Without nuclear power generation in the system I believe we will find it is close to impossible to deeply decarbonise the Australian economy

…but it would be a mistake to think that nuclear power in Australia is inevitable as a result

‘Fear always springs from ignorance’

— Ralph Waldo Emerson

‘we have a saying in the military that

knowledge dispels fear’

— Pete Goss

yachtsman, solo circumnavigator, entrepreneur

W. waste

A. accidents

R. radiation

N. nuclear proliferation

1. costs
2. time
3. waste

The three senior veterans of the **Chernobyl** NPP

Viktor Bryukhanov

Born 1 Dec 1935 Died 13 Oct 2021 (**85** *years* **316** *days*)

Manager of Construction and Plant Director, 1970–1986

sentenced to 10 years in a labour camp,
served 5, released September 1991

Nikolai Fomin

Born 1937 (**84** years old in 2021)

Chief Engineer, 1981–86

sentenced to 10 years in a labour camp,
released early on health grounds

Anatoly Dyatlov

3 Mar 1931 – 13 Dec 1995 (**64** *years* **285** *days*)

Deputy Chief Engineer, 1991–86

in the control room on the night of the accident and **sustained 35% burns and a dose of around 600 rem**

sentenced to 10 years in a labour camp, imprisoned Dec 1986,
served 4 years, released early in October 1990 on health grounds
published his perspective: www.neimagazine.com/features/feature how-it-was-an-operator-s-perspective

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TIME & TIDE | ALAN HOWE

Chernobyl chief engineer's career-ending meltdown

OBITUARY

Viktor Petrovich Bryukhanov
Nuclear power plant director.
Born Tashkent, Uzbekistan,
December 1, 1935; died Kiev,
Ukraine, October 13, aged 85.

Chernobyl, Fukushima, Three Mile Island – rather than places on maps, they are shorthand for nuclear accidents. Their names glow with a sense of radioactive dread.

Movies have been made about them. Yet nuclear power is perhaps the safest form of electricity generation. The UN believes 50 people died as a direct result of the Chernobyl meltdown in 1986 (but that 4000 locals will contract potentially lethal cancers as a result).

One man was killed at Fukushima in 2011 and two others were briefly in hospital having been exposed to high levels of radiation.

And if one of the 14,000 evacuated from around the Three Mile Island plant in 1979 broke a fingernail, then they are that event's sole casualty.

Meanwhile, 13 coalminers die each day in China. In its Benxihu Colliery Disaster, 1549 miners lost their lives, but it is not a name on the tip of anyone's tongue. Just last month, another Australian coalminer was killed, this time near Emerald in Queensland. In 2020, more people died building and maintaining wind farms than operating nuclear facilities over the last decade.

From left, Viktor Bryukhanov, Nikolai Fomin and Anatoly Dyatlov on trial for their roles at Chernobyl

But to Viktor Bryukhanov such statistics meant little. He oversaw the construction of the Chernobyl nuclear power plant in 1970 and ran it thereafter. Following the explosion, he was sacked. After a three-week trial before the USSR Supreme Court in 1987, he was convicted of gross negligence and of flouting safety regulations and sentenced with two others to 10 years in a labour camp – the maximum. He proclaimed his innocence for the rest of his life.

Bryukhanov grew up in Tashkent, the capital of Uzbekistan, 15 years after it had been absorbed into what was then the Russian Empire following which it became a Soviet Socialist Republic. The eldest of four brothers, he was clever and did a degree in electrical engineering before joining the Uzbekistan Academy of Sciences. He then worked at Tashkent's newly built, coal-powered Angren power station rising quickly through its ranks before moving on to a larger coal-fired operation at Sievierodonetsk in eastern Ukraine where he became deputy chief engineer.

In 1970, Bryukhanov – who for some years had been active in the Communist Party – was asked to oversee the construction of four nuclear reactors at Chernobyl. They were an unusual design used only in the Soviet Union and known as RBMK. Bryukhanov's experience was not in nuclear engineering, but RBMK reactors, often built hurriedly to impossible deadlines, were successfully operating elsewhere, though known to be unstable. Bryukhanov missed a few deadlines as work proceeded, but still managed to have the facility operating by 1977. What he could not know was that a fatal flaw had been built into the reactors' design which, when the incidents leading up to April 26, 1986, unfolded, fanned the flames of the world's worst nuclear accident and rendered futile attempts to control the situation. To save on running costs, control rods that dampened nuclear reaction rates incorporated boron carbide whose ends were coated in graphite. This would quickly increase temperatures. On the night of the inevitable nuclear accident they sent Chernobyl's reactor No. 4 out of control.

Bryukhanov, then aged 51, was at home. His phone rang with news they had a problem at the plant. A car was sent for him. As it approached the plant he could not see the 1000 tonne lid on reactor No.4. It had blown off and the building had collapsed – a red glow was illuminating the ruins. "This is a prison for me," he told the driver. He served five years and even returned to work at the plant.

Communist authorities remained silent on the accident. Four days later, a nuclear plant in Sweden detected unusually high radioactive emissions, and soon other European sites began to detect the same. Finally, Soviet officials reported meagre details. There had been "an accident at the Chernobyl Nuclear Power Plant. One of the nuclear reactors was damaged. The effects of the accident are being remedied."

The man who would be the last leader of the Soviet Union, Mikhail Gorbachev, may have sought more openness, but the nation wasn't there yet. When London newspapers published details of the scale of the disaster in Chernobyl, and when Germany demanded compensation for farmers whose crops were now banned from sale because of the fallout, the Communist TASS news agency responded angrily: "They in Bonn (East and West Germany were five years from unifying) have apparently forgotten their irredeemable debt to the Soviet people for the grief, murder, destruction and sufferings caused by German Nazism to the Soviet Union, to every Soviet family."

WASTE ‘narrative’ :

enormous

expensive

unsolved

The used fuel REALITY

small

inexpensive

solved

"…we must be prepared critically to examine the various options"

Peter Varghese AO, Chancellor

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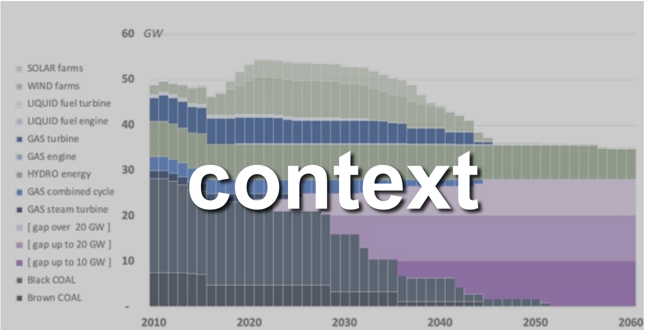
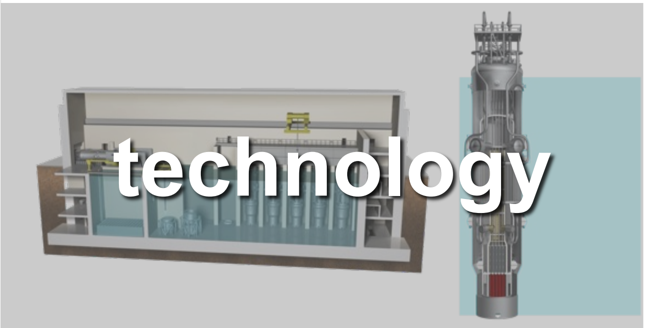
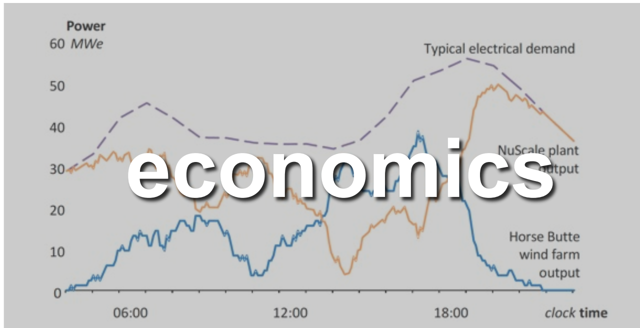
Helen Cook
Geordie Graetz
Mark Ho
Martin Thomas
Tony Irwin
Lenka Kollar
Graham Owen

SCOPE of the study







CONTEXT

Figure 1 Historical and projected retirements in the NEM and long-term SMR fleet scenarios to 2050

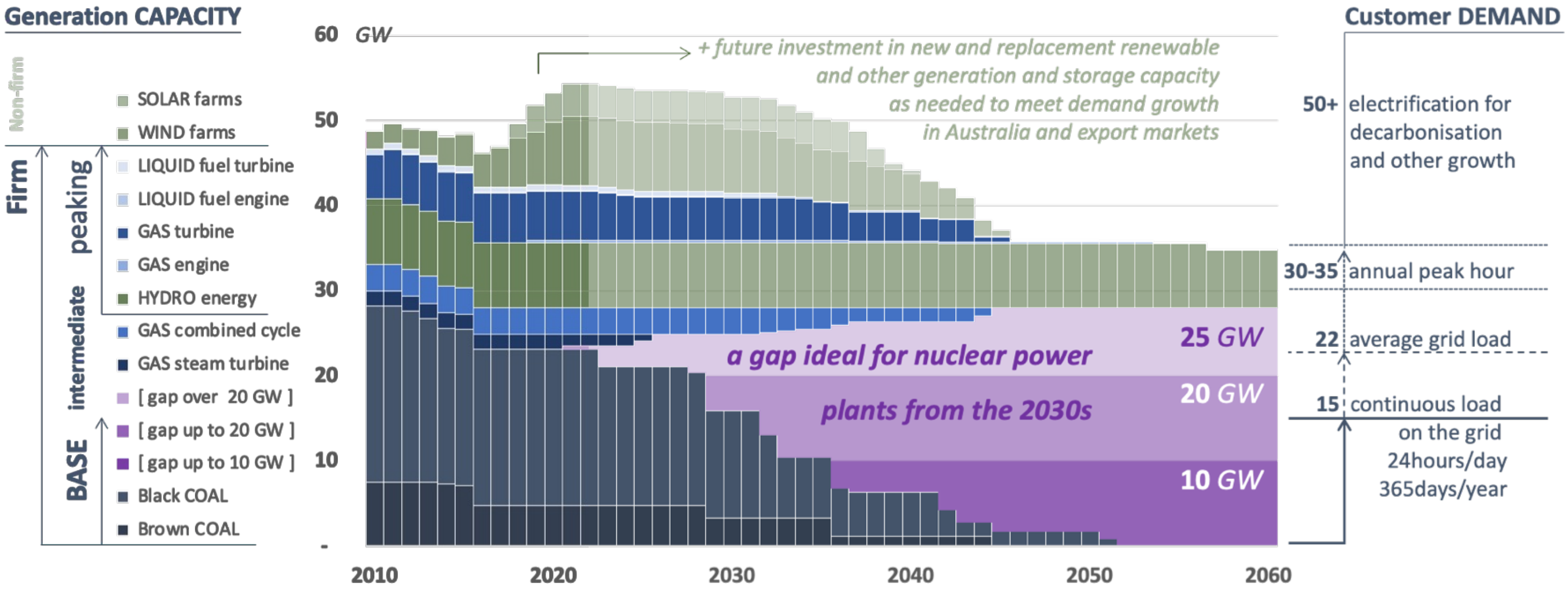
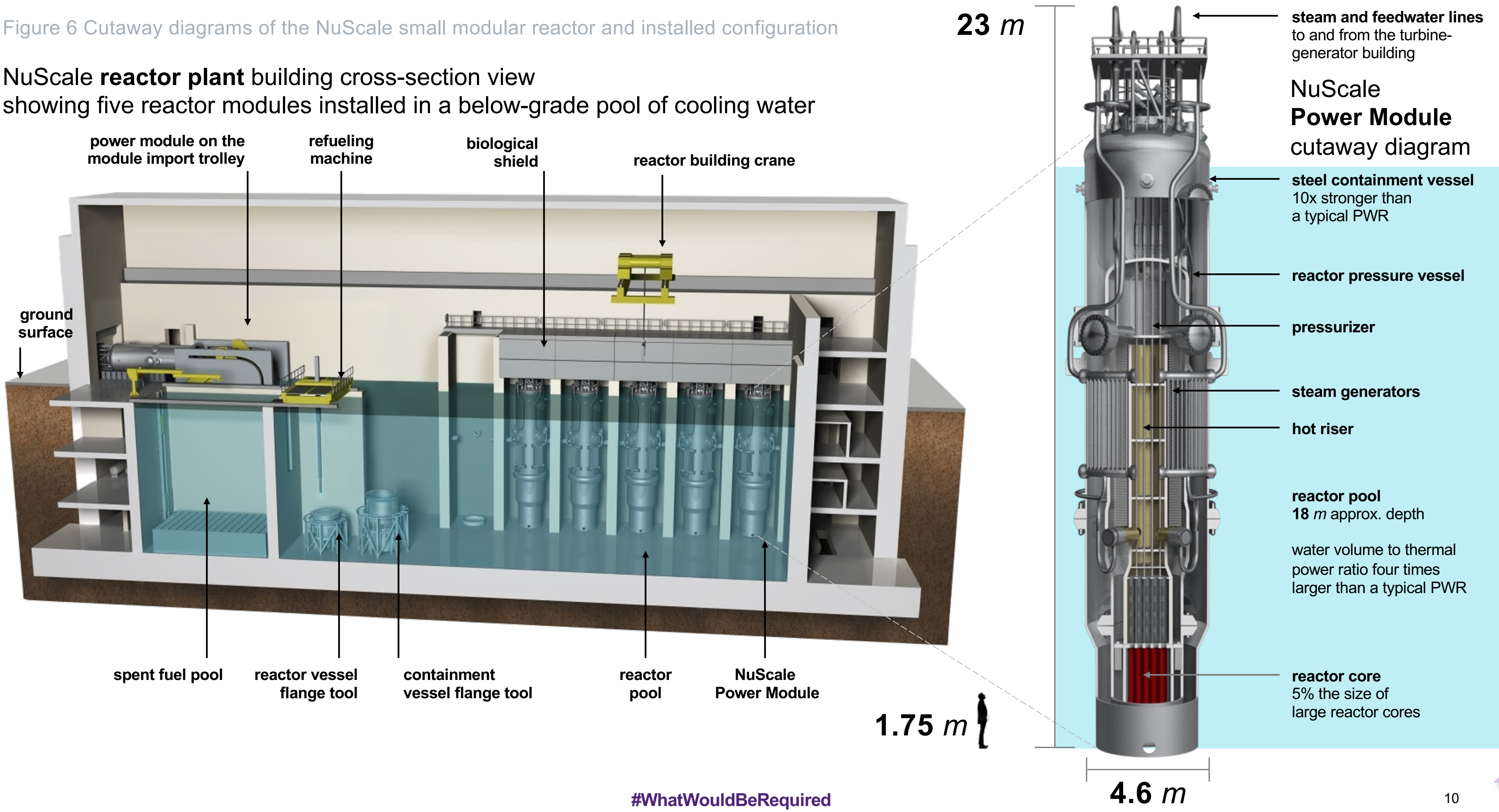


Figure 6 Cutaway diagrams of the NuScale small modular reactor and installed configuration

NuScale **reactor plant** building cross-section view
showing five reactor modules installed in a below-grade pool of cooling water



#WhatWouldBeRequired

Preliminary concept

The engineering project lifecycle

Timeline (NOT to scale)

GOVERNANCE

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

NPT** & various* ***Treaties

AUSTRALIA

various **Acts of Parliament**

ASNO	**ENCRC, EMM**	
ARPANSA	**ACCC**	**CCA**
ARWA	**AER**	**CER**
ANSTO	**AEMC**	**ARENA**
Snowy	**AEMO**	**CEFC**

CAPABILITIES

The University of Queensland Australia

Institutions — statutory and regulatory

Companies — government and private

Universities — teaching and research

People — local workforce and communities

#WhatWouldBeRequired

An analogy with another safety-critical industry

Image: QANTAS

SITING

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AUSTRALIA

Applicability

SMRs are designed to be used for:

- **Electricity**
- **Balancing** renewable energy
- **Hydrogen** production
- **eFuel** synthesis
- **Desalination** of seawater
- **Heat** for industry

Value

Real options to build nuclear plants with small modular reactors have substantial value arising from decarbonisation and deep uncertainty in grids


Proceedings of ICAPP 2015
May 03-06, 2015 – Nice (France)
Paper 15555

Can Nuclear Power and Renewables be Friends?

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Abstract – *The increasing penetration of renewables, especially wind generation, have dramatically changed the economics and realities of grid management in ways that now encourage some level of load-following capabilities for historically baseload plants, including nuclear. The NuScale small modular reactor design currently under development in the United States is well suited for integration with renewables because of several design features related to the nuclear steam supply system, the power conversion system, and the overall plant architecture. The multi-module nature of a NuScale plant allows the plant output to be varied in three ways spanning a wide range of different time frames: (1) taking one or more modules offline for extended periods of sustained wind output, (2) adjusting reactor power for one or more modules for intermediate periods to compensate for hourly changes in wind generation, or (3) bypassing the steam turbine for rapid responses to wind generation variations. Results are presented from a recent analysis of nuclear-wind integration that utilized historical wind generation data from the Horse Butte wind farm in Idaho. Also discussed is the experience of Energy Northwest in their implementation of limited load-shaping at the Columbia Generating Station.*

I. INTRODUCTION

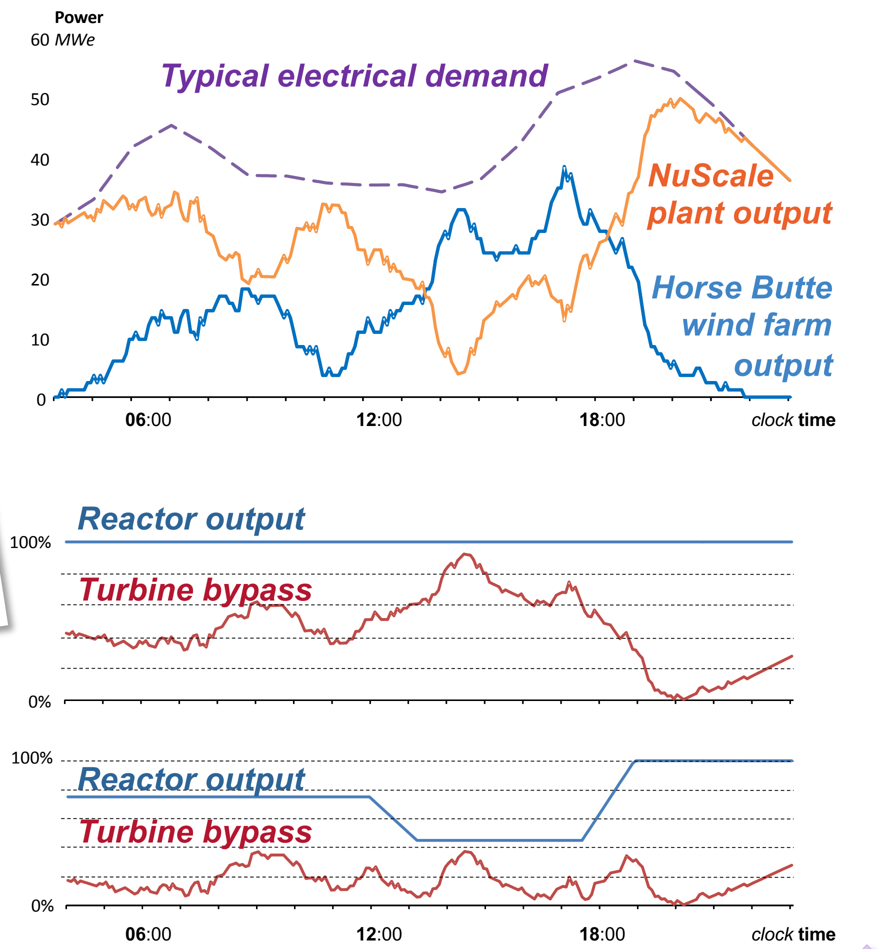
Competition for constrained federal funding and ideological biases have tended to pit various energy technologies against each other, especially between renewable sources, typically wind and solar, and traditional sources, including hydro, coal, natural gas, and nuclear. Of the traditional sources, only hydro and nuclear offer abundant power with virtually no emission of greenhouse gases (GHG). However, new sites for large hydroelectric plants are very limited and have their own environmental issues. As such, nuclear appears to be the only resource that has the potential to not only add to the "clean" energy provided by wind and solar technologies, but actually enable larger contributions of these renewable sources without jeopardizing grid stability or risking unmet electricity demand. However, doing so may require nuclear plant designs to incorporate features that enhance their load-following capabilities.

Conventional wisdom suggests that nuclear power plants should be operated continuously at full capacity and that natural gas plants are best suited to provide "peaking" capability to meet excess demand. This historical strategy has been driven mostly by economic considerations since nuclear plants have relatively high capital cost and low fuel cost compared to natural gas plants. Because of the low fuel cost in a nuclear plant, running the plant at 50% power has minimal impact on operations costs but reduces revenue by one-half. The increasing penetration of renewable sources, especially wind, has altered this economic argument since wind turbines are also capital-intensive (per unit of power produced) and their fuel cost is zero. Also, wind generation tax credits encourage their full-out operation. Finally, some regional policies require grid dispatchers to preferentially use renewable energy first, which exacerbates the economic challenges of operating base-load plants and are driving plant owners to change their concepts of economic dispatch.

Many nuclear plants currently operating were designed to load-follow and were originally outfitted with automatic grid control (AGC) features. However, the U.S. Nuclear Regulatory Commission established a policy that precluded the use of automatic dispatching for true load following, although they allow manual load-shaping if conducted by a licensed reactor operator. Globally, France's pressurized water reactors routinely load-follow due to the high

Ingersoll et al, *Can Nuclear Power and Renewables be Friends?*
Proceedings of ICAPP 2015
May 03-06, 2015 – Nice (France)
Paper 15555

Figure 16 SMR turbine bypass load following



#WhatWouldBeRequired

FINANCING

Table 5 Illustrative build-up of capital charge and financing structure, showing average energy unit costs

AACE case^	Lowest	Lower	CENTRAL‡	Higher	Highest	
Overnight CapEx	2 983	3 488	3 993	4 604	5 613	2020AU$ /kWe gross
TOTAL CapEx *	4 153	5 002	5 871	7 032	8 762	AU$M
…-of a-Kind	'Best' Nth	'Worst' Nth	5th-of-a-Kind	'Best 1st	'Worst 1st	Learning
Assumed build	36	42	48	54	60	months
LRACE	60	68	76	86	102	AU$ /MWh

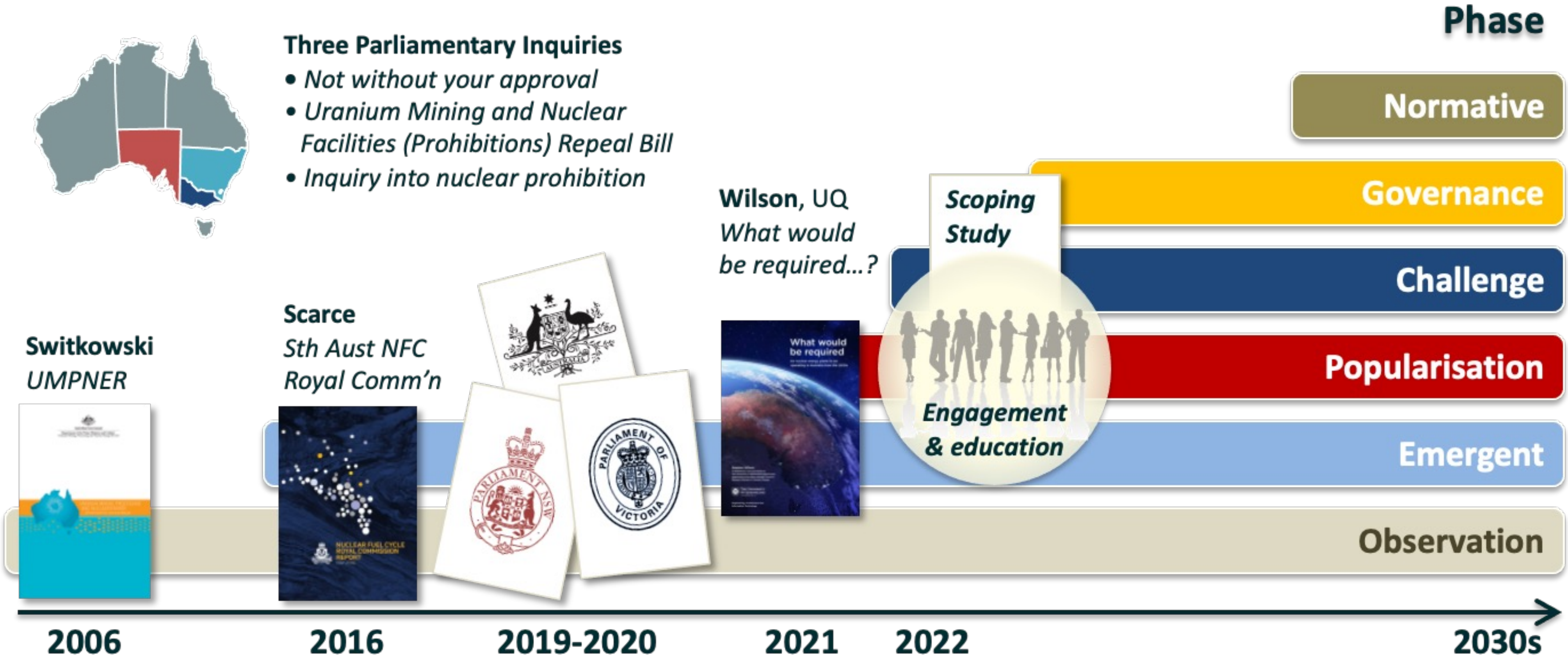
^ Based on the mix of class 3 and class 4 components
‡ Based on NuScale US$**2850**/$kW_e$ gross in 2017 US dollars
* for a **12**-module plant x **77** MW_e in a generic location

Discounted at ***5.3%*** per annum with capital recovered over **30** years
annual fixed O&M of **$100** /kW and variable O&M of **$10** /MWh
plant capacity factor of 95% giving 8322 hours per year at full load

Looking forward in Australia

AUKUS has catalysed the **popularisation** phase and the **challenge** phase will follow

Based on the Futureye Curve, 2015



#WhatWouldBeRequired

"…we must be prepared critically to examine the various options"

Peter Varghese AO, Chancellor

Context

1. **Technology**
2. **Management**
3. **Governance**
4. **Capabilities**
5. **Society**
6. **Siting**
7. **Economics**
8. **Financing**

Conclusions

Additional slides

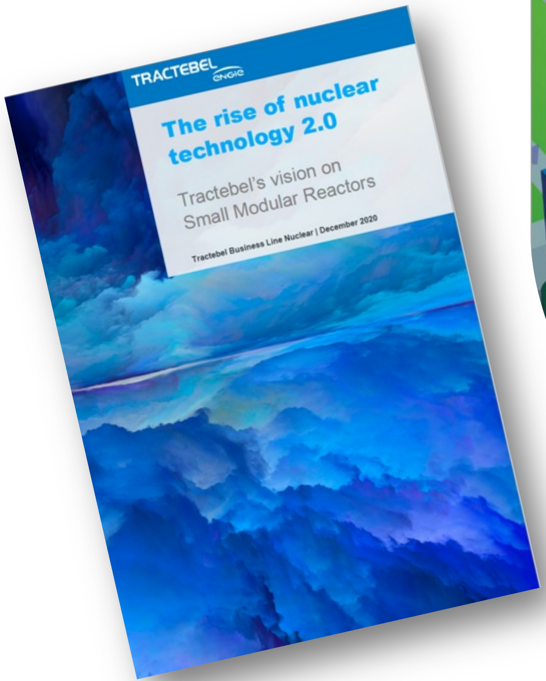
if needed during the discussion

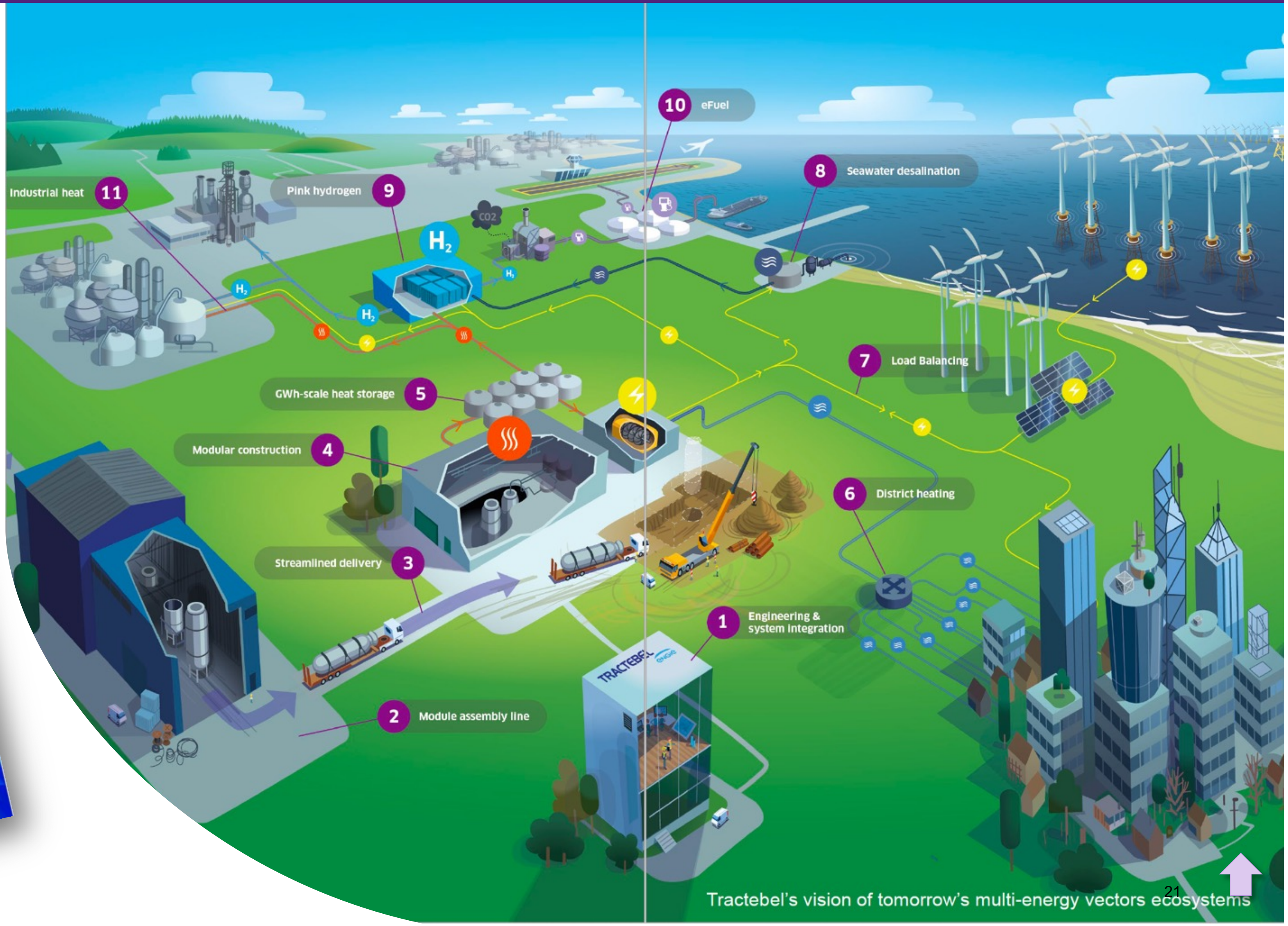
An SMR vision

Tractebel's vision on

Small Modular Reactors

December 2020

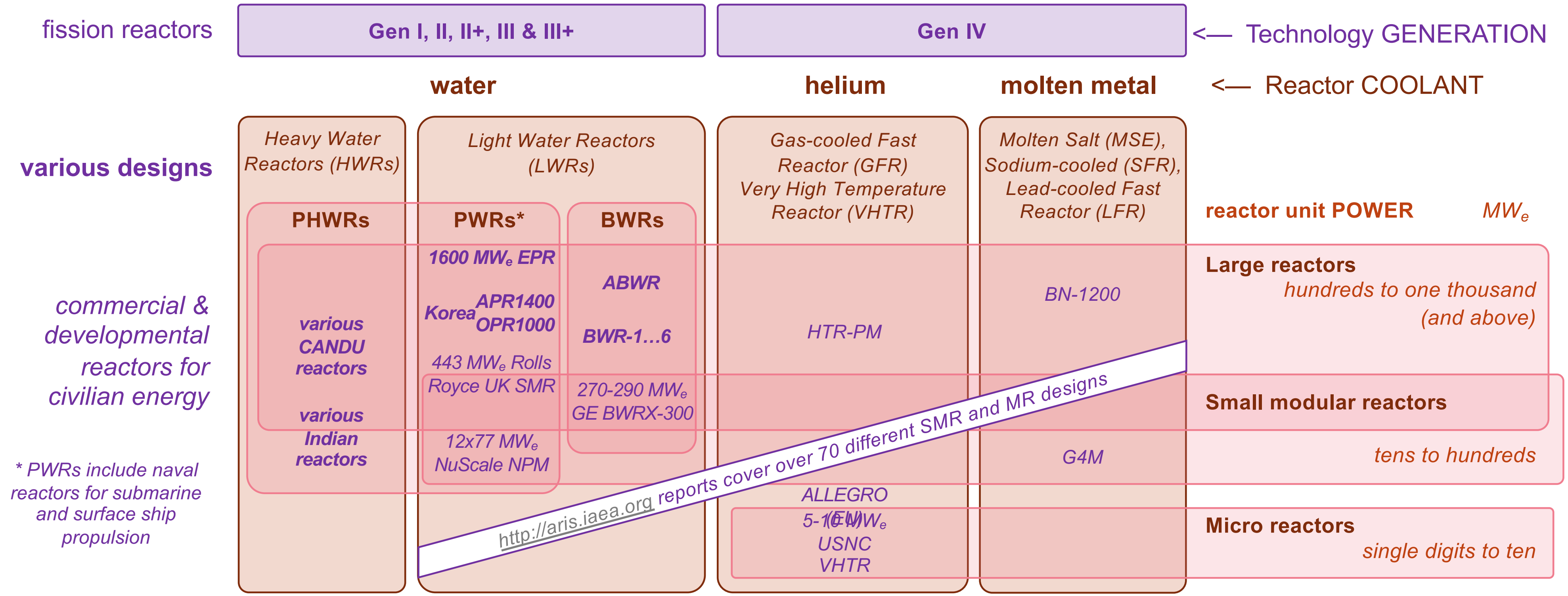




Tractebel's vision of tomorrow's multi-energy vectors ecosystems

REACTOR TYPES

Reactor types classified by fuel, design, coolant and scale, with several examples



#WhatWouldBeRequired

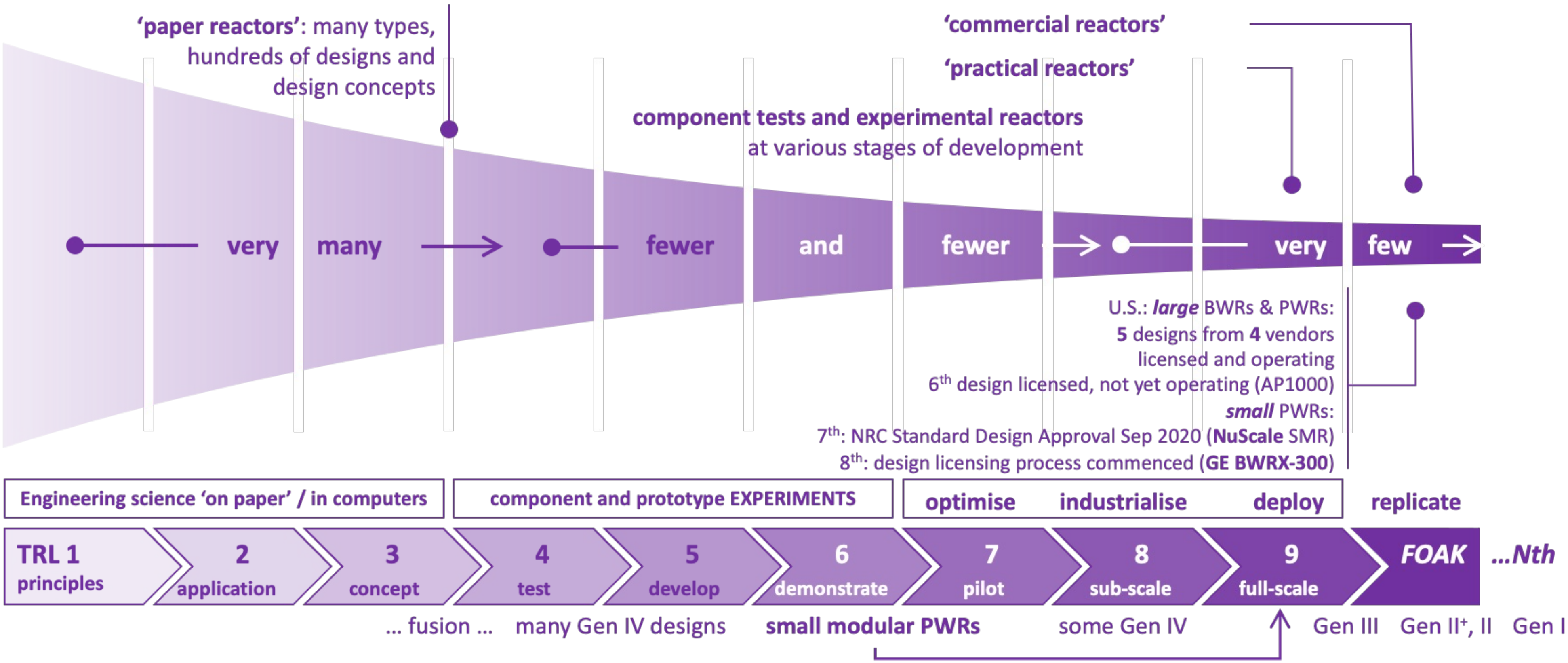
Comparison of nuclear energy with other power generation technologies

Energy form type	NUCLEAR	COAL black / brown	GAS	HYDRO power	WIND power on / offshore	SOLAR power large scale
Technology	nuclear reactor, steam generator and turbine	boiler, steam generator and turbine	combined- or open-cycle gas turbine or recip. engine	Francis reaction turbine	horizontal axis wind turbine (HAWT)	photo-voltaic (PV) cell
CO_2 kg/MWh	zero	831…1315	428…1492	zero	zero	zero
Unit sizeMW	5…50…1000+	280…750+(a)	1…500+	<1… 700	<1 … 13	<<1
Cost index $/kW	4000 to 8000	3300 to 5100	1400 to 1700	N/A (b)	1700 to 6000	1200, falling
Cost structure	highest fixed low variable	high fixed low variable	low fixed high variable	high fixed zero variable	low fixed(c) zero variable	low fixed(c) zero variable
Capacity Factor	90%+	70 to 90%	1 to 50%+	10-20% (d)	30 to 40%	15 to 24%
Output	AC	AC	AC	AC	DC	DC
	System services (frequency, voltage and resource stability)					
Grid security	Inherent	Inherent	Inherent	Inherent	Control-based	Control-based
Availability	>90%	>80%	>96%	>97%	annual CF, weather-dependent	
Dispatchability	Yes (e)	Yes (f)	Yes (g)	Yes (g)	No (h)	No (h)

DESIGN DEVELOPMENT

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Technology Readiness Level (TRL) classifications applied to nuclear reactor designs



#WhatWouldBeRequired

The engineering project lifecycle indicating stage gates for key decisions

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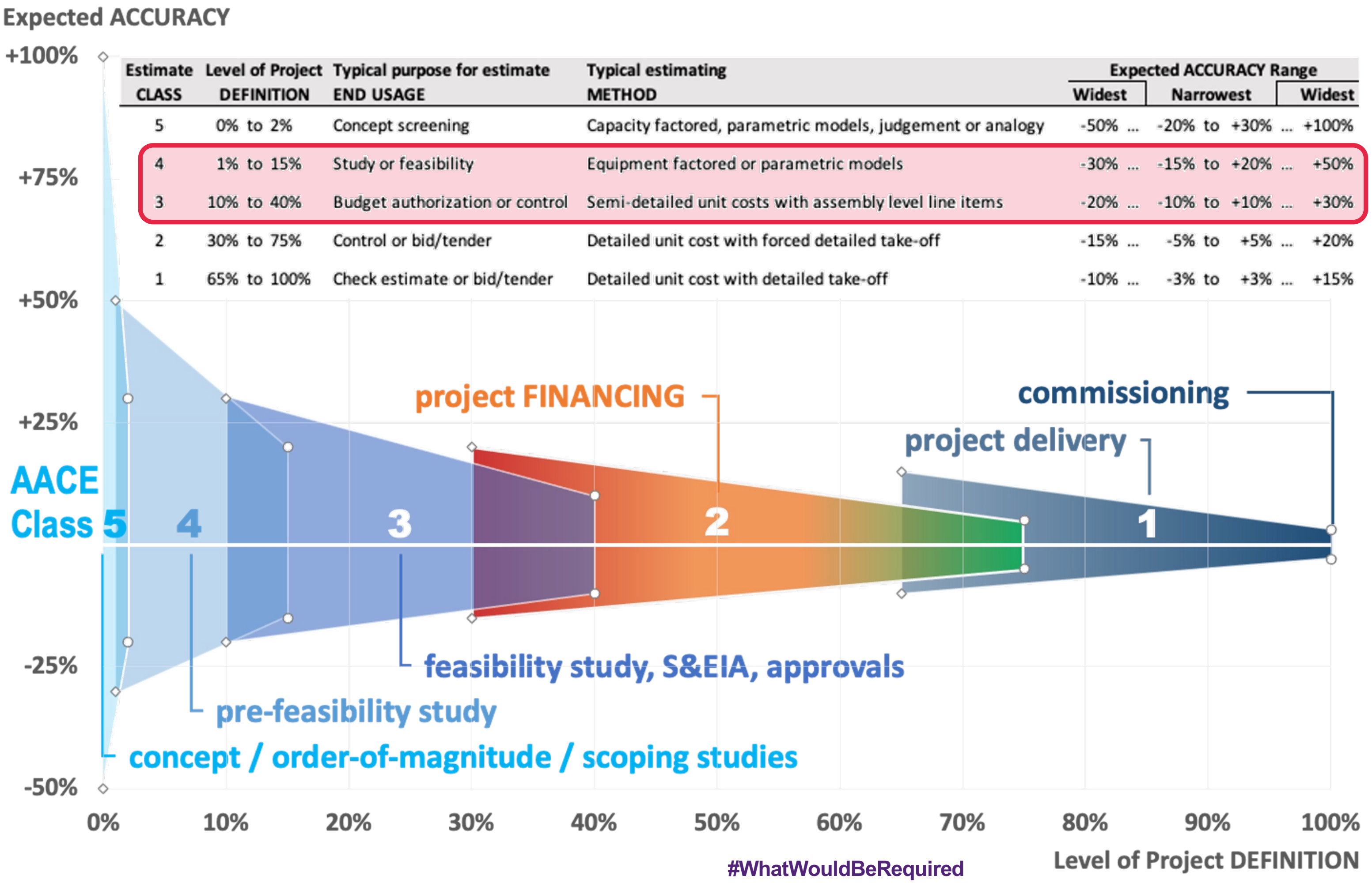
Cost estimate classification matrix and expected accuracy versus project maturity

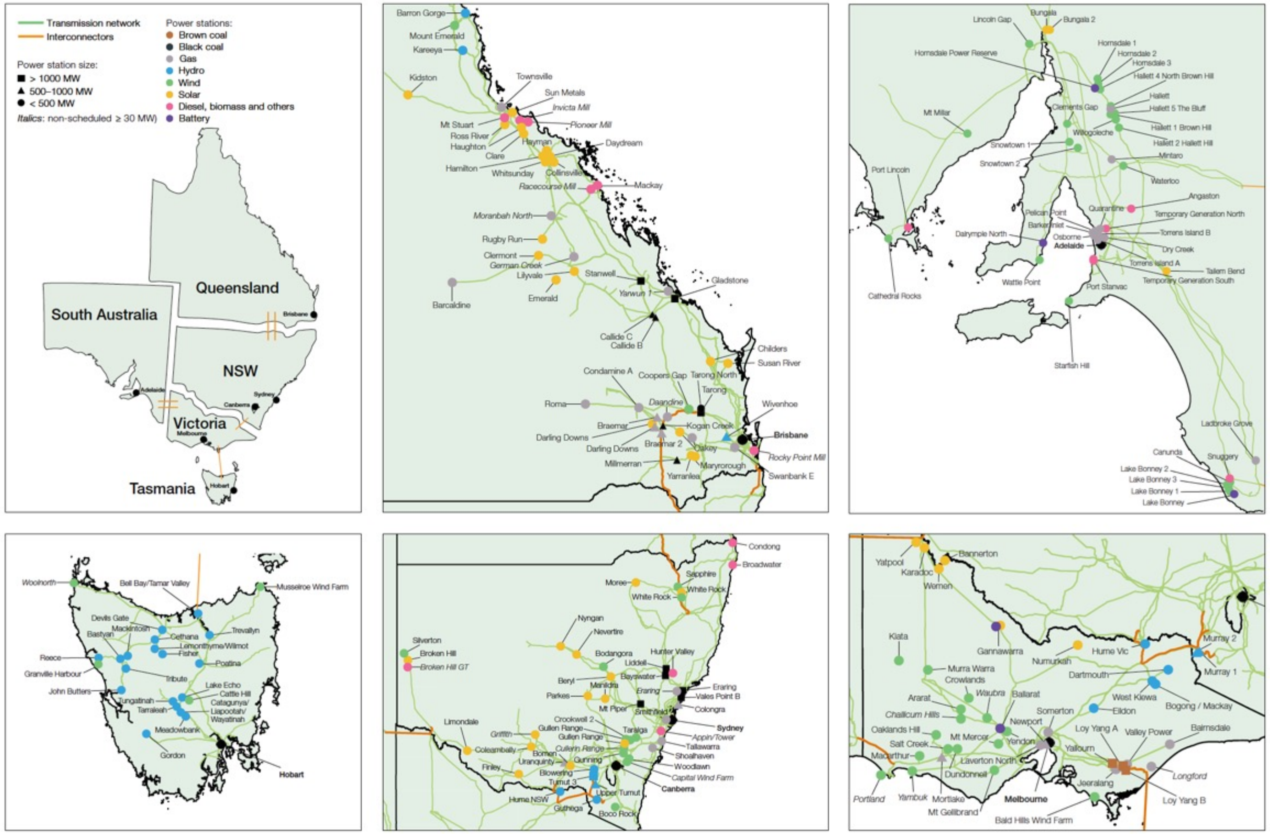
Estimate CLASS	Level of Project DEFINITION	Typical purpose for estimate END USAGE	Typical estimating METHOD	Expected ACCURACY Range Widest	Narrowest	Widest
5	0% to 2%	Concept screening	Capacity factored, parametric models, judgement or analogy	-50% ...	-20% to +30% ...	+100%
4	1% to 15%	Study or feasibility	Equipment factored or parametric models	-30% ...	-15% to +20% ...	+50%
3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	-20% ...	-10% to +10% ...	+30%
2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	-15% ...	-5% to +5% ...	+20%
1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	-10% ...	-3% to +3% ...	+15%

NuScale SMR development is here



#WhatWouldBeRequired

Generators and networks



Source: AER, 2020, *State of the Energy Markets*