# Australia’s nuclear options

## CEDA policy perspective

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committee for economic development of australia

**About this publication**
Australia's Nuclear Options

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# foreword

**For over 50 years CEDA has played an important role in driving robust debate on important economic issues confronting Australia.**

Energy, driven by a global push to address climate change and anticipated growth in energy demand, is a priority issue for CEDA. Policy decisions made now regarding present and future energy demand and supply will impact on Australia's economic competitiveness for decades to come.

This paper, *Australia's Nuclear Options*, is the first policy perspective to be released as part of CEDA's *Australia's Energy Options* research series. The next 12 months will see events, policy perspectives and the publication of a major research report that will also explore renewables, energy efficiency and policy settings.

Australia is at a critical junction in its energy future. Previously, with abundant and cheap alternative sources of energy such as coal or gas, nuclear was not an option that needed to be considered. This has allowed its potential economic contribution to solving Australia's energy needs to be subservient to political cowardice, resulting in prolonged debates on uranium mining and its almost complete dismissal from the climate policy debate.

However, the need to address climate change has altered the ball game. An energy supply such as Australia's, dominated by fossil fuels, will not be viable in the longer term.

Despite public unease with nuclear, CEDA has chosen to examine this issue because current public policy debate on how to decarbonise our economy relies on significant technological and cost breakthroughs surrounding renewable energy technologies, with no back-up options.

Renewables are likely to be the end game, but if the technological breakthroughs do not come quickly enough, or they cannot become economically viable without government subsidies, then in coming decades Australians will be faced with sky-rocketing electricity prices or an energy supply shortfall. These would have serious ramifications for Australia's future economic prosperity, impacting on all Australians from individual households to big business.

Nuclear, a proven low-emission energy source, is the obvious back-up option that needs to be explored.

Understandably, events such as Fukushima earlier this year raise concerns. However, what needs to be remembered is that modern reactors in the same scenario would have automatically shut down. Nuclear technology coming on stream now has advanced significantly, with significantly reduced waste and vastly improved safety.

What we need now is political leadership from all sides to allow a rational debate, not one based on vested interests, ideological views or outdated information and technology, but on current and projected technological and economic options available.

The reality is that even if we start considering nuclear as an option today, the time lag to allow for key steps including public consultation, regulatory changes, through to commissioning and construction, means that it is unlikely we could have an operational plant in the next decade.

This means that if the initial steps to review nuclear and explore if it is a viable option for Australia do not take place in the next few years, it won't be able to come on stream quickly enough to provide the back-up low-cost base-load energy we may well need as we transition from traditional energy sources.

Never in Australia's history has it been as vital as it is today to review nuclear as an option.  Australia no longer has the luxury of ignoring major commercially available low emission energy sources.

With many Australian families and businesses concerned about the impact of pricing carbon emissions and rising electricity costs, new technological advances in nuclear may offer options that will allow us to reduce our environmental footprint while also minimising energy price increases.

However, unless leadership is shown now on this issue, we will never know. CEDA hopes this policy perspective will be a valuable contribution to this debate.

Professor the Hon. Stephen Martin
Chief Executive
CEDA

# introduction

In the following policy perspective CEDA examines the environmental and economic issues associated with nuclear power and sets out a real options approach to enabling its future development.

## Australia's Energy Options

Australia is at a critical moment in determining its energy future. Energy demand is forecast to rise substantially with continued economic and population growth while policy makers grapple with how to decarbonise the economy. Meanwhile, global growth in energy demand is causing ongoing price rises in commodities. Given the long lifecycle of energy investments, policy decisions made to address these challenges will determine Australia's economic competitiveness for decades to come.

## The nuclear debate

Nuclear power is widely used throughout the world and represents one of the most reliable means of replacing fossil fuels. Only hydropower displaces more carbon emissions than nuclear energy, and Australia is already utilising all its reasonable hydropower resources. To not consider the nuclear option when trying to decarbonise the economy is tantamount to committing economic and environmental vandalism.

Detractors of nuclear power may consider the disaster at the Fukushima Daiichi nuclear reactor as sufficient cause to ignore it. However, the Fukushima Daiichi reactor was of 1960s vintage and modern reactor designs have passive safety features that preclude such a scenario occurring. Australia cannot afford to make policy decisions based on technology more than 40 years old. It would be equivalent to critiquing the rollout of the national broadband network based on assessments of the telegraph system.

Concerns that exporting greater amounts of uranium will contribute to nuclear weapons proliferation are also groundless. Nuclear power has already achieved widespread deployment and the nuclear genie is well and truly out of the bottle.[1]

There is a substantial opportunity for Australia to play a more fundamental role in the global nuclear fuel cycle. Australia's twin stabilities of political and geographic systems make it uniquely placed to hold nuclear waste material.[2] This would not be a global dumping ground but a sophisticated storage facility of relatively little material. Furthermore, technological developments in nuclear reactors may result in future generators using the waste products of current reactors as fuel.

So the economic opportunity for Australia is to sell uranium, then be paid for its storage and, eventually, be able to sell today's waste product as a fuel source for the next generation of reactors. This could be a lucrative industry built on world leading technology developed in Australia. It would also make a positive contribution to reducing the possibility of nuclear weapons proliferation and a major contribution to global mitigation of carbon emissions.

As the nation implements policies to reduce its carbon emissions, which will shift the economy from being among the highest polluters in the world to effectively zero carbon emissions, all available options need to be considered. Enabling nuclear deployment is equivalent to purchasing a call option to ensure the future supply of power in a decarbonised economy. Failing to prepare for the potential deployment of nuclear energy runs the risk that Australians continue to rely on fossil fuels as the costs of mitigating climate change are realised.

## A rational debate

In this policy perspective, *Australia's Nuclear Options*, a range of Australia's leading thinkers on nuclear energy consider aspects of the policy debate on the issue. They include the following perspectives:

- *The economic viability of nuclear power*. Professor Anthony Owen, Academic Director of UCL School of Energy and Resources, examines the purported "nuclear renaissance" and the challenges for realising nuclear power deployment, including its high upfront capital cost and construction risks;
- *The role of nuclear fission energy in mitigating future carbon emissions*. Professor Barry Brook, University of South Australia, Sir Hubert Wilkins Chair of Climate Change, considers the environmental opportunity cost of not using nuclear energy to decarbonise Australia;
- *Opportunities in the nuclear fuel cycle*. Dr Tom Quirk, who has spent 15 years as an experimental research physicist, university lecturer and Oxford don, reviews the nuclear fuel cycle and examines potential opportunities for Australia to contribute to global nuclear power generation and enhance its economic prosperity. This includes a potential US$16 billion industry in reprocessing and storing nuclear waste products;
- *Nuclear power in Australia's energy future*. Tony Wood, Program Director, Energy, Grattan Institute, describes the challenge involved in developing public policy when there is considerable technological uncertainty as to how Australia could transition from its comparative advantage in coal and natural gas to a decarbonised economy; and

- *Small Modular Reactors*. Tony Irwin, who has had 30 years experience commissioning and operating nuclear power plants in the UK, and was a member of a World Association of Nuclear Operators mission that reviewed operating practices at Russian RMBK reactors following the Chernobyl accident, describes the evolution of nuclear generation technology and how developments have the potential to alter the economics of nuclear energy.

These experts explain how, historically, nuclear power has predominately been deployed in countries that have internalised the cost of energy security, something Australia has not needed to do given its high quality reserves of coal and natural gas. Furthermore, the substantial upfront capital costs, and the large generation capacity associated with nuclear power plants have meant nuclear power was not ideal for Australia's energy market.[3]

Renewed global interest in replacing fossil fuels is generating technological innovations in a number of alternative energy sources. Australia must be able to capitalise on all developments if it is to wean the economy from fossil fuels.

## An irrational policy void

The public policy debate on climate change and Australia's future energy supply has a void surrounding the future role of nuclear power. Good public policy should be firmly based on known technologies while being suitably flexible to adapt for breakthroughs.[4]

Despite being a major source of commercially available low carbon energy in many countries, nuclear is being completely ignored by Federal Treasury's forecasts of the energy sector to 2050 or as part of any public policies to decarbonise the economy. It is unknown whether the Government's Energy White Paper will even devote one sentence to an issue that conceivably could solve Australia's low carbon energy requirements. At the same time, projections of Australia's future energy mix are based on technologies that require substantial breakthroughs to be commercially viable.

Behavioural economics provides insights as to why this void exists by explaining how human decision making is bounded in a number of critical ways relating to nuclear power.[5] These include a tendency to have a relatively strong reaction to extreme but unlikely events, to overestimate the probability of easily accessible outcomes, and pronounced loss aversion. Understanding the bounds of rationality suggests a way forward in the nuclear debate.

People evaluate extreme events that have large emotional outcomes disproportionate to intermediate risks which produce diffused results. Low level risks, such as fossil fuel power generators, where a large number of deaths have occurred but with less direct causality than those associated with the perceived risks of nuclear power generation, are more acceptable than nuclear power that has had extreme events but relatively fewer deaths. As a consequence, people evaluate the risks associated with nuclear power as being considerably higher than other forms of energy generation, despite the sector having one of the best safety records of any energy industry.

Decisions made on a desire to eliminate all forms of extreme risk can result in an accepting of more moderate but higher probability risk.[6] While rejecting nuclear energy may eliminate an extreme form of risk, the decision means accepting more probable outcomes associated with worsening climate change, as evidenced by recent decisions in Germany.

Results that are vivid and easily brought to mind are constantly ranked as being more likely than less accessible events. In this respect, nuclear energy has been involved with a number of extreme catastrophes that are easily brought to mind, such as Chernobyl, Three Mile Island and Fukushima Daiichi. The accessibility of these events contributes to the perceived high levels of risk associated with nuclear power despite advances in technology precluding such catastrophes reoccurring.

People are also loss adverse as typified by the adage “a bird in the hand is worth two in the bush.”[7] Nuclear power is currently evaluated as a gain and will not be perceived as a means of avoiding a loss, which will result in more widespread acceptance, until the costs of decarbonising the economy begin to be widely felt by households.

Australia’s comparative advantage is currently based on a low cost energy generated by burning abundant fossil fuels, resulting in our high per capita carbon emissions. Transitioning away from this will be expensive and will affect all households in Australia. Unless today’s political leaders make the right decisions, it will be too late for this source of energy to contribute to Australia’s efforts at mitigating climate change.

## Exercising the nuclear option

Historically it may have been politically expedient to ignore nuclear power. However, the developments in small modular reactors (SMRs) may make it very appropriate for Australia’s energy needs while future generations of nuclear power reactors may provide incredible sources of clean energy with high levels of safety.[8] The public policy position should be to enable the deployment of nuclear power in Australia should it prove viable.

There is little chance nuclear power will be accepted as a source of energy in a highly populated location without an established track record supplying energy to Australia. As a consequence, the most likely deployment option available would involve SMRs displacing coal or diesel generation in remote parts of Australia.

Once the Australian public has become comfortable with nuclear energy, and it has proven its safety, it will represent an option for greater deployment in the future. Future decisions would be about what proportion of Australia’s energy should be derived from nuclear power rather than whether or not it should be allowed.

Regardless of the eventual economics of SMRs, climate change is necessitating a reassessment of the deployment of nuclear power in Australia, the opportunity cost of which is clear. Even without deployment innovations, nuclear power should be a part of Australia's portfolio of policy responses to climate change. If SMRs develop as anticipated, then there may be a strong case for nuclear energy without imposing a cost on carbon emissions.

Two key steps to enabling nuclear power deployment involve:

- Establishing a national regulatory regime to oversee and monitor any potential deployment of nuclear power; and
- Training nuclear engineers by establishing an equivalent of the previous School for Nuclear Engineering or the Australian School of Nuclear Technology.

Given the potential for commercial SMRs to be available in 2020, the Federal Government should undertake these two steps immediately.

The costs of establishing a nuclear regulatory framework and developing suitably qualified technicians can be considered as the cost of purchasing a call option on greater flexibility for future energy supply. The value of any option is critically determined by the variability of the underlying asset. Given the uncertainty about the cost of decarbonised energy, purchasing a call option may prove to be an invaluable investment.

Ultimately whether nuclear power is suitable for Australia will be determined by technological advances in the near future. Political leadership will mean it is available as an option if it is necessary to ensure the ongoing prosperity of Australia.

Nathan Taylor
Chief Economist, CEDA

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## Endnotes

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# 1. The role of nuclear fission energy in mitigating future carbon emissions

## Professor Barry W Brook

Professor Barry Brook examines the case for nuclear fission as a contributor to future greenhouse gas abatement, nationally and globally.

# Introduction

Carbon-based fuels are the energy foundation upon which modern industrial civilisation has been built, but the end of the oil, gas and coal era now approaches – perhaps sooner than many realise. The reasons are manifold, but focus chiefly on economic supply limits, national imperatives of long-term energy independence, and the accumulating toll exacted by fossil-fuel combustion on local environments and the global climate system. In short, the modern world is caught in an energy-resource and global-warming pincer. For effective climate change mitigation, the global use of fossil fuels for electricity generation, transportation and other industrial uses will need to be substantially curtailed this century.[1]

Yet set against this is an unforgiving current reality: as the emerging mega-economies of Asia, the Middle East and South America strive to build the prosperity and quality of life enjoyed by citizens of the developed world, the demand for cheap, convenient energy grows rapidly. How to resolve this dilemma? This chapter looks at some of the proposed methods for decarbonisation, such as energy conservation and renewables, and considers the case for nuclear fission as a major contributor to future greenhouse gas abatement, nationally and globally.

**Professor Barry W Brook** is the Sir Hubert Wilkins Chair of Climate Change at the University of Adelaide. He is a leading environmental scientist and modeller and director of climate science at the University of Adelaide's Environment Institute. He's published three books, over 190 refereed scientific papers and regularly writes articles for the media. Professor Brook has received a number of distinguished awards for his research excellence and public outreach, including the Australian Academy of Science Fenner Medal and the 2010 Community Science Educator of the Year. His research interests are climate change impacts, simulation modelling, energy systems analysis (with a focus on nuclear power), and synergistic human impacts on the biosphere. He runs a popular climate science and energy options blog at http://bravenewclimate.com

# Energy problems and possible solutions

## Fossil fuel limits

The development of an 18th century technology that could turn the potential chemical energy of coal into heat and mechanical work – James Watt's steam engine – heralded the dawn of the Industrial Age. Our use of fossil fuels – coal, oil and natural gas – has subsequently allowed our modern civilisation to flourish. However, it is now increasingly apparent, that our almost total reliance on these forms of ancient stored sunlight to meet our energy needs, has some severe drawbacks, and cannot continue much longer.[2]

For one thing, fossil fuels are a limited resource. Most of the readily available oil used for transportation is concentrated in a few geographically favoured hotspots, such as the Middle East. Most credible analysts agree that we are close to, or have passed, the point of maximum oil extraction (often termed 'peak oil'), thanks to a century of rising demand.[3] We've tapped less of the available natural gas (methane), used mostly for heating and electricity production, but globally, it too has no more than a few more decades of significant production left before supplies really start to tighten and prices skyrocket, especially if we 'dash for gas' as the oil wells run dry. Coal is more abundant than oil or gas, but even it has only a few centuries of economically extractable supplies.[4]

Then there is climate change and air pollution. The mainstream scientific consensus is that emissions caused by the burning of fossil fuels, primarily carbon dioxide ($CO_2$), are the primary cause of recent global warming.[5] We also know that coal soot causes chronic respiratory problems, its sulphur causes acid rain, and its heavy metals (like mercury) induce birth defects and damage ecological food chains. These environmental health issues compound the problem of dwindling fossil fuel reserves.

Clearly, we must quickly transition away from our fossil fuel addiction. But how?

## Energy conservation

In the developed world (US, Europe, Japan, Australia and so on), we've enjoyed a high standard of living, linked to a readily available supply of cheap energy, based mostly on fossil fuels. Indeed, it can be argued that this has encouraged energy profligacy, and we really could be more efficient in the mileage we get out of our cars, the power usage of our refrigerators, lights and electrical appliances, and in the design of our buildings to reduce demands for heating and cooling. There is clearly room for improvement, and sensible energy efficiency measures should be actively pursued. However, in the global context, improving energy efficiency will not result in the world using less energy in the future. There are three obvious reasons for this.

First, most of the world's population is extremely energy poor. More than a third of all humanity, some two-and-a-half billion people, have no access to electricity whatsoever.[6] For those that do, their long-term aspirations for energy growth, to achieve something equating that used today by the developed world, is a powerful motivation for development. For a nation like India, with over one billion people, that would mean a twenty-fold increase in per capita energy use.

Second, as the oil runs out, we need to replace it if we are to keep our vehicles going. Oil is both a convenient energy carrier, and an energy source (we 'mine' it). In the future, we'll have to create new energy carriers, be they chemical batteries or oil-substitutes like methanol or hydrogen.[7] This will involve expending more energy than is involved in extracting oil. On a grand scale, that will take a lot of extra electrical energy, in all countries.

Third, with a growing human population (which we hope will stabilise by mid-century at less than 10 billion[8]) and the burgeoning impacts of climate change and other forms of environmental damage, there will be escalating future demands for clean water (at least in part supplied artificially, through desalination and waste water treatment), more intensive agriculture which is not based on continued displacement of natural landscapes, and perhaps direct geo-engineering to cool the planet, which might be needed if global warming tracks at the upper end of forecasts.

In short, the energy problem is going to get larger, not smaller, at least for the foreseeable future.

Improved efficiency in the way we use energy offers a partial fix, at least in the short term. In the broader context, to imagine that the global human enterprise will somehow manage to get by with less just doesn't stack up when faced with the reality of a fast developing, energy-starved world. Citizens in Western democracies are simply not going to vote for governments dedicated to lower growth and some concomitant critique of consumerism, and nor is an authoritarian regime such as in China going to risk social unrest, probably of a profound order, by any embrace of a low growth economic strategy. As such, reality is demanding, and we must carefully scrutinise the case put by those who believe that a wholesale reduction in energy use is the answer.

> "In an age of climate change, energy uncertainty and carbon prices, it is time for Australians to become 'Promethean environmentalists' and advocate for a policy that supports the inclusion of nuclear fission energy in the mix of low-carbon options for replacing fossil fuels (Prometheus, in Greek mythology, was the defiantly original and wily Titan who stole fire from Zeus and gave it to mortals, thus improving their lives forever). Prometheans are realists who shun romantic notions that modern governments might guide society back to an era when people lived simpler lives, or that a vastly less consumption-oriented world is a possibility. They seek real, high-capacity solutions to environmental challenges – such as nuclear power – which history has shown to be reliable."

Critics do not seem to understand – or refuse to acknowledge – the basis of modern economics and the investment culture. Some dream of shifts in the West and the East away from consumerism. There is a quasi-spiritualism which underpins such views. Yet at a time of crisis, societies must be ruthlessly practical in solving their core problems or risk collapse. First, there is an economic opportunity cost involved in reducing our energy use (beyond wastage, which clearly makes sense to avoid), given that economic growth, affluence and health are all underpinned by technological choices and the availability of reliable, cost-effective services.[9] Second, most people will object vociferously to measures that propose to, or are even perceived to lead to, a decline in their standard of living. We need to work with this reality, and seek, as an environmentally aware society, to deliver these aspirations in a sustainable way.

## Limits to large renewable energy

The most widely discussed pathways for alternative energy involve the expanded deployment of a range of renewable technologies, including harnessing the energy in wind, sunlight (directly via photovoltaic panels or indirectly using mirrors to concentrate sunlight), water held behind large dams (hydropower), ocean waves and tides, plants, and geothermal energy, either from hot surface aquifers (often associated with volcanic geologies) or in deep, dry rocks.[10] These sources are being constantly replenished by incoming sunlight or gravity (tides and hot rocks) and radioactivity (hot rocks). Wind is caused by differences in temperature across the Earth's surface, and so comes originally from the sun, and oceans are whipped up by the wind (wave power).

Some argue that large-scale utilisation of sunlight, wind, waves and plant life, combined with vast improvements in energy efficiency and energy conservation leading to a flattening or reduction in total energy demand, are the answer for decarbonisation.[11] Indeed, this is a widespread view among environmentalists and would seem to offer an acceptable solution, if the numbers could be made to work. However, many evidence-based analyses cast doubt on this supposition.[12] Technically, there are many challenges with economically harnessing renewable energy to provide a reliable, dispatch-on-demand power supply. This is a complex topic, and only some of the key issues can be touched on here.[13]

One problem is that all of the sources described above are incredibly diffuse – they require large geographical areas to be exploited in order to capture large amounts of energy. For countries like Australia, with a huge land area and low population density, this is not, in itself, a major problem. But it is a severe constraint for nations with high population density, like Japan or most European nations.[14]

Another is that they are variable and intermittent – sometimes they deliver a lot of power, sometimes a little, and at other times none at all (the exception here is geothermal). This means that if you wish to satisfy the needs of an 'always on' power demand, you must find ways to store large amounts of energy to cover the non-generating periods, or else you need to keep fossil-fuel or nuclear plants as a back-up. That is where the difficulties and costs really begin to magnify.

The Californian entrepreneur Steve Kirsch, has put the climate-energy problem succinctly:

> *"The most effective way to deal with climate change is to seriously reduce our carbon emissions. But we'll never get the enormous emission reductions we need by treaty. Been there, done that – it's not going to happen. If you want to get emissions reductions, you must make the alternatives for electric power generation cheaper than coal. It's that simple. If you don't do that, you lose."*[15]

Currently, no non-fossil-fuel energy technology has achieved this.[16] So what is stopping nations replacing coal, oil and gas infrastructure with renewable energy? It is not (yet) because of any strong, society-wide opposition to a switch to renewables. Instead, it is a combination of economic uncertainty, technological immaturity and prudent financial risk management. Key technological gaps include economic large-scale energy storage options (only pumped hydro has been used to date for this purpose) and resolving questions on the relative cost-competitiveness of managing daily-to-seasonal variability in supply and long-distance transmission. Clearly, it is still far from certain in what way the world will pursue a low-carbon future.

Recent peer-reviewed critiques of the future global role of renewable energy[17] provide details on the limitations associated with variability, dispatchability, large-scale energy storage, the need for overbuilding and geographical replication (and the likely consequence: “dumping” of unused excess energy), energy returned on energy invested, and other key points. There are also recent meta-reviews that consider technological maturity, cost and life cycle emissions as constraints on renewables’ capacity to displace fossil fuels.[18] The conclusion from this confronting work is that renewables alone will not be able to “solve” the greenhouse problem. Ultimately, as the urgency of climate change mitigation mounts, and requirements for sustainable growth in developing economies and replacement of ageing infrastructure in the developed world come to the fore, pragmatic decisions on the viability of all types of non-fossil technologies will have to be made. This will include a serious consideration of the relative costs and benefits of nuclear fission.

> “Advocating for a major role for nuclear fission does not, of course, mean campaigning against energy efficiency and renewable options. Under the right circumstances, these alternatives might be able to make an important contribution, and ideally, all low-carbon energy options should compete on a fair and level playing field to displace fossil fuels.”

## The best history has delivered

A study of the history of modern energy reveals a striking fact on large-scale energy resources. Nations have depended principally on either fossil fuels or two low-carbon alternatives: nuclear power or hydroelectricity. A number of countries in Europe rely almost exclusively on either nuclear power (France), hydro (Norway), or mix of the two (Sweden, Switzerland).[19] These are truly low-carbon economies, at least in terms of electricity generation. The future problem of oil replacement for transport and industry will require increased electrification and manufacture of synthetic fuels (liquid energy carriers), but hasn’t yet been achieved at large scale anywhere.

What of Denmark, which has taken a deeper-penetration wind route than any other country? It still only gets 20 per cent of its electricity from wind, but must also sell it cheaply to the rest of Scandinavia when production is higher than demand, and buy in coal-fired electricity when there is little wind. Even at this level of wind penetration, Denmark has among the highest greenhouse gas emissions per person in Europe, whereas nuclear-powered France has among the lowest.[20]

Australia has no access to large-scale hydro, beyond those schemes such as the Snowy Mountains and Tasmanian rivers that are already mostly developed – at substantial environmental cost. Australia does, however, have abundant uranium, and a high technology society in a geologically stable region, all perfect for the deployment of nuclear power. Although Australia should clearly not turn away from solar and wind, the comparisons above show that history is not on the side of these alternative technologies. No country to date has displaced its fossil fuel fleet by using these sources, for a number of practical engineering and economic reasons. One has to be an extreme optimist to imagine that this reality – this lesson of history – is going to miraculously change in the coming decades.

## The nuclear fission energy option

Since the 1970s, when prominent environmental groups such as the Sierra Club switched from being general supporters of fission (once considered by them to be a better option than large hydro dams) to trenchant detractors, nuclear power has fought an enduring battle to present itself as a clean, safe and sustainable energy source. Today, a mix of myths and old half-truths continue to influence people's thinking on nuclear power[21], whereas rose-tinted glasses are worn when looking at the other low-carbon technologies. Crises like that which occurred in March 2011 in Japan at the Fukushima Daiichi nuclear plant, triggered by a massive earthquake and tsunami impacting a 1960s-vintage reactor technology[22], amplify these feelings for many people. Yet, given the global environmental challenges we must deal with in the coming decades, closing off Australia's options on nuclear energy would be short sighted.

The opportunity cost of not deploying nuclear power is higher carbon emissions. This is a reality that the Germans will quickly discover. Having decided to wind back the deployment of nuclear power, they are planning two-dozen new coal-fired power stations.[23]

Some of the other regularly raised concerns about nuclear energy are that uranium supplies will run out, long-lived radioactive waste will be with us for 100,000 years, large amounts of carbon dioxide are produced over the nuclear cycle, it's too slow and costly, and a build-up of nuclear power will increase the risk of weapons proliferation. Yet the reality is surprisingly different, most of these disadvantages of nuclear power no longer apply, and none need do so in the future.

Worldwide, nuclear power is forecast to be an on-going contributor to electricity supply throughout the 21st century[24] (although equally, it is not currently being deployed at a rate anywhere near sufficient to displace fossil fuels any time soon). Of the G20 economic forum nations, 15 have nuclear power and four are planning to take it up in the near future[25], although now, as noted above, Germany has stated that it will attempt to phase out its use of nuclear fission by 2022.

In 2010, nuclear energy was used to generate commercial electricity in 31 countries, providing 74 per cent of total supply in the case of France, and a global total of 2,628 terawatt hours.[26] Based on standard emissions intensities for nuclear (20 kg $CO_2$-e/MWh) and coal (930 kg $CO_2$-e/MWh)[27], this is an effective saving of 2.4 billion tonnes of carbon dioxide annually. Only hydroelectricity displaces more fossil fuels than nuclear (3,250 TWh). By comparison, wind generation in 2010 was 14 per cent that of nuclear, while solar generated just 1.5 per cent as much.[28] In 2009–10, Australia exported 7,555 tonnes of uranium, all of which was used to fuel nuclear power plants.[29] If this electricity had instead been generated from brown coal-fired sources, an additional 370 million tonnes of $CO_2$ would have been released.[30] Clearly, foregoing nuclear means overlooking an already significant global contributor to low-carbon electricity.

The notion that expansion of nuclear power represents a proliferation risk is not valid given how extensively it is currently deployed. Nuclear power is commercially deployed in countries whose energy intensity is such that they currently constitute 80 per cent of global greenhouse gas emissions.[31] When you add those nations who are actively planning deployment or already have research reactors, this tally rises to over 90 per cent. As a consequence, displacement of fossil fuels by nuclear energy would not lead to a significant increase in the number of countries with nuclear resources. In this context, fears that a global nuclear renaissance will lead to the unfettered spread of risky technology is both wrong and counterproductive.[32] The nuclear 'genie' is already out of the bottle, and in recognition of this, we should instead discuss how, as a global society, we will use this low-carbon energy source safely and cleanly, with minimal risk and maximum advantage to all nations.

There are about 60 so-called Generation-III reactors under construction, including 28 in China, and many more in the late stages of planning.[33] In terms of costs and build times, modular, passive-safety designs, which can be factory built and shipped to site, have the potential to be game changers for an industry that has, in the past, been plagued by regulatory ratcheting and legal challenges against typical 'one off' designs. Instead, standardised blueprints with inherent safety systems are the clear way to remove the delays that killed deployment of nuclear power in the US in the 1980s.[34] France, with a rapid build-out of 59 reactors in 22 years (1978 to 1999), is a good example of how it could be done under the right political, economic and regulatory circumstances.

> "Today, a mix of myths and old half-truths continue to influence people's thinking on nuclear power, whereas rose-tinted glasses are worn when looking at the other low-carbon technologies. Crises like that which occurred in March 2011 in Japan at the Fukushima Daiichi nuclear plant, triggered by a massive earthquake and tsunami impacting a 1960s-vintage reactor technology, amplify these feelings for many people. Yet, given the global environmental challenges we must deal with in the coming decades, closing off Australia's options on nuclear energy would be short sighted."

The modern Generation- III reactor designs are efficient, with capacity factors exceeding 90 per cent, and have a high degree of passive safety based on the inherent principles of physics. For instance, the risk of a meltdown as serious as the Three Mile Island incident in the US (which resulted in no fatalities) has been assessed as extremely low for GE-Hitachi's new Economic Simplified Boiling Water Reactor, compared to earlier designs.[35] Of course to demand zero is to ask the impossible of any energy technology, given the possibility of beyond-design-basis events, and ignores the trade-off involved in fixing other major environmental problems with extremely high probabilities attached.

The future of nuclear power is potentially bright, *if* society and decision makers choose to make it so, by looking at the energy problem rationally. For instance, although government reports and the media hardly ever mention so-called 'fast reactors', these can provide vast amounts of clean, reliable energy for thousands of years. For instance, a technology developed between 1964 and 1994 at the Argonne National Laboratory in the US, the Integral Fast Reactor (IFR), fissions over 99 per cent of the nuclear fuel, leaves only a small amount of waste (one thirtieth of current reactors, or equivalent to less than one milk crate per year[36]) which drops below background levels of radiation within 300 years, shuts itself down if the control systems fail or the operators walk away, and its fuel cycle is extremely proliferation resistant.[37] As an added benefit, all of the nuclear waste generated over the last 50 years can be consumed as fuel in these new reactors. The IFR, and other 'Generation IV' designs[38] using depleted uranium and thorium, offers a realistic future for nuclear power as the world's primary source of sustainable, carbon-free energy with resources to power the world for millions of years.

Ironically, it's in places like China and India that these next-generation nuclear designs are now being most actively implemented, and we need to do more to support their efforts in a multi-lateral 'clean fission energy' initiative, including multiple demonstration units and international technology sharing agreements to speed up deployment schedules. China has commissioned two commercial fast reactors based on a successful Russian design, the BN-800. India has just announced that it plans to install almost 500 gigawatts of thorium-based nuclear power by 2050 and is opening a 500 megawatt fast reactor in 2012 (it's currently under construction).[39] Arguably, the die is now cast. It's time for all energy intensive nations to fast track the deployment of sustainable nuclear. But of course this won't happen with sufficient urgency until people get realistic about our future energy options. For climate's sake, we must start thinking critically.

For many other countries, such as Japan, Germany and Switzerland, with little land and many people, the options (beyond hydroelectricity in some places) for renewable energy alternatives are quite limited. In terms of non-hydro renewables, while Australia has the available land, large material requirements, high cost, and severe difficulties in managing variability through large-scale energy storage, the chance of successful decarbonisation without a significant tranche of nuclear energy is low. Although renewables have an important future role, we must accept the great need for concentrated sources of 'baseload' energy[40] that are not constrained by geography or intermittency.

Most Western countries are now moving slow in progressing their use of nuclear energy, or are rolling them back (or halting them), as evidenced by recent decisions in Germany, Japan, Switzerland and Italy. The best light one can cast on such extreme measures is that such nations have chosen to conduct the grand experiments that must, it seems, be tried, before enough of the general populace (and most environmentalists) can be convinced of the reality of the phrase: *'it's nuclear power, or it's climate change'*.There may be no silver bullet for solving the climate and energy crises, but there are bullets, and they are made of uranium and thorium.

So although the current lack of enthusiasm for nuclear energy in places like Australia, Germany and elsewhere is a real economic concern – seemingly putting short-term socio-political considerations ahead of long-term need – it perhaps is also inevitable. A dispassionate analysis of the situation suggests that we measure risks and opportunities appropriately, and on that basis, most should seriously consider deploying sustainable forms of nuclear energy – those which rely on inherent safety systems and full waste recycling – right now. If, as seems quite likely, the alternatives fail to deploy at scale and within reasonable budget, and do not displace fossil fuels or reduce emissions effectively, then nuclear must be available to play a role.

On the grounds of greenhouse gas mitigation and energy security, the public dialogue on nuclear power is as urgent as the debate on carbon prices and the need for climate change adaptation. There are significant opportunity costs tied to any decision for Australia to leave nuclear energy to others, and instead focus on a narrow portfolio of unproven low-carbon electricity options. A nation's sustainable energy future depends critically on choices made today. Some countries in the developed and developing world have already made their choice – for them, nuclear has a clear role, and the only open question is, how much?[41] For others, there remains great uncertainty. Whatever your position, the issue cannot be ignored in the low-carbon policy debate.

> "Some of the other regularly raised concerns about nuclear energy are that uranium supplies will run out, long-lived radioactive waste will be with us for 100,000 years, large amounts of carbon dioxide are produced over the nuclear cycle, it's too slow and costly, and a build-up of nuclear power will increase the risk of weapons proliferation. Yet the reality is surprisingly different; most of these disadvantages of nuclear power no longer apply, and none need do so in the future."

## Conclusion

In an age of climate change, energy uncertainty and carbon prices, it is time for Australians to become "Promethean environmentalists" and advocate for a policy that supports the inclusion of nuclear fission energy in the mix of low-carbon options for replacing fossil fuels (Prometheus, in Greek mythology, was the defiantly original and wily Titan who stole fire from Zeus and gave it to mortals, thus improving their lives forever[42]). Another term, recently used by futurist Stewart Brand, is "Ecopragmatists".[43] Prometheans are realists who shun romantic notions that modern governments might guide society back to an era when people lived simpler lives, or that a vastly less consumption-oriented world is a possibility. They seek real, high-capacity solutions to environmental challenges – such as nuclear power – which history has shown to be reliable.

Advocating for a major role for nuclear fission does not, of course, mean campaigning against energy efficiency and renewable options. Under the right circumstances, these alternatives might be able to make an important contribution[44], and ideally, all low-carbon energy options should compete on a fair and level playing field to displace fossil fuels. Ultimately, as the urgency of climate change mitigation mounts, and requirements for sustainable growth in developing economies and replacement of ageing infrastructure in the developed world come to the fore, pragmatic decisions on the viability of all types of non-fossil technologies will have to be made. Engineering and economic realities point to a large role for fission in this new energy future. It is time for Australia to open the electricity market up to this important option.

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# 2. The economic viability of nuclear power

## Professor Anthony D Owen

Professor Anthony Owen examines the economics of the purported “nuclear renaissance” and the challenges for realising nuclear power deployment.

## Introduction

After several decades of negligible progress on talks around nuclear, a nuclear renaissance has been stimulated by oil price spikes, concerns over energy security and the requirement to reduce emissions of greenhouse gases. In its 450 scenario[1], the International Energy Agency (2010) predicts a doubling of electricity generated by nuclear to 2030, stimulated by a carbon price and favourable government policies for mitigating investment risks in the industry. Due to long planning, design and construction timelines, the bulk of this increase is not expected to occur until after 2020. The IEA's forecasts represent an ambitious target, particularly given the poor construction record for nuclear plant over recent years and uncertainties surrounding the cost of building new plant.

## Nuclear power today

Worldwide there were 440 nuclear power reactors operating in September 2011, totalling 376.8 gigawatts (GW) of generating capacity, and supplying about 14 per cent of the world's electricity. Although this latter figure has remained relatively stable over the past couple of decades, indicating that nuclear power had grown at about the same rate as total global electricity production over the period, it dropped by an unprecedented two per cent in 2007 followed by a further half a percentage point drop in 2008, largely due to the rapid expansion of coal-fired power plants in China.

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As of September 2011 there were 62 reactors described as being "under construction" worldwide, 26 being in China, 10 in Russia, six in India, five in South Korea and just three in OECD countries (Finland[2], France and the USA[3]). However, for 13 of these 62 reactors construction started before 1990 and there must be doubts about whether these plants will ever be completed.

In its 2011 Annual Energy Outlook, the US Energy Information Administration (EIA) projected increased US installed nuclear capacity from 101.0 GW in 2007 to 110.5 GW in 2030 in its "reference case". The forecast expansion of nuclear power was highly dependent on various subsidies being extended to industry.

The EIA's forecast increase was anticipated to constitute 6.3 GW of capacity at new plants (the first few of which are eligible for the 2005 Energy Act [EPACT2005] tax incentives) and 3.8 GW of capacity expansion at existing plants. EPACT2005 provides an eight year production tax credit of $18 per megawatt hour (MWh) for up to six GW of capacity built before 2021, limited to $125 million per GW per year. If the capacity is reached before 2020 then the credit program ends and no additional units are expected.

The anticipated increase in capacity at existing units assumes that all additions approved, pending, or expected by the Nuclear Regulatory Commission will be carried out. Other incentives offered to the nuclear industry in EPACT2005 were loan guarantees for up to 80 per cent of project costs (valid for all GHG-free technologies), insurance protection against delays during construction and until commercial operation caused by factors beyond the private sector's control, limitation of liability resulting from an accident, all decommissioning trust funds to qualify for tax deductibility, and the authorisation of a $2.95 billion research and development portfolio. Several companies have started the licensing process for new plants, but firm orders have yet to be made and even under a "best case" scenario the first new plant would not come online at an existing site before 2015.

Even with this expansion of nuclear capacity, if it actually occurs, nuclear power's current 20 per cent share of total US power generation is expected to decline to 15 per cent by 2030. The EIA expects 50 per cent of all new generating capacity additions to 2030 to be coal in the absence of any carbon price being imposed on combustion of that fuel.

In summary, this is not a portrait of an industry in revival in western nations. Although the political will to expand nuclear capacity appears to be present in many OECD countries, as will be discussed later in this paper, privately-owned electric utilities do not appear to be in a position to comfortably support the expansion of nuclear power. In contrast, state-owned power companies in China, India, South Korea, and Russia have aggressive nuclear expansion plans in place.

## The cost of nuclear power

Nuclear power plants have a "front-loaded" cost structure; i.e. they are relatively expensive to build but relatively inexpensive to operate.

Although costs vary both between and within countries, about two-thirds of the costs of generating electricity from a nuclear power plant are accounted for by fixed costs arising from the construction process, with the remainder being fixed and variable operating costs. These costs generally break down in a ratio of two-to-one. The main fixed costs are capital repayments and interest on loans.  An allowance for decommissioning costs is also included in this item, although the timing and precise costs of decommissioning lack clarity. Fuel is a relatively minor component of operating costs, because uranium is in relatively abundant supply in terms of current requirements.

Once a nuclear power plant has been built, its construction costs have effectively been "sunk" and the plant's second-hand value is negligible. Thus it makes financial sense to operate the plant continuously based upon the fact that low fuel costs effectively yield a relatively low short run marginal cost for power production. Currently nuclear power is the cheapest form of electricity production in most OECD countries for existing plants. Utilities are attempting to extend the life of these plants to capitalise on this advantage. However, they appear very reluctant to invest in new nuclear plant without substantial government cost and market guarantees and other subsidies.

For new nuclear power plants their competitiveness depends on several factors. First, the cost of alternative technologies. Nuclear is likely to be particularly suitable for countries seeking energy security that are not well endowed with coal and/or gas reserves and must therefore import their fossil fuel requirements. Second, it depends on the overall electricity demand in a country and its rate of growth. Third, it depends on the market structure and investment environment.

In general, nuclear power's front loaded cost structure is less attractive to a private investor in a liberalised market that values short-term returns rather than a government-owned utility that has a longer-term perspective. Private investments in liberalised markets will also depend on the extent to which energy-related environmental externalities (for example, GHG emissions, emissions of local pollutants, and so on) and the value of energy security have been "internalised". In contrast, government investors can incorporate such externalities directly into their investment decisions, although this would contravene the polluter pays principle if it involves direct or indirect subsidies.

"Although the political will to expand nuclear capacity appears to be present in many OECD countries...privately-owned electric utilities do not appear to be in a position to comfortably support the expansion of nuclear power. In contrast, state-owned power companies in China, India, South Korea, and Russia have aggressive nuclear expansion plans in place."

Different countries have different approval processes, regulatory regimes and political systems, all of which impact on risk from the investors viewpoint. Construction delays, for example, can significantly increase interest payments during construction. Thomas (2005) reports that:

> *"Forecasts of construction costs have been notoriously inaccurate, frequently being a serious underestimate of actual costs and – counter to experience with most technologies where so-called 'learning', scale economies, and technical progress have resulted in reductions in the real cost of successive generations of technology – real construction costs have not fallen and have tended to increase through time."*

This lack of scale economies is not surprising given the lack of orders for new generation (often called Generation III+) reactors.[4]

The cost of capital is, together with construction costs, a major determinant of the cost of power from a nuclear plant. Most nuclear plants currently operating in OECD countries were built in an era when the power generation sector was a regulated monopoly. Thus the cost of capital was relatively low, as it was backed by government guarantee. In addition, any increase in costs during construction could be clawed back from consumers in the form of higher prices arising from the full cost recovery nature of the sector's pricing regime. Thus investment risk, which effectively was vested in the consumer/tax payer, was minimal and the cost of capital reflected this.

However, OECD electricity markets (including that of Australia) have undergone reconstruction, to various degrees, to a model that is driven by competitive forces, and thus the investment risk now falls on the generator rather than consumer. In such circumstances the real cost of capital could be expected to be considerably higher than under the former regime. Of course, this risk could be reduced by government guarantees but this would amount to a subsidy and would therefore be in conflict with the competitive market model.

Financial estimates of the cost of electricity generation from new nuclear power plants are subject to large variations, both between and within countries. Thomas (2005) lists a number of reasons for the divergence:

- It is always assumed that new plants would be much cheaper and more reliable than existing plants;
- Those with a vested interest in nuclear power would tend to produce the more optimistic costs and performance forecasts;
- Few orders have been placed in the past two decades on which to base forecasts;
- Very little real data on construction and operating costs are made public;
- Reactor designs (Generation III+) currently being considered in the USA and the EU are largely unproven; and
- Different assumptions regarding the opportunity cost of capital. Real rates of 10 per cent, or above, severely compromise the viability of nuclear power yet rates lower than this are difficult to justify for private investors.

## Projected power plant costs

Investment cost per kilowatt (kW) at the design stage for nuclear plant is about twice that for coal and three to four times that for combined cycle gas turbine plants. However, the costs of large scale engineering projects are notoriously difficult to estimate, being very country and site specific. A comparison of overnight costs of baseload electricity generating technologies scheduled to come on-line in 2015 in a number of OECD countries and China is given in Table 1.[5]

The overnight cost for a Generation III+ plant in the USA was estimated to be $3382/kW for a 1350 MW net capacity plant. Comparable estimates for 11 other OECD countries ranged from $1556/kW in South Korea to a high of $5863/kW in Switzerland. The overnight cost for China was broadly equivalent to that for South Korea.[6] Considerable variation of costs between countries for coal and off-shore wind is also evident, while combined cycle gas turbine (CCGT) costs

### TABLE 1:
### COMPARISON OF OVERNIGHT COSTS OF ELECTRICITY GENERATING TECHNOLOGIES (US$/KW)

| Country | Nuclear | Coal | Coal with carbon capture | Combined cycle gas turbine | Onshore wind |
|---|---|---|---|---|---|
| Belgium | 5,383 | 2,539 | | 1,099 | 2,615 |
| Czech Rep. | 5,858 | 3,485 | 5,812 | 1,573 | 3,280 |
| France | 3,860 | | | | 1,912 |
| Germany | 4,102 | 1,904 | 3,223 | 1,573 | 3,280 |
| Hungary | 5,198 | | | | |
| Japan | 3,009 | 2,719 | | 1,549 | |
| Korea | 1,556 | 895 | | 643 | |
| Netherlands | 5,105 | 2,171 | | 1,025 | 2,076 |
| Slovakia | 4,261 | 2,762 | | | |
| Switzerland | 5,863 | | | 1,622 | 3,716 |
| USA | 3,382 | 2,108 | 3,569 | 969 | 1,973 |
| China | 1,763 | 656 | | 538 | 1,223 |

Source: IEA/NEA (2010)

were significantly lower and less variable. Of particular note is the similar costs for nuclear and coal with carbon capture and compression (CC), but excluding carbon storage.

Not surprisingly, the levelised cost of electricity from these technologies exhibited a similar wide-ranging pattern to their overnight investment costs (Table 2). In each cell two values are given, corresponding to discount rates of five and ten per cent respectively. For the high capital cost technologies (i.e. nuclear, coal, and wind) the increase in the discount rate has a significantly more pronounced impact than for relatively lower capital cost technologies such as gas. In addition, the higher discount rate also has an adverse impact on coal generation using CC technology. For most countries in Table 1, nuclear has a clear cost advantage over the other technologies at the lower discount rate. An advantage that is either significantly reduced or disappears in favour of CCGT for the higher discount rate.

While the cost data and other parameters are based upon harmonised assumptions for a selection of OECD countries, they could act as indicative comparative technology cost estimates for Australia. A critical parameter in the calculations is the assumption of the cost of capital, particularly for technologies with long construction schedules. For example, a (real) discount rate of seven per cent would impose a discount factor on a project's net cash flow of 0.67 in year six. If the project's construction period had been five years, then this would correspond to the first year of revenue. However, historically, the nuclear industry (particularly in the US where there has not been a standard design for nuclear power plant) has been plagued by delayed construction schedules, for various reasons. As a

## TABLE 2:
## COMPARISON OF LEVELISED COST OF ELECTRICITY BY TECHNOLOGY (2015¢/KWH) AND DISCOUNT RATE*

| Country | Nuclear | Coal | Coal with carbon capture | Combined cycle gas turbine | Onshore wind |
|---|---|---|---|---|---|
| Belgium | 6.1<br>10.9 | 8.2<br>10.0 | | 9.0<br>9.3–9.9 | 9.6<br>13.6 |
| Czech Rep. | 7.0<br>11.5 | 8.5–9.4<br>11.4–13.3 | 8.8–9.3<br>13.6–14.1 | 9.2<br>10.4 | 14.6<br>21.9 |
| France | 5.6<br>9.2 | | | | 9.0<br>12.2 |
| Germany | 5.0<br>8.3 | 7.0–7.9<br>8.7–9.4 | 6.8–8.5<br>9.5–11.0 | 8.5<br>9.3 | 10.6<br>14.3 |
| Hungary | 8.2<br>12.2 | | | | |
| Japan | 5.0<br>7.6 | 8.8<br>10.7 | | 10.5<br>12.0 | |
| Korea | 2.9–3.3<br>4.2–4.8 | 6.6–6.8<br>7.1–7.4 | | 9.1<br>9.5 | |
| Netherlands | 6.3<br>10.5 | 8.2<br>10.0 | | 7.8<br>8.2 | 8.6<br>12.2 |
| Slovakia | 6.3<br>9.8 | 12.0<br>14.2 | | | |
| Switzerland | 5.5–7.8<br>9.0–13.6 | | | 9.4<br>10.5 | 16.3<br>23.4 |
| USA | 4.9<br>7.7 | 7.2–7.5<br>8.8–9.3 | 6.8<br>9.4 | 7.7<br>8.3 | 4.8<br>7.0 |
| China** | 3.0–3.6<br>4.4–5.5 | 3.0<br>3.3–3.4 | | 3.6<br>3.9 | 5.1–8.9<br>7.2–12.6 |

Source: IEA/NEA (2010)

* A harmonised carbon price of $30/tonne CO2 was assumed to be common over all OECD countries for the lifetime of all technologies. With the exception of the USA, fuel prices were also harmonised: $3.60/gigajoule (GJ) for black coal, $9.76/GJ for gas (OECD Europe) and $11.09/GJ for gas (OECD Asia). For the USA coal and gas prices were set at $2.12/GJ and $7.4/GJ, respectively. For China corresponding prices are $2.95/GJ and $4.53/GJ, respectively.

** No carbon price was imposed upon China. Add 2.5¢ to the cost of coal and 1.3¢ to that of gas to make China's figures comparable with the other countries given in the table.

consequence the discount factor for the first year of operation may be considerably lower, depending upon the extent of the delay. For example, a three year delay would imply a discount factor of 0.54, while a five year delay would yield one of 0.48.

Thus major delays in construction and/or a high discount rate could spell financial disaster for investments in high capital cost projects with long construction periods. Typically, for social infrastructure projects, the Australian state governments would set real social discount rates at around six to seven per cent on the basis that the financial return is augmented by a "social" return on the investment. However, private industry would require a pre-tax rate significantly higher than this as it would have little or no interest in a non-monetised social return.

# Nuclear power in Australia

Currently, Australia has no commercially operating or planned nuclear power reactors and, as a nation well endowed with low-cost reserves of coal, this position would have been unlikely to change in the foreseeable future were it not for the threat of an impending global environmental crisis arising from the combustion of fossil fuels.

This has not always been the case. Following the report of a feasibility study, in October 1969 the then Prime Minister John Gorton announced that the Commonwealth Government would construct a 500 MW nuclear power station on Commonwealth land at Jervis Bay on the south coast of New South Wales. Tenders were obtained, and site preparation and environmental studies were undertaken by the Australian Atomic Energy Commission (AAEC).[7] This was viewed as just the beginning of a substantial commitment by Australia to nuclear power. At the Australian and New Zealand Association for the Advancement of Science conference in May 1971, the Chairman of the AAEC, Sir Phillip Baxter, was quoted as stating that Australia's nuclear power capacity would reach 22.5 GW by 1995, and 36 GW by the year 2000, or 27.2 and 32.8 per cent respectively of projected total installed electricity capacity from all sources.[8] However, Baxter's crystal ball was abruptly shattered just a few months later when the Jervis Bay project was deemed to be uneconomic and all construction plans deferred. Subsequently the project was abandoned and the prepared site now serves as a car park for the local surfing community.

> "Currently, Australia has no commercially operating or planned nuclear power reactors and, as a nation well endowed with low-cost reserves of coal, this position would have been unlikely to change in the foreseeable future were it not for the threat of an impending global environmental crisis arising from the combustion of fossil fuels."

# Investing in power projects in Australia

Nuclear power is not the only industry where high capital cost and high risk characterise the industry. Ironically coal power plants fall into a similar category, but the technology has some beneficial characteristics that are not shared by nuclear such as mass produced components, availability of sites, low investor risk, and, until recently, a lack of significant public opposition to their construction. It is important to emphasise, however, that CCS technology may generate significant public opposition if there are strong community perceptions of risks associated with its deployment.

Power generation in the National Electricity Market (NEM) is dominated by coal plant, with open-cycle gas plant and hydro providing peaking power. In some states, where gas is readily available, combined cycle gas plant operates at base or intermediate load. However, it is only fairly recently that sufficient gas reserves have been identified in Queensland and NSW to permit expansion of this technology in those states. In addition, the mandatory renewable energy target (MRET) scheme has encouraged a significant expansion of new wind capacity in southern states, particularly South Australia. Wind power displaces baseload, and tends to discourage investment in traditional large-scale baseload technologies in favour of open cycle gas turbines to provide back up for the intermittent nature of wind generation.

> "In general, nuclear power's front loaded cost structure is less attractive to a private investor in a liberalised market that values short-term returns rather than a government-owned utility that has a longer-term perspective."

Gas technology has a number of advantages over coal and nuclear in a competitive marketplace. It is modular and has a relatively low unit capital cost compared with coal and nuclear technologies. Thus incremental expansion of generation capacity is possible as the market expands. It can also be largely pre-fabricated off site and assembled on-site within a year (for open cycle) and the cycle can then be closed when demand dictates to give a CCGT plant within a total construction period of around two years. The latter has less than half the $CO_2$ emissions of comparable coal-fired plant. Open cycle gas is ideal for load following and, although volatile gas prices could potentially be a deterrent to investment in this form of technology, high prices associated with meeting peak demand is an offsetting incentive. In contrast, current technology for coal and nuclear are relatively inflexible for load following.

In the National Electricity Market (NEM) states in particular, public opposition to new coal-fired power plants is likely to be strident. As a consequence, any application may be subject to delay due to public opposition in the Land and Environment Courts. While CCS technology may ameliorate public concern over the construction of new coal plant this has still to be tested. Gas has always got the political advantage of acting as the fall back supplier of power in a system containing a significant wind (or other intermittent renewable energy source) component.

## Enabling investments

The mature nature of the nuclear power sector means that most OECD countries, in particular Australia, do not have the graduate nuclear engineers necessary to oversee any "nuclear revival". From 1961 to 1986 there was a School of Nuclear Engineering at the University of New South Wales, and an Australian School of Nuclear Technology from 1964 to 1988 at the AAEC. Unfortunately interest in, and financial support for, nuclear power waned with a Labor government in long-term power in Canberra.

In addition, regulatory requirements, potential sites and public acceptability are all issues that need to be addressed well in advance of the planning stage for a nuclear plant. At present these issues have received negligible attention and hence a significant period of time must be expected to elapse before they can be addressed in the required level of detail. Water requirements for the current generation of nuclear and coal generation technologies are also an issue given Australia's frequent periods of drought (thus discouraging river cooling) and heavily populated Eastern coastline (thus discouraging seawater cooling).

# Conclusion

The NEM is currently dominated by coal-fired generation plant which, with the imminent introduction of carbon pricing in Australia, is a situation that is likely to change significantly over coming decades. In the context of a liberalised power market there are a number of key factors that currently argue against the introduction of nuclear power in Australia. These are:

- Tthe financial viability of nuclear power based upon current (Generation III+) technology;
- The inflexibility of nuclear power for load following given a significant amount of wind capacity in the NEM;
- Lack of access to suitable waterside sites;
- Lack of suitably qualified nuclear engineers; and
- Public opposition.

None of these factors are insurmountable provided that Generation IV technology can address the first three issues and simultaneously convince the finance sector that such investments would be financially viable, and that the Commonwealth and Australian universities can establish a national regulatory regime for nuclear power and appropriate training in nuclear engineering, respectively.  Thereafter the nuclear industry would have to convince the Australian public of the virtues of a technology that, to date, they have failed to embrace.

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## Endnotes

1 The 450 scenario depicts a world in which collective policy action is taken to limit the long-term concentration of greenhouse gases in the atmosphere to 450 parts per million of CO2 equivalent.

2 The Olkiluoto reactor in Finland is widely regarded as a special case. It is not being built for an electricity utility but rather for a consortium of industries who will guarantee to take all power on a “not-for-profit” basis. It will not therefore compete in the Nordic electricity market. Overnight construction costs were reported to be €3.2 billion (€2000/kW), with finance being provided by the Bayerische Landesbank (€1.95 billion) at a nominal interest rate of 2.6%, and loan guarantees of €720 million from the French and Swedish export credit guarantee agencies. It is currently three years behind schedule and the cost over-run is approaching 100 per cent.

3 Construction on the US reactor Watts Bar-2 started in 1972, but was frozen in 1985 and abandoned in 1994. Construction has now restarted and the reactor is expected to start operation in 2012.

4 The so-called Generation III+ design is likely to be the preferred technology choice for OECD countries over the next couple of decades. It differs from Generation III designs in that it incorporates a greater level of passive, as opposed to engineered, safety. It also benefits from standardisation and simplification of design, factors that should offer economies of scale in production, licensing, and operation.

5 The overnight cost of a plant is the cost that would be incurred if the plant were literally built “overnight”. This would include pre-construction costs, engineering, procurement and construction costs, and contingency costs. Interest during construction is not included.

6 Both China and Korea have under-valued currencies which would artificially lower the values in Table 1.

7 AAEC is now known as the Australian Nuclear Science and Technology Organisation (ANSTO).

8 Both of these projections were way off target. Installed electricity capacity from all sources was actually 37.7 GW in 1995 and 46.6 GW in the year 2000.

# 3. Nuclear power in Australia's energy future

## Tony Wood

Tony Wood discusses the policy challenges confronting Australia's transition from its comparative advantage in coal and natural gas to a decarbonised economy.

**Tony Wood** has more than 30 years' experience in the fertiliser, chemical, transport and energy industries.

He was an Executive General Manager for Origin Energy, a major, listed Australian energy company, from 2002 to 2008.

Tony is the Program Director, Energy at the Grattan Institute, and also works with the Clinton Foundation in the role of Director of the Clean Energy Program, where he leads their activities on accelerating the deployment of low emission energy technologies in the Asia-Pacific Region and coordinates their international partnership with the Global CCS Institute.

He is on the Executive Board of the Committee for Melbourne and he was seconded to the Garnaut Climate Change Review in 2008.

Tony is a member of the Northern Territory Chief Minister's Green Energy Taskforce and in late 2010 chaired a medium-scale solar working group for the Victorian Government.

## Introduction

Nuclear power has not been relevant to the public debate for many decades. Australia has had considerable comparative advantage in the availability and cost of primary energy resources, particularly for stationary energy. Large coal and natural gas reserves have meant that we have had the relative luxury of using fossil fuels for domestic energy supply, while exporting both of these fuels and also uranium to an increasingly energy hungry world.

Many of Australia's export markets do not have such luxury of choice. In the case of uranium, the availability of domestic fossil fuels has led to the generally bipartisan policy exclusion of nuclear energy, and limited real political debate on the direct and related issues of relative cost, waste management and weapons proliferation.

Recognition of the need to address climate change is now accepted on a bipartisan basis. Whatever policy approach is adopted to address this need, the implications for an energy supply dominated by fossil fuels are that the previous assumptions are no longer valid and previously accepted wisdom is no longer a sound basis for public policy on energy. In this context, a fully informed public debate on the merits of nuclear power for Australia is both merited and responsible.

## The challenge of decarbonising within 40 years

For many decades Australia's stationary energy supply has been based on accessible and abundant coal and natural gas, to the economic benefit of all Australians. A direct consequence is that our electricity is among the highest in the world in terms of tonnes of greenhouse gas emissions – primarily $CO_2$ – per unit of electricity. This is also behind our unenviable position at the head of the global league table of greenhouse gas emissions per capita.

Australia's electricity has to be close to zero emissions within 40 years if the nation is to contribute to a global objective of even a 50 per cent chance of constraining future global temperatures to the level agreed in Copenhagen by the countries of the world in 2009. In numerical terms, this means reducing the greenhouse gas intensity of electricity supply from more than 0.8 tonnes of $CO_2$ per MWh to less than 0.1 tonnes per MWh. At the same time the underlying energy demand is growing because of economic and population growth. Technological developments, such as the adoption of electric vehicles for transport, may also significantly increase future electricity demand.

Such a reduction in emissions represents a fundamental transformation of the electricity supply system, and will require a very different supply portfolio from that which exists today.

## Plausible futures and the underlying assumptions

Australian Government projections indicate that, to achieve this transformation, we could move from supply dominated by coal to one dominated by renewable energy and coal and gas with carbon capture and storage (CCS). In Treasury's projections, geothermal power could supply the largest share of the renewable mix. The challenge represented by such a projection is made more stark when we recognise that none of our electricity supply today involves either geothermal or CCS technologies and neither has been proven on a commercial scale in Australia.

> "The reality of climate change has removed the easy options of the past. The possibility of 100 per cent dependence on renewable energy in some form, or combination of forms, may be the longer term prize. In the meantime, policy makers have to contend with maintaining secure and reliable energy supply at affordable prices within an emissions-constrained environment. Fossil fuel power with CCS and nuclear power have the potential to form a major part of the short-medium term set of options."

Projections of this nature are based on complex economic and technology modelling and cannot be used as forecasts, although they are sometimes misused in precisely that manner. Those with the best data or the loudest voices on future technology costs tend to have a vested interest in presenting such data in a particular way, not necessarily the most credible. Inherent in the above projections are three central and almost obvious assumptions:

- Only technologies understood today can be effectively modelled;
- The projected mix of supply technologies is determined by forecasts of costs for each technology and physical constraints such as wind availability and the need for grid stability. The range of such cost forecasts is wide and widest for those technologies at the earliest stages of development; and
- Existing policy positions, such as "no nuclear", act as a further constraint in government modelling.

It would be at best naive, and at worst dangerous, to base policy primarily on such projections. For example, geothermal energy may turn out to take much longer to develop to commercial scale and may be considerably more expensive, while the parasitic energy load of CCS may turn out to remain much higher than the modelled assumptions in the published Treasury projections. On the positive side, solar thermal at scale may turn out to be much cheaper than assumed. A policy, or policy framework, that was based on the validity of the modelled assumptions without allowing for alternative outcomes could adversely impact on future energy security and/or costs. Therefore, in what way might the modelling of energy scenarios be used to inform today's policy considerations?

Firstly, while a winning technology may emerge in an emissions-constrained future, it is not at all clear which, if any, of those already identified, would be such a winner.

Secondly, the future cost of electricity could be considerably higher or lower than the central assumptions in the projections.

Thirdly, governments would be wise to make policy choices today that keep open the widest set of options for the future.

Exclusion of nuclear power rules out a technology that, on the basis of most plausible sources, could contribute substantially to Australia's future energy supply mix and may lower the overall cost in doing so. In his 2008 Climate Change Review, Ross Garnaut noted that if nuclear costs tended towards the lower end of the range of forecasts, and if CCS costs did the opposite, it would be in Australia's interest to review the current policy position that excludes nuclear power from the mix.

## The benefits of nuclear power

Nuclear power has the potential to provide a major source of electricity at competitive costs and with near zero greenhouse gas emissions. It is viewed that way by many countries today. Underlying support for nuclear power around the world led to recent reports such as that in *The Economist* suggesting that the world is embarking on a period of substantial growth in nuclear power, driven mainly by China, Russia and South Korea. Every country will have individual reasons that drive such choices; however they are likely to include some mix of reliability, cost, security and low emissions.

## The challenges of nuclear power

While nuclear power has this potential, real challenges exist. There is, as yet, no long term waste storage solution, safety and security concerns have been heightened post-Fukushima and resources constraints may emerge for both uranium supply and skilled people.

The recent incident in Japan has triggered individual country responses ranging from safety reviews through to fundamental moves away from nuclear power. This is also exemplified by Siemens' announcement that they will not build nuclear power stations in the future. Recent projects in the West do not have a good track record of completion within time and cost budgets. The absence of low-emission demand drivers, such as policies to price or constrain greenhouse gas emissions, is just as much a barrier for nuclear power as it is for other low-emission energy technologies. While the proposed Clean Energy Futures policy package will price carbon emissions, its future is far from certain. These last two challenges caused Citigroup to conclude in 2009 that the economics of nuclear power say "not in the West", unless governments take control or assume responsibility, at least for the price risk.

## Lead times in long term policy considerations

In common with any other major infrastructure project, the process to deploy a new nuclear power station on a greenfield site would be expected to follow a path of feasibility study, site selection, environmental impact assessment etc, through to tendering, construction and commissioning. This could take 10–15 years or more. In a country such as Australia, this would only happen if it was preceded by a political openness to the nuclear power option, public engagement and then political commitment. While these factors could shift quickly as with all things in politics, it is difficult to see such a shift occurring in less than five years. In a practical sense, Australia is running out of time to enable the deployment of nuclear power generation if it is to materially contribute to a decarbonised electricity supply portfolio by 2050.

> "Despite the tantalising fascination of new and exotic technologies, the issue is not primarily one of technology. Once the externality of the environmental impact of greenhouse gas emissions has been internalised through a mechanism such as an emissions trading scheme, the issue becomes one of economic policy."

## How might we think about the nuclear option?

In the absence of the necessity to respond to man-made climate change, the debate around nuclear power for Australia would not need to take place for many decades. The same applies to all other forms of low-emission technologies, including renewable energy. Reserves of coal and natural gas would have provided that comfort. However, much as we might wish otherwise, this is no longer the reality that faces us.

None of the technologies included in credible projections of Australia's energy supply mix in an emissions constrained future are without significant challenges. Coal and gas power generation with CCS remain unproven at integrated scale and current variants are a long way from achieving projected future cost reductions. Geothermal power, with the attraction of being a "base-load" renewable supply source, is impossible to ignore, even though technical breakthroughs seem as far off today as they were five or more years ago. Wind power has been quite successful with legislative support and continues to grow. However, it is likely to become increasingly expensive and/or meet increasing community opposition as favourable sites are exhausted. Although output is reasonably predictable over periods of weeks and months, intermittency of wind generation will curtail its contribution to the mix. As with wind, solar PV is an intermittent supply source and costs are still high. Solar thermal, coupled with gas or heat storage and built at optimal scale, may become commercially attractive. However, it is still at a relatively early stage of development, and correspondingly remains expensive. There are no easy or obvious solutions.

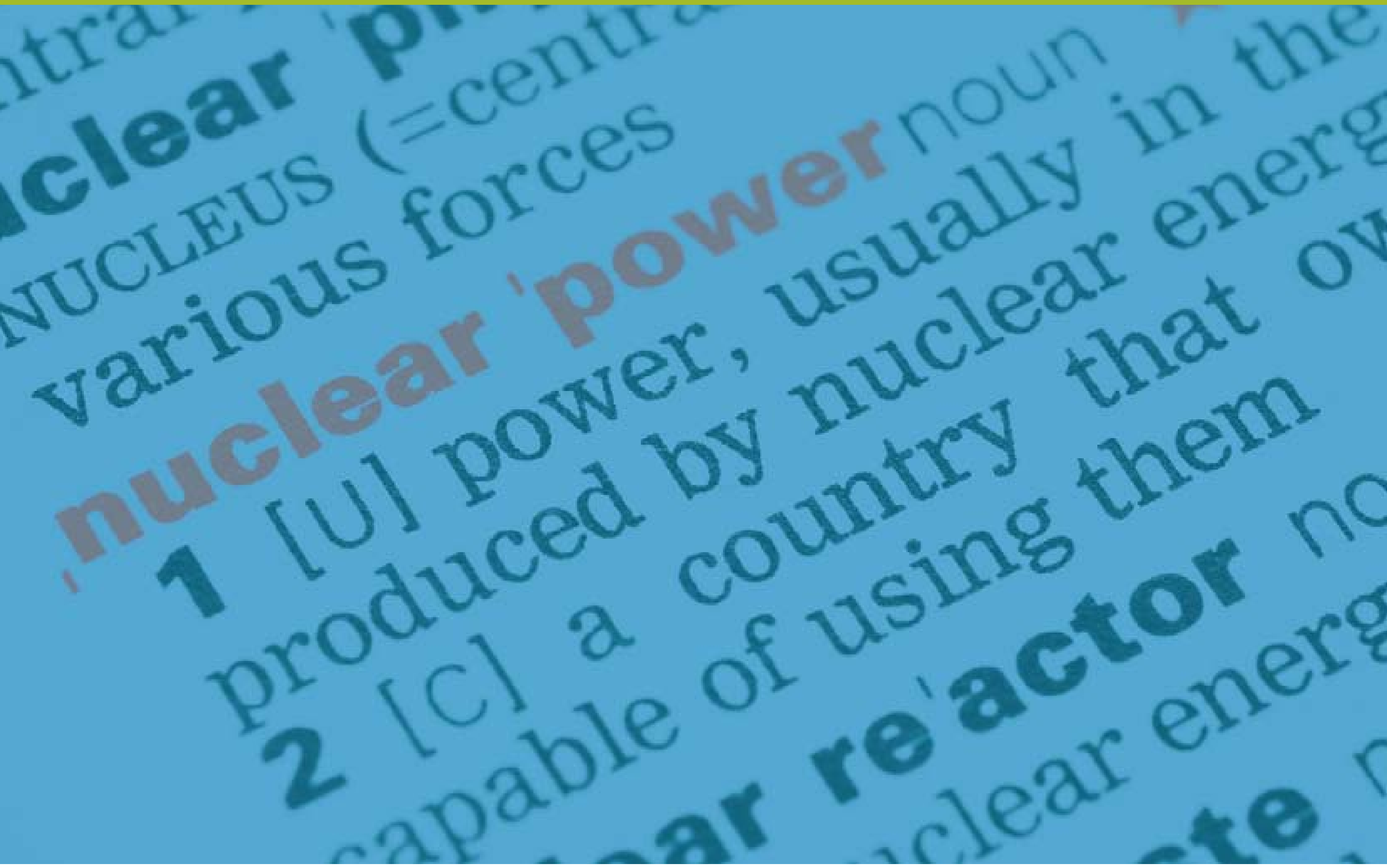
Despite the tantalising fascination of new and exotic technologies, the issue is not primarily one of technology. Once the externality of the environmental impact of greenhouse gas emissions has been internalised through a mechanism such as an emissions trading scheme, the issue becomes one of economic policy. Such a scheme is the first and central plank in an effective and efficient climate change policy response platform. There are sound theoretical and practical reasons why relying solely on such a scheme is unlikely to deliver an optimal mix of technologies, given long lead times and the range of current technology risk profiles.

> "In Treasury's projections, geothermal power could supply the largest share of the renewable mix. The challenge represented by such a projection is made more stark when we recognise that none of our electricity supply today involves either geothermal or CCS technologies and neither has been proven on a commercial scale in Australia."

Australian governments do not, however, have a good track record of picking and backing technology winners, a record shared with many other countries. On balance, a well crafted technology options strategy is likely to be an effective complement to the central policy instrument.

## Conclusion

Australia does not have an easy policy choice. The reality of climate change has removed the easy options of the past. The possibility of 100 per cent dependence on renewable energy in some form, or combination of forms, may be the longer term prize. In the meantime, policy makers have to contend with maintaining secure and reliable energy supply at affordable prices within an emissions-constrained environment. Fossil fuel power with CCS and nuclear power have the potential to form a major part of the short-medium term set of options. To exclude the nuclear power option from the serious policy debate could prove to be both short-sighted and costly for all Australians.



# 4. Small modular reactors

## Tony Irwin

Tony Irwin describes technological progress in Small Modular Nuclear Reactors which have the potential to fundamentally change the economics of the energy sector.

**Tony Irwin** is a Chartered Engineer who worked for British Energy (formerly the Central Electricity Generating Board) in the UK for more than 30 years commissioning and operating eight nuclear power reactors. Following the Chernobyl accident he was a member of a World Association of Nuclear Operators (WANO) mission that reviewed operating practices at Russian RMBK reactors. In 1999 he moved to Australia and joined the Australian Nuclear Science and Technology Organisation (ANSTO) and was reactor manager during the construction and operation of the OPAL research reactor. Since retiring from ANSTO in late 2009, he is a visiting lecturer for masters courses in nuclear science at the ANU and University of Sydney. Tony is also the Chairman of the Engineers Australia Nuclear Engineering Panel.

## Introduction

Small Modular Nuclear Reactors (SMRs) can supply low emissions, high capacity factor, reliable power in remote locations or for small grid systems. They represent a new stage in nuclear reactor design and have the capacity to provide an economically competitive method of electrical power generation.

The designs of SMRs will enable:

- Factory produced modules, ensuring economies of scale and potentially eliminating the major up front capital costs of nuclear reactors;
- Passive safety systems to provide enhanced security;
- Reduced requirements for technical workforces to install and maintain nuclear power plants; and
- A wider range of deployment options, including remote locations and for specific purpose energy generation, such as desalination plants.

The following paper details the type of technology that may be suitable for Australia and possible uses, key features, including safety, size and construction times, and examples of current uses.

## Evolution of nuclear power: Bigger was more economical

Historically nuclear power plants have been built larger and larger. This trend was an attempt to obtain economies of scale in deployment to overcome the high fixed construction costs. As a consequence, modern nuclear power plants incurred substantial financial costs and required large, well connected electricity grids. There were limited options for deployment of such energy generators in Australia.

The first commercial nuclear power plant connected to the grid was Calder Hall in 1956, located on the north west coast of England. It had an output of 40 MWe (enough electricity to supply 20,000 households). By the 1970s nuclear power generators were commonly producing an output of 900 MWeN (nett electrical output). In France, the standard unit had an output of 900 MWeN units and increased to 1300 MWeN in the late 1980s, and finally 1450 MWeN in the 1990s. Currently a 1650 MWeN Evolutionary Pressurised Water Reactor (EPR) is being built at Flamanville in France, which will supply the electricity demands of more than 800,000 homes.

Nuclear power stations of this magnitude are suited to areas with large local electricity demands or countries where there are large interconnected grid systems enabling large power transfers. In Europe for example, there is an extensive grid system enabling transfers between countries to meet demand.

There is a rule of thumb that an individual generating unit should not exceed 15 per cent of the grid capacity. This enables the grid to remain stable on the loss of the largest generating unit.

For many countries, and for isolated remote locations, current unit sizes are too large, and a market is emerging worldwide for SMRs. This new form of nuclear power plant is particularly suitable for remote locations and a market with relatively small electricity demand, like Australia. The capital cost advantage per kW installed capacity of larger reactors may soon be offset by modular factory built construction reducing the capital cost per kW installed capacity of SMRs.

Historically, the main driver for a country adopting nuclear power for electricity generation has been energy security. Many countries (for example France, Germany and Japan) turned to nuclear power in the 1970s when the cost of oil quadrupled. While energy security is still a major consideration, climate change is also emerging as a new driver for nuclear power, due to its near zero GHG emissions.

## The future of nuclear power stations: Small Modular Reactors

The International Atomic Energy Agency (IAEA) defines “small” as less than 300 MWe but many SMRs have outputs in the range 25–100 MWe. Depending on the technology, many SMRs designs can incorporate the following features:

- Provide power in remote locations where transport of fossil fuels for conventional electricity generating plant is expensive;
- Provide baseload power for small grids;
- Near zero emissions;
- Compact - small site area per kW installed capacity;
- Modules can be easily added as extra capacity is required;
- Electricity, steam and co-generation;

- Balance of plant equipment is conventional off-the-shelf steam turbine/alternator, pumps and electrical system;
- Turbine condenser that can be aircooled in remote locations where water supplies are restricted;
- Reliable, high capacity factor, not affected by weather conditions;
- Compact factory built transportable module;
- Economy and high quality assurance of factory mass production of a simple, standard design;
- Main modules are factory built, minimising on-site construction time / costs and reducing the probability of project delays;
- Simple design to operate and maintain (low maintenance costs for passive systems);
- High level of passive or inherent safety;
- Reactor modules are delivered with the fuel already installed, eliminating the need for initial fuel loading on site;
- Long periods between refuelling (eight–10 years, up to 30 years for some designs);
- Sealed core which is returned to the factory for refuelling, reducing the possibility of unauthorised interference with nuclear materials (proliferation resistant);
- Low and stable fuel costs (fossil fuel costs, particularly gas are expected to continue to rise);
- Fuel costs typically only 25 per cent of the production costs;
- Smaller initial capital investment compared to a large reactor;
- Sixty year life; and
- Reactor containment can be installed below ground providing protection against external hazards and unauthorised interference.

The possible uses for SMRs in Australia include powering Australian Defence Force sites, remote mining locations, large industrial sites requiring reliable, competitive cost electricity or process heat supplies, desalination plants, water treatment plants, recycling schemes or irrigation systems and baseload electricity supply for small grid systems.

A major advantage of SMRs is their passive safety. No electrical supplies or pumps are required to cool the reactor, as this is achieved by natural convection and gravity coolant feed. This feature ensures the reactor will remain safe under severe accident conditions. This also reduces the capital and maintenance costs compared to large power reactors and fundamentally changes the economic equation in favour of SMR nuclear power generation.

A modern 1,000 MWe nuclear power plant produces around 150 $m^3$ / year (two shipping containers) of low level radioactive waste (resins, filter cartridges, etc). This low level waste requires no shielding and needs to be stored for a relatively short period, less than 300 years. In most countries it is stored in concrete lined trenches in a near-ground surface repository. Due to its smaller size and simpler design, a SMR will only produce a fraction of this amount of waste, less than one small shipping container per year. There will also be a small amount of intermediate level waste, less than a fridge full, which can be stored on site in a shielded container. The long core life of many SMRs means fewer spent fuel assemblies to store, and there is the possibility in the future that spent fuel assemblies will be able to be used as fuel for large fast neutron reactors.

There is extensive experience of much of the technology employed by SMRs. For many years they have been the power supply for submarines and icebreakers, where totally reliable power with long periods between refuelling is essential. However, their commercial deployment has yet to be proven.

SMRs can be classified into three main types depending on the technology employed:

1. Light water reactors
2. Fast neutron reactors
3. High temperature gas reactors

## 1. Light water reactors

### Key features of Small Modular Light Water Reactors:

- Most common power reactor type, proven technology, extensive experience
- Uses cheap demineralised water as the primary coolant
- Natural coolant circulation and passive back-up systems for safety
- Coupled to standard turbine/generator as used in fossil fuelled plant

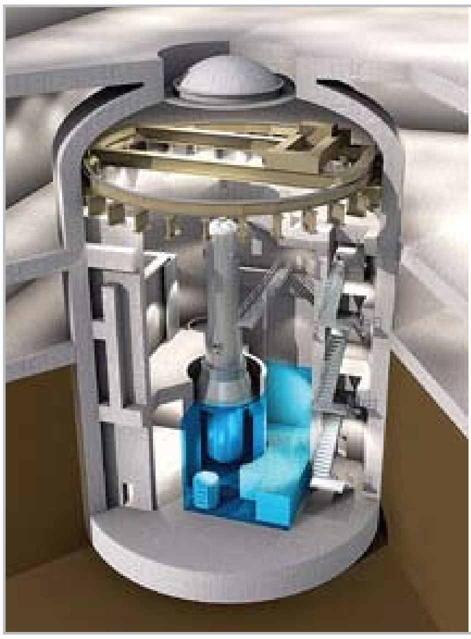
The majority (90 per cent) of nuclear reactors worldwide are known as Light Water Reactors because they use water as the primary coolant.

The most common power reactor type worldwide is the Pressurised Water Reactor (PWR), a type of light water reactor, originally based on the US naval reactor used for submarines. In a PWR, the primary coolant water is kept under sufficient pressure to prevent it from boiling, and the heat extracted from the nuclear fuel is transferred to a secondary water circuit in a heat exchanger where steam is produced to drive a turbine.  Fuel assemblies are similar to existing designs for large power reactors so there is no major development required. PWR technology has been licensed for more than 50 years so that the design certification process for a PWR SMR should be quicker than that for a more advanced innovative design.

Examples of Light Water SMRs and specifications based on this technology:

### Babcock & Wilcox (B&W) mPower reactor

B&W has over 50 years experience in manufacturing compact PWRs with long core life for the US navy.



**125 MWe Integral PWR**

- Reactor pressure vessel containing core and steam generators
- Complete module 4.5m in diameter and 23m high
- Factory built, rail shippable
- Thirty-six months construction
- Secure underground containment
- Simple passive safety
- Air cooled condenser for remote locations

Source: Babcock&Wilcox Nuclear Energy Systems, Inc

**B&W mPower reactor vessel with integral steam generator**

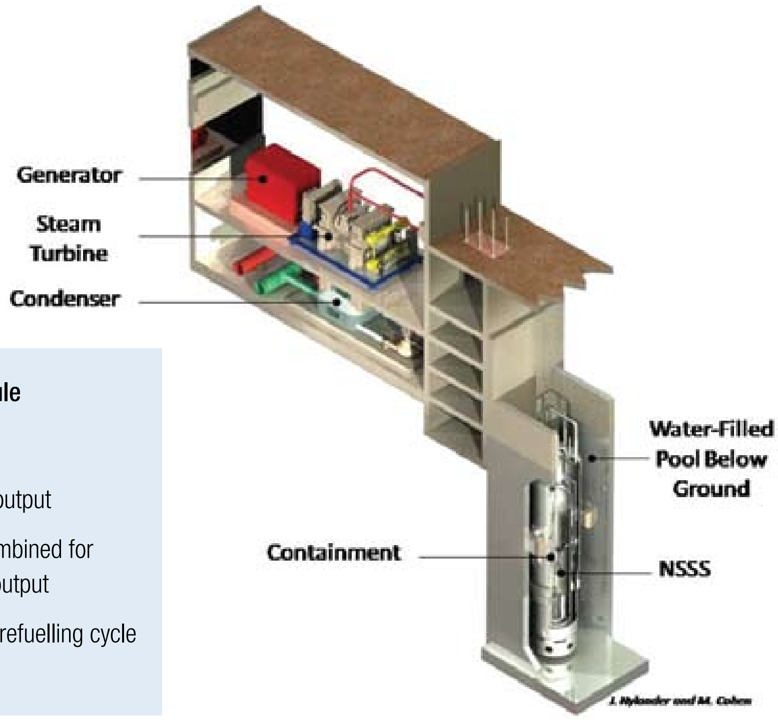
- Reactor pressure vessel 3.6m in diameter and 22m high
- Standard PWR fuel assemblies
- Five year operating cycle
- No active core cooling systems
- Passive decay heat removal
- Sixty year life

Source: Babcock & Wilcox Nuclear Energy Systems, Inc

B&W has constructed a test facility at the Centre for Advanced Engineering and Research (CAER) in Virginia. A scaled prototype is being constructed to support licensing.

### NuScale Power

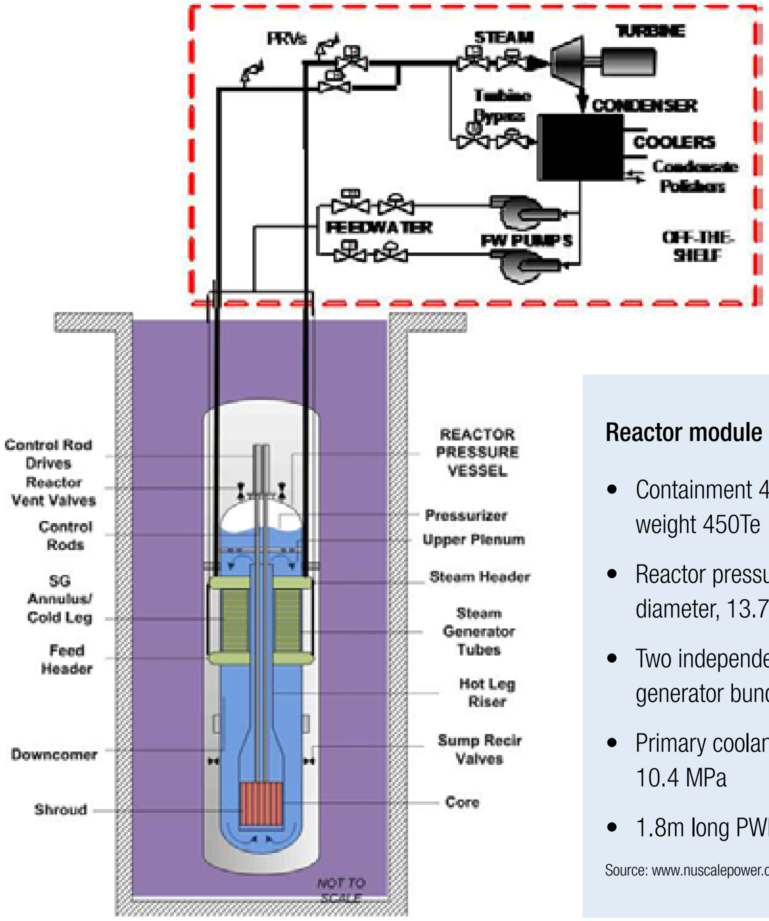
The technology for this small PWR originated in the US Department of Energy and was further developed by Oregon State University. It is now being commercially developed by NuScale Power Company.



**NuScale Power Module**

- 150 MWTh PWR
- 45 MWe electrical output
- Modules can be combined for required electrical output
- Twenty-four month refuelling cycle

Source: www.nuscalepower.com



**Reactor module**

- Containment 4.3m diameter, 18m high, weight 450Te
- Reactor pressure vessel 2.7m diameter, 13.7m high
- Two independent integral steam generator bundles, helical tubes
- Primary coolant natural circulation 10.4 MPa
- 1.8m long PWR fuel assemblies

Source: www.nuscalepower.com

Projected cost is US$4,000 per kW installed which compares with the $3,400/kW quoted for the Flamanville EPR (1650MWe) and approximately $3,000/kW for the Westinghouse AP-1000 (1200 MWe).

### Barriers to commercial deployment

- No US NRC (Nuclear Regulator Commission) design certification;
- No prototype with a proven operating record; and
- No factory for mass production.

### Timescale

- US NRC application for design certification 2012;
- Design certification 2014; and
- First operating unit 2018.

> "For many countries, and for isolated remote locations, current unit sizes are too large, and a market is emerging worldwide for Small Modular Reactors. This new form of nuclear power plant is particularly suitable for remote locations and a market with relatively small electricity demand, like Australia."

Other light water SMRs include:

**Westinghouse SMR** – 200 MWe PWR with passive safety features. Steam generator above the core. Module 4m in diameter and 25m high, installed below ground level. Application for US design certification is expected by 2012.

**South Korea SMART (System Integrated Modular Advanced Reactor)** – 330 MWTh/100 MWe PWR with integral steam generators designed by the Korea Atomic Energy Research Institute (KAERI). Three year refuelling cycle and 60 year life.

**Argentina CAREM** – 100 MWTh, 27 MWe PWR with integral steam generators designed by INVAP (the designer of ANSTO's 20 MWTh OPAL research reactor). Primary cooling by natural circulation.

**France AREVA NP-300** for power, heat or desalination based on the French nuclear submarine design, with passive safety systems. 50 – 250 MWe.

**Russia Akademik Lomonosov** – two KLT-40S reactors normally used to power icebreakers are being installed on a 20,000 Te barge to provide floating nuclear power for remote areas. Construction should be completed in 2011.

## 2. Fast Neutron Reactors

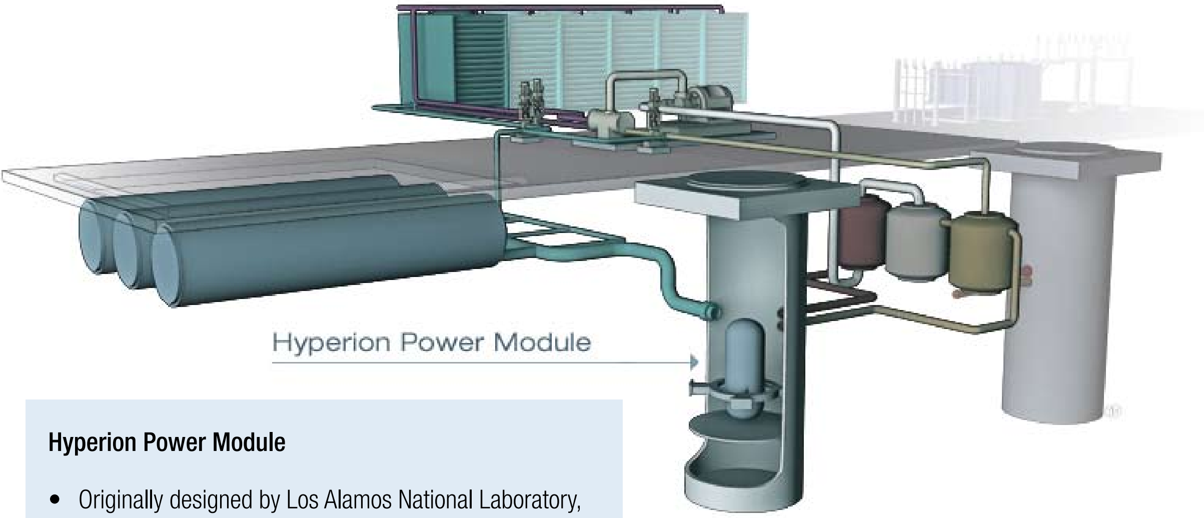
### Key features of Small Modular Fast Neutron Reactors

- Very compact design due to high conductivity liquid metal coolant;
- Higher efficiency than light water reactors due to higher operating temperature;
- Very long operating time between refuelling (30 years); and
- Inherent safety features.

Unlike the thermal neutron PWR, where the water slows down (moderates) the neutrons produced in the fission process, a fast reactor has no moderator and is smaller, simpler and has better fuel performance. There is extensive experience of fast reactor technology dating back to the 1950s, but new materials now available will enable the full potential of these systems to be realised. Fast reactors only require refuelling at very long intervals – up to 30 years. They operate at or near atmospheric pressure (this minimises plant stresses) and are inherently safe with a negative temperature coefficient which means if the temperature rises, the nuclear reaction is slowed and the power reduces. They are normally cooled by liquid metals with high conductivity and a high boiling point such as sodium, lead or lead-bismuth. Fast neutron SMRs have outlet temperatures of 500°C, and hence improved thermal efficiency (compared to thermal reactors). This outlet temperature is also suitable for hydrogen production. They typically use natural convection primary cooling systems and have passive back-up cooling systems which means that they do not rely on external power sources for safety.

Examples of fast reactor SMRs:

**Hyperion Power Module**



**Hyperion Power Module**

- Originally designed by Los Alamos National Laboratory, USA, now being commercially developed by Hyperion Power.
- Power 70 MWTh, electrical output 25 MWe
- Can also be configured for steam or co-generation
- Containment vessel 1.5m wide and 2.5m high
- Weight < 50 Te
- Coolant lead-bismuth
- Sealed core, refuelling interval eight–10 years, return to factory
- Sited underground
- Projected cost US$2,000/kW installed capacity when in mass production

Source: www.hyperionpowergeneration.com

### Barriers to commercial deployment

- Safety case needs to be developed to demonstrate safety under all accident situations;
- No US NRC design certification; and
- No prototype in operation.

### Timescale

- Application for US design certification 2012;
- US NRC design certification 2015; and
- Prototype in operation 2018.

Other small modular fast neutron reactos include:

**Toshiba 4S (Super-Safe, Small and Simple)**
Developed by Toshiba and the Central Research Institute of Electric Power Industry (CRIEPI) in Japan in collaboration with Westinghouse USA. 10 MWe or 50 MWe versions, sodium cooled, electromagnetic pumps, 550°C outlet temperature and passive safety features. Operates for 30 years without refuelling. The above ground turbine building occupies an area of 22m by 16m by 11m.

The first 4S SMR could be installed to provide electricity to the remote community of Galena in Alaska. The project started in 2004, and application for design certification is planned for 2012. Projected engineering, procurement and construction (EPC) cost is US$2,500/kW installed capacity, power cost is US$50–70/MWh.

**SSTAR (Small Sealed Transportable Autonomous Reactor)**
Developed by Lawrence Livermore, Argonne and Los Alamos National Laboratories in the USA. Factory fabricated, cooled by lead-bismuth with integral steam generator, 564°C outlet temperature. Sealed unit 3.2m in diameter and 12m high, installed below ground level. Thirty year life without refuelling. Main development is of a 45 MWTh/20 MWe version.

## 3. Very High Temperature Gas Reactor (VHTR)

### Key features of Small Modular Very High Temperature Gas Reactors

- Capable of operating at very high temperatures for hydrogen production or high efficiency (50 per cent) electricity generation;
- Proven fuel technology; and
- Inherent safety features due to fuel type and gas coolant.

This technology also dates back to the 1960s and reactors were built and operated in the UK, Germany and the US. The fuel is in the form of TRISO (tristructural isotropic) particles, <1mm diameter, combined with graphite and silicon carbide into pebbles or prisms and is stable to over 1600˚C. The preferred coolant gas is helium, with outlet temperatures up to 1,000˚C, enabling the reactor to be coupled to a Brayton cycle gas turbine/alternator with up to 50 per cent unit efficiency possible.

The VHTR is one of the six reactor types selected by the *Generation IV International Forum* in 2002 for future nuclear energy systems that would excel in safety, sustainability, cost-effectiveness and avoidance of misuse of nuclear materials (proliferation resistance). The VHTR is a US priority for the next generation reactors and fuel irradiation experiments and qualification of high temperature materials are in progress.

> "The possible uses for small modular reactor in Australia include powering Australian Defence Force sites, remote mining locations, large industrial sites requiring reliable, competitive cost electricity or process heat supplies, desalination plants, water treatment plants, recycling schemes or irrigation systems and baseload electricity supply for small grid systems.
>
> A major advantage of SMRs is their passive safety. No electrical supplies or pumps are required to cool the reactor, as this is achieved by natural convection and gravity coolant feed. This feature ensures the reactor will remain safe under severe accident conditions."

## Examples of VHTRs

**HTTR (High Temperature Test Reactor)**
Built by the Japan Atomic Energy Research Institute (JAERI), this 30 MWTh unit started operating in 1998. Based on the HTTR, JAERI is developing larger modules.

**HTR-10 (China)**
Ten MWTh high temperature gas cooled experimental reactor at the Institute of Nuclear and New Energy Technology (INET), Tsinghua University, north of Beijing. Started operating in 2000 at 700˚C, potential to 900˚C. Construction of larger versions approved in principle.

**PBMR (South Africa)**
The Pebble Bed Modular Reactor (PBMR) was developed by ESKOM in South Africa based on the 1980s German designs. The project reached an advanced state before the South African government removed funding in 2010.

## Barriers to commercial deployment

- Funding for development;
- Further development of high temperature materials required;
- No commercial sized (25 MWe) prototype operating; and
- No certification of a commercial sized reactor by a nuclear regulator (US NRC would be the preferred regulator).

## Timescale

- Construction of a commercial sized prototype 2015.

### Major issues for deployment of SMRs in Australia

- Change of law to allow licencing and construction of a nuclear power reactor for electricity generation in Australia;
- Changes in ARPANSA (Australian Radiation Protection and Nuclear Safety Authority) or establishment of a new nuclear regulator for licensing of nuclear power reactors;
- Availability of low level radioactive waste facility in Australia;
- Availability of SMRs with US design certification and proven operating record;
- Commitment of an electricity generation company, mining company or other organisation to a SMR program; and
- Identification of a suitable site.

### Timeline for deployment of SMRs in Australia

Following a change of law:

- + three years EIS (Environmental Impact Statement) for an identified site;
- + six years construction and operating licence; and
- + 10 years SMR in commercial operation.

## Conclusions

Any reactor design would still have to be licensed by an Australian nuclear regulator, following the required change in Australian law to allow a power reactor to be built in Australia. However, if this occurred new nuclear technologies coming on stream offer genuine options for Australia.

Small Modular Reactors are an option for electricity generation, process heat, and co-generation particularly for remote sites in Australia where transport of fossil fuel for conventional generating plant is expensive.

Light water SMRs could be US certified by 2015 and available before 2020.

Fast neutron SMRs may be available in the same time scale and could offer the advantage of very long intervals between refuelling and higher efficiency.

# 5. Opportunities in the nuclear fuel cycle

## Dr Tom Quirk

Dr Tom Quirk provides an overview of the nuclear fuel cycle and examines the potential opportunities where Australia could make a valuable contribution and enhance its economic prosperity.

**Dr Tom Quirk** trained as a nuclear physicist at the University of Melbourne. He has been a Fellow of three Oxford Colleges and has worked in the United States at Fermilab, the universities of Chicago and Harvard and at CERN in Europe. In addition he has been through the Harvard Business School and subsequently worked for Rio Tinto. He was an early director of Biota, the developer of an influenza drug. In addition he has been a founding director of the Victorian Power Exchange, Deputy Chairman of VENCorp, which managed the transmission and wholesale natural gas market and system planning for the electricity market in Victoria, and Chairman of Victrack, the owner of the railway assets in Victoria.

## Introduction

Australia has the potential to benefit extensively from its strategic position as an industrialised net exporter of energy. In particular, there are a number of elements of the nuclear fuel cycle where Australia could make a valuable contribution and enhance its economic prosperity.

Australia's reserves of uranium are the world's largest, with at least 23 per cent of the world total. While Australia is the third largest producer of uranium oxide, behind Kazakhstan and Canada, there is still considerable scope to expand exports of uranium given the unfavourable regulatory regimes operating in a number of States. Australia could also provide valuable reprocessing and disposal services that have the potential to generate up to US$16 billion annually.

There are significant opportunities for Australia to add value to the nuclear fuel cycle.

## Nuclear fuel cycle

The key stages in the nuclear fuel cycle are:

Front end processing, involving:

- mining with the production of yellowcake (approximately 90 per cent uranium oxides);
- conversion of yellowcake to uranium hexafluoride;
- enrichment of the uranium to three–four per cent U-235; and
- fuel rod fabrication incorporating uranium dioxide pellets in zirconium alloy tubes.

Energy generation, including:

- Loading;
- Burning with a yield of 360 MWh per kg of enriched uranium; and
- Unloading the fuel with local short term (years) storage.

Back end processing that involves:

- Reprocessing to separate fission products from uranium and plutonium;
- Disposal of either the fuel rods or the separated waste; and
- Recycling of reprocessed uranium and plutonium as mixed oxide fuel (MOX).

These stages are set out in Table 1 below.

Australia currently has no business activity beyond mining and has regulatory barriers for a number of activities at other stages. Despite these constraints, Australia has made significant technical contributions to enrichment through Silex Systems and the disposal of spent fuel with Synroc.

If Australia were to take advantage of the opportunities available in the nuclear fuel cycle the majority of the value added steps could be undertaken as stand alone business ventures. The exception is the fabrication of fuel rods which is specialised to particular fuel and reactor designs. As a consequence, this activity is closely tied to the supply of the reactor.

### TABLE 1
### PROCESSES IN THE NUCLEAR FUEL CYCLE

| **Front end processing** |
|---|
| Mining uranium |
| Conversion |
| Enrichment |
| Fuel rod fabrication |
| **Electricity generation** |
| Load fuel |
| Burn fuel in reactor |
| Unload fuel |
| **Back end processing** |
| Reprocess |
| Disposal |
| Recycle |

Back end processing involves both reprocessing and disposal. Reprocessing includes the separation of unwanted fission products from the uranium and plutonium that can be included with fresh enriched uranium in MOX (mixed oxide) fuel. Disposal could involve either complete spent fuel rods or the fission product waste in vitrified form.

## Mining

Australia has three operating mines at the present time, Ranger, Olympic Dam and Beverly (Table 2). These, and a group of some 10 exploration and development prospects, account for probably more than 23 per cent of the world's reserves.

Growing world demand for uranium is creating a substantial opportunity for Australia. Demand for uranium is expected to remain strong. Electricity demand is increasing twice as fast as overall energy use and is likely to rise 76 per cent to 2030. The Asian region is projected to more than double its needs by 2030. Nuclear power generation provided about 14 per cent of world electricity demand in 2007 and despite the events at Fukushima the building of new nuclear power generators will continue. A small displacement with the use of MOX fuels should be expected. In total it is equivalent to about a three year supply of natural uranium.

The only limits to the discovery and expansion of uranium exports come from government regulation. There is now no "three mines only" Commonwealth limit but individual state governments have restrictions. The election of a Coalition government in Western Australia has allowed the resumption of exploration for uranium over some of the most prospective areas in the country. However, unnecessary regulations restrict the capacity of mining companies to export uranium, making it more difficult to establish viable mines.

An often heard claim is that with limited uranium resources there is a limited supply life of 50 years and nuclear reactors are merely a short term source of energy. However, there are two important points to be made. First reserves and resources are determined by the price of the minerals being mined. At one point Energy Resources of Australia (ERA) doubled their uranium reserves not from more exploration and discovery but by lowering the cut-off grade in their mine planning model as the price of uranium had risen way above their assumed planning price. The second point is that there has been very little recent exploration for uranium given the present resources and political constraints. There will be a limit to the resource but there are very substantial global reserves. For the right price uranium can even be recovered from sea water.

**TABLE 2**
**RESERVES, RESOURCES AND PRODUCTION FROM AUSTRALIAN MINES**

| Mine | Reserves tonnes | Resources tonnes | Mining method | Annual production 2010–11 (tonnes) | Annual revenue at $120 per kg millions |
|---|---|---|---|---|---|
| Ranger | 16,000 | 116,000 | Open pit | 2,677 | |
| Olympic Dam | 747,500 | 2,445,000 | Underground | 4,012 | |
| Beverly | | 21,000 | In situ leaching | 347 | |
| **Total** | | | | **7,036** | **US$840** |

Mining uranium has important environmental benefits that extend beyond mitigating carbon emissions. An important comparison in exporting energy is that shipping 10,000 tonnes of yellowcake is the energy equivalent of shipping 200 million tonnes of thermal coal. Australia's present thermal coal exports are around 100 million tonnes. This requires between 3,000 and 4,000 voyages of bulk carriers through environmentally sensitive regions, such as the Great Barrier Reef. Export coal also has an environmental impact through the provision of harbours and railways. Enhancing uranium exports is an environmentally sensitive means of addressing growing global demand for energy.

## Cost of uranium oxide reactor fuel

To determine whether there are additional opportunities for Australia in the nuclear fuel cycle it is necessary to consider the costs associated with obtaining uranium oxide reactor fuel. The three key process segments are mining (discussed above), enrichment, and reprocessing and disposal.

In mid 2011, the approximate US dollar cost to create one kg of uranium as UO2 reactor fuel is shown in Table 3. This table highlights how the majority of the economic value add in the uranium fuel cycle occurs at the point of U3O8, enrichment and the back end of the fuel life cycle, the reprocessing or long term disposal.

**TABLE 3**
**US $ COSTS FOR PROCESSES IN THE URANIUM FUEL CYCLE**

| Process | Amount required | Cost per unit | Total Cost | Fraction of processes | | |
|---|---|---|---|---|---|---|
| Fuel front end | | | | Front | Back | Total |
| $U_3O_8$ | 8.9kg | $120 | $1,068 | 43% | | 30% |
| Conversion | 7.5 kg U | $13 | $98 | 4% | | 3% |
| Enrichment | 7.3 SWU[1] | $150 | $1,095 | 43% | | 31% |
| Fuel fabrication | 1 kg | | $240 | 10% | | 7% |
| **Total fuel in** | | | **$2,501** | 100% | | 71% |
| Fuel back end | | | | | | |
| Reprocessing[2] or long term disposal | 1 kg | | $1,000 | | 100% | 29% |
| **Total fuel cycle** | | | **$3,501** | | 100% | 100% |
| **Fuel cost for front and back ends per MWh** | | | | $7.00 | $3.00 | $10.00 |

Note:
1 SWU Separative work unit for uranium enrichment.
2 Reprocessing is approximately $600 per kg with $400 for disposal of resultant waste
Source: World Nuclear Association

Note that the cost of enriched uranium fuel at US or A$7.00 per MWh is more than the ACIL-Tasman calculations of the short run marginal cost of electricity from brown coal in Victoria at $2 to $5 per MWh. Marginal costs for black coal in New South Wales and Queensland are $6 to $17 per MWh. On the other hand a carbon tax would see these costs increase. A carbon tax of $23 per tonne of CO2 would increase brown coal costs by $35 and black coal costs by $25.

## Conversion and enrichment

The conversion of yellowcake to uranium hexafluoride is a small value adding step and plants are located in countries that have enrichment plants. Table 4 lists the major conversion plants operating at this time.

**TABLE 4**
**CONVERSION PLANTS**

| Company | Plant | Country | Capacity tonnes U as UF6 |
|---|---|---|---|
| Cameco | Port Hope, Ont. | Canada | 12,500 |
| Cameco | Springfields | UK | 6,000 |
| Atomenergoprom | Irkutsk and Seversk | Russia | 25,000 |
| Areva – Comurhex | Pierrelatte | France | 14,500 |
| Converdyn | Metropolis | USA | 15,000 |
| CNNC | Lanzhou | China | 3,000 |
| IPEN | | Brazil | 90 |
| **Total** | | | **76,090** |

Source: World Nuclear Association

A 10,000 tonnes capacity conversion plant operating at full capacity would generate annual revenues of US$130 million. The capital cost to build the plant is in the order of $200 to $400 million.

The development of enrichment plants has evolved with technological advances that have improved the energy efficiency of the process. The first plants were energy intensive and used gaseous diffusion to enrich the uranium. It has been estimated that seven per cent of the US electricity demand was from enrichment plants at the height of the cold war when 90 per cent U-235 was required not the reactor grades of three to four per cent for power generation. The development of centrifuge separation dropped the energy demand dramatically. Most plants use centrifuge technology but diffusion plants still operate in France and the USA.

Laser separation should offer a further reduction in energy needs. This approach may result in a highly profitable business if prices are set by the use of diffusion or centrifuge technologies. Global Laser Enrichment uses the technology developed by Silex Systems of Australia and licensed exclusively to the General Electric Company (GE) in 2006. GE, Hitachi (Japan) and Cameco (Canada) are all investors in Global Laser Enrichment. The technology is moving through development stages and a commercial production facility is being designed in order to obtain an operating licence. This might be granted as early as January 2012.

The lack of interest shown by the larger Australian mining and energy companies, and no doubt the absence of an enabling regulatory regime, has meant that a pioneering Australian technological breakthrough could not be developed in this country. As a consequence, a business opportunity has been lost where the technology should have delivered a major cost advantage over existing operations.

> "If climate change policies force the closing of coal fired base load power stations then nuclear power generation has the viable low CO2 emission replacement technology. Although it may take the experience of brownouts and blackouts before this is seen as a universal truth."

The capital cost of a centrifuge enrichment plant with enrichment capacity of eight million SWU, input capacity of 10,000 tonnes of uranium and an output of 1,500 tonnes of enriched uranium would be of the order of US$3,000 million with annual revenues of $1,000 million.

The capacity and distribution of enrichment plants is shown in Table 5.

**TABLE 5**

**WORLD ENRICHMENT CAPACITY – OPERATIONAL AND PLANNED (THOUSAND SWU/YR)**

| Company | Plant | Country | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|
| Areva | Georges Besse I[a] & II | France | 8,500 | 7,000 | 7,500 |
| | Idaho Falls | USA | 0 | >1,000 | 3,300 |
| JNFL | Rokkasho | Japan | 150 | 750 | 1,500 |
| Urenco | Gronau | Germany | 12,800 | 12,200 | 12,300 |
| | Almelo | Netherlands | | | |
| | Capenhurst | UK | | | |
| | New Mexico | USA | 200 | 5,800 | 5,900 |
| USEC | Paducah & Piketon[a] | USA | 11,300 | 3,800 | 3,800 |
| Global Laser Enrichment | Wilmington | USA | 0 | 2,000 | 3,500 |
| Tenex | Angarsk, Novouralsk, Zelenogorsk, Seversk | Russia | 23,000 | 33,000 | 30-35,000 |
| CNNC | Hanzhun and Lanzhou | China | 1,300 | 3,000 | 6,000-8,000 |
| Various | Kahutab | Pakistan | 100 | 300 | 300 |
| | Resende | Brazil | | | |
| | Rattehalib | India | | | |
| | Natanz | Iran | | | |
| **Total SWU** approx | | | **57,350** | **69,000** | **74–81,000** |
| Requirements (*WNA reference scenario*) | | | 48,890 | 55,400 | 66,535 |

a – Gaseous diffusion plants

Source: World Nuclear Association

The market for fabrication of fuel rods and assemblies is dominated by Areva with 35 per cent of the global market share, Westinghouse-Toshiba with 32 per cent and GNF (Global Nuclear Fuels led by GE with Hitachi and Toshiba) with 18 per cent. Since the fabrication of fuel rods or elements is tied to the construction of new reactors and the supply of established nuclear power plants, there is not an anticipated limit to supply for fuel rod fabrication and assembly.

The most recent estimates of the match between supply and demand for enriched uranium conclude that there is adequate capacity for conversion, enrichment and fuel fabrication. The capacity that does exist could easily be expanded to meet growing international demands.

Uranium enrichment is an important technology under tight international control to prevent the proliferation of nuclear weapons. Despite this some countries have developed nuclear weapons or are believed to be doing so. The new laser separation technology developed by Silex Systems may have substantial implications for weapons proliferations if it substantially reduces the cost of enrichment.

> "Growing world demand for uranium is creating a substantial opportunity for Australia. Demand for uranium is expected to remain strong. Electricity demand is increasing twice as fast as overall energy use and is likely to rise 76 per cent to 2030. The Asian region is projected to more than double it needs by 2030. Nuclear power generation provided about 14 per cent of world electricity demand in 2007 and despite the events at Fukushima the building of new nuclear power generators will continue."

## Nuclear power generation

There are no present plans for nuclear power generation in Australia. However, the time may come for a reassessment of public policy. This will be particularly true if carbon taxes are raised to a point where nuclear power becomes competitive with coal and renewables are unable to provide base load power.

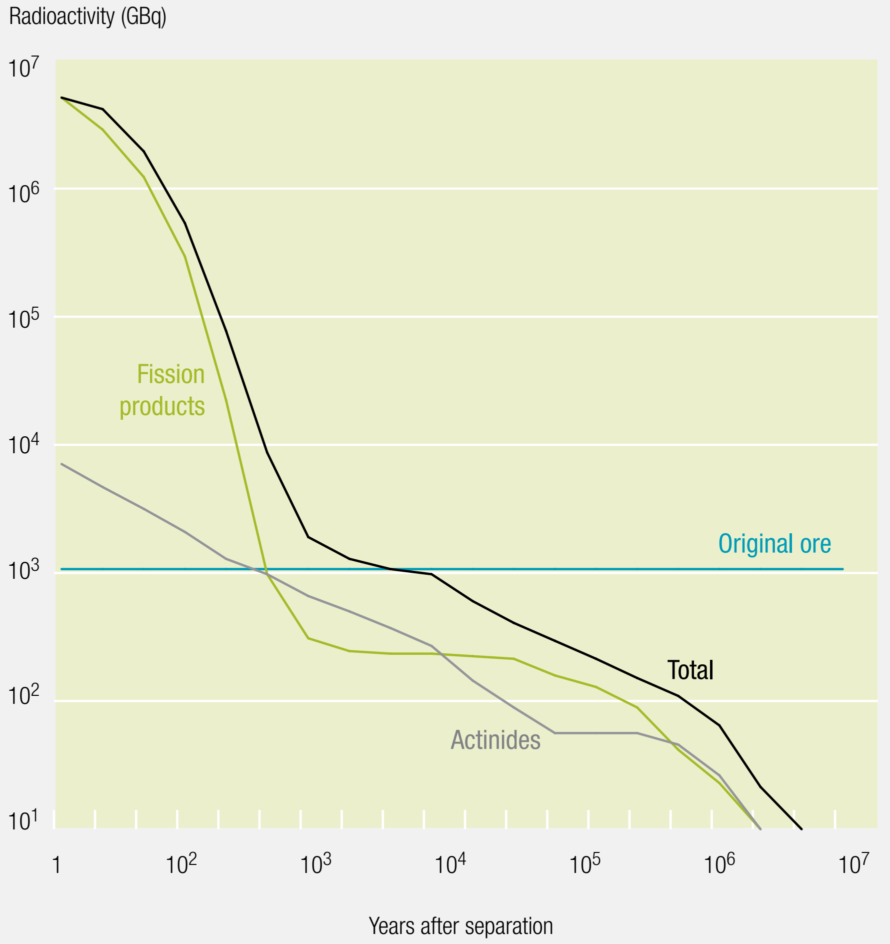
## Reprocessing and disposal

Reprocessing is an important element in the fuel cycle as it enables the recovery of unused uranium and plutonium from the used fuel elements. This closes the fuel cycle, gaining some 25 per cent more energy from the original uranium. In some countries, such as Japan this stage is regarded as contributing to energy security.

A 1,000 MWe nuclear reactor generates about 27 tonnes of spent fuel per year. Reprocessing separates the fission products from uranium and plutonium. After two years in a reactor, the spent fuel is 95 per cent U-238, one per cent U-235, one per cent plutonium and three per cent fission products and transuranic elements (actinides). Reprocessing reduces the volume of material to be disposed of as high-level waste to about one third of that for the spent fuel elements. Also the level of radioactivity in the waste from reprocessing is much smaller and drops off much more rapidly than in the used fuel itself which remains radioactive for tens of thousands of years. This is illustrated below in Figure 1.

**FIGURE 1**

**DECAY IN RADIOACTIVITY OF HIGH-LEVEL WASTE FROM REPROCESSING ONE TONNE OF SPENT PWR FUEL**



GBq = $10^9$ becquerel
The straight line shows the radioactivity of the corresponding amount of uranium ore.
NB both scales are logarithmic
Source: OECD NEA 1996, *Radioactive Waste Management in Perspective*

Some 290,000 tonnes of spent fuel has been discharged from power reactors over the last 50 years. Between now and 2030 an additional 400,000 tonnes of used fuel is expected to be generated worldwide with over half coming from outside North America and Europe. So far, only 90,000 tonnes of used fuel has been reprocessed. This represents a total of 690,000 tonnes of spent fuel that needs to be reprocessed or placed into long term storage.

Annual global reprocessing capacity is some 4,000 tonnes per year for normal oxide fuels but spent fuel is generated at about 12,000 tonnes per year and is anticipated to increase to over 20,000 tonnes per year by 2030. This means there is a shortfall for reprocessing capacity of approximately 8,000 tonnes a year at the moment and this will grow to approximately 16,000 tonnes a year by 2030.

The main reprocessing plants are in France and the UK serving customers world-wide. There is no reprocessing in the United States as this was stopped by President Carter in 1977.

**TABLE 6**
**WORLD COMMERCIAL REPROCESSING CAPACITY**

| Company | Location | Country | Fuel type | Capacity (tonnes per year) | |
|---|---|---|---|---|---|
| Areva | La Hague | France | LWR | 1,700 | |
| Nuclear Decommissioning Authority | Sellafield (THORP) | UK | | 900 | |
| Mayak Production Association | Ozersk | Russia | | 400 | |
| JNFL | Rokkasho | Japan | | 800 | |
| **Total LWR (approx)** | | | | | **3,800** |
| Nuclear Decommissioning Authority | Sellafield (Magnox) | UK | Other | 1,500 | |
| Bhabha Atomic Research Centre | Tombay, Kalpakkam and two at Tarapur | India | | 330 | |
| **Total other (approx)** | | | | | **1,830** |
| **Total civil capacity** | | | | | **5,630** |

LWR Light water reactor

The high level waste from reprocessing is immobilised in a vitrified form. It is shipped back to the country that generated the waste along with the stripped fuel that can be recycled as MOX.

Synroc, invented in Australia, is a ceramic capable of very high loading with radioactive waste. This is important as it reduces the volume of the material needed to immobilise the waste and hence the cost of disposal. It has been used for treating high level wastes generated by military programs in the United States.

In 1991 a Synroc Study Group recommended the establishment of an integrated spent fuel management industry with both Australian and international participation. The objective was the final disposal of high level wastes immobilised in Synroc on an Australian territorial site.

The concept was for the long-term storage and possibly final disposal of waste in a country which was neither the original user of the fuel nor its reprocessor. The potential economic benefits to Australia were very large. Even restricting the waste to Australian-sourced uranium would be a substantial annual market of 1,000 to 2,000 tonnes of spent fuel with $1 to $2 billion annual revenues.

> “Mining uranium has important environmental benefits that extend beyond mitigating carbon emissions. An important comparison in exporting energy is that shipping 10,000 tonnes of yellowcake is the energy equivalent of shipping 200 million tonnes of thermal coal. Australia’s present thermal coal exports are around 100 million tonnes. This requires between 3,000 and 4,000 voyages of bulk carriers through environmentally sensitive regions, such as the Great Barrier Reef.”

However the study also recognised that the political obstacles were substantial.

In the late 1990s the international repository idea was pursued by an Australian company, Pangea, with British Nuclear Fuels and NAGRA, which had a Swiss nuclear cooperative among its shareholders. The project foundered on the political obstacles. The idea is now being developed on a non-commercial basis by Pangea's successor, ARIUS.

It is clear from the limited available reprocessing capacity and the considerable accumulation of spent fuel that long term disposal, if not final disposal, is necessary. Long term disposal would allow future retrieval of the material for reprocessing.

The preferred solution is deep geologic burial. This is under development in Europe (Finland, Sweden) and in the USA possibly at Yucca Mountain although regulatory approval is stalled. In Australia the optimum geology occurs in remote regions of South and Western Australia and the Northern Territory. Such a mine is essentially an underground driveway with access to a number of chambers for the disposal of thousands of tonnes of material. This is not major bulk material handling but rather a high-quality material handling operation.

This repository project would provide the solution to the greatest unmet need of the nuclear fuel cycle, the long term or final disposal of nuclear waste.

> "The lack of interest shown by the larger Australian mining and energy companies, and no doubt the absence of an enabling regulatory regime, has meant that a pioneering Australian technological breakthrough could not be developed in this country. As a consequence, a business opportunity has been lost where the technology should have delivered a major cost advantage over existing operations."

## National and international issues

Any further involvement of Australian companies in the nuclear fuel cycle beyond mining uranium will depend on changing the public perception of nuclear energy. The problems in the nuclear power plant at Fukushima, coupled with the perception of disasters at Three Mile Island and Chernobyl have once again caused politicians and governments to over react to perceived dangers of nuclear power.

However, if climate change policies force the closure of coal fired base-load power stations then nuclear power generation has the viable low $CO_2$ emission replacement technology. Although it may take the experience of brownouts and blackouts before this is seen as a universal truth.

Internationally, Australia has been very thorough in establishing safeguards against the misuse of uranium. Australia is a party to the Nuclear Non-Proliferation Treaty (NPT) as a non-nuclear weapons state. The safeguards agreement under the NPT came into force in 1974 and Australia was the first country in the world to bring into force the Additional Protocol in relation to this, in 1997. In addition to these international arrangements Australia requires customer countries to have entered a bilateral safeguards treaty which is more rigorous than NPT arrangements. These treaties have been an obstacle to selling uranium to India. While the United States has managed to reach a safeguards agreement we have not.

Perhaps the greatest contribution that Australia can make to non-proliferation and more generally enhancing the security of nuclear power users around the Pacific and Indian Oceans is the development of a repository for spent nuclear fuel. There are very good reasons to host spent fuel and waste from any source. Australia's twin stabilities, geological and political, offer important advantages as a destination country.

## Conclusions

Australia plays no part in the enrichment or disposal of uranium fuel. Despite the creation of a new enrichment technology, there does not at this time appear to be an opportunity for participation in plant development.

There is a very substantial potential role for Australia to play in the safe disposal of used uranium fuel. The time scale for general agreement, site selection, planning, negotiation and construction is likely to be 10 to 20 years. If started now, it could be the beginning of a major contribution to the Australian economy with $2 billion revenues annually by simply taking 2,000 tonnes of spent fuel rods generated from our exports of uranium ore. This could rise substantially if the facility gained international acceptance. Australia would also be contributing to regional and global concerns about the use of nuclear power.

The limitation to any development remains political opposition to the further development of nuclear power.

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Footnote:

The World Nuclear Association at http://www.world-nuclear.org/ and AREVA Reference Documents contain much detailed information on the nuclear fuel cycle.

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