Nuclear Power:
Game Over

Humans globally consume roughly 15,000 gigawatts (GW) of power, in oil, coal, gas, nuclear, and renewables all added together.[1] To put it another way, it means that, on average, we use 15,000 gigajoules (GJ) of energy every second of every day. That is an enormous number, equivalent to switching on 15 billion electric kettles.

ARTICLE BY: **PROF DEREK ABBOTT**

On the other hand, 15,000 GW is a relatively small number as it is 5000 times less than the average solar power hitting the planet's surface. And remarkably, it is six times *less* than the solar power utilised by all plant life on Earth for photosynthesis.[2] By far, the plant kingdom has already beaten the human race to the punch in terms of

IMAGE: © Garry Knight - Flickr

IMAGE: © Lennart Tange - Flickr

the sheer magnitude of solar collection achieved.

Yet this means that maintaining our current levels of consumption in a sustainable manner requires harnessing only 0.02% of the light at the surface of our planet. So do we really need nuclear power? Is nuclear sustainable? Given the awesome potential of renewable energy, is there an economic place for nuclear power? Why is nuclear power globally in decline at present? What are the limitations?

These are some of the key questions we'll now examine.

Energy policy

Before we discuss power generation, it is important to first highlight that any robust government energy policy must be grounded by the concept of energy conservation. To understand why energy conservation and energy efficiency form the bedrock of policy, let us consider how power consumption can quickly add up and get out of hand.

Imagine 5 billion people all make one cup of tea per day, and overfill their kettles by as little as a quarter of a cup. Over a day, this excess requires an additional 2 GW of average power, which is equivalent to the output of the whole Hoover Dam.[3]

Consider the possibility of everyone on the planet driving a medium sized car for only one hour per day. That alone would average to two thirds of our total present global consumption, which is clearly unsustainable.

Suppose there were one billion medium-sized houses on the planet all heating or cooling by as little as 3°C relative to the outside temperature. By not having home wall insulation, the excess power needed would on average equal our total present global consumption. This alone illustrates the critical importance of having insulation standards for new buildings.

On the flip side, take an estimate of about 10 billion tungsten light bulbs in the world. On average each light bulb will be on about 10% of the time. If each was replaced with a modern LED light bulb – with a saving of 50W each – that equals a saving of 50 GW, the equivalent to about 50 nuclear power plants.

As such, there cannot be a future drive towards sustainable power generation without it being married to measures of energy efficiency and conservation.

Nexit: Nuclear Exit

Around the world the nuclear industry is in gradual, inexorable decline. Starting from 1954, it took the world 48 years to gradually ramp up to a peak of 438 commercial nuclear power plants in 2002. Today, in 2016, we have dropped to 402 reactors with further closures foreshadowed.[4]

A report from the Swiss banking investment sector[5] states "big, centralised power stations will not fit into the future European electricity system" and that they will share "the fate of the dinosaurs: too large, too inflexible, on their way to extinction."

Participating countries are closing down nuclear power plants (NPPs) faster than they are being built. Nuclear apologists point to China as a role model that is actively building a number of NPPs. The fact is that China has built $160 billion in overcapacity of coal plants that are unused.[6] Will their NPPs, which are presently under construction, become similarly redundant?

There simply aren't enough Chinese students rushing to enrol into nuclear engineering courses, to produce the workforce for an expanded nuclear program.[7] China's ambitious nuclear expansion plans would require at least 50,000 students to be

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trained by 2030, but barely a few hundred students raise their hands each year.[8] The shortage of trained nuclear technicians and engineers has already led to safety incidents.[8]

By contrast, in 2015, China invested five times more in renewables than nuclear power.[4] Those nuclear projects will take many years to complete, whereas renewables are deployed and put to immediate use. Moreover, China's nuclear investments may have an uncertain future and may meet the same fate as their renowned ghost cities. Significant Chinese street protests against nuclear, in 2013 and 2015, indicate a growing groundswell of discontent.[9,10]

Let us now examine some of the limitations of nuclear power generation that contribute to its uncertain future and an impending global energy market *nexit*.

THE COSTS OF DECOMMISSIONING A REACTOR AT TODAY'S PRICES ARE COMMENSURATE WITH BUILDING THEM IN THE FIRST PLACE.

Nuclear footprint

Nuclear marketeers brand NPPs as taking up a small physical land area with respect to renewables. However, consider all the processes and steps from mining uranium, processing it, burning it, and then dealing with the waste. Mark Z. Jacobson from Stanford University, has added up the footprint of all the globe's NPPs, their exclusion zones, and supporting infrastructure.[11] Jacobson found that if you divide that area by the total number of NPPs in the world, we obtain an average nuclear footprint[12] of about 4.5 km x 4.5 km, which is roughly the same for equivalent solar power.

A hypothetical nuclear utopia powering the entire world's energy needs would require in the order of 15,000 NPPs. This is a daunting scale-up compared to the dwindling number of 400 NPPs the world has at present. To see how impossibly challenging this would be, take a map of any country of the world and mark 100 possible locations for nuclear stations close to water and far from population centres. Even trying to place ten NPPs in acceptable locations is not an easy task. This obstacle alone counts out a nuclear utopia.

Uranium resource limits

But is a more modest vision of, say, 3000 reactors possible? This would at least replace all the world's coal-fired plants. Based on the known mining reserves of uranium there is about 200 years of uranium, if we consume it at the current rate.[13] Scale up to 3000 reactors and we have only about 25 years of power left. Clearly this is a proposition that isn't at all sustainable.

Nuclear apologists will then raise the question of yet undiscovered reserves of uranium. However, this makes little difference; if we double or quadruple the figure of 25 years, this is hardly a legacy investment for the future. One can't pluck imaginary figures that are any larger, as we know the abundance of uranium in the Earth's crust is about the same level as for *rare earth* metals.[14]

Proponents of nuclear power will then point out that there's over 500 years worth of uranium in seawater. However, this is a fruitless suggestion as the uranium concentration is tiny, at 3.3 parts per billion. The energy it takes to lift a bucket of seawater by 50 metres is equal to the energy you'd get from its uranium.[14] The energy return on investment simply doesn't add up.[15]

In order to address this issue, the counterpunch is the promise of breeder-style Generation IV reactors. These will potentially increase fuel lifetime by a factor of 60. This indeed would be impressive, as we can now lift the bucket of seawater by 3 km. However, these types of reactors are riddled with advanced materials issues that have not yet been solved. The metal parts of these reactors are exposed to higher temperatures, a higher corrosive environment, and a higher neutron flux than in conventional reactors[16] – suitable alloys

IMAGE: © IAEA Imagebank - Flickr

IMAGE: © Alex Hesse - Flickr

Nuclear power plants globally produce about 10,000 tonnes of spent fuel waste per annum.

that can withstand these conditions have not yet been found for long-term commercial operation.[17]

Governments do not form today's energy policy based on arguments that largely hinge on commercially unproven or non-existent hardware. This would be akin to forming health policy based on promised drugs that are yet unproven or undiscovered.

Reactor lifetime

A nuclear reactor has a lifetime of roughly 40 years.[4] Due to heat, high-energy neutrons, and corrosion, the metal nuclear vessel eventually cracks. Every device runs and gets hot – this sets a limit to the reliability and lifetime of any machine. Everything from a light bulb to a car engine eventually pops, and nuclear reactors are no exception. At the end of its 40-year life, a nuclear station has to be decommissioned.

The nuclear vessel itself becomes radioactive, weighs up to 500 tonnes, and has to be buried. The costs of decommissioning a reactor at today's prices are commensurate with building them in the first place. Attempts are made by NPPs to factor in decommission cost into their economics. However, who can predict what the costs will be 40 years into the future? Typically costs blow out and the taxpayer ultimately foots the bailout.

Elemental diversity

When an NPP comes to the end of its 40-year life, the metal reactor vessel and core are radioactive, as they have been exposed to high-energy neutrons. If there were a vast nuclear scale-up, where would we put all these 'glowing' vessels? Moreover, inside the vessel, hafnium may be used as a neutron absorber, beryllium a neutron reflector, and zirconium is used for fuel rod cladding. The steel that is used to construct the vessel has to be hardened against neutron damage, and so it is typically alloyed with elements such as molybdenum, niobium, and tantalum to name a few.[18]

Many high performance alloys in other industries use exotic metals too, but the point is that those metals can be recycled. Rare earth metals used in the renewable industry are recyclable too. In the case of NPPs the metals become radioactive and so a scale up to 15,000 reactors in the world would be out of the question, as it would limit our elemental diversity.

Is nuclear fusion the solution?

Nuclear fusion, if it ever becomes commercially useable, would be an even worse offender in terms of reduction in elemental diversity. What is not publicised is that the nuclear fusion process irreversibly consumes lithium.[18] Every laptop, mobile phone, and electric car needs this coveted element. Moreover, fusion reactors end up with radioactive vessels and still require decommissioning, so the quandary of that waste remains. For these significant practical reasons, fusion is unsustainable and not the panacea it is cracked up to be.

Nuclear waste

Nuclear power plants globally produce about 10,000 tonnes of spent fuel waste per annum.[19] When a spent fuel rod is removed from a reactor, the radiation level is so high that a one-minute dose at a metre's distance is lethal to humans. Each

The revolution we are witnessing is akin to the extinction of big powerful dinosaurs versus **resilient swarms of small ants working in cooperation.**

SOUTH AUSTRALIAN ROYAL COMMISSION

In 2016, there has been a Royal Commission to revisit renewed illusions of building an Australian nuclear industry. Australian Royal Commissions traditionally are implemented to investigate injustice, abuse, and matters with a dark underbelly.

A Royal Commission on a nuclear business proposition is about as out of place as a hamburger store in a police station. No one would dream of initiating a Royal Commission to seek 'permission' to build a solar power plant. To initiate such a process for examining a nuclear business model is self-defeating – it signals to the public that nuclear is on the back foot right from the outset.

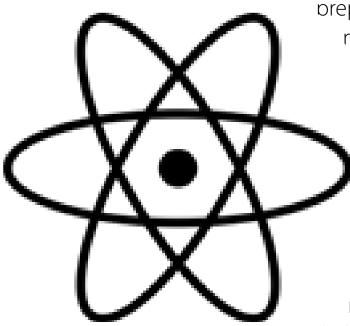
The outcome of the Royal Commission[38] is that nuclear power is not recommended (yet) and that it is feasible to store international high-level nuclear waste in South Australia for profit.

Not only is taking on an irreversible legacy short sighted, but given the nuclear industry is waning the economic risks are very high.[39]

spent fuel rod generates heat and has to be stored in a pool of water at least for five to ten years to cool down.

When a spent fuel pool runs out of room, the rods are then transferred into 100 tonne containers called *dry casks*. Each cask costs about $1 million each, and the spent fuel assemblies are transferred into the casks using costly robotic equipment to avoid human exposure. The casks are then filled with helium and are welded shut, at a cost of $500,000 each.

Dry casks are stored above ground, and the idea is that after about 50 years of further cooling the fuel can then be sent to a deep underground repository. Though, no country has yet succeeded in following through on this final costly step. A dry cask, which is stored above ground, in the meantime may corrode and leak, and transfer into a replacement cask is costly.[20]



Some isotopes in the spent fuel have decay half-lives over 10,000 years, and so an underground repository is the only viable final resting place for such waste.[21] To repackage spent fuel from a dry cask to a special repository canister is incredibly costly. For the manufacture of canisters and provision of the equipment to perform the repackaging operation, one is looking in the vicinity of $50 billion.[22]

When a canister is placed in a deep repository, bentonite clay is used to delay the penetration of water and moisture. The canister eventually cracks and corrodes with time. This is accelerated due to the radiation, from the inside, and by natural bacteria[23] from the outside. Once there is a leak, radioactive iodine-129 isotopes from the fuel can diffuse through rock.[19] Radioactive actinides from the spent fuel are released into the biosphere through water.[19] Should water ever breach the canisters, numerous chemical reactions can take place including the generation of explosive mixtures of hydrogen and oxygen.[19]

Why is nuclear so expensive?

The principal costs of NPPs are the capital cost of the power station and decommissioning. Then consider the enormous number of steps involved in preparing the fuel, its deployment in a highly complex nuclear station, and then the repackaging and disposal steps needed at the end of the fuel cycle. At each step there are safety risks to nuclear workers and so the complexity of the management flow snowballs due to the necessary governance structures that are put into place. As there are so many steps with attendant risks, the full end-to-end cost appears to climb.

Nuclear decommission costs are high, and it is estimated that the decommissioning contracts over the next 15 years

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will amount to $220 billion.[24] This sum is equivalent to the creation of solar power that would replace 44 nuclear stations.[25]

Renewables vs. nuclear

While nuclear power plants experience economic decline, renewables are rapidly growing and penetrating the market on an exponential curve. The global annual increase in renewable generation for 2015 alone was 50 GW for solar panels, 63 GW for wind power, and 28 GW for hydropower.[26]

Nuclear power is large and centralised, with enormous entry and exit costs. By contrast, renewables are made up of small modular units that yield a faster return on investment. The revolution we are witnessing is akin to the extinction of big powerful dinosaurs versus resilient swarms of small ants working in cooperation.

Nuclear power is sinking under the weight of its complexity, costs, and the headache of its waste issue. On the other hand solar power is brought to us via free sunshine exposing the promises of nuclear as mere moonshine.

Electricity prices

Nuclear advocates point out high electricity spot prices in regions with high renewable penetration.[27] However, it is a misdirection to conclude that renewables are therefore costly – after all, renewables have zero fuel costs. The plants with flexible controllable power (eg. gas turbines) naturally take advantage of the situation and bid higher prices during times when renewable generation is low.[28] Thus the solution is not to reduce the proportion of renewables, but instead to revise pricing policy to reflect the change in market dynamics and structure. The current policies are out-dated and based around the outmoded paradigm of all-controllable power generation.

A possible solution is that flexible controllable power sources (eg. gas, waste biomass fuelled power plants, solar thermal plants, pumped hydro, batteries etc) ought to be also rewarded for the 'insurance' they provide in backing up intermittent uncontrollable sources (eg. wind and rooftop solar), rather than solely for the energy they deliver so that they are not drawn into a price bidding game. Rewarding controllable sources for their back-up ability may provide investment incentives for such generators.

Intermittency

A common argument nuclear proponents raise is that renewables are intermittent; therefore nuclear power is essential to keep the lights on 24/7. This is wrong on a number of levels.

First, intermittency does not automatically imply unreliability. Take the analogy of rainfall. Rain is very intermittent and yet we have a continuous supply of water when we turn on the taps. Why? Because there is reservoir storage, river flow, and many pipe-interconnected collection areas and aquifers. Our water supply would be unreliable if we didn't adequately design an appropriate grid of pipework, dams, and reservoirs. There's no equivalent of a 'nuclear station' providing a constant baseload supply of water. The intermittency in rainfall becomes reliable due to planned storage and spatial diversity. The same principles apply to electricity.

Second, nuclear plants are intermittent too as they need planned shutdowns for maintenance and fuel rod changes. Then there are unplanned shutdowns, for example, if a pump breaks down or a critical pipe leaks. These 'minor' shutdowns often mean that 1 GW of nuclear power

The intermittency in rainfall becomes reliable due to planned storage and spatial diversity. The same principles apply to electricity.

IMAGE: © Koza1983 - Flickr

goes offline for 2–4 weeks. The ultimate in intermittency is when a nuclear station is closed down to due an accident or if a licence renewal has been refused due to old age. Then there's over a 10-year lead-time before a replacement nuclear plant comes online. So nuclear power is intermittent too, but simply on a different timescale.[29]

By contrast, it makes no difference to a grid when a solar panel is damaged. Moreover, it can be replaced within a day. The modularity and diversity of a network of renewable sources can be designed to be much more robust than *any* large centralised power station.

Grid stability

Nuclear lobbyists create a further false dilemma by suggesting renewables make the electricity grid unstable and therefore nuclear power is required to ensure stability. First, nuclear power is not required because controllable renewable sources (with synchronous generation, such as solar thermal, hydroelectric power, and pumped hydro) already stabilise the grid. It is true that other renewable sources do give rise to grid management issues, but this is bread and butter for grid engineers.[30] There are numerous research papers by grid engineers developing solutions for increased renewable penetration and none are suggesting the need for nuclear power.

In an Australian context, how does one adopt proven storage techniques for grid stability such as pumped hydro, when the country is mostly devoid of mountains? It is a fallacy to assume mountains are needed; as plateau regions provide perfect locations for pumping up water for later release and energy generation. For example, there is an ideal plateau of about 270 m high, between Port Augusta and Whyalla where seawater can be pumped for energy storage.

Nuclear in bed with renewables?

In desperation, nuclear advocates are putting a new spin on their marketing. The slogan now is that nuclear and renewables make perfect marriage partners, as nuclear provides the grid with 'baseload' power.

Unfortunately this pick up line cannot woo renewables into bed. The fact is that generators designed for constant baseload operation are exactly what uncontrollable renewable generators don't need. Uncontrollable renewables need flexible controllable sources of power such as hydroelectric power, pumped hydro, waste biofuels, solar thermal, and solar generated hydrogen or syngas to provide power when generation from intermittent renewable sources is insufficient to meet demand. Nuclear power plants work best when they provide a constant power output and they lack the agility to follow the variability of renewable generators.

One can manage different uncontrollable and controllable renewable sources to work together, making baseload generation redundant.[31,32] The concept of operating a power system with a traditional baseload plant is becoming outmoded[5] and significant future cost penalties are likely to be attached to generators designed for baseload operation[33].

Nuclear promotion goes to some lengths

to greenwash its image, in an attempt to make it appear on a par with renewables. But as we have demonstrated in this article, non-recyclable nuclear is highly resource-limited and therefore it isn't a renewable source.

Another form of greenwashing is the catchphrase 'nuclear saves lives' reminding us that radiotherapy is used in hospitals. Amputating gangrenous limbs also saves lives too, but it would be a logical fallacy to use that fact to improve the image of chainsaws.[34]

What really matters is *rate* of carbon footprint reduction

The spin put on nuclear power as having a 'low carbon' footprint is a further case of greenwashing. For example, if there were a threefold ramp up of nuclear power this century, it would result in a modest 6% carbon reduction.[35] On the other hand, the exponential uptake of renewables this century will far outstrip 6%.

What really matters is not the *present* carbon footprint today of each power source, but the *rate* of footprint reduction that they introduce. Presently nuclear is in decline, and solar uptake is exponentially growing. Thus the reduction in carbon footprint from solar will experience a 'compound interest' type of effect. Because the solar market is fast and flexible, whereas nuclear is economically slow and stunted, solar will vastly exceed nuclear in terms of *rate* of carbon mitigation.

In summary, the branding of nuclear as 'green' is fallacious and the opportunism of nuclear advocates proclaiming environmental concern is about as comforting as Donald Trump in a Mexican hat.

Should Australia adopt nuclear power?

The size of the Australian electricity market is of the order of $10 billion per annum,[36] which is relatively small. Therefore there isn't a business case to foot the bill for even one nuclear power station with its construction cost, decommission cost, and cost of spent fuel handling and repackaging.

Moreover, Australia simply doesn't have the existing infrastructure, training, and governance structures to support a nuclear industry. It would be risky for Australia to enter an area fraught with high uncertainty, given the present global decline.

Should Australia store nuclear waste?

Possible motivations to build a deep underground repository for international high-level nuclear waste, in Australia, are the promises of income, increased employment, and support of a waning Australian uranium export industry.[37]

However, it is important to note that no pro-nuclear power country has yet opened such a repository. To enter a new business space, where even the highly experienced players have not delivered, is to take on considerable economic risk and uncertainty.

To invest in an industry that is in global decline, does not appear to be as rational as investing in a growth area such as renewable energy. Renewable energy is

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Nuclear power is a clunky technology borne out of a bygone Cold War era. Its best days are over and it cannot form a key part of sustainable energy policy.

a business space where Australia has a multitude of trained engineers, existing infrastructure, and an abundance of sunshine. Building intentional renewable overcapacity in Australia will potentially be a wise investment, as that surplus can then be used to generate hydrogen or other fuels that can be liquefied and traded on overseas markets.

Lack of public acceptance

Obtaining public acceptance in a country that has traditionally been free of nuclear power would likely be insurmountable, given the decreasing world-wide levels of public support.[40]

Lack of public acceptance cannot be underestimated. Even in pro-nuclear France, riots took place in the 1990s that overturned the government's move to build a nuclear repository.[41] Renewed protests have taken to the streets in China only this year.[42]

The citizens in the countries, with the most nuclear experience, show increasing opposition[40] to expanding the nuclear industry,

1. Germany (90% opposed)
2. Mexico (82% opposed)
3. Japan (84% opposed)
4. UK (63% opposed)
5. USA (61% opposed)
6. China (58% opposed)
7. France (83% opposed)
8. Russia (80% opposed).

With the current debacle of escalating costs of the Hinkley nuclear plant, in the UK, it is likely a fresh poll would show even stronger UK opposition against nuclear and further support for renewable energy.

Conclusion

Nuclear power is a clunky technology borne out of a bygone Cold War era. Its best days are over and it cannot form a key part of sustainable energy policy.

The world doesn't have the capacity to rapidly scale up nuclear power generation. As well as resource and geographic limitations, there simply isn't the nuclear-trained workforce base. To install renewables, on the other hand, takes regular engineers of which there are millions in the world. Renewables therefore have a strong workforce base to draw upon.

Nuclear simply does not scale up in the time we need it. Renewables are flexible and uptake is fast with relatively low entry costs. Nuclear is burdensome and does not have the economic agility to survive a dynamically changing electricity market – it cannot adapt fast enough to competing game changers.

An economically declining nuclear industry is a dangerous one, as there is always the temptation to cut costs and fall short on safety standards.

The Economist[43] aptly points out: "As renewable sources of energy become more attractive, the days of big, 'baseload' projects.... are numbered."

There's been a game change, and it is game over for nuclear. AQ

IMAGE: © Mark Pitcher - Flickr

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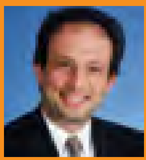

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Rejuvenating the Brain: Ageing with Cognitive Sparkle

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