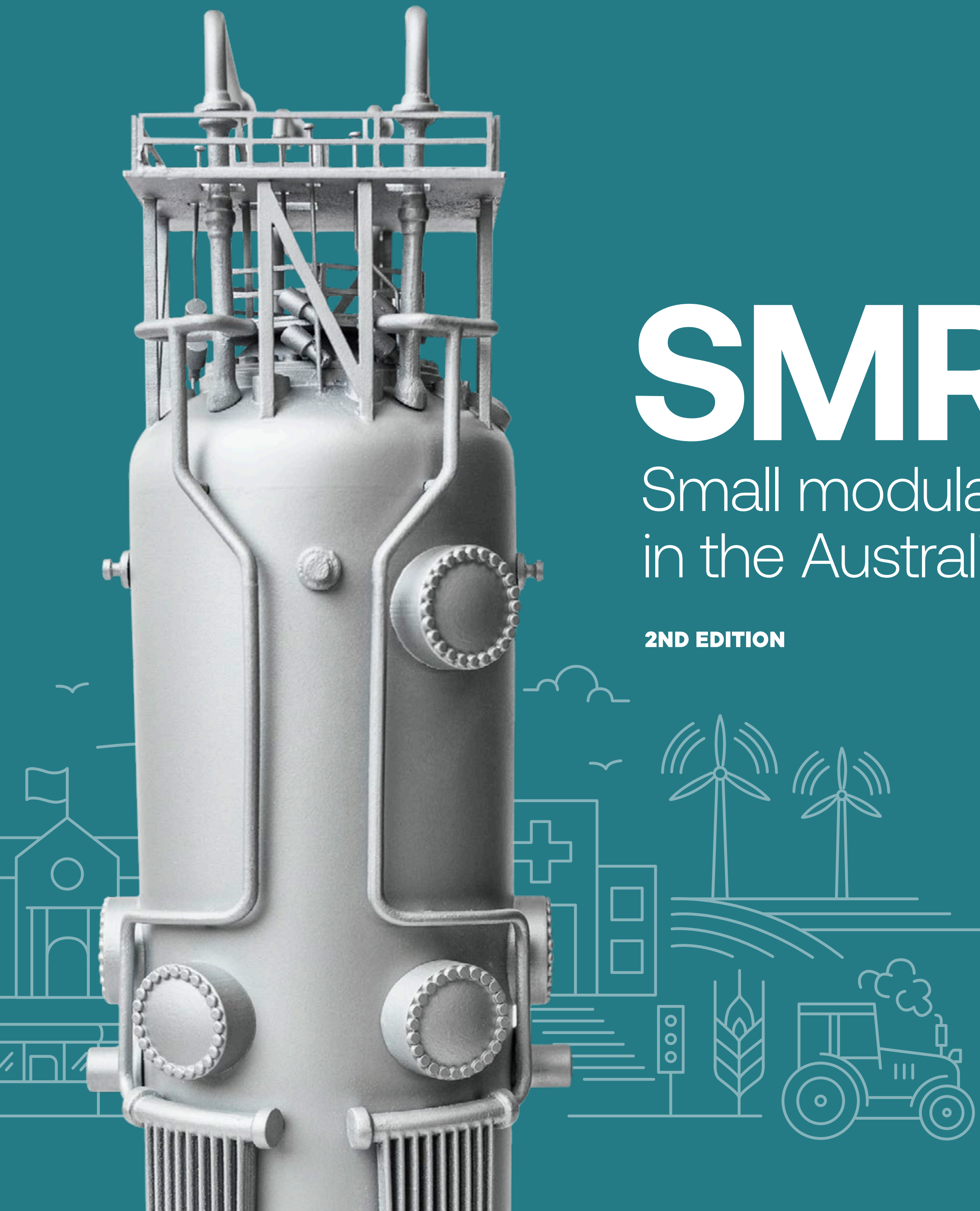

SMRs

Small modular reactors in the Australian context

2ND EDITION

There's more to Australian Mining

Global development of SMRs

World Nuclear Association

The benefits of SMRs

Lower cost

SMR construction time and capital costs are considerably less than large scale nuclear reactors or equivalent energy production methods.

Enhanced safety

Passive cooling systems, fewer mechanical parts requiring maintenance and auto fail safe makes SMRs among the safest forms of energy production.

Configurability

Factory-built and easily transportable, SMRs can be scaled to meet energy demand. Increasing capacity is as simple as adding another module.

Less waste

Some SMRs will use fuel more efficiently than current reactors, producing less waste. Advanced fuels will be easier to recycle for even greater energy production.

SMRs

Small modular reactors in the Australian context

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What are small modular reactors?

Small modular reactors are power generators of typically 300 MWe or less that use nuclear fission to provide clean, fully reliable heat and power, on-grid or off-grid.

p.19

Where can Australia put small modular reactors?

SMRs can connect directly to the existing grid, be used to power regions or independently supply mines due to their compact size, fuel density and ability to air cool.

p.23

What are the costs of small modular reactors?

Robust estimates suggest that by 2030 and beyond, SMRs will offer power to grids from $64 –$77 MWh, depending on size and type. The next 10 years are crucial.

This report was produced by:

Dr Ben Heard

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SMRs: an evolution of nuclear energy

Small modular reactors are an evolution of nuclear power generation technologies. Currently in use for maritime applications, including surface ships and submarines, SMRs are under active development in fourteen countries.

Small modular reactors (SMR) are bringing to market greater diversity in nuclear technologies, with lower projected costs, greater flexibility, greater versatility, and advanced safety cases.

Now that Australia has committed to building nuclear-powered submarines, Australia will need to develop the skills and expertise to support the new fleet. This capacity could also support the deployment of SMRs.

The new SMR designs are being commercialised to provide low cost 24/7 zero emission heat and power. With smaller size, lower unit costs and passive and inherent safety features, SMRs have the potential to deploy more quickly in a broader range of markets.

From replacing aging power plants in mature, slow-growing and (commonly) liberalised power markets; to developing nations with lesser underlying transmission infrastructure; to reliable clean power for remote, off-grid locations, SMRs can potentially underpin zero emission power supplies in many settings.

Several new designs are expressly intended to support operations in conditions of water scarcity, either entirely water-free by design, or with greater potential for dry-cooling in operations.

SMRs are intended to be built in factories and shipyards, delivering the economies of serial production with increased quality, shorter construction time, fewer manufacturing constraints and simpler safety cases.

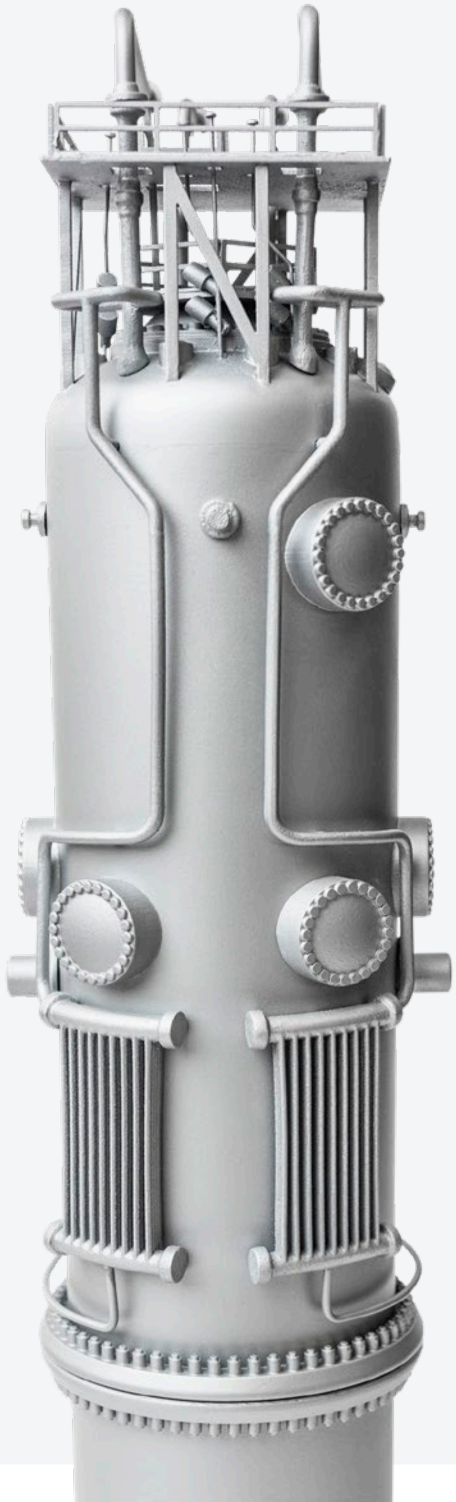
Delivered to site, SMRs will avoid the need for large, skilled construction teams to operate for long periods in potentially remote locations. This has the potential for meaningful reduction in cost.

With around 20,000 MW of baseload power stations due for retirement over the next 20 years, SMRs are ideally placed to be part of Australia's future energy mix.

They will be of a fit-for-purpose size, utilising existing power transmission and network infrastructure. This reduces the need for additional infrastructure spending and offers meaningful options to redeploy workforces and sustain local economies and communities.

SMRs will support the cost-effective integration of variable renewables by providing a flexible base that offers strong load-following. Their synchronous generation, which can run day-long in a net zero industrial system, will maintain the essential system grid security currently under threat from the close of baseload power stations.

A blend of clean generation sources will also maximise the cost-effective production of hydrogen and synthetic fuels, and ensure best, economical use is made of storage capacity in the grid. Their full-time production of emissions-free electricity and heat supports more efficient and productive paths to hydrogen production, as well as a broad range of industrial applications including ammonia production, food processing, synthetic fuels and metal ore processing and metal smelting.



Providing reliable, low cost zero emission industrial scale power makes SMRs an ideal power solution for remote mining operations. Powering desalination plants with 24/7 zero emission power offers the potential for greatly enhanced water security in a changing climate.

Positioned as multi-purpose devices in our energy systems, SMRs are a benefit multiplier on the road to net zero in a warmer world.

Focusing on three SMR designs – the NuScale Power ModuleTM, General Electric-Hitachi's BWRX 300 and Terrestrial Energy's Integral Molten Salt Reactor – this report highlights products that are on track for commercial operation during the late 2020s. Other SMR designs not covered in this publication, for example those of Rolls Royce, X-Energy and Ultra Safe Nuclear Corporation, are following similar regulatory approval timelines and passing important milestones. Future issues of this report will provide additional information about this family of technologies.

Levelised cost of electricity (LCOE) is an imperfect measure of both the total costs faced by energy consumers, and the value provided by different technologies. But, based on cost estimates and targets provided for this report, and applying conservative assumptions, the future LCOE of the SMRs deployed in Australia would be between $64/MWh and $77/MWH. If realised, this would make it the cheapest 24/7 zero emission power source available in Australia.

Changes in the economic, trade, security, policy and technology environments in which Australia operates means that new options for low-carbon energy sources will be required. This has become increasingly clear in the midst of unfolding global energy challenges across 2022. SMRs offer part of the solution to addressing these necessary requirements – reliable low carbon energy, with meaningful benefits in energy security and stability.

However, the benefits of SMRs are inaccessible to Australia under current policy settings. Policies can, ultimately, be changed quickly. But the acquisition and deployment of new technologies, while possible to accelerate, cannot be rushed.

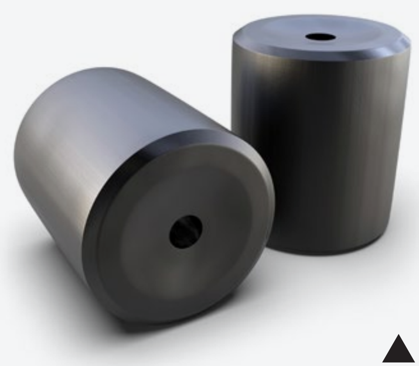
Technologies succeed in the context of capabilities. In capabilities, Australia has a reasonable foundation for future use of SMRs. But serious work is ahead if an industry and regulatory capability is to be achieved. Global developments in SMRs are swiftly overtaking the Australian status of "watching brief" expressed in the 2019 Energy White Paper.

A pivot will be required, from "watching brief" to roadmaps and action plans if we are to have a timely inclusion of these solutions in our energy mix.

This will allow Australia to match a diverse range of nations from Canada to Ghana who are actively establishing the context and capabilities to deploy SMRs.

From small to medium and back to small

Nuclear power is young. The first electricity was generated from fission in 1951 and lit just four 200 watt bulbs.[1] Yet just three years later a 10 megawatts-electric (MWe) reactor propelled the US Navy submarine USS Nautilus.



Fuel pellets Uranium pellets are inserted into rods which are used in the fuel assemblies of some SMRs. Each pellet is the size of a thimble and contains the same amount of energy as 5 barrels of oil.

By 1958 both the US and the United Kingdom were operating prototype commercial power plants of around 250 MWe in size.

As the technology developed, power plants became bigger. This allowed for economies of scale for continuous power generation. By the end of the 1960s 'orders were being placed for pressurised water reactors and boiling water reactors of more than 1000 MWe'.[2] This trend to larger reactors has continued. Mean unit size under construction today is 1125 MWe, up to the 1600 MWe European Pressurised Reactor.[3]

As innovation has expanded the range and types of different electricity generation, nuclear power has proven a mainstay in the diversified energy mixes of most developed nations – the epitome of large, reliable, centralised power production.

Nuclear power continues to grow into new markets worldwide. Large middle-income nations such as Turkey have first reactors under development.[4] Egypt has commenced construction on a nuclear power plant.[5] Meanwhile there is preparatory development in nations across the African continent.[6]

Australia as a member of the OECD and the G20 – and as a major exporter of uranium – is notable for its limited development of nuclear power technologies.

The unmatched advantage of nuclear power is the incredible energy density of zero-carbon uranium fuel.

Reactors around the world

As of August 2022 MWe Net

Source: World Nuclear Association

440
OPERABLE REACTORS
393,259 MWe

59
UNDER CONSTRUCTION
61,037 MWe

89
PLANNED REACTORS
90,197 MWe

340
PROPOSED REACTORS
375,962 MWe

Table 1 outlines the relative energy density of different fuels.

Because of enriched uranium's energy density, a nuclear power reactor might typically refuel only every 18-24 months, greatly reducing supply chain dependency.

No other power source matches the demonstrated reliability of nuclear fission, and no other power source offers such fuel security. Nuclear fission offers the potential to bring clean, reliable, affordable power all the way to where it is needed, unconstrained by the enormous volumes of fuel required or the reliance on continental-scale transmission.

This discussion paper provides an up-to-date summary of the development and road to commercialisation of small modular nuclear reactors (SMR) tailored to the Australian context.

In the decades of energy transition before us, it is essential that Australian governments, institutions, industry and communities remain well-informed about these developments to guide current and future decision-making.

TABLE 1

Energy density of fuels (MJ/kg)
Normalised to barrel of oil equivalent

Fuel	**Density**	**Compared to barrel of oil equivalent**
Firewood (Dry)	16	0.003
Lignite/brown coal (Australia, electricity)	c. 10	0.002
Sub-bituminous coal (Australian and Canadian)	c. 18	0.003
Hard black coal (Australian and Canadian)	c. 25	0.004
Natural gas	42-55	0.008
Liquefied petroleum gas (LPG)	46-51	0.008
Crude oil	42-47	0.007
Diesel fuel	42-46	0.007
Petrol/gasoline	44-46	0.007
Enriched uranium in light water reactor (To 3.5 per cent)	3,900,000	637

Source: Adapted from Ian Hore-Lacy's ***Nuclear Energy in the 21st Century, 4th Edition***, 2018.

How does an SMR work?

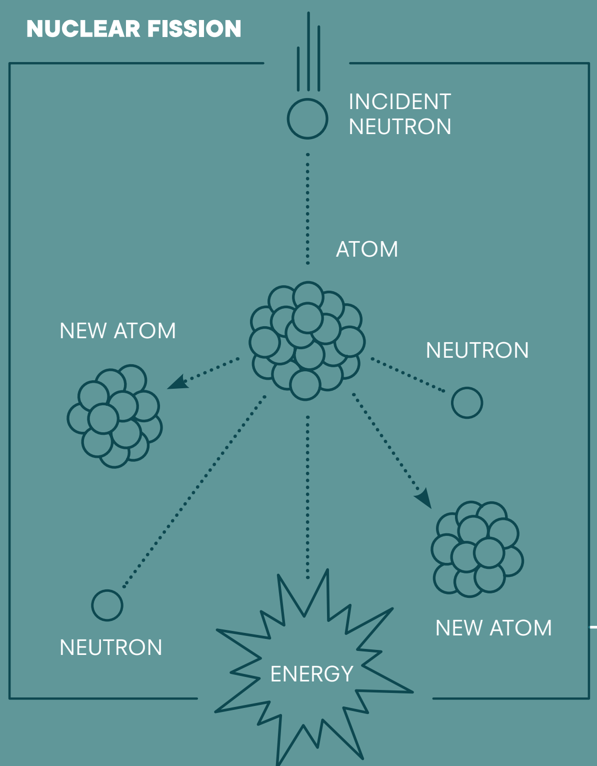
Source: US Department of Energy (energy.gov/ne)

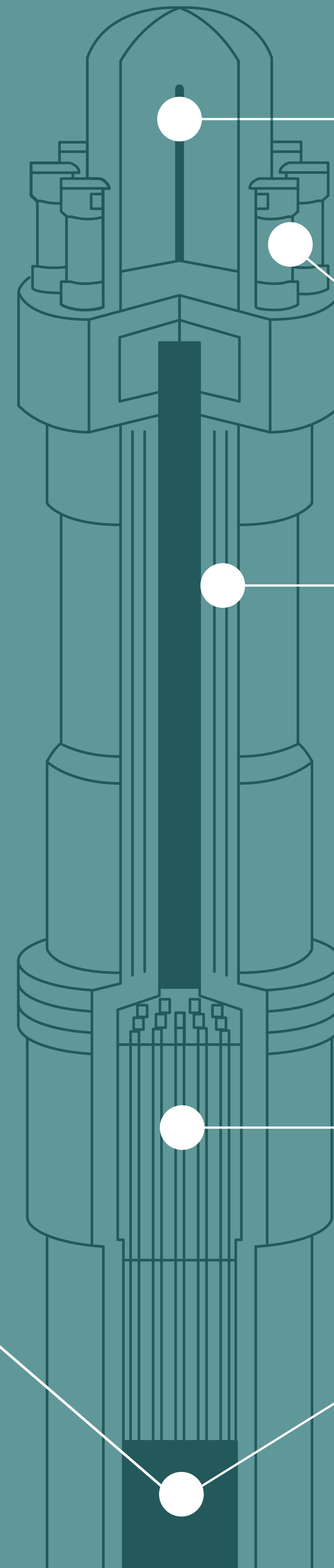
Like large reactors, SMRs use **NUCLEAR FISSION**, the splitting of atoms in the **REACTOR CORE**, to release heat and produce energy.

Commonly, **CONTROL RODS** made of neutron-absorbing material such as boron regulate the chain reaction.

Coolant moves the heat from the **REACTOR CORE** to a **STEAM GENERATOR**. The steam can drive a turbine for power production, or provide direct heating. Or advanced coolants might provide higher-grade heat directly for industrial applications.

NUCLEAR FISSION





SMRs can be installed on brownfield sites and use existing infrastructure to send power to the grid.

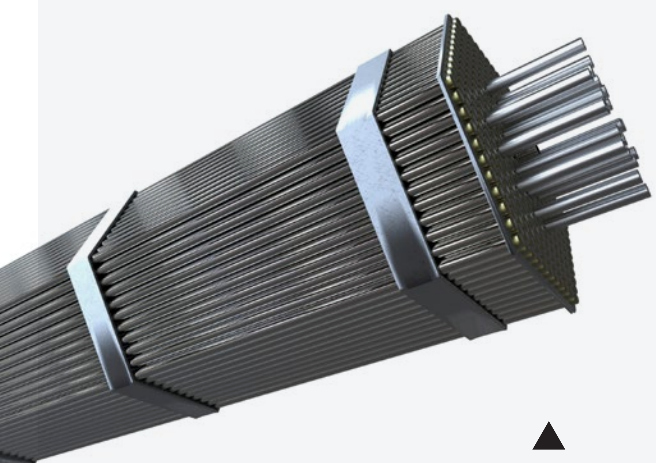
Note: A near-term commercial SMR, using lightwater-reactor technology with integrated steam generator

SMRs

What are small modular reactors?

What are small modular reactors?

Small modular reactors are advanced reactors that generally produce up to 300 MWe per module, with many expected to be made in factories and shipped to the destination power plant by road or rail.[7]



Fuel rods Some SMRs will use fuel assemblies that are much the same as most reactors in operation today. Others will take advantage of different fuel designs.

Most of the SMRs under development have incorporated advanced passive or even inherent safety features. Some SMRs are targeted at single module developments, with others intended to expand in line with demand to make up multi-module power plants.[8]

There are several motivations driving this return to smaller nuclear:

1. They will not require large, skilled construction teams to operate for long periods in potentially remote locations, where workforce turnover and premium pricing for human resources is a challenge.
2. Smaller units should benefit from the economics of serial production, with shorter construction time and simpler safety cases.
3. They will provide a fit-for-purpose option in a greater range of markets. That includes reliable clean power for remote, off-grid locations as well as the incremental replacement of aging fossil fuel infrastructure in mature, slow-growing and (commonly) liberalised power markets.

Australia potentially offers a significant market for SMRs with more than 20 GW of coal and gas-fired generating capacity forecast to retire from 2021-22 to 2041-42.[9]

A further 15 GW of fossil fuel will ultimately require displacement for Australia to transition to a power supply that is largely decarbonised. That condition must then be maintained and sustained in perpetuity as successive generations of energy assets reach end of life.

The development effort in SMRs is also seeing a return to some of the earliest days of nuclear power research before solid fuel, light-water reactors took the leap from submarine to land, and onto commercial dominance. The technologies under development for this new generation of nuclear power are diverse, including liquid fuels reactors, fast reactors and high temperature gas reactors.

This diversity might bring entirely new classes of product to the market, offering advantages such as higher temperatures for more versatile applications, longer fuel cycles (potentially exceeding 20 years), and also the complete recycling of existing used nuclear fuel – removing what is seen as one of their main disadvantages. The opportunity to design nuclear power for the markets of tomorrow is also bringing designs with swift and nimble load-following, facilitating better integration with variable renewable sources along with the ability to cost effectively meet 24/7 demand from industry and households.

The International Atomic Energy Agency lists more than 50 SMRs in development worldwide. In *SMRs: Small modular reactors in the Australian context*, we profile three SMRs in detail. These products have been selected to cover several different nuclear fuel cycles, as well as a range of sizes from 77 MW to 300 MW per module. All three products are sufficiently advanced as to be licensed or in pursuit of licensing with tier-1 nuclear regulatory agencies.

Applications beyond power

Both in Australia and around the world, the conversation about decarbonisation and future energy needs remains dominated by a discussion of electricity. That focus is important, but also partial – economies will need to consider total energy requirements. Even with Australia's exceptional reliance on fossil fuels in electricity production, this sector accounts for just under 34 per cent of Australia's greenhouse gas emissions. Transport, along with industrial processes and direct combustion, is responsible for more than 53 per cent, while agriculture, waste and fugitive emissions account for 13 per cent.

Developing low-carbon alternatives for all sectors of the economy will demand not only greatly-upscaled clean power production, but also versatile application of reliable, zero-carbon heat – and this can be provided in abundance with nuclear technologies.[10] SMR designs and sizes are likely to show more versatile deployment beyond electrical power, such as providing zero-carbon heat directly for industrial processes, hydrogen production or sea-water desalination. Meeting markets for process heat or cogeneration offers the prospect of a better return on investment.[11]

Process heat

Process heating supplies thermal energy to transform materials into a wide variety of industrial and consumer products, including commonly used materials (such as concrete and steel), chemicals (hydrogen, ammonia etc.), and processed food.[12] The requirements for quantity and temperature are diverse.[13] For example, food processing demands temperatures from 65-250°C. Some common chemical processes such as the production of hydrogen or ammonia demand 500-1000°C. The smelting of metals and the processing of metal ores applying calcination and hardening could demand 800-1500 °C.

Decarbonisation efforts in these sectors are immature with few interventions to displace carbon-based fuels. There is some technical potential for these requirements to be met by solar thermal, heat pumps and biomass, particularly for lower temperature applications like food processing.[14] However there are evident limitations to the scalability of renewable resources for lower temperature process heat and no foreseeable, cost-effective options for providing higher temperatures.[15]

Fortunately, nuclear technologies provide continuous and reliable heat at essentially any scale without resource constraint. Light-water reactors offer relatively useful outlet temperatures (approximately 300-350°C), with steam temperatures suitable to support district heating, hydrogen production, desalination or other lower-temperature industrial applications. Much development in the SMR sector is focused on reactors with outlet temperatures ranging from 500-1000°C, suitable for a broader range of industrial applications.

Hydrogen production

One important application of advanced nuclear reactors is the greenhouse gas-free creation of hydrogen.[16] Hydrogen is an ingredient of ammonia (a base component of fertilisers) and also acts as a reductant for iron production.

With clean, reliable, low-cost heat, hydrogen can be produced from the ambient environment using high-temperature steam electrolysis.[17] This could substitute for methane in ammonia production and promote direct-reduction iron production, resulting in higher quality iron with much reduced greenhouse gas emissions compared to blast furnace production.[18]

Synthetic fuels

Hydrogen can be combined with carbon dioxide to create synthetic crude oil (CnH_2n+2), methanol (CH_3OH), or dimethyl ether (C_2H_6O).[19] These chemicals are energy dense, stable, easily stored and transported and can be refined into the full range of hydrocarbon fuels. Along with greatly expanded electrification in several classes of transport, such fuels could all but eliminate net greenhouse gas emissions from transport and other processes that demand combustible fuel.

Desalination

Australia must also be realistic about emerging needs for additional clean power to remain resilient to a rapidly changing climate. Increasing use of seawater desalination is a prime example, and nuclear power already provides a demonstrated, mature technology for delivering large scale desalination without the use of fossil fuels.[20]

A holistic view of energy needs suggests that the role of nuclear fission in decarbonisation is greater than commonly understood. Cost-effective electricity might, in coming years, be one of many applications devised around the availability of reliable, cost-effective and high-grade heat. While effort and investment is required for Australia to achieve the uplift in national capabilities to deploy nuclear technologies, the benefits in clean industry and resilience across the 21st century are likely to be broad and enduring.

Given the nature of SMR technology, it is essential to more closely examine specific product development to understand the potential role of SMR in the Australian context.

NuScale Power

NuScale Power Module

Reactor	NuScale Power Module™
Developer	NuScale Power
Size	77 MWe module, up to 12 unit power plant (924 MWe gross, 884 MWe net)
Type	Pressurised water reactor
Fuel	Solid fuel in PWR fuel assemblies
Moderator	Normal (light) water
Primary coolant	Normal (light) water
Secondary coolant	Normal (light) water
Outlet temperature (°C)	300 °C
Capital cost	NOAK* for Australian deployment $5100/kW gross, $5400/kW net
Commercialisation summary	The design was approved by the U.S. Nuclear Regulatory Commission in September 2020. A utility customer (UAMPS) is proceeding with its Carbon Free Power Project which will see a NuScale power plant constructed at a site located at the Idaho National Laboratory. NuScale's commercialisation program continues with design finalisation and manufacturing trials ongoing and supports being able to deliver NuScale Power Modules to customers beginning in 2027.
Upcoming milestones	Watch for the release of higher-confidence cost estimates and milestone announcements in the development of the Combined Licence Application. Expect the final step in the US regulatory process with UAMPS' submission of the Combined License Application for the CFPP and subsequent review by the NRC, with nuclear construction of the project beginning shortly thereafter.

Image courtesy of NuScale

* NOAK = Nth of a Kind (i.e. when production is already occurring)

NuScale is a new entrant, single-purpose company founded in 2007, which has grown to more than 400 employees.

NuScale is focused on the development and commercialisation of the NuScale Power Module™, a 77 MWe factory-manufactured unit integrating the primary circuit components (reactor core, steam generator, pressuriser and containment) in a single high-integrity unit. The NuScale module is a greatly scaled-down pressurised water reactor – the most common commercial nuclear fuel cycle design in the world – using standard PWR fuel assemblies and normal water for coolant and moderator.

The modules are intended to be installed in arrays of up to 12 for a total maximum plant size of 924 MWe. Each module will have a dedicated steam generator, turbine, generator, condenser, and feed/condensate system and the plant will be operated via a single control room. As well as the anticipated benefits of simplified design and factory-based manufacturing, these relatively small modules offer potential commercial and project development advantages.

Large early spending commitments are not required and instead capital expenditure can be spread over time. Early modules can be acquired and commissioned to generate electricity and cash flow, with additional modules procured and commissioned over time, potentially in response to market requirements of load growth or scheduled retirement of existing aged generators.

The NuScale Power Module makes a strong claim to load following, marketed as a partner for grids with increasing supply of low marginal cost generation from variable renewables. Each module has three potential power regulation options, optimal for needs across different timeframes: turbine bypass, power reduction in the unit, or taking one or more units offline. With that power regulation available across each of the 12 modules, and optimised by the plant operating system, the NuScale Plant has modelled perfect load following of variable wind generation, with performance in excess of utility requirements.[21]

NuScale has innovated particularly in the emergency core cooling system. The modules are operated below ground level in a large heat sink in the form of a pool of water. In the event of total loss of station power, the modules direct decay heat from the core to the heat sink. The modules are passively cooled, firstly by water and eventually by air. This approach maintains the integrity of the fuel for as long as required with no operator intervention, no external power, and no additional water.

Such systems, along with the simplicity of the modules, are intended to eliminate high cost, high redundancy safety support systems, reducing both capital cost and ongoing maintenance and running costs. Elimination of any dependence on external power or reconnection to grid power represents an important advance in a simplified safety case.

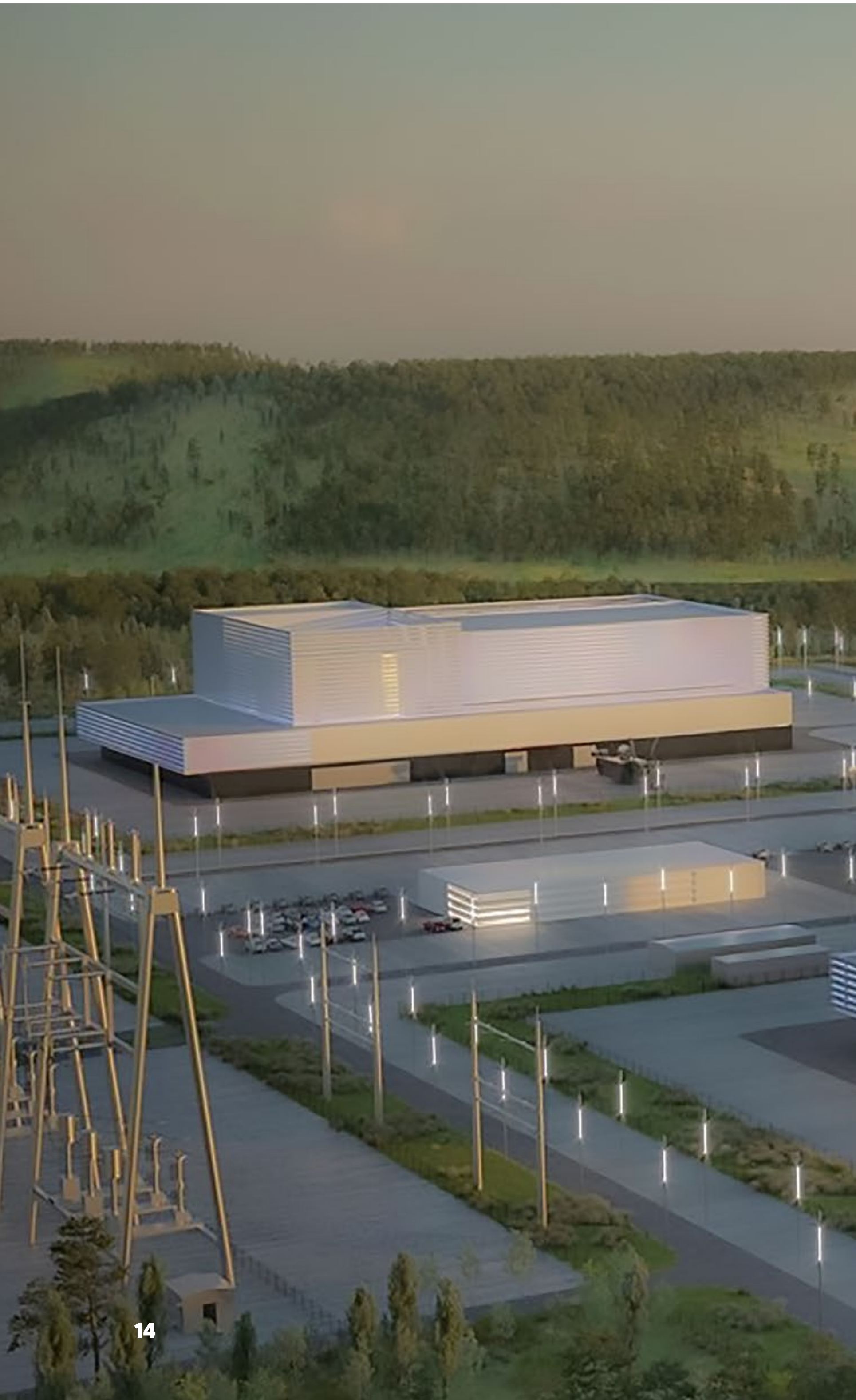
Other aspects, however, of the NuScale design, including the large pool for the heat sink, and the management of multiple modules through typical power plant operations such as shutdown and refuelling, might yet prove challenging to construction, commissioning and operation at a competitive price.

In September 2020, the NuScale Power Module became the first SMR design to complete licensing and technical review with the US Nuclear Regulatory Commission. This allows customers to develop the plant with confidence that safety aspects have been approved.

In 2022, the technical case for these safety characteristics has led to a validated rule change by the US Nuclear Regulatory Commission; that an official Emergency Planning Zone is not required beyond the fence of the site. This acknowledges 'technological advancements and other differences from large LWRs that are inherent in SMRs'.[22] That presents a material de-risking of a nuclear power plant project, opening up greater flexibility of siting to directly serve different loads and further reducing costs.

The Utah Associated Municipal Power Systems (UAMPS) , under its Carbon Free Power Project, is expected to be the first customer for a NuScale plant. First power is now proposed in 2029.[23] A US $1.4 billion cost sharing agreement with the US Department of Energy will substantially de-risk the decision to proceed.[24] A combined licence application is expected in 2024.

The site of the Idaho National Laboratory is the preferred site and UAMPS is proceeding with subscriptions for the first 117 MWe of the first plant.[25] This represents a path to commercial deployment in the 2020s. NuScale is also exploring deployment with relevant partners in Romania, Poland and Estonia.



GE Hitachi

GE Hitachi BWRX-300

Reactor	BWRX-300
Developer	GE Hitachi
Size	300 MWe (gross), single unit power plant (270-290 net)
Type	Boiling water reactor
Fuel	Solid fuel in BWR fuel assemblies
Capital cost	Vendor target cost of A$3200/kW net
Outlet temperature	300 °C
Commercialisation summary	Dominion Energy is the seed funding partner. Selected by Ontario Power Generation (OPG) as the SMR to be deployed at the Darlington New Nuclear Project site by 2028. Mitigating licensing risk by submitting Licensing Topical Reports (LTRs) to the US NRC for the differences compared to the licensed ESBWR. The first five LTRs have been approved by the US NRC. Undergoing Phase Vendor Design Review (VDR) with the Canadian Nuclear Safety Commission (CNSC).
Upcoming milestones	Watch for the completion of Phase 2 VDR in Canada and the application for a licence to construct, and higher accuracy cost estimates.

Image courtesy of GE Hitachi

GE Hitachi is one of the world's oldest and largest vendors of nuclear power plants.

The BWRX-300 is a 300 MWe nuclear reactor, based on General Electric's well-established boiling water reactor and fuel cycle design.[26] Sixty-one boiling water reactors are in operation around the world, mostly in the USA, Japan and Sweden.[27] The BWRX-300 is a smaller and much-simplified reactor based on the design of the Economic Simplified Boiling Water Reactor (ESBWR).

The ESBWR, a 1.5 GW reactor, received certification from the US Nuclear Regulatory Commission in 2014. It was approved for combined construction and operation licences in 2015 for DTE Energy and in 2017 for Virginia Electric and Power Company (Dominion Energy).[28] Despite the substantial investment in licensing, being ten years and approximately US$500 million, there have been no commercial developments of the ESBWR – possibly reflecting a change in markets from the beginning of licensing around 2005, such that the overall package size and marketing was 'not well suited to the current heat and power market'.[29]

The BWRX-300 intends to leverage this licensing pedigree, submitting Licensing Topical Reports (LTR) to the regulator to cover the differences between the ESBWR and the BWRX-300. The first LTR, covering the major differences, was submitted in December of 2019 and approved within 12 months. Three further LTRs were submitted in 2020. With this efficient process, the goal of 2028 deployment, while acknowledged as aggressive, appears plausible.[30]

The conventional economics of nuclear that drove the development of larger reactors suggests that larger scales deliver economic benefit. However, the BWRX-300 is an example where that wisdom, which became conventional in the earliest generations of development, might be up-ended. Innovative design around smaller reactor cores permits elimination of whole elements and systems from plant design, which ought to facilitate swifter, more reliable construction.

With the BWRX-300, GE Hitachi appears to have designed for cost, taking advantage of the attributes of a smaller reactor core.

Taking full advantage of the passive cooling possibilities of small reactor cores, the design is simplified in components. It is estimated to require 50 per cent less structural concrete per unit of power installed than the ESBWR. The slim dimensions of the core are within the scale of established tunnel boring equipment. This potentially enables a much-simplified construction process with the reactor containment vessel assembled above ground and then placed below ground in the 35 m deep hole.[31]

GE Hitachi also brings the advantage of being a global supplier of the non-nuclear balance of plant, having installed hundreds of steam turbine and generator sets of a type virtually identical to the BWRX-300.

The road to commercialisation of new nuclear technologies remains challenging. Spokespeople for GE Hitachi, acknowledging the painful memory of licensing ESBWR only to achieve no sales, have stated publicly that commercial partners are essential, and the development must 'follow the market'.[32]

For the BWRX-300, major US utility Dominion Energy represents early commercial interest, having invested seed funding for this development. Ontario Power Generation selected the BWX-300 from a shortlist of three to advance as the Darlington New Nuclear Project. This provides assurance of further development and maturity of design, engineering, planning and licensing, however remains short of a contract to build. Canadian utility SaskPower has made the same technology selection, for potential build commencing in 2029, a decision made in consultation with Ontario Power Generation.

In October 2022, Canada Infrastructure Bank committed a low interest C$970 million loan to the preparatory works for the Darlington New Nuclear Project. While not tied to this technology, the extension of finance is a strong signal of Canada's commitment to fission in its overall energy strategy and represents a vote of confidence in the future of new classes of nuclear technology.[33] GE Hitachi has made a strong statement with an announced cost target of US$2250/kW installed for the Nth of a kind plant.[34]

Terrestrial Energy

Integral Molten Salt Reactor

Reactor	Integral Molten Salt Reactor
Developer	Terrestrial Energy
Size	195 MWe net
Type	Molten salt, uranium fueled burner reactor
Fuel	Fluoride salt fuel with lightly enriched uranium, molten under normal operating conditions
Moderator	Graphite
Primary coolant	Uranium-fluoride salt (the fuel)
Secondary coolant	Fluoride salt loop (non-radioactive)
Outlet temperature (°C)	600-700°C
Capital cost	Vendor target cost of A$4100/kW installed
Commercialisation summary	Currently in Phase 2 of the Pre-Licensing Vendor Design Review with the Canadian Nuclear Safety Commission. Commercialisation focus upon industrial applications that benefit from high-temperatures.
Upcoming milestones	Expect completion of Phase 2 VDR in 2022. Watch for progressing partnerships in the industrial space to apply higher temperatures, including for repowering coal facilities.

Image courtesy of Terrestrial Energy

Terrestrial Energy is a Generation IV nuclear technology company headquartered in Ontario, Canada that is designing and commercialising the Integral Molten Salt Reactor (IMSR).

As the name suggests, the IMSR operates with a liquid fuel in the form of molten fluoride salt with dissolved uranium, departing from the fuel cycles that have dominated the first 70 years of commercial nuclear power. By returning to some of the earliest research and development in liquid fuel reactors, Terrestrial Energy is seeking to capitalise on numerous potential design advantages to commercialise a product that is decisively advantageous in cost compared with fossil fuels, while also offering diversity in applications for decarbonised energy supply.

The reactor at the heart of the IMSR is a 195 MWe unit. The reactor unit has a solid graphite moderator and is loaded with molten salt fuel with slightly enriched (2 per cent) uranium. The molten salt serves as both fuel and primary coolant, circulating freely in the reactor core which is entirely free of water. A secondary loop of molten salt is pumped through the core, exiting at 600-700° C. The reactor core is designed for a limited seven-year life, during which time it would be fed make-up fuel. At the end of its cycle the can would be removed, cooled and stored onsite, with a complete replacement can installed.

The relatively high outlet temperature and the use of a molten salt coolant is a point of difference for the IMSR. Thanks to the excellent thermal capacity of the molten salt used in the secondary coolant loop, this zero-carbon source of industrial-grade heat can be directed up to approximately 5 km from the reactor core to address any given requirement.

Electricity generation, with thermal efficiency of approximately 47 per cent, is one of several potential applications. Other possible applications on an exclusive or cogenerating basis include direct manufacture of hydrogen through high-temperature steam electrolysis, desalination of water, or provision of heat to other chemical manufacturing, processing or space heating operations.

While all nuclear plants are sources of carbon-free heat, the higher operating temperature, plus the use of molten salt in the secondary coolant loop, might address more of these energy requirements in a cost-effective, reliable, pollution-free technology.

The fundamental physics of liquid fuels also offer a distinguishing safety case, moving to 'inherent' safety – colloquially known as 'walk-away safe'. If the temperature of the liquid fuel increases beyond the design basis, it experiences a 'prompt' (meaning near-instantaneous) feedback which reduces the core reactivity, and consequently lowers the core temperature.[35] Other responses, including the thermal expansion of the fuel itself, also contribute to a strong negative coefficient of reactivity to temperature increase resulting in a design that is incapable of uncontrolled temperature increases.

In the event of reactor shutdown, the liquid fuel, being already molten, requires no active systems to remove decay heat. The fluoride salt fuels circulate passively in the fuel can, shedding heat over time. Without further intervention the fuel would eventually freeze to a safe state.

Beyond the simplified, factory-based manufacturing process that is expected to be a common feature of SMRs, Terrestrial Energy aims to capitalise on the distinguishing aspects of both liquid fuel and molten salt coolant loops to achieve cost advantages. The IMSR operates at atmospheric pressure, reducing the requirements for high grade structural steel and broadening competition in supply and manufacturing capability. The higher outlet temperature offers superior thermal efficiency in power generation, and combined with the molten salt carrier the IMSR might be well-placed to access several revenue streams. Finally, the overall safety case is substantially simplified, which can be expected to facilitate licensing as well as reducing operating costs.

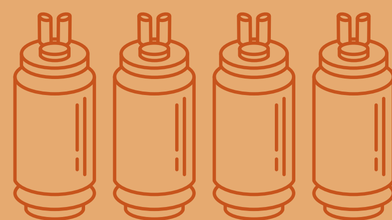
Terrestrial Energy IMSR is expecting to receive results from Phase 2 of the Canadian Nuclear Safety Commission's pre-Licensing Vendor Design Review before the end of calendar year 2022, a process which identifies any fundamental barriers to licensing. The funding for completion has been assured with a US$20 million direct investment from the Government of Canada itself announced in October 2020.[36] At the end of 2021 the IMSR was not advanced beyond final-three consideration by Ontario Power Generation for a new utility electric power plant. In response the development and commercialisation mission has broadened beyond electric utilities to leverage the high temperature system.

These applications are being directly investigated in agreement with KBR, examining application in hydrogen and ammonia production. A memorandum of cooperation with Korean engineering, procurement and construction (EPC) firm DL E&C signals the presence of a future build partner.

SMRs are an ideal fit for the Australian energy market

SMR MODULES have a similar capacity to many of the existing generator units that make up Australia's coal and gas-fired power plants.

For example, two **77 MW NUSCALE SMR** modules could easily replace an aging 150 MW coal or gas-powered turbine without the need for additional grid investment.



4 SMALL MODULAR REACTORS

COULD POWER...

1.2 million
AVERAGE AUSTRALIAN HOUSEHOLDS

MCA calculation based on average household electricity consumption of <8000 kWh per year. Each SMR = 300 MW

Lower cost

Construction time and upfront capital costs are considerably less than large scale nuclear reactors or equivalent energy production methods.

Enhanced safety

Passive cooling systems, fewer mechanical parts requiring maintenance and auto fail safe makes SMRs among the safest forms of energy production.

Configurability

Factory-built and easily transportable, SMRs can be scaled to meet energy demand. Increasing capacity is as simple as adding another module.

Less waste

Some SMRs will use fuel more efficiently than current reactors, producing less waste. Advanced fuels will be easier to recycle for even greater energy production.

SMRs
Where can Australia put small modular reactors?

Where can Australia put small modular reactors?

Unlike other fuel-based power generation sources, providing electricity with nuclear fission is not constrained by proximity to a body of coal, access to a gas pipeline, or a reliable source of sustainable biomass.

Nor it is dependent on exceptionally good solar or wind resources, connected with dedicated transmission corridors. From an engineering standpoint nuclear fission offers inherent flexibility in siting, arguably more than any other power source.

As a thermal power generating source, nuclear power plants require cooling in the same way as fossil fuel, biomass or solar thermal plants. Proximity to a reliable water source therefore remains advantageous, as is current practice for the bulk of Australia's power sector. However, given the absence of constraint based on proximity to fuel, nuclear reactors in Australia might take advantage of sites on Australia's extensive coastline. Such locations, also likely to be close to major electricity demand, can use non-potable ocean water to provide condenser cooling on a once-through basis. As already demonstrated at the Kogan Creek and Millmerran power stations, dry cooling is a mature solution for power generation where water availability is constrained. In summary, access to fresh water is not an automatic constraint on the use of nuclear technologies in Australia.

Plug and play

An additional advantage of SMRs, compared with nuclear technology in general, is that they present no technical impediment to connection to Australia's existing transmission network.

With a relatively small number of customers spread over the largest continuous electrical grid in the world, the Australian National Electricity Market is a 'long and skinny' grid, with minimal interconnection compared with, for example, the more densely meshed grids of the European Union or the United States. This constrains the size of single generating units that might be accommodated. If connecting a single generating unit of over 1000 MW, a grid must be resilient to the potential loss of that capacity.

The largest single generating unit in Australia is the 750 MW coal generating unit at Kogan Creek in Queensland. The bulk of Australian power is provided by units of less than 300 MW.

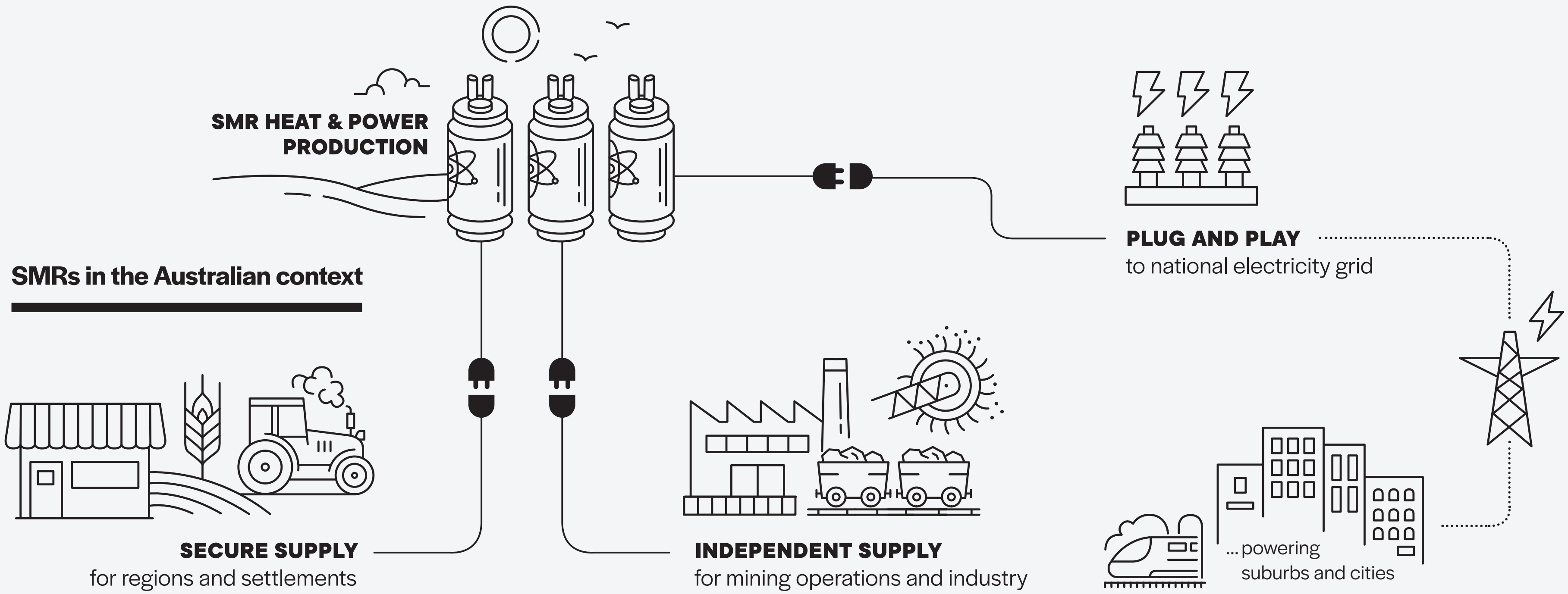
While large nuclear reactors could likely be accommodated near several of Australia's larger electricity demand centres, it is clear that SMRs, including the commercially near-term options profiled in this discussion paper, will be fit-for-purpose replacements of retiring coal and gas capacity. With 12,000 MW of coal and gas scheduled to retire between 2030-2040, flexible base, zero-carbon generating units in the form of SMRs make a strong case for direct replacement, and also offer the potential benefit for placement at the weaker ends of the electrical grid, to improve overall balance and system stability.

Saving capital, preserving communities

That represents potential for important time and cost savings in Australia's energy transition. SMRs would be facilitated in the Australian market by the currently foreseen expansion in the transmission network.[37] However expansion of that scale is not required as it is for hypothetical grids driven by variable renewable supply.[38]

To the contrary, SMRs offer the potential to fully capitalise on the value of the in-situ assets in the established corridors, not least the skilled workforces and communities who continue to provide so much of Australia's power. Australia's existing power generating nodes are well-established sites, in direct proximity to transmission lines with switchyards, with established sources of condenser cooling water.

One published study estimates that approximately $130 million worth of assets from existing coal plants could be reused in establishing a NuScale Power plant.[39] Studies suggest all workers in coal fired-power stations could be effectively cross-trained or retrained to staff a nuclear power station, with 667 direct, indirect and induced jobs



in the local community for each new plant for the 60-year operating life.[40] While greenfield sites might prove desirable for various reasons, brownfield sites, including existing coal-fired power stations, might be worthy of consideration, consultation and further study in the Australian context.

Powering mines and regions

In addition to replacing fossil fuel capacity in our existing grids, SMRs might provide realistic options for decarbonising large regional settlements and off-grid mining operations. Higher-temperature nuclear such as IMSR offers thermal efficiency in the range of the most modern natural gas plants, which provides power to remote settlements such as Alice Springs.

Other incoming designs are purpose-designed to serve remote communities and off-grid operations. Being potentially water free and offering decades of uninterrupted power, some of the earliest and most logical deployments of nuclear power in Australia might actually be away from our major transmission networks.

Where operations are more speculative, hybrid power systems of diesel fuel, solar and batteries are likely to remain solutions of choice. However, for establishing or repowering remote operations away from fossil fuel consumption and with exceptional reliability, the ability to bring mega watt decades of reliable power all the way to where it is needed is a potentially game-changing technology solution.

In summary, SMR technology has several potentially sensible uses in Australia's energy transition that are worthy of close consideration – joining renewable technologies to provide an incremental transition from retiring coal and gas assets; as an option for large, established settlements, and for smaller and remote off-grid settlements and operations. On a technical basis, their placement is relatively unconstrained compared with alternative generating options, and potentially advantageous in taking advantage of existing infrastructure and skilled workforces. Assuming a future legislative and regulatory environment that permits the use of this technology, actual siting will benefit from best practice, consent-based siting processes.

SMRs deliver low cost energy with a long operating life

Cost of electricity (A$, MWh)

ASSET LIFE

BETWEEN 25 AND 40 YEARS				40+ YRS
$100-$170				$64-$77
WIND + 6 hrs storage	**SOLAR** + 6 hrs storage	**GAS** + CCS (24/7)	**COAL** + CCS (24/7)	**SMR** (24/7)

Source: CSIRO, *GenCost 2019-20* (wind, solar, gas and coal). Calculations by Dr Ben Heard (SMRs, see Table 4, page 26).

Nuclear power has among the lowest life cycle emissions

Average lifecycle CO_2 equivalent emissions

BIOMASS	**SOLAR PV^**	**GEOTHERMAL**	**HYDRO**	**WIND***	**NUCLEAR**
230g per kWh	48g per kWh	38g per kWh	24g per kWh	11g per kWh	12g per kWh

Source: Intergovernmental Panel on Climate Change

^ Solar PV Utility

* Onshore=11 g per kWh; Offshore = 12 g per kWh.

SMRs

What are the costs of small modular reactors?

What are the costs of small modular reactors?

Assuming suitable legislative and regulatory structures were developed in Australia to support the deployment of SMRs, there remains the question of the business case for doing so. The affordability of SMRs, and their place in a future Australian energy market, are open questions.

There is a substantial body of work available regarding the cost of SMRs. However there is a lack of standardised methodology.[41] There is no publicly available as-built cost data on which to base assessments.[42] Few teams possess both the capability and remit to produce first-principles estimates of the economic competitiveness of SMRs.[43]

Efforts over the previous six years therefore depend to a greater or lesser extent on review and loading of estimates provided by developers and vendors.[44] That task is further complicated by attrition in some vendors and developers, and the demonstrable recent progress towards commercialisation for others, where knowledge and confidence in cost estimates is evolving swiftly.

An over-reliance on the useful but simplistic metric of levelised cost of electricity presents an additional challenge. This metric takes no account of overall system value and system costs, and the outputs are readily manipulated depending on prevailing assumptions.

The Australian Energy Market Operator goes so far as to caution that its published levelised costs of electricity for new projects in Renewable Energy Zones do not accurately represent power system requirements and can be 'optimistic, or even misleading'.[45]

Differences in the discount rate applied have the potential to heavily weight the results either for or against assets with larger capital expenditure, longer build times and longer life (such as nuclear power stations or hydroelectric plant), or lower capital expenditure, shorter build times and shorter life (such as solar photovoltaic and onshore wind developments).

Discount rates of 10 per cent for example, heavily penalise long-lived assets with larger construction timelines and larger up-front capital, yet this is not necessarily representative of the realities of financing major energy developments in many parts of the world. A short review of the application of discount rates is provided in Appendix 1.

For our considerations in the Australian context, we are applying 5.9 per cent, consistent with the rate applied to all technologies by the Australian Energy Market Operator and CSIRO.

In this pre-commercial window for SMRs, the honest position in the Australian context acknowledges uncertainty, while remaining well-informed and up-to-date. Where estimates of levelised cost of electricity are made, they should be transparent and traceable in all assumptions.

In SMRs as in nuclear in general, overall costs are strongly driven by the capital cost. Table 2 provides a summary of capital cost estimates for SMRs from a small subset of studies conducted over the last five years.

The range of capital costs is indicative of this pre-commercial uncertainty. Nonetheless recently published, but unverifiable cost estimates of AU$16,000 kW fall well outside the upper end of the range in recently published studies and estimates.[46]

Table 3 presents capital cost estimates per kW of installed capacity, provided by vendors profiled in this study, with comment on the nature of the estimate. The maturity of the estimates varies between vendors and will be updated as higher maturity estimates become available.

To estimate levelised cost of electricity, it is necessary to determine the Total Overnight Cost of the project. These estimates will typically include, in addition to total plant costs, a component of project contingency, and a basket of potential costs grouped as "owner's costs". The scope of these costs vary by customer, project (including site-specific needs), and technology, including different national and regional contexts. Definitions of costs for inclusions in owner's costs vary in relevant literature, and depend on cost estimation guidelines. Furthermore, some vendors might include some "owner's costs" in published estimates where the confidence is high (e.g. licensing cost). Any generic attempt at estimation is both important and necessarily coarse. Here, a conservative 25 per cent loading has been added to estimates of overnight capital costs to account for contingency and owner's costs in the Australian context.

These estimates will be progressively refined.

Based on the estimates summarised in Table 3, Table 4 provides estimates of the total capital expenditure and levelised cost of electricity (LCOE) for SMR nuclear from the vendors profiled in this discussion paper, at a discount rate of 5.9 per cent, consistent with the main rate applied in the 2020 Integrated System Plan.

Based on the cost findings in Table 4, if vendors achieve their cost targets, SMRs would likely play an important role in Australia achieving and maintaining a decarbonised power supply.

The levelised cost of electricity is substantially less than recent estimates for wind and solar appended to dedicated pumped hydro storage.[47]

This does not account for the enhanced reliability, limited investment required in grid enhancement, and security that is brought to the grid from new firm, synchronous capacity. Nor does it account for the versatile applications of industrial heat, hydrogen production and desalination, and suitable use in any grid scale storage.

SMRs would also offer long term operations well beyond the economic life of 40 years, delivering zero-carbon electricity from fully depreciated assets for decades, potentially to the end of the century.

The onus remains squarely on developers and vendors to continue the transition from design and engineering into commercialisation, which can provide firm cost evidence from delivered projects. Costs in the Australian context will also be influenced by future regulatory settings, which are presently unknown. The estimates provided here will be updated in coming years as such evidence becomes available. This will reduce the uncertainty associated with the capital costs, and justify better resolution and distinction for operational costs, thermal efficiency, build time, owner's costs and contingency.

TABLE 2

Capital cost estimates for SMR from three independent studies

A$, 2020

WSP Parsons Brinkerhoff (2015) based on adjusted vendor est. from National Nuclear Laboratory (2014)	Low	Central	High
SMR small	$7315	$8597	$10,328
SMR large	$8032	$9470	$11,317

Energy Innovation Reform Project (2017)	Minimum	Average	Maximum
Anonymised study of seven vendor cost details	$2886	$5317	$8231

SMR Roadmap (2018)	Low	Median	High
Analysis of 47 estimates from vendors and literature	$4953	$7312	$9781

Such costs might include general administration, project management, legal and financial advisory services; site selection and licensing, environmental monitoring and preparatory works, site support infrastructure such as electrical interconnections, water supply, roads and harbours; licensing and permitting, interfacing with regulatory bodies; public relations; taxes and legal fees; other preoperational costs.

For more information, please refer to *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*, OECD/NEA, 2020.

TABLE 3

Estimated overnight capital costs and owner's costs

A$, 2020

SMR	**Overnight capital cost** Per kW net of installed capacity	**Description**	**Australian owner's costs and contingency** Per kW of installed capacity (generic estimate, 25% of OCC)
NuScale Power Module (NuScale Power)	$5100 NOAK	Conforms to AACE International Class 4 cost estimate with over 14,000 line items (equipment, material, etc) priced using Fluor's current proprietary cost data or actual vendor quotes	$1257
BWRX- 300 (GE Hitachi)	$3200 NOAK	Publicised target cost	$800
Integral Molten Salt Reactor (Terrestrial Energy)	$4100 FOAK	Disclosed target of US$3000/kW	$1025

Note: FOAK = First of a kind; NOAK= Nth of a kind

TABLE 4

Estimated levelised cost of electricity (net) for SMRs from three vendors

A$, 2020

Product	**Capacity** MWe	**Total overnight cost** $/kW installed	**Total overnight cost** Total, million	**Asset life** Years	**Capacity factor** %	**Fixed O&M** $ per kW	**Variable O&M** $ per MWh	**Fuel** $ per GJ HHV	**Thermal efficiency** %	**Build time** Years	**Output p. a.** GWh	**LCOE** 5.9%
NuScale Module	884	$6750	$5636	40	90%	$80	$1	0.6	33%	3	6969	$77
BWRX-300	280	$4000	$1120	40	90%	$158	$2	0.6	33%	3	2365	$64
IMSR	390 (2 x 195)	$5125	$1999	40	90%	$158	$2	0.6	45%	3	3074	$72

Note: Total overnight cost = overnight capital cost plus 25% owners cost and contingency

Conclusion

To achieve an effective energy transition, nations must acknowledge that a decarbonised economy is not a finish line, but a state of operations that must be achieved and sustained in perpetuity.

In the Australian context, it is openly acknowledged that this is a journey of several decades, demanding a dynamic, whole-of-system roadmap that must be resilient to change across a period of multiple uncertainties, and draw upon a diverse technology mix.[48]

With changes that are likely in the economic, trade, security, policy and technology environments in which the Australian energy system operates, enhancing Australia's optionality for low-carbon energy sources represents critical risk management.

Zero-carbon energy is required in different forms and locations for myriad different applications in industrialised economies. In that context, even if today's estimates on time and cost prove premature, it appears likely that SMR nuclear will have a substantial place in a lowest-cost decarbonised economy, particularly accounting for the requirements for industrial heat, electrification of transport, and production of fresh water and synthetic fuels. The commercial availability of these technologies to Australia will widen the road to that decarbonised future.

However it is not plausible that Australia could wait until globally available price evidence is beyond uncertainty, and then swiftly acquire and deploy SMRs on the basis of isolated commercial decisions.

Deploying nuclear power technologies requires a national uplift in competencies and capabilities that a country retains from that point forward. That journey might be accelerated, particularly for a nation with established capacity like Australia, but it cannot be rushed. Considering the sustained progress in the development of SMRs, that journey should arguably be initiated sooner rather than later.

Between the first and second issue of this discussion paper, milestones have been achieved which reinforce that an important technology trend is becoming established. Increasing commitment to first build, establishing locations for SMR factories and fuel manufacturing facilities, and significant regulatory rule changes that reflect advancing technology, all point to improving prospects for new classes of nuclear.

Serious challenges remain, including the challenging commercialisation journey, achieving sufficient orders to justify investments, and international regulatory harmonisation to support higher volumes and predicatable delivery. However the energy crisis gripping the world, amplified by the invasion of Ukraine, has focused attention on the energy security fundamentals that accompany the decarbonisation benefits of nuclear technologies, and emphasised the great value of fission.

Early actions that are low-cost and no regrets can create greater optionality in Australia's energy transition and widen the availability of decarbonising technologies in future. This will avoid playing catch-up, as competitive advantage in critical sectors moves towards nations as diverse as Canada to Ghana that have already achieved, or are actively establishing, the necessary conditions for SMR deployment.

Discount rates – further discussion

An important consideration in calculating and publishing levelised cost of electricity is the appropriate discount rate to apply to the cost-benefit analysis. This is a critical parameter of analysis whenever costs and benefits differ in their distribution over time, and especially where they occur over long time periods.[49]

In the case of policy-based investments that might be tied to responding to a long term issue like climate change, there are arguments for lowering discount rates to infer greater value on benefits received in future, and arguments for raising the rate based on discouraging delay in action.[50]

When the discount rate is higher, future costs and benefits count for less, favouring projects with benefits that accrue early.[51]

An illustrative example was the Stern report regarding climate change action in the UK, which assumed a real discount rate of 1.4 per cent.[52] The conclusions of this report were promptly and firmly challenged as being dependent on this outlying (low) discount rate and not representative of, or resilient to substitution with, assumptions that were consistent with interest rates, the market and savings rates at that time.[53]

Nonetheless, lower discount rates are common in environmental applications where returns accrue in the distant future. For example the United States Environmental Protection Agency recommends a discount rate of 2-3 per cent, and no discounting for intergenerational projects.[54]

Steinbach and Staniaszek recommend discount rates for energy system analysis of 1-7 per cent, representing risk-free discount rates, declining over long time horizons, for which long-term governments bonds are an appropriate proxy.[55] For commercial and industrial investors, these authors recommend a range of 6-15 per cent.

The energy plan for Saudi Arabia assumes a base case real discount rate of 5 per cent, and tests against 3 per cent and 10 per cent.[56] An assessment of renewable energy scenarios for Saudi Arabia by the Tyndall Centre applies a discount rate of 8 per cent, though this also relates only to renewable energy projects with assumed lifetime of 25 years.[57]

The OECD/IEA tests against three discount rates (3, 7 and 10 per cent) in the 2015 edition of Projected Costs of Electricity where previous editions have examined only 5 and 10 per cent. Historically low global interest rates are one reason cited for lowering the discount rates.[58]

In a 2017 report commissioned by the Australian Government, Jacobs Group presents findings on the basis of a 7 per cent discount rate. It further suggests a differentiated weighted average cost of capital for investment in different types of generation, based on perceived market risk, ranging between 6.6 per cent for renewables and open cycle gas turbines and 9.9 per cent for coal projects. Nuclear projects were excluded from consideration (without comment or justification).[59]

A recent modelling study of the Australian National Electricity Market that focused on wind, solar photovoltaic, and pumped hydroelectric storage applied a real discount rate of 5 per cent in determining levelised cost of electricity.[60] Recent global nuclear developments are being delivered with very low cost of finance to fast-growing middle-income nations. This likely reflects a longer-term, nation-building outlook for the borrower (the nuclear customer) as well as an interest in developing long term strategic, industrial and commercial partnership from the lender (in these cases also the nuclear vendor).

This examination of the use of discount rates in energy literature suggests some important guidelines:

1. there is no single 'correct' discount rate readily identifiable across literature; therefore it is informative to test across a range of discount rates;
2. consideration of environmental issues and intergenerational equity, exemplified by the challenge of responding to climate change, support the application of lower discount rates, perhaps as low as 3 per cent real and certainly 5 per cent real;
3. higher discount rates are more indicative of commercial rates of return and shorter investment time horizons.

We applied a real discount rate (i.e. not including inflation, as opposed to nominal discount rate) of 5.9 per cent to calculate the levelised cost of electricity from SMR nuclear, consistent with the rate applied for all generation and transmission investments in the Integrated System Plan 2020 from the Australian Energy Market Operator.

Ensuring a supply of low-cost finance for long-lived clean energy projects could be examined as a policy response.

Assumptions for SMR LCOE

Asset life

An economic life of 40 years is applied for this assessment. This is consistent with the economic life assigned by Lazard.[61] It is longer than the 30 year economic life applied in GenCost.[62] The design life of new nuclear power plants is 60 years, and cost-effective refurbishment provides proven avenues to long-term operations of potentially 100 years.[63] The value of a nuclear plant is thus greater than revealed by the levelised cost of electricity over an economic life of 40 years, particularly in the context of a national energy transition that must be achieved and sustained in perpetuity.

Fuel cost

Nuclear fuel costs are well-understood, relatively stable, and tend to decline with advanced fuel and reactor design and better reactor operation. A cost of A$0.60/GJ is a reasonable estimate.[64]

Fixed and variable operational and maintenance costs

Fixed and variable operational and maintenance costs of SMRs will vary by design. As the maturity of cost estimates increases, it will be beneficial to differentiate the estimated operational costs for different SMR designs.

For the purposes of these calculations, where design-specific estimates were not provided we have taken median values from ten published estimates, converted to A$ in 2020, of $158/kW installed for fixed costs and $1/MWh for variable costs. Where design-specific estimates were provided (as in the NuScale Power Module™) we have applied those estimates ($80 and $0 for fixed and variable respectively).

Waste management costs

Waste management costs are not typically included in levelised cost of electricity calculations for any energy source. However, it is both a common question relating to nuclear power, and an important consideration for whole-of-life-costs for all energy sources – for example, the relatively nascent offshore wind sector is currently tackling these questions for the first time.[65]

Nuclear power is arguably the most mature energy source regarding planned waste disposal costs.[66] Established practice in the nuclear industry is to levy a small sum per unit of electricity sold for the life of the plant.[67]

Based on work of the government of the United Kingdom relating to Waste Transfer Pricing for new nuclear build, we have assigned an additional $1/MWh to the Variable O&M to account for Waste Transfer Pricing, addressing used nuclear fuel and intermediate level waste.[68]

Thermal efficiency

Thermal efficiency of SMRs will vary by design. We have applied thermal efficiency of 33 per cent for the light-water reactors (BWRX-300 and NuScale Module), and 45 per cent for the higher temperature reactor (IMSR).

Capacity factor

Across the ~100,000 MWe nuclear fleet of the United States, which includes reactors up to 50 years old, the average capacity factor was 93.4 per cent in 2019.[69] From a technical specification point of view, SMRs can be assumed to offer 90 per cent average capacity factor.

References

R Adams, "X-300 Blazing a Different Kind of Trail in Small Nuclear Reactor Development," Atomic Insights, https://atomicinsights.com/x-300-blazing-a-different-kind-of-trail-in-smaller-nuclear-reactor-development/.

D al-Qa'dah, *Updated Generation Planning for the Saudi Electricity Sector*, Electricity & Cogeneration Regulatory Authority (ECRA), Riyadh, Saudi Arabia, 2005.

Y Al-Saleh, P Upham and K Malik, *Renewable Energy Scenarios for the Kingdom of Saudi Arabia*, Tyndall Centre for Climate Change Research, Manchester, UK, 2008.

Andolu Agency, "Welded reactor cover completed for Turkey's first nuclear plant: Akkuyu NPP," Daily Sabah, https://www.dailysabah.com/energy/2020/01/23/welded-reactor-cover-completed-for-turkeys-first-nuclear-plant-akkuyu-npp.

Arup, *Cost Estimation and Liabilities in Decommissioning Offshore Wind Installations*, Energy and Industrial Strategy Department of Business, Edinburgh, UK, 2018.

Australian Energy Market Operator, *Draft 2020 Integrated System Plan*, AEMO, Sydney, NSW, 2019.

Australian Energy Market Operator, *2020 Integrated System Plan*, AEMO, Australia, 2020.

G Black, and S Peterson, *Economic Impact Report: Construction and Operation of a Small Modular Reactor Electric Power Generation Facility at the Idaho National Laboratory Site, Butte County, Idaho*, Boise State University & University of Idaho, Idaho, USA, 2019.

A Blakers, B Lu, and M Stocks. "100% renewable electricity in Australia," *Energy,* 133, 2017, pp. 471-482.

X Chen, A Kotlyarevsky, A Kumiega, J Terry, B Wu, S Goldberg and E A Hoffman, *Small Modular Nuclear Reactors: Parametric Modeling of Integrated Reactor Vessel Manufacturing Within A Factory Environment Volume 2, Detailed Analysis*, Argonne National Laboratory, Idaho Falls, Idaho, 2013.

O Chvlala, *Basic dynamics of graphite moderated LEU fueled MSRs*, University of Tennesse Knoxville, Knoxville, Tennessee, 2014.

C Dahlgren, "BWRX-300 Deep decarbonisation with nuclear (video presentation)." In *Clean District Heating with Small Nuclear Reactors,* seminar, Helsinki, Finland, 2020.

P Danko, "Startup planning nuclear plants passes milestone." *Portland Business Journal*, https://www.bizjournals.com/portland/news/2019/07/23/startup-planning-nuclear-plants-passes-milestone.html.

Department of Energy and Climate Change, *Waste Transfer Pricing Methodology for the disposal of higher activity waste from new nuclear power stations,* DECC, London, UK, 2011.

J Dewitte. Video Call, 17 June 2020.

Energy Options Network, *Zero-Carbon Hydrogen: An Essential Climate Mitigation Option, Nuclear Energy's Potential Role*, Delaware, 2020.

M Fürsch, S Hagspiel, C Jägemann, S Nagl, D Lindenberger and E Tröster. "The role of grid extensions in a cost-efficient transformation of the European electricity system until 2050," *Applied Energy,* 104, 2013, pp. 642-652.

GE Hitachi Nuclear Energy, *BWRX-300 Fact Sheet*, GE Hitachi Nuclear Energy Americas LLC, 2019.

GE Hitachi Nuclear Energy, "BWRX-300." General Electric, https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/bwrx-300.

W Gerardi and P Galanis, *Emissions mitigation policies and security of electricity supply*, Jacobs Group (Australia) Pty Limited, Melbourne, VIC, 2017.

L M Germeshuizen and P W E Blom. "A techno-economic evaluation of the use of hydrogen in a steel production process, utilizing nuclear process heat," *International Journal of Hydrogen Energy,* 38, 2013, pp. 10671-10682.

P Graham, J Hayward, J Foster and L Havas, *GenCost 2019-20*, CSIRO, Australia, 2020.

M Harrison, *Valuing the Future: the social discount rate in cost-benefit analysis*, Productivity Commission of the Commonwealth of Australia, Canberra, ACT, 2010.

B P Heard, *Submission to: GenCost 2019-20: preliminary results for stakeholder review*, Bright New World Limited, Adelaide, SA, 2020.

I Hore-Lacey, *Nuclear Energy in the 21st Century, World Nuclear Association*, London, UK, 2018

D T Ingersoll, C Colbert, Z Houghton, R Sunggerud, J W Gaston and M Empey. "Can Nuclear Power and Renewables be Friends?" Paper presented at the ICAPP, Nice, France, 2015.

International Atomic Energy Agency, *New Technologies for Seawater Desalination Using Nuclear Energy*, IAEA, Vienna, Austria, 2015.

International Atomic Energy Agency, "Power Reactor Information System," IAEA, https://www.iaea.org/pris/.

International Atomic Energy Agency, *Advances in Small Modular Reactor Technology Developments*, IAEA, Austria, 2018.

International Atomic Energy Agency, *Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System*, IAEA, Austria, 2018.

International Atomic Energy Agency, "Small Modular Reactor (SMR) Regulator's Forum," https://www.iaea.org/topics/small-modular-reactors/smr-regulators-forum.

International Atomic Energy Agency, "Industrial Applications and Nuclear Co-Generation," IAEA, https://www.iaea.org/topics/non-electric-applications/industrial-applications-and-nuclear-cogeneration.

M Jaszczur, M A Rosen, T Śliwa, M Dudek and L Pieńkowski. "Hydrogen production using high temperature nuclear reactors: Efficiency analysis of a combined cycle," *International Journal of Hydrogen Energy,* 41, 19, 2016, pp. 7861-7871.

Lazard, *Lazard's Levelised Cost of Electricity Analysis - Version 12.0*, Lazard, 2018.

K Lovegrove, S Edwards, N Jacobson, J Jordan, J Peterseim, J Rutowitz, H Saddler, M Watt and J Wyder, *Renewable energy options for Australian industrial gas users*, IT Power Australia Pty Ltd, Canberra, ACT, 2015.

K Lovegrove, S Edwards, N Jacobson, J Jordan, J Peterseim, J Rutowitz, H Saddler, M Watt and J Wyder, "Renewable energy options for Australian industrial gas users," Canberra, ACT; IP Power, 2015.

W D Magwood, *Funding Mechanisms for Radioactive Waste Management*, OECD/NEA, Vienna, Austria, 2014.

B Mignacca and G Locatelli. "Economics and finance of Small Modular Reactors: A systematic review and research agenda." *Renewable and Sustainable Energy Reviews,* 118, 2020.

T Naegler, S Simon, M Klein and H C Gils. "Quantification of the European industrial heat demand by branch and temperature level," *International Journal of Energy Research,* 39, 15, 2015, pp. 2019-2030.

National Nuclear Laboratory, *Small Modular Reactors (SMR) Feasibility Study*, National Nuclear Laboratory, London, UK, 2014.

Nexant, *Variable Operations and Maintenance Cost*, California ISO, Folsom, CA, 2018.

W D Nordhaus, "A Review of the Stern Review on the Economics of Climate Change," *Journal of Economic Literature,* XLV, 2007, pp. 686-702.

Nuclear Energy Institute, *Nuclear By The Numbers*, Nuclear Energy Institute Inc., Washington, D.C., 2020.

Nuclear Regulatory Commission, "Emergency Preparedness for Small Modular Reactors and Other New Technologies," Federal Register, https://www.federalregister.gov/documents/2020/05/12/2020-09666/emergency-preparedness-for-small-modular-reactors-and-other-new-technologies.

NuScale Power, *Upgrading America's Energy System*, NuScale Power LLC, Portland, OR, 2017.

NuScale Power, *Repurposing US Coal Power Plant Sites and Revitalizing Communities*, NuScale Power, Portland OR, 2020.

OECD/IEA/NEA, *Projected Costs of Generating Electricity*, Organisation for Economic Co-operation and Development/ International Energy Agency, Paris, France, 2015.

Oklo Power, *Part II: Final Safety Analysis Report*, Oklo Inc., California, USA, 2020.

G A Olah, A Goeppert and G K S Prakash, *Beyond Oil and Gas: The Methanol Economy*, Wiley-VCH, Weinheim, Germany,

S Patel, "GEH Launches NRC Licensing Process for BWRX-300, an ESBWR-Derived SMR," *Power Magazine*, https://www.powermag.com/geh-launches-nrc-licensing-process-for-bwrx-300-an-esbwr-derived-smr/.

Power Technology, "El Dabaa Nuclear Power Plant." https://www.power-technology.com/projects/el-dabaa-nuclear-power-plant/.

R A Rodríguez, S Becker, G B Andresen, D Heide and M Greiner. "Transmission needs across a fully renewable European power system," *Renewable Energy,* 63, 2014, pp. 467-476.

J Siegel, "Nuclear advocates fret as first maker of small modular reactors encounters trouble," *Washington Examiner*, https://www.washingtonexaminer.com/policy/energy/nuclear-advocates-fret-as-first-maker-of-small-reactors-encounters-trouble.

J Steinbach and D Staniaszek, *Discount rates in energy system analysis – Discussion Paper*, Building Performance Institute Europe, Brussels, Belgium, 2015.

N Stern, *The Economics of Climate Change: The Stern Review, Cabinet Office – HM Treasury*, Cambridge University Press, UK, 2007.

E Taibi, D Gielen and M Bazilian. "The potential for renewable energy in industrial applications," *Renewable and Sustainable Energy Reviews,* 16, 1, 2012, pp. 735-744.

Thomson Reuters Foundation, "As Africa looks for clean power, interest in nuclear grows," *The Japan Times*, https://www.japantimes.co.jp/news/2020/04/10/business/africa-clean-power-nuclear/#.Xro3QRMzZhE.

R Tidball, J Bluestein, N Rodriguez and S Knoke, *Cost and Performance Assumptions for Modeling Electricity Generation Technologies*, NREL, Fairfax, Virginia, 2010.

US Department of Energy, *TA 61: Industrial Process Heating Systems*, US Department of Energy, Washington D.C., 2015.

US Department of Energy, *Strategy for the Management and Disposal of Used Nuclear Fuel and High Level Radioactive Waste*, US Department of Energy, Washington, D.C., 2013.

US Environmental Protection Agency, *Guidelines for Preparing Economic Analyses*, Environmental Protection Agency, Washington, D.C., 2000.

US Environmental Protection Authority, *Documentation for EPA's Power Sector Modelling Platform v6 Using the Integrated Planning Model*, Washington, D.C., 2018.

US Department of Energy Office of Nuclear Energy, Science and Technology, *The History of Nuclear Energy*, Washington, D.C., (Undated).

J Walls, "Nuclear Power Generation – Past, Present and Future." Chap. 1 In *Nuclear Power and the Environment*, edited by Ronald E. Hester and Roy M. Harrison. Issues in Environmental Science and Technology: RSC Publishing, 2011.

World Nuclear Association, "The Economics of Nuclear Power," World Nuclear Association, http://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

World Nuclear Association, *The Enduring Value of Nuclear Energy Assets*, World Nuclear Association, London, UK, 2020.

World Nuclear Association, "World Nuclear Power Reactors & Uranium Requirements," https://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx.

World Nuclear News, "First licence for ESBWR," World Nuclear Association, https://www.world-nuclear-news.org/NN-First-licence-for-ESBWR-0105157.html.

WSP/Parsons Brinckerhoff, *Final Report: Quantitative Analysis and Initial Business Case – Establishing a nuclear power plant and systems in South Australia*, WSP/Parsons Brinckerhoff, Adelaide, SA, 2016.

Endnotes

1. US Department of Energy Office of Nuclear Energy, Science and Technology, *The History of Nuclear Energy*, Washington D.C., (Undated).
2. J Walls, "Nuclear Power Generation – Past, Present and Future," in *Nuclear Power and the Environment*, ed. Ronald E. Hester and Roy M. Harrison, Issues in Environmental Science and Technology, RSC Publishing, 2011.
3. World Nuclear Association, "World Nuclear Power Reactors & Uranium Requirements", https://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx, 2020.
4. Andolu Agency, "Welded reactor cover completed for Turkey's first nuclear plant: Akkuyu NPP", https://www.dailysabah.com/energy/2020/01/23/welded-reactor-cover-completed-for-turkeys-first-nuclear-plant-akkuyu-npp, Daily Sabah, 2020.
5. World Nuclear News, *Construction of Egypt's first nuclear power plant underway*, https://world-nuclear-news.org/Articles/Construction-of-Egypts-first-nuclear-power-plant-u, 2022.
6. Thomson Reuters Foundation, "As Africa looks for clean power, interest in nuclear grows", https://www.japantimes.co.jp/news/2020/04/10/business/africa-clean-power-nuclear/#.Xro3QRMzZhE, *The Japan Times*, 2020.
7. International Atomic Energy Agency, "Small Modular Reactor (SMR) Regulator's Forum", https://www.iaea.org/topics/small-modular-reactors/smr-regulators-forum, 2020.
8. International Atomic Energy Agency, *Advances in Small Modular Reactor Technology Developments*, IAEA, Austria, 2018.
9. Australian Energy Market Operator, *2022 Integrated System Plan*, AEMO, Australia, 2022.
10. International Atomic Energy Agency, "Industrial Applications and Nuclear Co-Generation", https://www.iaea.org/topics/non-electric-applications/industrial-applications-and-nuclear-cogeneration, IAEA, Undated.
11. International Atomic Energy Agency, 2018, op. cit.
12. US Department of Energy, TA 61: *Industrial Process Heating Systems*, US Department of Energy, Washington D.C., 2015.
13. T Naegler et al., "Quantification of the European industrial heat demand by branch and temperature level," *International Journal of Energy Research*, 39, 15, 2015, pp. 2019-2030.
14. E Taibi, D Gielen, and M Bazilian, "The potential for renewable energy in industrial applications," *Renewable and Sustainable Energy Reviews*, 16, 1, 2012, pp. 735-744.
15. K Lovegrove et al., *Renewable energy options for Australian industrial gas users*, IT Power Australia Pty Ltd, Canberra, 2015.
16. Energy Options Network, *Zero-Carbon Hydrogen: An Essential Climate Mitigation Option*, Nuclear Energy's Potential Role, Delaware, 2020.
17. M Jaszczur et al., "Hydrogen production using high temperature nuclear reactors: Efficiency analysis of a combined cycle," *International Journal of Hydrogen Energy*, 41, 19, 2016, pp. 7861-7871.
18. L M Germeshuizen and P W E Blom, "A techno-economic evaluation of the use of hydrogen in a steel production process, utilizing nuclear process heat," *International Journal of Hydrogen Energy*, 38, 2013, pp. 10671- 10682.
19. G A Olah, A Goeppert and G K S Prakash, *Beyond Oil and Gas: The Methanol Economy*, Wiley-VCH, Weinheim, Germany,
20. IAEA, *New Technologies for Seawater Desalination Using Nuclear Energy*, IAEA, Vienna, Austria, 2015.
21. D T Ingersoll et al., "Can Nuclear Power and Renewables be Friends?", ICAPP, Nice, France, 2015.
22. Nuclear Regulatory Commission, "Emergency Preparedness for Small Modular Reactors and Other New Technologies", https://www.federalregister.gov/documents/2020/05/12/2020-09666/emergency-preparedness-for-small-modular-reactors-and-other-new-technologies, Federal Register, 2020.
23. J Siegel, "Nuclear advocates fret as first maker of small modular reactors encounters trouble", https://www.washingtonexaminer.com/policy/energy/nuclear-advocates-fret-as-first-maker-of-small-reactors-encounters-trouble, *Washington Examiner*, 2020.
24. US Department of Energy, "DOE Approves Award for Carbon Free Power Project", https://www.energy.gov/ne/articles/doe-approves-award-carbon-free-power-project, 2020.
25. S Patel, "Shakeup for 720 MW nuclear SMR project as more cities withdraw participation", https://www.powermag.com/shakeup-for-720-mw-nuclear-smr-project-as-more-cities-withdraw-participation/, 2020.
26. GE Hitachi Nuclear Energy, *BWRX-300 Fact Sheet*, GE Hitachi Nuclear Energy Americas LLC, 2019.
27. World Nuclear Association, *Nuclear Power Reactors*, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx, 2022.
28. World Nuclear News, "First licence for ESBWR", https://www.world-nuclear-news.org/NN-First-licence-for-ESBWR-0105157.html, World Nuclear Association, 2015.
29. R Adams, "X-300 Blazing a Different Kind of Trail in Small Nuclear Reactor Development", https://atomicinsights.com/x-300-blazing-a-different-kind-of-trail-in-smaller-nuclear-reactor-development/, *Atomic Insights*, 2020.
30. S Patel, "GEH Launches NRC Licensing Process for BWRX-300, an ESBWR-Derived SMR", https://www.powermag.com/geh-launches-nrc-licensing-process-for-bwrx-300-an-esbwr-derived-smr/, *Power Magazine*, 2020.
31. Adams, "X-300 Blazing a Different Kind of Trail in Small Nuclear Reactor Development", https://atomicinsights.com/x-300-blazing-a-different-kind-of-trail-in-smaller-nuclear-reactor-development/, *Atomic Insights*, 2020.
32. C Dahlgren, "BWRX-300 Deep decarbonisation with nuclear", video presentation, Clean District Heating with Small Nuclear Reactors seminar, Helsinki, Finland, 2020.
33. GE Hitachi Nuclear Energy, "GE Hitachi Working with Ontario Power Generation on SMR Technology Options", https://www.ge.com/news/press-releases/ge-hitachi-working-ontario-power-generation-smr-technology-options-ontario, 2020.
34. GE Hitachi Nuclear Energy, "BWRX-300", https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-

overview/bwrx-300, General Electric, 2020.

35. O Chvlala, *Basic dynamics of graphite moderated LEU fueled MSRs*, University of Tennesse Knoxville, Knoxville, Tennessee, 2014.

36. World Nuclear News, "Canadian government invests in SMR technology", 16 October 2020

37. Australian Energy Market Operator, 2020, op. cit.

38. R A Rodríguez et al., "Transmission needs across a fully renewable European power system," *Renewable Energy*, 63, 2014, pp. 467-476.

39. NuScale Power, *Repurposing US Coal Power Plant Sites and Revitalizing Communities*, NuScale Power, Portland OR, 2020.

40. G Black and S Peterson, *Economic Impact Report: Construction and Operation of a Small Modular Reactor Electric Power Generation Facility at the Idaho National Laboratory Site, Butte County, Idaho*, Boise State University & University of Idaho, Idaho, USA, 2019.

41. B Mignacca and G Locatelli, "Economics and finance of Small Modular Reactors: A systematic review and research agenda," Renewable and Sustainable Energy Reviews, 118, 2020, pp.

42. WSP/Parsons Brinckerhoff, *Final Report: Quantitative Analysis and Initial Business Case – Establishing a nuclear power plant and systems in South Australia*, WSP/Parsons Brinckerhoff, Adelaide, SA, 2016.

43. X Chen et al., *Small Modular Nuclear Reactors: Parametric Modeling of Integrated Reactor Vessel Manufacturing Within A Factory Environment Volume 2, Detailed Analysis*, Argonne National Laboratory, Idaho Falls, Idaho, 2013.

44. National Nuclear Laboratory, *Small Modular Reactors Feasibility Study*, National Nuclear Laboratory, London, UK, 2014.

45. Australian Energy Market Operator, 2020, op. cit.

46. P Graham et al., *GenCost 2019-20*, CSIRO, Australia, 2020.

47. ibid.

48. Australian Energy Market Operator, 2020, op. cit.

49. M Harrison, *Valuing the Future: the social discount rate in cost-benefit analysis*, Productivity Commission of the Commonwealth of Australia, Canberra, ACT, 2010.

50. ibid.

51. ibid.

52. N Stern, *The Economics of Climate Change: The Stern Review, Cabinet Office – HM Treasury*, Cambridge University Press, UK, 2007.

53. W D Nordhaus, "A Review of the Stern Review on the Economics of Climate Change," *Journal of Economic Literature*, XLV, 2007, pp. 686-702.

54. United States Environmental Protection Agency, *Guidelines for Preparing Economic Analyses*, Environmental Protection Agency, Washington, D.C., 2000.

55. J Steinbach and D Staniaszek, *Discount rates in energy system analysis – Discussion Paper*, Building Performance Institute Europe, Brussels, Belgium, 2015.

56. D al-Qa'dah, *Updated Generation Planning for the Saudi Electricity Sector*, Electricity & Cogeneration Regulatory Authority (ECRA), Riyadh, Saudi Arabia, 2005.

57. Y Al-Saleh, P Upham, and K Malik, *Renewable Energy Scenarios for the Kingdom of Saudi Arabia*, Tyndall Centre for Climate Change Research, Manchester, United Kingdom, 2008.

58. OECD/IEA/NEA, *Projected Costs of Generating Electricity*, Organisation for Economic Co-operation and Development/International Energy Agency, Paris, France, 2015.

59. W Gerardi and P Galanis, *Emissions mitigation policies and security of electricity supply*, Jacobs Group (Australia) Pty Limited, Melbourne, VIC, 2017.

60. A Blakers, B Lu, and M Stocks, "100% renewable electricity in Australia," *Energy*, 133, 2017, pp. 471-482.

61. Lazard, *Lazard's Levelised Cost of Electricity Analysis – Version 12.0*, Lazard, 2018.

62. Graham et al., 2020, op. cit.

63. World Nuclear Association, *The Enduring Value of Nuclear Energy Assets*, World Nuclear Association, London, UK, 2020.

64. "The Economics of Nuclear Power", http://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx, World Nuclear Association, 2016.

65. Arup, *Cost Estimation and Liabilities in Decommissioning Offshore Wind Installations*, Energy and Industrial Strategy Department of Business, Edinburgh, UK, 2018.

66. W D Magwood, *Funding Mechanisms for Radioactive Waste Management*, OECD/NEA, Vienna, Austria, 2014.

67. United States Department of Energy, *Strategy for the Management and Disposal of Used Nuclear Fuel and High Level Radioactive Waste*, US Department of Energy, Washington, D.C., 2013.

68. Department of Energy and Climate Change, *Waste Transfer Pricing Methodology for the disposal of higher activity waste from new nuclear power stations,* DECC, London, UK, 2011.

69. Nuclear Energy Institute, *Nuclear By The Numbers*, Nuclear Energy Institute Inc., Washington, D.C., 2020.

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