... what are the expenditures on these policies?

National and international expenditures:

Nearly all national policies include massive supporting incentives and targets (*aka subsidies*). For Australia the figure is already approaching \$A100 million. For the world it is nearly \$US37BN, with another \$US300BN promised from private sector. But still need \$US1,200BN to meet NZE 2050 targets.

These policies are hugely aspirational – and hugely expensive.

Are they the very best use of our scarce capital? That must be for you to decide!

**Thank-you all for your kind
attention!**

Discussion and questions?