



Policy Forum Article

Closing the Cycle: How South Australia and Asia Can Benefit from Re-inventing Used Nuclear Fuel Management

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Abstract

A large and growing market exists for the management of used nuclear fuel. Urgent need for service lies in Asia, also the region of the fastest growth in fossil fuel consumption. A logical potential provider of this service is acknowledged to be Australia. We describe and assess a service combining approved multinational storage with an advanced fuel reconditioning facility and commercialisation of advanced nuclear reactor technologies. We estimate that this project has the potential to deliver a net present value of (2015) AU\$30.9 billion. This economic finding compares favourably with recent assessment based on deep geological repository. Providing service for used nuclear fuel and commercialisation of next generation nuclear technology would catalyse the expansion of nuclear technology for energy requirements across Asia and beyond, aiding efforts to combat climate change. Pathways based on leveraging advanced nuclear technologies are therefore worthy of consideration in the development of policy in this area.

Key words: used nuclear fuel, integral fast reactor, PRISM, pyroprocessing, technology, climate change

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This article investigates a novel approach to the integrated management of used nuclear fuel and development of advanced nuclear recycling facilities. Economic analysis demonstrates potential net benefits of tens of billions of dollars for this integrated approach, hypothetically based in South Australia to serve primarily the Asian market. Energy policy implications include potential unshackling of nuclear development in Asia, assisted by the provision of a used fuel service via Australia.

1. Introduction: Addressing a Need

Humanity faces a daunting challenge this century: to rapidly phase out the use of fossil fuels to mitigate climate change whilst simultaneously delivering a secure, long-term energy supply for modern society. Nuclear fission has an enormous and proven potential to supply reliable baseload electricity and displace fossil fuel power plants and, at a deployment rate in some nations, commensurate with the demands for clean energy this century (Qvist & Brook 2015). The fundamental advantages of nuclear power (a compact and near-zero-carbon energy source with energy dense fuel) remain critically important in many Asian markets, which are experiencing continued growth in population and electricity demand (Nuclear Energy Agency 2012; International Atomic Energy Agency 2014). One of the most enduring obstacles to accelerated expansion of nuclear electricity generation has been the uncertainty surrounding the management of used nuclear fuel. There is approximately 270,000 tonnes of heavy metal (tHM) of used nuclear fuel in storage worldwide

(World Nuclear Association 2015). In addition, approximately 12,000 tHM of used nuclear fuel is produced each year (World Nuclear Association 2015). Recent estimates suggest this will exceed 1 million tHM by 2090 (Cronshaw 2014; Cook *et al.* 2016).

There is no multinational spent fuel repository available today (Feiveson *et al.* 2011). The International Atomic Energy Agency states that a disposal service for used fuel would be an attractive proposition for smaller nuclear nations and new market entrants (International Atomic Energy Agency 2013). For instance, the mature energy market of Singapore has near-total reliance on imported natural gas for electricity (Energy Market Authority 2015a, b) to serve a developed population of 5.4 million residents. A moderate-sized nuclear sector (approximately 10 GW installed) (Energy Market Authority 2015a, b) offers high-certainty decarbonisation with enhanced fuel security. Fast-growing demand in the developing-nation market of Indonesia means electricity use is expected to almost triple from 2011 to 2030, predominantly based on coal (International Energy Agency 2013) with 25 GW of new coal generation planned from 2016 to 2025 (PWC Indonesia 2016). An approved, regional solution to used fuel management might catalyse acceleration of energy investment away from fossil fuels in this region and toward nuclear fission, with commensurate benefits in reduced greenhouse gas emissions and reduced air pollution.

Countries with already established nuclear power programmes also require services. Japan has accumulated US\$35 billion for the construction and operation of a nuclear repository (World Nuclear Association 2014). South Korea faces impending shortages of licensed storage space for used nuclear fuel (Dalnoki-Veress *et al.* 2013; Cho 2014) and has expressed an urgent need for more storage (Kook 2013). In 2015, Taiwan Power Co. sought public bids worth US\$356 million for offshore used fuel reprocessing services, at a price of nearly US\$1,500 kgHM⁻¹ (Rosner & Goldberg 2013), to be funded from its *Nuclear Back-End* fund, which currently totals US\$7.6 billion (Platts 2015).

Australia, in contrast to its near neighbours in Asia, has long been considered a logical jurisdiction for the management of used nuclear fuel thanks to a convergence of factors.¹ Highly stable geology, finance, institutions and politics promote confidence in the international community. Australia has the advantage of respected nuclear regulatory bodies in the Australian Radiation Protection and Nuclear Safety Agency and the Australian Safeguards and Non-Proliferation Office and a 50-year history of successful operation of a research reactor and associated facilities (run by ANSTO). Australia has been ranked first in the world for the last three years for nuclear security (Minister for Foreign Affairs 2016). Australia's institutions retain the justified confidence of the international community.

The establishment of the South Australian Nuclear Fuel Cycle Royal Commission in 2015 resulted in a detailed examination of the potential for Australia's expanded involvement in the nuclear fuel cycle. Its terms of reference included exploring opportunities that may lie in the back end of the fuel cycle, as well as the potential for generation of electricity from nuclear reactors.

The Royal Commission delivered findings in May 2016 (Nuclear Fuel Cycle Royal Commission 2016). It ruled out any involvement in the development of advanced nuclear technologies in South Australia in the short term, including reactor technologies capable of recycling used nuclear fuel. Related investigations of the used fuel management and disposal market were thus limited in scope to geological disposal concepts. However, the same analysis identified the potential future pathway of used fuel for 'new generations of nuclear reactors' that could 'both provide an

1. A major research programme in the 1990s by Pangea Resources identified Australia as the optimal siting for a multinational geological waste repository for spent nuclear fuel. The proposal failed to find support among the Australian Government and public and was abandoned. For more information, see the World Nuclear Association webpage *International Nuclear Waste Disposal Concepts*.

income stream and avoid some significant costs', choosing to leave this as un-modelled upside (Cook *et al.* 2016). These decisions left potentially viable pathways unexamined. Given that (i) the cost of a geological disposal facility has been estimated at AU\$33.4 billion (Cook *et al.* 2016); (ii) the lead time to emplacement in geological disposal is estimated at 28 years (Cook *et al.* 2016); and (iii) the demonstrable need for global-scale generation of clean electricity and heat, we argue it is important for any jurisdiction to explore, from the outset, pathways that consider the recycling of used fuel and the development of advanced nuclear reactors. If sufficiently large economic benefits can be demonstrated, an argument can be formed for inclusion of advanced nuclear technology deployment in policy options for managing the back end of the nuclear fuel cycle.

Given the component parts of a comprehensive recycling solution to used fuel management are either well established or ready for commercialisation, we sought to investigate a pathway not considered by the Royal Commission, namely, whether the implementation of such an *integrated* solution might be economically beneficial by defining a project and assessing the business case. In this paper, we discuss the proposed project and the outcomes of our assessment of the business case.

2. Forming a Viable Solution

Although technically well supported, the securing of a radiotoxic waste product in the form of used nuclear fuel, in geological disposal, for potentially hundreds of centuries presents a worrying philosophical problem for any society to face. We therefore chose to assess the economic viability of an alternative technical pathway based on

- an above-ground independent spent fuel storage installation (ISFSI) (discussed later) to be developed synergistically with
- modern, full-fuel recycling fast neutron nuclear reactors and low-cost, high-

certainty disposal techniques for eventual waste streams.

An ISFSI refers to a stand-alone facility for the containment of used nuclear fuel in dry casks for a period of decades (Casey Durst 2012). Cumulative international experience in interim management of used nuclear fuel provides a vast technical and operational record of practices (International Atomic Energy Agency 2007; Werner 2012). Recent ruling from the US Nuclear Regulatory Commission stated that used nuclear fuel may be stored safely in an ISFSI legally for around a century. (Werner 2012). The advantages of this approach have been documented along with operational and maintenance requirements (Bunn *et al.* 2001; Hamal *et al.* 2011; Rosner & Goldberg 2013), the physical resilience of the containment (Lee *et al.* 2014) and the end-of-life considerations (Howard & van den Akker 2014). One identified advantage is retaining flexibility to deploy alternative solutions such as fuel recycling.

All constituent heavy-metal elements of used nuclear fuel, other than about 3–5 per cent of fission products (the isotopes that are created from uranium after it has been fissioned in a reactor), can be recycled as fuel for a fast neutron reactor. This first requires electrolytic reduction for converting oxide fuel to metal and removing most of the fission product gases, followed by electrorefining to further cleanse the fuel of fission products and, finally, segregating the main metals (uranium, plutonium, minor actinides) for the fabrication of new fuel rods (Argonne National Laboratories/Merrick and Company 2015). The viability of this process, known as pyroprocessing, was established many years ago at the level of high-capacity testing (Argonne National Laboratories/US Department of Energy Undated). Research and investigation into pyroprocessing has continued to the present day at Idaho National Laboratories (Simpson 2012). This ongoing research process has permitted refinement of the process towards commercialisation. Detailed design and

costing is available of a commercial-scale oxide-to-metal fuel conversion and re-fabrication facility, demonstrating the feasibility of a closed fuel recycling facility operating at a rate of 100 t year⁻¹ (Argonne National Laboratories/Merrick and Company 2015). Such a facility is included as a component in our project.

The impact of such developments on the goals of nuclear non-proliferation must be examined carefully. Safeguarding nuclear actions is rendered more effective by technologies with intrinsic technical barriers to nefarious use. Materials directly usable for weapons cannot be produced by pyroprocessing. The plutonium product is inherently co-mingled with minor actinides, uranium and ‘hot’ trace fission products (Hannum *et al.* 1996) because of the separation being electrolytic and not chemical. Pyroprocessing is thus far more proliferation resistant than the existing aqueous-chemical plutonium–uranium extraction processes (known as PUREX, which has been used since the 1940s). Recycling processes take place via remote handling in hot cells. This presents physical–radiological barriers that increase the ease of monitoring and provide the fuel with a ‘self-protecting’ barrier that results in difficulty of access and diversion of the fissile material (Till & Chang 2011). Furthermore, the responsible centralisation of the used fuel material in a single approved location with international oversight would assuredly deliver a net security benefit at the global scale (Evans & Kawaguchi 2009).

Pairing the recycling technology with an advanced fast neutron reactor unlocks the full benefits of the used fuel material. One example of this technology is the Power Reactor Innovative Small Module (PRISM) from GE Hitachi (2014). Each pair of PRISM modules offers 622 MWe of dispatchable, near-zero-carbon² generation by making use of two nuclear reactors of 311 MWe each. This size provides no barrier to connection in the Australian National Electricity Market, including in smaller regions like South Australia (Electranet 2012). With flexibility in core configuration, the PRISM can offer a conversion

ratio (transmutation of fertile to fissile isotopes of actinide elements) of <1 or >1, providing an effective, direct route to net consumption and rapid elimination of long-lived material or alternatively rendering existing used fuel a potentially vast source of further energy (Hannum *et al.* 1996; Triplett *et al.* 2010). Following a fuel cycle, the recycling facility cleans the metal fuel and re-casts new metal fuel pins with the addition of make-up material from the used fuel stockpile (Argonne National Laboratories/US Department of Energy Undated). The removed impurities, mostly fission products, are small in mass and short-lived, rendering management and disposal well-within institutional capabilities (Brook *et al.* 2015).

With the inherent safety properties that accompany the use of metal fuel and metal coolant (Wade *et al.* 1997; Triplett *et al.* 2010; Till & Chang 2011; International Atomic Energy Agency 2012; Brook *et al.* 2014), PRISM has the necessary design attributes of a successful nuclear energy system that could be feasibly deployed in the near term (Brook *et al.* 2015) and provides sufficient data for consideration and assessment in our project.

It is important to consider why other nations may not be actively pursuing this technology commercialisation pathway. Densely populated, fast-growing economies across Asia need the reliable clean energy output that a functioning nuclear sector offers, in order to support broader economic development. The pursuit of solutions to the back end of the fuel cycle is not, of itself, a priority particularly while current generation nuclear fuel remains low cost and reliable in supply. For other nations, the level of interest in implementing a technology-based solution may be higher.

2. In this context, zero-carbon refers to the point of generation. While all generation sources have embedded carbon dioxide emissions from across the life cycle, nuclear reactors are among the least carbon-intensive energy sources across the full life cycle. The reactors under discussion here, that recycle fuel rather than mining it, will be even lower in life cycle emissions. Life cycle emission results from the National Renewable Energy Laboratory are found at http://www.nrel.gov/analysis/sustain_lca_results.html

However, idiosyncrasies of geology, climate and geopolitics render them less suitable to housing such a group of facilities, with high barriers to implementation. Finally, a compelling commercial case may be weak on a nation-by-nation basis, whereas aggregating the proceeds of multiple national used fuel budgets at one multinational facility changes that commercial equation.

3. Determining the Business Case

Our project thus merges (i) an ISFSI; (ii) a fuel recycling facility; and (iii) metal fuelled, metal cooled fast breeder reactors based on the PRISM design. For eventual disposal of fission products, our project assumes the use of deep borehole disposal (Brady *et al.* 2012). The full details of the business case assumptions are provided in Data S1.

In order to capture a range of potential outcomes, we estimated the business case for nine scenarios and selected three illustrative scenarios (low, mid and high) based on a range of assumptions for key variables. These scenarios are defined in Table 1. The capital and operating costs for all scenarios are shown in Tables 2 and 3, respectively, and described in further detail in Data S1. These assumptions were applied to determine net present value (NPV) of the integrated process, including disposal of fission products in deep boreholes, over a 30-year project life at a 4 per cent

discount rate. The impact of different discount rates ranging from 1 to 10 per cent is shown in Data S2. The NPV outcomes at 4 per cent discount rate are shown in Figure 1.

The business case reveals a multibillion dollar NPV in all scenarios except the illustrative low scenario. The illustrative mid-range scenario delivers NPV of AU\$30.9 billion at 4 per cent discount rate.

4. Comparing Findings with the Royal Commission

In the analysis supporting the final report of the Royal Commission (Cook *et al.* 2016), a similar project was assessed, predicated on first establishing above-ground storage for used nuclear fuel. Key differences in the favoured scenario modelled by the Royal Commission include

- greater assumed volumes of material to be stored, that is, a bigger project
- higher assumed base case ‘price to charge’ for acceptance of used fuel
- longer assumed period for accepting used fuel material
- no integrated commercialisation of recycling and advanced reactor technology
- no revenues related to the sale of electricity from nuclear power plants
- establishment of permanent geological disposal facility
- revenues from the acceptance of intermediate level waste.

Table 1 Scenarios and Key Assumptions for the Business Case Assessment of Used Fuel Storage and Recycling

Scenario	ISFSI [‡] size (tHM [‡])	Fuel custody price to charge (2015 AU\$ tHM ⁻¹)	Electricity price (2015 AU\$ MWh ⁻¹ [§])
L40 (low scenario)	40,000	685,000	20
L60	60,000		
L100	100,000		
M40	40,000	1,370,000	50
M60 (mid scenario)	60,000		
M100	100,000		
H40	40,000	2,055,000	80
H60	60,000		
H100 (high scenario)	100,000		

[‡]Intermediate spent fuel storage installation.

[‡]Tons of heavy metal.

[§]Megawatt hour.

Table 2 Summary of Capital Costs for the Business Case Assessment of Used-Fuel Storage and Recycling

ISFSI [†] size (tHM) Capital Item	40,000 Cost (2015 AU\$ million)	60,000	100,000	Source
ISFSI	912	1,026	1,245	Electric Power Research Institute (EPRI) (2009)
Fuel recycling and fabrication plant		617		Argonne National Laboratories/Merrick and Company (2015)
PRISM [‡] 622 MWe		8,302		United States Department of Energy (2014a, 2014ab)

[†]Intermediate spent fuel storage installation.

[‡]Power reactive innovative small module.

Table 3 Summary of Operational Costs for the Business Case Assessment of Used-Fuel Storage and Recycling

ISFSI [†] size (tHM [‡]) Operational item	40,000 Cost (2015 AU\$ million)	60,000	100,000	Source
ISFSI loading	620	698	853	Electric Power Research Institute (EPRI) (2009)
ISFSI caretaker	6	7	8	Electric Power Research Institute (EPRI) (2009)
Fuel recycling and fabrication plant		70		Argonne National Laboratories/Merrick and Company (2015)
PRISM [§] 622 MWe [¶]		208		United States Department of Energy (2014a, 2014ab)
Deep borehole disposal		0.086		Adapted from Brady <i>et al.</i> (2012)

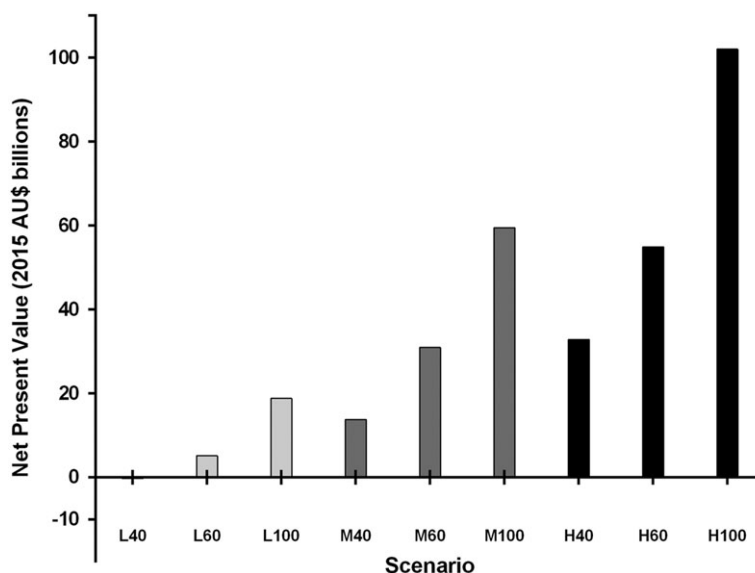
[†]Intermediate spent fuel storage installation.

[‡]Tons of heavy metal.

[§]Power reactive innovative small module.

[¶]Megawatt electric.

Figure 1 Net Present Value of the Nine Business Case Scenarios Defined in Table 4, 30-Year Project Life, 4% Discount Rate.



A compare-and-contrast between the base case of our analysis and the base case of the Royal Commission is given below.

As shown in Table 4, as well as recommending a much larger role in accepting used fuel, the Royal Commission directs revenue (at a capital expenditure of AU\$33.4 billion) towards geological disposal, while our concept directs revenue toward recycling and clean electricity generation (at a capital expenditure of <\$10 billion). Both projects delivered NPV in the tens of billions. The larger NPV of the Royal Commission project is substantially explained by (i) the much larger assumed revenues from accepting 2.3 times more used fuel material; (ii) accepting intermediate level waste for disposal; and (iii) the higher assumed price paid (AU\$1.75 million ton⁻¹) for the used fuel material (our assumed base case price was AU\$1.37 million ton⁻¹). In Table 5, the results of our analysis are updated to reflect the higher assumed price for used fuel acceptance identified by the Royal Commission. The NPV changes from AU\$30.9 billion to AU\$44.1 billion.

On the basis of this analysis, we argue that commercial development of advanced nuclear reactors, treated as principally a recycling facility paired with an ISFSI, is economically viable immediately. Deploying advanced nuclear reactors for their recycling capabilities represents an innovative approach to both the development and deployment of low-carbon energy technologies and the resolution of long-standing challenges related to used nuclear fuel.

5. Limitations and Uncertainties

The novel nature of this business case involves inevitable uncertainties. Our transportation costs were based on inclusive estimates for a national facility serving the United States using ground transport only. In addition to such ground transport costs, ocean-going transport will be required to South Australia. Recent work suggests ocean transport costs to South Australia of AU\$7,500 to AU\$37,500 tHM⁻¹ (Cook *et al.* 2016) with this range covering a range of potential customer nations. Present value outcomes of this study will not be materially altered by these inclusions that assessed 'price to charge' across a range of approximately AU\$1.3 million tHM⁻¹.

The lack of services, globally, for the management of used nuclear fuel means that the assumed 'price to charge' was based on desktop sources. This is an obvious limitation; such a market is not yet established and tested. However, more recent willingness-to-pay analysis supported a higher base case price than that used in our analysis (Cook *et al.* 2016), suggesting that any uncertainty is likely to be positive for the present value outcomes of our proposed pathway (Table 5). The sensitivity of our project to the assumed capital expenditure of the nuclear reactors was tested in a cost overrun scenario (Data S4), which found positive NPV in all but the low scenario.

Table 4 Comparison of Project Assumptions between Cook *et al.* 2016 and Heard and Brook (2016, this article)

Assumptions	Royal Commission	Heard & Brook
Amount of used fuel accepted (tHM [†])	138,000	60,000
Fuel custody price to charge (\$million ton ⁻¹)	1.75	1.37
Period of used fuel acceptance (years)	82	20
Capital cost of fuel recycling (\$billion)	N/A	0.617
Capital cost of fast reactors (\$billion)	N/A	8.3
Capital cost of geological disposal facility (\$billion)	33.4	N/A
Price of sold electricity (\$ MWh ^{-1‡})	N/A	50
Sold electricity per year at commissioning (MWh)	N/A	5 million
Intergenerational discount rate (%)	4	4
Net present value (\$billion)	51.4	30.9

Note: All dollar figures are 2015 Australian dollars.

[†]Tons of heavy metal.

[‡]Dollar per megawatt hour.

Table 5 NPV Outcomes for [Author Names] Proposed Business Case Based on Price to Charge and Intergenerational Discount Rate Applied by the South Australia Nuclear Fuel Cycle Royal Commission (Cook et al. 2016)

Price to charge ton accepted ⁻¹ (2015 AU\$ million)	NPV [†] Heard and Brook (2015 AU\$ billion at 4% intergenerational discount rate)
1.37	\$30.9
1.75	\$44.1

[†]Net present value.

6. Conclusion

The South Australian Nuclear Fuel Cycle Royal Commission provided an important opportunity for an evidence-based reappraisal of the opportunities available in serving the back end of the nuclear fuel cycle. However, the analysis undertaken under that process chose a deliberately constrained pathway that neglected to examine opportunities based on advanced nuclear technologies and recycling of used nuclear fuel. Our proposal identifies the opportunity for an integrated financial project to commercialise new technologies that allow the complete recycling of used nuclear fuel, with the production of abundant, near-zero-carbon clean electricity (and industrial heat) as a result. If implemented, this would make an important contribution in the fight against climate change, nuclear proliferation and containment of pollution while potentially offering (2015) AU\$30–44 billion in present value. Implementation of an integrated solution could also play a vital role in shifting the balance of energy decision-making, particularly in the fast-growing Asian region, away from polluting fossil fuels and towards clean, near-zero-carbon nuclear generation by providing assurance of responsible and secure centralised management of used nuclear fuel.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site.

- Data S1.** Detailed business case.
- Data S2.** Net present value outcomes for discount rates ranging from 1% to 10%.
- Data S3.** Fuel inventory modelling.
- Data S4.** Capital cost overrun contingency modelling.
- Figure S4.** Net-present value of the nine business case scenarios defined in Table 1, 30-year project life, 4% discount rate and contingency capital costs of 140%.