What would be required

for nuclear energy plants to be operating in Australia from the 2030s

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THE UNIVERSITY
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About this report

The work is informed by research on engineering and economics, by energy markets, law and policy. But you do not need to be an engineer or an economist or an energy trader, a lawyer or a politician to read it. The document is intended for interested, non-technical, non-specialist readers. Each chapter can be read as a short paper on its headline topic, while collectively they aim to answer the research question in the title.

This report is not intended to be an advocacy document for nuclear energy. (Nor is it an anti-nuclear document.) The authors of this report have generally come to the view that Australia should embrace nuclear energy. But not all of the authors have always held that view. Our own personal views as to why Australia would be better off with nuclear energy than without it span a range of reasons, from climate change to minimising land footprints, to grid strength, energy security and reliability, and long-run cost.

Readers will likely have their own personal views on the role that nuclear energy should play in Australia. Like all readers you may be curious or have questions. Like many Australians, your view may have changed in recent years, or it may still be evolving. This report does not set out to change your view nor to persuade you of one thing or another. The authors hope to answer some of your questions, and to provide a preliminary response to the research question posed by UQ alumnus and benefactor of the Barry Murphy Scholarships in Nuclear Engineering, who inspired and encouraged our work:

What would be required for nuclear energy plants to be operating in Australia from the 2030s?

Foreword

Universities are institutions committed to teaching, research and the enrichment of their societies.

They must be prepared to push out the boundaries of knowledge and to contribute to a deeper understanding of the challenges that face our nation and beyond.

One of those challenges is how best to ensure a clean energy future for Australia. What is the best combination of technologies to provide for reliable emissions-free electricity generation at affordable cost?

There is no single correct answer to this question. Opinions will vary and differ. But if we are to have any chance of arriving at workable answers we must be prepared critically to examine the various options. That is the purpose of this Preliminary Concept Study which is a combined effort by senior students at the University of Queensland under the leadership of Professor Stephen Wilson, Head of the Centre for Energy Futures in the Faculty of Mechanical and Mining Engineering, and assisted by voluntary contribution from many experienced mentors and advisors in nuclear science and engineering here and overseas.

Ever since I was involved, as a young diplomat, in the negotiation of bilateral nuclear safeguards agreements I have been interested in how nuclear energy can be deployed in a way which is safe, affordable and prevented from contributing to the proliferation of nuclear weapons. As the country with the largest reserves of uranium in the world, these are questions which should be a part of our public debate. Does it remain sensible for such a country to export uranium but prohibit the safe use of this technology for itself? The prohibition of nuclear energy reflected the concerns of the time, especially about safety and waste disposal. But does it still make sense for our times where climate change is a more urgent issue and where today's modern, more compact engineering designs, especially small modular reactors (SMRs) have reframed the safety and security concerns? These are some of the questions this study examines.

Sound policy should be based on the best available information. Nuclear power understandably attracts much emotion and I hope this study can help to place the nuclear energy debate in a wider context. After all we can never find the right answers unless we address the right questions.

Peter Varghese AO

CHANCELLOR
THE UNIVERSITY OF QUEENSLAND
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Abbreviations

AACE	Association for the Advancement of Cost Engineering, AACE International publishes a method for project cost estimation in process industries, considered to be the benchmark
AAEC	The former Australian Atomic Energy Commission, which was replaced by ANSTO under the 1987 Act
AEMC	Australian Energy Market Commission, responsible for managing the process of updating electricity and gas market rules in response to rule change requests from stakeholders
AEMO	Australian Energy Market Operator
ANSTO	Australian Nuclear Science and Technology Organisation, formed in 1987, which operates a reactor at Lucas Heights in Sydney, NSW
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ARWA	Australian Radioactive Waste Agency
ASNO	Australian Safeguards and Non-proliferation Office
BWR	Boiling Water Reactor, a type of LWR that converts reactor heat to steam to drive a turbine directly [1]
CCGT	Combined Cycle Gas Turbine, a type of power plant
CNSC	Canadian Nuclear Safety Commission
COAG	Council of Australian Governments
CPPNM	*Convention on the Physical Protection of Nuclear Material* in force since 22nd October 1987
DCF	Discounted cash flow, a financial analysis method: see John Burr Williams (1938) on investment; Joel Dean (1951) on capital budgeting
DoE	Department of Energy, a part of the U.S. Government
ECA	Export credit agency, a type of financial agency through which a government supports the export of the nation's goods or services, such as the Export-Import Bank of the United States (Ex-Im)
EIA / ESIA	Environmental impact assessment / environmental and social impact assessment
EPBC	*Environmental Protection, Biodiversity and Conservation Act*
EPC	Engineering, procurement and construction: a standard contracting form for project delivery
EPZ	Emergency Planning Zone: the area surrounding a nuclear power plant identified to facilitate a pre-planned strategy for protective actions during a defined emergency [2]
ESB	Energy Security Board
FID	Final investment decision
FOAK / NOAK	First / Nth-of-a-Kind: the first / Nth plant of a given design to be built (should specify: globally, or locally)
GW	Gigawatt, a plant-scale unit of power: 1000 MW, or one million kW, or one billion watts
HTGR	High temperature gas-cooled reactor
IAEA	International Atomic Energy Agency, established independently of the United Nations *through its own international treaty*, the IAEA Statute, the agency is based in Vienna and reports to both the United Nations General Assembly and Security Council
IDC	Interest during construction, which is normally capitalised and added to the 'overnight capital cost'
IEA	International Energy Agency, an OECD agency based in Paris
IFNEC	International Framework for Nuclear Energy Cooperation
kW	Kilowatt, a unit of instantaneous power on the scale of a house or rooftop solar PV system
kWh, MWh, GWh	Kilowatt-hour, megawatt-hour, gigawatt-hour: the energy content of that power sustained for an hour
LCOE	Levelised cost of energy, a simple metric often cited to compare dissimilar generation types
LOCA	Loss of coolant accident
LGC	Large generator certificates for renewable energy
LWR	Light water reactor, the most common type of power reactor, cooled and moderated with ordinary water, in BWR or PWR designs [1]
ML	Megalitre, the unit of bulk water, equal to one million litres or one thousand cubic metres
MMR / MR	Micro modular reactor; or simply micro reactor; defined by the IAEA as able to generate up to 10 MW_e of power per individual reactor unit
MW, MW_e, MW_{th}	megawatt, megawatts of electrical power, megawatts of thermal power equal to 1000 kW
NEA	Nuclear Energy Agency: an OECD agency
NEM	National Electricity Market: spans Queensland, New South Wales, the Australian Capital Territory and Jervis Bay Territory, Victoria, South Australia and Tasmania
NEPIO	Nuclear energy programme implementing organization, a general term the IAEA uses for the national co-ordinating mechanism
NPM	NuScale Power Module™
NPP	Nuclear power plant
NPT	*Treaty on the Non-Proliferation of Nuclear Weapons* of 1 July 1968, which entered into force on 5 March 1970; see Endnote *h*
NPV	Net present value, estimated using a DCF analysis
NRC	Nuclear Regulatory Commission, the U.S. Government's regulator of the nuclear industry
NRWMF	National Radioactive Waste Management Facility
OCGT	Open Cycle Gas Turbine, a type of power plant
OECD	Organisation for Economic Cooperation and Development
OPAL	Open Pool Australian Light water research reactor at Lucas Heights, NSW, developed and operated by ANSTO
OSU	Oregon State University
PPA	Power purchase agreement: a long-term wholesale contract
PHWR	Pressurised heavy water reactor, similar to a PWR, but using heavy water, rather than light water for cooling
PV	Photovoltaic, the technology type of solar panels
PWR	Pressurised water reactor, a type of LWR that transfers reactor heat via a steam generator secondary loop to drive a turbine indirectly [1]
RAB	Regulated asset base: commonly used for setting regulated prices for transmission and distribution networks, proposed in the United Kingdom as a model for nuclear power plants
SMR	Small modular reactor, defined by the IAEA as 50 to 300 MW_e per individual reactor unit
STEM	Science, technology, engineering and mathematics (education)
TRL	Technology Readiness Level, a concept originated by NASA researcher Stan Sadin in 1974 [3][4][5]
UMPNER	*Uranium Mining, Processing and Nuclear Energy Review*: also known as the Switkoswki Review, 2006
UQ	The University of Queensland
WACC	Weighted average cost of capital, reflecting the cost of debt and equity in the capital structure
WANO	World Association of Nuclear Operators
WNA	World Nuclear Association
WNTI	World Nuclear Transport Institute

Summary

The findings of this report emerge from a holistic research view, not from separately assessed facts. The study refers to an example of a small modular reactor (SMR) design. Findings and recommendations correspond with chapter numbers.

Findings from the research

The over-arching research finding is that Australia has the capability to make use of nuclear energy from the 2030s.

1. New TECHNOLOGY creates opportunities for reliable, zero emission replacements of Australia's aging coal fleet.
2. ENGINEERING needed for nuclear energy plants would follow well-established project management processes.
3. Existing REGULATIONS and INSTITUTIONS provide a sound foundation; but enhancement would be needed.
4. Australia can prepare CAPABILITIES to plan, finance and build nuclear energy plants to operate from the 2030s.
5. Building public TRUST is vital, by taking time for thoughtful discussion, listening, consideration and understanding.
6. SITING is not as constrained as for large nuclear reactors, given SMR plants' small footprints and safety approach.
7. ECONOMIC strategies based on options are needed to manage large uncertainties that affect all energy futures.
8. Governments' roles in FINANCING are indispensable, to ensure private capital can play its vital role throughout.

Observations on creating real options

- Practically deployable real options are valuable in the presence of uncertainty, *even if they are not exercised*.
- Work needed to build real options also builds the capability that will be needed in case the option is exercised.

Creating value for citizens and governments

- APPROACH nuclear energy dispassionately and be informed—as for any major policy or investment decision.
- VIEW nuclear energy broadly and strategically, not from narrow economic, social or and financial perspectives.

A practical programme of action

Develop a program to create REAL OPTIONS for projects in steps that follow the project development cycle stages.

1. ASSESS and track development of nuclear energy technologies that may be needed in Australia from the 2030s.
2. EXPLAIN the engineering and manufacturing aspects and other synergies of deploying SMR plants in Australia.
3. IDENTIFY governance and regulatory framework updates needed for nuclear energy and prepare the legislation.
4. BUILD on existing capabilities, draw on international support and collective experience, educate and train people.
5. INVOKE the spirit of national consensus demonstrated in the great economic reforms of the 1980s and 1990s and LISTEN to and answer the questions of people in local communities across the diversity of Australian society.
6. INVITE local communities to express interest in hosting an SMR plant, engaging consistently with communities.
7. COMMENCE a national, public-private program of work as outlined, coordinate it well and sustain it continuously.
8. DEFINE the roles that the Australian government will need to play for projects to be investable and bankable.

Next steps

Building on the Australian Government's 2020 watching brief on SMR technology and the Australia-UK technology co-operation partnership, a natural next step is for the government to sponsor a scoping study to evaluate the range of choices for deployment in Australia, while developing a legal and regulatory infrastructure suitable for SMRs and fit for the 21st century.[6,7] These steps will create real options to replace Australia's ageing coal fleet with zero emission firm alternatives—a strategic approach to manage uncertainty by preparing to be in a position to adopt nuclear energy.

Preface

This report is written for you. The aim is not to persuade but to inform readers, who will form their own views.

Our research explored how a practical plant could be deployed in Australia, applying the project development cycle used by well-managed engineering projects.

In recent years interest in nuclear energy has increased among both young and older Australians. Three state and federal parliamentary inquiries conducted in 2019 and 2020—following the South Australian Nuclear Fuel Cycle Royal Commission in 2016 and a Commonwealth review in 2006—show growing interest on the part of governments and members of various parliaments.

This study takes a different tack: envisioning a future beyond repeal of the laws banning nuclear energy with the development real options to use nuclear energy.

The report aims to bring the topic to life by being as practical as is possible in a preliminary concept study. The report aims to provide straightforward information and includes recommendations on next steps. We hope it answers some of the questions that you may have, and that the references and data sources provided allow you to dig deeper if you wish.

All modern energy systems are the result of great collaborative effort, sustained continuously, deployed, operated, and increasingly interconnected on a continental scale. Many of the supply chains for engineering technology and resources operate globally.

The physical energy systems we have all grown up benefiting from—or taking for granted—were largely endowed to us by our elders' generations. They embody and reflect judgements and decisions, compromises and choices, expertise and effort, and—historically—broad agreement that spanned society. Long-lived assets comprise these systems, so the energy mix tends to change very gradually. Technologies and energy forms, the structure and design, the ownership and governance of our present energy systems come to us from previous waves of innovation, development, and investment.

An energy sector operating on competitive market principles—such as we have in Australia today—was built and still operates with an enormous degree of cooperation and collaboration, honed with a degree of competition, and overseen by the regulatory authorities. Even fiercely competitive pursuits such as professional sport are characterised by 99% cooperation and 1% competition: everyone must agree on the rules, venue, and time of the contest. Only then can the competition occur, under the authority of the umpires or referees on the field, and of a governing body in the background.

All energy sector projects—and power generation plants in particular—are complex undertakings made possible by extensive collaboration between many parties. Most parts of the electricity industry consist of assets and operations that are licensed by government. Siting decisions and approvals, generator licenses, transmission connection agreements, rights of way, financing agreements and so on, are common to all electricity generation projects, including nuclear power plants. Nuclear energy projects have some additional requirements that are specific to that type of technology. Setting out those requirements is an important part of answering the question in the title of this study.

This report brings together information, knowledge and understanding from a summer research project at the University of Queensland. With COVID-19 travel restrictions preventing overseas travel, seven researchers were employed under the Barry Murphy Scholarships in Nuclear Engineering. Each took on research for one chapter. Three graduate engineers volunteered to mentor the students, with particular attention to the linkages between chapters, aiming for consistency and avoidance of gaps in the many issues that cut across the chapter themes. Industry mentors—all highly experienced professionals with decades of experience in Australia and internationally—also volunteered to advise the student researchers. The co-authors and contributors—researchers, mentors, and industry experts—as well as peer reviewers and supporters are acknowledged on the inside back cover.

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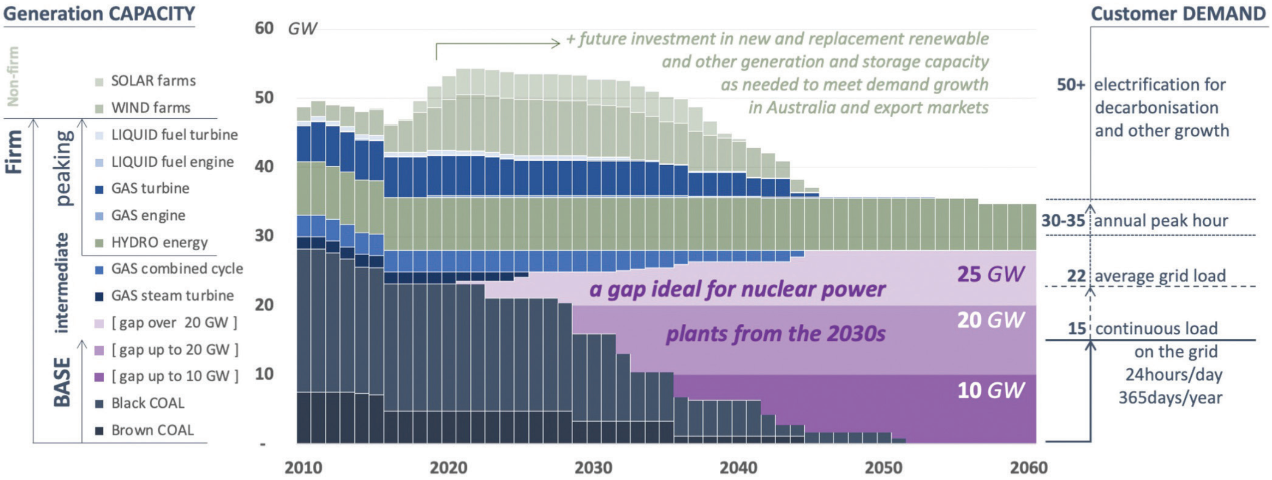
Context

In Eastern Australia in 2020, coal generated about 65% of annual electricity consumed, balanced by hydropower (8%), natural gas (7%) and supported by liquid fuels (less than 1%) with the balance from wind and solar. Since 2010, almost all new plant capacity added has been wind power in large scale wind farms (now generating 10% of consumption), and solar power: mainly behind-the-meter on households' and businesses' rooftops (almost 7% of consumption) and more recently in large scale solar farms (approaching 4%). **Practically all of the generation capacity retired, removed and decommissioned since 2010 has been thermal plant, predominantly coal fired.** In Western Australia there is proportionately less coal (42%), more gas (35%), more wind (20%), and no hydropower.[8]

Australia's large, high-quality energy and resource endowments allowed earlier generations the luxury of choosing a national energy mix from an embarrassment of riches, while offering customers in export markets—notably in Japan, Korea, Taiwan and South-East Asian countries—a full menu of choices according to their own energy needs and national preferences for affordability and security, and their environmental considerations: including coal, gas and uranium exported by Australia. Passing over commercial nuclear energy has been perhaps the most notable difference between Australia's choices and those of the countries in our export markets. With the closure of Hazelwood, all of Australia's 1960s vintage coal plants have now been decommissioned. The 16 coal plants operating in the National Electricity Market (NEM) in 2021 were commissioned between the 1970s and 2000s. Assuming a 50-year life, those plants will all be decommissioned between the 2020s and the 2050s. Commercial considerations of the plant owners will strongly influence actual retirement dates. Each coal-fired unit ranges from 280 to 750 MW, while gas-fired units can range from 1 to 500 MW or more.

Whether essential service providers, households or businesses, most electricity consumers expect a secure, affordable, competitive and low carbon electricity supply that is always "on" at their service. Trading off service quality for reduced emissions is possible but that is not a choice that any other country is likely to make, and nor is it a choice that Australians would be expected to make. Expected retirement of the fleet of coal-fired power plants creates an opportunity for Australia to embrace nuclear energy, as shown in Figure 1. Deployment of a 21st century fleet of nuclear plants up to about 25 GW, would form the backbone of a robust, affordable, decarbonised grid, complemented by our 20th century hydro plants, along with renewable energy and storage. Relying only on renewables and storage requires 150 GW or more of system capacity.[9,10]

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



Source: Author's chart based on data from AEMO Assumptions with plant lives standardised; see also p.16 Figure 10 of Ref. [11]

Background

Australia is a founding member and represented on the Board of the International Atomic Energy Agency (1957). In every decade between the 1960s and 2010s Australia ratified international treaties with direct or indirect relevance to nuclear energy. Eight treaties relate variously to the peaceful use of nuclear energy, non-proliferation of nuclear weapons and test bans, the protection of nuclear materials, and nuclear safety. Three treaties relate to climate change. There are laws currently in force prohibiting the peaceful use of nuclear energy in Victoria (1983), New South Wales (1986), the Commonwealth (1999) and Queensland (2007). Through ANSTO, Australia is recognised internationally as a leader in nuclear research, medical isotope production, advanced materials science and technology for radioactive waste management. OPAL is the third Australian research reactor since the 1950s.[12]

Since the Switkowski Review in 2006, there have been four federal and state reviews and inquiries on nuclear energy: in 2016, 2019 and 2020.[13-17] Apart from the UN *Framework Convention on Climate Change* in 1992, the Hilmer Review on *National Competition Policy* in 1993, the *Kyoto Protocol* in 1997, the launch of the NEM in 1998, the EPBC Act 1999, the Renewable Energy Target (RET) in 2001, and the UN *Paris Agreement* of 2015, there have been countless reviews, inquiries, white papers and reports on climate change, renewable energy and the electricity system.[18-29]

Purpose and rationale

Submissions to the above reviews, committee members, and others have made the case both for and against the repeal of the laws preventing the peaceful use of nuclear energy in Australia. This report has a different purpose, which is to answer the research question:

What would be required for nuclear energy plants to be operating in Australia from the 2030s?

This question demands a practical, concrete, specific, time-focused response. The least to be gained is better-informed public discussion than would otherwise be the case. Actual public benefits are likely to be greater. Removing bans on nuclear energy will create value by allowing study and preparation of real options to build nuclear power plants that may be called for from the 2030s, and which have long development lead times.[30 31]

Eastern Australia has a generational opportunity arising from the 23 gigawatt problem outlined above: retirement of the fleet of 16 operating coal-fired power plants that form the basis of the existing interconnected system. Western Australia has four small coal fired power plants south of Perth with a total capacity of just under 1.7 GW.

The rationale for undertaking this study in 2021 stems from growing public interest in nuclear energy, especially among younger Australians; demands to reduce greenhouse gas emissions to net zero by 2050; growing realisation that 'this will be hard'[32]; and alignment of expected coal plant retirements with the time needed to discuss, agree, plan and deploy nuclear energy plants.

Approach

The research undertaken in this study involved a combination of meetings with mentors; identifying and summarising key information relevant to Australia from secondary source documents; interpreting international information and translating or 'triangulating' to the Australian context; interviews with industry experts; comparative analysis; compilation, processing and analysis of data where needed; and application of analytical and explanatory frameworks.

The structure of this report

Chapter 1 addresses relevant nuclear **technology**

Chapter 2 is on engineering and project **management**

Chapter 3 is on **governance** related to nuclear energy

Chapter 4 is on **capabilities** of people and institutions

Chapter 5 is on **society**, public confidence, and consent

Chapter 6 is on **siting** processes and approaches

Chapter 7 is on various **economic** factors

Chapter 8 is on the requirements for securing **financing**

Chapter 9 provides **conclusions** in the form of key findings, recommendations, and next steps.

1. Technology

Types of nuclear reactors

There are various types of nuclear reactor technology and designs. Civilian reactors were originally derived from U.S. naval (submarine) reactors in the 1950s. This report focuses on fission reactors for civilian energy, as fusion energy technology is presently experimental.[a]

It is common to classify fission reactors by the coolant used in the design. Figure 4, shows four generations of design with typical units' megawatt electrical (MW_e) power. Light water reactors (LWRs) are the most common type deployed around the world.

Deployment of nuclear energy from the 2030s in Australia requires a focus on uranium-fuelled fission reactors, and on licensed safe designs using proven technology ready for commercial deployment.

Design developments relevant to Australia

In 2020 the government set a watching brief on SMRs. In 2021 an Australia-UK partnership was announced on six key technologies including SMRs, advanced nuclear designs and enabling technologies.

The IAEA defines SMR unit sizes as 50 to 300 MW_e. Multi-unit plants may total up to 1 GW_e or more.

Among LWRs, Figure 2 shows that the pressurised water reactor (PWR) variety have become more common than boiling water reactors (BWRs).

FIGURE 2 Reactors by year, type and size

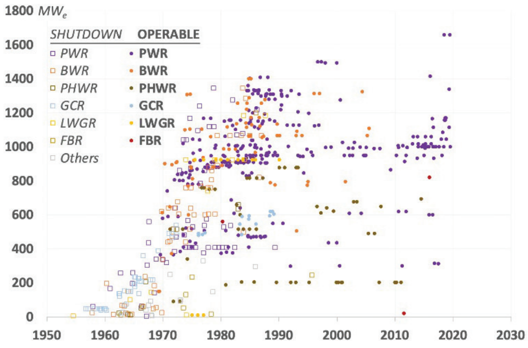
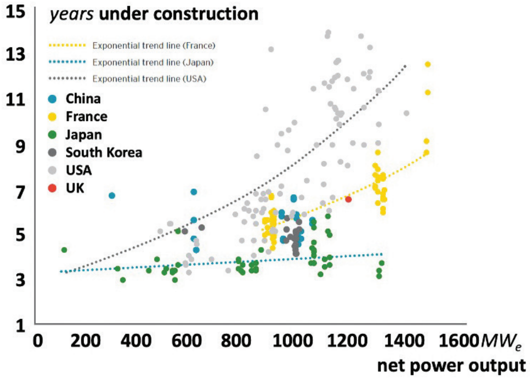
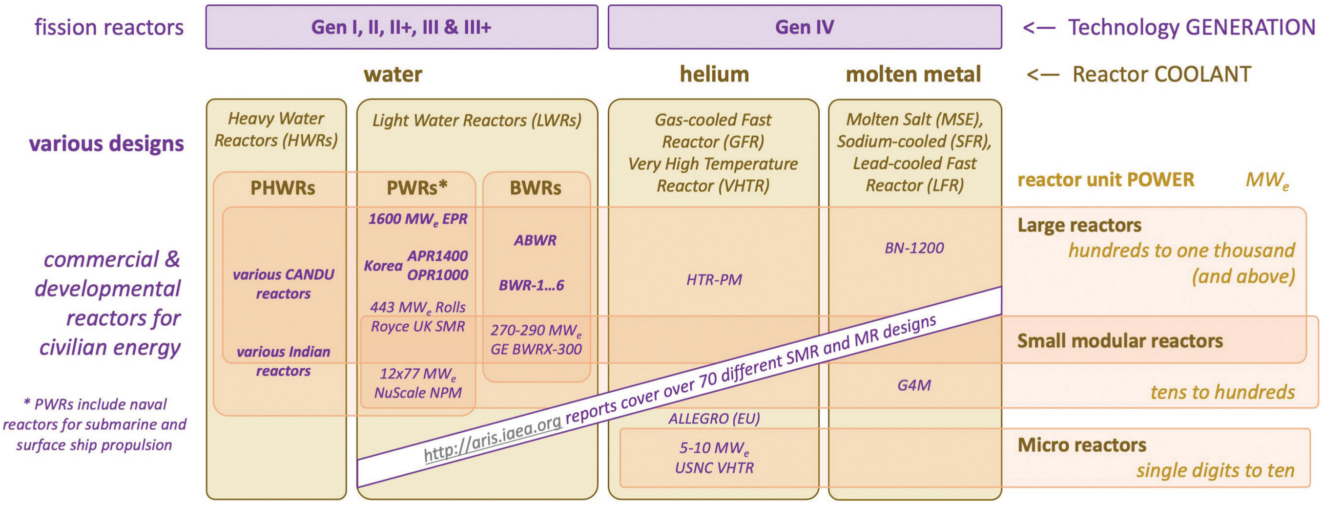


FIGURE 3 Construction time versus reactor size



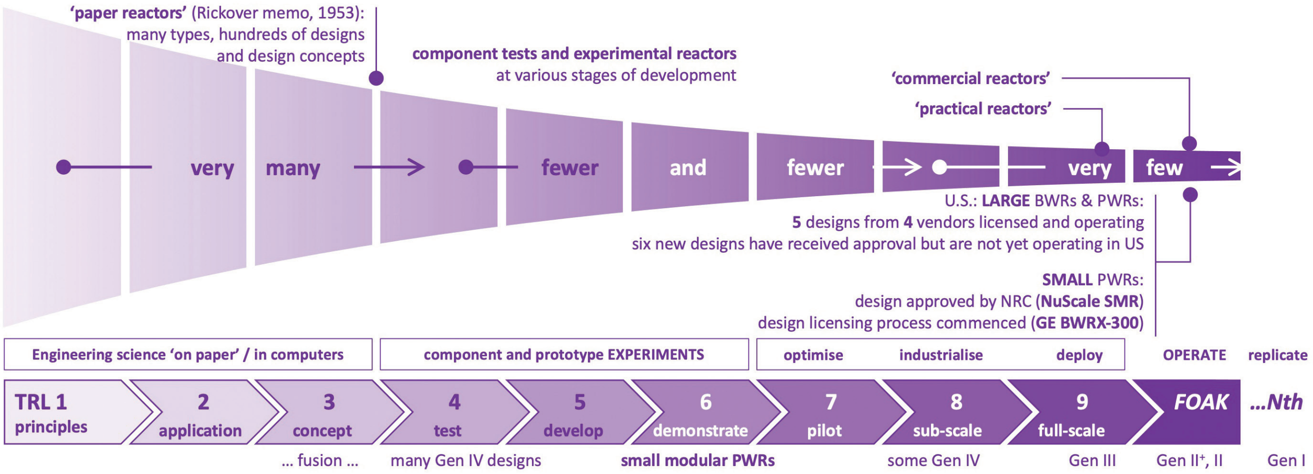
Source: Lewis et. Al., 2016, Ref. [33]

FIGURE 4 Reactor types classified by fuel, design, coolant and scale, with several examples of designs



Source: Authors' diagram. References include a survey of designs [34] and descriptions of many types of SMR designs [35]

FIGURE 5 Technology Readiness Level (TRL) classifications applied to nuclear reactor designs



Source: Authors' chart, adapted for nuclear reactor technology from NASA, Defence, EPRI and others [4,5,36-43]

Reactor technology and drivers of cost

The 20th century pursuit of economies of scale through larger individual reactors is also evident in Figure 2. Lengthy construction periods, delays, and high capital costs have contributed to negative perceptions of the commercial attractiveness of nuclear power. While these challenges tend to be associated with larger unit sizes for U.S. and French projects, Figure 3 shows China, Japan and Korea have been less prone to delays.

Few nuclear power plants (NPPs) have been built in OECD countries since 1995. Schedule delays and other factors that drive project cost increases explain and reduce the wide gap in project cost outcomes between Europe/North America and the rest of the world.[44]

Large reactors have a high proportion of on-site construction and fewer learning opportunities, while SMR technology seeks cost reductions through highly standardised designs for series production, faster learning rates, economies of replication enhanced by modularisation, and factory fabrication.[45] While not a 'silver bullet', this approach should reduce cost risks.

Modularity is now a broad trend in engineering design.[46] The change in nuclear power plant design thinking to small and medium-sized light water reactors can be traced at least back to 1990 in Japan.[47] By the year 2000, the U.S. DoE was committed to supporting the development of small modular reactor designs.

Availability, safety and maturity of SMRs

Civil nuclear power has accumulated 18,000 reactor-years of experience across more than 30 countries and has a safety record that compares favourably with other safety-critical industries.[48,49] SMRs apply modularisation and passive safety techniques to well-understood PWR technology. The NEA and ARIS document more than 70 designs of SMRs and micro reactors (MRs) from vendors in the United States, Canada, the United Kingdom and other countries.[34,35] Figure 5 distinguishes concepts and prototypes from commercially available designs using their TRL. Reactor designs licensed and deployed have always been far fewer than proposed design concepts.

The NuScale Power Module™ (NPM) can be traced from an R&D program conceived in 1999 as the Multi-Application Small Light Water Reactor led by nuclear engineering Professor José Reyes at Oregon State University, with the Idaho National Laboratory, advisory firm Nexant, and supported by the U.S. DoE.[50-52] NuScale was founded in 2007. On 31 December 2016 applied to the U.S. Nuclear Regulatory Commission (NRC) for certification of the design. The NRC issued the *Final Safety Evaluation Report* in August 2020 and the *Standard Design Approval* on 11 September 2020, the first milestone of its kind for an SMR design.[53,54] This '... means that customers can move forward with plans to develop NuScale power plants, knowing that safety aspects of the NuScale design are NRC-approved.'[55]

‘Full certification... allows a utility [in the U.S.] to reference the design when applying for a combined license to build and operate a nuclear power plant.’[56]

In December 2019 GE Hitachi (GEH) submitted to the NRC the first of several licensing topical reports (LTRs) for the **BWRX-300 small modular reactor** (SMR). At the time of writing GEH had submitted five LTRs and the NRC had issued three Final Safety Evaluation Reports (FSERs), with two scheduled for December 2021 and January 2022. ‘‘GEH expects these safety related LTRs to serve as a foundation for the development of a Preliminary Safety Analysis Report that could potentially be submitted to the NRC by a utility customer.’[57]

Needs and opportunities in Australia

Table 1 provides a comparison of nuclear power with other forms of electricity generation. The numbers represent ranges present in Australia or typical values. Gigawatt-scale (1000 MW_e) reactors are considered too large for the Australian power grid, where existing large units range from 500 to 750 MW_e. Plants ranging from several hundred to several thousand megawatts, being comprised of multiple SMR units, would be ideally sized for Australian conditions and requirements, and could be readily integrated into the existing system. For example, a six-module GE-Hitachi BWRX-300 plant would have a total capacity of 1.8 GW_e. A plant with 12 NuScale 77 MW_e modules would be just under 1 GW_e.

TABLE 1 Comparison of nuclear energy with other power generation technologies

Energy form type	Nuclear	Coal black or brown	Gas or liquid fuel plants	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	Photo-Voltaic cell
Operational CO_2 emissions, kg/MWh	zero	831...1315	428...1492	zero	zero	zero
Unit size, MW	5...50...1000+	280...750+(a)	1...500+	<1... 700	<1 ... 13	<<1
Cost index, AU$/kW	4000 to 8000	3300 to 5100	1400 to 1700	N/A (b)	1700 to 6000	1200, falling
Service life, years	40 ... 60 ... 80	50	25+	100+	20-30	20-25
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 capacity factor, weather-dependent	
Dispatchability	Yes (e)	Yes (f)	Yes (g)	Yes (g)	No (h)	No (h)

Notes: based on authors’ research and the publicly-available AEMO Excel file 2021 inputs and assumptions workbook for the non-nuclear technologies.

a) Western Australia’s coal-fired power plants include old units with smaller unit sizes than those in Eastern Australia.

b) Hydro power costs are highly site-specific. New energy hydro is very unlikely to be developed in Australia.
(Snowy 2.0 and other pumped hydro plants are an annual load, equal to round-trip losses).

c) The costs elsewhere in the system of integrating variable renewable energy are not included here but rise with market share

d) Inflow constrained: Snowy Hydro generates 4500 GWh per year on average from 4100 MW of capacity, for 12.5% availability.[58]

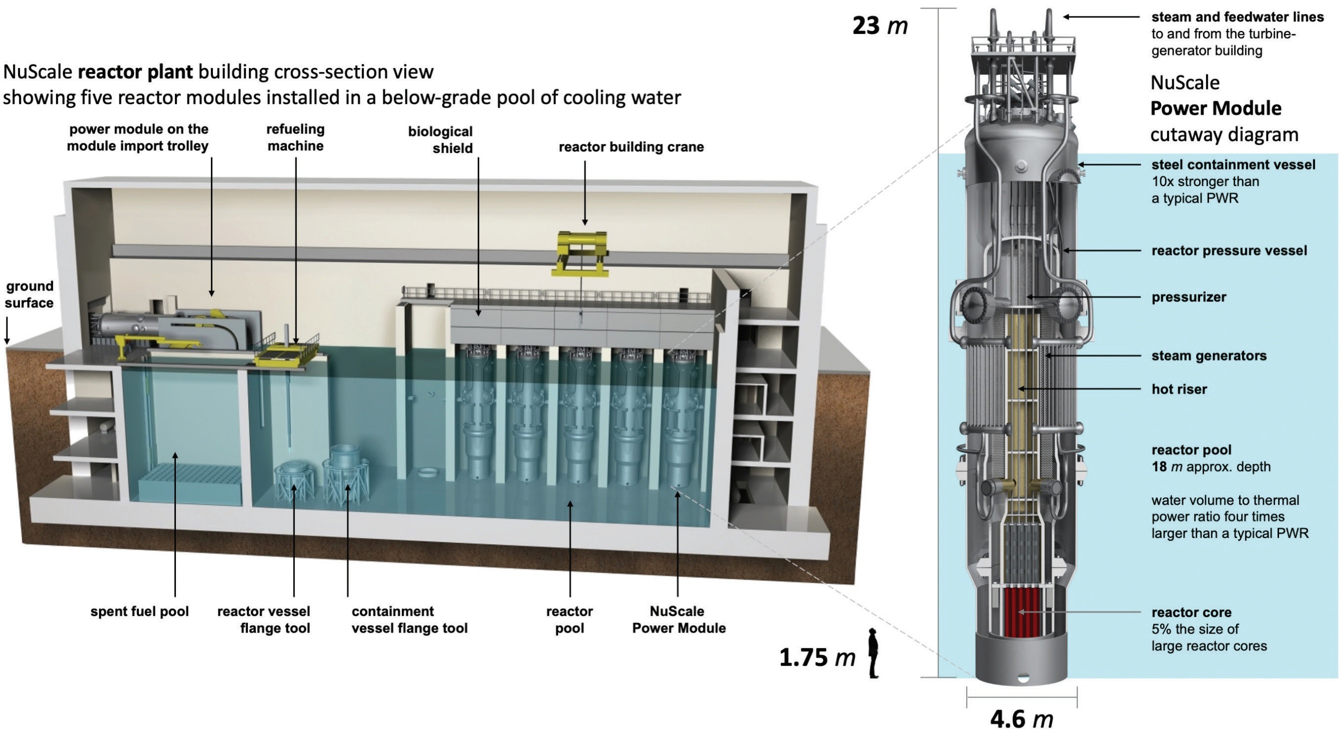
e) Most large nuclear plants were not originally designed to vary their output. Small modular plants can be designed for fully flexible output, as needed to balance volatile wind generation. The NuScale plant is an example of such a design.

f) Coal plants have minimum stable generation levels between 25% and 50% (typically 40%) of maximum. Operators generally prefer not to shut down and restart. Coal units can typically ramp up or down at about 4 to 5 MW per minute (the range is 1 to 9).

g) Combined cycle gas turbines are not much more flexible than coal plants. Open cycle gas turbines and reciprocating engines can ramp generation output up and down more rapidly. All thermal plants have a ‘minimum generation’ limit and other constraints on start-up and shut-down. Hydro turbines can adjust their output very quickly from any point between zero and full load and, although the specific response characteristics depend somewhat on details of each design.

h) Wind and solar power are sometimes referred to as semi-scheduled, as their output can be reduced, but not increased by the system operator. AEMO assumes that no solar capacity is available at the time of system peak and that at the 85% percentile between 5% and 20% of wind power capacity (values specific to states and seasons) will be available at the time of system peak.

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



Source: diagram courtesy of NuScale Power. For information on the NuScale first-of-a-kind project with UAMPS see: www.uamps.com/Carbon-Free

Replacing retiring coal plants with new modular nuclear plants would eliminate emissions on a large scale and increase reliability and flexibility without compromising the grid services that underpin system strength. Unlike replacing coal-fired generation with renewable energy only, carefully considered deployment of SMR plants would not require additional large investments in transmission and storage; nor would low-emissions or 'net zero' power systems require radical re-engineering to ensure their stable operation.[59-63]

While nuclear energy is usually considered for power systems, SMR plants can also be configured to provide other energy services.[64,65] 'Multi-vector energy system' concepts integrate SMRs with heat, CO_2-free production of 'pink' hydrogen, 'eFuel' molecular synthesis, seawater desalination, industrial or district heat in dedicated mode or with electricity cogeneration, and balancing of variable renewable energy generators.[66,67] Our research finds electricity is likely to be the first case for nuclear energy in Australia. Other applications are likely to be of increasing interest in the longer term, particularly in the context of policies and strategies seeking net zero emissions, especially in hard-to-decarbonise sectors.

Selected case study: the NuScale SMR

A specific case study helps focus our research question. NuScale's design has been chosen for several reasons. Sufficient information is publicly available. After 20 years, more than US$400 million in U.S. Department of Energy cost-shared financial assistance awards, and more than $700 million in private sector investment, the design has progressed furthest among SMRs. With NRC approval, the first-of-a-kind (FOAK) plant can be built in the U.S.[68] Further plants deployed in the U.S. and Canada would encourage Australia to prepare the option for a collective innovation-decision as an early adopter.[69]

The design integrates the reactor pressure vessel, containment vessel, pressuriser, and steam generators all into a single packaged module: the NPM. This design eliminates the need for coolant pumps and all the large pipe systems as historically used in large reactor designs.[70] Technology validation is based on physical testing at engineering facilities in the U.S., Canada, Germany and Italy.[71] Figure 6 shows a single SMR reactor module, and how it is located in a below-ground pool in the reactor building. Chapter 6 includes an aerial view of a complete plant.

2. Management

> *Focus on using proven project and construction management practices to increase the probability of success in the execution and delivery of new nuclear power plants.*
>
> — MIT Energy Initiative, 2018[72]

Project management discipline is crucial

From conception through development, from financing through project delivery to commissioning, and during operation to closure, large engineering projects should follow the **project lifecycle framework** discipline shown in Figure 7, as referenced throughout this report. A series of decision stage gates are represented in the figure by traffic signs. Key deliverables and milestone documents are flagged. Cost estimate classes, project definition levels, and accuracy ranges in Figure 8 correspond to the project lifecycle stages in Figure 7.

Ten keys to successful nuclear projects

High-cost nuclear projects can draw down three or more times the capital of similar low-cost projects. A UK study in 2019-20 on nuclear energy found that a 'relatively small number of understandable factors drives the cost of nuclear plants.' Low-cost projects tended to:

1. choose Nth-of-a-Kind over First-of-a-Kind designs
2. complete the plant design before construction
3. engage an experienced EPC consortium
4. procure via an experienced supply chain
5. plan in detail before starting construction
6. recruit experienced construction management
7. use low cost and highly productive labour
8. re-use the design many times in a fleet programme
9. locate multiple units at a single site, and
10. focus on cost reduction and improved performance,

High-cost projects tended to the opposite, worsened by:

- major regulatory interventions during construction
- litigation between project participants
- significant delays and rework due to supply chain
- long construction schedules, and
- insufficient oversight by the owner.[44]

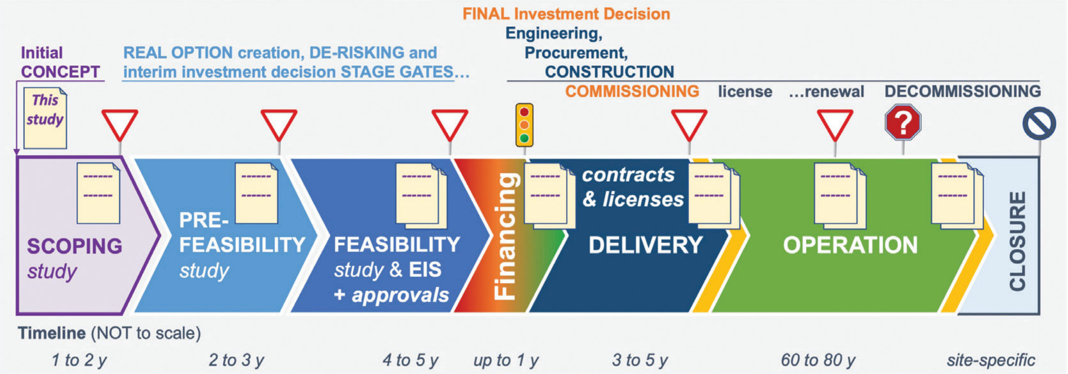
Use decision stage gates for 'de-risking'

A *Preliminary Concept Study* can begin the process. An 'order of magnitude' or scoping study is followed by a pre-feasibility study, then feasibility studies (including environmental and social impact assessment, approvals, permits and licenses) and financing, followed by detailed design, construction, commissioning and operation. Operations cease after a closure decision on any type of asset, and the decommissioning process begins. The site is then either re-used or rehabilitated.

Nuclear energy has specific characteristics, but many of the observations that follow apply to any major project.

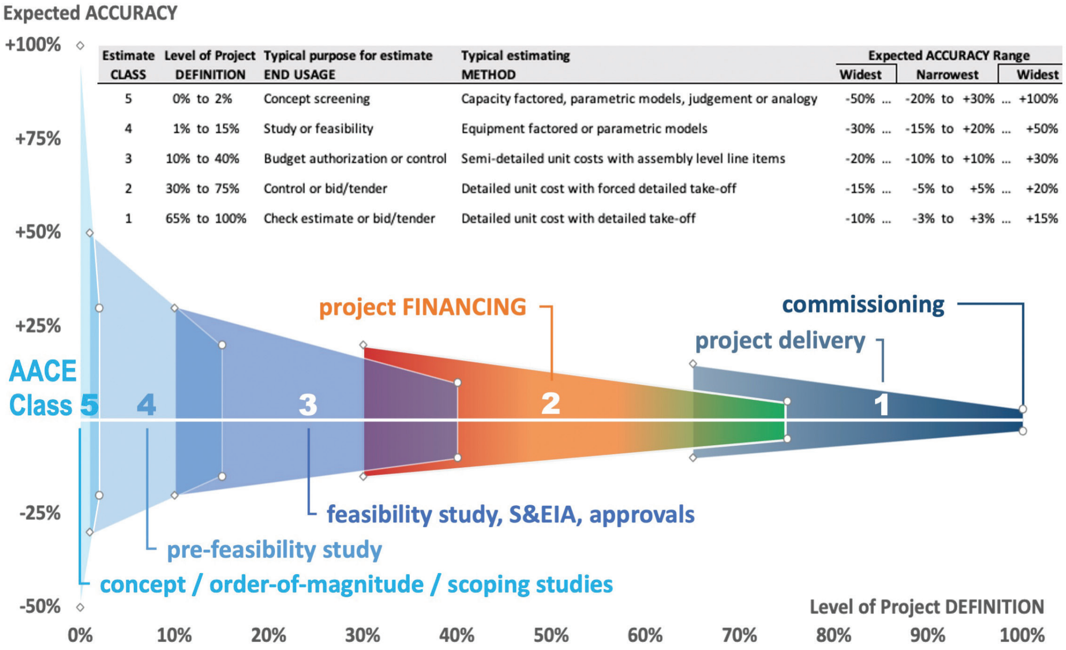
- **Risk is high in the early stages** from many unknowns and large uncertainties. The studies 'de-risk' the project to create economic and financial value through a sequence of *real options*, which may subsequently be 'exercised' by committing to and investing in the next step in the process.[30] *Many people mistake a best case for a central estimate*.
- **A series of interim investment decisions** '...made *sequentially*, and in a particular order' reduce uncertainty systematically. At each stage gate, it is possible to proceed immediately, to wait, to sell to another entity, or to abandon a project.[73]
- **Prior to financing, all of the project development funding is at-risk equity**. The financing process secures the debt capital needed to enable the engineering, procurement and construction (EPC) contracts for physical delivery of the project.
- **Many parties are involved in the process** for any large engineering project: the proponent, investors, lenders, customers, and communities, through to regulatory bodies and governments. The IAEA's guidelines focus on preparatory organization, construction, and commissioning.[74]
- **The process takes time**: noting the importance of community support and national strategy for nuclear power, in the 2006 the Switkowksi Review estimated 10, 15 or 20 years to operation as 'accelerated,' 'average' or 'slow' timelines for the process to commissioning (only large plants were considered).[13]

FIGURE 7 The engineering project lifecycle indicating stage gates for key decisions



Source: Greig, Wilson (2013 to 2020) adapted from engineering professional practice course teaching materials, University of Queensland

FIGURE 8 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%

Source: Author's diagram using the information in the inset table from reference [75]

Technology choice and plant design

While this study uses the most mature SMR design to illustrate the answer to the research question, a scoping study should select a short-list from the long list of large and more than 70 small modular and micro reactors. The characteristics of locations suitable for each type should also be considered by the scoping study. The pre-feasibility study would then select from the short-list the design and location for preparation of subsequent feasibility studies: one for each potential project.

BOX 1 Case study: OPAL research reactor

The reactor in Sydney shows Australian engineers' ability to procure, construct, commission and operate safely and reliably a nuclear reactor and associated facilities. An Australian client and Australian engineering companies worked with an international technology vendor (from Argentina), supported by an Australian supply chain to deliver the project on time and within budget. The reactor has built up a track record of high availability. 'OPAL continued to consolidate its reputation as one of the world's most reliable and available multipurpose reactors.'[76]

Cost estimation for the case study design

In 2011, Fluor Corporation invested US$30M to become the majority shareholder in NuScale Power and is the engineering, procurement, fabrication, and construction (EPFC) lead for plant construction. In 2017 Fluor estimated the cost to build a *complete plant* using proprietary data or vendor quotes for more than 14,000 line-items of equipment, materials and other inputs.[b] A non-destructive examination process has been developed and transportation costs estimated by an expert heavy load transport engineering team.[70] At the time of writing, UAMPS had contracted Fluor to prepare a class 2 estimate, based on commercial vendor bids, for a 6-unit plant under the Carbon Free Power Project to be built at the Idaho National Laboratory. Our study uses Fluor's published cost estimate as shown in Box 2.

BOX 2 Case study plant capital costs

The estimate of overnight cost per unit of capacity is US$2850 /kW$_e$ in 2017 dollars, as announced in 2020 along with an increase of (gross) electrical power per module to 77 MW$_e$.[77] Our case study is for a plant with 924 MW$_e$ output from 12 modules of 77 MW$_e$, giving an overnight base construction cost in 2017 dollars of US$2.633 billion. We converted this number to 2020 Australian dollars, added an estimate for owners' costs, applied project contingencies, and added interest during construction (IDC) to estimate total project costs.

We used a 2019 paper with information from NuScale based on the Fluor cost estimates grouped into ten categories of capitalised direct and indirect costs.[78] We assigned the relevant estimate class to each category, then applied the values in Figure 8 to each category, allowing us to estimate the recommended AACE confidence intervals for the blend of class 4 and class 3 estimates behind the published US$2850 /kW$_e$ number.

Our imported-to-local cost ratio (first estimate) is 45:55, assuming a single rate for currency conversion; fully imported reactor, turbine and electric plant equipment; and other cost categories sourced in Australia. The general engineering steps after the final investment decision (FID) for an SMR plant are described below.

Factory manufacturing of reactor modules

NuScale's technology vendor business model allows for module manufactured by more than one company. Modules could be manufactured in Australia or overseas for shipping to an Australian port, delivered to site, then installed. In 2018 NuScale selected BWX Technologies to provide manufacturing input leading to fabricating the first NPMs.[c] The companies are collaborating to update the design, optimising for manufacturing and transport and reducing overall costs of the NPMs. In 2019 Doosan of Korea entered into an agreement with NuScale for strategic cooperation and investment to support NPM deployment worldwide. Doosan is now also an investor in NuScale, as are other companies.[70,79]

Constructing civil works and site facilities

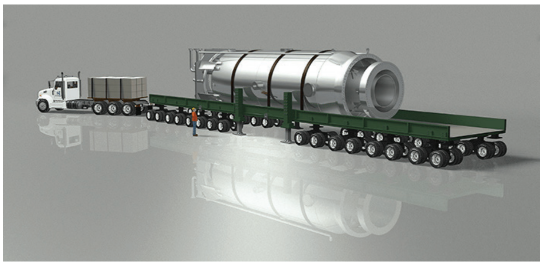
Between 2000 and 2005, an Australian Joint Venture of John Holland Evans Deakin Industries delivered the building, civil, infrastructure and non-nuclear electrical, process instrumentation and mechanical works at ANSTO's OPAL reactor. Over 60 staff and 300 people on-site delivered AU$160 million of design and construction work for the AU$300 million project.[80] Civil works for an SMR plant at the scale of the NuScale design will be larger and more complex than those for the 20 MW$_{th}$ OPAL reactor, but simpler and smaller than for large GW-scale NPPs: the company draws analogies with shipbuilding and aircraft assembly.

Transport to site and installation

Reactor modules as in Figure 9(a) are designed to be factory fabricated and assembled for transport to site by rail, ship, barge or truck, to install in a building of the type in Figure 6. Site installation effort is reduced by modular construction techniques where appropriate and simplified civil construction.[81] Final delivery of all modules would be by road, unless there is access to tidewater. Modules manufactured offshore would be shipped to a major port. Figure 9(b) shows an example of a larger pre-fabricated heavy engineering module, moved over a longer distance, than required for NPMs.

FIGURE 9 Visualisation of module delivery

(a) Artist's impression:
NuScale Power Module™ delivery to site



Source: NuScale

(b) Heat exchanger delivery from Coffs Harbour to Olympic Dam: 2400 hp from 4 prime movers towing 358 tonnes 2250 km

Source: photograph supplied by Graham Owen / TOLL Group

Fuel assembly transport and storage

Fuel assemblies are required for each reactor's first core and each refuelling. Safe transport of fresh reactor fuel is well-established: around the world, about 20 million transportations of radioactive materials of all kinds occur safely each year, by sea, rail, road and air.[82] ANSTO has long experienced in the safe transport and storage of fresh reactor fuel for Australia's reactor in Sydney.[d]

Commissioning and plant operation

Nuclear plants are commissioned in three stages: before fuel load; with fuel to reach 'first criticality'; and to full load and testing under contingencies.[e] Commissioning must confirm the safe and effective functioning of all operational and emergency systems and procedures before an operating license is issued. Training and certification of the operators is a key element.[83]

Management of spent fuel and waste

Following established practice, NuScale SMR plants are designed to store spent fuel for at least five years in an 18m deep pool of water, enclosed by stainless steel and reinforced concrete in a seismic category 1 building.[84] After cooling, used fuel may be stored in robust containers on a concrete pad (dry cask storage) for the life of the plant, or moved earlier to long-term storage.[f]

> *What you normally hear about as nuclear waste is actually the "used fuel" removed from a reactor, which still contains approximately 96 percent of the original fuel that can be recovered to produce new fuel.*[84]

Long-term safe options include fuel reprocessing; re-use in fast neutron reactors; or permanent storage in stable rock in chasms (as at Onkalo in Finland) or in deep boreholes (as with Deep Isolation's technology).[85-88] **Australia could develop similar options, and should do so in parallel with development of SMR plants.** Australia developed ANSTO Synroc® waste treatment technology and also has ideal conditions for safe stewardship of spent fuel and high-level nuclear waste.[14]

End-of-life decommissioning

SMR modules must be decommissioned at the end of their operating life (usually 60 to 80 years) and the site either prepared for re-use or rehabilitated. Australia has experience in safe and proven decommissioning methods.89 Plant owners are generally responsible for estimating decommissioning costs, which provide a basis for accumulating funds needed to cover the actual cost of decommissioning activities.[90,91][g]

Findings and recommendations

Australia has or can acquire the engineering capabilities needed to deploy SMR plants following well-established project management processes. Opportunities for Australian industry range from module and equipment manufacturing and transport to all aspects of site installation, including civil, structural, mechanical, electrical and instrumentation. Scope to build regional export businesses aligns with the Clean Energy priority of Australia's Modern Manufacturing Strategy, and with the Defence priority.[92,93] The scope for synergies between reactor and submarine manufacture should be explored. A scoping study should compare module manufacturing options for Australian projects.

To be in a position to deploy SMR plants in Australia in the 2030s, the engineering profession and governments would need to begin preparing now.

3. Governance

The body of international nuclear law, the national law that gives effect to Australia's treaty obligations, and the institutions with governance authority in the energy and nuclear sectors and over relevant regulatory processes are described below. These comprise what the IAEA refers to as the **legal and regulatory infrastructure**. State legislation is noted, as are energy governance and steps needed prior to deployment of nuclear energy.

International law, roles and obligations

Australia engages with, and contributes to, a number of international organisations in the nuclear sector.[94] Australia is a founding member of the International Atomic Energy Agency (IAEA) and has ratified a range of international treaties and conventions that constitute the substance of international nuclear law in: (i) nuclear **non-proliferation** and nuclear **weapon test bans**; (ii) nuclear **security**; and (iii) nuclear **safety**. The following treaties are of particular note for this study.

The *UN Treaty on the Non-Proliferation of Nuclear Weapons* —generally referred to as 'the NPT'—was signed by Australia in 1970 and was ratified by Australia on 23 January 1973.[95] In connection with the NPT, under the *Agreement between Australia and the IAEA for the Application of Safeguards*, which entered into force on 10 July 1974, **Australia upholds safeguards** on all source or special fissionable material in all peaceful nuclear activities within its territory.[96] The *Additional Protocol to the Safeguards Agreement*, in force since 12 December 1997, enhances the IAEA's ability to **verify the peaceful nature** of Australia's nuclear activities.[97][h]

The *Convention on the Physical Protection of Nuclear Material* (CPPNM), in force since 22 October 1987, commits the parties to provide **physical protection to nuclear material** in international transport, and to criminalise various activities in relation to unauthorised dealings with nuclear material. The *Amendment to the CPPNM*, in force since 10 April 2007, extends physical protection obligations to material in domestic use, storage or transport, and to nuclear facilities.

The *International Convention for the Suppression of Acts of Nuclear Terrorism*, in force since 6 March 2012, requires that Parties must establish criminal offences with appropriate penalties in relation to several offences relating to **nuclear terrorism**. The *Convention on Nuclear Safety*, in force for Australia since 24 March 1997, establishes **fundamental safety principles for the siting, design, construction, commissioning, operation and decommissioning of nuclear power plants**. The *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, in force since 3 November 2013, establishes* **fundamental safety principles applying to the management of spent fuel and radioactive waste.** Both conventions create a peer review mechanism. Australia is active in peer review of the implementation of these conventions by the other parties.

Australian legislation and regulations

Ratification of a treaty binds a party to the obligations set forth in the treaty as a matter of international law. The Australian Parliament implements Australia's treaty obligations through legislation—an **Act of Parliament**. In an Act, parliament may assign power to a minister, executive official, government department, or agency, who then, under the authority conferred on them by the Act, can create "delegated legislation" (**regulations, standards, ordinances**, and other **instruments**) to give effect to some part/s of the parent Act. These do not need to be approved directly by either House of Parliament but, like the parent Act, these require Royal Assent by the Governor-General before they become law. Various **Commonwealth Acts and regulations** are relevant to this study, including those noted below.

The *Nuclear Non-proliferation (Safeguards) Act 1987* establishes the statutory office of Director of Safeguards in the Australian Safeguards and Non-proliferation Office (ASNO), provides the basis for Australia's **safeguards system**, and implements Australia's obligations under the NPT, IAEA safeguards and the CPPNM.[98]

The *Customs Act 1901* provides for controls on **imports to and exports from Australia**. The *Customs (Prohibited Imports) Regulations 1956* prohibits **the import of radioactive substances** unless the approvals of the Minister for Health and the Minister for Home Affairs are obtained. The *Regulations 1958* prohibit the **export of Australian uranium** unless the approval of the Minister for Resources and Energy is obtained. Conditions from the NPT, the South Pacific Nuclear Free Zone Treaty Act 1986 and safeguards agreements apply. The *Defence Trade Controls Act 2012*, touches on **nuclear materials**.

The *Atomic Energy Act 1953* specifies that **discoveries of naturally occurring uranium and thorium** in Australia must be reported to the Minister within one month from discovery.

The *Australian Radiation Protection and Nuclear Safety Act 1998* establishes the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) and Australia's regulatory regime for uranium mines, nuclear installations and other **radiation sources**. The *Regulations 2018* specify the technical aspects and standards of the regulatory regime.

The *National Radioactive Waste Management Act 2012* creates provisions for the selection of a site, and the subsequent establishment and operation of a centralised **radioactive waste management** facility, work that is led by the Australian Radioactive Waste Agency (ARWA).[99]

The *Environment Protection and Biodiversity Conservation Act 1999* ('EPBC Act') provides **assessment and approvals processes Australia-wide** for actions of National Environmental Significance. Bilateral agreements between the Commonwealth and States are made to prevent assessment duplication, although no such agreement exists for approvals. **Actions of National Environmental Significance** are defined in the *Regulations 2000*, which specify the technical and procedural aspects of the assessments and approvals processes.[100]

The *Australian Nuclear Science and Technology Organisation Act 1987* replaced the former Australian Atomic Energy Commission (AAEC) with ANSTO as the main **nuclear research** organisation.

A key issue: bans in current legislation

The EPBC Act (and, for Commonwealth entities, the ARPANS Act) prohibit deployment of commercial nuclear power plants and associated fuel facilities in Australia.

The EPBC Act contains numerous references to nuclear energy throughout. A key example is *s.140A: No approval for certain nuclear installations*.

BOX 3 Section 140A of the EPBC Act 1999

The Minister must not approve an action consisting of or involving the construction or operation of any of the following nuclear installations:

(a) a nuclear fuel fabrication plant;
(b) a nuclear power plant;
(c) an enrichment plant;
(d) a reprocessing facility.

The EPBC Act prevents the construction or operation of nuclear power plants and associated fuel cycle facilities, but it does not prevent preparatory work such as scoping and pre-feasibility studies on topics including economics and bankability, social acceptance, licensing, technology and the environment. A history of Australia's nuclear prohibition, with a focus on the ARPANS and EPBC Acts is included in an inquiry submission from 2019.[101]

State legislation

A number of Australian states also have legislation prohibiting the deployment of commercial nuclear power plants and associated fuel cycle facilities, including:

- **Victoria**: *Nuclear Activities (Prohibitions) Act 1983*
- **New South Wales**: *Uranium Mining and Nuclear Facilities (Prohibitions) Act 1986*
- **South Australia**: *Nuclear Waste Storage Facility (Prohibition) Act 2000*
- **Queensland** *Nuclear Facilities Prohibition Act 2007*

Nuclear power is not prohibited in **Western Australia**, where the Australian Fleet Base West is approved by ARPANSA for visits by nuclear powered warships.

Energy and its governance in Australia

Australia's energy sector is extensive, encompassing upstream resources, on- and offshore infrastructure, an export sector larger than the domestic market, electricity and gas transmission networks interconnected across state borders, a mix of government and private sector ownership, and a combination of unregulated, regulated, and competitive wholesale and retail market domains. The NEM spans six jurisdictions from South Australia to Queensland across one of the longest interconnected transmission networks in the world. The NEM has wholesale and retail market competition, as does Western Australia's Wholesale Electricity Market (WEM).

All major energy resources are present in Australia: oil, gas, coal, hydro resources and renewable energy. Over 30% of the world's economically recoverable uranium reserves are in Australia, which are mined processed and exported as uranium oxide (U_3O_8). Enriched uranium is imported in fuel assemblies for ANSTO's multi-purpose research reactor. Australia's regulation in the nuclear sector is currently focused on managing health, safety, and environmental risks through ARPANSA, and through ASNO on security and compliance with obligations under international treaties and conventions.

Figure 10 shows governance institutions in Australia's nuclear, emissions reduction, renewable energy, electricity and gas sectors, identifying the statutory regulatory, agency, corporate, operational and advisory bodies, and flagging key legislation.[102] There is a large overlap between governance of emissions reductions and of energy, but presently no overlap between either of those domains and the nuclear sector.

The *Australian Energy Market Agreement* between the Commonwealth, states and territories governs electricity and gas at the federal level.[103] The Australian Consumer and Competition Commission (ACCC) has a broad remit across sectors under the *Competition and Consumer Act 2010*, including energy market monitoring, competition and consumer protection.[104] The Australian Energy Regulator (AER), which shares staff, resources, and facilities with the ACCC but has an independent board, sets network prices, monitors compliance with market rules, regulates some retail markets, publishes information on the energy markets, and assists the ACCC on enforcement, mergers, and authorisations.[105] The Australian Energy Markets Operator (AEMO) manages the markets and system security. The Australian Energy Market Commission (AEMC) is the rule-maker for electricity and gas markets.[106]

Capabilities, gaps, needs and support

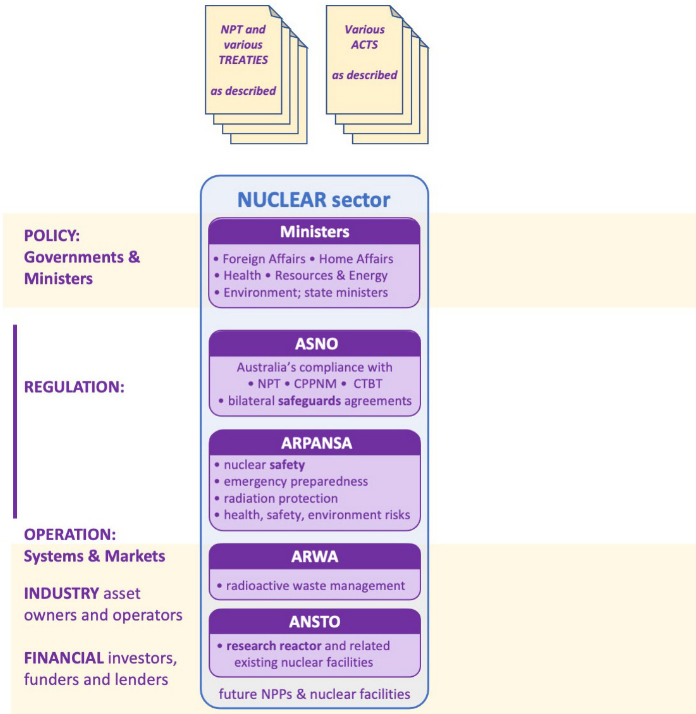
Australia is an IAEA founding member; a member of the Nuclear Energy Agency (OECD-NEA) since 1973; a uranium oxide fuel supplier to the global nuclear energy industry; a party in good standing under the international treaties and conventions on safety, security and non-proliferation as well as our safeguards commitments; and an active member of the Generation IV International Forum.[108-112] It is a core part of the IAEA's remit to provide substantial support to countries considering nuclear energy, and to review their progress, if requested.[i]

Australia's existing legal and regulatory framework needs to be expanded and strengthened in a number of key areas to operate nuclear energy plants safely and responsibly: Australia's current reactor regulations are suitable only for research reactors. ARPANSA and ASNO have excellent international reputations and could be granted expanded mandates with the authority and resources appropriate to regulate commercial nuclear plants and associated fuel cycle activities.

Appropriate licensing processes and regulations will need to be developed for all stages of the NPP lifecycle. The industry will need to make extensive use of offshore technology, as do various other safety critical industries in Australia. Licensing is usually managed as a two stage process: construction and commissioning. The regulator must first be satisfied that operator training is completed prior to commissioning.[j]

Laws on nuclear liability are required, and essential for foreign reactor supply, as well as investment and financing.[113] The national law must be compliant with international law. If Australia decided to move ahead with a nuclear energy programme it would likely ratify one or more of the existing international treaties on third party liability for nuclear damage in the event of an accident. There are multiple conventions on nuclear liability, including the *Vienna Convention on Civil Liability for Nuclear Damage*, the *Joint Protocol*, and the *Convention on Supplementary Compensation* (CSC). Australia is a signatory to the CSC. *The Law of Nuclear Energy* discusses choice of conventions.[113]

FIGURE 10 Key institutions in the governance of Australia's energy and nuclear sectors



Work will be required in this area to identify the most appropriate approach for Australia.

Many of the 19 nuclear infrastructure issues defined by the IAEA have a legal or regulatory aspect: the national position, nuclear safety, management, funding and financing, the legal framework, safeguards, radiation protection, the regulatory framework, the electrical grid, human resource development, stakeholder involvement, site and supporting facilities, environmental protection, emergency planning, nuclear security, the nuclear fuel cycle, radioactive waste management, industrial involvement, and procurement.[114,115] Each issue is considered at a more general level in the other chapters of this report.

Governance steps to deployment

To adopt nuclear energy, Australia's legal and regulatory infrastructure should be sufficiently developed so that the regulator is resourced and ready to scrutinise, and if appropriate, licence the first plant. **Co-ordination by an implementing body** is vital throughout:

> *An important element of the Milestones approach is a mechanism to coordinate efforts among the many organizations and individuals with roles in considering and developing a nuclear power programme…referred to as a nuclear energy programme implementing organization (NEPIO).* [114]

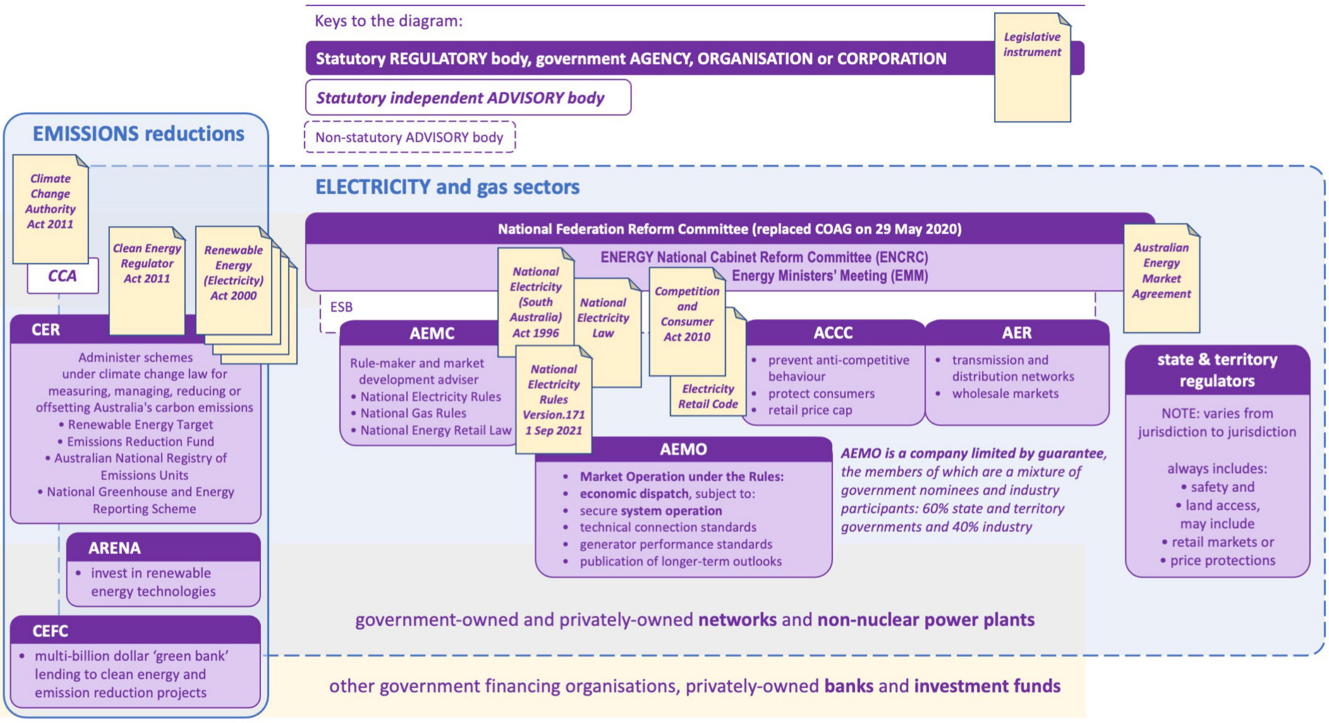
In Australia, the organisations most likely to play crucial roles in the process of adopting nuclear energy are the Australian, State and Territory governments; **ministries and statutory bodies** in the energy and nuclear sectors, especially ANSTO, ASNO, ARPANSA and ARWA; advice from the CCA and the ESB, AEMO, AER, and AEMC. The Australian Law Reform Commission may provide advice to the Government if an issue is referred to it by the Attorney-General of Australia.

The first three major tasks are:

(a) a detailed review of existing legislation and institutions;

(b) analysis of gaps and regulatory capacity strengthening; and

(c) work on repealing the bans and drafting laws needed to regulate nuclear energy in Australia.



Source: Authors' research, adapted from: [107] and updated with reference to: [98,102-106]. Note that the National electricity market applies to plant connected to a grid extending from Queensland through New South Wales and Victoria to South Australia and Tasmania. Separate rules apply in WA and Northern Territory.

4. Capabilities

> *Maintaining human skills and industrial expertise should be a priority for countries that aim to continue relying on nuclear power.*
>
> —IEA, 2019[116]

Requirements

A broad range of technical skills, capabilities and knowledge are essential for the safe operation of nuclear power plants. It is important to keep in mind that the majority of the positions in a nuclear power plant are for non-nuclear specialists including in engineering, technical and trade roles. The approach to training for the construction, commissioning, and operation of ANSTO's research reactor is a practical demonstration at a small scale of what can be done. The elements of sustainable human resource capabilities include:

- building on Australia's foundation of sound science, technology, engineering and mathematics (STEM) in schools and university engineering programs, and in the Technical and Further Education (TAFE) sector
- leveraging mature university programmes in nuclear engineering, nuclear health and safety
- identifying experienced project managers
- thoroughly trained operating staff, which will be a requirement to obtain an operating licence
- access to a simulator for each type of reactor built
- capable people to staff the nuclear regulator, and the nuclear security and safeguards agency, and
- experienced, capable technical and trades people.

Experience

Capabilities that Australia can build upon and resources to draw upon meet the requirements for skills include:

- existing facilities, people, nuclear education programmes and world-leading engineering and scientific research capabilities in Australian universities and at ANSTO
- decades of uranium mining in the resources sector,
- a track record and long involvement in international organisations and governance
- support for the overall nuclear program from the IAEA and the OECD-NEA, and
- consulting engineering groups with experience in detailed design of major projects including nuclear projects: the OPAL research reactor is a good example of management of a complex nuclear project in Australia.[80]

Companies operating in Australia with nuclear experience or nuclear businesses overseas include:

- **ANSTO** (Government operator of research reactor)
- **Arup** (large nuclear engineering projects in the UK)
- **BHP** (Olympic Dam Operations in South Australia)
- **CLP International** (the parent company of Energy Australia, which has an equity share in China's first nuclear power plant at Daya Bay, Guangdong)
- ***DUNE*** (nuclear project development studies)
- **Engie** (which owns and operates NPPs in Belgium)
- **Fluor** (the parent company of NuScale Power)
- **Frazer-Nash Consultancy** with nuclear experience
- **GE** (a major nuclear technology vendor)
- **GNE Advisory** (specialist nuclear energy legal firm)
- **Helixos** (project management and stakeholder engagement experience in the nuclear sector in Australia and the United States)
- **John Holland** (the Australian engineering contractor on construction of the OPAL reactor for ANSTO)
- **Mitsubishi Heavy Industries** (nuclear technology)
- **SMR Nuclear Technology** (nuclear development)
- **Worley** (advising the National Nuclear Plants Authority on construction of Egypt's first NPP)

In addition to nuclear-specific work, experience is transferrable from other Australian engineering projects including LNG liquefaction plants, pressure vessels, civil engineering, aerospace and component manufacture, defence industries, logistics, shipping and overland transport of large modules and heavy equipment and of uranium, fuel rods and spent fuel.

University courses and nuclear research

The **Australian Institute of Nuclear Science and Engineering** (AINSE) was established in 1958. It co-ordinates access to ANSTO's facilities by universities and other tertiary institutions.

Switkowski examined nuclear education and training, identified existing Australian resources and potential future requirements in chapter 10. Appendix R lists Australian R&D, Education and Training, concluding:

> *There is a global shortfall of skilled persons in the nuclear industry. Many countries are significantly increasing their efforts in nuclear education and training to address this shortfall. New educational consortia are being formed, both within and between countries. Should Australia decide to expand its involvement in the nuclear fuel cycle then it will need to boost its level of nuclear education and training considerably.*[13]

Following earlier experience from 1954-1986 teaching nuclear engineering, in 2014 **UNSW** Sydney once again offered a Masters of Engineering Science (MEngSci) in Nuclear Engineering oriented towards nuclear power engineering. ANSTO and Imperial College, London are key partners. Four core courses cover: an introduction; reactor physics; the fuel cycle; and safety, security and safeguards of nuclear fission technology. Programs and courses are shared with PLuS alliance partners Arizona State University and Australia's Department of Defence. The revitalised program is growing and has taught 252 enrolments, to date, in the specialist nuclear courses.

The education offering is strengthened by a research program linked with global industry partners in nuclear fuels, waste management, nuclear materials and nuclear safeguards.[117] Since 2021, UNSW represents Australia on the advisory council of the OECD Global Forum on Nuclear Education, Science, Technology and Policy, a group convened to, 'bring to the fore the perspectives of the world's leading nuclear academic institutions on… issues in international policy discussions.'[118]

Following the 2006 Switkowski Review, the Australian National University (ANU) and the University of Sydney also offered nuclear science programmes and courses.

In Dec 2007, the Institute of Nuclear Science was established in the School of Physics at the **University of Sydney**. In 2008-2011, a Master of Applied Nuclear Science programme was introduced. This was initially successful and supported by ANSTO, but was unable to attract enough students without a larger number of job opportunities in Australia and has not been offered since 2012. From 2016, the *Energy and the Environment* course in the Faculty of Engineering has included a lecture on 'Introduction to Nuclear Engineering.'[119]

ANU has offered a Master of Nuclear Science programme since 2007, leveraging particular ANU strengths in accelerator science, science and public policy, and fusion.[119] **Wollongong University** specialises in courses in radiation medicine and radiation detection.

UQ engineering faculty members have experience in the nuclear sector in the UK and Japan, in robotics and materials engineering. Mechanical engineers at UQ are using computational and theoretical research methods for fusion containment for international collaboration.[k]

Employees and plant staffing needs

The 2016 census data shows 8,065 people employed in fossil fuel electricity generation; of 10,268 in all electricity generation; of 54,001 in electricity supply and 115,753 in electricity, gas, water and waste services; in a workforce of 10.68 million and a population of 23.4 million. Table 2 shows coal-fired plants by state, their installed capacity and the people employed—estimated based on power plants by ABS SA3 statistical areas—as 240 people per plant on average, excluding city office-based roles.

TABLE 2 Employment in coal-fired power plants

State	Plants Nº	Capacity MWe	Employees approx.
Queensland	8	8 126	1 500
NSW	5	10 280	1 400
Victoria	3	4 820	1 300
Subtotal NEM	16	23 226	4 200
Western Australia	4	1 677	600
TOTAL Australia	20	24 903	4 800

Source: [120,121]; authors' estimates

The local workforce and communities

Table 3 shows staffing for a 12-module SMR plant.

TABLE 3 Employment in a NuScale power plant

Job positions	
Plant Manager	1
Department Managers	6
Operations	45
Radiation Protection	17
Chemistry	14
Work Control	13
Outage Planning	21
Instrumentation & Controls (I&C)	10
Mechanics	8
Electricians	11
Systems Engineering	9
Reactor Engineering	5
Licensing	5
Emergency Preparedness	2
Training	19
Site Support / Facilities	13
Correction Action Program (CAP)	2
Supply Chain	5
Fix It Now (FIN) Team	15
Backshift Supervisor	1
Security	48
TOTAL number of positions	**270**

Source: Reproduced from [122], Appendix B

By education level there are: **45** roles requiring a **Bachelor of Science or Engineering**—some but not all in nuclear engineering or nuclear science—such as department managers, technical supervisors, and system engineers; **162** roles requiring an **Associate Degree**, **vocational education**, or **nuclear industry experience**, such as plant operators, maintenance craftsmen, radiation protection chemistry, technicians, and training staff; **61** roles requiring **high school education**, such as site support craftsmen, security officers, storekeeper; and **2** roles are at entry-level, for administration support.[122]

Jobs during construction, commissioning, in regulation, education, training, or in the supply chain for the plants are not included in the above. Table 4 shows similarities between equivalent roles in coal and SMR plants.

TABLE 4 Comparable coal and SMR plant roles

Coal-fired power plant position	NuScale equivalent position
Senior Management	
Plant Manager	Plant Manager[a]
Operations Manager	Operations Manager[a, b]
Maintenance Manager	Maintenance Manager[a]
Engineering Manager	Technical Services Director[a, b]
Common Facilities Manager	Site Support Services Supervisor
Operations	
Assistant Ops Manager	Shift Manager[b]
Shift Supervisor	Control Room Supervisor[b]
Control Room Operator	Reactor Operator[c]
Field Operator	Non-licensed Operator
Outage Planning	
Outage Manager	Generation & Planning Manager[a]
Planner	Planner
Maintenance Planning	
Maintenance Supervisor	Maintenance Supervisor
Foreman	Work Control Lead
Planner	Planner
Engineering Technician	Work Control Scheduler
Maintenance	
Boilermaker	Mechanic
Steam Fitter	Mechanic
Mechanic	Mechanic
I & C Technician	I & C Technician
Electrician	Electrician
Heavy Equipment Operator	Site Support Craftsman
Auto Mechanic	Mechanic
Labour Foreman	Site Support Craftsman
Laborers	Site Support Craftsman
Metal Fabricator / Welder	Site Support Craftsman
Tool Room Specialist	Tool Crib Attendant
Engineering	
Thermal Station Engineer	Design Engineer
System Engineer	System Engineer
Site Project Engineer	Component Engineer
Shift Engineer	Staff Technical Advisor
Project Manager	Supply Chain Specialist
Environmental	
Environmental Board Operator	Radwaste Operator
Environmental Operator	Non-licensed Operator
Plant Chemist	Chemistry Technician[d]
Coal Yard and Railroad	
Coal Yard Specialist	Site Support Craftsman
Coal Handler	Site Support Craftsman
Railroad Specialist	Site Support Craftsman
Railroad Train Operator	Site Support Craftsman
Security	
Security Guard	Nuclear Security Officer

Notes: a) Nuclear power plant experience requirement of 4 years b) Senior Reactor Operator License required c) Reactor Operator License required d) Limited to secondary and auxiliary water chemistry analyses.

Source: adapted from [122], Table 3, p.11.

Like coal-fired plants, nuclear power plants require skilled technicians and trades people. While retirement for some may coincide with retirement of the coal plant where they work (Figure 1), younger locally-based employees are likely to view as attractive opportunities to retrain to work in a nuclear power plant. Retraining coal-fired power station staff was a feature of the early UK nuclear program and continues today.[l]

Power plant jobs support families and also benefit local communities. Companies with major assets that are large employers in regional areas in industries supplying goods or services (in this case electricity) outside the local region tend to have a positive flow-on effect on employment in the local economy beyond the direct employment of staff and the hiring of contractors.[123] Census data from 2016 shows that employees in coal- and gas-fired power plants are more highly paid than in industries in general. While those plants have a similar proportion of managers and professionals (29%) as the general workforce (35%), the proportion of technicians and trades workers (45%) is well above that in the general workforce (14%). Those employees also often have enduring connections with the local community.

Operator training in reactor simulators

An important element of nuclear training is the use of a reactor simulator. A full replica of the control room is common in many industries: for example, air traffic control towers, aircraft cockpits, and electricity system control rooms. AEMO has a full replica alongside each control room used for training and visitor briefings. Each type of nuclear reactor in the UK was built with a complete replica control room with a computer model of the plant so that all routine and accident conditions could be simulated. The OPAL reactor at ANSTO has replica control panels and a computer plant model for training.

NuScale commissioned its first control room simulator in 2012 and a second in 2017 to be used to develop plant operating procedures and for training future nuclear plant operators. The system provides monitoring and control for a 12-module plant in a single main control room. A factsheet on the simulator is available online.124 Oregon State University, Texas A&M and the University of Idaho have each received US$ 250,000 to 300,000 of funding from the U.S. DOE '…to build NuScale reactor simulators…for research, education, K-12 outreach, and public advocation regarding nuclear power and Small Modular Reactor technology' which operate via remote communication with NuScale servers in Oregon.[125] [m]

Because the nuclear regulator must first be satisfied that operator training is completed prior to commissioning, good forward planning of the training schedule needed to build the capabilities and capacity for commissioning and operation phases is crucial to avoid costly delays.[n]

Findings and conclusions

There is time to expand, develop and deliver education and training programs for a future nuclear energy industry workforce in Australia from the 2030s.[126] Australia's IAEA and OECD-NEA memberships and partnerships with countries that have deployed nuclear power plants can accelerate and strengthen that work. Australia can also benefit from overseas nuclear education programs and links with overseas institutions.[o]

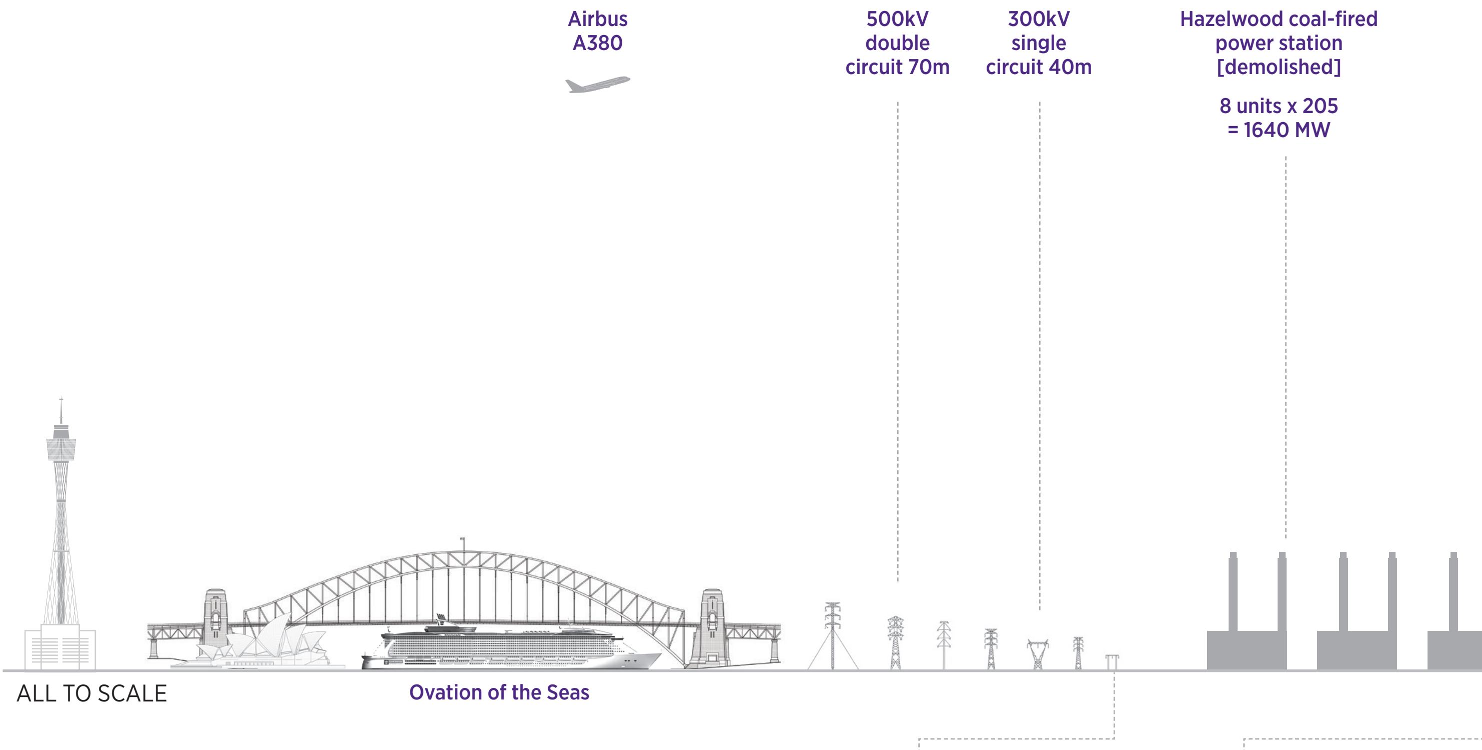
Opportunities for skilled and experienced technicians and trades people employed in coal-fired power plants to be retrained should be explored in subsequent studies. In addition to the ability and opportunity to train people for good careers in the nuclear industry, Australia is an attractive country in a strong position to recruit high quality people internationally. Notable senior people in the sector came from overseas and organisations in Australia's nuclear sector are regularly contacted by people overseas with nuclear experience seeking opportunities in Australia.

Recommendations on capabilities

There is not time for undue delay. The global demand for people with nuclear education and training reinforces the case to strengthen and support Australia's education and training system to prepare the engineers, technical and trades people needed for nuclear energy plants to be operating in Australia from the 2030s. Education improves optionality with low risk.

Australia must strive to ensure STEM education in the school system provides a stream of university entrants with the capabilities to study nuclear engineering and other technically demanding disciplines, and should follow the requirements for human resource development for a nuclear power programme.[115]

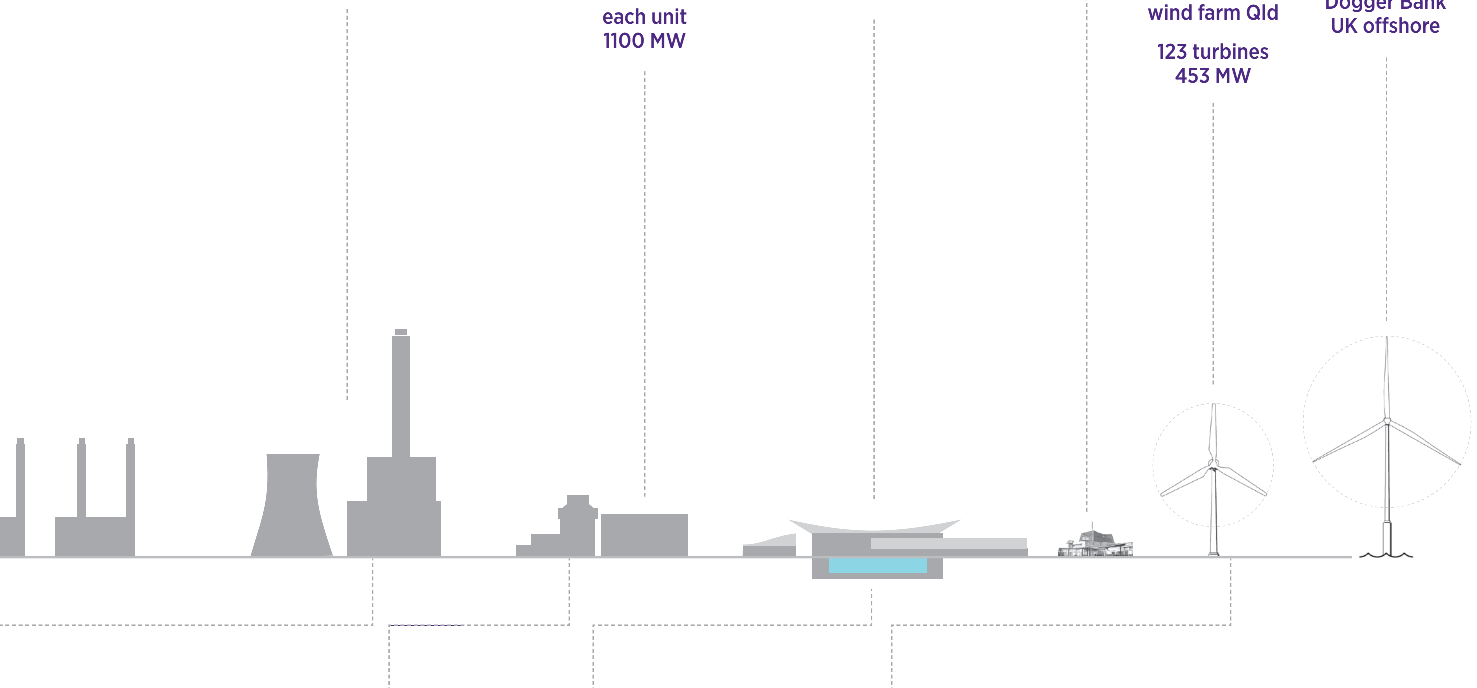
FIGURE 11 Footprints & profiles of electricity generation technologies



This infographic presents a comparison of some basic data of these electricity technologies:

- a 1960s brown **coal** PP
- a 1990s brown **coal** PP
- a 2010s large **nuclear** PP
- a 2020s 12-module **SMR** PP
- Australia's largest **wind** farm
- Australia's largest **solar** farm

Plant	Hazelwood	Loy Yang
Year commissioned [& decommissioned]	**1968** [2017]	A: **1986** B: **1995**
Process	combustion & sub-critical steam	combustion & sub-critical steam
Technology	boiler / turbine	boiler / turbine
Fuel	brown coal	brown coal
Emissions intensity tCO2/ MWh	1.400	**A**: 1.155 **B**: 1.141
Single unit size MW_e (gross)	8 x **205**	**A**: 1x**530** + 3x**560** **B**: 2 x **500**
Capacity MW_e (gross)	1640	A: 1650 B: **1000**
Local **footprint** for 8 TWh /y	~**25** sq.km	~**25** sq.km
Annual **availability *factor***	n/a	B: 90+%
Maximum **energy** MWh /y	n/a	**8 000 000**
Dispatched in 2019 MWh /y	n/a	7 891 750



Loy Yang B coal-fired power station
2 units x 500
1000 MW

AP1000 Toshiba Westinghouse Gen III nuclear power plant*

each unit
1100 MW

NuScale SMR 12-reactor plant
12 units x 77

924 MW

ANSTO OPAL reactor building

Coopers Gap wind farm Qld

123 turbines
453 MW

Currently world's largest turbine GE Haliade X Dogger Bank UK offshore

Large nuclear	Small modular	Coopers Gap	Western Downs
2018	late-2020s	**2020**	2022
nuclear fission & steam	nuclear fission & steam	wind turbine & DC-AC inverter	photovoltaic & DC-AC inverter
PWR	PWR	HAWT	PV
uranium	uranium	wind	solar
Zero	Zero	Zero	Zero
1157	12 x **77**	**3**.7	0.316 /panel **9**.167 /string
1157	**924**	**462**	**453**
<**1** sq.km exc. EPZ	~**1** sq.km inc. EPZ	>**500** sq.km	>**500** sq.km
90+%	95+%	38%	25%
9 000 000	**7 300 000**	**1 500 000**	**1 000 000**
8 987 000	n/a	n/a	n/a

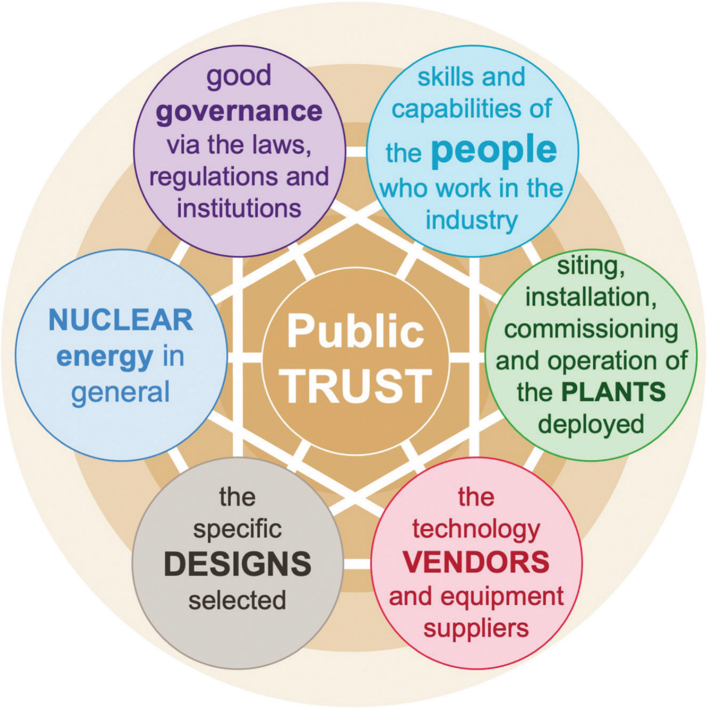
5. Society

Establishing community confidence is vital

Australia has long been a 'land of innovators' and 'early adopters and avid users of technology' ranking equal first with Sweden and Singapore in technological readiness.[127-129] However, to adopt SMR technology in Australia naturally requires a 'collective innovation-decision' of society, not 'optional innovation-decisions' of individuals independent of others, nor an 'authority-based innovation-decision' of a CEO or a government. This could be socially unifying, and would need to be.[69]

Siting, project economics and financing all require public trust to be sufficiently secure throughout the lifecycle of projects—from development and construction to commissioning, and during operation through to plant decommissioning and preparing the site for its next use by either rehabilitation or repurposing. Figure 12 represents the major elements needed to create and sustain public trust in commercial nuclear energy. Each element is strongly interconnected with all of the others. These basic elements are present in any other safety-critical industry, commercial aviation being one example.

FIGURE 12 Key elements of public trust



Source: Authors' chart, reflecting research and experience

Securing public trust is central to the subject of this study. For nuclear energy plants to be operating in Australia from the 2030s, the nation will need to become comfortable with nuclear energy in general and with the specific technologies selected; with plant deployment and operation; updates to the laws, regulations and institutions governing the sector; and the capabilities and skills of the people, industry and regulatory institutions.

Securing agreement on principles before debating the details was a key ingredient of the energy sector reform processes in the 1990s.[130,131] That process built upon economic reform foundations established from 1983: a Prices and Incomes Accord with the union movement before the election was followed by a National Economic Summit a month after the Hawke-Keating government took office, which 'involved all political parties, unions and employer organisations and aimed to form a national consensus on economic policy.'[132,133]

Broad and enduring community support is essential in the energy sector, and especially for nuclear power. The approach to community engagement must be capable of engendering such strong support. Therefore, gaining and securing public trust is not a one-off event: engagement with stakeholders needs to be at the heart of an on-going process. When done well, it is commonly referred to as ensuring a 'social licence to operate.'

Leadership will have vital roles to play at many levels and in various forms throughout the process, as was the case in the 1980s and 1990s reforms. A well-led national conversation will reduce the risk of giving up without duly considering the opportunity to deploy nuclear energy.[134]

Observations on the context and outlook

A Roy Morgan survey in 2019 found that: '**A narrow majority of 51% (up 16% since July 2011) of respondents say Australia should develop nuclear power to reduce Australia's carbon dioxide emissions**. Just over a third 34% (down 24%) say no, Australia shouldn't, while 15% (up 8%) can't say. The survey also found that 'more than half of those surveyed—54 per cent—[were] unaware that nuclear power is banned in Australia'; that 'four in 10 Australians support lifting the ban on nuclear power in Australia and 39 per cent support the use of nuclear power in Australia.' 'Support for nuclear power grew to 55 per cent when those polled were asked whether they would accept lifting the ban on the use of nuclear power in Australia if they knew that a majority of Australians supported it.'[135]

A Newspoll in September-October 2021 found a higher proportion who think Australia should "definitely" develop (25 per cent) or "should consider" (36 per cent) nuclear power stations in the future, while 27 per cent said "no."

Establishing public confidence in nuclear energy involves trust at multiple levels: in the **companies** that design, provide, install and operate the technology; and in a variety of institutions—**governments** that make the laws and their agencies that regulate the industry; in both traditional and social **media** platforms; and in non-governmental organisations (**NGOs**) that report news, information and influence opinions.

Australia's 'informed public' is substantially more trusting of institutions in general than is the 'mass population': a pattern observed in all countries, although Westerners trust institutions less than people in Eastern societies. In 2021, Australians' trust in companies, governments, the media and NGOs increased substantially, and by more than in any other country.

Australian society has made major changes before. The 1980s economic policy reforms and the introduction of competition and private ownership to the electricity sector in the 1990s provide examples of such changes.18 **National consensus-building** across the institutions of government, business, academia, and civil society, communicated through the media, played a central role in the reform process. Leadership, persistence, public understanding and persuasion were also vital elements.

Thought leaders and champions of change will need to invoke a similar spirit for Australia to consider nuclear energy, to enable preparation of options for plants to be operating from the 2030s, if, when and where needed.

Proposed principles for discussion

A draft set of high-level principles is suggested below, with a view to initiating public discussion.

1. **Australians have a stake in the national energy mix, its environmental and social impacts**, and public debate indicates the public 'owns' its stake.
2. **Governments have enduring responsibilities in the energy sector**, regardless of the extent of competition and private investment. Even without nuclear energy, the public perceives governments' responsibilities as extending well beyond minimal light-handed regulation. This is evident from the way Australians think about energy markets, law and policy over 25 years after the Hilmer review.
3. **Civil discussion can and should be recognised as healthy, non-hazardous, and essential for national progress**. Thoughtful, respectful, sincere and informative public discussion and debate is vital. Non-emotive, well-informed debate lowers the political temperature and may depoliticise public discussions. To the authors' pleasant surprise, many Australians are curious, ready, willing and happy to discuss nuclear energy calmly. *A 'social licence to discuss' nuclear energy already exists*.
4. **Nuclear energy can and should be treated as a normal industrial activity**—as it is in many countries—with health, safety, and safeguard provisions consistent with international treaties.

5. **The need to secure and maintain public trust is not unique to nuclear energy**: it is vital for any major project or long-term policy decision.
6. **Each citizen's views are respected, but no one person has the authority to impose a choice on society, nor to veto the consensus of society**. Each person will have their own priorities, concerns about nuclear energy, and perception of risks.
7. **All energy policy choices, not only on nuclear energy, require a long-term view**. Energy systems are comprised of assets with very long lives. Lenders' and investors' time frames tend to be shorter than the concerns of society in general.
8. **Most energy policy questions do not have black and white 'right or wrong' answers**. Judgement is required of governments, investors, and society as a whole. For all countries all choices involve some combination of favourable and unfavourable consequences: *'...we found that no single energy source is perfect in every aspect.'*[136]
9. **Creating real options is a prudent response to uncertainty**, whether in business, or public policy.[31,73] Legal prohibitions on nuclear energy destroy value because options have value even if they are not subsequently exercised. Creating an option is not a commitment to exercise it later. Not to create real options now forecloses our ability to choose later. Real option creation is apt for long-lived assets with long-lead times and is consistent with public aspirations political impetus to replace Australia's ageing coal fleet with zero emission alternatives.
10. **The consensus of society will be a composite** that must balance Australia's national needs, local communities' aspirations to host nuclear energy plants, the views of individual citizens, and the concerns of civil society, consistent with Australia's international obligations, having due regard for our internal circumstances and external challenges.

Models for community engagement

Community engagement is a two-way process, not to be confused with 'public education' campaigns, 'benefit-selling' by advocates, publicity and public relations campaigns, or with commercial or political advertising.

The process needs to allow people sufficient time to listen, engage, ask questions, think, discuss, consider, and form a settled view. Family, friends, neighbours, colleagues, and acquaintances often 'test' their thinking and views with each other over time on big questions. There are signs that process has begun with nuclear energy but is still at an early stage in Australia in 2021.

Good policy reform and community engagement models:

- adopt an approach that works in parallel with the policy process and stages of project development
- are sustained throughout the life of the policy reform or project development cycle
- 'seed', 'fertilise' and facilitate constructive discussion with
- people representing a diverse range of views
- address in good faith, transparently and thoughtfully all of the topics of interest, concern, controversy or
- disagreement, without fear or intimidation
- use a two-way informing-and-listening process with effective communication protocols and channels
- allow proponents and opponents both to make their case and to understand properly other viewpoints
- allow sufficient time for the process to work properly
- include all required levels, from national dialogue, to state-specific and interactions with local communities
- learn from other countries' experience, and
- provide processes and mechanisms for consensus to be discovered or to emerge from diverse views.

Local and international experience should be carefully reviewed to identify which approaches have worked well and which have not before a specific model is deployed to engage with Australians about the possible adoption of nuclear energy plants. Examples may include:

- the Gas Industry Social & Environment Research Alliance (GISERA) for community engagement[137]
- the citizens' panels in South Australia on the nuclear fuel cycle[138]
- methodologies used by specialists in a variety of industry contexts [139,140]
- the Canadian SMR Roadmap process,141 and
- Fermi Energia proposed SMR plant in Estonia. [142]

Australia can draw upon IAEA resources and expert peer support. The IAEA recommends a three-phase 'milestones approach,' beginning with pre-project activities following a country deciding to include nuclear energy as an option in its national energy strategy.[115]

Good governance is an essential element for building public trust. The IAEA is a respected source of information and advice on the requirements for good governance in nuclear energy. As a founding member country, Australia participates in IAEA peer reviews of the nuclear sector in fellow member countries.

Nuclear energy is a safety-critical industry. Models for community engagement should recognise that each person comes to accept and 'become comfortable' (or not) with any given technology in their own way in their own time. Considering how people become comfortable with air travel—a safety-critical industry that is an everyday part of life for many people—illustrates this.

Public trust is about a lot more than science and engineering knowledge. Research suggests technical experts and people with a STEM education are more likely to support nuclear energy.143 Yet most people do not feel the need to become an expert in aerodynamics before boarding an aircraft. Everyone is aware that there is some residual risk. By choosing to fly, people reveal a belief that the risk is acceptably small. Passengers trust their personal safety to the people, the organisations they work for, and technology: aircraft designs, designers and manufacturers, airline, pilots and maintenance crews, air traffic controllers, regulatory authorities, and all of the systems and procedures.

Leadership is needed

Signs of an awakening of interest in nuclear energy among Australians point to the need for leadership. The social licence to discuss nuclear energy already exists. There is public appetite for talks by informed experts. There is now a need for thoughtful leadership in the national interest, with a long-term perspective, mindful of the need for a coherent and strategic approach.

Leadership comes in a variety of forms, each of which can play a vital role. Any new policy, program or project needs people with the purpose, vision, time, resources, and energy to champion the case tirelessly. Encouraged by proponents, advocates and supporters, strengthened by opponents and critics, a champion may emerge from government, academia, business or civil society.

Government: champions may emerge from among members of parliament at national or state level, whether at back-bench or indeed ministerial level. Champions may also emerge in local governments, from which support will be very valuable.

Academia: intellectual leadership is needed. That includes roles of disinterested public leadership as well as thought leadership and trusted interpreter roles. Public enterprise is as important as private enterprise.

Business sector leadership by respected people and companies is invaluable. In the United States, wealthy individuals have been providing financial and intellectual public leadership on nuclear energy for many years.

Citizens can provide leadership by engaging actively with the conversation: both individually at the inter-personal level in communities, the workplace, and families; and collectively as part of civil society through membership in organisations including labour unions and by participating in public discussion fora.

Recommendations

Leaders must build a firm and abiding foundation of public trust in nuclear energy as a real option for the nation—that is a core requirement for nuclear energy plants to be operating in Australia from the 2030s.

Community engagement is crucial to develop public confidence and support for policy change and projects. The process cannot be rushed: to allow Australians to engage meaningfully, it should begin without delay.

The process should begin by agreeing on principles, an approach that has worked well previously in Australia, notably for electricity market reforms in the 1990s.

Key issues need to be identified and addressed transparently. Public concerns are likely to include aspects of risk management ranging from safety (accidents), health (radiation), and the environment (including management of spent fuel and radioactive waste), through to economics (including investment).

Leadership on all levels will be required to sustain a serious dialogue that leads to a national consensus.

6. Siting

General principles related to plant siting

Like all other types of power generation, SMRs must be placed on a chosen site. Siting processes for any power plant require a set of approvals: from environmental and social impacts to landowner approvals to transmission system connections. Many approvals are the same for any type of plants, while others are specific to the energy form and technology. Air quality studies play a key part in siting coal and gas-fired plants; hydrological considerations for hydropower; noise, visual and birdlife impacts can affect wind power siting. For nuclear plant siting emergency planning requirements are often key, and defence against terrorism must also be considered.

Before considering SMR plant siting, it is useful to have a sense of how existing power plants were sited, general principles for siting power plants, and an eye to what has worked well elsewhere. Synchronous generators form a 'grid' inseparable from the electricity network, so there may be opportunities for renewing and re-using existing sites and infrastructure. Re-using power plant sites to leverage transmission infrastructure is a good example of repurposing assets. Quotes from wind farm siting research interviews point to the vital importance of host communities.[144] While some surveys suggest a negative 'Fukushima effect,' research in Japan finds a 'reverse NIMBY effect.'[145,146]

Power generation siting involves consideration of various criteria, ranging from technical to economic, environmental and legal requirements, and also encompassing social and political considerations. From technical and economic points of view, there are some general principles that apply to any form of power generation. These include the following considerations:

- **Modern electricity service is provided by a vast, complex, interconnected physical system**, defined by a mix of generation types and locations, a transmission and distribution network topology, time-diversity in the profile of loads of the demand served, and deep interactions between the system levels.
- **The system levels need to be considered jointly**, must integrate seamlessly in real time, and in the long run are ideally co-optimised across generation (level 1), transmission (level 2), distribution (level 3) and demand (level 4).[q]
- **Only the top and bottom system levels are amenable to market-type competitive forces**; the middle two levels (transmission and distribution networks) are considered as 'natural monopolies.'[r]
- **Connection of any new generator to a power system has complex physical effects on the system and economic and financial effects on the market**, *including favourable or unfavourable affects attributable to the specific site*. A particular new generator may be financially favourable for its owner, while being technically or economically unfavourable from a system or market perspective.[s]
- **Alignment between asset-level private interests and system-level public concerns remains a practical challenge in electricity systems and markets**: this does affect the application to electricity systems of market principles discovered by Adam Smith and of economic theory since Alfred Marshall.
- **Power plant siting today sits somewhat uneasily between central planning models and outcomes of laissez-faire free markets**. This is not to detract from the pioneering work of Schweppe at MIT in the 1980s and advances around the world since in the theory and practice of electricity market design.[147][t]
- **There remains a need for in-depth co-ordination** —even in a competitive or liberalised electricity market—between generation and transmission investment decisions, which are interwoven with siting decisions. This principle inevitably leads to comparisons with central planning or 'intervention.'
- **There is no power generation plant type that offers only advantages and no disadvantages** from a siting point of view, just as no single energy source is perfect in every aspect.[136]

Australia's present generation-transmission system configuration reflects the above general principles.

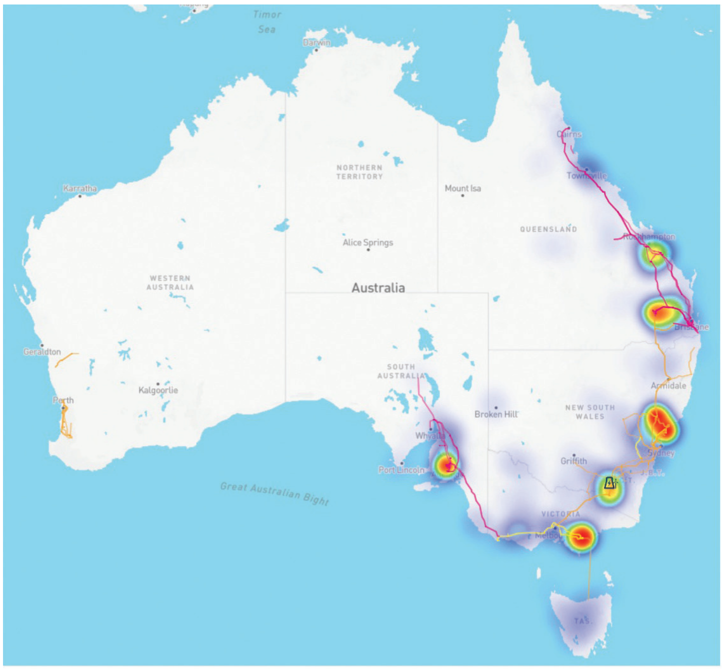
How existing power plants were sited

Large non-nuclear power plants are sited in rural and regional Australia.*u* Five original power grids were centrally planned, designed, developed, and constructed by engineers in state electricity commissions and in the federal Snowy Mountains Hydro-Electric Authority. These were interconnected later to enable a 'national market' that is anchored by plants at large coal fields several hundred kilometres from capital cities, and by hydropower plants between Sydney and Melbourne, the two largest load centres. Figure 13 shows transmission and NEM generation, clusters of large plants, and the spread of renewables. The online version is interactive.

The corridor linking the Hunter Valley to Sydney, the Snowy Mountains and the Latrobe Valley to Melbourne forms the electro-mechanical heart of the grid. The network stretches over 5000km, interconnecting with Adelaide and northward to Olympic Dam in South Australia, along the coast and Great Dividing Range through coastal NSW to Brisbane, the Surat and Bowen Basin coal fields and to Far North Queensland. Tasmania's hydropower system is connected via submarine high voltage DC cable across Bass Strait.

Australian coal and hydro plants are sited at or near the primary energy resource. With smaller footprints, visual profiles and emissions, gas-fired power plant siting is more flexible, so they tend to be located near high pressure gas transmission pipelines and high voltage electricity transmission lines, and closer to large demand centres. Like coal and hydro plants, large solar farms and wind farms must be located at the desired resource. Wind farms tend to be sited on ridgelines and coastlines, large scale solar farms in areas of high irradiance. Proximity to existing transmission is preferred to minimise connection costs. In contrast with existing plant types, nuclear power plant siting is *not* constrained by fuel availability, because the high energy density fuel can be transported to the plant safely and economically.

FIGURE 13 Eastern Australia's electricity system



Source: www.aemo.com.au/aemo/apps/visualisations/map.html

Comparing approaches to siting

The **conventional** or traditional 'top-down' centralised planning methods used historically by government agencies or commissions, and more recently by private developers, identify sites then engage with stakeholders. Possible sites emerge from a filtering process using a set of scientific, technical, or objective criteria. A filtering approach is difficult to avoid where primary energy location is crucial. Renewable energy zones for the AEMO *Integrated System Plan* are an example.[148-150]

Criteria for siting any type of large facility—including nuclear reactors—may be thought of in two categories: 'must not' and 'good to have'. *Exclusionary criteria* each rule out areas as unsuitable for that type of operation. *Discretionary criteria* are considered in the areas that remain and need to be considered collectively. Traditionally, after filtering and screening to identify potential sites, 'affected communities' are contacted. Stakeholder engagement may include information provision, persuasion or 'benefit selling.' This has been described as decide-announce-defend ('DAD') or if abandoned ('DADA').[151]

A **contemporary, community-led** 'ground-up' approach known as 'DAVE': declare-acknowledge-vision-evaluate, seeks to *engage communities to identify sites as an outcome from the process*, reversing the conventional approach of identifying a short-list of sites then seeking to engage with communities and stakeholders.

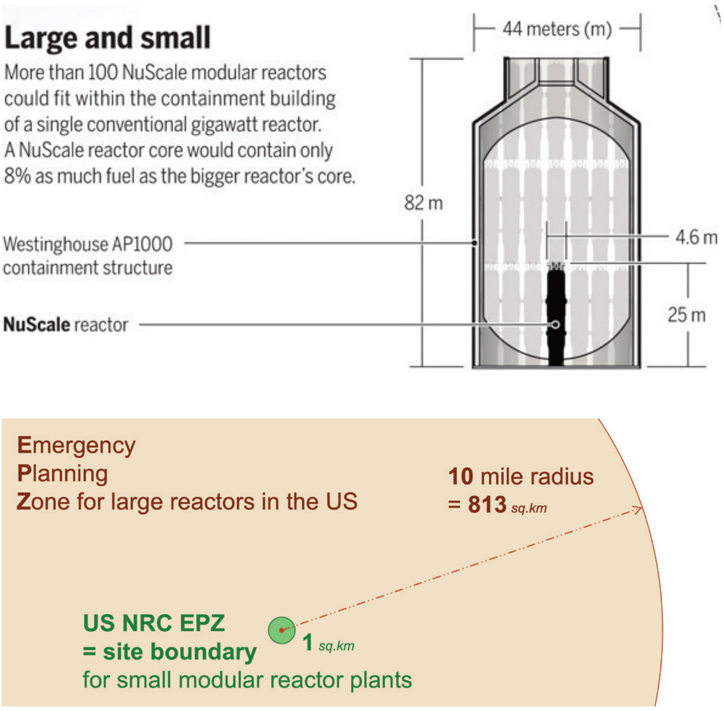
BOX 4 Changing the approach: a case study

The siting process for Australia's National Radioactive Waste Management Facility (NRWMF) provides a case study contrasting two approaches. Site searching began in the late 1970s using the conventional top-down approach, with no site accepted. In 2011, then-Minister Ferguson changed to a bottom-up approach, inviting applications from communities interested in hosting the facility.[152] A site has now been selected and important supporting legislation passed with bipartisan support in June 2021.[153] The explanation of the successful site selection process, including the community consultation and all of the printed materials provided to communities are available on the website of the Department of Industry, Science, Energy and Resources.[99] The licensing process is described in documents on the ARPANSA website.[154]

BOX 5 IAEA guidance regarding siting

SMRs have specific characteristics that may make them different from large reactors in the context of siting and approval of the environmental and social impact assessment (ESIA) study. These characteristics relate to the power generated, the footprint of an SMR site, modular design, non-electric applications, siting locations, underground construction, refuelling, source term, and waste management. [157]

FIGURE 14 SMRs compared with large reactors



Sources: (a) Science, 2019[158] (b) Authors' chart

SMR plant siting in Australia

As Figure 14 shows, large reactors have very large containment structures and are surrounded by large emergency planning zones. In other countries they are typically on coastal sites or near large rivers for cooling. In comparison, SMRs containment is integrated with the reactor vessel, the emergency planning zone (EPZ) need not extend beyond the site boundary, and dry cooling is possible, as noted in chapter 7.[155,156]

A NuScale SMR plant would have up to 12 reactor modules, and hence the plant would have a power output approaching that of the large reactor shown in Figure 14. With small individual reactor cores, compact facility design allowing a small site footprint and a very small EPZ, and scope for reduced water dependence, SMRs have more possible sites than large reactors.

A site boundary of 40 acres or 16 hectares is very compact (ha).[2] The Australian Parliament House complex occupies a 35 ha site and the University of Queensland's St Lucia campus covers 114 ha. Even one square kilometre (sq.km), as shown in the lower part of Figure 14, which is 100 ha or just under 250 acres is tiny compared with the 16km (10 mile) radius EPZ for a large reactor in the U.S.—covering over 800 sq.km, which is 80,000 ha or almost 200,000 acres: over 100 average Victorian farms, 30 average NSW wheat farms, or nearly 20 average Queensland farms. In a peri-urban context, the EPZ for a large reactor is equivalent to much of the metropolitan area of Sydney or Melbourne, or about one-third the land area of the Australian Capital Territory, for example.

Applying a top-down conventional approach to siting the NRWMF would show that vast areas would be suitable based on the technical criteria.

Additional considerations apply to siting an SMR plant, compared with a nuclear waste management facility. However, the absence of constraints that apply to large reactors means that the range of possible SMR plant sites is likely to be broad. Hence, the openness of local communities to host an SMR plant is likely to be a pivotal factor in the siting process.

FIGURE 15 An aerial representation of the site area for a NuScale Power Plant

Source: Image courtesy of NuScale Power

Renewing and reusing what we have

The end-of-life for existing Australian power plants is already in view (Figure 1). Not only coal-fired plants, but all gas plants, wind turbines and all solar PV panels on rooftops and in large farms will have passed their normal retirement dates by 2050. Only hydro plants, which have operating lives of 100 to 150 years, will remain without the need for major life-extending capital.

This challenge is a once in a generation opportunity. One approach is to build everything afresh—generation, transmission connections and network reinforcements—on greenfield sites and in new transmission corridors. AEMO's *Integrated System Plan* contains much of this approach. However, this is not the only approach:

> *There is an enormous amount of sunk capital in old technologies, and their ability to be adapted and evolved and to make a difference today is far greater than people estimate. But we like the shiny new stuff, because we think new stuff is better than old stuff, even if you've got to wait 10 or 20 years for it to be competitive.*
>
> — Grant King, 2021[159]

The Chair of the Climate Change Authority, Grant King made this point at the Minerals Council of Australia 2021 conference in '...a landmark speech indicating where his leadership would take the Climate Change Authority...' in which he '...reiterated his longstanding support for the introduction of nuclear energy into the grid.'[159]

The potential to reuse old coal plant sites for new SMR plants is one opportunity to make use of what we have: an idea that has been studied in the U.S.[122] In Australia there are industrial sites, with transmission connections and other tangible infrastructure, close to communities with a skilled workforce interested in jobs where family members may today be employed at ageing coal plants.

Findings and Recommendations as to *what would be required* for siting SMRs

Adopting a contemporary, community-led, ground-up approach to siting changed the game for the NRWMF. A similar approach would make sense for siting of SMR plants in Australia. SMRs (Figure 15) naturally suit a similar approach. An open invitation for interested communities to express interest could be used to initiate a community-based engagement process.

7. Economics

> *Post-pandemic recovery plans to reconcile climate objectives with economic goals need to put system costs at the heart of energy policy.*
>
> *Moving to a carbon neutral electricity system without nuclear power would significantly increase system costs and threaten security of supply.*
>
> *Achieving cost-effective decarbonisation requires structural reform of the electricity market.*
>
> —OECD-NEA, 2020[160]

Prospects for nuclear energy in Australia

Economic considerations were debated in the three recent parliamentary inquiries on nuclear energy.[15-17] Annual consumption tends to dominate our thinking: we see kilowatt-hours (kWh) on our electricity meters and bills. Yet generation costs are a relatively small part of retail energy tariffs, which include costs rolled up from inter-linked services provided by plants and networks.[29]

Much public discussion focuses on the levelised cost of energy (LCOE): a simple metric to compare high capital and low operating cost plants with those of the opposite cost structure. LCOE is not an investment-grade metric: it is a handy yardstick, blind to essential system-level considerations.[161-163] Cost estimates for nuclear energy can range from $65/MWh or below (less than a new coal plant) to well over $300/MWh (above high-cost diesel generators) by adjusting a few input assumptions.[164]

Firm capacity is needed to meet customers' needs for and expectation of energy available on demand.

Energy economics begins with capital costs, yet the class and accuracy of estimate are often not mentioned. When two per cent of a project is defined—suitable for concept screening—the expected accuracy range for a Class 5 estimate can be as wide as half or double the central cost estimate (–50/+100%): Figure 8.[75]

Various economic advantages of SMRs are intended to arise in the manufacturing and installation phases.[165] Standardised mass-production of reactors in controlled indoor environments at specialised factories can provide a more efficient, stable, and consistent supply chain than on-site reactor construction. The rationale for SMRs in the UK context can be translated to Australia.[33] The capitalised costs of SMRs compare favourably with large reactors: a U.S. report finds a 38% cost advantage.[78] [v]

Australia benefits from global market access to complex engineered products made in specialised factories: from commercial aircraft to gas turbines, boilers and steam turbines; to wind turbines, hydro turbines, solar panels and batteries. Australia would benefit from access to SMR technology and participating in the supply chain.

While up-front investment is the most important cost at the plant level, the economics of nuclear energy really need to be assessed at the energy system level, with the wider economy in view, and over the long-term. Nuclear energy is able to provide a reliable foundation for deep decarbonisation, without either technical problems, or very high total system costs, or both. [166]

The macro- and microeconomic context

Like any programme of major engineering projects at a multi-billion-dollar scale, deploying commercial nuclear energy plants would directly affect Australia's economy. Modelling the influence on rates of inflation, interest, GDP growth, employment, and foreign exchange; and the effects on investment, trade flows, employment and industrial value added is outside the scope of this study.

The 'counterfactual' or the assumed alternative future without nuclear energy would be the key to a study of macroeconomic effects. Any realistic scenario of Australia's energy future—either with or without nuclear energy—would require substantial capital investment, including importing engineering equipment to refurbish or replace ageing and retiring power plants. The *incremental* effects versus the alternative are what matter. Up-front costs for nuclear energy need to be viewed in this context, and across the whole system.

Nuclear energy would also have microeconomic effects, notably on prices. Volatile rising prices are likely in markets aiming to decarbonise without nuclear energy. Sufficient nuclear capacity should stabilise electricity prices and reduce volatility. Indirect economic effects—such as confidence in more predictable electricity prices and stable supply—are as important as direct economic effects on value creation throughout the economy.[72,167]

Lessons from recent experience

Among observations that may be drawn from Australia's electricity market experience in recent years are that:

- Weather-dependent power plants with zero marginal cost entering the market on a rational financial basis can disturb the economics of a power system in far-reaching ways, in both the short- and the long-term.
- Policy and regulatory decisions—not just 'pure market forces'—profoundly affect electricity prices.
- There is far more to costs and prices than simple estimates of the levelised cost of energy suggest.[166]
- The predictive power of wholesale electricity spot price forecasting models is severely limited:[w]

  > *No-one can produce a bankable price forecast of this market*[x]

- The effects of changes in the electricity generation mix can ripple far beyond wholesale price formation: network costs and retail pricing can also be affected.

Roles that nuclear energy can play

Most commercial nuclear plants generate electricity for power grids. However, nuclear energy can also be used as a source of industrial or district heat, for desalination of seawater, or for hydrogen production.

Combining functions through the co-production of two or more of the above outputs may allow a reactor to run at constant output by producing an alternative product during periods when demand for the main product is low. This is an appealing concept, particularly for products where the cost of storage is not prohibitively high. Fresh water, and possibly hydrogen in the future, may meet this requirement. However, it must be noted that the utilisation factor of the secondary product plant will tend to be low, being limited to the 'valleys' in the hourly time profile of demand for the main product—electrical power.

Scale and physical economics

Physical factors provide the economic foundations for any energy technology. For nuclear energy, key factors include the physical scale and fixed capital required, the form and density of the energy input, the conversion efficiency, integration with the wider grid system, the services provided by a plant in support of the system, and the services required of the system by a plant.

Chapter 1 noted the trend from the 20th century towards very large unit sizes in nuclear energy engineering, but that diseconomies in many cases overwhelmed the economies of scale that were the goal. The SMR engineering philosophy focuses instead on economies of series achieved at an optimum reactor unit scale. [165]

Some familiar analogies illustrate the balance between economies of scale, of series, and integration within a system. In civil aviation the Boeing 737 range and the Airbus A320 family dominate units produced and units in service. The Boeing 747 and Airbus A380 have markets, but in most cases maximum scale is not optimum scale.

Wind and solar power also provide instructive examples. Scale economy is a key factor in reducing wind power costs: turbines have increased in size from tens of kW to designs now exceeding 10 MW. Further large increases in scale are not expected: the blades of the largest wind turbines are already much longer than the wings of an Airbus A380 (Figure 11). Wind power has also benefited from economies of series; because even with the largest turbines each large wind farm has dozens of turbines, and grid systems are measured in thousands of MW.

The basic unit of solar photovoltaic (PV) is tiny. A panel module combines between 36 and 96 cells; a string connects multiple modules; each solar PV farm has many strings. Economies of series come from volume manufacturing, technical and material cost efficiencies, and installation efficiencies in large solar farms.

One of the most important economic aspects required for nuclear energy plants to be operating in Australia from the 2030s is to identify the *optimum* unit scale, rather than the maximum available scale.

Nuclear energy can integrate well with an electricity generation mix, and also has applications for water security, heat supply and hydrogen production.[66]

Water

Water security is a key issue in Australia and energy, water and the climate are linked.[168]

Power plants can be large freshwater users. Eleven of the 16 coal-fired power plants in Eastern Australia use freshwater at rates of 1500 to more than 3000 L per MWh: recirculating or once-through in cooling towers. Two are dry-cooled supercritical and three are saltwater-cooled. A NuScale plant with wet cooling at nominal conditions would use 2800 L per MWh. **Air-cooling the steam cycle reduces this to zero**, and has been selected for the first plant in Idaho.[168,169] (Note that the large pool in Figure 6 is for emergency heat removal.)

Desalination plants have been built in Australia for water security. A desalination plant could be integrated with an SMR plant to use either heat or electricity from nuclear energy, or a combination of the two.170 Removing salt is energy-intensive: typical desalination plants, such as the six in several Australian states, use about 3 to 3.6 MWh per ML. The typical plant capacity is between 150 and 300 ML per day. Bulk water desalination is expensive, up to $1000 per ML, and needed only during droughts.

While desalination alone is unlikely to provide an economic basis for SMR plants, it may have some synergies when combined with power generation.

Heat

Delivering high temperature heat without emitting CO2 is a key challenge in hard-to-decarbonise industries.[171,172] Gen IV high temperature reactors may have future roles in this application, as does hydrogen. The steam outlet of PWR reactors including the NuScale design is just above 300ºC: a low temperature by industrial standards. Unlike cold northern hemisphere climates where district heating is used or where there are large clusters of heavy industry, **there is limited commercial demand in Australia for low temperature heat at large scale**.

Hydrogen

Hydrogen is being widely proposed as a large-scale, transformational 21st century energy carrier. Its attributes point to potential uses in a wide range of applications, including as a carbon-free alternative to fossil fuels, especially as a partial (blended) or complete substitute for natural gas, and as a basic input for emissions-free production of synthetic liquid fuels to displace crude oil refining. Hydrogen can be stored and then used directly for combustion in burners, boilers, engines or turbines; in stationary fuel cells; or in fuel cell electric vehicles.

A 'hydrogen-based' energy strategy makes sense if production is carbon-free and economic. While curtailed and intermittent renewable energy is being studied as a power source for hydrogen production, it may be competitive and more economic to produce hydrogen continuously via electrolysis using nuclear energy.

The cost to produce, store and deliver hydrogen via electrolysis from any primary energy source is currently high, suggesting that the commercial time to deploy at large scale could be comparable to that required for nuclear energy development.

Electricity

The rationale for nuclear energy in Australia's electricity generation mix is based on:

- challenges and opportunities from Australia's looming coal fleet retirements (Figure 1)
- lessons from recent experience described above
- inability of other emissions-free technologies to offer the full set of grid services that SMRs can provide.

Coal-fired capacity in Eastern Australia totals 23 GW— almost 25 GW after adding Western Australia—all of which is expected eventually to retire. Installed coal-fired capacity is about equal to average system demand and accounts for about 70 per cent of annual energy. The system demand is continuously above about 15 GW. Peak demand is 30 to 35 GW, depending on weather.

Nuclear power and coal-fired power are as close to complete substitutes as any two forms of electricity generation. Both can provide the full range of system services needed for secure and reliable operation of a synchronous grid. The major differences between them are high CO2 emissions for coal versus zero operating emissions for nuclear power, and some differences in capital and fuel costs. New SMR technology has some advantages over coal plants (and some large reactors):

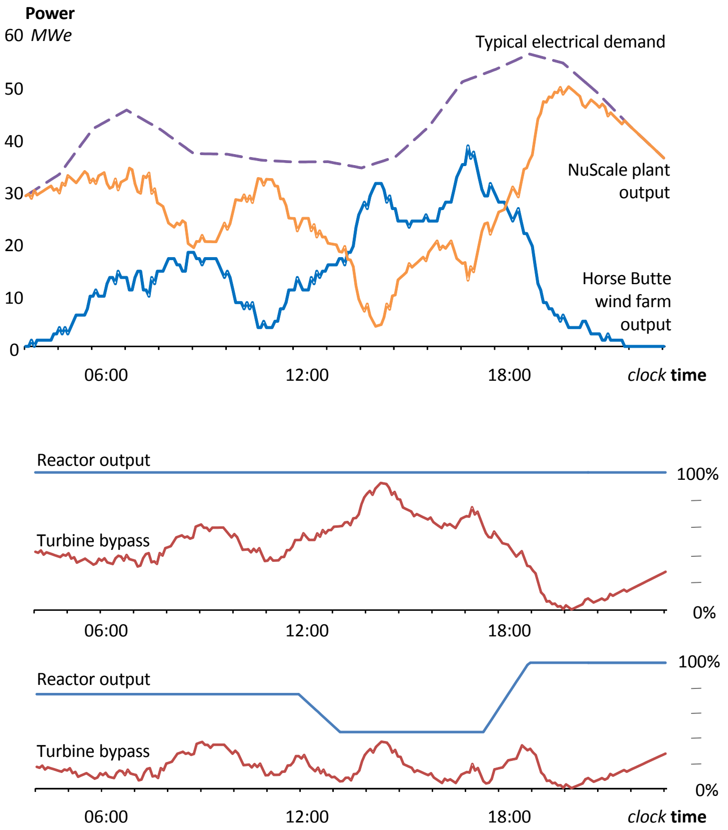
- flexible capacity deployment, due to small unit sizes
- more flexible operation, also due to smaller unit sizes
- longer periods between scheduled maintenance
- easier refuelling and no need to locate near fuel
- the capability to ramp up and down rapidly using steam turbine bypass (see Figure 16)
- the capability to operate in island mode, and
- the capability to black-start the system.

NuScale designed their SMR plant with the last three capabilities listed above in response to customer requests. Flexibility—of deployment, in operation, and the maintenance profile—combined with the relative ease of substitution for coal point to the potential for Australia to deploy SMR plants between 2030 and 2050. Plants of 4-, 6- or 12-units would provide capacity of 77 MW_e per unit, for up to 884 MW_e net power sent-out.

> *Modularity creates options…Modularity makes complexity more manageable…enables parallel work and is tolerant of uncertainty. … Modular designs create value in the form of valuable real options.*[31]

A fleet of SMRs of up to 20 GW capacity would provide for a gradual, managed replacement of the retiring 20th century coal fleet, without unwelcome economic shocks or deterioration of reliability standards, and eliminate the majority of electricity sector CO2 emissions. In such a scenario, most of the problematic system operation and market design issues that the AEMC, AEMO and the Energy Security Board are struggling to resolve would tend to reconcile with fewer technical challenges.

FIGURE 16 SMR turbine bypass load following



Top panel: example of NuScale load-following to compensate for generation from the Horse Butte wind farm and daily demand variation
Lower panels: Two load-following options to achieve the NuScale module output shown in the top panel: using only turbine bypass, or (as in the bottom panel) using a combination of reactor power manoeuvring and turbine bypass

Source: Ingersoll et al (2015) [173]

Economics of technology and real options

The real option value of various low CO2 energy technologies was estimated in a 2010 report by the Australian Academy of Technology and Engineering.[174] Large (Gen III) reactors were considered, but not SMRs. SMR technology is now approaching commercialisation, understanding of renewable energy costs has changed, as have commodity prices, expectations, and aspirations on the magnitude of future CO2 emission reductions. All these changes are timely reminders that uncertainty—which is what gives rise to option value—is inescapable.

The case study design used in this report is an example involving a university, gov ernment and businesses of deploying over US$ 1.1 billion of public and private capital for engineering research, design, technology development and licensing to create real options: from a research concept at Oregon State University in 2000, a design spun out into a company in 2007, strategic investment by Fluor in 2011 and through the formal licensing process for design certification since 2016.[175]

Recommendation—create real options

Australia should focus on creating project-based real options for deployment of SMR technology. Understanding the option value is the first step to decide how far to progress the option and what one should be prepared to pay for the option.

8. Financing

> *Modular design and factory construction mitigates project management risk, which is the single most-important obstacle to financing [large, gigawatt-scale] Generation III nuclear projects.*
>
> —IEA, 2019 [116]

The crux of any major project is financing

Any major engineering project 'hinges' on the financing stage. Referring to Figure 7, a project exists 'on paper' before financing; after FID, the project is real. The formal financing process itself has a short duration compared with the rest of the project lifecycle, but the pre-financing development stages reflect the need to secure debt in the capital structure to allow equity holders to 'leverage up' their returns, and financing plays an ongoing role after financial close and throughout the project lifecycle.

Securing debt financing demands discipline and is usually the acid test in the Final Investment Decision (FID) for a project. Bankers bring a natural caution, and their experienced eye for risk also plays a vital role in tempering the natural optimism of project developers, future owners and operators. Banks generally use a 'herd' approach to financing to minimise risk. Untested projects usually have a financial design stage where the 'arranger' assesses project risk, returns and appetite.

For any major project, financing crystallises all aspects affecting engineering feasibility, commercial viability, social acceptability, and environmental sustainability. The 'PESTLE' acronym helps recall myriad political, economic, social, technical, legal and environmental factors that must all be considered and managed.

A system view of investment is needed

Chapter 6 on siting discusses the scale of the need—and comparison with alternatives—for generation capacity able to provide the portfolio of energy and system services that SMR plants offer. The importance of adopting a whole-of-system view for investment in generation—explained in Chapter 7 on economics—applies with particular emphasis to nuclear energy.[164]

All scenarios call for large-scale financing

All technologies for reducing CO_2 emissions require increases in capital (relative to labour, fuel and other on-going annual or variable costs). This is broadly the case in electricity systems, for other forms of energy, and also in other sectors. Any low- or no-carbon future requires larger capital allocation than higher carbon cases, so the need for financing on a very large-scale is not unique to nuclear energy. In all cases the scale of the challenge is compounded by the required pace of project planning, approval, development, financing and construction.[171]

To put the plant cost estimates in perspective, estimates of the **total financial capital Australia will need to invest** to replace plants decommissioned by 2050 are in the order of $150 billion, varying from $75 to 300 billion, regardless of the configuration of the generation-storage-transmission system. A well-delivered SMR fleet of 20 GW (for example) would leverage existing physical capital such as sites and network assets, securing the system at the low end of the range of total system costs, without CO_2 emissions. The **annual NEM wholesale electricity revenue pool** at market clearing prices is on the order of AU$15 billion (about $75/MWh), ranging from under AU$10 billion ($50/MWh) to about AU$20 billion ($100/MWh) in previous years. The annual GDP of the Australian economy is on the order of $2 trillion, and the pre-pandemic 2019-20 federal budget revenue (and government expenditure) was roughly $500 billion.

Table 5 translates the estimates from Box 2 into the capital costs for project financing. The published estimate in 2017 currency of US$2 850 per kWe of capacity for a plant with 12 x 77 MW_e modules was converted to 2017 Australian dollars at that year's mean of daily exchange rates, then adjusted to 2020 currency with the World Bank GDP deflator for Australia. We adjusted to 2020 dollars and capitalised Australian published estimates of owners' costs for NPP project development and regulatory/ licensing costs, and added interest during construction (IDC) over the assumed construction period at the weighted average cost of capital (WACC). Project contingency of 30% for the AACE estimate class was added for total project costs.[176]

Our 'central estimate' is a project capital cost for a 12-module plant of AU$5.9 billion and a long-run average cost of energy of AU$76/MWh, composed of a capital recovery charge of AU$54/MWh—or a 30-year annuity of $447/kW of firm capacity—plus AU$22/MWh to cover fuel and operation and maintenance costs for energy. Following AACE, we estimate 80% confidence level ranges for capital cost of AU$4.2 to 8.8 billion and a total average energy cost range of AU$60 to 102 /MWh.

Keys to successful financing are clear

The key variables for any major project in any country are those that entail risk and affect returns:

- The future revenue stream must be sufficiently certain: sales arrangements are most critical.[178]
- Financing must allow for a competitive weighted average cost of capital—based on the interest on debt, coupons on special bonds issued, and the total return including dividends expected by shareholders.

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

NuScale/Fluor central estimate [77] (AACE class 3-4, U.S. ref. unit cost basis)	AACE lower	2 850	AACE upper	2017US$ /kW_e gross
Overnight capital cost on a per unit capacity basis (2017US$ to 2020 AU$)	2 893	3 993	5 613	2020AU$ / kW_e gross
CapEx on a total plant overnight cost basis	**2 757**	**3 690**	**5 187**	**AU$M**
Owners' costs: AU$2015, adjusted to AU$2020	203	393	765	AU$M
CapEx: overnight costs plus owners' costs	**2 959**	**4 083**	**5 952**	**AU$M**
Construction period (authors' conservative assumptions)	36	48	60	months
Interest During Construction (IDC) approximate	235	433	789	AU$M
CapEx including owners' costs, IDC capitalised @WACC	**3 195**	**4 516**	**6 740**	**AU$M**
Project Contingency 30%	958	1 355	2 022	AU$M
CapEx including IDC and Contingencies authors' estimate	**4 153**	**5 871**	**8 762**	**AU$M**
10% Government finance		yield 1.0%		
20% Special purpose bonds		yield 3.0%		
40% Commercial debt plus ECA finance		yield 6.1%		
30% Equity portion		yield 7.2%		
Illustrative WACC with the above assumptions		**5.3%**		
Capital recovery period		30		years
Fixed operation & maintenance per unit of capacity		100		AU$ /kW
Capacity charge as an annuity	316	447	667	AU$ /kW /y
Plant Capacity Factor		95%		of capacity x 24h/d x 365d/y
Operating hours per year		8 322		h /y
Capital recovery charge expressed per unit of output	**38**	**54**	**80**	AU$ /MWh
Annual fixed O&M expressed per unit of output		12		AU$ /MWh
Fuel + variable operation & maintenance		10		AU$ /MWh
Long-run average cost of energy, levelised over 30 y capital recovery	**60**	**76**	**102**	**AU$ /MWh**

Sources: Authors' estimates and calculations, using key inputs from NuScale as cited and described in chapter 2: references [77,78,177]; and Table 6.1 from report for ref. [14]: WSP Parson's Brinkerhoff (Feb 2016) *Quantitative Analysis and Initial Business Case – Establishing a Nuclear Power Plant and Systems in South Australia.*

- Financing repayment terms must align with the asset useful life. A standard three-to-seven-year tenor—with banks doing a 'sweep' on the renew date with the option not to refinance—won't work in this case.
- The amount and timing of capital expenditure is paramount, and so is minimising the risk of delays. Project size can strongly affect the risk premium.[179]
- For capital-intensive energy projects such as nuclear power plants, operating expenditure is important, but has less influence on financing than the above.

All new plants need long-term contracts

The Millmerran supercritical coal-fired power plant in Queensland, constructed between 1999 and 2003, was and still is the only privately-developed coal-fired generator in Australia. The plant was developed by InterGen (a joint venture of Shell and Bechtel) along with investment from Marubeni Corporation, GE Structured Finance, the EIF Group and Tohoku Electric Power. It was financed '...on a merchant basis. There [were] no power purchase agreements for the sale of electricity from the plant.'180 At the time, the AU$1.5 billion project was '...the largest project in the world to be funded on a non-recourse project finance basis,' and '... the second largest private investment project [in any sector] in Queensland.' This is the exception that proves the rule. Such 'merchant financing' on the basis of a wholesale price forecast, is no longer possible in Australia. That is the meaning of the quote on p.31: No-one can produce a bankable price forecast of this market.

The non-bankability of new power generation projects without long-term offtake agreements is becoming an increasingly critical issue as major plants retire. Long-term contracts are the key mechanism for ensuring certainty of revenue, and hence for securing financing, as foreseen by Joskow and Schmalensee at MIT:

> *...we find it hard to imagine that base-load power plants anything like those we see today would be constructed in the face of the extraordinary additional opportunism risks inherent in a regime permitting only spot market sales.*
>
> —Paul Joskow and Dick Schmalensee, 1983[181]

In practice, for ***any*** new power generation projects in Australia today to be 'bankable'—i.e. to secure debt financing—long-term power purchase agreements (PPAs) with 'blue chip' creditworthy offtakers are required.182 Wholesale market price volatility driven by variable renewable energy is a key reason.

Wind and solar farms are themselves financed on the basis of long-term contracts. The electricity generated is 'bundled' with large generator certificates (LGCs), which are the main motivation for those PPA contracts and a key source of revenue for project developers until the Renewable Energy Target scheme sunset year of 2030. The LGCs acquit the legal liability of retailers and large consumers, by ensuring they do not incur fines for non-compliance. Similarly, offtake agreements in long-term contracts with future SMR plants might be written for hydrogen, desalinated water, industrial heat, or emission reductions, in addition to electricity, either as bundles or as portfolios of contracts with separate parties. Nuclear energy plant financing must consider risk, returns, and opportunities for owners to monetise the sources of value their long-lived assets provide to the system, in a context replete with deep and complex uncertainty.[178,183]

PPAs would be up to 40 years for nuclear, 30 for coal, 15 for gas, shorter for wind and solar. This is a problem area as only Governments can provide security to underpin the longer-term risks taken by the banks. Yet *Australian governments are already underwriting* all wind and solar capacity (through various laws and schemes), new pumped hydro (2000 MW Snowy 2.0), new open-cycle gas peaking plant (660 MW Kurri Kurri), batteries and new transmission investments. The financing problem is now spreading to *existing* coal plants with calls for the federal government to step in as a lender of last resort due to difficulties securing bank finance.[184]

Market rules and key roles in financing

Governments may underwrite, lend to, or invest directly in new power generation to decarbonise, or due to the unwinding of earlier governments' retreat from the electricity sector after electricity reform and privatisation. Whatever of the driver, the examples above suggest that federal and state governments of all persuasions are recognising a practical need, at least tacitly through their policies and actions. Even after competition reforms and (re-)introducing private investment in electricity, '*governments "own failure" in nationally significant infrastructure, and have an inescapable obligation to ensure it is built, maintained and operated in the long-run national interest.*'[185] The *National Electricity*

Rules is in version 173 at 10 October 2021 and 1666 pages long (on 1 January 2020, version 132 was 1573 pages long). Version 59 of the National Gas Rules of 27 May 2021 runs to 639 pages. Investor confidence in government policy, plans and intent is indispensable. Continually changing market rules tend to undermine confidence building new assets with lifespans of many decades.

Proponents and opponents agree that **governments have crucial roles in nuclear energy** in liability cover and insurance, as recognised in the law of nuclear energy internationally and by nation states.[113] Direct government participation in financing is usually also needed. Governments are indispensable, but also need private sector involvement: in nuclear engineering and technology; for developing, investing in, and lending to projects; and in asset operation and management.

Illustrative capital structure

Many elements are essential for successful project financing. The illustrative financing structure shown in Table 5 includes government and private sector roles. Each bank has maximum exposure limits, as low as $30 million, or as high as several hundred million, depending on the asset and its context. Hence, debt for financing SMR plants as part of the transformation of Australia's energy sector is expected to require large international consortia of Australian, American, European and Asian Banks. Consortia for later projects would be expected to be smaller, as learning effects reduce capital costs.

The calculation behind the illustrative example in Table 5 *conservatively excludes* the financing advantages from staged deployment and commissioning of modules. It treats the whole project as a single 'lump' ignoring the improvement in net present value on both the revenue and cost sides expected to be available for SMR plants from commissioning each small module in sequence.[z]

Models for financing

'Aside from 'traditional' [direct] government funding, there are now six alternative methods: corporate balance sheet financing; the French Exeltium model; the cooperative Finnish Mankala model; vendor equity; [Export Credit Agency] ECA and debt financing; and private financing with government support mechanisms. In practice, projects tend to progress using a mix of these funding mechanisms.'[183,186] Large, privately-owned U.S. utilities with regulated tariffs provide the leading example of corporate balance sheet financing.[187] In the French model, industrial investors contract to take electricity for a mix of fixed and variable pricing, which they can either use themselves or sell to the market. Participants in the Finnish Mankala model are allowed and obliged to purchase electricity from the power plant equal to their shareholding at cost price, which they can use or sell into the market.[183]

'Technology vendors will only invest in the most advanced projects that are likely to succeed, will allow them to receive a return on their investment in the shortest possible time, and provide an option to exit the project at the earliest possible opportunity.'[186]

It is expected that ECAs will play a key role in securing commercial debt financing. The U.S. Export-Import Bank can now finance nuclear plants.[188] Government support mechanisms can take a variety of forms, including guarantees and revenue or pricing support. The U.K. government has underwritten the large Hinkley Point C nuclear plant with a contract for difference, and has more recently considered a regulated asset base (RAB) model to underpin financing of new nuclear plants.[189]

> *Investment policies need to overcome financing barriers through a combination of long-term contracts, price guarantees and direct state investment.*
>
> —IEA

Recommendations for financing SMRs

Both government and private sector involvement would be needed to finance nuclear plants. Australia has had success with mixed models in energy and other sectors. The federal government can begin to create confidence by funding a scoping study to build on this preliminary concept study, then by supporting a pre-feasibility study and subsequent feasibility studies. While this work can begin prior to legal reform, repealing the bans and implementing the required legal framework would be expected to have an appreciable effect on confidence. Strong, respected, and credible proponents or sponsors need to be encouraged: they are essential to navigate each SMR project from development through financing to delivery and through commissioning into operation.

A *series* of projects comprising a programme would be better suited to efficient financing than one-off plants. A *pilot plant* is needed before a series can be secured.

9. Conclusions

This study report responds to a simple question:

What would be required to deploy nuclear energy in Australia from the 2030s?

Findings

1. **Technology** emerging in SMR designs for nuclear energy plants developed from well-proven PWRs, and with operational safety and other design improvements, would meet Australia's current and future energy needs safely and effectively. The commercialisation timeframe aligns with deployment in Australia from the 2030s, and allows for orderly replacement out of Australia's retiring coal fleet using plants with zero operational emissions, comparable average costs, and more flexible technical performance specifications than other new plants. At the level of the overall system, SMRs promise to meet the engineering, economic and environmental requirements and demands of Australia more comprehensively and cost-effectively than alternative technologies could.
2. **Management** capabilities required to deploy and operate SMR plants already exist in Australia in some form. Additional capabilities or increased capacity can be acquired and available by the 2030s *if we act now*. Many engineering fields in Australia—from defence to aerospace to advanced nuclear research and materials science—are more technically advanced than is required to deploy commercial nuclear energy plants. Australia has a long track record of operating internationally-sourced safety-critical technologies, and deployment of nuclear power plants would follow well-established and proven engineering project management processes.
3. **Governance** of Australia's nuclear sector is provided by well-formed and ably-staffed institutions empowered by legislation consistent with our national obligations under international treaties and conventions. Supervision of non-proliferation safeguards and security; safety, health and environmental protection; and management of radioactive waste is clear. The legal and regulatory framework will need to be expanded and strengthened in a number of key areas to deploy nuclear energy, as current regulations are suitable only for research reactors. Appropriate licensing processes and regulations will need to be developed, which the IAEA and OECD-NEA can support, for all stages of the NPP lifecycle. Meanwhile, electricity markets are in the early stages of profound transformation: governance is more complex than for the nuclear sector in many ways, and overlaps with the governance of emission reductions. Work includes: review of legislation and institutions; gap analysis and capacity strengthening; the repeal of bans and drafting of new laws to regulate nuclear energy.
4. **Capabilities** required to commit to, contract, construct, commission, regulate, and safely operate nuclear power plants based on SMRs and eventually to decommission them do exist in Australia. Some SMR requirements are similar to coal-fired power plants, so scope exists for plant staff retraining. Building the full *capacity* to qualify and prepare people able to plan, finance and build nuclear energy plants ready to operate from the 2030s will require foresight and direction, forethought and planning. Education and training in Australia, and skills transfer from other industries—supplemented as and when required by experienced professionals from overseas—can deliver that capacity.
5. **Society** will need to be engaged openly through a process that seeks to build public trust by taking time to agree on principles, and engage in thoughtful evidence-based discussion and mature debate. That work can build on growing interest and upon recent parliamentary inquiries. The process must facilitate mutual listening to diverse views and perspectives; seek to understand, consider and respond to genuine concerns; identify key issues clearly and systematically; and connect them with Australia's available choices, in a national dialogue invoking the spirit of consensus of earlier reforms. Engagement with local communities is vital. The process must not be rushed, nor allowed to be captured, and should use approaches known to work well. With a decade or so before nuclear energy may be deployed in Australia, an orderly process to make informed adoption of nuclear energy possible should be commenced now.

6. **Siting** for SMR plants faces fewer technical and regulatory constraints than large nuclear plants because of their smaller footprint and higher inherent safety. Site identification, study and selection nonetheless need to build on abiding public trust in people, institutions, and the selected technology. A government or private developer attempting to impose a siting decision via a top-down 'decide-announce-defend' approach would be more likely to induce outrage than to be successful. A bottom-up engagement model is more likely to succeed: inviting expressions of interest, declaring the dilemmas to be faced, acknowledging concerns, co-developing a vision with local communities and stakeholders, and transparently evaluating joint progress. Sites with ageing coal plants have some advantages in being repurposed for SMRs, including local energy sector people likely to be suited to retraining and community revitalisation.
7. **Economics** for nuclear energy is dominated by up-front capital costs, as is the case for hydropower, wind power, and solar power. A long-term view of 40 to 80 years is needed because nuclear asset life, while shorter than for hydropower, is far longer than for wind or solar power. Electricity economics must be viewed from a system perspective, which the LCoE metric cannot do. SMR plants could play other roles: hydrogen production, desalination, and industrial heat may complement electricity generation. Well-informed expectations and understanding of costs, disciplined project management, and selection of the optimum scale of units and plants are all important. Without options for nuclear energy, we could easily be in a scenario in which it is impossible simultaneously to meet service reliability standards and emissions targets at reasonable (or indeed any) prices.
8. **Financing** is the crux of any project development. Private capital will be vital for financing nuclear energy plants, but there are some roles that only governments can play. This should not be viewed as a special nuclear energy exception, because it is already the general rule. Power generation projects in the NEM can no longer be financed without a long-term offtake contract, and direct or indirect government intervention in the market now influences all generation investments and divestments.

Recommended practical actions

1. **All Australians should be informed** about current developments in nuclear energy **technology**.
2. **Companies should study opportunities** for project **management** of nuclear energy plants in Australia.
3. **The Australian Government will need to form a NEPIO** to coordinate all of the work required, from **governance** to possible deployment and beyond.
4. **Australia's leading education, research and training institutions** will need to strengthen **capabilities**, leveraging Australia's long-standing memberships of the IAEA and OECD-NEA.
5. **Public figures and thought-leaders should initiate and sustain discussion** in a spirit of national consensus like that shown in the major economic reforms of the 1980s and 1990s, and maximise opportunities to listen to and engage with people in local communities throughout Australian **society**.
6. **Local leaders can articulate their vision** for **siting** projects that could be deployed from the 2030s.
7. **Energy and emissions reduction** policy and NEM redesign should be technology neutral, and able to benefit from the **economics** of nuclear energy.
8. **Leaders in politics, business, banking and regulatory agencies all have roles** to create real options, enable nuclear energy project **financing**, and ensure that the output is affordable.

Next steps

Building on the Australian Government's watching brief on SMR technology in 2020 and the technology co-operation partnership with the U.K., a natural next step is for the government to sponsor a **scoping study** to evaluate the range of choices for Australia to prepare to be in a position to adopt nuclear energy. A short-list would then be selected for a **pre-feasibility study**. In parallel, leaders in government, academia, business and civil society would engage in public discussion. 'Knowledgeable **commitment** to a programme'—IAEA milestone one—would need to be reached before the full **feasibility study** of the option to contract the first plant.

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Appendix A Chronology

1901	**Commonwealth** of Australia established 1st January
	Commonwealth *Customs Act*
1914-18	Australia's involvement in World War I
1919	In **Britain** New Zealander Rutherford leads the work to split the atom at Cambridge— forerunner of nuclear fission energy
1917-23	Russian Revolutions and Civil War, establishment of the **Soviet Union**
1939-45	**Australia** in World War II
1945	**United States** uses nuclear weapons against **Japan** on Hiroshima (6th August) and Nagasaki (9th August) to end WWII
	In the **United Kingdom** the term 'cold war' is used by George Orwell in a newspaper article 19th October
1946	**British** Prime Minister Churchill delivers his 'Sinews of Peace / Iron Curtain' speech in the **United States** at Westminster College, Fulton Missouri
1949	**Commonwealth** Industrial Atomic Energy Policy Committee (1949-52) formed by the Australian Government
1952	**Commonwealth** Atomic Energy Policy Committee formed by the Australian Government
1953	**Commonwealth** Atomic Energy Act: statutory basis for Australian Atomic Energy Commission (1952-87) 15th April
	US President Eisenhower's 'Atoms for Peace' speech to the UN 8th December paves the way for the IAEA
1954	**United States**' USS *Nautilus*, world's first nuclear powered submarine launched 21st January
1954	**USSR** achieves the world's first grid-connected nuclear reactor: 20 MW_{th} / 5MW_e at Obninsk, 27th June
	United States first commercial demonstration PWR at Shippingport, PA—construction started 6th September
	United States Atomic Energy Commission Chairman Strauss' 'too cheap to meter' speech, 16th September
1956	**Commonwealth** *Customs (Prohibited Imports) Regulations* (under which ARPANSA issues permits for imports)
	Britain achieves the world's first full-scale commercial nuclear power plant 4 x 60 MW_e Calder Hall opened 17th October
1956-57	British atomic weapons testing at Maralinga in South Australia
1957	**International** Atomic Energy Agency (IAEA) founded 29th July with Australia as a founding member
1958	**United States** Shippingport 60 MW_e PWR commissioned on 26th May
	Commonwealth *Customs (Prohibited Exports) Regulation 9* under the *Customs Act* (1901) 'requires an export licence for the export of radioactive material including refined uranium, plutonium and thorium' [14]
1961	Construction of the Berlin Wall commenced
1966	Beginning of 30-year French nuclear weapons testing program on South Pacific atolls 2nd July
1968	**International** *Treaty on the Non-Proliferation of Nuclear Weapons* (NPT) (a UN treaty)
1973	ratified by Australia 23rd January
1979	**United States** experiences a serious reactor accident at Three Mile Island Unit 2, near Harrisburg, Pennsylvania, 28th March
1979	**International** *Convention on the Physical Protection of Nuclear Material* (CPPNM) entered into force 8th February 1987, ratified by Australia 22nd September 1987, *Amendment* 2005
1983	**Victoria** *Nuclear Activities (Prohibitions) Act*
1983	MIT Press in the **United States** publishes Joskow and Schmalensee *Markets for Power: an analysis of electric utility deregulation* —a book that foresees investment challenges now confronting electricity markets
1985	**International** *South Pacific Nuclear-Free Zone (SPNFZ) Treaty of Rarotonga* entered into force 11th December 1986
1986	**Russia** experiences a catastrophic reactor accident at Chernobyl Unit 4 RBMK, Ukraine, USSR, 26th April
	Commonwealth *South Pacific Nuclear Free Zone Treaty Act*
	NSW *Uranium Mining and Nuclear Facilities (Prohibitions) Act*
1987	**Commonwealth** *Australian Nuclear Science and Technology Organisation Act* dissolves AAEC, forms ANSTO
	Commonwealth *Nuclear Non-proliferation (Safeguards) Act*
1988	MIT Press in the **United States** publishes Schweppe et al *Spot Pricing of Electricity*, 30th November —describing the theoretical basis for competitive electricity market designs such as Australia's NEM
1989	in **Germany** Berlin Wall falls on 9th October
1989	**United States** Shippingport 60 MW_e PWR decommissioned in December
1991	Soviet Union dissolved

1992	**International** *United Nations Framework Convention on Climate Change* (UNFCCC) ratified by Australia 30th December 1992
1994	**International** *Convention on Nuclear Safety* (an IAEA treaty) entered into force on 24th October 1996, ratified by Australia in March 1997
1995	**Victorian** Power Exchange (VPX: forerunner of the NEM) established
1996	Last French nuclear weapons test in the South Pacific 27th January
1996	**International** *Comprehensive Nuclear-Test-Ban Treaty* (CTBT) opened for signature in September 'prohibits nuclear weapon test explosions'[14] ratified by France 6th April 1998, Australia 9th July 1998
1997	**International** *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* (a UN treaty) entered into force 18th June 2001, ratified by Australia in August 2003
	International *Kyoto Protocol* adopted at the Third Conference of the Parties to the UNFCCC 11th December ratified by Australia 12th December 2007
1998	**States and the Commonwealth** establish Australia's National Electricity Market (NEM)
	Commonwealth *Comprehensive Nuclear Test-Ban Treaty Act*
	Commonwealth *Australian Radiation Protection and Nuclear Safety Act*
1999	**Commonwealth** *Environment Protection and Biodiversity Conservation Act* 'specifically prohibits approval of actions involving the construction or operation of a nuclear fuel fabrication plant, a nuclear power plant, an enrichment plant, or a reprocessing facility' [14]
2000	**Commonwealth** turnkey contract signed for new research reactor at Lucas Heights
	South Australia: Nuclear Waste Storage Facility (Prohibition) Act
2001	**Commonwealth** *Renewable Energy (Electricity) Act*
2005	**International** *Convention on the Suppression of Acts of Nuclear Terrorism* ratified by Australia 16th March 2012
2006	**Commonwealth** Switkowski review / UMPNER: *Uranium Mining, Processing and Nuclear Energy—Opportunities for Australia*
2007	**Queensland** *Nuclear Facilities Prohibition Act* 28th February
	ANSTO's new OPAL multi-purpose reactor for research and medical isotopes opened 20th April
2011	**Japan** experiences catastrophic reactor accidents at Fukushima Daichi following the Great East Japan Earthquake and Tsunami, 11th March
	Commonwealth *Clean Energy Act*, establishing carbon pricing (CPRS), in effect from 1st July 2012
2012	**Commonwealth** *National Radioactive Waste Management Act*
2014	**Commonwealth** CPRS repealed 17th July, effective 1st July
2015	**International** *Paris Agreement* on Climate Change, 12th December
2016	**South Australia** *Nuclear Fuel Cycle Royal Commission* ('The Scarce Report')
2018	**Commonwealth** *Australian Radiation Protection and Nuclear Safety Regulations*
2019	**Commonwealth** *Not without your approval: a way forward for nuclear technology in Australia*, Report of the inquiry into the prerequisites for nuclear energy in Australia, House of Representatives Standing Committee on the Environment and Energy, November
2020	**NSW** Report Nº46 Uranium Mining and Nuclear Facilities (Prohibitions) Repeal Bill 2019 Standing Committee on State Development NSW Legislative Council, March
	Victoria *Inquiry into nuclear prohibition*, Legislative Council Environment and Planning Committee, Parliament of Victoria, November
	United States NRC issues the Final Safety Evaluation Report in August and Standard Design Approval in September, first for an SMR
2021	**Commonwealth** Energy Security Board publishes *Post-2025 market design directions paper*, 5th January; provides *Post 2025 Market Design Final Advice to Energy Ministers*, 26th August on reforms of the NEM through the energy transition, noting that '...to date no gigawatt-scale system has ever operated without some synchronous generation online...' (and mentioning nuclear energy briefly with reference to France and, elsewhere, to the UK)

Key

🟦	International treaties and conventions, under the United Nations or otherwise
🟨	Acts of parliament of Australian states and the Commonwealth
🟧	Major civilian nuclear energy reactor accidents
▌	Treaty, Convention, Statute, Act, Regulation, Report, Speech or Milestone
▌	War, Military or Geopolitical Event

Endnotes

a Researchers around the world, including at UQ and elsewhere in Australia, are working on nuclear fusion generation, which uses forms of hydrogen called deuterium and tritium for fuel. The secrets to maintaining stable operation of a fusion reactor are being sought in theoretical simulations and experimental facilities, which will then need to show how to generate more energy than they consume. The timing of those future major achievements and breakthroughs cannot currently be predicted with any certainty.

b The Fluor estimate for the plant as a whole conforms to AACE 18R-97–Class 4 estimate (1% to 15% project definition). The cost estimation for the reactor modules was more detailed (based on 10% to 40% definition). AACE International publishes cost estimation methods that are widely considered the benchmark for projects in the process industries.

c Selection followed an 18-month process with expressions of interest from 83 companies based in ten countries, indicating the level of interest in the technology and the industry.

d OPAL uses fuel assemblies composed of 21 fuel plates measuring 70.2 x 655 x 1.35 mm. There are 16 fuel assemblies in the core. Source: Dr Mark Ho, ANSTO.

NuScale's SMR design uses standard LWR fuel in 17 x 17 configuration, each assembly is 2m in length; fuel is enriched at less than 5 percent; the refuelling cycle up to 24-months. Source: www.nuscalepower.com/technology/technology-overview

e As with large reactors, each unit of an SMR must be commissioned individually. Benefits are expected from commissioning of common facilities before the first module is installed, and from learning via feedback from commissioning many modules.

f **Low-level** waste from a 12-unit SMR plant each year would fit in two 40 ft shipping containers. These include site clothing and scrap metals, have very low-level radioactivity, and are easy to handle. **Intermediate-level** waste, such as fuel packaging and reactor module components, is more radioactive but has no self-heating properties. Most of it comes from decommissioning of nuclear plants and can be stored in surface facilities with protective walls. **High-level waste**, including spent fuel rods, is self-heating due to radioactive decay, and remains extremely radioactive and hot for many years.

'The new [National Radioactive Waste Management Facility (MRWMF)] will:

- permanently dispose of low-level radioactive waste
- temporarily store intermediate-level waste.

A separate future facility will permanently dispose of Australia's intermediate-level waste.'

www.industry.gov.au/policies-and-initiatives/australian-radioactive-waste-agency

High-level waste from a fleet of nuclear energy plants would initially be cooled on site (all nuclear power plants, including the NuScale SMR design have provision for this). Subsequently it can be stored on site in dry casks, and transferred to long-term storage at the end of life. Alternatively, the waste could be periodically moved to long-term storage.

g Small modules should be easier to decommission and 'uninstall' than large site-built structures. Worldwide, decommissioning experience is considerable, with proven techniques and equipment. Most parts of a plant do not become radioactive or are contaminated at only very low levels and most of the metal can be recycled. Decommissioning costs are a small fraction of total costs. About 115 commercial power reactors, 48 experimental or prototype power reactors, over 250 research reactors and several fuel cycle facilities, have been retired from operation. At least 17 of more than 160 power reactors have been fully dismantled, over 50 are being dismantled, over 50 are in safe enclosure for deferred dismantling, three have been entombed, and for others the decommissioning strategy is not yet specified.

h Cook (2018, p.44) notes:

'In 1954, the UN General Assembly resolved to establish an international atomic energy organisation. The *Statute of the International Atomic Energy Agency* opened for signature on 20 October 1956 and was approved by 82 states. The purpose of the IAEA is defined as follows:

The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose.

The functions of the IAEA include safeguards provisions in art.III of the Statute. These provisions authorise the IAEA to establish and administer a system of safeguards to prevent the use of nuclear technology other than for peaceful purposes. ...

Therefore, the **IAEA safeguards system actually pre-dates the major treaty on the subject**, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which entered into force on 5 March 1970. Although the IAEA safeguards system predates the NPT, the NPT creates a binding obligation on states to accept IEAEA safeguards on certain nuclear materials and activities.

The *Treaty on the Prohibition of Nuclear Weapons* (TPNW) was opened for signature on 20 September 2017. The TPNW is the first global legally binding Treaty prohibiting nuclear weapons.

The TPNW does not contain a separate verification regime. Each state party must conclude and maintain its existing safeguards agreements with the IAEA.

The TPNW will enter into force 90 days after the date on which 50 states have deposited an instrument of ratification.'

i The IAEA performed an Integrated Regulatory Review Service (IRRS) review for Australia in 2018, and a follow-up mission is planned for 2021-22.

j Typically, the license to construct a nuclear power plant allows the **construction** up to and including final hot system tests (IAEA Stage A) but not including fuel loading. The commissioning process, allowed only after the nuclear regulator has issued the operating licence, includes fuel loading, initial criticality (Stage B) and power raising.

k In inertial confinement fusion, conditions to initiate fusion reactions are achieved by using high powered lasers to implode capsules containing deuterium-tritium fuel. Hydrodynamic instabilities drive mixing between the fuel and capsule material, which prevents a fusion burn from consuming the fuel. Researchers at UQ, in collaboration with experimental researchers at laboratories in other countries, use computational and theoretical approaches to investigate multi-fluid plasma effects on these instabilities, and how they might be mitigated using applied magnetic fields.

l Currently the UK Nuclear Skills Strategy Group (NSSG) is accountable for developing a nuclear skills strategy. EDF (Électricité de France) operates the UK's nuclear power plants and also owns Cottam coal-fired power station which is closing. EDF supported a development program to bring experienced individuals into its nuclear power business.

m Deployment of reactor simulators in Australia may be somewhat more expensive than in the U.S. because they will require a secure server solution in-country. NuScale trains professors and other staff to operate the simulators in U.S. universities, provides a handbook and ongoing support. Extra staffing is not required but may be desired if a facility is used to give frequent public tours.

n For the OPAL reactor, operator training was completed on a schedule designed to ensure that there was no delay in the issue of an operating licence. There is a recent example where this was not achieved. KEPCO (South Korea) constructed 4 x APR 1400 nuclear power plants at the Barakeh site in UAE. Construction was completed to schedule with the first reactor completed in March 2018. However, the UAEA nuclear regulator (FANR) could not issue the licence to load fuel as operator training was not completed. The operating licence was issued in February 2020—a costly delay to commercial operation.

o Examples include the Dalton Nuclear Institute (UK) and the World Nuclear University (IAEA/WANO/WNA).

p Each year since 2000, Edelman has surveyed people around the world and reported on trust generally in the four types of institutions mentioned here. www.edelman.com/trust/ The surveys for the Edelman trust barometer define the informed public as aged 25-64, college-educated, in the top 25% of household income per age group in each country, and self-reporting significant engagement in public policy and business news.

q Energy storage, historically limited to pumped hydro at level 1, now includes technologies that can be incorporated at any of the four levels. Pumped hydro and nuclear generation assets represent a classic pairing of technologies observable in a number of systems around the world.

r The Hilmer Review (1993) of National Competition Policy recommended 'that all Australian Governments adopt a set of principles aimed at ensuring that, as part of reforms to introduce competition to a market traditionally dominated by a public monopoly, the public monopoly be subject to appropriate restructuring. The principles deal with: • the separation of regulatory and commercial functions of public monopolies; • the separation of natural monopoly and potentially competitive activities; and • the separation of potentially competitive activities into a number of smaller, independent business units.' Executive Overview, p.xxx to xxxi.

s The intention of market design and the detailed rules is to avoid such situations, but that may be difficult or too complex to achieve in all cases.

t AEMO's preparation and publication of an Integrated System Plan is a need perceived relatively recently, suggesting that the ten-years ahead view updated an published annually in the *Electricity Statement of Opportunities* (ESOO) for the market, investors, lenders (and governments) to consider, is no longer considered sufficient.

u In Australia and most other countries, the original early power stations on inner city sites—some of their buildings are now 'powerhouse' museums, art galleries, theatres, cinemas, restaurants and apartments—had been replaced with large plants, near primary energy sources by the mid-20th century.

v The report details costs using three-digit codes of account for a 12-module NuScale SMR plant and a common large PWR reactor design of 1147 MW_e. The authors found per-unit capital costs of less than US$3500/kWe for the SMR plant versus almost US$5600/kWe for the large reactor.

w For example, few, if any of the major electricity market price forecasting models correctly predicted the price impacts of the closure of the Hazelwood power station.

x Referring specifically to the National Electricity Market, this is a verbatim quote from an interview conducted in June 2017 with one of the most senior and experienced bankers in Australia: someone with over 25 years of experience financing the Australian energy sector. The research interview was part of a series of interviews with almost all of the major Australian, Asian, American and European Banks active in financing Australian energy and infrastructure assets, conducted for a confidential client. The face-to-face and telephone research interviews found that, since at least 2017, the view distilled in this quote has been universally held by the banks. In most of the interviews, this view was put forth before the corresponding question in the discussion guide had been asked. Anecdotal conversations since 2017 have done nothing to indicate that the view has changed. If anything, such conversations have strengthened the 2017 research finding.

y There are various techniques for storing hydrogen as a gas, a liquid, in a carrier chemical, or as a solid. The technologies are at various stages of maturity. Hydrogen (H2) can be stored in a pressure vessel as a gas, as a cryogenic liquid at –253ºC (20ºK); it can be transformed to ammonia (NH3) using the Haber-Bosch process; to various other carrier chemicals via other processes; or in a solid matrix as a metal hydride. CSIRO has developed membrane technology that facilitates conversion in either direction between H2 and NH3. Advantages and disadvantages, and the capital and operating costs vary between storage techniques and technologies.

z Progressive deployment of individual SMR modules can provide early positive project cash flow, reducing project and making financing of a series of module additions more attractive and easier than is the case for plants with a one or few large, gigawatt-scale reactors.

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