Assessing Nuclear Power Using a Risk-based Framework

R.J. Passey, MacGill, I.M. and Watt, M.E.
Centre for Energy and Environmental Markets
School of Electrical Engineering and Telecommunications
University of NSW
Sydney 2052
AUSTRALIA
E-mail: r.passey@unsw.edu.au

Abstract

The level of interest in nuclear power has significantly increased over the last few years, both internationally and more recently, in Australia. The Prime Minister announced the establishment of a Prime Ministerial Taskforce to undertake an objective, scientific and comprehensive review into uranium mining, processing and the contribution of nuclear energy in Australia in the longer term.

We apply a risk-based assessment framework to the use of nuclear power in Australia - from mining of uranium ore through to storage of radioactive waste. The evaluation criteria are technical feasibility, delivered energy services, present and possible future costs, potential scale of abatement delivered in both the short and long term, and other environmental and societal outcomes.

This assessment highlights some key questions regarding the use of nuclear power to reduce Australia's emissions: the need for an inflexible form of generation, its high yet uncertain costs, the impacts of mining uranium ore, the consequences of low probability yet catastrophic events, its delayed contribution to abatement, and the need to safely dispose of radioactive material and avoid proliferation.

It is clear that maximising our opportunities for deployment of abatement technologies requires a coherent innovation strategy that supports a portfolio of promising options in order to minimise risk, despite the inevitable uncertainties pertaining to any individual technology. Thus, rather than focusing on whether one particular technology can solve Australia's abatement task, emphasis should be on policies that will drive a mix of technologies and processes which will achieve this with least societal, economic and environmental disruption.

1. INTRODUCTION

Nuclear power has well and truly returned to the political agenda, both in Australia and internationally. In Australia, the focus of the Federal government has recently expanded from whether mining and export of uranium should be permitted to increase, to exploring the possibilities of Australian-based enrichment, power generation, reprocessing and waste storage. There has been considerable speculation as to what is driving this apparent change of position from the Federal Government's earlier views, as demonstrated in their Energy White Paper of 2004, where nuclear power was given low priority. The Government itself argues that climate change is the key issue (PM, 2006).

Governments around the world face a changing set of challenges for their energy sectors - reducing greenhouse emissions from energy supply, while ensuring energy security and continued economic development. This requires development of policy frameworks that allocate limited resources in a way that minimises not only the long-term abatement costs but also the risk of wider social, environmental and economic impacts. Such allocation requires assessment of the various technology options, and development of policies that will drive innovation in terms of deployment of those deemed appropriate and commercially viable, and development of those that may be in the future.

A particular difficulty for policy makers is balancing the risks of trying to 'pick winners' against the need to appropriately focus policy efforts on different technology options. A risk-based assessment framework can provide valuable assistance in comparing the different options. In this paper we explore the use of such a framework to assess the potential use of nuclear power in Australia. This type of assessment has to consider the full range of social, environmental and economic impacts throughout the conversion chain that includes mining, processing and enrichment, fuel fabrication, power generation, potentially reprocessing, decommissioning and storage of radioactive waste. While it is not possible to examine all the impacts in great detail here, those likely to be most relevant to a comparison of different energy options can be highlighted. We particularly focus this assessment on the construction of a nuclear power plant in Australia before 2020. This is because, if construction is to occur after that time, there is no need for current policy efforts to focus on nuclear power, and it is uncertain what other technology options will be available at that time.

Our analysis focuses on the potential role of nuclear power in reducing emissions in the Australian electricity sector given that this is the claimed primary driver for considering the technology. We firstly highlight the need for innovation to address climate change before discussing the recent support for nuclear power, and in particular the ANSTO report *Introducing Nuclear Power to Australia: An Economic Comparison*. To explore what rationale might lie behind this focus, we apply a simple technology assessment framework to the use of nuclear power in Australia. Finally we highlight the implications this may have for energy policy in Australia.

2. INNOVATION POLICY FOR CLIMATE CHANGE

Achieving major emissions reductions in the energy sector in a cost-effective manner is likely to require a portfolio of approaches and technologies on both the supply and demand sides. The different possible abatement technologies have very different characteristics and are at different stages of development. A coordinated package of policy measures is required, therefore, to provide support throughout the different stages of research, development, demonstration and deployment through which successful technologies must pass on their way to widespread diffusion. Technology-push policies are more appropriate at the earlier stages of development while market-pull policies are more appropriate during the latter stages. A portfolio approach is likely to provide the overall least-cost outcome in the long term, because failure to identify and develop any one viable option would increase the marginal abatement cost of others and thus costs overall. Care must also be taken to ensure that the strategy chosen keeps the door open for as many future options as possible. Major investment in any one technology, including establishment of the associated infrastructure and institutional framework, often serves to block the introduction of others.

Current Australian energy innovation policy focuses very much on technology-push through research, development and some demonstration. Commonwealth support for energy technologies that use non-renewable fuels is currently very targeted, with an apparent emphasis on trying to pick winners - firstly carbon capture and storage (CCS) and now possibly nuclear energy (AG, 2004; PM, 2006). There is comparatively minor emphasis on market-pull deployment of existing low-emission energy technologies: measures in place include the Commonwealth MRET, PVRP and RRPGP and a range of energy efficiency regulations. The Commonwealth's broader greenhouse abatement policy mirrors this, with emphasis on AP6 and its technology-focused Task Forces, rather than the Kyoto Protocol and international emissions trading. The Australian States are to an extent focusing more on market-pull, with measures including the QLD 13% gas target, the Victorian VRET, the NSW GGAS and proposals for a National Emissions Trading Scheme.

3. WHY THE RENEWED INTEREST IN NUCLEAR POWER?

The most obvious driver for the recent surge in interest in nuclear power has been widespread recognition that climate change is a serious threat, however energy security concerns in response to high and increasingly volatile oil and gas prices have also been influential in many countries. Support has not only come from the nuclear industry itself but also from some associated with the environment movement, for example James Lovelock (McCarthy, 2004), and most recently in Australia, from Tim Flannery (Stevenson, 2006).

A survey in mid 2005 commissioned by the International Atomic Energy Agency, that questioned

1,000 people in each of 18 countries[1] found that: “an average of one-third of respondents (34%) believe countries with nuclear power plants should use the ones they already have, but not build new ones; three in ten (28%) believe nuclear power is a safe and important source of electricity and that interested countries should build new nuclear power plants; and one-quarter (25%) say that nuclear power is dangerous and that all operating nuclear power plants in the world should be closed down as soon as possible”. When the potential climate benefits of nuclear energy were stressed, there was increased support for expansion of nuclear power in 14 of 18 countries, with an overall average increase of 10 percentage points (from 28% to 38%), and a decrease in opposition to new plants (from 59% to 47%). This led the survey authors to conclude “climate change messaging may have a positive impact on certain small segments of society when it comes to improving people’s attitudes toward expanding the use of nuclear power” (Globescan, 2005).

In Australia, in June 2006 the Prime Minister announced the establishment of a Prime Ministerial Taskforce to “undertake an objective, scientific and comprehensive review into uranium mining, processing and the contribution of nuclear energy in Australia in the longer term” (PM Press Release, 2006). That this focuses on a particular technology rather than more broadly on the range of possible options to reduce emissions from Australia’s energy sector, has been interpreted by some observers as support for nuclear power, not just an impartial investigation (BCSE, 2006). There are parallels between the Howard government’s support for nuclear power and its support for carbon capture and storage technologies. Both have been proposed by some as a ‘magic bullet’ answer to climate change, both are closely related to two of Australia’s export industries, and neither are likely to see any significant commercial deployment for well over a decade. This contrasts with the Government’s approach to renewable energy. The 2004 review of the Mandatory Renewable Energy Target recommended that the target be increased by 2020, so as to sustain the market and the industries which have developed since the current target was set. The Government rejected this recommendation on the basis of cost, and despite the emissions reduction, industry development and supply diversity it would provide.

Currently, it appears that most Australians do not favour nuclear power generation or enrichment in Australia, but do favour continued export of uranium. A Newspoll of 1200 people conducted in May 2006 (before the Prime Minister announced the review of nuclear power in Australia), found that 51% of respondents were against a nuclear reactor for power generation in Australia, and 38% were in favour. There was much higher support amongst Coalition supporters (53% in favour) than Labor supporters (60% against), and amongst men (51% in favour) than women (62% against). When asked about enrichment for export in Australia, 59% were against and 25% were in favour. Again support was greatest amongst Coalition supporters and men. However, the clear majority of respondents were in favour of continued export of uranium, with 65% in favour and 28% against. Those surveyed were not asked about storage of nuclear waste (Newspoll, 2006).

3.1. The ANSTO report “Introducing Nuclear Power to Australia”

In March 2006 Professor John Gittus prepared the report *Introducing Nuclear Power to Australia: An Economic Comparison* for the Australian Nuclear Science and Technology Organisation (ANSTO). In essence it outlines two finance plans which result in electricity generated in Australia by the fifth copy of a Generation III+ Pressurised Water Reactor (PWR), the Westinghouse AP1000, costing less than electricity from either coal-fired or gas-fired plant (Gittus, 2006).

The first finance plan claims no government subsidy is required; instead the financial risks are shared between stakeholders, government and the risk-transfer market. This results in an electricity cost of $38/MWh for the fifth copy of an AP1000. However, it requires the government to take 56% of the construction risks by providing a loan to cover the first of a kind (FOAK) capital costs for a nuclear plant being built in Australia. Government is also expected to take on a number of operational risks that, according to the report, and based on risk-based probability vs consequences calculations, total $40.1m per year. The loan plus interest and the operational risk insurance premium would be repaid once the power station was operating. This plan assumes the first four AP1000’s would be built in countries such as China and the USA, and the learning established in these countries transferred to

[1] Argentina, Australia, Cameroon, Canada, France, Germany, Great Britain, Hungary, India, Indonesia, Japan, Jordan, Mexico, Morocco, Russia, Saudi Arabia, South Korea, and the United States.

Australia.

A number of issues arise here. Firstly, tying the government's repayments to the power station's operation might seem to work against the government's clear role in reducing electricity demand. Secondly, part of the construction risk that government agrees to cover is the possibility that government will "delay licensing the Plant or refuse Consents and require costly design changes". This leads to a clear conflict of interest for government regarding adherence to design and operational safety requirements. Thirdly, as stated in the Gittus report, the AP1000 is yet to be built anywhere in the world and the FOAK costs could be greater than estimated. In this case the government (taxpayers) assumes the risk of providing extra finance, possibly to the point where its loan is not fully repaid. Finally, the $40.1m/year operational risks include: severe accidents (as discussed below); that the electricity produced may be too expensive and so unable to bid into the electricity market ($2.3m/yr); and the impacts of new government policy that increases safety requirements ($0.47m/yr) or changes market trading arrangements ($2.3m/yr) or requires premature closure of the plant ($0.47m/yr)[2]. Again there are clear conflicts of interest regarding safety requirements, and additional conflicts regarding premature closure of the plant. These issues are especially relevant since the construction costs of nuclear plants completed during the 1980s and early 1990s in the United States and in most of Europe were much higher than predicted today by the nuclear industry. The cost overruns were due to a combination of regulatory delays, redesign requirements, construction management and quality control problems (MIT, 2003).

According to the UK Government's Sustainable Development Commission (SDC), construction of nuclear plant is likely to be subject to moral hazard, increasing the risk of cost-overrun. Investors and companies that take part in nuclear projects could "take on higher levels of risk than otherwise under the expectation that the Government would be unwilling or unable to let the project fail" (SDC, 2006). This is especially relevant for the financial plans suggested in the Gittus report, since government would itself assume a significant level of risk.

The use of risk-based probability vs consequences calculations by Gittus for a nuclear power plant in Australia is questionable. For example, the risk-based cost of changes in market trading arrangements is given as $2.3m/yr, calculated assuming a 1 in 1000 probability event, with a cost equal to the value of the nuclear power plant ($2.3b). While this methodology may be appropriate for averaging out such costs for a very large number of installations where this event could occur, for a single installation the cost will be either zero or around $2.3b.[3]. Furthermore, investment decisions must focus on downside risks.

The Gittus report states "Government takes, as Governments do with all existing nuclear power stations, half the Operational Risk. It does this by agreeing to pay all costs, to Third Parties, of the most severe nuclear accidents". This seems to imply that all governments pay all costs of severe nuclear accidents. However in the USA, under the Price-Anderson Nuclear Industries Indemnity Act, government covers damages above $US10 billion, insurance companies cover up to $US300 million, and the Price-Anderson fund makes up the difference. The Price-Anderson fund is financed by each of the US nuclear power companies providing, in the event of a severe accident, $US15 million per year until either a claim has been met, or each company has provided $US95.8 million. This is a clear subsidy by government and should be recognised as such.

It is worth noting that Governments of countries with existing nuclear power stations have little choice but to accept the uninsurable risks of severe accidents. Those countries without nuclear power stations still have a choice. The Ukrainian and Belarusian governments estimated the cost of the Chernobyl disaster at US$120 to US$130b and US$35b respectively (BBC, 1998). The cost of simply encasing the Chernobyl Unit 4 to prevent release of radioactive material for 100 years is expected to be US$768m (CSF, 2000). No plans for the next hundred years have yet been made, nor for the next.

The Gittus report's second finance plan involves government subsidising both capital and operating costs (which include the risk-based costs outlined above). Again assuming the first four AP1000's would be built in other countries and the learning established in these countries would be translated to Australia, government is required to provide 14.3% of the construction cost and pay a subsidy of

[2] The report gives this cost as both $470m and $0.47m however the $470m is probably a typographical error.
[3] Note that by our calculations the cost should also be divided by the years of reactor life (50) giving $46k/yr.

21.41% of the cost of electricity produced by the station for the first 12 years of operation. Assuming a 1000MW plant would cost about $2.3 billion, it would require a government capital subsidy in the order of $330 million. Assuming the plant produces 7.45TWh per year, the ongoing operational subsidy would be about another $60 million per year for 12 years, or $720 million in total. Of course there is no guarantee that these cost estimates are likely to be relevant for the first nuclear power plant in Australia, with the cost of major infrastructure projects traditionally being greater than expected, especially likely when FOAK learning is expected to be transferred from another country.

The report estimates that spent-fuel management[4] would be an additional 2% of the electricity cost, as would power station decommissioning, and disposal of intermediate and low level waste. These costs would increase the required government support of operational costs by another 6% to 27-28% or an additional $190m. The decommissioning costs are also given as 9-15% of the capital cost, which would mean $225m to $375m. This is significantly lower than recent decommissioning estimates if new plant were built in the UK which, at between £220m/GW and £440m/GW, equate to between $550m and $1,100m[5] (SDC, 2006). Estimations such as these, that generally assume accrual of a proportion of the ongoing plant revenue into a fund, while applying significant discount rates to future costs, are very difficult to make well.

The report estimates that between $6.8m/year and $9.6m/year will be required to maintain the radioactive waste storage facility and add containers as storage needs grow - for the first 20 years in a storage pond then another 100 or so in above-ground facilities. The cost of the subsequent storage facility, presumably deep underground, does not appear to have been directly included. Assuming a reactor life of 40 years, the waste would spend another 80 or so years in above-ground storage before being transferred underground. At this time there is no fully operational repository storing waste in this manner, so the costs remain somewhat speculative.

It is not clear why the report describes these arrangements as a “profitable nuclear power station”. Similarly, it is hard to see how they are consistent with the statement in the report’s introductory letter by Ian Smith that “International studies have consistently shown that nuclear generation produces the lowest cost electricity, even without considering the payment of a carbon tax” (Gittus, 2006). The key point here is that the development of policy that will determine the nature of Australia’s energy investments over the coming decades deserves much more rigorous analysis.

4. TECHNICAL ASSESSMENT – NUCLEAR POWER

4.1. Technical feasibility

Nuclear power is clearly technically feasible – it currently provides about 15% of the world’s electricity. Pressurised water reactors (PWRs) are one of the most common types of reactors, with over 200 operating worldwide, and use ordinary water as the primary coolant, as the secondary coolant, and for neutron moderation[6]. Heat from the reaction is transferred to the primary coolant loop then through a heat exchanger to the secondary coolant loop, which produces steam to drive a turbine. The primary coolant loop is kept at very high pressure so it doesn’t boil.

A nuclear reactor is described as being passively safe if it doesn’t require an operator to shut it down in the event of an accident. PWRs, such as the proposed AP1000, are described as having passively safe operating characteristics. As the coolant heats it becomes less dense and can create voids of steam, both of which reduce its moderating ability and so act as a negative feedback to reduce the reaction rate. However, for this is insufficient to ensure safety and so operator actions are also required. A disadvantage of this negative feedback is that the introduction of cold water into the cooling system can increase the reaction rate (PWR, 2006).

[4] In this report spent-fuel management refers to disposal of high level radioactive waste because reprocessing of spent fuel was considered too costly.
[5] Assuming AUD1 = GBP0.4
[6] Neutron moderation occurs when fast neutrons produced during a nuclear reaction are slowed down forming thermal neutrons capable of sustaining a nuclear chain reaction.

Westinghouse describes the AP1000 as using an open fuel cycle, meaning uranium is firstly enriched then used once in the reactor and the resulting waste is not reused in any way. According to the Gittus report the AP1000 can also operate using a closed fuel cycle. This means it can use MOX fuel, which is produced by combining the plutonium separated from spent reactor fuel[7] with depleted uranium. The depleted uranium is produced when natural uranium (0.71% U-235) is purified to produce enriched uranium (3-5% U-235) for use in the power station. Compared to an open fuel cycle, use of MOX fuel decreases the amount of uranium required and the volume of waste produced, but involves the production of purified plutonium and so increases proliferation risks (MIT, 2003).

The most important thing to note is that the proposed AP1000 has not yet been built anywhere in the world while there is only limited experience with the other Generation III reactor designs. Surprises are inevitable, and in such types of projects surprises tend to be unpleasant. However, these plants are likely to deliver greater safety and better economics than the Generation II plants in current use.

4.2. Delivered energy services

The energy services required by society are heat, cold, light, motive force and power for electronic equipment. These needs can be met from both the supply and demand side using a number of different technologies and processes.

Nuclear power stations are used to meet baseload demand.[8] The need for a nuclear power station in Australia will be determined by both the growth in demand for baseload power, wider energy industry objectives and associated policies, and the cost and feasibility of alternatives. Under an essentially BAU scenario, baseload power demand in Australia is currently not predicted to outstrip supply until after 2014 (BCSE, 2006a). Actual demand will be determined by a number of factors including the rate of implementation of demand side management options such as distributed generation and energy efficiency, which will in turn be influenced by government policies at both the Federal and State levels. Demand could also be reduced if a price is placed on greenhouse emissions or if oil prices remain high or even go higher – entirely possible over the next 15 years. It is worth noting that construction of a nuclear power station in Australia could only arise as part of a major transformation of the energy policy environment in Australia and it can therefore be expected that there would be other major changes from BAU that accompany it.

The short-term needs for increased baseload are expected to be met by both capacity additions to existing coal-fired plant (eg. Mt Piper and Loy Yang) and combined cycle gas turbines (eg. Nowra, Marulan, Bega, Mortlake and Quarantine power stations) (NEMMCO, 2006). Over the longer term, the only realistic timeframe for a significant nuclear build, nuclear power will have to compete with other existing baseload options such as new coal- and gas-fired plant as well as emerging technologies that might include Hot Fractured Rock geothermal plant, bioenergy and fossil fuel plant with Carbon Capture and Storage. For example, the 100MW IGOC ZeroGen project in QLD is aiming for commissioning by 2010 and demonstration by 2011 (ZeroGen, 2006). Demonstration of CCS in Australia is being driven by the desire to demonstrate a technology that could potentially reduce the greenhouse emissions of our exported coal, currently around 35 times the value of uranium exports (ABARE, 2005).

The nature of the demand profile will likely change over the next 15 years, because of both increases in peak demand and the increased penetrations of variable and somewhat unpredictable stochastic plant such as wind power. Both winter and summer peak demand are expected to grow at faster rates

[7] The spent fuel contains actinides which are the heaviest elements found in used reactor fuel, many of which have long half-lives, including isotopes of uranium, plutonium, neptunium, americium and curium. It also contains a significant amount of U-235 but cannot be used as fuel because some of the fission products inhibit the nuclear reaction.

[8] Like all generation options, nuclear plant cannot be relied upon as a constant source of baseload power – hence the need for spinning reserve and ready reserve which each are typically about equal to 3% of system load (NEMMCO, 2005). Apart from scheduled maintenance, unforeseen circumstances can result in plant being taken offline. In both Germany and Spain nuclear plant were either closed or slowed down when river water used for cooling became too warm in the 2006 heatwave. At much the same time four of Sweden's nuclear plant were closed down when the backup power used to circulate cooling water failed in one plant, and it was realised this problem could be generic.

than baseload. For example in NSW, while baseload is expected to grow by 1.9% per year over the next 10 years, winter and summer peaks are expected to increase by 2.1% and 2.7% respectively (Transgrid, 2005). As a result, the load profile will become ‘peakier’ over time, increasing demand for new intermediate and peaking plant in preference to baseload. Penetration of stochastic renewable energy resources such as wind energy into the NEM may increase over the next 15 years and beyond. The Victorian government has recently set a mandatory target of 10% additional renewable energy use by 2016 and the South Australian government has set an aspirational target of 20% renewable energy use by 2014. Modelling of least-cost abatement both in Australia and internationally shows increased use of renewable energy, even where CCS proves commercially viable (IPCC, 2006; ABARE, 2006). Integration into electricity networks that have high penetrations of such plant may be more difficult for thermal baseload power stations, such as coal-fired and nuclear plant, that are less able to rapidly respond to changes in demand.

4.3. Present and possible future costs

Although nuclear power generation is clearly technically feasible, the real cost of generation is less clear. According to some studies, electricity from existing nuclear plant is amongst the lowest in the world (Gittus, 2006). According to others, such plant were built by government-owned or regulated investor-owned vertically integrated monopolies, and so were shielded from market forces. Many of the risks associated with construction costs, operating performance, fuel price changes, and other factors have been borne by government (MIT, 2003). This disagreement with existing power stations highlights the difficulty in accurately costing plant, such as the AP1000, that are yet to be built anywhere in the world.

As discussed above, the Gittus report states that nuclear power would only be cost-effective in Australia with significant government support and risk underwriting. This high cost of nuclear is in agreement with a recent study by an interdisciplinary Massachusetts Institute of Technology research team which found nuclear to be more expensive than both coal and gas-fired generation under current fossil-fuel prices and regulatory frameworks. The MIT study assumed that capital and operating costs would be reduced by 25% compared to current plant, commercial and regulatory risks would be reduced to that of conventional fossil fuel plant, zero waste management costs, and a US$50/tonne on CO_2 emissions. It concluded that “….it is extremely unlikely that nuclear power will be the technology of choice for merchant plant investors in regions where suppliers have access to natural gas or coal resources. It is just too expensive. In countries that rely on state owned enterprises that are willing and able to shift cost risks to consumers to reduce the cost of capital, or to subsidise financing costs directly, and which face high gas and coal costs, it is possible that nuclear power could be perceived to be an economical choice” (MIT, 2003).

Nuclear power is a relatively mature technology and so its costs are unlikely to decline appreciably in the future unless radically new designs are used such as, for example, the Generation IV plants proposed post 2030. According to a report by the UK Government’s Performance and Innovation Unit, although the costs of nuclear are expected to reduce over time because of learning effects, this is not expected to occur as fast as it will for less mature technologies such as renewables. Nuclear power has a slower innovation rate because of its longer lead times, shorter production runs that reduce economies of scale for manufacturing of components, and delays to design changes when new designs need to be relicenced (PIU, 2002). The International Atomic Energy Agency report learning rates[9] of 0% to 5% for nuclear plant, 6% to 14% for wind power and 10% to 15% for photovoltaics (IAEA, 2003). These figures are especially relevant considering the relative sizes of the nuclear and wind industries and therefore their capacity for expansion – 361GW of nuclear in 2002 providing 15% of global electricity and about 48GW of wind in 2004 providing less than 1%, and more wind than nuclear capacity was installed in 2005 (EIA, 2005; WF12, 2005).

In terms of the net effect on Australia’s economy, in addition to the direct electricity price impact on competitiveness, the proportion of Australian content of capital expenditure should also be taken into account. It has been estimated that about 50% to 80% of the capital costs of a typical wind farm, but a far lower proportion of the costs of a coal-fired plant represent Australian content (MacGill et al., 2002). Since no electricity-generating nuclear plant has been built in Australia and there is only very

[9] The percentage decrease in capital costs for each doubling in cumulative installed capacity.

limited local capability, the great majority of equipment and most expertise would all have to be imported. Given that fuel costs are a low proportion of total costs for a nuclear plant, it is unlikely that Australia would have any competitive advantage in terms of delivered energy costs compared to other countries.

4.4. Potential scale of short and long term abatement delivered

Recent work suggests that the global climate appears to be more sensitive to greenhouse emissions than previously thought, and that even moderate warming may have significant risk of irreversible damage, and the possibility of step-changes in climate behaviour make even incremental increases in greenhouse gas concentrations potentially dangerous (DEFRA, 2005; Hadley, 2005). Findings such as these have lead the EU amongst others to adopt a target of keeping global warming to less than 2^oC above pre-industrial levels (Hansen, 2006). This might well require atmospheric greenhouse gas levels to be stabilised at around 400-450ppm, which in turn will most probably require global emissions to peak before 2020, then reduce by as much as 50% below 1990 levels by 2050. Further, delaying emissions reductions by 20 years could require levels to be reduced at three to seven times the rate than if action begins now. Recent work in Australia also highlights that delaying action increases electricity price impacts and reduces both GDP and employment (ABRCC, 2006).

Under the existing greenhouse-related policies and programs of Commonwealth, State, Territory, and Local governments, Australia's emissions are projected to be 22% higher than 1990 levels by 2020. Emissions from the stationary energy sector, which make up nearly one half of Australia's total emissions, are projected to increase by 70% by 2020. Electricity generation makes up 70% of the stationary sector emissions (AGO, 2005). Therefore, it is particularly important to develop and implement sound climate change policy that will drive innovation in the electricity industry.

It is certainly possible that in the longer term nuclear power could make a contribution to reducing Australia's emissions. However, a number of factors limit the potential scale of short and medium-term abatement offered by a nuclear power plant, including its construction date and the emissions intensity and operational characteristics of the alternative(s) – whether this is some form of generation or reduced energy demand. As discussed above, it is unlikely baseload capacity would be required in Australia before 2015, and then questionable that nuclear would be favoured over other technologies that are also available to generate electricity with reduced emissions, such as gas-fired CCGT. However, if a nuclear baseload plant is built in 2015, any contribution to abatement between now and 2020 would be limited,[10] especially since this period would include that plant's construction emissions. Similarly, the UK SDC concluded that, even for the construction of 10GW of plant in the UK, "it is clear that the nuclear contribution to a 2020 CO_2 reduction target would be limited" (SDC, 2006).

4.5. Other environmental and societal outcomes

All energy technologies have a variety of environmental and social impacts, ranging from fuel provision (natural gas explosions and inundation by large hydro dams) to final operation (greenhouse emissions from fossil fuel plant and visual intrusion by wind farms). However, nuclear power is unique in that the radioactive nature of its fuel and waste products makes their management a priority. The following briefly discusses the impacts of mining uranium ore, low probability yet catastrophic events, disposal of radioactive waste, decommissioning of nuclear facilities, and proliferation.

Mining uranium ore

Uranium ore bodies currently mined in Australia contain less than 1% uranium oxide (U_3O_8), where the uranium consists of 0.71% U-235, 99.28% U-238, and about 0.0054% U-234. Uranium ore is associated with radium, which is a decay product and more radioactive than uranium. Radium decays to produce radon gas, which is more radioactive again and has a short half-life of 3.8 days. They all

[10] Assuming a 1000MW nuclear power plant was built instead of a modern 1000MW coal-fired plant (with an emissions intensity on 0.7Mt/MWh), it would avoid the release of about 5Mt of greenhouse emissions per year. This would be just over 2% of the electricity sector's 2020 emissions as projected by the AGO (2005). By way of comparison, a 1% national energy efficiency target implemented in 2005 was projected to reduce emissions by about 5Mt/yr by 2008, then 10Mt/yr by 2012 and so on (ACG, 2004).

release alpha particles as they decay. An alpha particle loses its energy in a very short distance in dense media, meaning it doesn't penetrate very far through skin but releases a lot of energy when it does. Thus alpha particles are most dangerous if the material is inhaled or ingested. Radon gas is the most dangerous of these, as it can accumulate in buildings and drinking water and cause lung cancer.

The uranium mining industry in Australia is governed by a number of Codes of Practice, Standards and safeguards that aim to minimise release of, and exposure to, these sources of radioactivity. However, in response to numerous leaks and spills in Australian mines, the Senate ECITA References Committee on the Environmental Regulation Of Uranium Mining was established and concluded (i) uranium mining presents unique hazards and risks to both human health and the environment; (ii) a pattern of underperformance and non-compliance can be shown; (iii) there were gaps in knowledge and an absence of reliable data on which to measure the extent of contamination or its impact on the environment; (iv) operations of mines suggests that short-term considerations have been given greater weight than the potential for permanent damage to the environment; (vi) changes were necessary in order to protect the environment and its inhabitants from 'serious or irreversible damage; and (vi) the frequency of leaks and spills is evidence that self-regulation by the mining companies has failed to prevent incidents which have the potential to cause significant environmental damage (ECITARC, 2003). Thus, despite a number of safeguards, accidents can and do happen.

Low probability yet catastrophic events

While the likelihood of an operational accident at a modern nuclear power plant in Australia is relatively low, malevolent actions are receiving increased attention. This could range from theft of plutonium produced for MOX fabrication to create a nuclear device, to theft of any sort of radioactive material to create a 'dirty' or radiological bomb, to attack or sabotage of a nuclear plant - which could release significantly more radioactivity than a nuclear weapon. As recently as June 2005 the U.S. Nuclear Regulatory Commission expressed concern that nuclear power plants in the United States could not fend off a terrorist attack (GSN, 2005).

It is always difficult to properly assess, let alone manage, such risks. In such situations it is instructive to learn from the experts in risk, the insurance industry. In a recent report, the reinsurance[11] company Swiss Re stated "one of the most perilous shortcomings in traditional property insurance and reinsurance concerns inadequate nuclear risk exclusions". As a result they propose "a specific agreement to eliminate gaps in reinsurance exclusions" in order to protect insurance companies from any exposure to property damage caused by a nuclear event (Swiss Re, 2003). As discussed earlier, insurance companies are not currently prepared to insure the full costs of nuclear accidents.

Radioactive waste and possible proliferation

Radioactive waste is produced during enrichment, reprocessing, and power station operation and decommissioning. High level waste (including spent fuel), which makes up 2% of the waste by volume but over 90% of the radioactivity, must be appropriately managed for hundreds of thousands of years (SDC, 2006). To put this in perspective, the Egyptian pharaohs were in power only 5 thousand years ago, and *homo sapiens* are understood to have appeared in East Africa between 100,000 and 200,000 years ago. At this stage the most advanced waste disposal technology relies on deep underground burial. After 50 years of nuclear power use, only one country (Finland) is in the process of developing an agreed deep disposal repository that is certainly, at this stage, world's best practice. However, best practice is rarely standard practice and it is questionable that all other countries will follow suit.

Reprocessing has been suggested as one solution to reduce the volume of radioactive waste and deal with possible shortages of uranium, however it produces purified plutonium which might potentially be used to make nuclear weapons. According to both the SDC and the MIT study, high costs and pollution and proliferation concerns suggest that reprocessing should not be part of the nuclear fuel cycle of a new generation of nuclear plants (SDC, 2006; MIT, 2003). Indeed, in the EU, for these very reasons, spent fuel from new nuclear power stations may not be reprocessed (SDC, 2006). It is interesting to note that the Opposition political party in the Northern Territory is promoting that state as a reprocessing site (ABC Radio, Aug 2006).

There are a variety of Codes of Practice, Standards, Safeguards and Treaties, including the Nuclear

[11] A reinsurance company provides insurance to insurance companies.

Non-Proliferation Treaty, to limit the non-peaceful use of nuclear weapons. However, such agreements are reliant on political and social stability for hundreds of thousands of years, as well as maintenance and transfer of the knowledge required to identify and safeguard radioactive materials. Also, the focus of these safeguards is to prevent nuclear material falling into the 'wrong' hands, they have little effect if it does. As noted by the SDC, "Terrorist organisations, almost by definition, operate outside national and international law, and therefore safeguards to protect against proliferation are almost irrelevant to such groups" (SDC, 2006).

5. POLICY IMPLICATIONS AND CONCLUSIONS

This assessment highlights some key questions regarding the use of nuclear power to reduce Australia's emissions: the need for an inflexible form of generation, its high yet uncertain costs, the impacts of mining uranium ore, the consequences of low probability yet catastrophic events, its delayed contribution to abatement, and the need to safely dispose of radioactive material and avoid proliferation.

Australia's current electricity system requires significant changes to reduce its greenhouse emissions. These changes require innovative policies both to develop promising technologies and implement existing near-commercial options. Such policies themselves drive technology innovation, both directly through R&D but also through competition between industry sectors involved in deployment. The Commonwealth government's apparent focus on attempting to pick winners is a very high-risk strategy. Opting for nuclear might well preclude many other options because of the large economic, environmental and social resources that would be absorbed – not only by the power plant itself but also by the associated infrastructure and institutional framework. It would also increase Australia's reliance on imported technology and especially expertise, given our limited experience with nuclear technology at Lucas Heights and complete lack of experience with nuclear power generation.

Many other low-emission technologies can be used to generate electricity and, while these also have impacts, their potential for serious long-term consequences would seem to be far less than for nuclear energy. There are also significant opportunities to improve efficiency at the point of end-use. Maximising our opportunities for deployment of abatement technologies requires a coherent innovation strategy that supports a portfolio of promising options despite their inevitable uncertainties and hence risk. Thus, rather than focusing on whether one particular technology can solve Australia's abatement task, emphasis should be on policies that will drive a mix of technologies and processes likely to achieve this with least societal, economic and environmental disruption.

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