Blueprint Institute

The lowest cost net-zero grid

A critical analysis of the potential role of nuclear energy in Australia

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About Blueprint Institute

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Attribution

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Executive summary

Australia faces a huge challenge in meeting its target of generating 83% of National Electricity Market (NEM) electricity from renewables by 2031. To be absolutely clear, that target is not the subject of this paper. Nuclear energy cannot possibly be part of the fuel mix that contributes toward that target.

Due to legislative and regulatory barriers associated with nuclear energy, combined with the need to gain broad social licence, even ardent proponents of nuclear concede that under the most ambitious timeframe it will be at least a decade, if not more, before any form of the technology is deployable in Australia.

Meanwhile, AEMO has repeatedly warned that electricity shortages and blackouts may arrive as soon as 2025 as coal plant closures accelerate and investment in new generation capacity lags. Therefore, independent of its cost, nuclear energy is not a technically realisable solution to the NEM's immediate crisis. In order to avoid calamitous blackouts, we have no choice—at least in the short-term—but to double down on renewables and conventional and proven firming technologies. This means a drastically accelerated deployment of batteries, solar, onshore wind, pumped hydro, and gas, along with a corresponding build out of transmission infrastructure.

Accordingly, this paper's assessment of the potential role of nuclear energy in Australia is **strictly limited to a decade or more from now**—specifically, from 2040 forward. As we will show, a holistic model that takes into account the total system cost (TSC) of a fully decarbonised NEM in 2050 reveals a strong argument that a small, but significant, level of nuclear energy has a critical role to play in order to achieve decarbonisation at the lowest possible cost.

Importantly, it must be stressed that this paper is focussed on modelling decarbonisation of the NEM in isolation from the broader economy. This is to say that the cheapest decarbonisation pathways of heavy industry, transport, and other non-grid entities are not modelled, nor are the ways in which the decarbonisation pathways of these entities may impact the cheapest decarbonisation pathway of the energy grid. Were a fully integrated, economy-wide decarbonisation cost model to be developed elsewhere (a monumental undertaking far beyond the capacity of the model used in this paper), it may show different results.

If there is a single point we would like readers and policymakers to take away from this paper, it is that inappropriate and misleading metrics are being used now to make critical decisions that will lock us into a suboptimal and more expensive decarbonisation pathway far into the future.

Instead of analysing the cost of each generation technology in isolation—like levelised cost of energy (LCOE) or overnight capital cost (OCC) does—it is critical we instead look at the total system cost (TSC) of the grid. That is the metric that ultimately matters because it determines what consumers will end up paying for, either indirectly through taxes and subsidies or directly through electricity bills.

It is precisely through this holistic TSC approach, that we have identified that nuclear power—specifically small modular reactors (SMRs)—unexpectedly could have a small, but vital role in minimising consumer costs in a heavily decarbonised NEM in 2050.

Specifically, our analysis shows that in 2050, a 90-99% decarbonised NEM without SMRs would result in an additional TSC of $4.5-5/MWh or approximately $1.3-1.4 billion per year. This cost would ultimately make its way to the consumer in one form or another and is likely to increase over time.

Contrary to orthodox thinking within the climate advocacy movement (of which Blueprint is certainly a member), our analysis demonstrates that one of either nuclear or carbon capture storage (CCS) is likely needed to achieve deep decarbonisation levels of greater than 90% in the NEM in 2050. Indeed, without the use of nuclear or CCS technology, attaining NEM decarbonisation levels of greater than 98% in 2050 would result in an extreme increase in TSC to the consumer of $70.8/MWh or $20.2 billion per year.

These results should ***not*** be misinterpreted as a recommendation to immediately halt our current construction of renewable generation in lieu of erecting nuclear reactors left, right, and centre. Far from it. SMR technology is not yet mature, so in order to keep costs at a minimum, we should be looking at importing what is known as next-of-a-kind reactors—the type of SMR reactors that have established a strong track record in other countries, have come down the cost curve, and have had their kinks sorted out—not a speculative first-of-a-kind reactor.

The critical point this paper and its data will show is that both 'sides' of the nuclear debate in Australian politics are wrong. The left is blinded by its ideological opposition to nuclear power to the point that it has been unable to have a rational debate about its potential merits decades from now. Similarly, the right desperately wants to use the imagined prospect of an immediate and sensational breakthrough in nuclear power to halt the ongoing build out of renewables that is expensive, but ultimately necessary. Nuclear power is not a miraculous solution to our energy needs, but neither is it a technology we can afford to dismiss out of hand.

Considering the potential necessity of nuclear power in the upcoming decades, along with the requirement for widespread social licence to repeal the legislated ban, and the long lead times for technology of this nature, the government must begin a rational conversation—free of ideological bias—with the Australian public now.

This paper initiates this desperately needed conversation. Accordingly, we have prepared a set of six recommendations for the government to begin implementing immediately to ensure the stage is appropriately set for the gradual introduction of nuclear power in Australia beginning in 2040 and beyond.

Summary of recommendations

1. Lift the ban on nuclear energy generation in Australia.
2. Commit further to building capacity of renewables in recognition of the fact that in the lowest cost decarbonised grid they still have the largest role to play.
3. Design education campaigns around safety and the potential role of nuclear in decarbonising the grid in order to obtain broad social license.
4. Initiate community engagement programs to acquire social license for potential SMR sites and transmission infrastructure regions.
5. Develop an appropriate plan for long term radioactive waste disposal in Australia.
6. Adopt the IAEA's Milestone Approach and commence the necessary feasibility studies to determine optimal locations for SMR construction and associated costs.

Summary of findings

1. Achieving a net-zero grid at the lowest cost to consumers demands technology agnosticism from decision makers. The more technologies are limited (including nuclear), the more expensive the total system cost.
2. With all technologies available, the lowest total system cost grid in 2050 still requires a large growth in renewables to 120-145GW—supplemented by 20GW of storage.
3. In order to attain deep decarbonisation levels of greater than 85% in the NEM in 2050, nuclear energy—in the form of SMRs—is required to minimise costs. Specifically, a 90-99% decarbonised NEM lacking SMRs—but including every other available generation technology—would result in an additional TSC of $4.5-5/MWh or approximately $1.3-1.4 billion per year in today's dollars.
4. Without the use of SMR nuclear or CCS technology, attaining NEM decarbonisation levels of greater than 98% in 2050 would require more than 300GW of renewables and almost 50GW of storage capacity. This exponential growth of the grid is entirely unfeasible and results in an extreme increase in TSC to the consumer of $20.2 billion *per year*.

How have we determined whether the NEM will require nuclear energy in the coming decades?

Blueprint Institute has collaborated with Professor Geoff Bongers and Andy Boston to model the TSC of decarbonising the NEM in order to ascertain which mix of technologies produces a net-zero grid at lowest cost to the consumer. This model is an iterated version of Professor Bongers and Mr Boston's peer reviewed electricity system model called Modelling Energy and Grid Services (MEGS). Blueprint's iterated version includes the 2022 GenCost capex data as inputs.

As described by Professor Bongers and Mr Boston, "the fundamental objective of MEGS is to model both thermal generation based electricity systems and fully decarbonised electricity systems of the future, which are likely to be made up of a wide range of generation and storage technologies. The MEGS model outputs are designed to be those most useful to system planners and public policy decision makers in order to assist them in identifying technology portfolios that will lead to reduced emissions, whilst maintaining the essential system security, all, ***at minimum cost to the consumer.***"

MEGS has been validated against actual historical generation data on a state-by-state basis for each of the five states in the NEM. This validation exercise was conducted against both overall annual generation for each state, and at a more granular hour-by-hour level for a standard 'complex weather week.' MEGS was able to replicate annual generation and hour-by-hour data, including fuel mix, interconnector, and storage usage, with a good level of accuracy for all five states.[1] This reinforces confidence in MEGS's outputs with respect to future NEM decarbonisation scenarios.

MEGS differs from many other models in that it eschews commonly used metrics—like LCOE and OCC—that analyse the cost of a given generation technology in isolation, rather than as a constituent part of a grid whose needs are growing ever more complex.

For example, LCOE and OCC do not factor in grid services like inertia, reserve, and frequency response that have traditionally been provided for free by coal-fired power plants that are now shutting down. Nor do they consider the integration costs of new transmission infrastructure to connect variable renewables to the grid, or the diminishing returns associated with adding more variable renewables to a specific location or grid already saturated with them.

As the small number of coal-fired generators that currently provide the bulk of the NEM's capacity retire and are replaced with a large and diverse portfolio of intermittent renewable generation assets, relying on these aforementioned narrow metrics can lead to extremely misleading conclusions. A policymaker concerned with minimising the total cost of a decarbonised NEM requires a more comprehensive metric that takes into account the costs associated with integrating all generation technologies, including intermittent renewables, in order to get an accurate understanding of the costs and tradeoffs.

Accordingly, MEGS assesses TSC because that does factor in diminishing returns to conventional renewables, the ever-increasing cost of transmission infrastructure, and the varied grid services provided by different generation technologies. Unlike LCOE and OCC, which are primarily used by investors to optimise their return on capital, TSC is most concerned with and most closely reflects the final price paid by consumers for electricity.

[1] Please see Decarbonised Electricity for more detailed information on MEGS, including a comprehensive presentation of the validation results on pg. 22-24

Why renewables and storage alone will not be able to achieve 100% decarbonisation at a reasonable cost, if at all.

The necessity of keeping the lights on in a complex energy grid like the NEM as it simultaneously undergoes a rapid transition to intermittent renewables fast presents ideological zealots on both sides of the nuclear debate with insurmountable factual hurdles.

The pro-nuclear camp has no convincing answer on how to justify the astronomical cost of a large build out of nuclear power—be it of the traditional or small modular reactor variety—compared to mature and cheap renewable competitors like solar PV and onshore wind.

Meanwhile, the anti-nuclear camp has yet to grapple with the fact that intermittent renewables combined with storage solutions like pumped hydro and batteries cannot, by itself, sustain a secure and reliable decarbonised NEM.

We base this latter conclusion on a study by Boston et al., 2022, which centres on a theorised simplified version of the NEM. This simplified version is renewable dominant. It consists of just legacy hydropower, along with an overbuild of intermittent renewable generation capacity such that 120% of yearly demand could be met from an equal contribution of solar and onshore wind power.

The security and reliability of this system was tested against 15 years of historical weather data from 2005 to 2020. Simulations were conducted using that weather data to determine the amount of electricity generated by variable renewables on an hourly basis.

This generated electricity was first allocated to meet demand, following which, presuming a surplus relative to demand and sufficient storage capacity, the electricity was stored with an assumed efficiency of 80% using pumped hydro. In the case where storage facilities were already full, excess renewable generation was curtailed.

Simulation results show that excess renewable generation is routinely curtailed for much of the year, particularly during the average summer day, when both solar PV and wind output is high. This also implies that modelled storage capacity—about four days of average NEM-wide demand, or 3.3TWh—is surplus to requirements and not being used for most of the year. For further context, 3.3TWh is roughly equivalent to the output of nine Snowy 2.0s, which is under construction and now forecast to cost around $10 billion. Furthermore, it is not certain that sufficient sites exist in Australia to build this level of pumped hydro storage, but Boston et al. nevertheless included it in order to build a scenario that was as favourable to renewables as possible.

It is the winter months that are the problem. Even in the best case scenario of a fully interconnected NEM with no transmission constraints, the simulation saw blackouts in six of the 15 years modelled, all during the winter months of June, July, and August.

The worst year in terms of electricity shortfall occurred in 2010 during which a series of meteorological events known as *dunkelflaute* or 'dark doldrums' occurred. These are recurring, but unpredictable stretches of time when wind and solar power output is severely depressed, often in conjunction, because of low wind speeds and low solar irradiance.

In 2010, problems began in mid-May as low wind output drew on storage. Wind lulls continued intermittently until storage was completely drawn down by early June. Continued low renewable output combined with exhausted storage caused blackouts for *most of June and July*. It was only in August that the series of *dunkelflaute* ended, and storage levels began to recover, and not until mid-September that storage levels again reached full capacity.

It should be noted that while 2010 happened to be the worst of the 15 years, 15 years is not a particularly large sample size, particularly in the midst of a changing climate that is becoming more variable. The study also included as a baseline a very large assumption tilted in the NEM's favour—namely, a fully interconnected NEM with no transmission constraints. Should states fail to coordinate to build this pricey infrastructure and go their own way, so to speak, additional costly storage will be needed to ensure each of their needs are met independently.

The results highlight the near impossibility of the dual goals of relying solely on variable renewable generation and avoiding extended blackouts. Even if it is technically possible, there is certainly no way to do so inexpensively. This study already generously included a 20% overbuild of renewable generation relative to demand, and four days worth of storage that was only ever drawn on for about four months per year.

Results of MEGS model

The original MEGS model used CSIRO's GenCost 2019 figures as baseline inputs to model the TSCs for a wide range of decarbonisation scenarios for the NEM at a single point in time—2050.

Since, in the interim, GenCost 2022 has been released, Blueprint Institute has collaborated with Professor Bongers and Mr Boston to update the MEGS model to incorporate the updated capex costs. Capex values were calculated according to the mean values from 2030-2050 in CSIRO's central "Global net-zero post 2050" scenario, except for nuclear SMR, which was averaged across 2040-2050 as we assumed next-of-a-kind SMRs would not be commercially available at a reasonable cost in Australia until 2040 at earliest.

As with any complex model of this nature, MEGS contains several key assumptions regarding the status of the NEM in 2050. These include an assumption that Snowy 2.0 is complete and operational. MEGS also models the effects of interconnector upgrades and ultimately determines that an optimised NEM in 2050 would include the four additional interconnectors listed below.

- An additional interconnector linking Queensland and New South Wales with 1GW of capacity each way
- An additional interconnector linking New South Wales and Victoria with 1GW of capacity each way
- An additional interconnector linking Victoria and South Australia with 500MW of capacity each way
- A new interconnector linking South Australia and New South Wales with 500MW of capacity each way

Technology restrictions	No restrictions		Ban on nuclear generation		Ban on carbon capture and storage		Ban on both carbon capture and storage and nuclear generation	
Percent of NEM decarbonisation achieved in 2050	90%	99%	90%	99%	90%	99%	90%	98.5%
TSC ($/MWh)	101.1	122.3	105.7	127.3	101.1	132.1	106.8	191.7
TSC ($billion/year)	28.8	34.8	30.1	36.2	28.8	37.6	30.4	54.6
TSC increase ($/MWh)			4.5	5.0	0.0	9.8	5.7	70.8
TSC increase ($billion/year)			1.3	1.4	0.0	2.8	1.6	20.2
Capacity (GW)								
Nuclear	9.5	4.5	0.0	0.0	9.5	27.3	0.0	0.0
CCS	0.0	5.0	0.8	9.9	0.0.	0.0	0.0	0.0
Renewables	120.5	144.9	178.6	120.7	120.5	41.9	166.0	324.2
Unabated fossil fuels	35.4	35.5	44.3	34.7	35.4	20.1	44.6	40.5
Storage	20.1	20.5	35.6	22.3	20.1	14.0	21.8	46.2
Total	**185.6**	**210.3**	**259.3**	**187.6**	**185.6**	**103.2**	**232.4**	**410.9**
Generation (TWh)								
Nuclear	68.4	31.4	0.0	0.0	68.4	213.4	0.0	0.0
CCS	0.0	23.2	4.1	54.9	0.0.	0.0	0.0	0.0
Renewables	193.0	219.6	268.4	211.6	193.0	66.9	256.6	292.7
Unabated fossil fuels	30.1	17.8	22.1	25.0	30.1	5.7	35.1	4.9
Storage	-5.4	-5.7	-8.5	-5.7	-5.4	-1.5	-5.8	-11.2
Total	**286.0**	**286.3**	**286.0**	**285.9**	**286.0**	**284.5**	**285.9**	**286.5**

Table 1 Summary of MEGS output for NEM in 2050 using GenCost 2022 capex data

Source CSIRO, Blueprint Institute analysis, Professor Geoff Bongers, Mr Andy Boston.

After applying the new GenCost inputs, in the base case without any technological restrictions, as decarbonisation levels increase from 90-99%, we expect to see large increases in renewable capacity to approximately 120–145GW respectively, paired with around 20GW of storage capacity. This confirms our initial hypothesis that, in the short-term, an accelerated buildout of renewable capacity is a necessity.

Each of the points in **Figure 1** is a result of a stochastic process that represents a viable—that is to say, secure and reliable—NEM fuel-mix portfolio in 2050 at a particular decarbonisation level and TSC[2]. The MEGS model consists of over 3000 of these solutions. The blue line at the bottom represents the optimal TSC frontier as it traces through the lowest TSC points at each level of NEM decarbonisation. The red line, by contrast, traces through the lowest TSC points without SMRs in the fuel-mix. Both lines have an upward slope, indicating that TSC increases as decarbonisation increases.

MEGS estimates the cost of an SMR ban begins to show its effects if one were to attempt to reach levels of decarbonisation substantially greater than 85%. The exclusion of SMRs reaches its peak cost at levels of decarbonisation between 90-99%. At those intervals, as represented by the gap in **Figure 1** between the optimal TSC curve in blue and the no-SMR restricted curve in red, an additional TSC of $4.5-5/MWh or approximately $1.4 billion per year would ultimately make its way to the consumer.

It may seem odd at first glance that, in all scenarios, even in cases of deep decarbonisation, MEGS universally retains a significant level of fossil fuel capacity. This is due to the need for dispatchable peaking capacity to ensure grid security given the predominance of intermittent renewables.

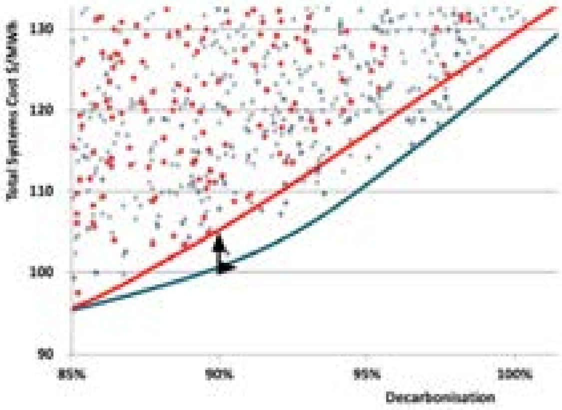


Figure 1 Impact of ban on SMR nuclear technology on TSC

Source Blueprint Institute analysis, Professor Geoff Bongers, Mr Andy Boston.

This fossil fuel capacity also appears in AEMO's latest ISP—although at a lower capacity—where they state that 10GW of gas-fired generation for peak loads and firming will be a "critical need… through the ISP time horizon to 2050."[3]

This point only reinforces the need for SMR technology in order to reach deep decarbonisation levels of 99% economically. A ban on nuclear technology is antithetical to this goal, and prompts greater reliance on continuing to operate unabated thermal coal or gas-fired generators in conjunction with the only negative emissions technology available in GenCost—bioenergy with carbon capture and storage (BECCS). As seen in **Figure 2**, this could potentially be a very expensive proposition, since the averaged capital cost of BECCS has almost tripled since 2019.

We also note that *any restrictions* on available technologies inevitably raises TSC. This is particularly relevant with respect to carbon capture and storage (CCS). To say that the green movement in Australia is currently virulent in its opposition to CCS would be an understatement.

[2] Please see pg.13-17 of Decarbonised Electricity for more detailed information on MEGS, including its solution procedure and constraints to ensure grid services are satisfied for all five states in the NEM.

[3] The fundamental difference between MEGS and AEMO's ISP model (both TSC models) is that MEGS concludes that we need much more firming capacity in 2050 in order to have a secure and reliable NEM that can stand up to 'dark doldrum' weather events, meet peak demand with sufficient reserve capacity, and maintain adequate access to ancillary grid services.

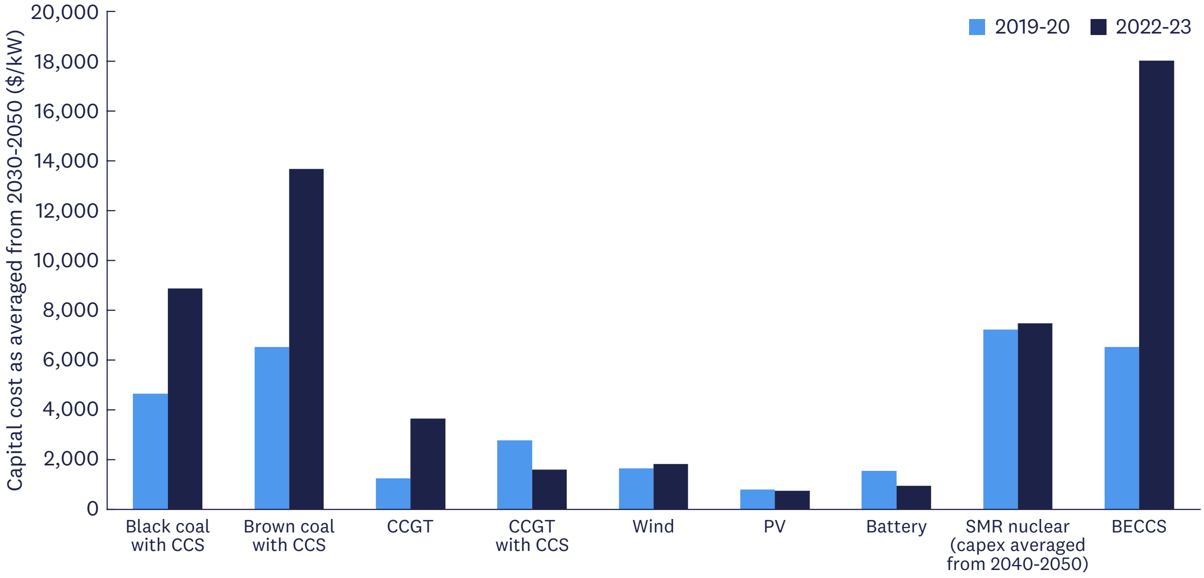


Figure 2 GenCost mean 2030-2050 capital costs, for years 2019-20 and 2022-23

Source CSIRO

The use of nuclear technology can vastly reduce the need for CCS in deep decarbonisation scenarios, but it cannot eliminate it completely. As seen in the 'no nuclear' scenario, the model estimates at 99% decarbonisation, the NEM would require 10GW of CCS capacity that generates 55TWh of electricity. Allowing the use of nuclear power significantly reduces the figures to 5GW and 23.2TWh, respectively.

The nightmare scenario, however, is if we cannot overcome our ideological intransigence with respect to technologies that have traditionally raised the green movement's ire. That is represented by the 'no CCS and no nuclear' scenario. In that scenario, even at just 98.5% decarbonisation, the cost is astronomical—an additional TSC of $20.2 billion per year. Furthermore, ensuring the security and reliability of that grid will require over 300GW of renewable capacity and nearly 50GW of storage. That is nearly three times as much renewable capacity and more than double the storage capacity relative to the optimal TSC pathway. It is simply not a technically or politically feasible scenario.

Blueprint initially began this project with the hypothesis that nuclear power was too expensive, too slow, and too late. But, given data that contradicts our hypothesis, we must change our conclusions. There is a strong case that nuclear power has a small but important role to play in a deeply decarbonised NEM in 2050, and an even stronger case that ideologically based technological restrictions only serve as a costly barrier to our net-zero goals. We must accept this reality and begin preparing accordingly.

Caveats and limitations

A crucial limitation to this paper is its heavy reliance on the 2022 GenCost data set. We are well aware of the annual controversy surrounding the release of GenCost. Once again, this year, proponents of nuclear power, across the media, government, and academia, have attacked CSIRO's modelling of nuclear power as biased and too expensive, and cast doubt on its consistent prediction that intermittent renewables are the cheapest form of electricity available.

There are seeds of truth embedded in this stream of criticism, even though much of it appears politically motivated. For example, GenCost 2022 assumes an operational lifespan of just 30 years for an SMR. This is surely too short. After all, SMRs are just scaled down versions of modern conventional nuclear reactors, which have operational lifespans of between 40–60 years, and many nuclear utilities claim that reactors can remain viable for up to 80 years. Extending the life of an SMR by a factor of two or three could potentially make it a larger player in an optimal TSC scenario.

CSIRO does not have an easy job in producing a GenCost report. Projecting the future cost of a wide range of generation technologies (particularly immature ones such as SMRs and CCS) is inherently speculative, especially when one is asked to produce a forecast nearly 30-years into the future.

In the absence of a more comprehensive, non-partisan, and reliable data set, however, we strongly believe that CSIRO's GenCost, despite its flaws, contains the most appropriate and defensible inputs for our model.

Rather than interpreting the results of MEGS as precise predictions, we would encourage readers to take away two strong signals that MEGS consistently communicates, despite relatively noisy variances in inputs from year to year.

1. We need a mix of all available low emissions technologies to reach deep decarbonisation at the lowest possible TSC.
2. Any constraints on ideologically controversial technologies like nuclear (SMRs), CCS, and BECCS are likely to have large and extremely costly effects in deep decarbonisation scenarios.

Explanation of discrepancies between MEGS and AEMO's *Step Change* scenario

MEGS fuel-mix portfolios for deep decarbonisation in the NEM in 2050 differ significantly from AEMO's *Step Change* scenario as described in the 2022 ISP. Regardless of technology restrictions, MEGS calls for much more dispatchable capacity than *Step Change*, and importantly, recommends that it is generated by thermal plants rather than relying on battery and other storage solutions.

Specifically, in order to achieve 99% decarbonisation with no technological restrictions, MEGS maintains 35GW of fossil fuel capacity—a mix of open-cycle and closed-cycle gas turbines—augmented by 4.5GW of SMR nuclear and 5GW of capacity from CCS fossil fuel plants.

By comparison, *Step Change* has just 10GW of gas-fired capacity, and instead relies primarily on 31GW of dispatchable storage from decentralised sources like virtual power plants, and a further 16GW of dispatchable capacity from a mix of utility-scale batteries and pumped hydro.

The main reason for the discrepancy in model results is that MEGS concludes that we need much more firming capacity in 2050 in order to have a secure and reliable NEM that can stand up to 'dark doldrum' weather events, meet peak demand with sufficient reserve capacity, and maintain adequate access to ancillary grid services.

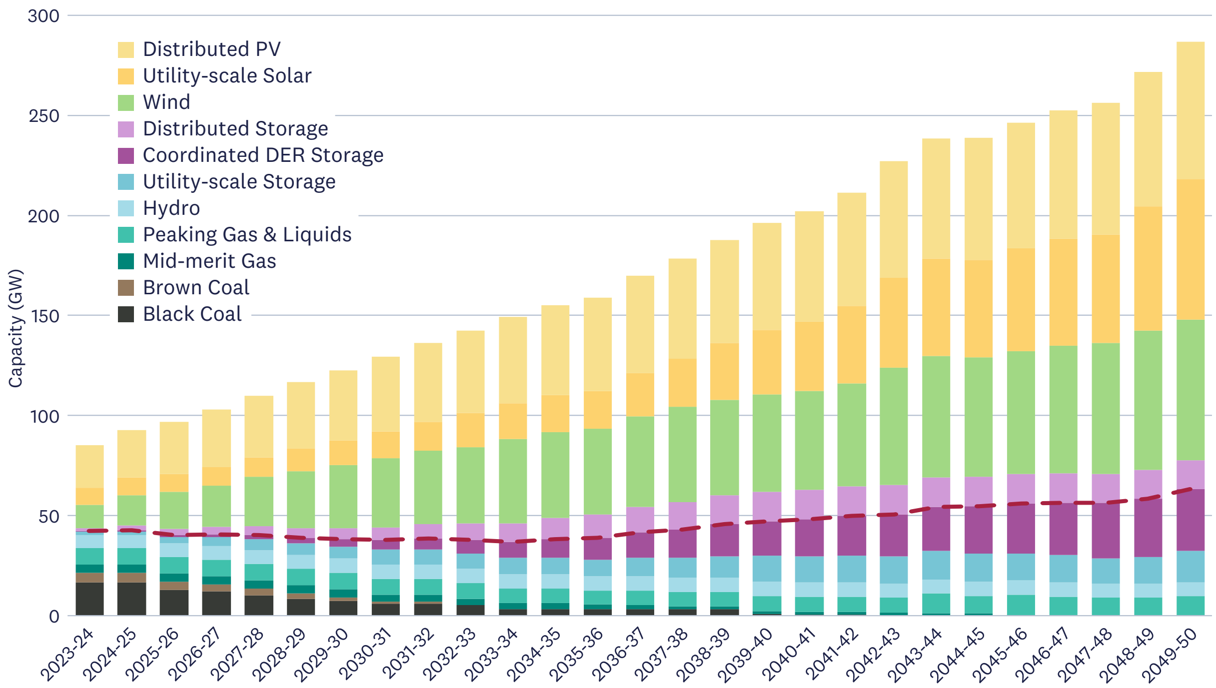


Figure 3 AEMO's *Step Change* scenario forecasts explosive growth in variable renewable capacity through 2050—dispatchable firming capacity, by contrast, experiences little growth.

Source AEMO

Step Change can certainly withstand short-term reductions in variable renewable energy generation. It is difficult, however, to envision such a portfolio holding up against a weather event similar to the *dunkelflaute* Australia experienced in the winter of 2010 when wind lulls lasted for weeks and storage was rapidly drained.

The fundamental problem is lieu of the firming capacity provided by thermal plants in MEGS—which can sustain grid reliability indefinitely, given sufficient capacity and fuel—*Step Change* substitutes 640GWh of utility-scale battery and distributed energy resources—a relative pittance in the context of the 2050 NEM which is currently projected to consume around 300TWh of electricity annually.

Simply put, the grid described in *Step Change* is not as robust to long-tail risks like extreme weather events and less reliable than the grid proposed by MEGS.

Conventional Nuclear Power: A Global Summary

Conventional nuclear power—as opposed to the new generation of SMR technology—represents a significant, yet declining share of global low carbon energy. Nuclear energy peaked in 1996 when it produced 17.5% of global commercial gross electricity.

A steady decline has followed. By 2021, conventional reactors generated just 9.8% of global commercial gross electricity—a historic 40-year low. That same year, wind and solar alone surpassed the contribution of nuclear energy, recording a record share of 10.2% of global electricity generation.

The past two decades have seen a pronounced slump in conventional reactor installations. The decline has been particularly evident in the West, and trends are expected to continue in the near term. A growing number of conventional nuclear reactors across the globe are facing decommission prior to the expiry of their operational licence. New builds are also rare and subject to cost blowouts and long delays. In fact, over the past 30 years, only five countries have begun construction on their first reactors.

As of mid 2022 there are 411 nuclear reactors globally, operating in 33 countries, reaching a total capacity of 369GW. The vast majority of nuclear energy generation is concentrated in a handful of countries, these being the US, China, France, Russia, and South Korea, which collectively generate over 70% of all nuclear electricity in the world (see **Figure 4**).

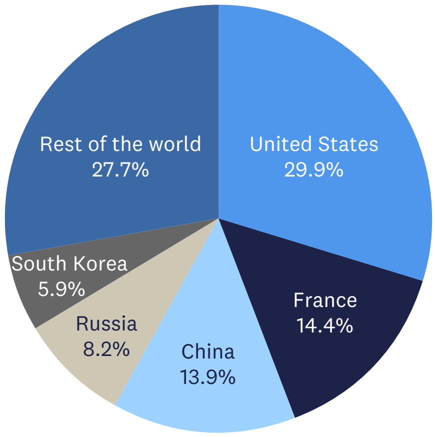


Figure 4 World nuclear electricity generation is mainly concentrated in five countries (2022)

Source US Energy Information Administration

How did we get here?

Nuclear energy first emerged from excitement over the civilian applications of a new military technology. It was this Cold War desire to maintain dominance in the atomic field that saw the rapid uptake in nuclear reactors, particularly within the US and Soviet Union.

The mid 1970s and 80s saw the greatest waves of nuclear reactor startups. The Chernobyl accident in 1986 put an end to this golden age of nuclear expansion. Heightened concerns surrounding the safety of nuclear power, combined with increased competition from other energy sources—including the declining price of natural gas—led to a number of nuclear plant closures in the early 1990s.

A further collapse of public confidence in the safety of nuclear power followed the 2011 Fukushima nuclear disaster. As illustrated in **Figure 5**, governments around the world responded by shutting down their reactors at an unprecedented pace. Japan suspended nearly all operating nuclear power plants. Soon after, in a surprise decision made by the conservative leaning government, Germany announced it would also phase out nuclear power. Belgium, Spain, Taiwan, and Switzerland also announced plans to phase out their nuclear programs in the wake of the disaster.

While Western countries have historically held a significant share of global nuclear capacity, their grip on market leadership has weakened as new builds have become increasingly rare and expensive. In sharp contrast, Russia and China have been actively pursuing the expansion and exportation of their nuclear programs.

China has become the outlier expander of its nuclear energy share, as it seeks to minimise its dependence on fossil fuels. As illustrated in **Figure 5**, during the past 20 years, China has been responsible for over half of the world's nuclear reactor startups. In addition, 40% of reactors currently under construction globally are in China. The average reactor in China is just nine years old, making it by far the youngest nuclear fleet in the world. China aims to double its share of nuclear electricity supply to almost 10% by 2035. Although according to recent projections, this target is unlikely to be met.

Russia has long viewed its nuclear program as a source of strategic influence and is the dominant supplier of nuclear technology to the international market. As of mid-2022, Russia has operational nuclear reactors in a total of 11 countries. "A further 17 are currently under construction, including four each in China and India, and three in Turkey."

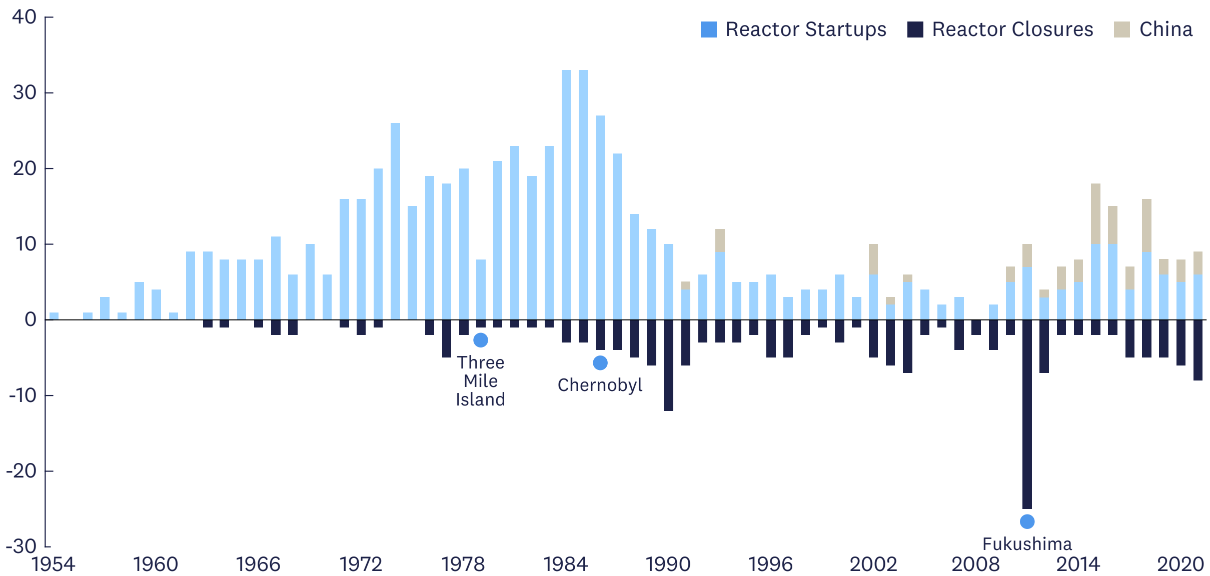


Figure 5 Global nuclear reactor start-ups and closures, highlighting a dramatic spike in closures following Fukushima (1954–2020)

Source World Nuclear Industry Status Report

Of course, Russia and China are able to expedite the process with the backing of the state. The highly centralised nature of their political systems means that even extremely complex and expensive infrastructure projects—like nuclear reactors—need only gain approval from a small cadre of powerful state officials. Furthermore, since the nuclear industry enjoys state-approval, it is largely insulated from public scrutiny and does not have to contend with widespread public opposition. It should thus come as no surprise that the average construction time for a nuclear reactor in China is six years, compared to 10 in the West.

Proponents of conventional nuclear energy will often point to examples of successful and relatively timely deployment within authoritarian countries as evidence of its commercial viability, but this is misleading. A more worthy exercise would be to evaluate the experiences of countries with a political and economic system comparable to our own.

The early adopters of nuclear energy are now confronted with the challenges of maintaining an ageing nuclear fleet. In the US, the world's leading nuclear power producer—the mean age of reactors is now over 40 years. Several reactors have closed prior to their license expiration due to increasing competition from much cheaper energy sources.

In 2022, nuclear's share of commercial electricity generation in the US slumped to a 26-year low of 18.2%. Today, there is only one conventional reactor under construction in the US.

Similar trends are evident across the West. Last year, France shut down nearly half of its reactors after evidence of cracks and corrosion were found. The prolonged shutdowns resulted in severe energy shortages in the middle of winter, and the French Government resorted to importing electricity from Germany.

The false dichotomy of renewables vs nuclear

The prevailing political debate in Australia often revolves around a binary choice between investment in renewables or nuclear power generation. However, this is in contrast to the experience of other nations—where renewables and nuclear are seen as complementary components of a diversified energy mix.

Globally, renewables continue to be prioritised as the most expedient and fiscally sound means to achieve decarbonisation. This is underpinned by policy packages such as the Inflation Reduction Act in the US, India's emission reduction targets, and the newly released REPowerEU plan.

Renewables are outcompeting nuclear in both levels of total investment and subsequent electricity production. In 2021, total global investment in non-hydro renewable electricity capacity reached a record of US$366 billion in 2021 compared to just US$24 billion for nuclear. Wind and solar are now largely considered the cheapest form of electricity in the world.

Furthermore, whilst nuclear's share of gross global electricity generation has been on the decline, non-hydro renewables added 2,749TWh of power globally from 2011 to 2021. This is more than eighteen times the net increase of nuclear power, which grew by only 148TWh over the same period. In 2021 the combined output of solar and wind alone surpassed that of nuclear. It is clear that in most cases, concentrated investment in the rapid deployment of renewables remains the immediate focus in the quest for a decarbonised electricity sector.

Whilst renewables are significantly easier, faster, and cheaper to build than nuclear—their intermittent nature and the difficulties associated with integrating them into a secure and reliable grid currently prompts reliance on fossil fuels for firming. The war in Ukraine has predictably compromised supply chains and sent many EU states which depend on Russian gas exports into turmoil. As a result, several countries, including Germany, have been forced to turn to coal as a temporary measure to keep the lights on. This has reinforced a collective sense of urgency amongst developed states to wean themselves of fossil fuels. In the wake of the invasion, Belgium announced it would be delaying its planned phase out of its nuclear fleet by 10 years. Even the Finnish Green Party, long a hot-bed for anti-nuclear sentiment, now supports nuclear power as they recognise the need for it as a small but significant part of their energy system to act as firming capacity makeup.

The Biden administration has concluded that taking advantage of its existing nuclear fleet offers the greatest chance of meeting its carbon reduction targets. A US$6 billion grant program under the Infrastructure Investment and Jobs Act will be made available to existing nuclear power plants which are facing closure due to economic reasons. The move is designed to keep the electricity supply secure as the penetration of intermittent renewables is ramped up.

South Korea also reversed their nuclear phase out policy upon the election of Yoon Suk-yeol in March 2022. The Yoon administration has announced ambitious plans to turn South Korea into a "nuclear reactor superpower" with a goal to increase the share of nuclear power in the future electricity mix, to 33% by 2030 up from 27% in 2020.

Small modular reactors—the future of nuclear energy?

While conventional nuclear power plants face a myriad of obstacles in the 21st century energy ecosystem, attention has turned to new nuclear technology in SMRs. SMRs encapsulate the same science as traditional nuclear fission plants, but are much smaller in physical design and output capacity. The stated rationale for this reduction in size is a potential reduction in the large scale fixed costs and build times associated with conventional nuclear reactors. In theory, this makes SMRs more affordable, flexible, and easier to build.

SMRs are considered to be the next-generation of nuclear fission reactors. They are designed to produce up to 300MW of energy per module—which is around one-third of the power capacity of conventional reactors. SMR proponents maintain that using module factory fabrication can lower costs through standardised production processes and short construction times.

There are currently 71 SMR projects across the globe—with a definitive leading design yet to emerge. There are multiple design classes of SMRs—with the most popular being light water reactors, fast neutron reactors, and molten salt reactors. Across the world, governments and the private sector have invested in prototype projects, demonstrating the interest in the potential of SMRs. However, despite their promise, SMRs are not yet commercially available.

SMR advocates claim they will produce less waste than traditional fission plants. Most SMR designs will be fuelled by uranium, and they will use less fuel than conventional plants. Yet, one critical analysis suggests that SMRs will actually be more wasteful per unit of energy produced than their traditional counterparts—by factors of 2 to 30.

The modularity of SMRs means that reactors will be manufactured in portable segments. This leverages scalability for streamlined production. Their configurability improves the versatility of nuclear power to meet energy demand and increases the number of potential reactor construction sites across the world.

SMRs are likely to be suitable for brownfield sites, which may reduce search duration, and leverage existing transmission infrastructure, resulting in lower costs. Some SMR financing models have leveraged the modularity of the reactors during the construction phase—utilising the revenue generated by the initial module installations for cashflow support as subsequent modules are installed.

Expanding an electricity grid faces two key obstacles—a lack of transmission infrastructure, and the costs of grid connection. SMRs are designed to possess a distinct advantage over renewables due to their capability to run remotely off-grid, thereby enabling the production of clean energy in remote locations. This would allow for SMRs to be situated in regions with poor transmission infrastructure or capacity to plug into the grid. Microreactors, typically generating up to 10MW, would have a proportional advantage in these regions.

In an Australian context, this means that SMRs could be used in relatively remote locations with high energy needs that are currently met by fossil fuels. Specifically, a potential use case for SMRs outside the NEM is in the mining sector, which would benefit from a reliable, non-intermittent source of energy to electrify and decarbonise their operations.

The economic reality

For all their technological promise, SMRs are beset with many challenges to their commercial viability.

Indeed, definitively proclaiming SMRs as 'the future of energy' is misleading—the reality is that SMRs remain mostly unproven, and even proponents of their potential use (such as ourselves) concede it will be more than a decade, if not longer, until they can be deployed at any meaningful scale. The SMR hype is often driven by awe of the technology, at the expense of economic substance.

A common claim from advocates is that SMRs will be much less expensive to build than traditional nuclear power plants. Whilst technically true, the claim is misleading and often gets conflated with the claim that SMRs are inexpensive. While SMRs may be cheaper overall, they have higher unit economics than traditional reactors. The cost per megawatt of generation capacity is higher for SMRs, because the loss of revenue for generating a smaller quantity of energy is not parallel with a commensurate fall in construction cost.

As with all major infrastructure projects, without adequately coordinated private financing, SMRs will suffer from budget creep. In 2019, the Rolls-Royce SMR prototype was estimated to cost £1.5 billion—but this figure has blown out to £4.37 billion in 2022. The NuScale reactor has faced similar cost blowouts. It is therefore critical that regulatory environments are established that encourage private investment in SMR technology.

Technology readiness

Contrary to the claims of some overly enthusiastic members of parliament, SMRs have a technology-readiness problem. Most SMRs are currently in conceptual design phases. **Figure 6** demonstrates the current status of SMR projects globally. Of the 71 SMR projects across the globe that are recognised by the IEA, only three of them are in operation—and only a further three are under construction. This means that 92% of the SMR projects globally remain in various stages of design.

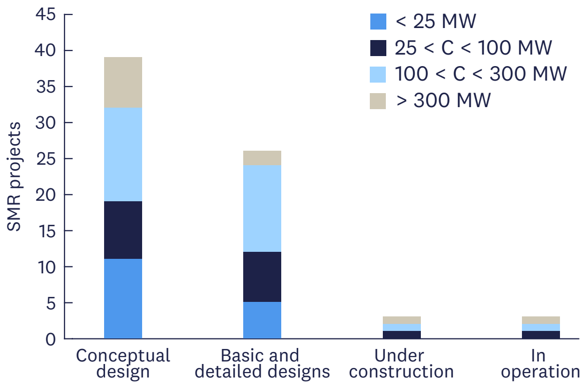


Figure 6 SMR technology remains immature (2022)

Source IEA

China and Russia are home to the only operational SMRs. The Russian modules were completed nine years later than originally scheduled, and their performance has been described as 'mediocre.' China connected the world's first SMR to the grid in 2021—five years behind schedule. The module was shut down after only a few days (the general lack of transparency surrounding the Chinese nuclear program means that the reasons for the shutdown are unknown).

For SMRs to scale up, a 'status quo' will need to be developed. The market will need to select a winner amongst the early prototypes, and regulation, safety constraints, siting, and licensing will need to converge to a standardised model. This will considerably add to an already lengthy time schedule.

Macro conditions and economies of scale

The current macroeconomic environment presents headwinds for all large, risky infrastructure projects, including SMRs. Projects of this kind are very sensitive to interest rates and inflation—and the SMR prototypes that do exist were born in favourable economic conditions. Should interest rates around the world remain elevated, there will be further incentive for investors to de-risk and move away from speculative infrastructure projects.

Some of the leading SMRs, including the NuScale model, are currently financed with an investment off-ramp structure, where funding is contingent on meeting strict economic goals—such as levelised cost of energy targets. These projects could lose significant blocks of funding if they experience blowouts due to inflated input costs and high interest rates. Ultimately, most SMR project estimates rest upon the assumptions that the project will be fully financed—which may depend on an insurmountable increase in derisking.

Those eager for SMRs due to their likelihood to achieve cost reductions via learning effects should be wary of historical precedent. Nuclear power has a poor track record of learning rates in manufacturing costs and deployment. Both France and the US have seen reactor construction costs increase over time.

Investment barriers and product-market fit

Despite their promise, SMRs have significant regulatory hurdles to overcome before being approved for market. Even if the illegality of nuclear power in Australia is overlooked, licensing for operation, safety approvals, and cost estimates all present barriers to entry.

Currently, some of the leading SMR projects require further derisking to accumulate the adequate capital levels required to finance projects in full. Due to such high capital costs, each SMR requires a tailored cap table of prospective stakeholders to appropriately delegate risk across investor classes.

Ad-hoc financing structures, idiosyncratic to each SMR project, may stifle the development of the SMR industry as a whole—pushing the timeline to establish the industrial requirements to manufacture, export, build, and operate efficiently.

Further, the industrial scaling of SMRs also rests on the implicit assumption of product-market fit already existing in energy markets. Whilst some countries have shown genuine fiscal interest in the development of SMRs, there has yet to be a country committed to scaling SMRs to a significant stake in their energy grid.

This presents a vicious cycle for SMRs—investors are too risk-averse to take on such a large project with uncertain market demand, which then means there is less demand to subscribe to a project that does not have the adequate investment secured. For SMRs to reach commercial viability, there has to be a unified approach between SMR developers (private companies), institutional investors, and prospective customers. These close relationships are a prerequisite to delivering a suitable product at an optimal cost for the consumer.

Legislative barriers

Recommendations 1 & 2:

- ***Lift the ban on nuclear energy generation in Australia.***
- ***Commit further to building capacity of renewables in recognition of the fact that in the lowest cost decarbonised grid they still have the largest role to play.***

In 1998, a ban was implemented in Australia explicitly prohibiting the construction of a nuclear power plant. The stated purpose of the ban was to safeguard both people and the environment against the potential hazards of nuclear radiation. Australia remains the sole G20 nation to have imposed a prohibition on nuclear energy.

The developments in nuclear technology since the ban's implementation have prompted several state and federal parliamentary inquiries to re-evaluate the merits of the ban—bearing mixed results. A 2019 inquiry by the Victorian Parliament concluded that, while reliable economic information is limited given the absence of nuclear energy in Australia, it is not a fiscally responsible energy source for the government to subsidise.

Other inquiries reached more optimistic conclusions. A federal inquiry recommended the adoption of a holistic approach to considering the possibility of nuclear energy in Australia. Similarly, the New South Wales Parliament's inquiry found 'no compelling justification' to exclude nuclear energy as a policy consideration for the state. A 2016 inquiry by the South Australian Parliament also recommended pursuing the removal of federal prohibitions on nuclear power.

In light of our findings in this paper, derived from our iterated MEGS TSC model, which clearly demonstrate that SMRs are a small, but important, part of the lowest cost net-zero grid in 2050, we believe there is no rational reason to maintain a legislative prohibition of nuclear energy. This is not to advocate for immediate public investment into developing onshore nuclear technology—but instead, to develop a level of regulatory agility in the event new nuclear technologies become commercially viable in future. Assuming steady advancements in SMR technology, lifting the ban would enable Australia to quickly take advantage of the benefits associated with next-of-a-kind reactors, should this new technology first be proven viable overseas.

The end goal for public policy decision makers should be the pursuit of the most cost-efficient pathway to a reliable, carbon-free energy grid—which we know will necessarily include a mix of intermittent renewables, and firming technologies (of which SMRs are but one). This is a positive-sum game where the premium is diversification.

In a legislative sense, the responsible path forward is thus to keep all options open and undertake the groundwork necessary for a potential rollout of SMRs by 2040 (which our modelling demonstrates is the earliest they are likely to be commercially viable in an Australian setting). This does not mean significant investment aimed toward construction in the immediate future, but instead, repealing the legislated ban, and conducting feasibility studies paired with programs aimed at gaining broad social license.

Practicalities

Social license

Recommendations 3 & 4:

- ***Engage with state and local governments to design education campaigns around safety and the potential role of nuclear in decarbonising the grid in order to obtain broad social license.***
- ***Initiate community engagement programs to acquire social license for potential SMR sites and transmission infrastructure regions.***

This report is primarily an economic analysis of SMR's commercial viability. However we cannot ignore the perceived safety risks surrounding nuclear technologies. We must recognise the enormity of the challenge for nuclear energy with regard to social license, and acknowledge the difficult task for the industry to change the paradigm that has kept nuclear power at bay in Australia.

Nuclear accidents and the safety paradigm

Research has shown that the disruptive effects of the Three Mile Island accident in 1979 is one of the primary reasons the US has experienced the most dramatic cost escalations in reactor construction and maintenance of any other nuclear power. After the meltdown, all nuclear reactors in the midst of construction faced formidable regulatory roadblocks and saw their costs escalate to nearly triple that of those completed prior to 1979. Between 1978 and 2013, the US did not initiate the construction of a single nuclear reactor.

No industry is immune from accidents—but the presence of irrational and misleading fearmongering surrounding nuclear energy is undeniable. As **Figure 7** demonstrates, fossil fuels were responsible for a far greater number of deaths than any other energy source in 2021—which is consistent with historical data. Environmental harm from oil spills have also resulted in death tolls that significantly outnumber deaths caused from nuclear accidents. Indeed, even hydropower and wind power have higher fatality rates than nuclear power.

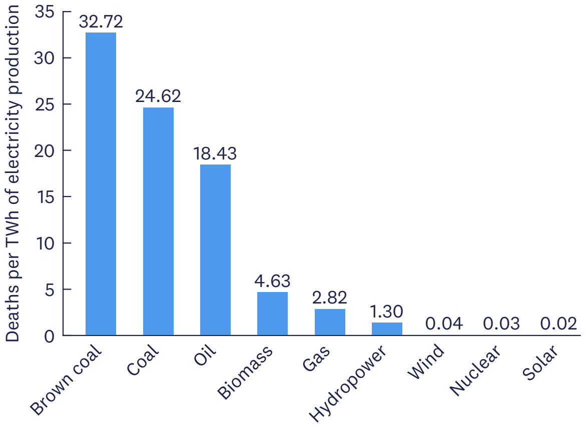


Figure 7 Nuclear is one of the safest forms of electricity production (2021)

Source Our World in Data

Since the world's first ever nuclear power station was connected to the grid in Obninsk in 1954, there have been only three noteworthy accidents involving the civilian application of nuclear power. Of these, only Chernobyl resulted in the direct death of members of the public.

Indeed, even in Chernobyl's aftermath, contrary to the unfounded (and in some cases intentionally falsified) claims of hundreds of thousands of deaths, of the 134 workers who were assigned to clean up duty and subsequently suffered from acute radiation syndrome, there were 28 fatalities. Of the remaining 106 workers, just four more had confirmed cases of cancer and two were subsequently diagnosed with leukaemia. Today, the residents around Chernobyl can move around freely without fear of radiation poisoning or other detrimental impacts on their health.

This previous paragraph's intention is not to make light of the Chernobyl disaster, nor the deaths associated with it. Rather, we seek to place the effects of the worst nuclear disaster in history in context. Again, as illustrated in **Figure 7**, we numb ourselves to a far greater number of deaths every year from fossil fuels, as it has become business as usual.

Contrary to the deeply unscientific narrative often pushed by the Green movement, by any empirical measure, SMRs are one of the safest power generation technologies available. Nuclear reactors designed in the West have always had fundamentally different and safer designs, meaning they cannot possibly ever have suffered from a Chernobyl style disaster. With respect to SMRs in particular, safety margins have only improved with time, with passive safety systems now fully incorporated. That is to say, SMRs are designed to self-limit their nuclear fission reactions and shut themselves down without human intervention needed in the event of a safety risk.

Despite ample empirical evidence demonstrating nuclear power's safety, lack of effective public communication has resulted in an information vacuum that has been filled by ideologues who deploy falsified data and misinformation to stoke fear.

The existing nuclear ban in Australia only lends unwarranted legitimacy to safety concerns that lack evidence. Removing the ban on nuclear energy should thus be accompanied by a public education campaign designed to assuage deeply ingrained perceptions of nuclear's dangers. It is difficult to conceive of an uptake in private investment into costly and experimental nuclear projects without this paradigm shift.

Recent polling states that 38% of Australians would like to see increased investment in nuclear technologies. Whilst significant, achieving the necessary level of public confidence is still a distant goal.

Being cautious not to invalidate the legitimate concerns of the public surrounding nuclear energy, an education campaign would be effective at stemming the flow of misinformation and building public confidence in nuclear as a safe, emissions-free technology.

' Not in my backyard '

Social license is not restricted to easing concerns in relation to nuclear accidents. Australia also faces the challenge of acquiring the social license to build infrastructure and transmission.

Community backlash is mounting for the prospect of installing transmission lines for renewable energy projects across Australia. Despite general enthusiasm for renewable energy, nimbyism continues to permeate around concerns associated with large infrastructure projects of any description. This will predictably be an even larger concern for nuclear energy, as this sentiment is amplified by the perceived safety risks.

Nimby attitudes are not necessarily anti-renewables or anti-progress, but are commonly idiosyncratic concerns about the project—often exacerbating planning duration and cost from site search. In some cases, community backlash has ceased projects altogether. Australia is no exception to these challenges—and we can expect this to be a significant challenge for Australia's nuclear prospects without adequate end-to-end community engagement.

Waste

Recommendation 5: *Develop an appropriate plan for long term radioactive waste disposal in Australia.*

Nuclear fuel can be used for three to five years. After this, it is still highly radioactive and needs to be appropriately stored and disposed of. Because nuclear waste can remain dangerously radioactive for thousands of years, any disposal plan must, with a high degree of certainty, be able to communicate the danger associated with the disposal site far into the future. A scientific discipline—called nuclear semiotics—has developed to deal with this problem. Its main aim is preventing human intrusion into radioactive sites that can potentially remain dangerous for generations.

According to the IAEA, nuclear waste must be managed in a manner that "protects human health and the environment…without imposing undue burdens on future generations". Due to complex regulatory environments, and stringent legislation and guidelines, disposal methods are limited. The only current widely accepted way of disposing of high-level nuclear waste in the long-term is in deep geological repositories—which, while safe, can be costly. Nonetheless, as seen across the spectrum of nuclear applications, technological advancement is at the forefront. Fourth generation fast neutron reactors are being developed that can burn the long-lived component of high-level nuclear waste, meaning it breaks down into harmless matter over centuries.

There is also potential for a closed fuel cycle where spent nuclear fuel, or nuclear waste, can be reprocessed and recycled. Reusable components that have yet to undergo fission, including uranium, plutonium, and minor actinides, make up over 96% of the waste. Around 17% of France's electricity comes from recycled nuclear fuel, making it a leading global player in nuclear fuel recycling. Notwithstanding the cost and Australia's ample uranium supply, if the government decides to pursue nuclear energy, we recommend it prioritises the development of a fuel recycling program. Such a program would not only reduce the amount of nuclear waste requiring storage, which comes with a high cost, but also serves as a fuel source for reactors—thereby extending the capacity of our uranium reserves, and allowing us to grow uranium exports.

Failure to adequately prepare for nuclear waste management could result in severe consequences, as seen in the US. The US does not currently reprocess fuel and has 80,000MT of spent fuel that sits in casks on-site. Due to the absence of a geologic repository in 1998, when the Department of Energy was designated to assume ownership of the fuel, utilities had no option but to retain it on their premises. Subsequently, utilities filed a lawsuit against the government because of this failure, leading to an ongoing annual expenditure of US$500 million to facilitate the utilities' self-storage of their nuclear waste. If Australia were to consider nuclear power for energy generation, an appropriate plan for long term radioactive waste disposal is imperative.

Uranium reserves

As **Figure 8** shows, Australia is home to the largest uranium reserves in the world. With around a third of the world's total uranium riches, Australia is positioned to become a uranium exporting superpower if SMRs indeed scale commercially

Whilst there are undoubtedly barriers to realising the economic potential in mining uranium (e.g. Russia's monopoly on industrial capacity to produce high-assay-low-enriched-uranium in commercial quantities needed for most SMRs designs), a proliferation of SMRs globally presents Australia with unprecedented economic opportunity to recoup at least part of the revenue base that will be lost from coal exports as the world transitions toward net-zero.

Uranium prices are forecast to lift from US$51 a pound in 2022 to US$60 a pound by 2024. Further, global uranium shortfalls have become a real prospect in the wake of years of low prices and underinvestment in transitioning energy grids away from thermal coal.

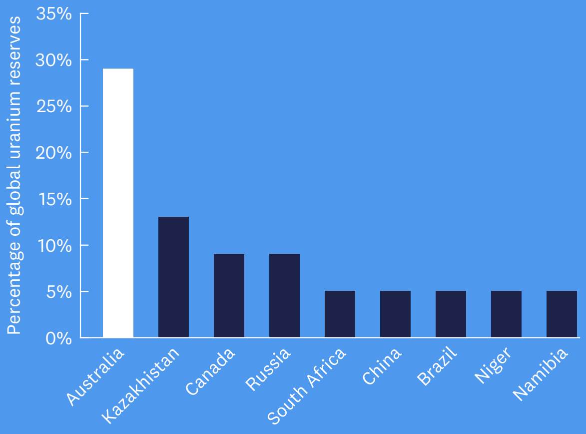
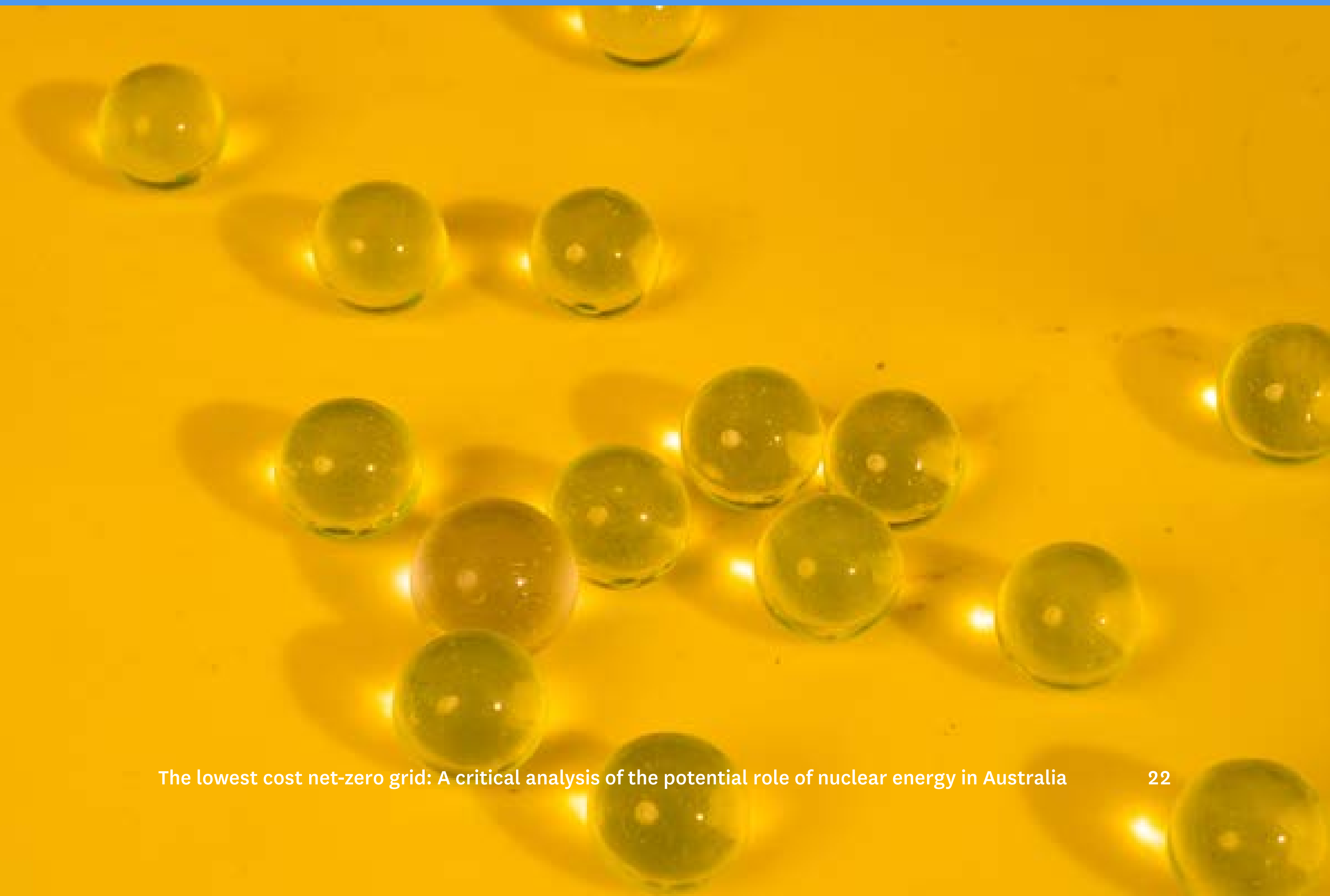


Figure 8 Australia possesses the world's largest share of global uranium reserves (2019).

Source Ağbulut et al. 2019

Australian exports are forecast to rise from 4,500 tonnes to around 5,500 tonnes by 2023–24 as the Honeymoon uranium mine reopens. Price and volume growth is expected to increase Australian uranium export values from $564 million in 2021–22 to around $880 million by 2023–24. As global demand increases, this has the potential to reach over $9.5 billion per year by 2040.



Nuclear Fusion—shooting for the stars

An emerging nuclear technology that has grabbed the attention of both international governments and private enterprise is fusion. Similarly to fission or conventional nuclear, fusion would be an abundant carbon free energy source. However, the marked advantage embodied by fusion power lies in its inherent safety—devoid of any long-term high-level nuclear waste—while capable of releasing four times more energy than fission does. Following disasters such as Chernobyl and Fukushima, the safety of fusion is not only practically significant but bodes well for commercial success given the importance of public perception.

The deuterium-tritium fusion reaction, as shown in **Figure 9**, has been the predominant focus for researchers looking at energy generation. This is because the reaction is deemed most practical—capable of producing a higher energy gain at lower temperatures compared to other elements.

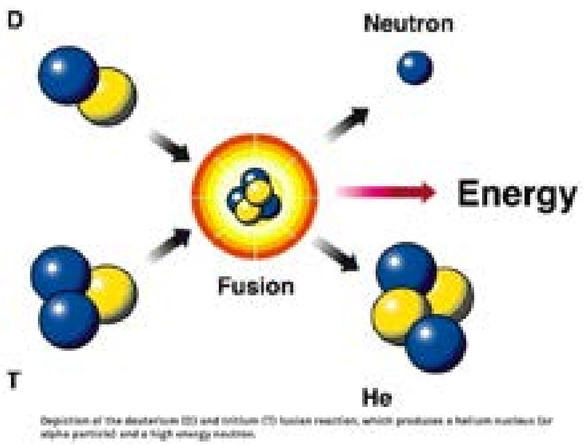


Figure 9 The deuterium and tritium reaction—the main reaction used in fusion energy generation

Source Office of Science

Nuclear fusion releases an enormous amount of energy—so much so that it is the same reaction that powers the sun. Specifically, the extreme temperature and the immense gravitational pressure provides the nuclei with enough energy and proximity to allow their mutual electric repulsion to be overridden by the attractive nuclear force.

Nuclear fusion for energy generation is still in the early R&D stage. The perennial obstacle scientists have to overcome is how to create a sustained fusion reaction that results in a net energy gain—in other words, the energy outputs exceed the energy inputs.

Despite the colossal technological breakthroughs that are needed, there have been promising developments. The Experimental Advanced Superconducting Tokamak, based in China, achieved world records for the longest sustained plasma temperature and in the US, scientists have, for the first time, been able to conduct a controlled fusion ignition that resulted in more energy than it took to create.

Unlike fossil fuel generation, or even traditional nuclear, fusion's fuel source—deuterium and tritium—are abundant and easily obtained. However, while igniting fuels like coal is straightforward, it is a much more complex task for hydrogen isotopes. The breakthrough ignition comes after decades of research. Evidently, the science and innovation needed to deliver such milestones are extraordinary. The laser used in the ignition exceeded the energy used in the entire US power grid, and the plasma reached temperatures ten times hotter than the centre of the sun.

However, there is still a long road ahead before we can safely rely on fusion for energy generation. The spark ignited energy manifested as energetic particles, necessitating further advancements to sustain the reaction and transform the energetic particles into electricity. Another significant challenge to master is how to get the plasma—the matter in which fusion reactions occur—to endure the extreme temperatures needed to replicate the conditions of the sun. The plasma needs to reach temperatures exceeding 150 million degrees Celsius—containing this plasma safely thus makes fusion an equally ambitious engineering challenge.

Furthermore, whilst the fusion ignition did result in more energy than the laser used, this does not include the 300 megajoules of energy needed to generate the two megajoule laser beam, demonstrating how inefficient the 'driver'—the external energy source to heat the fuel capsule—is. A commercial reactor would also require the structural integrity to withstand neutron bombardment.

Nonetheless, the enthusiasm for fusion is real—for proof, look no further than the growth of private sector investment. **Figure 10** shows that, over the past two decades, private investment in fusion energy has nearly tripled—with approximately 75% of all fusion investment occurring since 2021. Private funding for fusion has now reached a cumulative total of US$5.9 billion, with US$1.4 billion of funding secured in just the last year alone. It is difficult to imagine a commensurate acceleration in SMR investment should fusion be able to reach its projected US$40 trillion market valuation.

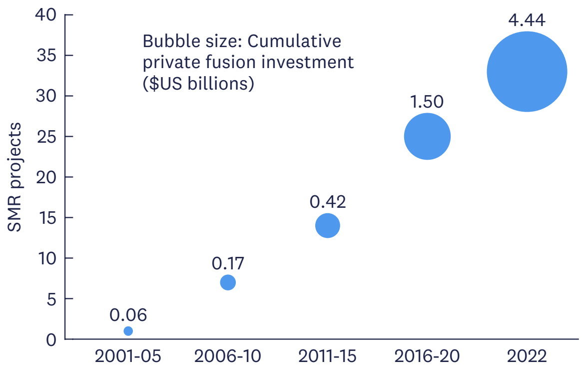


Figure 10 Private investment into fusion is growing at a rapid pace

Source McKinsey & Company

One of the most promising demonstrations of fusion being used as a viable carbon-free energy source will be the International Thermonuclear Experimental Reactor (ITER). ITER members—the US, China, the European Union (through Euratom), India, Japan, Korea, and Russia, comprising 35 nations—are collaborating to build ITER, at a cost of around US$65 billion. Although such a display of international collaboration points to the promise of ITER, it is still a long way from being operational and has been subject to safety concerns, delays, and cost increases. ITER was originally expected to be operational by 2035 however, due to technical and safety setbacks this timeframe is being revised.

The claims that fusion power could be ready as early as 2030 are misguided. While the recent breakthroughs and growing investment alludes to the potential of fusion power, we are still decades away from a functional fusion reactor prototype that could be commercially scalable, and we do not have decades to waste in meeting our net-zero targets.

With strong cost-competitiveness from renewables generation, it would require an extraordinary advancement in fusion to warrant divesting in renewables. That being said, Australia should adopt a philosophical position that is supportive of nuclear technology, but only consider it seriously if it becomes economically viable. We should closely watch the evolution of fusion and amend legislation to move toward a robust regulatory and financial framework to be able to capitalise on fusion energy. To safely produce even more energy than fission that results in no long-lived highly radioactive waste would be nothing short of a miracle.

Fusion vs SMR investment: A race between moonshots?

A key determinant of the viability of nuclear technologies will be the investment trends over the coming decade.

Whilst fusion remains at an even earlier stage of public R&D across the globe—and there are more private companies building SMRs—most SMR projects are at least partially or majority funded by government. This points towards a general level of infancy across the SMR space, and to suggest that there is a private SMR 'industry' is misleading.

A greater level of private financing will ultimately be integral if SMR projects are to come to fruition. But with the much greater potential upside of nuclear fusion in mind, it seems plausible that SMR investment may decline should progress in fusion technology accelerate.

Whilst SMRs are considerably further along the development curve than fusion, it is still decades away—and if there is a choice between two moonshots, then fusion offers much more upside potential than SMRs. There is already evidence of a growing investor appetite for nuclear fusion projects.

Microsoft has recently bet on fusion's viability, making the first power purchase agreement to buy fusion electricity from fusion startup Helion Energy by 2028. Helion will be subject to financial penalty should they fail to produce 50MW of fusion electricity after one year. This is without doubt an ambitious goal for Helion—but with many prominent investors backing fusion companies, it raises the question of whether SMRs might go to market as antiquated relics.

Recommendation 6: *The government should adopt the IAEA'S Milestone Approach and commence the necessary feasibility studies to determine optimal locations for SMR construction and associated costs.*

The International Atomic Energy Agency (IAEA) offer a comprehensive, phased program designed to assist countries determine whether nuclear energy is suitable to meet their energy needs and if so, provide guidance on how to implement a nuclear program. To enable an informed and constructive assessment of nuclear's potential, the government should adopt the IAEA Milestone Approach, the first step of which includes a pre feasibility study. Feasibility studies will allow the government to examine the availability of suitable sites, the infrastructure requirements, and the environmental impacts alongside the regulatory requirements for SMRs, such as licensing, safety, and security standards.

A white paper including; a detailed overview of the SMR technology, its advantages, including job creation, and energy security, and challenges including the proliferation of nuclear materials, the long-term storage of nuclear waste, and human capital needs will also be indispensable in preparing for the potential introduction of SMRs in 2040.

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