Minerals
Council of
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nuclear

Decarbonising Australia's industrial heat sector

Contents

Prepared for the
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Resourcing tomorrow
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Foreword

Decarbonising industrial heat is a major challenge.

Industrial heat helps provide the essential and foundational materials of modern life; everything from the food we eat, to the homes we live in, to the employment and investment opportunities that contribute to prosperity for all Australians.

It is also an activity that is responsible for more emissions than cars and presents vastly greater technical and commercial challenges than decarbonisation of the electricity supply. But while it may pose a challenge, it also represents a great opportunity for Australia to drive emissions reductions.

With diversity of needs, applications, locations and scales, all solutions must be in play when it comes to decarbonising industrial heat – this includes the family of advanced nuclear and small modular reactors. Nuclear is the only technology pathway that can bring reliable heat directly to industry at virtually any scale, in virtually any location.

The suite of nuclear technologies offer:

- **Diversity of size and modular build** making them better able to directly serve industrial users
- **Passive and inherent safety** offering the potential of direct co-location with other industrial facilities as an addition to an industrial precinct
- **Higher temperatures** providing potential solutions for a large segment of this difficult to decarbonise sector
- **Flexible operations and cogeneration** allowing facilities access to heat and power through tailored production and output based on requirements
- **New heat transfer mediums for industry** such as molten salt or hot inert gas like helium.

These technologies could also support other essential decarbonisation pathways, such as electrification and large-scale hydrogen production, and contribute much needed stability and resilience to the electricity grid. Implementation fits neatly within the land footprint of existing transmission networks, requiring little expansion, and could provide certain and lasting employment opportunities in towns and cities.

A clever, all-of-the-above, integrated portfolio strategy encompassing these solutions stands the best chance of decarbonising industrial heat in a way that is internationally competitive. Other industrialised nations are advancing these portfolios in partnership with industry. Australian industry, however, remains constrained by an exclusionary technology policy. This approach fails to fully activate Australian industry in the development of fit-for-purpose solutions which will bring forward the investment needed.

Australia needs a more determined approach for the decarbonisation of industrial heat and this requires open, impartial consideration of how to apply the power of fission to this difficult to decarbonise sector.

Tania Constable
Chief Executive Officer
Minerals Council of Australia

Introduction

The key to decarbonising Australia's industrial heat sector is fission.

When the Intergovernmental Panel on Climate Change published its first scientific assessment in 1990, the year 2050 seemed far off. That target is now just 27 years away. Commitments to net zero greenhouse gas emissions are being made by governments, corporations and industries. Yet reaching net zero emissions by 2050 remains an unresolved challenge.

There has been considerable focus on the energy sector, particularly electricity supply. While a large source of greenhouse gas emissions, the focus on electricity is disproportionate to the technical challenge, hence the focus here on industrial heat.

Decarbonised electric grids are long proven through the use of nuclear fission and hydro-electricity. Regionally advantageous contributions from wind and solar power also now support decarbonised grids.

Industrial heat solutions using nuclear technology represent a significant opportunity.

There are genuine challenges in science, technology and engineering in the difficult to decarbonise sectors, those that provide the most foundational products of modern society: food, fertilisers, cement, steel, chemicals, value-added minerals and paper. Sectors that are also major sources of employment and revenues for Australia.[1]

The decarbonisation challenge is not just electricity; these sectors also need heat.

Modern industrial processes require the reliable delivery of heat at temperatures up to, and exceeding, 1,000°C. For a decarbonised future, the world needs alternatives to unabated fossil fuel combustion to provide heat to global industry.

Heat is delivered through many long established processes involving combustion gases or production of steam which are not amenable to or cost effective in electrified solutions.[2] Various renewable energy options are constrained in their techno-economic potential to directly deliver vast quantities of reliable heat. These challenges demand a greater share of attention by public policy makers and industry practitioners, particularly in relation to funding, research and development, to establish a portfolio of deployable solutions that meets both the diversity and scale of the need.

Nuclear fission is one such solution which can provide high temperature process heat, with full reliability and no fossil fuel combustion, from relatively tiny amounts of energy inputs. While fission already provides about 10 per cent of global electricity, the provision of heat has been limited to some cogeneration benefits from the relatively low temperatures of light-water nuclear reactors.

This is changing with the commercialisation of advanced reactor technologies and small modular reactors. Smaller, hotter and more scalable than alternatives, and now designed with passive or inherently safe fuel management, they offer potential for co-location with industrial production. Advanced nuclear energy brings a powerful tool to address difficult to decarbonise sectors.

This report provides essential information for understanding this challenge in the Australian context. Work is required, starting now, to join up this class of technologies to the difficult to decarbonise processes. A credible portfolio of solutions is needed from the full range of technologies to meet the diverse heat needs of industry. That means understanding the challenge, dispassionately appraising the options and engaging industrial users in the journey to a net zero future.

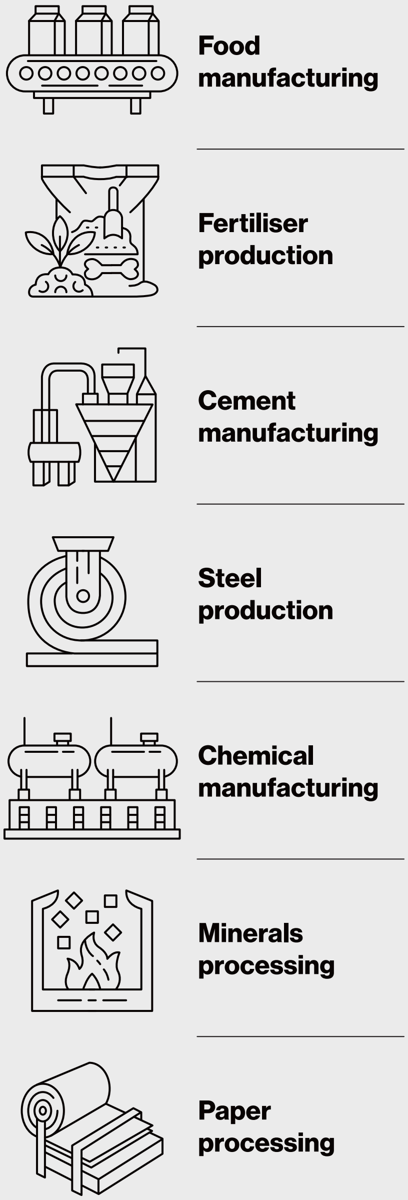
If Australia is to remain competitive, Australian industries need all the tools available to their competitors. Limiting the options available to Australian industry risks the loss of those industries, along with their jobs and revenue, to jurisdictions which can outcompete domestic industry with better solutions.

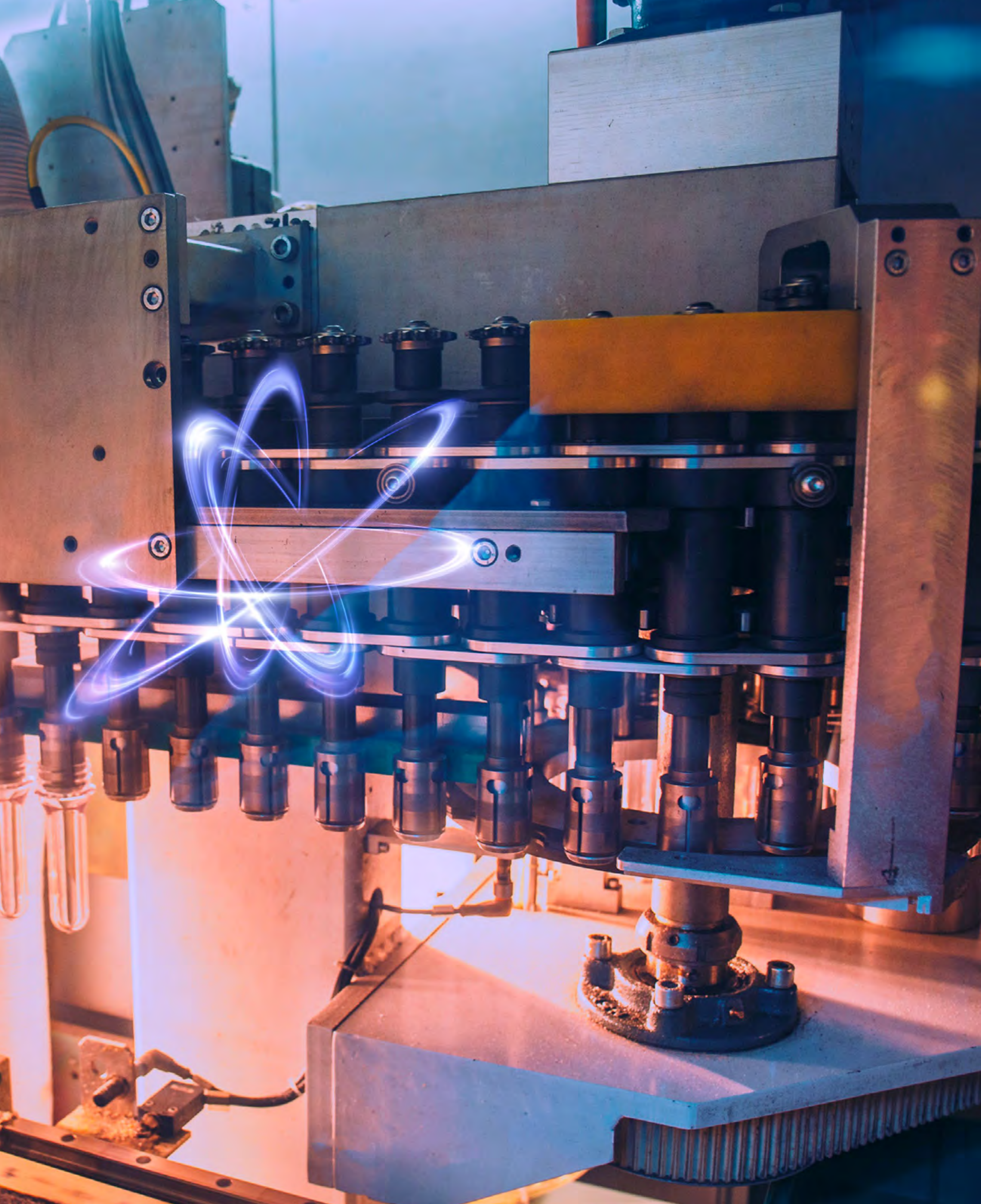
Nuclear fission for energy is inaccessible to Australian industry under current policy settings. It is a failing that Australian research and academic and industrial literature has no consideration of fission for industrial decarbonisation. This leaves Australia with a gap in knowledge and planning compared with nations including the United States, Canada, the United Kingdom and China. Nations without this constraint will develop revitalised, decarbonised industries to compete against Australia in an increasingly climate conscious world.

With less than three decades remaining to 2050, Australia has enough time to correct our technology course, but little time to waste. Australia needs all available options to create a credible roadmap to net zero.

FIGURE 1

High energy use industries





The decarbonisation challenge

Delivering reliable process heat is critical to modern economies.

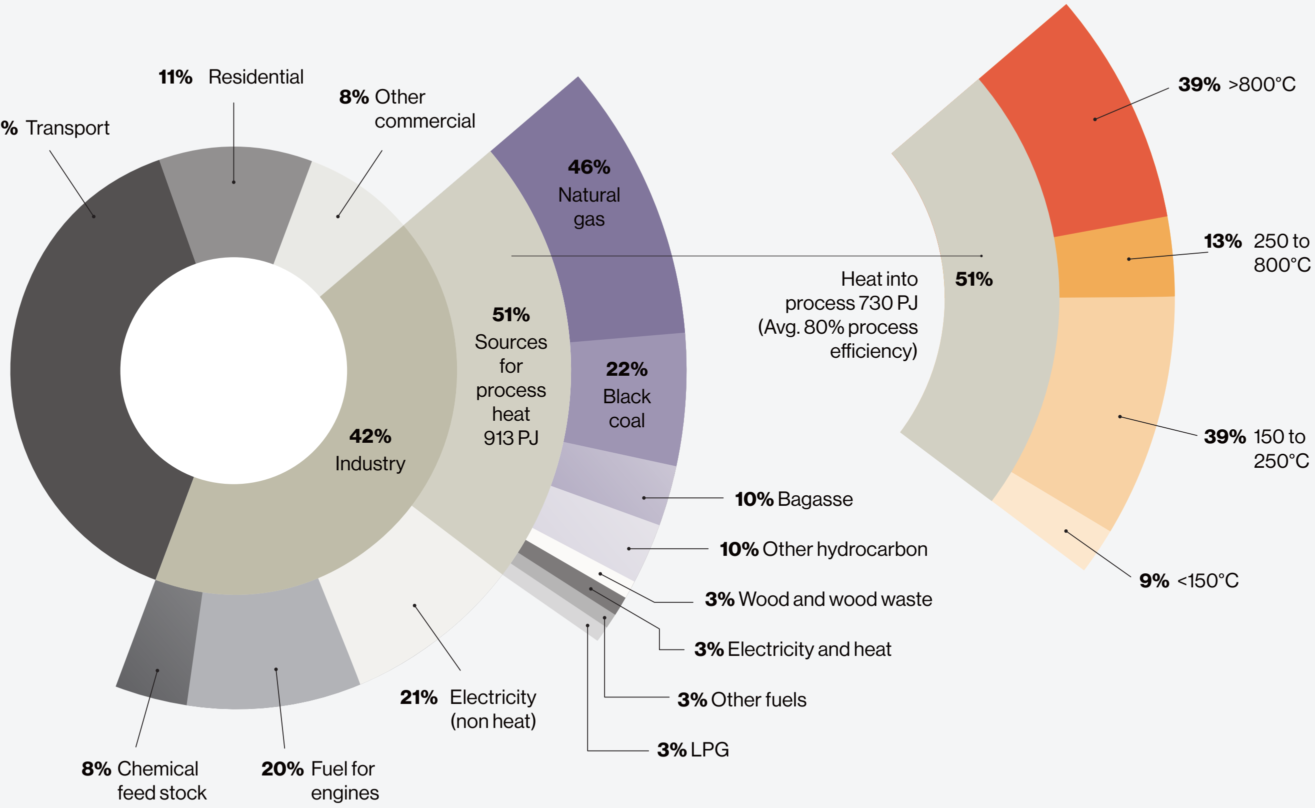
Heat is an essential input to many of the most critical operations in global industry. Whether food, chemicals or construction material, delivering reliable process heat to industry is key in maintaining a modern economy and way of life. Industrial energy demand accounts for 42 per cent of Australia's total final energy consumption, of which half is used for process heating.[3]

The delivery of industrial heat is diverse for specialised applications. It is commonly supplied in the form of heated water, steam, combustion gases or electrified elements. The International Energy Agency's *World Energy Outlook 2017* predicts that heat in the lower temperature bands (<400°C) will make up around three-quarters of the overall increase in global industrial heat demand up to 2040, driven by less energy-intensive industries.[4]

FIGURE 2

Australia's industrial heat sources

Source: ITP Thermal, *Renewable Energy Options for Industrial Process Heat*, ARENA 2019.



Process heat in 'low' and 'very low' categories (<250°C) is common to industries including oil and gas extraction, paper processing, and food and beverage manufacturing. Typical operations use indirect heating via thermal oil, water or low-grade steam and include processes such as steaming and drying.

Medium temperature heat is often demanded in the oil and gas sector, both in extraction, where steam is injected into oil wells for enhanced recovery (250-350 °C), and in the refining process such as fractional distillation and catalytic cracking.[5] Chemical manufacturing is another major sector for medium temperatures. The synthesis of ammonia, the key input to global fertilisers, plastics and synthetics fibres, is delivered between 400-500°C. The production of ammonia is responsible for approximately 2 per cent of total global final energy consumption.[6]

The high temperature requirements are dominated by the metals, cement and chemicals manufacturing sectors. This is often delivered by direct heating through gas-fired furnaces – for example, in steam methane reforming (hydrogen production), or electrical heating utilised in the arc furnaces and electrolysers in metals processing. Whilst these sites vary in heat demands, the largest facilities are among the largest consumers of energy in the country.[7]

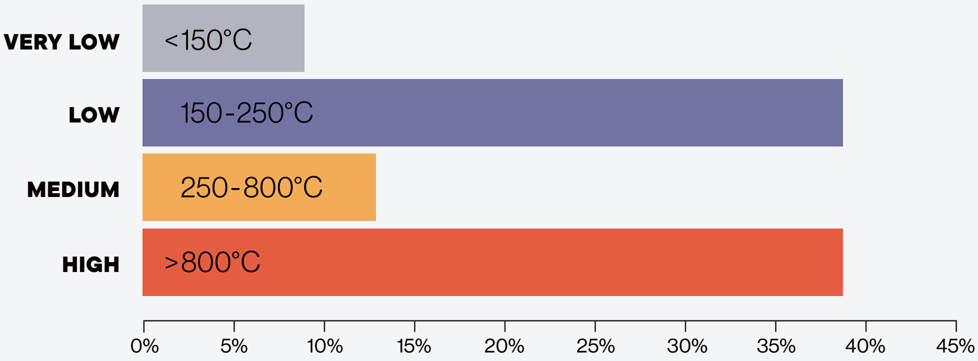
Australia's largest metals, cement and chemical manufacturing facilities are among the country's biggest consumers of energy.

Industries and individual facilities might rely on processes that span temperature bands, employing a range of systems and mediums for heat delivery. The heat generation plants are commonly owned, operated and co-located with the industrial facilities. This allows close control and integration with processes as well as reducing transmission distance and resultant losses.

FIGURE 3

Australia's industrial heat demands by grade

Source: ITP Thermal, *Renewable Energy Options for Industrial Process Heat*, ARENA 2019.



Given the requirements in co-location, size, versatility, reliability and affordability, fossil fuels deliver more than 80 per cent of Australia's supply of industrial heat (46 per cent natural gas, 22 per cent coal, 13 per cent oil and other hydrocarbons), while biomass gives renewables a 13 per cent contribution in this energy mix.

Greenhouse gas emissions from industrial heat, at 21.1 per cent of Australian emissions in 2022, was a bigger contributor to national emissions than the entire transport sector – second only to electricity generation.[8] Australian emissions from this sector have consistently grown, largely untouched by any energy transition.

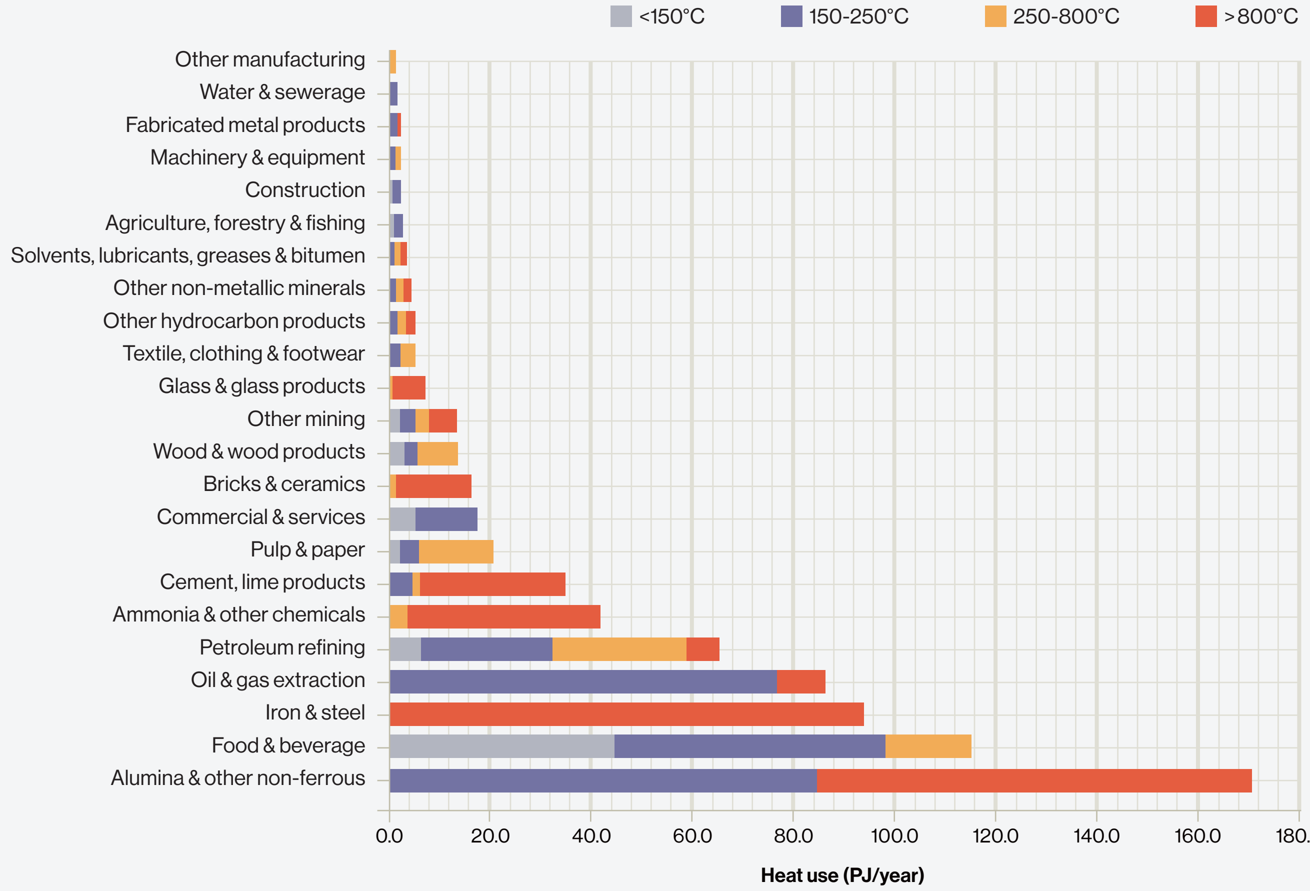
Achieving decarbonisation of these sectors in Australia will require a portfolio of feasible technology options to match processes and facilities, maintain cost competitiveness and provide resilience to shifts in national and international policies related to climate change.

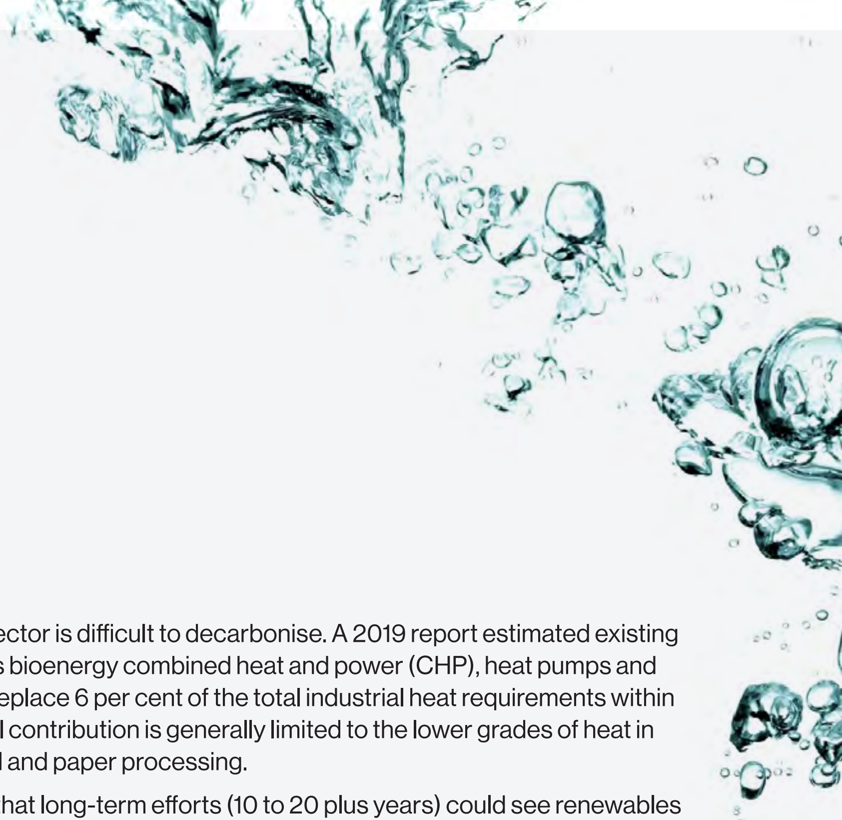
Fossil fuels deliver more than 80 per cent of Australia's supply of industrial heat.

FIGURE 4

Typical industry heat demands

Source: ITP Thermal, *Renewable Energy Options for Industrial Process Heat*, ARENA 2019.





The decarbonisation gap

A realistic view of renewable energy capabilities is required.

The industrial heat sector is difficult to decarbonise. A 2019 report estimated existing technologies such as bioenergy combined heat and power (CHP), heat pumps and solar could feasibly replace 6 per cent of the total industrial heat requirements within five years.[9] This small contribution is generally limited to the lower grades of heat in applications like food and paper processing.

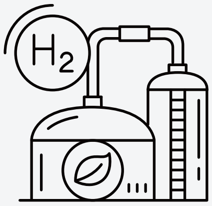
The study suggests that long-term efforts (10 to 20 plus years) could see renewables take up to a 42 per cent share in the energy mix. This is based on assumptions of significant technological leaps and cost declines, as well as reconfiguration of established industrial processes. A factual and realistic view is required of the capabilities of renewable technology solutions and the gaps in the challenge of decarbonisation of the industrial heating sector.

Clean hydrogen

Hydrogen provides a potentially attractive solution, especially where consumers are looking to decarbonise processes that are fuelled by natural gas. Hydrogen and methane have similar properties and so retrofitting existing plant and established processes is possible. Hydrogen also plays a potential role as a direct reductant, taking the place of fossil fuels such as coking coal. This dual role might support hydrogen as an attractive solution for some needs.

Large-scale, affordable supply of decarbonised hydrogen presents challenges. When delivered via electrolysis, the affordability demands a very low price of electricity, a very high load factor for the electrolysers, and steep falls in the cost of the electrolysers. Alternatively, supply could come from reforming fossil gas, with the addition of carbon capture and storage (CCS). This provides a small portion of today's hydrogen production.

Storage and transportation of hydrogen is more challenging than for natural gas and so production close to point of use is an advantage. This can limit the potential of both renewable electricity generation and CCS. Irrespective of its origin, affordable clean hydrogen will be in high demand as an alternative to fossil fuels in sectors such as transport, and as a direct chemical feedstock. It is therefore essential to maximise efforts in achieving affordable supply and to develop alternative solutions to minimise reliance.



Clean hydrogen

Clean hydrogen is a sustainable form of hydrogen fuel produced through steam methane reforming by combustion fuels with carbon capture and sequestration, or electrolysis involving renewable or nuclear energy sources splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2). Clean hydrogen production generates no emissions.

Biomass and biofuels

Biomass is the only non-fossil energy source playing a significant role in the industrial heat sector, largely owing to its role in the food, beverage and paper industries. These sectors have an abundance of readily available feedstock, often as by-products of the industry itself. Such organic material commonly provides direct process heating through simple combustion in industrial boilers. Its suitability is limited by the combustion characteristics of the biomass – its higher moisture content and lower energy density requires greater throughput than fossil fuels.

Biomass can also provide indirect fuel sources. Anaerobic digestion generates combustible biogas that can directly replace natural gas in heating or cogeneration in a combined heat and power engine. However, as the material throughput for anaerobic digestion is comparatively large and is also variable depending on available feedstock, it is limited in scalability.[10] In addition to biogas, liquid biofuels including biodiesel and ethanol-based fuels are derived from well-established processes and provide possible alternatives to diesel-fired heating operations.

All biomass-derived applications face challenges in upscaling. The required high mass throughputs demands co-location of industry with biomass feedstock production, storage and processing sites to minimise the cost and environmental impact of transportation. Unless it is sourced as a by-product of existing operations, biomass competes with other land uses, driving conversion of lands from forests or other biomes into production crops. Biodiesel additionally encounters competition in its end-state use as it is a potentially valuable transport fuel, especially in heavy goods vehicles and cargo ships where alternatives are limited.

Biomass and biofuels

Biomass energy is derived from organic materials, such as plants, wood, agricultural residues, and organic waste. It converts the chemical energy stored in these biological materials into usable energy forms like heat, electricity, or biofuels. Common methods of generating biomass energy include burning wood for heat, using crop residues for biofuel production, and anaerobic digestion of organic waste to produce biogas.

Electrification

Some industrial heat requirements are electrified. High temperature applications include direct process heating through electrified elements, most notably in electrolytic smelting. This means of heating requires huge amounts of electricity. Tomago aluminium smelting plant demands 850 MWe, 12 per cent of the grid capacity in New South Wales.[11] Electrification also provides opportunities at the lower temperatures, with electric boilers able to provide indirect heating to processes via creation of heated water and steam, and heat pumps able to provide steady heat in the 'very low' temperature grade. A wide range of electrification solutions can be expected to play some role in transitioning the delivery of industrial heat. However, with only 3 per cent of Australia's industrial heat currently provided with electricity, overreliance on the electrification pathway presents risks to successful decarbonisation.

Electrification in industrial heating is supplied by centralised electricity grids or onsite fossil fuel burning generators. Whilst the high reliability of central power grids is advantageous, it relies on decarbonisation of those grids while improving affordability and reliability such that it can serve industrial requirements. Challenges are already apparent in Australia's energy transition to replace existing aging generators, meet growing demand, and overcome bottlenecks in transmission infrastructure for accessing greater quantities of wind and solar power. Servicing the industrial heating load via wholesale electrifications will amplify these challenges. A 2023 report by the Australian Energy Market Operator forecasts that without new commitments to improving generating and storage capacity, grid reliability will rapidly fall below acceptable levels in all mainland states from 2027.[12] Direct electrification of personal and light commercial transport will drive additional competition for a decarbonised electrical grid supply.

Industrial consumers might decarbonise their own operations while maintaining commercial or operational control of the generating assets via decentralised, co-located electric heating supply. For solar and wind generation, the variability in production, large land footprint, and dependence on high-quality resources at great distance from industry limits their plausible role.

Electrification

Electrolytic smelting is a metallurgical process used to extract metals from their ores through the application of electrical energy. Two electrodes are immersed in an electrolysis cell, which contains a solvent or molten form of ore concentrate. The positive electrode, called the anode, attracts negatively charged ions from the ore, causing them to release electrons and become neutral atoms or ions. These neutral atoms or ions are then deposited on the negative electrode, known as the cathode, as pure metal.

Solar thermal

Solar energy can provide heating via a thermal medium. Flat-plate and evacuated tube collectors are common in domestic heating (the very low temperature band <150°C). Parabolic trough and Fresnel technologies can deliver up to 450°C, while heliostat-tower and dish arrangements can achieve temperatures up to about 1,000°C and include the use of molten salts as a heat carrying medium.

However, the feasibility is limited. Firstly, the land use requirements are prodigious. The Miraah facility in Oman produces steam for enhanced oil recovery with peak capacity of 330 MWe. It occupies around 200 acres (80.9 hectares), equivalent to 40 times the playing surface of the Melbourne Cricket Ground.

Secondly, the variable supply means the plant only achieves around a 15 per cent capacity factor, providing supplementary steam generation while relying on fossil fuels to account for daily and seasonal variations.

Thirdly, it demands an optimal solar resource. This constrains its feasible role to support existing industry in established locations.

Carbon capture and storage

Carbon capture and storage is widely accepted as a necessary decarbonising pathway, including for affordable supplies of hydrogen. The pipeline of planned projects is increasing, with the global capacity of facilities in development growing 44 per cent over the 12 months to 2022.[13]

Despite the recent growth of the industry, the technology remains relatively early in development. CCS is likely to play a role in addressing the provision of industrial heat, but CCS technologies need to develop further. This again shows why having a wide range of solutions will provide the most efficient pathway to net zero emissions, and hence the need for mature and emerging fission solutions to be included in the mix.

Solar thermal

Solar thermal energy harnesses the sun's heat to generate electricity or provide heat for various applications. Unlike photovoltaic solar panels that convert sunlight directly into electricity, solar thermal systems focus sunlight onto a receiver, usually a fluid-filled pipe or a solid material, which heats up. This heat is then used to produce steam that drives a turbine to generate electricity or to provide space heating, hot water, or process heat.

Carbon capture & storage

Carbon capture and storage involves capturing carbon dioxide (CO_2) emissions from sources like power plants or industrial facilities, transporting the CO_2 to a storage site, and securely storing it underground in geological formations such as depleted oil and gas reservoirs or saline aquifers. There are several capture technologies, including post-combustion, pre-combustion, and oxy-fuel combustion capture methods.

Filling the gap with fission

Fission can deliver industrial heat whenever, wherever and at whatever scale it is needed – with zero carbon emissions.

Against the challenging requirements of industrial heat, fission offers unique and important characteristics. Fission provides heat directly from a fuel supply which is affordable, plentiful, dense and carbon-free. Further, fission delivers operational performance which matches the high availability requirements of industry and supports stable, reliable, affordable, decarbonised electricity to the central grid. The potential outcome is heat wherever needed, whenever needed, at whatever scale needed, without carbon combustion.

The dominant type of nuclear reactor in use, the light-water reactor, offers temperatures of about 300°C. Normal (light) water serves as both the primary coolant for moving heat, and the moderator, which slows neutrons to support the chain reaction. However, this water cannot exceed 374°C – the critical point of water – limiting the operating temperature. Today's nuclear power stations were also designed to produce electricity. They have trended to very large size and are generally set apart from other industries to take advantage of transmission lines to move electricity through an electricity grid to point of consumption.

Expanding the use of fission to meet more industrial heat requirements relies, in part, on more fit-for-purpose nuclear technologies. Small modular reactors and advanced nuclear reactors can serve first and foremost as nuclear heat plants.

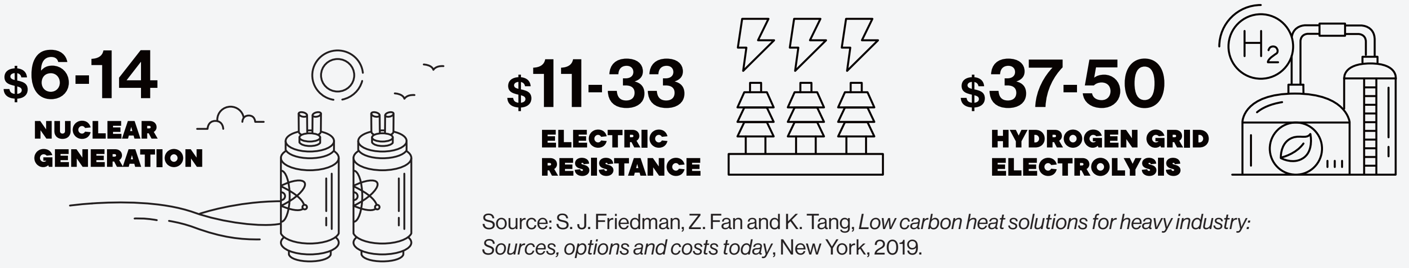
Electricity production is just one of many valuable applications.

These new technologies bring powerful characteristics for industrial heat requirements.

- **Diversity of size and modular build:** With a range of smaller reactor units being brought to market, small modular reactors and advanced nuclear reactors could better serve industrial users and settings, placed close to industry able to scale heat supply easily through the addition of new units.
- **Passive and inherent safety:** Advanced safety cases offer the direct co-location with other industrial facilities. The elimination of any regulated requirement for emergency planning zones means the heat plant can be a straightforward addition to an industrial precinct.
- **Higher temperatures:** Innovative designs and fuel cycles aim to bring temperatures up to 1,000°C which will offer potential solutions for a large segment of this difficult to decarbonise sector.[14]

FIGURE 5

Generic cost comparison for delivery of heat ($US/GJ)



$6-14
NUCLEAR GENERATION

$11-33
ELECTRIC RESISTANCE

$37-50
HYDROGEN GRID ELECTROLYSIS

Source: S. J. Friedman, Z. Fan and K. Tang, *Low carbon heat solutions for heavy industry: Sources, options and costs today*, New York, 2019.

- **Flexible operations and co-generation:** Nuclear heat plants can generate electrical power as one of many potential applications. Facilities and operations requiring both heat and power can access this through co-generation, tailoring production and output based on requirements.
- **New heat transfer mediums:** Where light water reactors generate steam, other reactor designs create useful heat vectors for industry, such as molten salt or hot inert gas like helium.

The density of nuclear fuel overcomes the limitations of biomass solutions, which become unsustainable and unaffordable when applied at scales beyond local facilities. With no dependence on the quality of a solar or wind resource, fission-heat can co-locate with industry. The direct provision of heat via a range of different carriers offers potentially simplified retro-fitting pathways for industries with long lived assets.

By providing heat directly, fission complements increasing electrification and eases the strain on electrical supply and transmission networks. The connection of cogenerating fission plants to our grid will also support electrification, where it is selected by industry, with clean, firm supply and much needed stability in the grid.

By applying fission to suitable industrial applications, hydrogen supplies can be allocated where only hydrogen will do, such as the highest temperature processes, long haul road transport, and feedstock for iron production and fertiliser manufacturing. Using fission will help ensure clean hydrogen delivers its highest value work, as well as supporting affordable production of hydrogen itself.

Further work is required to translate this obvious potential into mature, deployed solutions. Fortunately, this research, development and deployment is actively underway outside of Australia and has progressed substantially in the last five years. Four examples are provided on the next page.

Combustion and fission

Combustion produces heat through chemistry – the rapid oxidation of substances such as coal, oil, gas or biomass. The breaking of a chemical bond, like that between carbon and hydrogen (such as in methane gas) produces about four electron volts of heat and releases carbon dioxide and other waste products.

Fission produces heat by splitting a large atom into smaller atoms. Fissioning a single uranium atom produces about 200 million electron volts of heat, with no release of carbon dioxide while containing the waste products.

Heat, and lots of it, without burning anything. That's fission.

Reactors already provide heating requirements

China's Haiyang nuclear plant was commissioned for power generation in 2018, but retrofitted in 2021 with a heat recovery system designed to use residual heat in the secondary circuit for a district heating network.

This system now supplies 345 MWe of emissions-free hot water to Haiyang, providing zero carbon space heating for more than 200,000 residents. This project is planned for expansion at the Haiyang station alongside similar projects at various stages of completion across China.

Similar success has been found in the application of nuclear heat and power to seawater desalination. Desalination is energy intensive, using heat in flash distillation and electricity in reverse osmosis. These plants are often coupled with cogeneration facilities which also supply electricity to the grid.

Due to the low temperatures required in flash distillation, light-water reactors are suitable. For example, the Aktau BN-350 fast reactor in Kazakhstan, supplied up to 135 MWe of electric power while producing 80,000 m^3/day of potable water over some 27 years to 1999.

Dow and X-energy

United States

Xe-100 Gen IV high temperature gas-cooled reactor

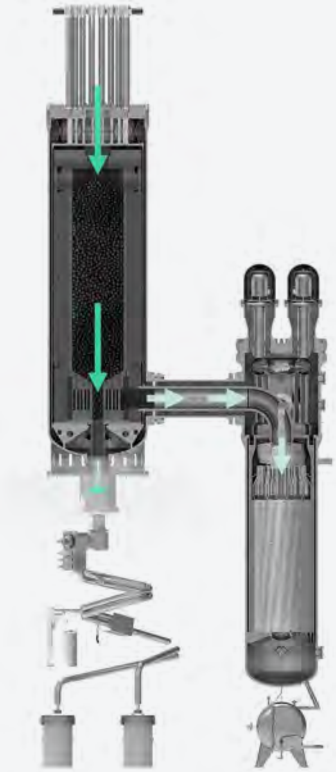


Image: X-energy

X-energy is a nuclear reactor and fuel engineering design company in the United States. The Xe-100, its flagship reactor design, is a Generation IV high temperature, gas-cooled reactor that uses inert helium as the primary coolant.

This 200 MWth/80 MWe reactor is fuelled with tri-structural isotopic (TRISO) fuel particles, around the size of a poppy seed, encapsulated within three layers of carbon and ceramic-based materials. This robust structure can contain all radioactive material in all reactor conditions. It cannot melt, having been tested to up to 1,800°C. These particles are fabricated into fuel pebbles (approximately the size of a billiard ball) containing around 18,000 of the TRISO particles. With a fuel load of approximately 200,000 pebbles, the Xe-100 is intended to offer 60 years of continuous operations without the requirement of refuelling shutdowns.

This fuel, along with the absence of water in the reactor, means helium temperatures of up 750°C can be achieved. This super-heated helium resembles the combustion gases which are used in many heat applications today, offering a relatively simplified path to decarbonisation of some industrial processes. The reactor shuts down automatically in the event of overheating, and residual heat is passively dissipated without damage to the fuel of the reactor, making the reactor 'walkaway safe'.

This solution is being advanced by Dow, one of the world's largest chemical and materials companies. Dow is working with X-energy under a joint agreement to develop and demonstrate the reactor technology at their Seadrift industrial site, for the direct provision of heat and power from four of the Xe-100 units, at a reported price of US$2 billion.[15] This will replace the onsite gas-fired generation which produces the majority of steam and power requirements today. This development and collaboration is supported by the US Department of Energy's Advanced Reactor Demonstration Program. The fuel fabrication facility for the TRISO pebbles is under construction in Tennessee. [16]

NuScale and Nucor

United States

VOYGR pressurised water-cooled reactor

Image: NuScale Power

Nuclear fission has the potential to immediately provide decarbonisation to processes which are already electrified. Partnerships are being forged on this basis. Small modular reactor developer NuScale signed a memorandum of understanding in 2023 with one of the America's largest steel producers, Nucor. This is aimed at assessing the viability of co-locating NuScale's VOYGR plants with Nucor's scrap-recycling electric arc furnace steel mills, providing low emission steel production at scale as part of Nucor's Econiq net zero program.[17]

The scalability of the VOYGR products (462 MWe and 924 MWe) would allow tailoring of supply to match the needs of bigger sites or shared industrial zones. The passive safety features of the advanced reactor design, eliminating the need for external grid connections or emergency planning zones, improves plant siting flexibility for industrial users like Nucor.

Terrestrial Energy

Canada

Integral Molten Salt Reactor

Image: Terrestrial Energy

The Integral Molten Salt Reactor (IMSR) from Canadian company Terrestrial Energy is water-free, using a molten salt fuel to create and circulate heat from the fission chain reaction to a secondary non-radioactive molten salt loop. This secondary salt will be heated to 585°C and can be delivered to industrial customers several kilometres from the nuclear facility. This temperature is ideal for several chemical and industrial processes, including the manufacturing of ammonia. It can also heat steam for highly efficient electricity production or provide tailored co-generation solutions.

The reactor also provides inherent safety by taking advantage of fuel that is molten in normal operations and operating at normal atmospheric pressure. The unpressurised fuel automatically slows the chain reaction if temperatures exceed the design, and will remain in place and cool – another 'walkaway safe' outcome based on different design principles.

Terrestrial Energy is the first advanced nuclear reactor to complete pre-licencing activities in Canada. With no fundamental barriers to licencing, it is now expanding operations in Alberta where it is expected to contribute to the decarbonisation of heavy industry.

Consortium

China

High Temperature Gas-Cooled Pebble Bed Module

Image: China National Nuclear Corporation

In 2022, China Huaneng, China Nuclear Engineering Corporation, and Tsinghua University's Institute of Nuclear and New Energy Technology commissioned the first two modules of the High Temperature Gas-Cooled Pebble Bed Module (HTR-PM).[18]

These commissioned reactors have design and performance characteristics in common with the Xe-100 – pebble fuel, helium coolant and outlet temperatures of 750°C. The modules are 250 MWe each, with a further 18 modules intended for this location. The commissioning and attainment of full power confirms China has the world's first modular high temperature gas-cooled pebble reactor.[19] The stated intention is to deliver power and industrial heat for chemical processes.

At another location, China has achieved 24-hour district and industrial heat delivery from the Quinshan nuclear power station. While these are lower temperature reactors, China is establishing knowledge and experience in the application of this zero carbon heat source.

Interfaces and applications

Fission can help Australia achieve a smooth transition for vital industries.

The addition of advanced nuclear reactors, with the provision of reliable zero carbon heat at point of use, would add powerful tools to decarbonise Australian industry. These novel heat sources could be effectively coupled to long established, vital industries to achieve a smooth and successful transition.

Case study: Ammonia

Ammonia is a key component in producing nitrogen-based fertilisers that boost crop yields. Approximately 85 per cent of ammonia is used in agriculture.[20] Over 70 per cent of production comes from the Haber-Bosch process, in which natural gas is used both as a feedstock and heating fuel. Both major reactions in Haber-Bosch process require heat – the steam-methane reforming reaction to produce hydrogen requires steam input at 700-1000°C, whilst the Haber reaction is carried out at around 400°C.

Haber-Bosch accounts for around 20 per cent of industrial natural gas demand worldwide, whilst the direct emissions associated with global ammonia production amount to 450 megatons carbon dioxide.[21] The environmental impacts of ammonia production will grow as global food demand rises alongside growing populations. Australia makes two million tonnes of ammonia per year. Decarbonisation of this sector must be addressed to achieve net zero, and fission could have an important part to play.

As outlined over the page in figure 7, reactors under development, including molten salt and high temperature gas reactors (HTGR) have the potential to deliver heating to temperatures within the range of demand of the Haber-Bosch process. For the steam methane reformation, an advanced nuclear solution could generate the full demand of steam at 700°C for feedstock, and for heating of the production unit. Using conventional methods to exchange heat from the gaseous or molten salt reactor coolant to a steam generation plant, the process heating can be provided without fossil fuel combustion. The lower temperatures for the Haber reaction can be achieved through similar means. Lower temperature steam could be generated from the same cycle of coolant as it reaches its reactor inlet temperature (around 400°C).

The other major source of emissions from the Haber-Bosch process is the carbon dioxide produced as a by-product of the hydrogen generation. Around 65 per cent of the carbon footprint associated with steam-methane hydrogen production is accounted for in this by-product stream.[22]

Hydrogen made through electrolysis is currently prohibitively costly for industry. Advanced nuclear reactors open the possibilities of high-temperature steam electrolysis (HTSE). HTSE takes advantage of the much higher efficiency of electrolysing high temperature steam as opposed to water.

Commercialisation of HTSE must overcome challenges relating to expected equipment degradation, lifetime and associated costs. However, recent research and demonstration suggests that operating electrolysers with steam in the intermediate temperature ranges (around 600°C) could improve thermal efficiencies by 30-50 per cent, resulting in significantly reduced costs per unit hydrogen produced.[23] Nuclear powered hydrogen production by HTSE could be one of the cheapest sources of decarbonised hydrogen, even competing with the cost of steam-methane reforming with CCS.

Advanced nuclear technologies therefore offer pathways to fully decarbonising one of the world's most energy and emissions intensive industrial processes.

FIGURE 6

Advanced nuclear and SMR supports multiple pathways for decarbonisation of industrial heat

Source: Minerals Council of Australia.

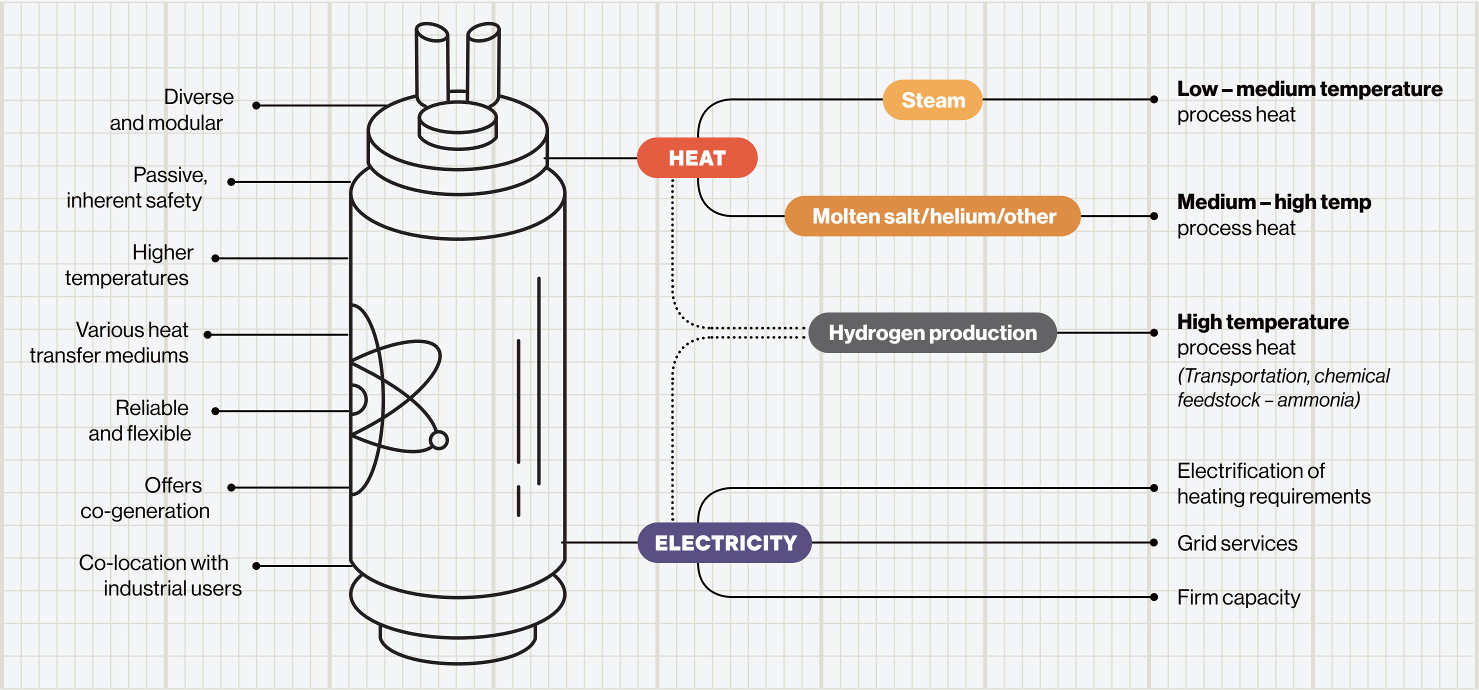
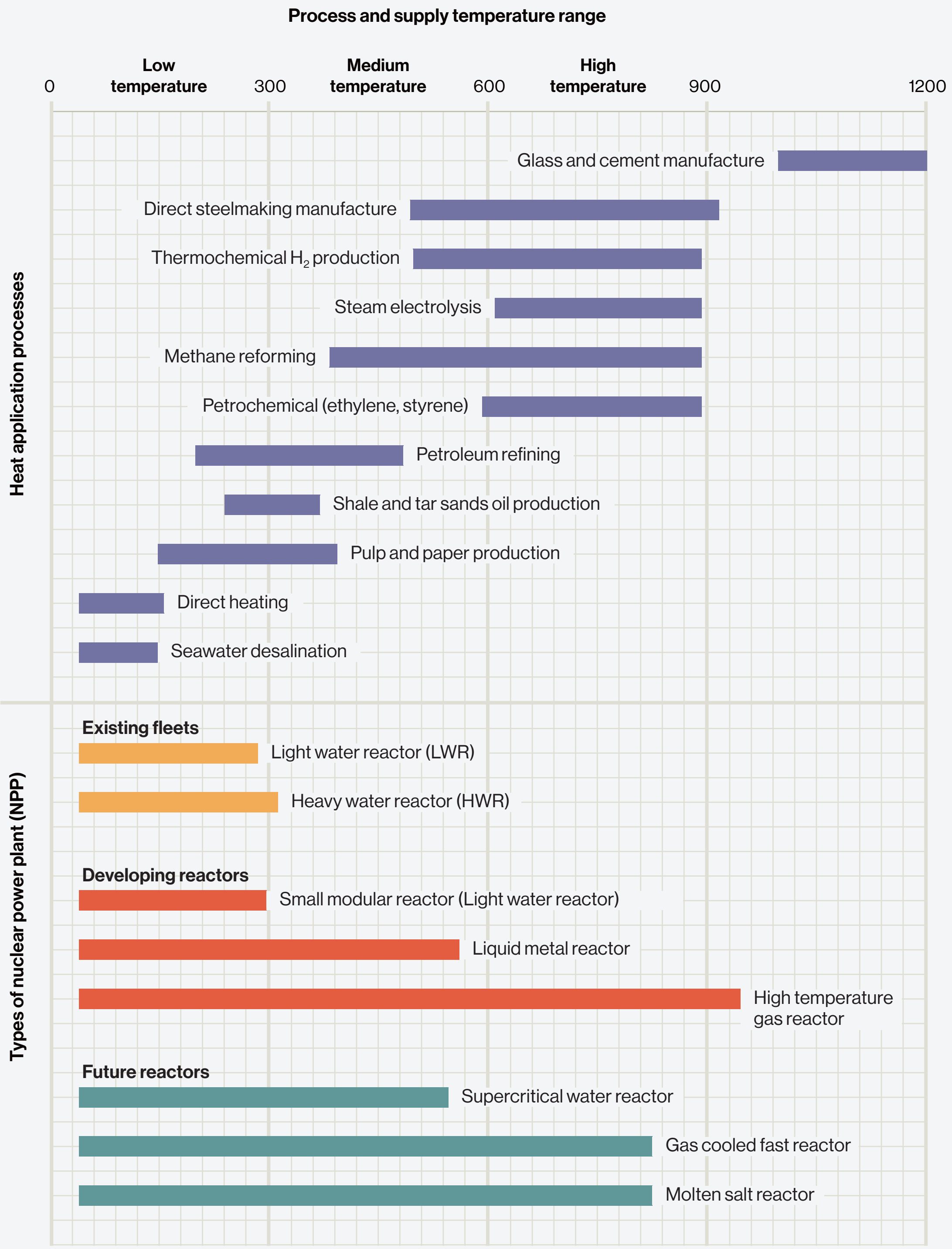


FIGURE 7

Temperature ranges of heat application processes and types of nuclear plant sources

Source: World Nuclear Association, 'Nuclear Process Heat for Industry', September 2021.



Conclusion

Fission can play a central role to decarbonise industry.

Across decades of discussion of climate change, decarbonisation and achieving net zero emissions, the specific challenges of decarbonising industrial heat requirements have been disproportionately neglected. This is despite the sector being responsible for more emissions than cars, presenting vastly greater technical and commercial challenges than decarbonisation of electricity supply, and providing the most essential and foundational materials of modern life, from the food we eat to the homes we live in.

A dispassionate appraisal of global literature quickly reveals why this sector is difficult to decarbonise. With a wide diversity of needs, applications, locations and scales, all solutions must be in play. Among the available solutions, the family of advanced nuclear and small modular reactors is unique. It is the only solution that can bring reliable heat directly to industry at virtually any scale, in virtually any location. It can do this while also supporting other essential decarbonisation pathways, such as electrification and large-scale hydrogen production, and contribute much needed stability and resilience to the electrical grid. Its implementation demands only a fraction of the vast expansion of transmission networks that Australia is deploying. Its energy density requires a relatively small land footprint and provides certain and lasting employment opportunities in towns and cities.

Advanced nuclear fission and SMRs do not provide a silver bullet to the challenge of decarbonisation of industrial heat. Neither does electrification, renewables, hydrogen or combustion of fossil fuels with CCS. A clever, all-of-the-above, integrated portfolio of these solutions stands the best chance of delivering on this challenge, and the multiple benefits of fission suggest it will play a central role.

While partner and competitor nations are advancing these portfolios in partnership with industry, Australian industry remains constrained by exclusionary technology policy. This is at odds with Australian commitments to net zero emissions. It fails to fully activate Australian industry in the development of fit-for-purpose solutions in which they can confidently invest. Australia needs to approach the decarbonisation of industrial heat more seriously. That means commencing the processes needed to apply the power of fission to this difficult to decarbonise sector.

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November 2023

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