Nuclear For Climate Australia

Nuclear Power Plant Technologies

5th March 2020

1.1 The Imperative of Addressing Australia's Energy Trilemma

Nuclear Energy must be the centrepiece of Australia's Low Carbon Future. It's our best option to reduce emissions, while at the same time providing a least-cost system with 24/7 reliability. Nuclear Energy can resolve the energy trilemma of low emissions while ensuring low cost and reliability.

The need to replace aging coal plants requires the reactor programme to commence as soon as possible and definitely within 10 years.

Nuclear energy provides approximately 10% of the world's electricity from about 440 power reactors. It is the world's second largest source of low-carbon power (29% of the total in 2017).

1.2 Nuclear Power Plant Evolution

Nuclear power plants are undergoing constant development as shown in Figure 1.

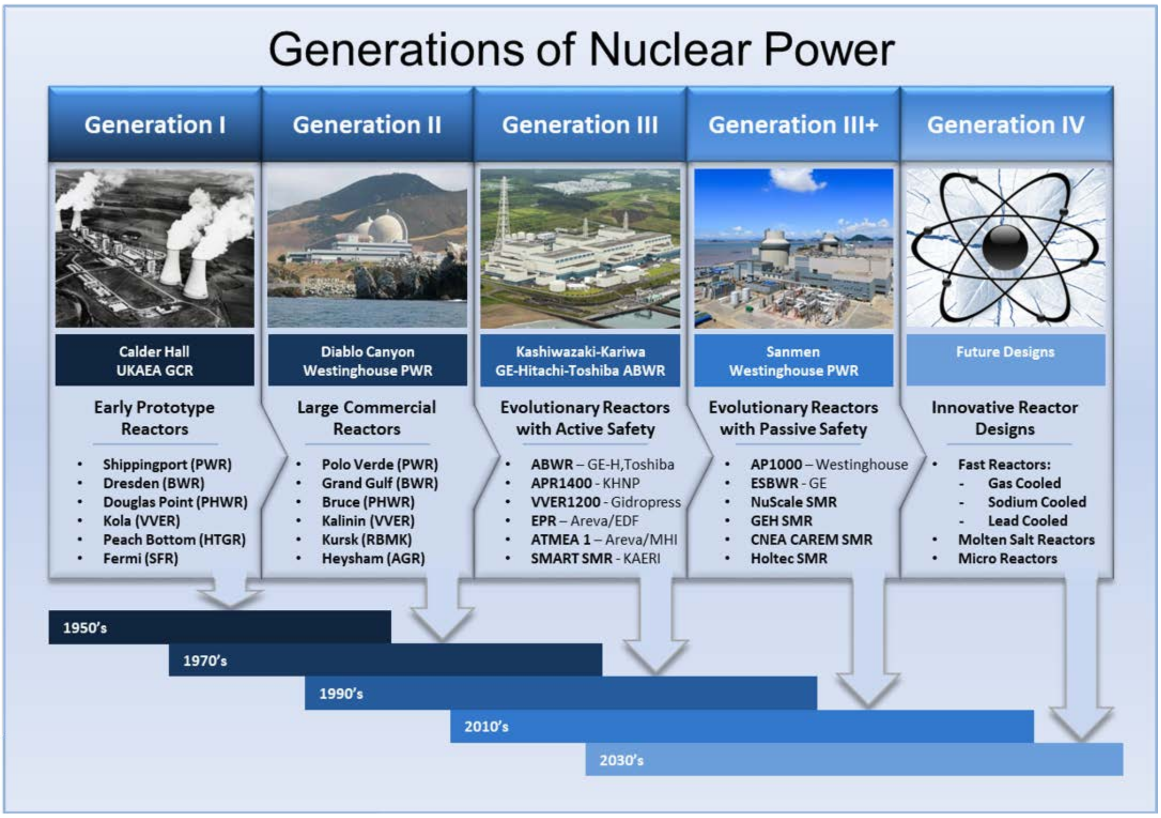
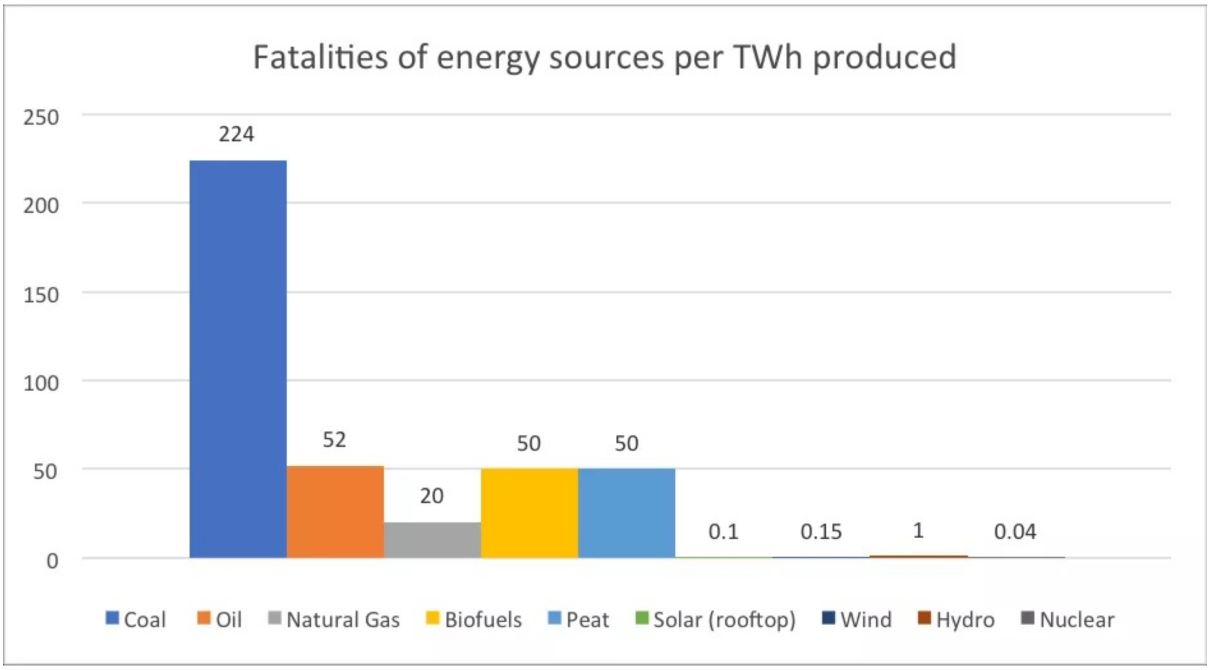


Figure 1 - Evolution of nuclear power plants

The vast majority of existing nuclear power plants, generating safe, clean, reliable electricity in the USA, Japan, Europe and elsewhere are Generation II. The nuclear power plants used in western nations such as Pressurised Water Reactors (PWR), Boiling Water Reactors (BWR), Gas Cooled Reactors in the UK and CANDU reactors in Canada have proven to be far safer than any other electricity generating source.



Generation III and III+ are newer reactors with increased safety, lifetime and operational performance.

Generation III reactors achieve improved safety performance over older units by increasing the number of active safety systems available. This has the benefit of creating more redundancy of systems to provide backup in the unlikely event of an accident, but consequently increases complexity. Active safety systems use AC electricity to power pumps and actuators to maintain cooling following an accident or “station blackout” (loss of onsite and offsite power), with diesel generators to provide backup power. Many Generation III reactors also address “aircraft crash protection” and provide “core catchers” to contain the corium in the case of a meltdown. Most Generation III reactors are constructed in a traditional “stick build” process, meaning the majority of structures are assembled in place at the construction site.

Generation III+ reactors achieve their improved safety performance utilizing “passive safety” systems. Passive safety systems use only natural forces such as gravity and convection to provide cooling in accident scenarios. In a station blackout (i.e. as happened in the Fukushima Daiichi accident), these reactors will shut themselves down without AC power or operator action and maintain core cooling for at least 72 hours, using only natural forces. After this period, further water and equipment is available onsite to maintain cooling indefinitely. These reactors also address aircraft crash protection and are equipped with systems to maintain corium in the reactor vessel in the case of core meltdown, negating reactor vessel breaches and the need for core catchers.

Passive safety systems result in a significant simplification of the nuclear power plant, greatly reducing complex componentry and site footprint. This also results in an improved “man-machine interface”, requiring less operational and maintenance staff. This can be of particular interest to new and developing nuclear nations.

Another feature of Generation III+ reactors is their utilisation of advanced “modular construction” methods. Modular construction increases the amount of factory build, increasing efficiency and quality, while creating parallel construction paths and removing congestion from the build areas.

Some Generation III+ reactors also have advanced load-follow capabilities using a dedicated system of control rods to efficiently vary reactor output, without the need for changes in reactor chemistry (changing the boron content of the reactor coolant water). This achieves 5% per minute ramp up or down of output without generating increased chemical effluents. Nuclear power plants are most cost-effective when operating at 100% output in “baseload” mode, but flexibility to balance the variable nature of renewable sources is becoming increasing important for grid stability.

The Generation III and III+ nuclear power plants shown in Figure 1 are either pressurised or boiling light water reactors, typical of the majority of the operating fleet. Exceptions include the Canadian CANDU reactors, which uses heavy water as the moderator and Gas Cooled Reactors which use graphite as a moderator.
That process uses “thermal spectrum” or slow-moving neutrons, which have been slowed or “moderated” by light or heavy water or graphite. These slow-moving neutrons are able to split or fission the uranium nucleus more readily than fast moving neutrons.

Generation IV will be the next big step in reactor design. Many will be evolutions of earlier Generation I prototype technologies.

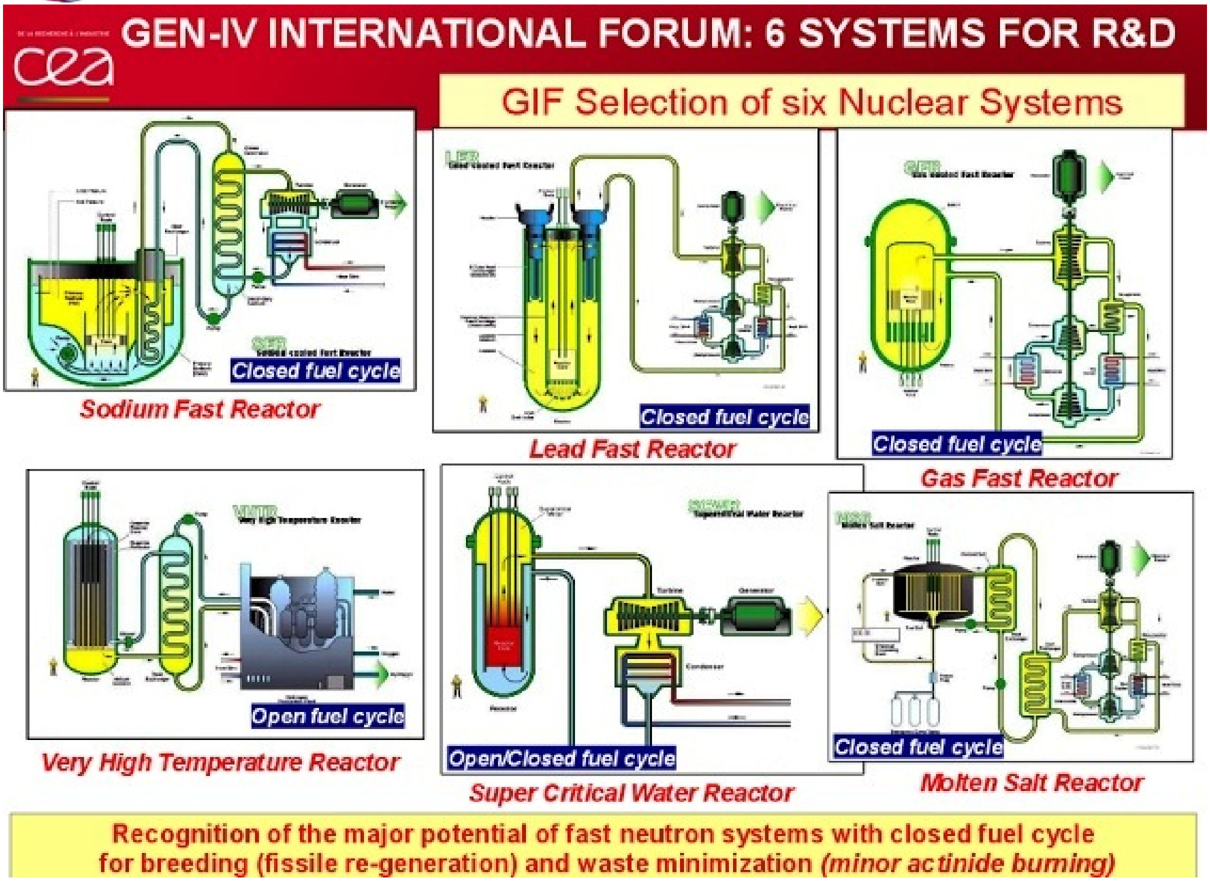


Figure 2 - Generation IV systems

Generation IV nuclear power plants have the following key benefits and features:

1. Five of the options can use a "Closed Nuclear Fuel Cycle". In simplest terms, our current nuclear power plants use less than 2% of the potential energy from the natural uranium.[i] The used fuel then either goes off to waste or a portion is recycled but there are limits on this process. This "Open Cycle" is very wasteful of uranium resources.

2. By using "Fast Spectrum Reactors" in a "Closed Fuel Cycle", more of the uranium can be consumed and very small amounts of long-lived nuclear wastes such as Plutonium, Neptunium and other transuranic isotopes are produced. Even the long-lived wastes from our current reactors can be burned up resulting in fission products being the only wastes. With half-lives of about 30 years, these fission wastes require storage for only around 300 years.

3. These closed fuel cycle reactors can provide a 50-fold improvement in fuel use. Uranium then becomes effectively an unlimited resource and the problem of long-term nuclear wastes is significantly reduced.

4. At least three designs operate at or near atmospheric pressure which effectively eliminates the need for a high-pressure containment and primary coolant circuit. This has the potential to reduce construction costs
5. Load following is more readily achieved.
6. Some designs suit high and very high temperature outputs. This allows for more efficient hydrogen manufacture and the extension of low carbon operations into metals smelting and transport fuel synthesis.
7. Many of these designs promise cost effective power generation with low emissions and high safety factors once the designs mature.

Small Modular Reactors (SMR) are at the development stage and are mostly a variation of Generation III+ technologies. Others further down the track such as Terrestrial Energy's Integral Molten Salt Reactor are Generation IV.

The World Nuclear Association[ii] notes the enormous potential of SMRs rests on a number of factors, (some of which are typical of the Generation III+ reactors on which they are based):

1. SMRs can be built in a controlled factory setting and installed module by module, improving construction quality and efficiency.
2. Their small size and passive safety features suit countries with smaller grids and less experience of nuclear power.
3. Small size and construction efficiency lead to easier financing compared to larger plants.
4. Achieving economies of series production for an SMR design will reduce costs.
5. Small power, smaller radioactive inventory, compact architecture and employment of passive concepts leads to less reliance on active safety systems and additional pumps, as well as AC power for accident mitigation.
6. Potential for below ground or underwater location of the reactor units providing more protection from natural or man-made (e.g. aircraft impact) hazards.
7. The modular design and small size lends itself to having multiple units on the same site.

8. Lower requirement for access to cooling water – therefore suitable for remote regions and for specific applications such as mining or desalination.
9. Ability to remove reactor module or in-situ decommissioning at the end of the lifetime.

One such unit is that of NuScale which consists of six or twelve 60MW units arranged in a pond as shown in Figure 3. This uses Generation III+ pressurised water reactor technology. The nuclear power units comprise the reactor plus pressuriser and steam generator and weigh in at about 700 tonnes each. In practice these may need to be broken down into sub-assemblies for more economic transport.

Figure 3 - NuScale 360 MW nuclear island.

In a practical sense, these nuclear power plants can really be labelled Small Reactors. While the nuclear power module has been modularised, the balance of plant, including the associated structures, requires conventional construction. As a study by MIT[iii] has found strict attention to cost reductions of these structures is essential if SMR's are to achieve their promise.

The overall plant layout is shown in Figure 4 and shows the significant civil engineering and building component required to house these individual modules.

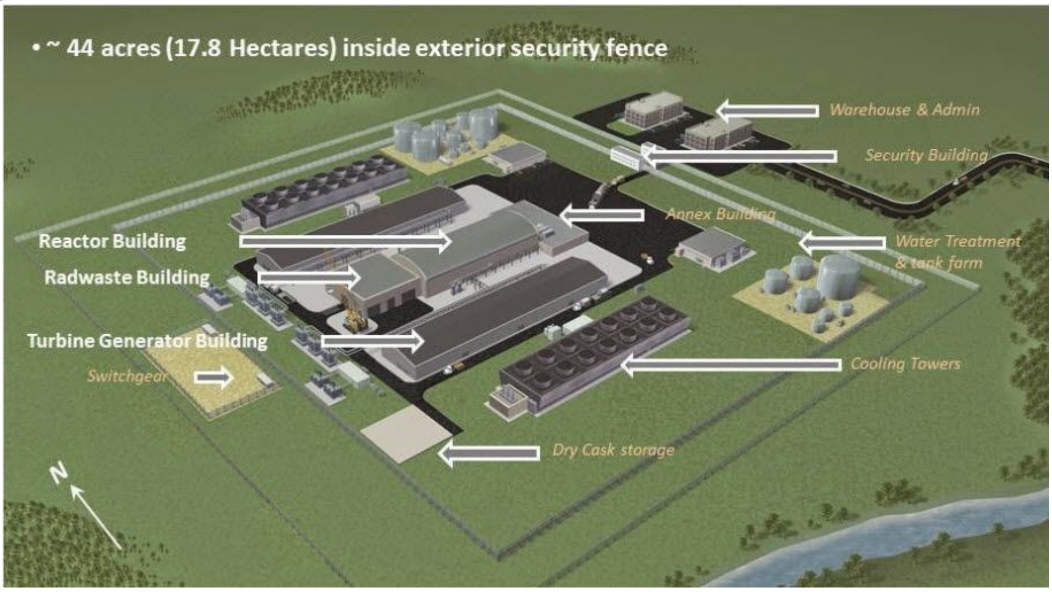
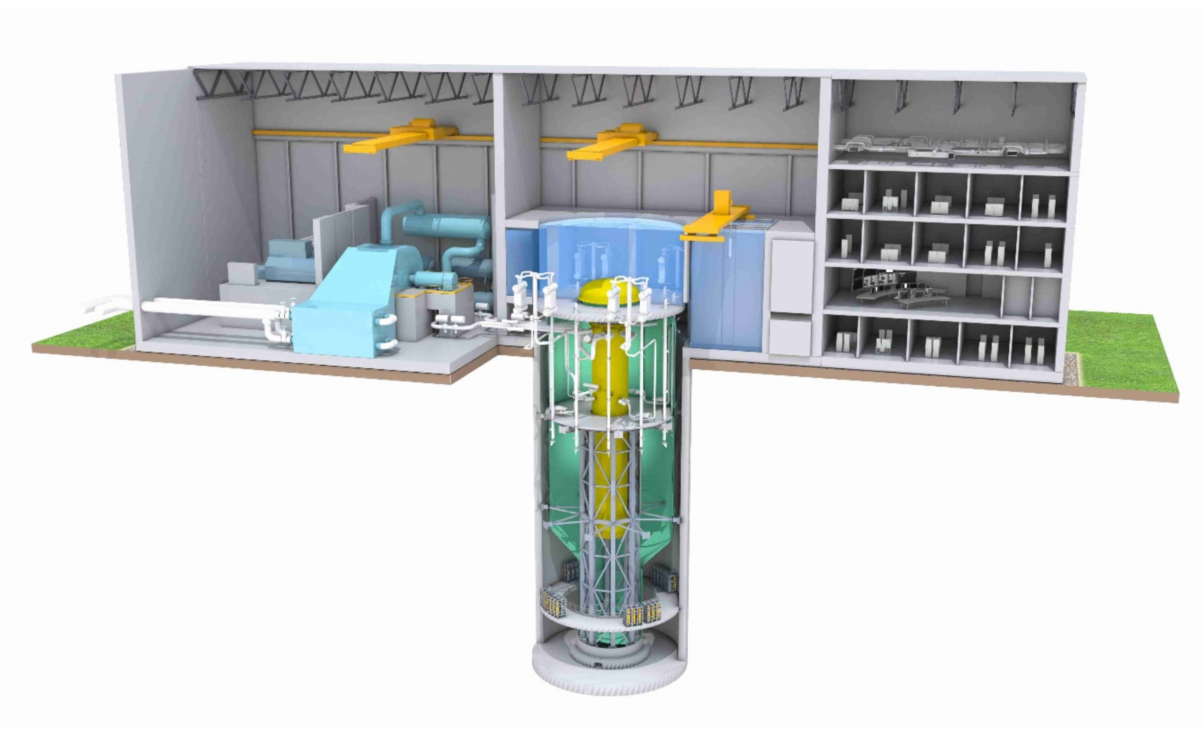


Figure 4 - NuScale plant layout

Another promising Generation III+ SMR is the BWRX 300 from General Electric Hitachi[iv]. This 300MWe design appears to have taken the MIT recommendations on board particularly with respect to the civil engineering structures.



Compared to large reactors, the BWRX-300 aims to achieve about a 90 percent volume reduction in plant layout. Notably, it is designed to reduce building volume by about 50 percent per MW, which should account for 50 percent less concrete per MW. For example, the large 1,520 MWe ESBWR has approximately 160,000 m3 of safety related concrete while the BWRX-300 has only 15,500 m3. The BWRX-300 aims to significantly improve the next wave of reactors due to its affordability and advantageous size.

It's early days however this SMR aims to generate electricity on a competitive basis with gas turbines and renewable energy generators. It aims to have a 60% reduction in capital cost compared to typical waster cooled SMR's and to be deployed by 2028.

1.3 Nuclear Power Plants for Australia

It would be advisable that Australia not be a pioneer with a new technology for its initial journey into nuclear power generation. The first step is a major leap when one considers all of the infrastructure that needs to be in place for construction and operation of a nuclear plant - a new technology will simply add to the development process.

For Australia, the requirement is to use a safe, proven reactor technology with low financial risk. Such a nuclear power plant will enable the culture of safety and confidence to be developed that is essential for the nuclear fuel cycle. It would also help new industry and jobs to develop because they would be engaging with known technologies and commercial realities rather than developmental ventures.

Figure 5 - Generation III+ nuclear power plants - Sanmen Units 1 & 2 AP1000's

Image from Westinghouse and World Nuclear News

For this reason preference should be given to those reactor designs that are currently being deployed and operated such as Westinghouse's 1.1 GW sized AP1000 nuclear power plant shown in Figure 5. The AP1000 plant is designed to fully leverage advanced modular construction methods and four units have been completed and are in full commercial operation, with several more in the construction and planning phases. The first-of-a kind unit, Sanmen 1, completed its first refuelling outage in record time and was named the top performing plant in China by the World Association of Nuclear Operators (WANO).

The use of larger reactors would be complimented by Small Modular Reactors (SMR's) such as the NuScale, GEH's BWRX 300 or Generation IV plants such as Terrestrial Energy's IMSR reactor as and when they become available as "Nth" of a kind plants. Without a significant change in climate change policies, it's hard to see even the first of these being available before the early 2030's.

The option of Small Modular Reactors should be investigated provided those reactors are sufficiently advanced in their licensing and deployment. For the purposes of decarbonising our economy and achieving low cost reliable electricity, we must remain focused on near term real and achievable goals.

SMR's as currently envisioned have the advantage of being able to operate over larger extremities of the existing grid without significant upgrades and costs being incurred. The study should identify suitable sites for SMR's.

1.4 Large Reactor Options

Internationally, new power reactor construction is concentrated on the successful Pressurised Water Reactors (PWR's) designs with less emphasis on Boiling Water types.

There are currently 46 nuclear power plants under construction worldwide not including prototypes. Only five of these are being constructed using plants from the USA (AP1000) or France (EPR) which have incurred significant time and cost over-runs, as an all-too-common characteristic of first-of-a-kind projects. First-of-a-kind SMR and Generation IV reactor projects are expected to face similar challenges. The rest are of Russian, Chinese and South Korean origin that may reflect a truer benchmark cost.

Over 100 power reactors with a total gross capacity of about 120,000 MWe are on order or planned and only a couple in the USA are Small Modular Reactors.

Many of the nuclear power plants currently under construction or planned are in nations of far less wealth than Australia and/or with more constrained grids. These include Bangladesh, Argentina, Romania, Turkey, Egypt, Kazakhstan, Pakistan, Finland, Hungary, Slovakia and Uzbekistan. It is not credible to assume that all these nations are failing to maintain competitive power prices with nuclear energy.

Reactors that are currently being built and/or exported around the world are the:

1. AP1000 (1150 MWe) from Westinghouse.
2. APR-1400 (1400 MWe) marketed by Korea Electric Power Corporation.
3. VVER 1200 and 1000 models from OKB Gidropress in Russia.
4. EPR - Evolutionary Pressurised Water Reactor from EDF in France.
5. Hualong One 1150MWe pressurised water reactor from CGN/CNNC in China.
6. Candu EC 6 (700 MWe) from Canada.
7. ABWR - Advanced Boiling Water reactor from Hitachi GE.

Of these reactors, the Westinghouse AP1000, the ABWR and the APR 1400 are currently licensed by the Nuclear Regulatory Commission in the United States.

Within the UK, the EPR, the Westinghouse AP1000 and the ABWR have all passed approval by the Office of the Nuclear Regulator

The first five reactors are known as Pressurised Water Reactors or PWR's. The CANDU is a unique Canadian design that uses natural unenriched uranium in a horizontal array of tubes known as a calandria. The seventh type is a boiling water reactor, which operates at a lower pressure than the other types.

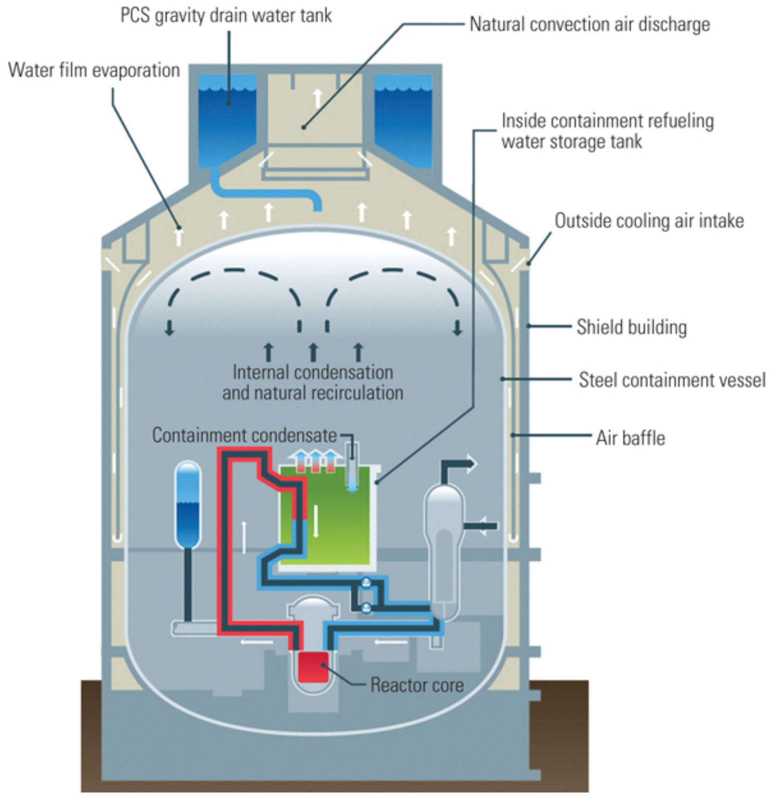


Figure 6 - Westinghouse AP 1000 passive safety system schematic

The initial scoping of the Australian Nuclear for Climate Project will reference power plants similar to the Westinghouse AP1000 of the type shown in Figure 6 with its electrical capacity of 1150MWe.

1.5 Wealth creation and employment

With the retirement of Australia's aging coal fired power stations we can build 1.1-Gigawatt nuclear power plants. They could be linked to the existing grid and use the cooling resources of existing coal plants.

An employment and economic analysis of such a single unit plant was recently completed in Finland for its new Hanhikivi 1 nuclear power plant. This indicates that for a similar plant in Australia:

- 20,000 people would be employed during the course of construction
- Up to 4,000 would be working simultaneously
- 500 people would be employed during plant operations in very highly technically fulfilling roles.
- 2,600 jobs would be created by the cascading effect on training, education, accommodation and allied industries

Renewable Energy projects have manufacturing costs which are dependent on low labour rates in developing nations and they have very high levels of imported content. Nuclear energy however represents an opportunity for the industrial renewal of the Australian manufacturing sector especially in regional Australia.

A fleet of nuclear power plants can have steadily increasing the local content. This happened most strongly in France, South Korea, Japan and more recently in China. The same could happen in Australia. The very first plants could have at least 70% local content for labour and materials. Risk informed sourcing is a process used to ensure commodities and labour skills match the level of sophistication relevant to a particular process. As Figure 7 and Figure 8 show this could steadily build into the higher risk areas, which in practice only make up a small part of the project value.

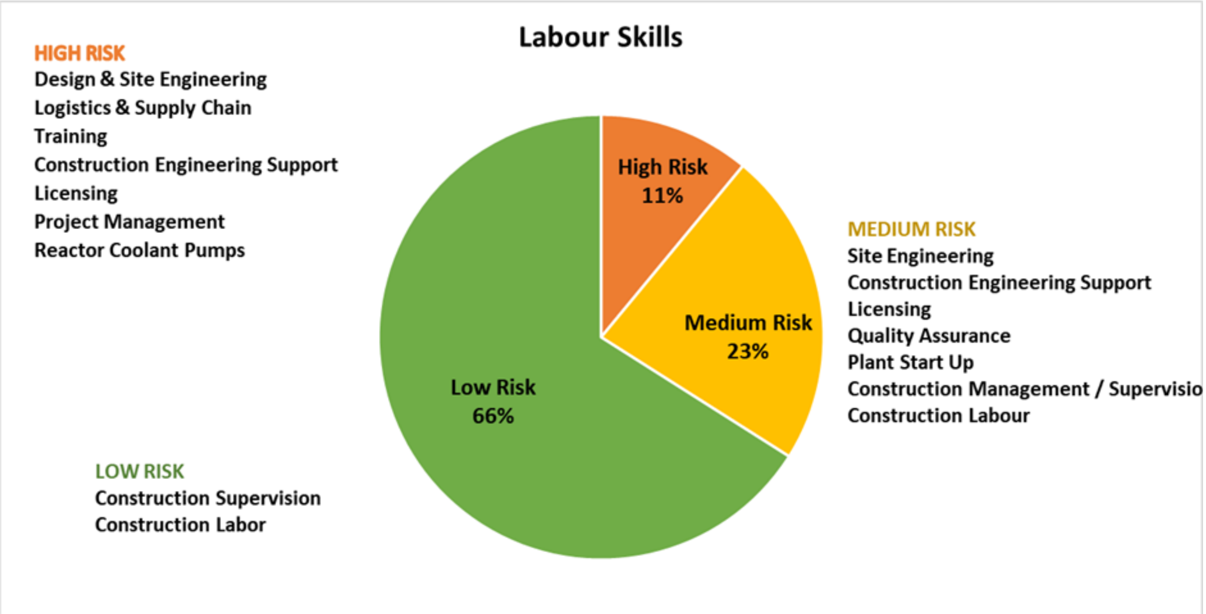


Figure 7 - Proportion of Labour

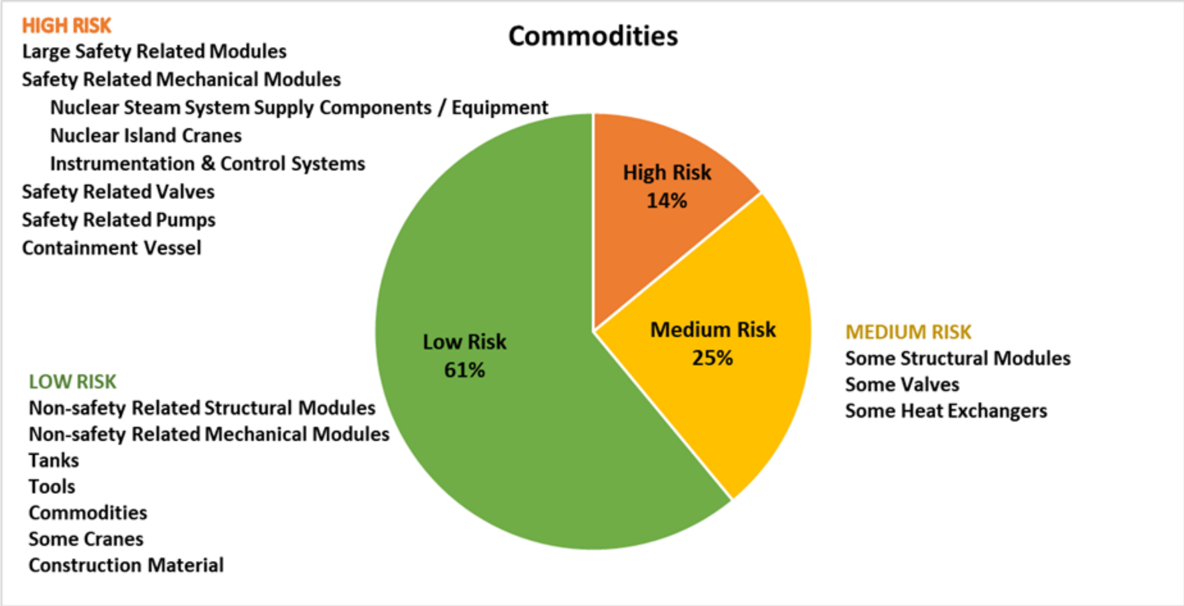


Figure 8 - Proportion of Commodities

1.6 Final Comment

Right now Australia is faced with the critical issue of choosing our future power system. International Energy studies by the OECD[v] have shown that a system that includes nuclear energy is less costly than one that excludes it.

Our future energy systems need to be planned around the critical trilemma of carbon reductions, reliability and low cost. In addition we need to address issues of long-term strategic benefits, community stability and our industrial future especially for regional Australia. We also need to make sure that our future energy systems are environmentally and socially sustainable and don't become a blight on our landscapes as for example happens with wind turbines around the globe. We can also leverage Australia's abundant uranium resources to maintain national energy security. In the future, as water poverty becomes more and more of an issue, nuclear power can also provide a low-carbon option for sea water desalination.

A system based on nuclear energy has the potential to power Australia for a century and can grow to replace fossil fuel use in transport, steels making and a host of other energy intensive industries.

Robert Parker
Nuclear for Climate Australia
And Vice President,

Australian Nuclear Association

Ph +61 (0)2 48771320
Mobile 0428 482 066
https://nuclearforclimate.com.au/
www.nucleraraustralia.org.au

[i] "Fast Spectrum Reactors" Waltar, Todd and Tsvetkov 'Fast Spectrum Reactors para 1.4.2
[ii] https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx
[iii] https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf
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[v] OECD/NEA, The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables