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Potential Applications of the Modern Nuclear Fuel Cycle to Australia

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In this white paper we present a brief survey of the opportunities and challenges facing the development of nuclear fuel cycle facilities in Australia. We selected South Australia (SA) as an example for our analysis, since this state has shown early interest in decarbonizing its power sector and attention towards potential business opportunities related to the nuclear fuel cycle. However, the findings are likely to New South Wales (NSW) and other states as well.

Opportunity #1: Decarbonization of the power sector

The key question addressed here is whether nuclear should play a significant role in decarbonizing SA's power sector. SA has been aggressively pursuing the deployment of renewable energy (wind in particular) with the intent to reduce carbon emissions. SA has been partially successful towards this goal (relatively to the rest of Australia), but at the cost of higher electricity prices and lower reliability of its grid.

Our analysis used GenX, an optimization tool specifically developed and validated at MIT to study the effect of the generation mix on the carbon intensity and the cost of electricity in power systems[1]. Here we have used GenX to find the generation mix that provides the minimum total system cost, expressed as the average cost of electricity (in 2017 USD $/MWh) in SA, for given decarbonization targets. We selected the following input:

- The hourly power demand in SA over the course of 2017, i.e., a total of 8760 entries.
- The hourly load factors for solar and wind in SA (using actual data from wind farms and solar PV panels in SA), i.e., a total of 8760 entries each for wind and solar.
- The capital, fixed and variable O&M and fuel costs for all power generators, as well as backup and storage required to accommodate the intermittent renewables.
- The ramp-up rates and cycling parameters (minimum up and down times, start-up cost) for all power generators, i.e., how quickly a generator can come online when needed and how fast generators can adjust their output.

GenX uses the inputs to determine the generation and storage installed capacity and hourly operation decisions that would supply demand at minimum cost while fulfilling the emissions limits. We performed the GenX optimization calculation for various "scenarios", e.g., a scenario may exclude nuclear or may prevent existing wind from being retired. For each scenario we performed the calculation for various carbon constraints, i.e., the maximum allowable CO_2 emission rate in that system (gCO2/kWh). The current world-average carbon intensity of the power sector is about 500 gCO2/kWh, while it is 780 gCO2/kWh in Australia. In SA it was 560 gCO2/kWh in 2015[2]. Our estimate of the current SA figure is 290 gCO2/kWh[3]. According to climate change stabilization scenarios developed by the International Energy Agency in 2017, the power-sector carbon intensity targets to limit global average warming to 2°C range from 10 to 25 gCO2/kWh by 2050 and less than 2 gCO2/kWh by 2060. The results of our calculations are shown in Figures 1 and 2 and Table I, where all scenarios analysed are listed, and numerical values for the required capacities and incurred costs are reported.

These results suggest that with a modest amount of nuclear power in the SA generation mix (i.e., between 600 and 1500 MW of capacity) the average cost of electricity in SA can be kept reasonably low even in deeply decarbonized scenarios. Without nuclear, the average cost of electricity in SA would rapidly increase with decreasing carbon emissions (Figure 1), which seems consistent with what is actually happening. If nuclear is excluded, an enormous build-out of wind, solar and storage capacity

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[1] Jenkins, J., and N. Sepulveda. 2017. "Enhanced Decision Support for a Changing Electricity Landscape." http://energy.mit.edu/publication/enhanced-decision-support-changing-electricity-landscape.

[2] "A low carbon investment plan for South Australia", report, Gov. of South Australia, 2015.

[3] http://www.cleanenergyregulator.gov.au/NGER/National%20greenhouse%20and%20energy%20reporting%20data/electricity-sector-emissions-and-generation-data/electricity-sector-emissions-and-generation-data-2016-17

is required to achieve the decarbonisation goal; natural gas and coal backup cannot be used extensively in such scenarios because of their carbon emissions (Figure 2). It is the capital cost of this renewable and storage capacity build-out that drives up the average cost of electricity in such scenarios.

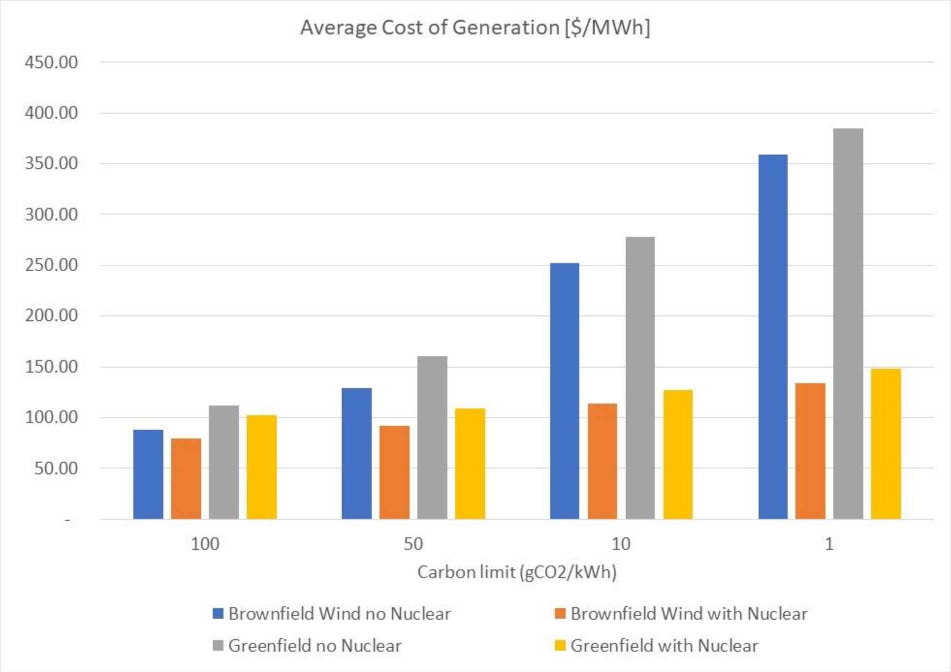

Figure 1. Average system cost of electricity (in USD $/MWh) in SA for different carbon constraints (gCO2/kWh) and four scenarios. "Brownfield Wind" refers to scenarios in which existing SA wind generation is included (and treated as fully-amortized). "Greenfield Wind" allows for an unconstrained optimal mix, in which the capital cost of wind has to be recovered. The cost escalation seen in the no-nuclear scenarios with aggressive carbon constraints is mostly due to the additional build-out and cost of energy storage, which become necessary in scenarios that rely exclusively on variable renewable energy technologies.

Note that in our analyses we made very generous assumptions about the future cost of wind, solar and storage capacity[4]. As of now, no storage technology (except pumped hydro) is available at the scale and cost required for grid applications. Moreover, we have not taken into account any environmental constraints or land availability that might limit the renewable capacity build-out. Further, we have not analysed extreme scenarios of multiple days with no wind or sunshine. Finally, we have not considered the potential grid reliability issues (e.g., voltage and frequency stability) arising from large instantaneous variations of renewable generation. As such, we deem our analysis to be quite robust and conservative, strengthening the conclusion that indeed some nuclear capacity could be very valuable to the SA power system[5].. We surmise that similar results would apply to other Australian states as well as the country as a whole, as suggested also by other recent analyses[6].

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[4] Cost estimates for renewables and storage are the mid-2040 projections from the National Renewable Energy Laboratory's (NREL) 2016 Annual Technology Baseline and Standard Scenarios: https://www.nrel.gov/docs/fy16osti/66944.pdf For nuclear we assumed an overnight capital cost of $5000/kW, consistent with the same NREL's outlook, and 8 years construction schedule. These figures are much higher than those observed for nuclear plants recently built in South Korea, China and Japan.

[5] We did perform sensitivity analyses around the cost of nuclear, the price of natural gas, the availability and efficiency of carbon capture and sequestration technologies, the effectiveness of demand management and energy efficiency, for several other regions of the world, using the exact same methodology based on GenX, and found that the optimal generation mix is affected only minimally.

[6] Heard, B., 2018, "Identifying the role for nuclear power in Australia's energy transition", Frazer-Nash Consultancy; Barr, R., et al, 2018, "Reliable and Affordable Electric Power Generation - why Australia should develop a balanced mix of generation options". https://epc.com.au/index.php/nem-model/

Table I. Results for all SA scenarios analysed. Cases 1 through 8 are the "brownfield wind" scenarios. Cases 9 through 16 are unconstrained by existing capacity. Cost figures are in 2017 USD. As of 2017, the SA electrical generation capacity was as follows[7]: natural gas (2670 MW), wind (1700 MW), solar PV (780 MW), diesel (290 MW). Therefore, to achieve the 100 gCO2/kWh "brownfield wind" scenario without nuclear (Case 1 in this table) would entail complete elimination of the existing diesel capacity, a significant reduction of the natural gas generation capacity, installation of over 1200 MW of additional wind capacity, almost doubling the current solar PV capacity, and importantly over 1600 MWh of storage capacity.

Cases	Nuclear Available	CO2 Emissions LIMIT [gCO2/kWh]	Existing Wind Capacity [MW]	Capacity Open Cycle Gas Turbine (OCGT) [MW]	Capacity Combined Cycle Gas Turbine (CCGT) [MW]	Capacity Coal (IGCC) [MW]	Capacity Nuclear [MW]	Capacity Wind [MW]	Capacity Solar PV [MW]	Capacity Battery Storage [MW]	Capacity Battery Storage [MWh]	System Total Cost [$]	Average Cost of Generation [$/MWh]	System Total Demand [MWh]
1	NO	100	1806	600	1500	0	0	2885	1425	826	1652	$ 1,025,220,495	$ 88.13	1.16E+07
2	NO	50	1806	400	1000	0	0	3882	2907	2700	5401	$ 1,501,293,680	$ 129.05	1.16E+07
3	NO	10	1806	0	1500	0	0	4486	7535	8100	16200	$ 2,933,444,220	$ 252.16	1.16E+07
4	NO	1	1806	0	500	0	0	3027	13720	13383	26765	$ 4,178,700,321	$ 359.21	1.16E+07
5	YES	100	1806	1000	1000	0	600	1806	0	6	13	$ 923,303,180	$ 79.37	1.16E+07
6	YES	50	1806	1200	500	0	900	1806	0	276	553	$ 1,069,276,715	$ 91.92	1.16E+07
7	YES	10	1806	400	500	0	1200	1806	409	1090	2181	$ 1,326,884,797	$ 114.06	1.16E+07
8	YES	1	1806	0	500	0	1500	1806	404	1485	2971	$ 1,554,363,073	$ 133.61	1.16E+07
9	NO	100	0	400	1500	0	0	2783	1545	841	1683	$ 1,306,794,512	$ 112.33	1.16E+07
10	NO	50	0	400	1000	0	0	3923	2821	3122	6244	$ 1,873,612,798	$ 161.06	1.16E+07
11	NO	10	0	0	1500	0	0	4643	7229	8269	16538	$ 3,236,122,984	$ 278.18	1.16E+07
12	NO	1	0	0	500	0	0	3027	13720	13383	26765	$ 4,475,787,321	$ 384.74	1.16E+07
13	YES	100	0	1000	1000	0	900	365	0	147	295	$ 1,191,129,593	$ 102.39	1.16E+07
14	YES	50	0	600	1000	0	1200	0	0	242	484	$ 1,270,207,140	$ 109.19	1.16E+07
15	YES	10	0	600	500	0	1500	200	111	819	1637	$ 1,480,589,671	$ 127.27	1.16E+07
16	YES	1	0	0	500	0	1800	0	573	1031	2062	$ 1,723,408,048	$ 148.15	1.16E+07

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[7] https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/SA_Advisory/2017/South-Australian-Electricity-Report-2017.pdf

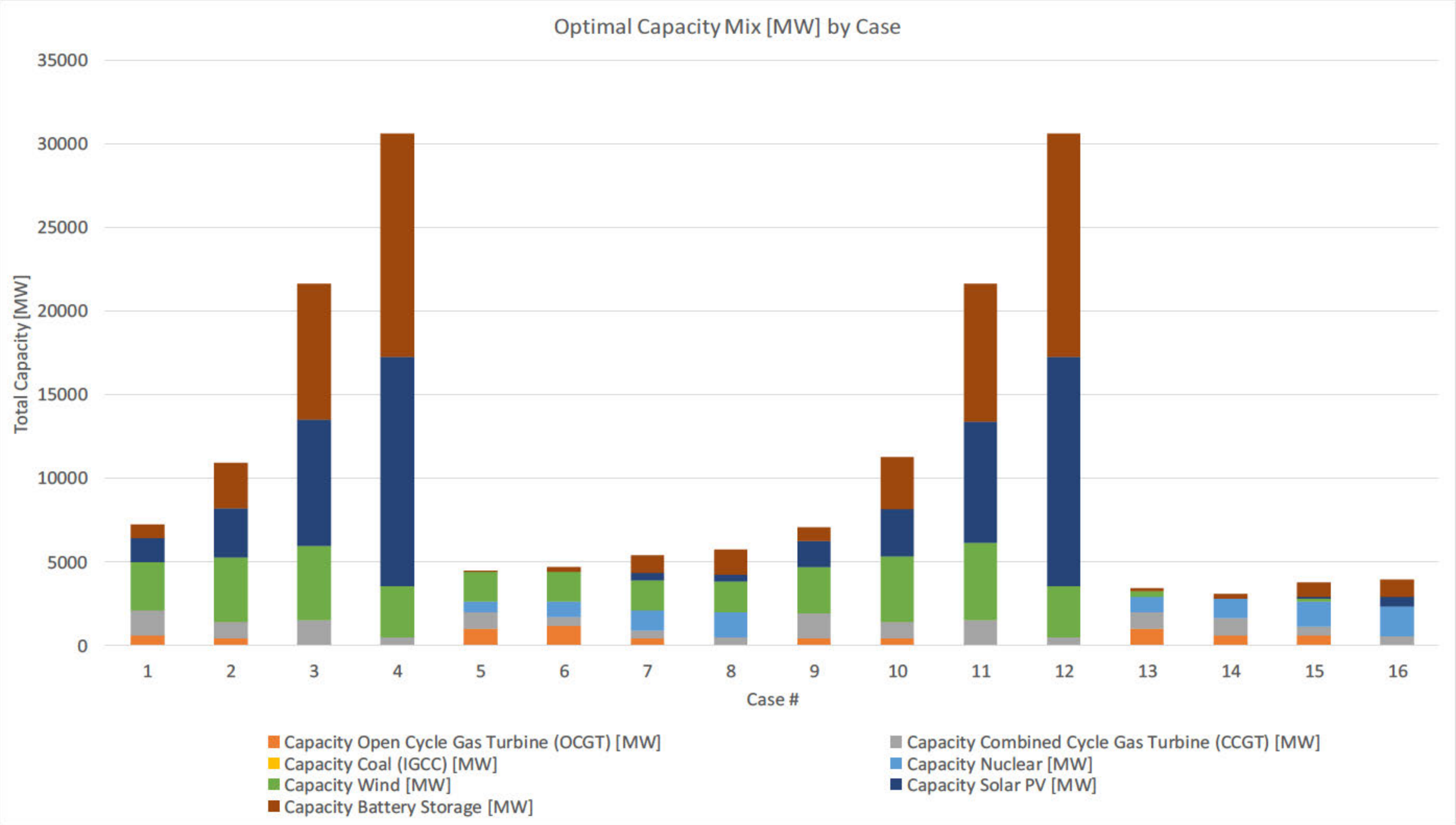

Figure 2. Installed capacity of various generation and storage technologies for all SA cases analysed. Note the contrast between the required installed capacity for renewables vs. nuclear to achieve the same decarbonization objective. Note: storage has been plotted in power units [MW] instead of energy units [MWh]. The assumed storage technology provides 2 MWh of energy storage for every MW, i.e., an energy-to-power ratio of 2 hours, consistent with Li-ion batteries.

Given the small nuclear capacity required to meet the decarbonization targets in SA, the traditional large GW-scale Light Water Reactors (LWR) are probably not the most attractive option. A new class of Small Modular Reactors (SMRs), which are based on LWR technology, as well as the now mature Generation-IV High-Temperature Gas Reactor (HTGR) technology would seem more suitable. These systems can be deployed in units of 50-300 MW each, thus matching demand more gradually, reducing the amount of capital at risk at any given time in the project, allowing for more serial and standardized construction in factories or shipyards, and potentially affording greater average plant availability. With the increasing role of variable renewables on the grid, a certain flexibility in operations is expected from all dispatchable power generators. Large nuclear plants were traditionally designed for baseload operation, but, as has been recently demonstrated in Europe and the United States[8], they can adapt to provide load-following generation, and the new reactors are being designed for that capability from the start. Load-following operation in nuclear reactors is executed through the combined control of core power and turbine bypass, the latter allowing for rapid adjustment of the electric output, at the expense of somewhat lower plant efficiency (i.e., lower conversion ratio of heat to electricity). Even more sophisticated load-following approaches might be possible if nuclear reactors were coupled to heat storage, a technology that is now being deployed at the gigawatt-hour scale for concentrated solar power. The cost of heat storage is an order of magnitude less than the cost of electricity storage (pumped hydro, batteries, etc.), and is expected to be available by the time nuclear reactors could be deployed in SA[9].

The HTGR operates at higher temperature, thus has a higher plant efficiency, and can also more readily supply heat to certain industrial processes requiring high-temperature heat (e.g., production of hydrogen and synthetic fuels). Note that neither SMRs nor HTGRs require fresh-water cooling; they can both function with ocean-water cooling, like most nuclear power plants around the world, and even with air (dry) cooling, again at the expense of plant efficiency. Both SMRs[10] and HTGRs[11] are now being licensed and deployed internationally. Therefore, these technologies will be available for deployment also in Australia within the next decade. Other reactor technologies that could be considered in the longer term (i.e., two decades away) include liquid-salt cooled reactors and liquid-lead cooled reactors. We deem the sodium fast reactor technology ready for deployment now but not attractive, because it typically requires fuel reprocessing and plutonium separation, which creates nuclear proliferation concerns.

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[8] Jenkins, J, et al. 2018. "The benefits of nuclear flexibility in power system operations with renewable energy." *Applied Energy* (222): 872-884.

[9] Forsberg, C., 2018 "Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels", *Nuclear Technology (In Press)* https://doi.org/10.1080/00295450.2018.1518555

[10] https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale.html

[11] Zhang, Z, et al. 2016. "The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation." *Engineering* 2 (1): 112-118.

Opportunity #2: New economic development

The various steps of the so-called once-through nuclear fuel cycle are shown in Figure 3 below.

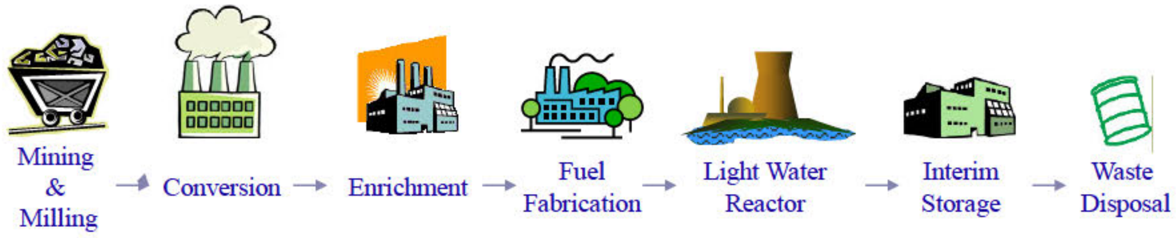

Figure 3. The once-through nuclear fuel cycle: uranium is mined from common minerals and converted from a solid oxide (U_3O_8) to a gaseous fluoride (UF_6) for processing in the enrichment plant where the content of fissile uranium (^{235}U) is increased from 0.7 w% to 3-5 w%, which makes it usable in LWRs. Spent fuel from LWRs is first stored and then ultimately disposed of underground.

We note that uranium mining, milling and extraction are already well developed in Australia, which currently supplies about 10% of the world's uranium demand, but possesses roughly a third of the world's uranium reserves. Meanwhile there is a worldwide excess of industrial capacity for uranium conversion and uranium enrichment as well as fabrication of fuel assemblies for LWRs, thus no *new* major business opportunities for Australia are anticipated in those activities.

There are however potentially massive economic opportunities associated with the deployment of power reactors and fuel storage and disposal facilities in SA. Briefly, in addition to serving the needs of the decarbonized electric grid discussed above, a significant fraction of the electricity generation from a nuclear power plant in SA could be devoted to production of desalinated water (via reverse osmosis), which in turn would be used to develop farming of high-value crop on semi-arid, currently un-utilized land in the Eyre Peninsula. Mutual synergies would exist between the nuclear plant and the desalination plant in that electricity supply to the desalination plant would ensure a steady revenue stream for the power plant. In turn, the desalination plant using nuclear electricity would be emission free and could operate 24/7 with high reliability.

Initial revenues to finance the nuclear power plant, desalinated water plant and distribution system for farming would come from the deployment of an interim Spent Nuclear Fuel (SNF) surface repository, which could accept SNF from other nuclear countries within 3-5 years. The combined economic impact from SNF shipment and storage, nuclear power plant and water desalination plant operations and new farming activities would easily be in the billions of dollars per year, making SA a major global hub for clean energy and high-value crops. A more detailed assessment of these opportunities has been discussed in a separate publication[12].

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[12] J. Buongiorno, N. Sepulveda, L. Rush, "Potential Applications of the Modern Nuclear Fuel Cycle to (South) Australia", CANES Report ANP-TR-182, Massachusetts Institute of Technology, Rev. 1., November 2018.

Typical Concerns

Nuclear Safety

In terms of worker safety and protection of the public and the environment, the nuclear industry has one of the best safety records among all industries. However, serious accidents such as Fukushima and Three Mile Island have occurred, and while their radiological consequences are practically non-existent[13], they have renewed public concerns about the safety of nuclear installations. For example, in the wake of Fukushima, five countries (Germany, Switzerland, Belgium, Taiwan, and South Korea) announced their intention to ultimately phase out nuclear energy, though to date only Germany has taken immediate action toward actually implementing this policy.

For three decades now the nuclear industry has been developing new reactor technologies that greatly reduce the probability and consequences of accidents. This is accomplished through a combination of (a) so-called passive safety systems (requiring no emergency AC power to maintain reactor cooling), (b) more automated operations and response to abnormal conditions (thus making the plant less susceptible to human errors), and (c) more robust containment designs (making it un-necessary to evacuate the local population in case of a major accident at the plant). Such design evolution has already occurred in some large LWRs and is exhibited in recent plants built in China, Russia, and the United States. The LWR-based SMRs and the HTGRs recommended for deployment in SA also possess such features.

High Level Waste (HLW)

The term HLW commonly refers to Spent Nuclear Fuel (SNF), i.e., the left-over material from generation of electricity in nuclear power plants. While this material is highly radioactive and long-lived, it is generated in very small amounts that can be easily contained and managed at low cost for long periods of time (Fig. 4). While the HLW disposal issue is universally considered a barrier to the expansion of nuclear energy use, its political dimension far outweighs the technical challenges. There exist several robust technical solutions for HLW management, such as interim storage in dry casks and permanent disposal in geological repositories with excavated tunnels or deep boreholes — the greater difficulty, historically, has been siting such facilities. But the evidence suggests that these solutions can be implemented through a well-managed, consensus-based decision-making process, as has been demonstrated in Finland and Sweden[14,15].

The preferred nuclear waste form for SA would be SNF dry casks (shown in Figures 4, 5 and 6). Dry casks are suitable for surface storage, do not require any special geology and will last for centuries with minimal maintenance and cost. They can also be replaced, as needed. Dry cask storage provides time for decay of short-lived radionuclides that, in turn, lower the ultimate cost of geological disposal. Over a period spanning more than three decades, the US nuclear industry has safely loaded and placed into storage over 2700 SNF dry casks. Adopting this form of storage in SA, for both domestic and international HLW, would be a tremendous economic opportunity (worth billions of dollars per year in collected fees), with miniscule public health risk.

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[13] United Nations Scientific Committee on the Effects of Atomic Radiation. 2017. "Developments since the 2013 UNSCEAR report on the levels and effects of radiation exposure due to the nuclear accident following the Great East-Japan Earthquake and Tsunami - A 2017 white paper to guide the Scientific Committee's future programme of work." New York.

[14] Fountain, H. 2017. "On Nuclear Waste, Finland shows U.S. how it can be done." *The New York Times*, June 9.

[15] Plumer, B. 2012. "What Sweden can teach us about nuclear waste." *The Washington Post*, January 28.

Figure 4. SNF in dry casks is shown here at the Connecticut Yankee nuclear power plant site. This storage area is all that is left of the now decommissioned nuclear plant, which generated 580 MW of electricity for 21 effective full-power years. We estimate that if SA were to use nuclear power at 1000 MW (thus providing about 75% of SA's total electricity demand) for 40 effective full-power years, the total number of dry casks accumulated would be about 140 (source: http://www.connyankee.com/html/fuel_storage.html)

Figure 5. Dry casks containing spent nuclear fuel are inspected at an unspecified US nuclear power plant. The cask design includes radiation shielding, so that approaching and handling these casks exposes the workers to a negligibly low radiation dose. (source: Nuclear Energy Institute)

Figure 6. Highway Patrol Officers conduct radiological surveys and mechanical inspections on the first Nevada Test Site transuranic waste shipment at the Area 5 Radioactive Waste Management Complex located on the Nevada Test Site. These shipments travel on normal public roads to their final destination at the Waste Pilot Isolation Plant near Carlsbad, New Mexico. (source: NNSA)

ACRONYMS

AC	Alternating Current
CCGT	Combined Cycle Gas Turbine
HLW	High Level Waste
HTGR	High Temperature Gas Reactor
IGCC	Integrated Gasification Combined Cycle
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
NFCRC	Nuclear Fuel Cycle Royal Commission
NNSA	National Nuclear Security Administration
NPP	Nuclear Power Plant
NREL	National Renewable Energy Laboratory
NSW	New South Wales
OCGT	Open Cycle Gas Turbine
PPA	Power Purchase Agreement
PV	Photo Voltaic
SA	South Australia
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
US	United States
USD	Unites States Dollars