TERRESTRIAL ENERGY

Submission to the Inquiry into the Prerequisites for Nuclear Energy in Australia

The Integrated Molten Salt Reactor from Terrestrial Energy is a revolutionary nuclear reactor design. Through the deployment of sealed, integrated reactor cores running on liquid salt fuels, the IMSR® achieves step change improvements in safety and commercial viability. High temperature operation makes the IMSR® a deployable, clean replacement for fossil-fueled industrial heat.

9-16-2019

TERRESTRIAL ENERGY INC
2275 Upper Middle Road East, Suite 102, Oakville, Ontario, Canada L6H 0C3
+1 (604) 329-1210
+1 (604) 608-3282

TERRESTRIAL
ENERGY

To the Standing Committee on Environment and Energy

Terrestrial Energy is grateful for the opportunity to provide this submission to the Inquiry into the Prerequisites for Nuclear Energy in Australia. These prerequisites, forming the basis of the Terms of Reference, are:

a. waste management, transport and storage,

b. health and safety,

c. environmental impacts,

d. energy affordability and reliability,

e. economic feasibility,

f. community engagement,

g. workforce capability,

h. security implications,

i. national consensus, and

j. any other relevant matter.

This submission focuses on *d. energy affordability and reliability* in order to highlight the advantages enabled by Terrestrial Energy's technology. In summary:

- Australia's National Hydrogen Strategy has identified substantial potential for hydrogen production and export after 2030
- Terrestrial Energy's IMSR® technology is designed as an efficient and economical source of non-combustion industrial heat, with commercial deployment by the end of the 2020s
- Research is underway to couple IMSR® technology to advanced hydrogen production, with current cost projections being competitive with steam methane reforming
- Economical and clean hydrogen production illustrates the wider potential for IMSR® technology to rapidly drive decarbonisation in both electricity and non-electrical sectors.

TERRESTRIAL ENERGY

Terrestrial Energy Inc. is a private Canadian Company developing proprietary ("Generation IV") nuclear technology, the Integral Molten Salt Reactor (IMSR®), for global commercial deployment within the next ten years. IMSR® is a small modular advanced nuclear power plant that is based on demonstrated technology and has the potential to revolutionize the cost-competitiveness of nuclear power generation in global energy markets, with nuclear safety excellence and waste management advantages. Terrestrial Energy's IMSR® will provide carbon-free heat and power to global industry at a cost that is competitive with coal and natural gas.

Terrestrial Energy holds patent and patent applications as part of global program to secure the intellectual property protection on IMSR® power plant design.

The Company consists of a team of credentialed scientists and businessmen – over fifty directors, officers, engineers and scientists. During Phase I of its four-phase business plan, the Company assembled a technical team, a management team and a corporate governance infrastructure. The board of directors has six members, the management team is comprised of seven individuals leading the team of technical experts. An International Advisory Board of supports and advises Terrestrial Energy. Together this represents a team of notable and well-respected capabilities with members demonstrably credentialed in the fields of nuclear science and engineering, nuclear regulation, international business, finance, environmental protection, and the power utility industry. Two members of the technical team were previously from the Oak Ridge National Laboratory (ORNL) and one – recently deceased – worked extensively on the original ORNL Molten Salt Reactor program; a program that forms the foundation of proven technology upon which the IMSR® is based. The Company has strong connections with leading nuclear laboratories globally, including the Canadian Nuclear Laboratory and ORNL.

In 2015, the Company engaged with the Canadian nuclear regulator for Phase 1 its vendor design review process for the IMSR®, rated at 195 MWe. This successful review was completed in 2017 and on schedule. Phase 2 of the vendor design review began in 2018 and is scheduled to be completed in early 2021.

We are pleased to bring this submission to the Inquiry into the Prerequisites for Nuclear Energy in Australia being held by the Standing Committee on the Environment and Energy. We regard Australia as a potential market for the IMSR® power plant deployment should it amend the current legislation that prohibits the nuclear fuel cycle. This submission is structured into an introduction, a concise context for and description of the IMSR®, and its potential for non-electric industrial application exemplified by large-scale clean hydrogen

TERRESTRIAL
ENERGY

production. While the case in favour of an IMSR® power plant being a source of competitively-priced, high scalable, ultra-low emission electric power that is reliable and dispatchable is just as robust as when our submission was made to the South Australian Royal Commission in 2016, the IMSR® power plant is equally applicable as a versatile source of highly valuable industrial-scale heat that has many industrial applications including in natural resource extraction.

Introduction

The controlled and stable fissioning of uranium is used for producing safest and most reliable, around-the-clock electricity in thirty sovereign nations. Nuclear energy provides ten percent of global electricity, with over 50% of the non-fossil electricity in the USA, the EU, South Korea, Taiwan, and other regions.[1] Eighteen-thousand cumulative reactor-years of operation have been achieved, in stable power grids, under extremes of weather, and with several serious but extremely rare accidents from the standpoint of a major industrial enterprise.

Far from having any nuclear reactors for power production, Australia has in place federal legislation to prohibit the relevant minister from approving any such capacity, regardless of advances in technology, favourable economics, vendor interest, or even environmental benefits, despite the prohibition existing in environmental legislation. As nations, scientists, NGO's and corporations develop the sophisticated bounding understanding of climate changes and our global energy system, a consensus has now emerged that we cannot achieve necessary decarbonization without nuclear energy as an important component of our energy mix.

In the decades prior to the establishment of the prohibition, various formal proposals for commercial nuclear energy had existed at one time or another in New South Wales, Victoria, South Australia, and Western Australia, along with plans to pursue the enrichment of Australian uranium in Queensland. It should be noted that the envisaged power plants were of 1950s and 1960s vintage designs. The options that will be commercially available in the 2020s are far superior in various respects, especially in terms of economic performance than nuclear power based on modern derivatives of 1950's vintage designs – "conventional" nuclear design.

[1] world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

TERRESTRIAL ENERGY

Support for Nuclear Energy

In 2015, the Labor government of South Australia, called a Royal Commission into the nuclear fuel cycle, which is noted in this parliamentary inquiry's terms of reference.

After inclusive and comprehensive consultation, the final report recommended to the South Australia's Labor government the following:

- remove at the state level, and pursue removal of at the federal level, existing prohibitions on the licensing of further processing activities, to enable commercial development of multilateral facilities as part of nuclear fuel leasing arrangements;
- pursue removal at the federal level of existing prohibitions on nuclear power generation to allow it to contribute to a low-carbon electricity system, if required;
- promote and collaborate on the development of a comprehensive national energy policy that enables all technologies, including nuclear, to contribute to a reliable, low-carbon electricity network at the lowest possible system cost;
- collaborate with the Australian Government to commission expert monitoring and reporting on the commercialisation of new nuclear reactor designs that may offer economic value for nuclear power generation;
- pursue the opportunity to establish used nuclear fuel and intermediate level waste storage and disposal facilities in South Australia consistent with the process and principles outlined in Chapter 10 of this report;

Although a referendum was mooted, the process took a different direction following the Royal Commission. In its aftermath, however, an indication of public sentiment was captured by the annual Sunday Mail survey. Out of 4,000 voluntary respondents, more than 56% were in favour of developing a nuclear industry in the state. About 40% agreed that a nuclear power station should be built.[2]

It may be inferred that political leadership, through inclusive and transparent consultation, creates a climate of confidence, in which greater support can be readily expressed, where in normal circumstances, only committed opposition would be heard.

[2] adelaidenow.com.au/news/south-australia/exclusive-sunday-mail-your-say-sa-survey-reveals-majority-support-for-a-nuclear-industry/news-story/cff9431e96da29fbd239ce9ba103cd61

TERRESTRIAL ENERGY

Next Generation Technology

There are 52 nuclear power plants officially under construction in 18 countries. Almost all these units are conventional models of the pressurised water or boiling water type. Although there are variants of these models, the next-generation (“Generation IV”) advanced reactor designs such as the IMSR® encompass innovations such as the following:

- Use of a thermally stable coolant in the form of a molten salt in conjunction with a thermally stable salt fuel;
- Avoidance of water, an unstable coolant, and hence avoidance of a highly pressurized cooling system with attendant engineering complexities that are substantial;
- High temperature operation for superior power generation efficiency and hence superior financial performance
- High temperature operation permitting far broader industrial application;
- Compact, modular and transportable componentry;
- Less complexity in power plant design and simpler modular construction permitting shorter construction times;
- Elimination by design of the most conceivable failure scenarios of conventional reactors;
- Mitigation of all conceivable failure scenarios as part of the design.

Many proposed advanced reactors are based closely on reactors that were built and extensively tested last century in national laboratories and naval operations. These include sodium-cooled fast reactors, molten salt reactors, and gas-cooled pebble bed reactors.

In 2017, Australia, represented by ANSTO, acceded to the framework agreement of the Generation IV International Forum (GIF), an international collaboration to develop next generation reactors for civilian energy production, superintended by the OECD.[3] One of the concepts on which Australia is nominated is molten salt reactors. In 2019, Terrestrial Energy was named as the first ever non-country member to the GIF.[4]

---

[3] ansto.gov.au/news/australia-joins-international-collaboration
[4] terrestrialenergy.com/2019/05/terrestrial-energy-joins-generation-iv-international-forum

TERRESTRIAL
ENERGY

The Integral Molten Salt Reactor

Canada-based Terrestrial Energy was formed in 2013 with the goal of bringing a molten salt reactor to market in the 2020s. By 2015, the basic design and operation of the IMSR® had been defined in a Conceptual Design Report. Some of the details were included in Terrestrial Energy's submission to the South Australian Royal Commission; the basic points are the following:

- The design is based on the Molten Salt Reactor Experiment operated successfully at Oak Ridge National Laboratories in the 1960s, and subsequent related design refinement of the Denatured Molten Salt Reactor in the 1970s;
- The IMSR® is a graphite-moderated, thermal-spectrum design in which a molten fluoride salt eutectic containing a proportion of <5% ^{235}U low enriched uranium functions as the fuel and coolant;
- The design is a pool-type reactor with no penetrations below the level of coolant;
- Atmospheric pressure operation, excess reactivity and other physical feedbacks confer intrinsic safety to the design; there can be no "meltdown" scenario, owing principally to the fact that the fuel is already melted;
- The IMSR® "Core-units" are designed to be replaced every seven years, and function as secure medium-term used fuel storage following the completion of their seven-year operating life;
- Output temperature from the secondary heat exchanger is 600°C+.

The high-temperature output leads to highly significant increase in thermodynamic efficiency of electric power generation (expected to be about 48%) and by extension a 48% increase in financial performance of plant.

The same heat can also be supplied to off-site (3 km remote) and remote industrial facilities, where it can directly replace the combustion of fossil fuels for process heat. This heat is delivered through pipelines containing nitrate-based solar salt at operating temperature. It must be clearly understood that this salt is separated from the reactor fuel/coolant by an intermediary loop that isolates it completely from radioactive materials.

TERRESTRIAL ENERGY

The first commercial IMSR400 power plant (195 megawatt-electric), is on track for construction, licensing and commercial operation at a Canadian site such as the Chalk River Laboratories in the late 2020s.[5]

Hydrogen in Australia

In this submission, the potential for non-electric industrial energy supplied by the IMSR® will be illustrated by clean hydrogen production.

A recent review of the global picture highlighted 19 "hydrogen strategies" from around the world.[6]

In the context of Australia's evolving energy sector, the opportunity for a hydrogen industry is being revisited in earnest and potentially at large scale.[7] This effort currently involves industry and other stakeholder engagement, coordination with foreign trading partners (most notably Japan), innovations in the domestic market, associated engineering challenges, and standards and regulatory development.

However, the fundamentals of hydrogen do not change:

- To be a clean resource, it must be produced from water without fossil fuels;
- The enthalpy of formation of a mole of H_2 from water is 286 kilojoules;
- Its physical characteristics are different to other transportable fuels like petrol and LNG.

As detailed by the International Energy Agency this year, hydrogen is not a clean fuel due to the almost exclusive use of fossil fuel in its production. It is sourced from natural gas (76%) and coal (23%), with the remaining sources being oil with electrolysis of water with electricity supplying an unremarkable and small portion. In the global context, any scaling up of non-fossil production will be starting from a miniscule baseline.

The COAG Energy Council National Hydrogen Strategy has outlined the opportunity for Australia in its first issue paper,[8] highlighting IEA global market demand forecasts in exajoules (EJ) (2030: 14 EJ; 2040: 28 EJ; 2050: 78 EJ), and the potential for Australia to

[5] globenewswire.com/news-release/2019/02/27/1743347/0/en/Terrestrial-Energy-Completes-Preliminary-Siting-Study-at-Chalk-River-Laboratories.html
[6] energynetworks.com.au/news/energy-insider/19-strategies-15-countries-one-element
[7] industry.gov.au/news-media/australias-hydrogen-potential-a-message-from-the-chief-scientist
[8] consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/

manufacture 4.18 EJ of clean hydrogen annually.[9] Hydrogen production must be undertaken at a large industrial scale to achieve the efficiencies required to result in cost-effective hydrogen and competitiveness with fossil fuels.

Clean Nuclear Hydrogen

Recently, the Japan Atomic Energy Agency achieved the thermal-chemical production of hydrogen in a process designed to be coupled with its High Temperature Gas-Cooled Reactor design. This catalytic process will be an alternative to electrolysis, emits no emissions in the operation[10] and is an example of the thermal-chemical hydrogen production potential of the IMSR® power plant.

In the US, Exelon is leading a partnership of national laboratories in repurposing conventional nuclear capacity for hydrogen production via high temperature electrolysis (HTE). This initiative aims to achieve hybrid nuclear operations with enhanced flexibility to meet the needs of evolving electricity networks while adding a new revenue stream.[11]

<u>IMSR® Hydrogen</u>

Terrestrial Energy is also working with the US national laboratory system to pursue high temperature electrolytic production of hydrogen. This is a natural fit for the reactor design given its high outlet temperature and safe, versatile working fluid.

The operation of the nuclear hydrogen system would begin the same as for electricity production: fuel salt circulates around the IMSR® Core-unit and exchanges heat to the intermediate salt loop, which exits the reactor to flow to the secondary non-nuclear heat exchanger. Independent of power generation, the final salt loop delivers high grade heat to the advanced high-temperature electrolyser, wherein water under pressure is split with electricity and separated into hydrogen and oxygen on opposite sides of the electrolyte.

Several types of advanced electrolysis are under active research in the US which could be optimised for this process. The most promising involves a proton permeable solid oxide electrolyte and operates between 550°C and 650°C, a strong match for IMSR® heat. The

---

9 1 kg H_2 = 141.9 MJ
10 jaif.or.jp/en/jaea-achieves-150-hours-of-continuous-hydrogen-production-toward-utilization-of-heat-from-htgrs/
11 hydrogen.energy.gov/pdfs/review19/h2052_boardman_2019_p.pdf

TERRESTRIAL
ENERGY

potential advantages of this type of electrolysis were noted in the CSIRO Hydrogen Roadmap.[12]

Terrestrial Energy has also investigated an alternative, efficient thermochemical / electrochemical cycle for hydrogen production, in collaboration with Southern Company and several US national laboratories.

Economic Comparison

In the COAG Energy Council's National Hydrogen Strategy, the cost of production of electrolytic hydrogen powered by solar or wind renewable electricity is anticipated to fall in the next decade. This cost decline is crucial to begin replacing conventional fossil fuel generated hydrogen which has associated emissions.

The two important factors are therefore the cost and the emissions intensity per kg of hydrogen. The most recent estimates[13] are tabulated here.

	\$/kg H_2	CO_2/GJ	% capacity factor
Steam methane reforming	2.27—2.77	54	90+
Black coal gasification	2.57—3.14	107	90+
Dedicated renewable energy electrolysis	11*	—**	35
IMSR®	3.11—3.26*	0.007	90+

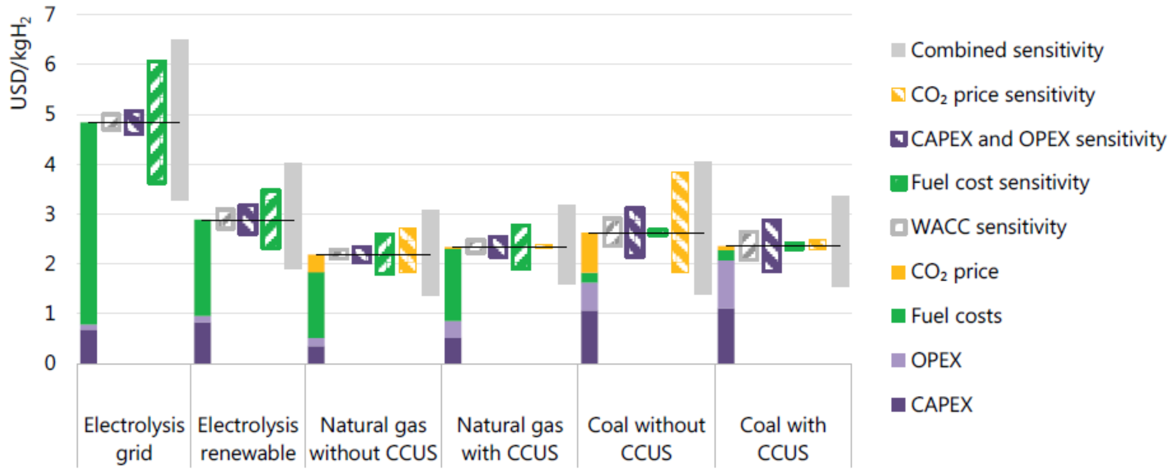
* Estimated.
** Operational emissions are zero for non-combustion sources of electricity, however there will be lifecycle emissions involved. As assessed by the royal commission, these median values are taken to be 45 gCO_2e/kWh (0.162 per GJ) for solar PV and 11 (0.040 per GJ) for wind. The additional embodied energy due to the electrolytic equipment will increase these numbers but quantification is beyond the scope of this submission and should be the subject of future feasibility studies. LCA emissions will also be higher for fossil sources but only marginally as operational emissions dominate.

The kilogram cost range of hydrogen from the IMSR® high temperature electrolysis process is calculated based on the current exchange rate at the time of writing, from a value range of \$2.10 to \$2.20 USD per kg provided by national laboratory research. It is used here for the purpose of comparison, however the cost of production achieved in Australia would be

[12] csiro.au/~/media/Do-Business/Files/Futures/18-00314_EN_NationalHydrogenRoadmap_WEB_180823.pdf
[13] energy-transition-hub.org/files/resource/attachment/energy_hub_h2_20181214.pdf

TERRESTRIAL
ENERGY

influenced by regionalisation. The chart below, which was cited in the COAG issue paper, is from the IEA Future of Hydrogen report, and presents a global future cost context.[14]



Hydrogen production costs for different technology options, 2030

Capacity Factor

As stated in the CSIRO Hydrogen Roadmap, co-located solar PV and wind will achieve 35% utilisation of electrolysis plant.

As this is an electrical process, it's conceivable the addition of yet-to-be-developed and proven storage capacity would enable a higher capacity factor by avoiding some idle or under-utilised plant time. This however, would incur extra capital cost. Moreover, the embodied energy of storage, especially batteries, would increase the full LCA emissions intensity of the electrolysed hydrogen.

Hydrogen production using high temperature electrolysis with industrial heat provided by the IMSR® can operate continuously as needed. The full-time operation of the IMSR® heat source requires only minimal regular addition of "top-up" fuel salt, and a single Core-unit is designed for a seven-year lifespan.

The detailed comparison of these options alongside fossil sources of hydrogen should be the subject of future feasibility studies.

[14] iea.org/publications/reports/thefutureofhydrogen/, see report for chart assumptions.

TERRESTRIAL ENERGY

Conclusion

The potential for next generation nuclear energy technology to contribute to Australia's power networks is a complex discussion. All else being equal, the regulatory and workforce capacity in Australia should be sufficiently prepared around the time that advanced reactors have been built and commissioned in foreign nations.

IMSR® power plant technology can play a large and important role to help Australia move toward a power system that is clean, reliable and affordable, in conjunction with continued development of cost-effective renewable energy resources. Crucially, IMSR® also offers cost-effective industrial grade heat to provide Australian industry with an affordable, zero-carbon substitute for coal and gas, and to power industrial processes without greenhouse gas emissions.

Hydrogen serves as possibly the simplest industrial product that can be manufactured at competitive cost using clean emissions-free, non-electrical nuclear energy. The estimates in this submission serve to broaden the potential sources of hydrogen Australia may utilise to meet the anticipated future national needs and foreign markets. High temperature electrolysis using IMSR® heat is positioned to be the most competitive and reliable source of clean hydrogen available to a nation such as Australia. The IMSR® would potentially meet further national industrial needs, both heat and electrical.

TERRESTRIAL
ENERGY

Appendix

This appendix contains, for reference, the original submission to the South Australian Nuclear Fuel Cycle Royal Commission. The information is still accurate, although substantial engineering, licensing, procurement, siting and collaborative commercial work has been undertaken since 2016.

An example of such work includes an independent assessment of full lifecycle emissions due to a plausible deployment of an IMSR® power station, beginning in Canada. The estimated emissions intensity figure is estimated to be in the low single digits of grams of carbon dioxide equivalent per kilowatt hour (gCO_2e/kWh).

Another example is First-of-a-Kind and Nth-of-a-Kind cost estimates for the IMSR®. These estimates are normally useful for informing the “overnight capital cost” or “cost per kilowatt installed” projections of power station development proposals. Terrestrial Energy has had the anticipated materials costs assessed. The IMSR400, 195 megawatt-electrical, is fundamentally intended to be delivered as a power plant for under USD $1 billion. With modular design, the technology is expected to accrue component production and plant construction economies of scale from broad deployment, which will achieve a total CAPEX of under 3,000 USD per kilowatt installed. In Australian dollars at current exchange rates this is the equivalent of 4,400 AUD per kilowatt installed.

Terrestrial Energy is progressing as planned through Canada’s pre-licensing process, towards expected commercial deployment in the late-2020s.

TERRESTRIAL
E N E R G Y

Submission to the South Australian Nuclear Fuel Cycle Royal Commission, 8th March 2015

3.1 Are there suitable areas in South Australia for the establishment of a nuclear reactor for generating electricity? What is the basis for that assessment?

IMSR® is suitable for deployment across South Australia. We note the issues raised in precursor to this question in Issues Paper 3.

The IMSR® concept is based on small reactors cores that may be deployed as modules to create large power stations. With core sizes of 300 MWth[1] and 600 MWth, generation from IMSR® could be easily spread to balance generation across the relatively "skinny" South Australian grid. This also allows generation to be located to target specific new demand that may arise such as mining or mineral processes. The size of the units and the ability to build incrementally mitigates the risk of over-investment for South Australia for scenarios of either slow growth in new demand or replacement of incumbent generators for the purpose of decarbonisation.

Traditional build concerns for nuclear generation are not relevant to the IMSR®. As previously highlighted, the largest component is the integrated core. This is to be manufactured in an assembly line manufactory setting with high levels of quality control and is then transportable by truck or rail for installation. On site construction and associated local impacts are therefore minimised. The core is replaced once every 7 years.

Operations of the IMSR® are minimally invasive. The reactor development will be low rise, with below-grade reactor cores as a standard design feature.

The IMSR® has no potential vectors for the release of waste to the surrounding local environment. The reactor core remains sealed for 7 years of operation plus a multi decade period of on-site cooling before removal to centralised decommissioning. Gaseous fission products are removed and contained. The operation requires the delivery of less than 12 metric tonnes of LEU fuel for the entire lifetime of the replaceable core-unit. Volumetrically, this equates to 0.6 cubic meters. Otherwise, it entails no deliveries of fuel by road, rail or pipeline, and no combustion of fuel. Operation of the IMSR® will entail far less noise, waste and pollution concerns than existing fossil plants in South Australia.

[1] Since the time of writing, Terrestrial Energy has settled on a 400 megawatt-thermal core design for our demonstration unit, however claims regarding the IMSR300 size remain conceptually accurate for the purpose of this appendix.

On the basis of the matters raised relating to this question in Issues Paper 3, the IMSR® is suited for broad deployment across South Australia.

3.2 Are there commercial reactor technologies (or emerging technologies which may be commercially available in the next two decades) that can be installed and connected to the NEM? If so, what are those technologies, and what are the characteristics that make them technically suitable? What are the characteristics of the NEM that determine the suitability of a reactor for connection?

This submission describes Terrestrial Energy's reactor design called the Integral Molten Salt Reactor (IMSR®). For reasons to be discussed, this reactor is eminently suitable for connection to Australia's National Electricity Market. This initial response provides a summary of the main features of this reactor and its suitability in the National Electricity Market. More detailed discussion of key issues of safety, waste and economics are addressed in further detail in response to subsequent questions.

The IMSR® is a liquid fuelled, graphite moderated, burner reactor. It has been developed from over five decades of research and development into liquid fuelled reactors. The IMSR® operates with a proprietary liquid fuel salt eutectic. The IMSR® design permits the use of a salt that is plentiful, cost effective and produces little tritium in operation, much of which can be captured using existing methods. This is only possible with a burner reactor as the much higher neutronic efficiency of a breeder fuel cycle, mandates the use of lithium fuel salts; these produce much higher quantities of tritium during operation. Furthermore the IMSR®'s 7-year fuel cycle is materially longer than that of conventional reactor systems in commercial use today and so consumes far more of its nuclear fuel. As a result the IMSR® requires 1/6th the amount of uranium fuel and so delivers exceptional fuel resource efficiency on a per kWh basis.

Innovative design characteristics and decisions overcome historic challenges of both liquid-fuelled reactors and the well-understood limitations of solid-fuel reactors that make up the mature nuclear energy sector today. As a result, the IMSR® offers transformative cost advantages that will enable it to compete in mature and established markets, on price alone.

The most important innovation presented by the IMSR® is the integrated, replaceable reactor core, the "Core-unit". A long-standing challenge for liquid fuel reactors has been the longevity of reactor core materials. Of the greatest importance in this regard is the lifetime of the graphite moderator. The use of graphite imparts many advantages in MSR design and its performance is extensively understood. However its lifetime is directly related to the power density that is employed. Retaining an economic power-density in the design requires regular replacement of the moderator. This is challenging as the core would need to be opened, and elaborate protocols would be required to manage the handling of the irradiated graphite moderator as well as managing the release of volatile fission products. Such complex maintenance protocols with attendant regulatory burden would heavily detract from the reactor's commercial merit.

Terrestrial Energy's IMSR® seeks to maximize the simplicity and advantages of the graphite-moderated MSR-Burner approach, while also offering a novel solution to the concerns listed above through a simple but major change in basic reactor design. This patent-pending solution integrates all components of the reactor core that operate on the hot salt into a permanently sealed core-unit, which would be replaced periodically at an estimated cost of $50 Million CAD for the largest IMSR600 model, which is rated at 600MWth, or approximately 291 MWe. (The fuel costs for this model are negligible.) The power output from this model is equivalent to the electrical power output of 5.25 million metric tonnes of bituminous coal, which has a value today of approximately $350 million USD. The economics of the replaceable unit are robust and justified. The IMSR® has achieved a design allowing a seven-year operational life of a sealed core unit. This confers several economic advantages:

- Allowing far higher and more economically viable power densities
- Allowing assembly-line style manufacturing of the cores, permitting the highest levels of quality control and the lowest levels of site-to-site variation
- Allowing centralised return and decommissioning of cores, potentially paired with fuel recycling

With replaceable core-units and the ability to refurbish other components, such as steam generators or turbines, a many decades-long plant lifetime is possible. The overall advantages of this "sealed *and* swapped" approach include easier regulatory compliance, reduced R&D, and operational lifetime confidence.

At the end of its seven-year run, the operational IMSR® Core-unit would be shut down and coolant lines would be connected to a new IMSR® Core-unit in an adjacent containment silo. The spent IMSR® Core unit can remain in place for the next seven years, and at any later point, fuel salt can be removed for reuse, recycle, or conversion to waste form.

This manufacturing and design philosophy represents a departure from traditional forms of nuclear energy that are based around achieving long lifetimes to minimise amortized capex per year and demonstrate economic viability. By accepting and embracing the possibilities of replaceable low-cost cores, IMSR® delivers an entirely different value proposition than the traditional, solid fuel light-water reactor industry. Therefore from an economic perspective, the IMSR® is highly suitable for Australia's National Electricity Market. The economic performance of the IMSR® is discussed further in response to questions 3.15 and 3.16

The IMSR® uses a molten salt liquid fuel mixture made up of the fuel salt (uranium fluoride) and the salt coolant (carrier salt). This provides the foundation for an enhanced safety profile in this reactor, which achieves "walk-away" safety. From a safety perspective, and from the point of view of securing public confidence, the IMSR® is highly suitable for Australia's National Electricity Market. Safety related details are discussed further in relation to question 3.9 and 3.13.

Terrestrial Energy may develop an 80 megawatt thermal (MWth) (32.5 MWe) unit first and target off-grid markets. South Australia and Australia has many remote settlements and mineral resource operations demanding reliable electricity supplies. The IMSR80 will be strong competitor in these markets.

The larger IMSR® units will be 300 MWth (141 MWe) and 600 MWth (291 MWe). This size range is ideal for the displacement of fossil fuel generators from the National Electricity Market. The IMSR300 and IMSR600 could be connected within South Australia with no network enhancements, as it is well within the modelled limit of 450 MWe[2] . Therefore from the perspective of the size of the units, there are few barriers to the inclusion of IMSR® in the National Electricity Market.

If paired with suitable fuel recycling facilities, the IMSR® burner can deliver near-complete elimination of long lived transuranic wastes. Waste and decommissioning issues are discussed further in response to question 3.12.

[2] (Electranet 2012)

TERRESTRIAL
ENERGY

Submission to the South Australian Nuclear Fuel Cycle Royal Commission, 8th March 2015

3.3 Are there commercial reactor technologies (or emerging technologies which may be commercially available in the next two decades) that can be installed and connected in an off-grid setting? If so, what are those technologies, and what are the characteristics that make them technically suitable? What are the characteristics of any particular off-grid setting that determine the suitability of a reactor for connection?

Yes. As per the response to question 3.2, the first priority for the IMSR® is the 80 MWth unit targeting off-grid settings. This has been pursued with the remote settlements of Canada in mind, and such remote circumstances are wholly applicable to the South Australian setting.

TERRESTRIAL ENERGY

Submission to the South Australian Nuclear Fuel Cycle Royal Commission, 8th March 2015

3.4 What are the conditions that would be necessary for new nuclear generation capacity to be viable in the NEM? Would there be a need, for example, for new infrastructure such as transmission lines to be constructed, or changes to how the generator is scheduled or paid? How do those conditions differ between the NEM and an off-grid setting, and why?

Answers to these questions depend on the type of nuclear power plant under consideration. Establishing traditional, large, solid fuel nuclear plants might require substantial changes in Australian pricing policy and network infrastructure.

The IMSR® business model is predicated on short life core, not long life, and the core replacement is low in cost. This does not demand the long-term security of price of large, solid fuel generators with cores designed for 60-year lives and very-high upfront capital investment. IMSR® would require no special policy to enable financing due to the vastly improved business model provided by short-life cores and assembly-line manufacturing that diminishes requirements for up-front capital and improves early rates of financial return.

Thanks to the small generating units, no new infrastructure is likely to be required for connection.

South Australia's high and potentially growing stock of wind generating units may necessitate additional transmission in order to also take full advantage of the highly reliable, low cost, pollution-free power from the IMSR® which can be exported during overnight low demand to displace brown and black coal generation in other NEM jurisdictions including Victoria and New South Wales.

IMSR® would require no special treatment in the NEM for dispatch. It would compete directly on price of electricity supplied. Forecast pricing and high capacity factor suggest IMSR® would succeed in displacing existing incumbent fossil generators from the NEM on a wholly competitive basis. Any policy geared toward accelerated transition to clean energy sources, be it carbon pricing or mandated targets such as, for example, a technology-neutral clean energy target, would hasten and aid this market transition. Further discussion of the economic performance of IMSR® is provided in response to question 3.15 and 3.16.

Changes in key policies including the EPBC Act (1999) and the ARPANS Act (1998) are prerequisites for serious efforts to bring the benefits of the IMSR® technology to Australia.

3.6 What are the specific models and case studies that demonstrate the best practice for the establishment and operation of new facilities for the generation of electricity from nuclear fuels? What are the less successful examples? Where have they been implemented in practice? What relevant lessons can be drawn from them if such facilities were established in South Australia?

While best-practice examples of existing technology can be identified, the IMSR® has been designed to overcome the many inherent disadvantages of the mature nuclear industry, particularly in matters of cost, time to construct and deploy, and scalability.

As such, there are few relevant case studies, globally, providing insight into the specific advantages offered by the IMSR®.

One relevant generalisation is that achieving the highest possible level of recognition of design approvals from other regulators in mature nuclear markets is a crucial step in quickly establishing facilities for nuclear generated electricity.

3.7 What place is there in the generation market, if any, for electricity generated from nuclear fuels to play in the medium or long term? Why? What is the basis for that prediction including the relevant demand scenarios?

We note the discussion preceding this question in Issues Paper 3 pertaining to the National Electricity spot market, moderating demand and existing excess capacity.

Scenarios of strongly growing demand are necessary for investment in conventional nuclear *where the costs of the new nuclear generation substantially exceeds the existing average costs of generation*.

However the IMSR® will deliver electricity at a cost that is wholly competitive in the existing Australian market; not only with other newly constructed generators, but with existing market average prices.

Therefore, even in a "worst case" investment scenario of sustained low growth in demand, generation from IMSR® technology will compete. Its introduction to the National Electricity Market would bring with it the advantage of highly reliable generation infrastructure with no emissions of greenhouse gas.

While demand has moderated in the National Electricity Market, this is unlikely to remain the case in the long term. Australia is maintaining strong population growth through immigration. Population is currently forecast to double by approximately 2050[3]. Scenarios of flat or declining demand under such conditions could be achieved only under policies of extreme energy conservation. Such scenarios would be challenged by new sources of demand such as transport electrification. It would therefore be prudent for South Australia and the whole National Electricity Market to plan for an eventual resumption in demand growth.

While South Australia has led Australia in the uptake of renewable technologies, it remains connected to the NEM and is a net-importer of electricity[4]. This is one of the most greenhouse gas-intensive electricity supply systems in the world. Signs of more robust international action on tackling climate change continue to grow[5]. From a risk-management perspective, Australia must plan the deployment of reliable sources of zero-carbon generation to complement the growing stock of variable renewable generators. Otherwise

[3] Syed (2012)
[4] Heard, Bradshaw and Brook (2015)
[5] The White House (2014)

Australia risks a potential sudden downgrade in terms-of-trade in the future due to the greenhouse gas intensity of domestic production.

It is therefore imperative that South Australia and the National Electricity Market develop and prepare options to meet demand growth that are both non-variable and zero-carbon[6]. The IMSR® is a transformative nuclear technology that would meet this need.

Finally, in the event of any scenarios of demand growth, the small and flexible unit size of the IMSR® is ideally suited to South Australia. It may serve either as incremental addition to overall supply, or as a tailored supply solution to a new demand source such as mining, mineral processing or manufacturing. The latter offers the potential to revolutionise the development of remotely located mineral deposits.

[6] Heard, Bradshaw and Brook (2015)

TERRESTRIAL
E N E R G Y

Submission to the South Australian Nuclear Fuel Cycle Royal Commission, 8th March 2015

What issues should be considered in a comparative analysis of the advantages and disadvantages of the generation of electricity from nuclear fuels as opposed to other sources? What are the most important issues? Why? How should they be analysed?

To gain a holistic view of the relative merits of electricity sources we recommend the Royal Commission considers:

- Whole-of-lifecycle impacts on mortality and morbidity, normalised for the quantity of electricity produced.
- Cost of generation installed ($ per kW)
- Levelised cost of electricity (LCOE, $ per kWh)
- Whole-of-lifecycle production of greenhouse gas emissions
- Capacity factor
- Variability and climate dependency
- Raw material consumption normalised for the lifespan and generating capacity of the generator
- Production and management of wastes
- Operational pollution (e.g. emissions)
- Scalability, relevant to the demands of the 21st century for clean electricity
- National fuel security
- Fuel mining impacts
- Land footprints and consumption, particularly impacts on sensitive wilderness or biodiverse areas.

Across the criteria named above, the nuclear energy sector, over a history of more than 50 years, has performed extremely well[7].

Nonetheless, inherent disadvantages in current generations of solid fuel reactors have contributed to constraining uptake of nuclear technologies. This has been the impetus behind the development of the IMSR®. The IMSR® will deliver step-change improvements in safety, fuel efficiency, scalability and cost while retaining the traditional advantages of nuclear energy in reliability and low-greenhouse production.

---

[7] These issues are reviewed for South Australian conditions in Heard and Brown (2012)

3.9 What are the lessons to be learned from accidents, such as that at Fukushima, in relation to the possible establishment of any proposed nuclear facility to generate electricity in South Australia? Have those demonstrated risks and other known safety risks associated with the operation of nuclear plants been addressed? How and by what means? What are the processes that would need to be undertaken to build confidence in the community generally, or specific communities, in the design, establishment and operation of such facilities?

The central pillar of nuclear reactor safety regardless of reactor system, is a strong independent regulatory body that mandates strict adherence to disciplined operating procedures and promotes a safety culture within the industry. However the inherent safety of reactor system remains strongly technology dependent.

The IMSR® is a completely different reactor system at the most fundamental level. The IMSR®'s safety and commercial case is also completely different. It is a nuclear technology with a very different social and economic narrative. IMSR® renders historic accident types as not merely implausible but physically impossible.

However there will be no substitute for open and informed discussion and skilful risk communication in developing consensus for the developing of nuclear generating capacity in South Australia; this process will be given a boost by the very different design attributes of the IMSR®.

There are two types of nuclear accidents. The first occurs when a reactor's power spikes to damaging levels, as happened, for example, in the 1986 Chernobyl accident. This is a "criticality accident", a rare form of accident that is concurrent with a substantial degradation in safety culture and adherence to approved operating protocols. The IMSR®s are inherently and extremely resistant to "criticality accidents" for a number of reasons.

Firstly, the IMSR® does not need the "excess core reactivity" of a LWR. LWRs are loaded up with fuel for 18 months of operation. In contrast, MSRs can be fueled slowly and continuously.

Secondly, without any active system support, the IMSR® reactor core will respond instantly to an increase in criticality and its associated rise in fuel salt temperature. The chain reaction slows and the reactor starts to shut itself down. This is due to the reactor's "negative temperature reactivity coefficient". This is term-of-art, which signifies that the reactor is self-regulating; it is stable in operation.

TERRESTRIAL
E N E R G Y

All reactors have such a desired negative coefficient, but the coefficients for IMSR®s are far more negative.

The important negativity of this coefficient is determined by the interplay of three factors:

1. **Fuel-salt density.** A decrease in density removes fuel-salt from the core, changing the fuel-to-moderator ratio and increasing neutron leakage.

2. **Doppler broadening of resonance-absorption peaks.** Higher temperature produces broader peaks.

3. **Graphite temperature.** Higher temperature shifts the Maxwellian neutron peak to higher energy, and into (or out of) fission-resonance peaks.

These three factors must combine to yield a negative coefficient overall, and ideally all three factors separately will make negative contributions. Modelling to date confirms negative contributions from all three factors in the IMSR®, yielding a highly negative coefficient value overall.

A buoyancy-driven control rod is the primary shutdown mechanism for the IMSR®. It is a simple rod, slightly denser than the fuel-salt at operating temperature and held above the core by the pumped circulation of the fuel. If pumping ceases, or if the fuel-salt rises in temperature (thus expanding and decreasing in density), the control rod passively drops into the core and takes the reactor subcritical.

The control rod is backed up by a thermally activated “poison pill” that injects neutron absorbers into the fuel-salt if the temperature rises even higher; the reactor cannot then be restarted until the neutron absorbers are filtered out or chemically removed. This safety feature is not possible in solid fuelled reactor systems.

For this reason IMSR® criticality accidents that may damage the reactor core or endanger the public are a physical impossibility.

The second type of nuclear power plant accident is caused by a failure to remove decay heat from the reactor core after shutdown, a “decay-heat” accident. The Three Mile Island and Fukushima accidents are examples of such an accident.

The dispersion of heat from a reactor core is the central and critical mechanism that supports the safety of any reactor system. MSR and the IMSR® specifically can use liquid convective flow as method of heat dispersion; this is not possible with solid fuelled reactor systems, the fuel is a solid. These systems must rely on the permanent supply of pumped coolant to the reactor core. The failure to maintain this permanent supply was the mechanism behind the Three Mile Island and Fukushima accidents. The IMSR®, employing a liquid fuel with its natural property of convention, is not reliant on a permanent supply of pumped coolant to the reactor core. This makes for an entirely different safety case for the IMSR® where the failure pathways of historic decay heat reactor accidents are absent.

The IMSR® has developed a patented in-situ method to provide the highest level of reliable, passive heat removal.

The IMSR® Core-unit operates within a concrete containment shell lined with a 1-meter-thick layer of solid buffer salt surrounded by a water jacket. The buffer salt is a salt eutectic, chosen to achieve the target melting point. This salt remains solid while the reactor is operating within normal temperature ranges. At a temperature about 50°C above the normal operating temperature of the IMSR® reactor core, the buffer salt melts, and upon melting, its thermal properties change. In addition to absorbing the latent heat of melting, once a liquid, the salt will circulate by natural convection and conduct heat away from the IMSR® Core-unit. In combination, these two effects alone permit the buffer salt to dissipate heat for the first two days of decay heat without any operator intervention.

A water jacket of coiled piping around the buffer-salt liner then provides a subsequent means of decay-heat removal. It is connected to a nearby above-ground water tank, so that any steam generated within the water jacket is passively captured by condensation in the water tank, heat then being released to the surrounding atmosphere. With these two mechanisms in place, decay heat is managed for the duration necessary to secure a robust safety case. In addition, tertiary heat dissipation is provided by thermal radiation through the shielding cap.

Collectively these mechanisms permit the removal of decay heat from the IMSR® reactor core. Together with criticality control, this secures the passive safety case. The reactor is “walk-away safe”. Control rods or poison pill shut the reactor down, no further intervention is necessary.

The IMSR® uses liquid (or molten) fuel, thereby rendering the term “meltdown” irrelevant. The IMSR® operates at atmospheric pressure, and has no potential for energetic chemical reactions, such as the hydrogen explosions seen at Fukushima. No water or steam is present in the core, or anything that could produce hydrogen, and potentially cause a secondary explosion. The IMSR® operates at 1 atmosphere of pressure, and lacks any internal driving forces that can spread radioactive material. By comparison, LWRs operate at 160 atmospheres of pressure in normal conditions.

Furthermore, and of great safety importance, the fuel (uranium, thorium, plutonium, etc.), and fission products, remain locked within the liquid salt, even in the case of an extreme external event that manages to breach the many levels of containment surrounding the MSR. In even these highly unlikely scenarios, any released salt would cool and solidify, immediately causing nuclear reactions to cease. Only a few of the fission products in the molten salt are volatile and can conceivably depart.

An IMSR® is therefore inherently stable and delivers safety at a small fraction of the cost of pressurised, solid fuel LWRs. The known failure modes of conventional nuclear plants, the failure modes of Three Mile Island, Chernobyl and Fukushima, have been comprehensively and successfully addressed in the IMSR® design.

3.11 How might a comparison of the emission of greenhouse gases from generating electricity in South Australia from nuclear fuels as opposed to other sources be quantified, assessed or modelled? What information, including that drawn from relevant operational experience should be used in that comparative assessment? What general considerations are relevant in conducting those assessments or developing these models?

This is a mature area of academic enquiry with consistent conclusions that are accepted at the highest levels[8]. Studies indicate that, across the full lifecycle, nuclear energy is among the lowest greenhouse-gas forms of electricity production. Studies have been prepared specifically for Australian conditions and meta-review of the relevant literature has been undertaken by an Australian University[9].

The IMSR® is likely to deliver even better performance in this regard than conventional nuclear thanks to:

- Lesser energy inputs for liquid fuels than traditionally fabricated solid fuel rods and large complicated fuel assemblies
- Higher efficiency in the use of mined uranium inputs by a factor of six
- Operations at atmospheric pressure, demanding lesser inputs of steel and other reinforcing materials

[8] Moomaw et al. (2011)
[9] Lenzen (2008)

3.12 What are the wastes (other than greenhouse gases) produced in generating electricity from nuclear and other fuels and technologies? What is the evidence of the impacts of those wastes on the community and the environment? Is there any accepted means by which those impacts can be compared? Have such assessments making those comparisons been undertaken, and if so, what are the results? Can those results be adapted so as to be relevant to an analysis of the generation of electricity in South Australia?

Thanks to the long fuel-cycle and very high efficiency core of the IMSR®, this design achieves less outputs of waste per unit electricity than traditional nuclear generation.

Table 1 IMSR® waste (indicative) versus LWR waste

Normalised to a 1 GWe-year	LWR	IMSR®
Fuel (tonnes)	250	35
Plutonium waste- kg, without recycling	250	36
Plutonium waste- kg, with recycling	Approx. 50 % reduction	Virtually nil
Fission product waste, kg	1200	800
Gaseous fission product waste (m3)	39	26

The principal operational waste from the IMSR® will be the spent fuel cores, being the contained fuel salt and ancillary devices.

Indicatively an IMSR80 will deliver 1.4 tonnes of waste fuel from seven years of operations.

There is the potential for the IMSR® to further reduce waste both upstream and downstream of operations.

Firstly, the spent fuel salt is highly recyclable. A single-batch process after many years of use to recycle transuranic elements (in particular plutonium) would give a waste profile virtually free of transuranic wastes, which are currently viewed as "troublesome" but in fact contain enormous quantities of fission energy that can be extracted in the IMSR®.

A centralised chemical fuel recycling facility[10], using processes of electrochemical separation, can remove the small quantity of fission products from the liquid fuel salt. The remaining uranium and transuranic elements can either remain in salt solution for re-use in another IMSR® core, or be fabricated into solid fuel for reuse in, for example, a sodium cooled fast breeder reactor[11]. The ultimate destination would depend on operational and commercial considerations. However the important point is that with sufficient recycling capabilities only the small amount of fission products *need* be disposed of as waste. These fission products are relatively short lived (approximately 30 year half-life)[12]. As such their safe management and disposal is well-within institutional capabilities and timeframes.

Secondly the uranium and transuranic input to the fuel salt might itself be derived from existing used fuel rods from the traditional nuclear power sector. The same type of centralised recycling facility could extract usable transuranic elements, principally plutonium, from solid metal oxide fuel rods. As such the operation of the IMSR® might require little or even no upstream mining for the initial fuel.

Note, these advantages are not inherent to the IMSR® proposal. However the IMSR® can operate synergistically with advanced recycling facilities to deliver large quantities of highly reliable electricity with the production of only tiny quantities of fission-product waste, and also alleviate the challenge of managing stockpiles of the long-lived transuranics held in used solid fuel.

The other main waste outputs of the IMSR® are the reactor core vessel itself. After draining of the liquid salt, this vessel will require decontamination flushing with non-radioactive salt to reduce residual activity to a minimum. The core would then be stored for several years to allow the decay of any activated material or residual fission products. At this time, the core would likely be classified as either intermediate level waste or, more likely, low level waste. This will require disposal at an approved facility.

[10] Such as that described in Argonne National Laboratories/ Merrick and Company (2015)
[11] Triplett, Loewen and Dooies (2010)
[12] Till and Chang (2011)

3.13 What risks for health and safety would be created by establishing facilities for the generation of electricity from nuclear fuels? What needs to be done to ensure that risks do not exceed safe levels?

The nuclear industry, to date, has achieved an outstanding operational safety record normalised for electricity production against all other energy sources for power production[13]. This has been achieved through robust engineering and regulatory responses to credible events and serious accidents. On the basis of evidence, the risk in establishing facilities of the generation of electricity from nuclear fuels will be very low.

However this safety record has come at the cost of nuclear reactors carrying a design and regulatory legacy that has increased cost and constrained deployment and has arguably failed to secure public confidence.

As previously documented, the unique design attributes of the IMSR® have *eliminated* the most challenging operational safety elements of solid fuel nuclear reactors. Recapping, the IMSR®:

- Operates at atmospheric pressure
- Utilises a liquid fuel, rendering the concept of “meltdown” redundant
- Passively cools for indefinite periods, rendering the reactor “walk-away safe”
- Loses criticality and shuts down automatically with temperature increase beyond normal operations
- Operates free of water in the core, eliminating the potential for production of explosive hydrogen
- Is incapable of generating sufficient mechanical or chemical energy to cause the explosive distribution of core material
- Keeps fissile material chemically locked in a liquid salt fuel, which freezes to a solid in the event of distribution by extreme external forces
- Will be based on assembly-line construction of standardised reactor cores, permitting outstanding quality control
- Uses sealed cores with long-operational life for recycling and disposal at dedicated centralised facilities. This again maximises quality control and minimises occupational exposures.

[13] (Bickel & Freiedrich 2005; Burgherr and Hirschberg (2008); Kharecha and Hansen (2013); Markandya and Wilkinson (2007))

In summary, the risk associated with the nuclear power industry is low on the basis of half a century of evidence and study. In advancing nuclear technologies, South Australia could put these matters beyond any and all credible doubt through the adoption of IMSR® technology that revolutionises the safety case for nuclear-generated electricity.

3.15 What impact might the establishment of a facility to generate electricity from nuclear fuels have on the electricity market and existing generation sources? What is the evidence from other existing markets internationally in which nuclear energy is generated? Would it complement other sources and in what circumstances? What sources might it be a substitute for, and in what circumstances?

3.16 How might a comparison of the unit costs in generating electricity in South Australia from nuclear fuels as opposed to other sources be quantified, assessed or modelled? What information, including that drawn from relevant operational experience, should be used in that comparative assessment? What general considerations should be borne in mind in conducting those assessments or models?

The IMSR® is, first and foremost, a commercial development. Ipso facto, this reactor development is intended be commercially competitive in free electricity markets with the ability to displace other sources of supply and capture market share.

Existing evidence and commercial assessments of nuclear electricity cost performance have little relevance to the IMSR® due to the revolutionary manufacturing, deployment and operational concepts of this reactor.

IMSR® cost estimates to date indicate the IMSR600 and IMSR300 will deliver grid-connected electricity to market at US$43 and US$59 per MWh respectively on a levelised cost basis. These costs will be scrutinised and refined further in Phase II of the research and development program.

South Australian spot prices averaged AU$68 per MWh in 2013-14[14]. It can be generally asserted therefore that under these conditions the IMSR600 and IMSR300 would be heavily dispatched into the South Australian market, taking share from other dispatchable generators. Weekly spot prices from July 2012 to September 2014, and volume-weighted

[14] Australian Energy Regulator (2014)

annual average spot prices across all National Electricity Market jurisdictions[15] suggest IMSR300 and IMSR600 would win consistent levels of dispatch into the market and potentially would win constant, year-long dispatch i.e. IMSR® could become Australia's new baseload.

Based on price in the National Electricity Market, the IMSR® would likely substitute for gas generation, followed by black coal, followed by brown coal.

Given what the IMSR® price is an estimate for new plant, its ability to potentially displace established, incumbent and in some cases fully depreciated suppliers in the National Electricity Market is an excellent price outcome.

Any return to carbon pricing or furthering of technologically-inclusive clean energy policy in Australia would serve to extend this market advantage further.

We note the increasing penetration of wind energy in South Australia. Currently wind energy is subsidised into the National Electricity Market. Wind energy wins priority dispatch by virtue of low operating costs and assured revenue from the sale of certificates[16].

Introduction of the IMSR® would likely have no negative impact on market penetration of wind and solar PV electricity in the National Electricity Market for the foreseeable future for three key reasons:

1. NEM-wide, penetration of wind and solar energy remains relatively low (4.4 % and 2 % of all electricity respectively[17])
2. NEM-wide, coal and gas generation remain dominant (74 % and 12 % respectively[18])
3. Pricing of IMSR® will compete with baseload suppliers
4. IMSR® load-following capability far exceeds that of any conventional nuclear power plant

If IMSR® were added to the National Electricity Market it would firstly take market from higher-priced gas generation, then black coal generation, and finally brown coal generation. Sufficient levels of interconnection from South Australia to the National Electricity Market will

[15] Australian Energy Regulator (2014)
[16] Heard, Bradshaw and Brook (2015)
[17] Australian Energy Regulator (2014)
[18] Australian Energy Regulator (2014)

ensure both wind and IMSR® can dispatch low-cost clean electricity at all times. Meanwhile solar PV will continue to lower midday and early evening summer peaks in demand[19].

Penetration of wind in South Australia may rise to levels where even very-low cost, clean generating IMSR® would be forced to curtail dispatch. Such scenarios are distant and can be managed by good planning.

In the shorter term, the strong automatic load following capability of the IMSR®, related to the strong negative temperature reactivity coefficient, makes it a good partner to assist in the efficient management of the variable output from wind generation.

[19] Australian Energy Market Operator Ltd. (2014)

CONCLUSIONS

We applaud the Government of South Australia for undertaking this structured enquiry into the potential for nuclear technologies to benefit the people of South Australia.

The IMSR® represents an advantageous advanced nuclear reactor design that can deliver low cost, reliable clean energy. Engagement with this technology provides the potential for longstanding beneficial outcomes in research, development, manufacturing and clean energy for South Australia.

To conclude this submission, we wish to raise the following potential actions and outcomes for consideration by the Royal Commission:

Collaborative research partnerships

ANSTO is a world-class nuclear physics research facility. Terrestrial Energy would welcome the opportunity to expand our research at ANSTO with respect to online fuel reprocessing. The end goal of such research would be to create a next generation of IMSR®-based technology that includes a centralised reprocessing facility, and as a whole, forms a closed fuel cycle -- consuming 100% of its own fuel and 100% of its own long-lived waste during the normal course of operations. Terrestrial Energy suggests that the IMSR® is an excellent technology with which to pursue this goal, and this research would be world-leading in our view. Terrestrial Energy would be pleased to fund this research.

Low cost transition of the Australian electricity sector

As an end-user market, Australia is important to Terrestrial Energy. We wish to deploy the IMSR® to hasten the replacement of ageing coal capacity globally by providing a scalable, low cost alternative. Australia represents a substantial market in this regard. Facilitating such a transition would seem prudent on the part of Australia as the world moves toward a more coordinated response to climate change. This cannot happen in the presence of legislation in direct antipathy to nuclear technology, even the most advanced designs. We urge the Royal Commission to consider the benefits to Australia of removing such legislative barriers.

Advanced manufacturing targeting the growth Asian energy markets

The growth energy markets for Asia are important for Terrestrial Energy, both to replace existing coal and to steer new investments away from coal. These markets are embracing nuclear technology, seeking ways to decrease coal use, and their energy demand growth is far greater over the next generation than OECD markets[20]. South Australia provides a potentially attractive base of operations for assembly-line manufacturing as a launch pad for Asian deployment of IMSR® units. Such a facility will bring tremendous job opportunities to the local economy -- numbering in the thousands. Such a facility would characterize the state of the art in nuclear technology globally, and may attract other high-tech industries to the zone as well. Terrestrial Energy would like to discuss siting such a facility in South Australia.

Synergistic infrastructure development

Terrestrial Energy notes the high level of interest, globally, from advanced nuclear technology designers in South Australia's Royal Commission process. Some other advanced nuclear infrastructure, particularly centralised facilities for the recycling of nuclear fuel, would provide important and enticing synergies relating to the IMSR®. The collective pull of intellectual capital toward South Australia will itself become an attractive feature of this jurisdiction. We encourage South Australia to think in terms of these potential synergies to maximise benefits to both the South Australian economy and to advanced nuclear developers

Direct Investment

Terrestrial Energy has embarked on Phase II of its research and development program for the IMSR®. We would be interested to discuss the potential for South Australia to secure a financial interest in this stage of development to boost the probability of benefitting from IMSR® developments in future.

[20] US Energy Information Administration (2013)

TERRESTRIAL
ENERGY

Submission to the South Australian Nuclear Fuel Cycle Royal Commission, 8th March 2015

REFERENECES

Argonne National Laboratories/ Merrick and Company 2015, *Summary Report: Conceptual Design of a Pilot-Scale Pyroprocessing Facility*, The Landmark Foundation, Idaho Falls, Idaho USA.

Australian Energy Market Operator Ltd. 2014, *Heatwave 13-17 January 2014*, Australian Energy Market Operator Ltd, Australian Energy Market Operator Ltd, New South Wales.

Australian Energy Regulator 2014, State of the Energy Market, Commonwealth of Australia, Canberra, ACT.

Bickel, P & Freiedrich, R 2005, *ExternE: Externalities of Energy*, E Communities, Luxembourg.

Burgherr, P & Hirschberg, S 2008, 'Severe accident risks in fossil energy chains: A comparative analysis', *Energy*, vol. 33, no. 4, pp. 538-553.

Electranet 2012, *South Australian Annual Planning Report* Electranet, Adelaide, South Australia.

Heard, B, Bradshaw, C & Brook, B 2015, 'Beyond wind: furthering development of clean energy in South Australia', *Transactions of the Royal Society of South Australia*, vol. 139, no. 1.

Heard, B & Brown, J 2012, *Zero Carbon Options: Seeking an economic mix for an environmental outocme*, ThinkClimate Consulting, Adelaide, South Australia.

Kharecha, PA & Hansen, JE 2013, 'Prevented mortality and greenhouse gas emissions from historical and projected nuclear power', *Environ Sci Technol*, vol. 47, no. 9, May 7, pp. 4889-4895.

Lenzen, M 2008, 'Lifecycle energy and greenhouse gas emissions of nuclear energy: A review', *Energy Conversion and Management*, vol. 49, pp. 2178-2199.

Markandya, A & Wilkinson, P 2007, 'Electricity generation and health', *The Lancet*, vol. 370, no. 9591, pp. 979-990.

Moomaw, W, Burgherr, P, Heath, G, Lenzen, M, Nyober, J & Verbruggen, A 2011, *Annex II methodology*, IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, New York, NY, USA.

Syed, A 2012, *Australian Energy Projections to 2049-50*, Bureau of Resources and Energy Economics, Commonwealth of Australia, Canberra, Australia.

The White House, Office of the Press Secretary, 2014, 'US-China Joint Announcement on Climate Change', Washington, D.C., obamawhitehouse.archives.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change.

Till, CE & Chang, YI 2011, *Plentiful Energy: The Story of the Integral Fast Reactor*, Charles E. Till and Yoon Il Chang, CreatSpace Publishing, Idaho Falls, Idaho, USA.

Triplett, BS, Loewen, EP & Dooies, BJ 2010, 'PRISM: A competitive small modular sodium-cooled reactor', *Nuclear Technology*, vol. 178, pp. 186-200.

US Energy Information Administration 2013, *International Energy Outlook 2013*, UDo Energy, Washington, DC.