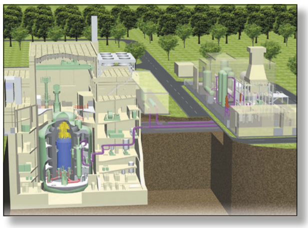
Nuclear Technology Development and Economics
2022

High-temperature Gas-cooled Reactors and Industrial Heat Applications



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Nuclear Technology Development and Economics

High-temperature Gas-cooled Reactors and Industrial Heat Applications

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Foreword

In order to achieve a carbon-neutral economy and society, the decarbonisation of the industrial sector, which accounts for more than a quarter of global energy-related carbon dioxide (CO_2) emissions, is an unavoidable challenge. The industrial sector requires a large heat supply at high temperatures, and the lack of commercially viable low-carbon technology options at present makes this challenge difficult to overcome. The high-temperature gas-cooled reactor (HTGR), which is one of the Generation IV nuclear technologies, can generate high-temperature heat that could be used for industrial applications on a large scale and its technical maturity is based on over half a century of development and the operational experience of several experimental and commercial-scale demonstration reactors.

This report presents the results of a Nuclear Energy Agency (NEA) study on the potential and limitations of HTGRs for industrial heat applications. It reviews the technical features and the development status of HTGRs as a low-carbon heat source and discusses how this technology could meet the process heat requirements of different industrial processes. The primary focus of the study is on the potential industrial applications of HTGR heat in the next decade or so, but it also looks at opportunities beyond that. The report discusses the remaining challenges, limitations and recommendations for the practical industrial deployment of this technology.

Acknowledgements

This report was prepared by Hiroyuki Goto, from the Nuclear Energy Agency (NEA) Division of Nuclear Technology Development and Economics (NTE), based on literature reviews, expert interviews, and the discussion in the NEA Workshop on High-temperature Reactors and Industrial Heat Application on 7 October 2021. Management oversight and additional input was provided by the Head of NTE Division, Diane Cameron, and Chief Energy Economist Jan Horst Keppler (NTE). Additional reviews and input were provided by members of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC).

Valuable comments and contributions were provided by Dr Michael Fütterer (European Commission Joint Research Centre), Dr Hiroyuki Sato (Japan Atomic Energy Agency), Dr Bronwyn Hyland and Mr Brandon Eifler (Suncor).

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List of abbreviations and acronyms

CCUS	Carbon capture, use and storage
CO_2	Carbon dioxide
GIF	Generation IV International Forum
HALEU	High-assay low-enriched uranium (fuel)
HTGR	High-temperature gas-cooled reactor
HTSE	High-Temperature Steam Electrolysis
HTTR	High Temperature engineering Test Reactor
IAEA	International Atomic Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JAEA	Japan Atomic Energy Agency
LOFC	The Loss of Forced Cooling (Project)
NEA	Nuclear Energy Agency
NGNP	Next Generation Nuclear Plant (project)
R&D	Research and development
PRPPWG	Proliferation Resistance and Physical Protection Working Group (GIF)
SAGD	Steam-assisted gravity drainage
TRISO	Tri-structural isotropic (fuel)
US DOE	United States Department of Energy
VHTR	Very high-temperature reactor

Executive summary

High-temperature gas-cooled reactors (HTGRs) could be a technical solution for industrial sector decarbonisation

The decarbonisation of the industrial sector, which accounts for around a quarter of global energy-related carbon dioxide (CO_2) emissions, is crucial to achieving carbon neutrality. However, this sector is recognised as one of the "hard-to-abate" sectors because it requires a large amount of high-temperature heat supply, which is currently provided by the burning of fossil fuels. Low-carbon technologies that are available as alternatives have so far been challenged by considerations of cost and commercial competitiveness.

The high-temperature gas-cooled reactor (HTGR) is a helium-cooled graphite-moderated nuclear fission reactor technology, using fully ceramic fuels, and one of the advanced nuclear technologies currently under development. With its projected capability to provide a stable supply of heat of around 550°C and above on a large scale, it could be a practical option for decarbonising industrial heat sectors while contributing to the security of supply through diversification of energy sources.

The HTGR has over a half century of development history including operating experience of several experimental reactors and commercial-scale demonstration reactors. Its flexible features in output size, operation (including cogeneration) and deployment address various requirements from multiple industrial heat consumers. From a nuclear safety perspective, modern HTGRs can be designed such that they rely on the inherent safety characteristics of Tri-structural isotropic (TRISO) coated fuel particles, a graphite moderator and helium coolant, which enable self-stabilisation of reactor power at a very low level and passive removal of decay and residual heat in the event of an accident. TRISO fuel maintains robust confinement of radioactive materials, and the reactor temperature does not rise steeply during an accident due to a low reactor power density and a large thermal capacity of the graphite core structure. This results in the reactor core temperature staying below the maximum acceptable temperature for the fuel without relying on operator intervention or external power supply for several days to over a week after an accident. These enhanced safety features have been proven through various analyses and experimental demonstrations.

HTGR heat could be applied to various industrial sectors and the availability of steam pipeline systems would provide the nearest-term opportunity for HTGR heat application

This Nuclear Energy Agency (NEA) report explores potential applications of HTGR heat in different industrial sectors. The ease or difficulty of applying HTGRs in each industry sector is primarily determined by the process temperature, system compatibility, and plant energy demand size. From the perspective of process temperature and system compatibility, applications based on steam pipelines for their heat supply are considered as the nearest-term opportunities for HTGR heat. Such applications include district heating, seawater desalination, bitumen recovery from oil sands, chemical complexes, and soda ash production. These applications could be decarbonised rather quickly by replacing existing fossil fuel-fired steam boilers and cogeneration plants with HTGRs in cogeneration mode. Other applications could be added at a later stage and require further efforts to integrate HTGR heat supply, such as significant process redesign or development of new technologies. From the perspective of plant energy demand size, the scalability and the capability for combined heat and power operation of HTGRs enable this technology to meet a range of size and performance requirements for industrial customers. This aspect also allows HTGRs to benefit from economies of series through a fleet approach.

The potential of HTGRs for industrial decarbonisation will be maximised by the development of advanced low-carbon hydrogen production methods and very high-temperature reactor (VHTR) technology

Aside from the nearest-term opportunities for HTGR heat application, HTGR heat can be used for conventional hydrogen and ammonia production process by natural gas reforming, albeit with some engineering efforts in process modifications. However, the contribution of this method to CO_2 emissions reduction is limited to 15-30% due to process-related emissions that cannot be addressed by energy source substitution. Therefore, while overall impact could be reduced as hydrogen and ammonia replace fossil fuels in the industrial and transport sectors, significant amounts of carbon emissions will remain given that the demand for hydrogen, ammonia, and synthetic fuels as alternative low-carbon fuels for transport and industries is expected to dramatically increase in the future. A more thorough decarbonisation of hydrogen and ammonia production could be achieved by using HTGR heat and electricity for advanced low-carbon hydrogen production methods, e.g. High-Temperature Steam Electrolysis (HTSE) or thermo-chemical cycles. Although these approaches are currently under development or at the stage of demonstration, they are expected to achieve higher energy efficiency for producing hydrogen than low-temperature electrolysis, which relies on electricity alone. For the longer term, the development of very high-temperature reactor (VHTR) technology, which generates core outlet temperatures of over 950°C and provides high-temperature helium of over 900°C for industrial processes, would further increase efficiency and competitiveness of hydrogen production using high-temperature nuclear heat.

Challenges and recommendations for HTGR deployment for industrial heat applications

Despite its technical maturity and potential contribution to reduce carbon emissions from industrial heat sectors, no HTGR has been connected to an industrial process for this purpose and the technology has yet to demonstrate its practical applicability. The reasons for this lie mainly in the availability of cheap fossil fuels and insufficient incentives to reduce carbon emissions. This is currently changing and HTGRs may be brought into the centre of the debate, recognising the technology as an effective means for decarbonisation of industrial applications. However, there are still some challenges for industrial players to develop and deploy HTGRs for industrial heat applications.

1. *Site or process-specific analysis and demonstration of the coupling of HTGRs to industrial processes*

In recent years, some industries have begun to take an interest in HTGR technology as an alternative heat source for decarbonising their industries, but uncertainty over a range of issues has deterred them from taking further steps. These include uncertainties in the compatibility with their existing processes and facilities, the cost and time to deployment, and regulatory implications. While there are many existing studies on the performance of HTGRs, further technical, economic and regulatory feasibility studies on the whole system, taking into account the coupling and co-location of HTGRs with real industrial processes and installations, will help industry remove these uncertainties and fully quantify the applicability and benefits of this technology. The planning and execution of demonstration projects using actual facilities will be the most convincing avenue towards deployment of nuclear cogeneration technology with HTGRs. Engagement with the national nuclear regulator at an early stage of the project planning will also contribute to the successful completion of such projects by clarifying regulatory implications and licensing pathways.

2. *Communication and collaboration between industrial players from different sectors, as well as a wide range of stakeholders*

To tackle the challenges outlined above, it is necessary to involve a wider range of stakeholders. From a technical and operational perspective, co-operation between nuclear technology developers, potential nuclear operators and interested industrial heat users is essential to understand the potential interaction between nuclear energy and industrial facilities, and to design and evaluate the overall system.

Unlike in the typical case of nuclear installations for power generation, HTGRs for industrial heat applications must be physically connected to industrial facilities and located relatively close to industrial and, sometimes, residential areas. This implies the need for engagement with wider stakeholders to gain public understanding and acceptance of this nuclear application. Along with ensuring the highest levels of nuclear safety and environmental protection, the development of effective public communication about the advanced safety features of HTGRs, their applications in industry and their societal benefits, such as contribution to climate change mitigation, energy security, and national and local economies, are recommended.

3. *Clarification and co-ordination of regulatory scheme*

The jurisdictional scope and boundary requirements of nuclear and related industrial regulations with regard to the connection of HTGRs to industrial processes will provide the basis to develop concrete system configurations and business schemes. The establishment of such a regulatory scheme requires interactions between regulatory authorities in nuclear and relevant industrial sectors, as well as interested industrial players. Engagement of relevant industrial and regulatory bodies from an early stage of the project planning will contribute to the effective development of industrial schemes and system configurations to successfully complete such projects.

4. *Development of a HALEU fuel supply chain in a timely manner*

Ensuring the availability of high-assay low-enriched uranium (HALEU) fuel, which has uranium enrichment levels between 5% and 20%, is another important issue. All major commercial HTGR concepts currently proposed rely on HALEU fuel. The demand for HALEU fuel is expected to increase from the mid-2020s and reach a considerable level thereafter, reflecting the growing interest in advanced nuclear reactors and accident-tolerant fuels for conventional light water reactors. At present, HALEU fuel is not produced in sufficient amounts to allow for large-scale HTGR deployment and the development of HALEU fuel supply capacity, including enrichment, reconversion, transportation, and fabrication, is crucial to support the future development and deployment of HTGRs and other advanced nuclear technologies. There is also currently limited knowhow and production capacity of HALEU fuels in NEA member countries. This capacity development requires not only a significant upfront investment, but long years of work, including regulatory certification, e.g. the acquisition of additional HALEU enrichment capacity takes several years or more from the proposal of a plan to the start of production. Therefore, clear prospects regarding both the wide adoption of such advanced nuclear reactor technologies and the availability of HALEU fuel are necessary to reduce market risks and uncertainty and encourage private investment.

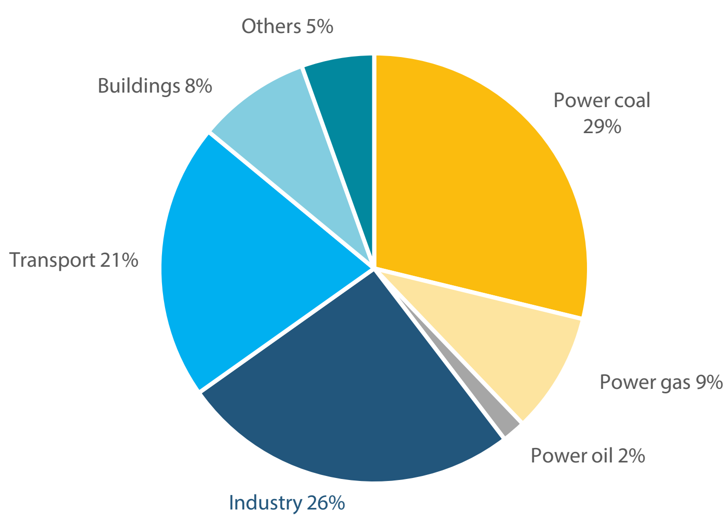
5. *Governments' commitment to decarbonisation policy and the provision of predictable and effective incentive schemes*

As with many innovative decarbonisation technologies, the development of industrial heat applications for HTGRs requires long-term efforts and significant investment. The development of supply chains, in particular for HALEU fuel availability, also requires significant upfront investments and would need to be configured in a comprehensive and timely manner. In addition to building proper regulatory frameworks, governments can encourage industrial sectors to engage in development and deployment of this deep decarbonisation technology by improving the stability and predictability of the business environment. Due to the lack of technical and market experience of the HTGR industrial heat application, combined with the high capital costs and long asset lifetime associated with nuclear projects in general, governmental commitment to risk reduction is thus essential for the private sector and investors to engage in such projects. At a more practical level, market schemes and subsidy programmes to support low-carbon technologies will play an important role in providing industry with some visibility of potential future revenues from these technologies.

Chapter 1. Background

The Intergovernmental Panel on Climate Change (IPCC) Special Report *Global warming of 1.5°C* published in 2018 (IPCC, 2018) established that achieving carbon neutrality by 2050 should be a shared goal worldwide. The energy sector is responsible for almost three-quarters of global greenhouse gas emissions. Despite the rapid growth of low-carbon power generation technologies, such as solar and wind power, and electric vehicles that have emerged in the last decade, there exist significant gaps in achieving carbon neutrality; nations will be required to increasingly decarbonise electricity grids and electrify more and more economic activities. Additionally, they need to reduce carbon dioxide (CO_2) emissions from sectors that are difficult to electrify, such as industries that require high-temperature process heat. The industrial sector, which accounts for approximately one-quarter of global energy-related carbon emissions (Figure 1.1, IEA, 2021), is considered to be one of the hardest-to-abate sectors, due to its need for high temperatures and large-scale heat supplies, highly competitive market situation, and longer asset life. Today, many heavy industries rely on combined heat and power from fossil energy sources.

Figure 1.1: **Global energy-related CO_2 emissions by sector, 2020**



Notes: Emissions from industry sector include process emissions.

Source: IEA, 2021.

Nuclear power, along with hydropower, has been contributing to reducing CO_2 emissions in the energy sector since the first nuclear power plants began operating in the mid-twentieth century, and it will continue to do so in the future. Indeed, nuclear power has been the largest low-carbon electricity source in advanced economies. Beyond power generation, nuclear technology can also be used as a low-carbon process heat source. Over the past few decades, nuclear cogeneration has been performed in many countries. Examples include seawater desalination, paper and cardboard manufacturing, heavy water production, and salt refinement, where nuclear reactors have been providing a heat source up to around 150°C. The high-temperature gas-cooled reactor (HTGR), one of the advanced nuclear reactor technologies currently under development, can typically produce 700°C[1] or higher reactor outlet temperature, which could expand the range of applications for low-carbon nuclear heat and contribute to deep decarbonisation of industrial heat sectors (NEA, 2021).

This report aims to explore how HTGR technology could be implemented in the field of industrial process heat supply, with a focus on the more immediate possibilities in the next decade or so. For this purpose, Chapter 2 will provide an overview of the technological features of the HTGR as an industrial process heat source and their current development status. Chapter 3 will discuss potential industrial applications of HTGR heat in the near term. Chapter 4 will present the remaining challenges for a large-scale industrial deployment of this technology. Finally, Chapter 5 will summarise the key findings and recommendations for policymakers to advance the development and deployment of HTGRs for industrial heat applications.

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1. Some of the HTGR concepts being pursued in the private sector have core outlet temperatures lower than 700°C. One example is shown in Table 2.1, Chapter 2.

Chapter 2. An overview of HTGRs for industrial heat supply

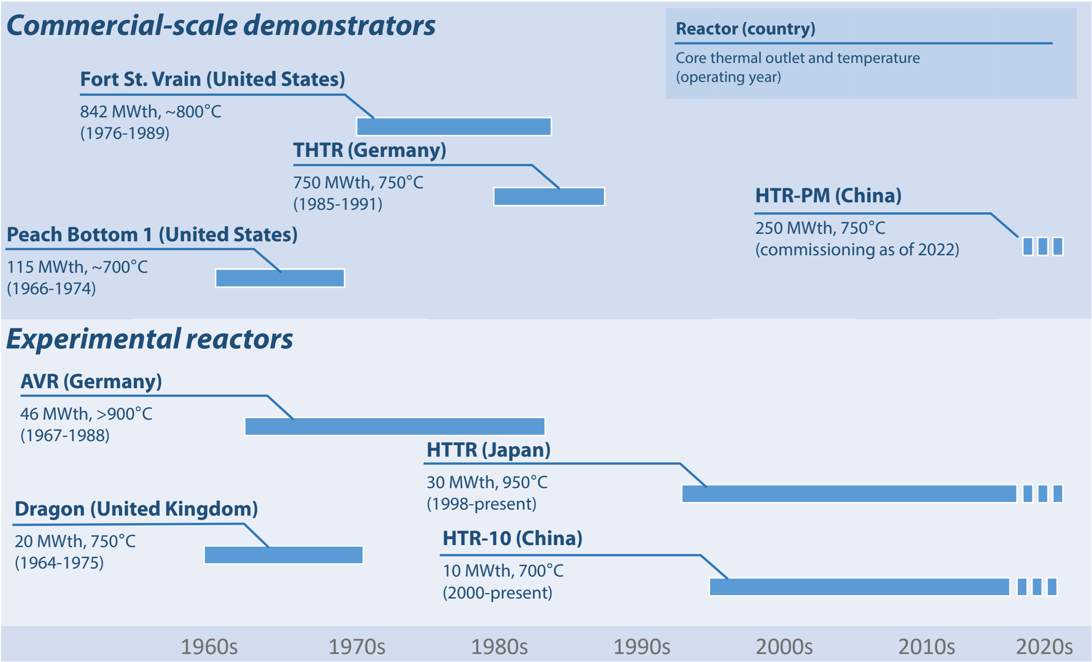
2.1. Definition and history of HTGRs

The high-temperature gas-cooled reactor (HTGR) is a helium-cooled graphite-moderated nuclear fission reactor technology that uses fully ceramic fuels. It is characterised by inherent safety features and excellent fission product retention in the fuel and graphite compared to conventional nuclear reactor technology (GIF, 2020).

As the name suggests, its reactor outlet temperature, typically between 750°C and 950°C, is significantly higher than that of conventional nuclear reactors; for example, a standard outlet temperature for pressurised water reactors is around 320°C. This high output temperature not only increases the conversion efficiencies of power generation, but also expands opportunities for using nuclear heat as industrial process heat at a higher temperature range that is difficult to reach by conventional nuclear reactors. In the longer term, the operating temperature could reach upwards of 950°C. Such reactors, however, will require the use of new structural materials (GIF, 2020).

The first HTGR was proposed in a 1945 design study in the United States. In the 1960s, experimental HTGRs emerged in the United Kingdom, the United States, and Germany, followed by commercial-scale demonstrators in the United States and Germany, reactors that operated from the mid-1970s to early 1990s. Operating experiences and design improvements are reflected in the two experimental HTGRs that are currently operating in Japan and the People's Republic of China . These reactors have been demonstrating stable operation and system safety performance without any significant technical problems (Fütterer et al., 2021; Beck and Pincock, 2011).

Figure 2.1: **Operating history of HTGRs**



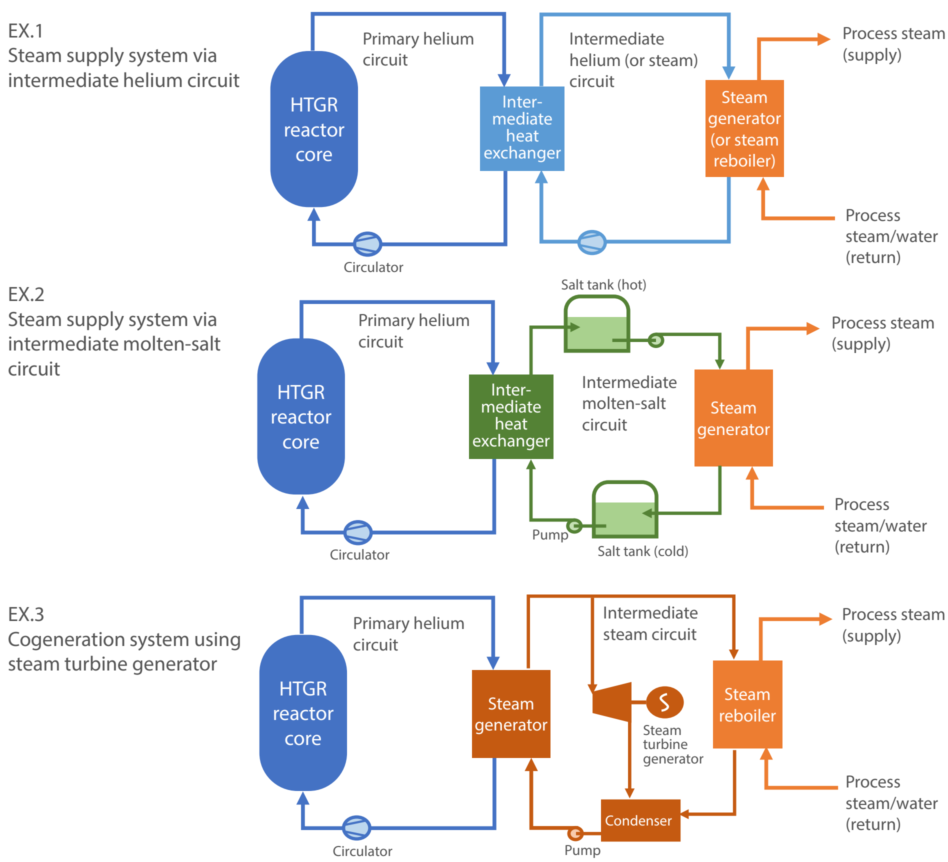
Source: Beck and Pincock, 2011; CNNC, 2021.

2.2. **Technical characteristics of HTGRs**

2.2.1. ***Heat supply capability***

HTGRs can supply high-temperature nuclear heat that can be used not only for power generation but also for industrial process heat. In the currently proposed HTGR concepts for early deployment, the typical core outlet temperature ranges from 600°C to 750°C. The heat is then transferred via intermediate heat exchangers or steam generators to the secondary heat medium, which transfers the heat to external applications such as power generation and industrial processes (Figure 2.2). The temperature and pressure of the secondary heat medium depends on the system design and nature of the heat medium, ranging from 550°C to around 700°C (Table 2.1). Aside from these reactors proposed for commercial use, the High Temperature Engineering Test Reactor (HTTR), an experimental reactor in Japan, operates with an outlet temperature of up to 950°C and secondary heat temperature of up to 900°C. The output sizes of the HTGRs can be flexibly designed up to 625 megawatts thermal [MWth] for block-type reactors and 250 MWth for pebble-bed reactors[1] (Fütterer, 2021). Most concepts are modular in design and offer the installation of multiple units to increase scalability and operational flexibility. Figure 2.2 shows examples of proposed system configurations where heat is delivered in the form of steam.

Figure 2.2: **Examples of HTGR system configurations for industrial process steam supply**



1. There are two types of core assemblies in HTGRs. The pebble-bed type contains fuel particles compacted into graphite spheres (pebbles) which form the reactor core. In the hexagonal block-type assembly, the fuel particles are compacted into cylinders (compacts) and inserted into graphite blocks that constitute the core. The pebble-bed type is characterised by on-line refuelling capability, while the block-type can achieve higher power output (Kunitomi et al., 2002; Gougar, 2019; GIF, 2020).

Table 2.1: **Technical specifications of different HTGR design concepts**

Reactor design	SC-HTGR	GTHTR300C	HTR-PM	Xe-100	MMR®	U-Battery	(Test reactor) HTTR	(Test reactor) HTR-10
Reactor thermal output (MWth)	625	600	250	200	15	10	30	10
Primary reactor coolant	Helium 750°C 6.0 MPa	Helium 950°C 5.1 MPa	Helium 750°C 7.0 MPa	Helium 765°C 6.0 MPa	Helium 630°C 3.0 MPa	Helium	Helium 850-950°C 4.0 MPa	Helium 700°C 3.0 MPa
Intermediate heat medium	Steam 560°C 16 MPa	Helium 900°C 5.15 MPa	Steam 567°C 13.25 MPa	Steam 565°C 16.5 MPa	Molten salt 560°C 0.5 MPa	Nitrogen or helium 710°C	Helium 775-905°C 4.1 MPa	---
Fuel type	TRISO fuel	TRISO fuel	TRISO fuel	TRISO fuel	TRISO fuel	TRISO fuel	TRISO fuel	TRISO fuel
Fuel material and enrichment	UCO 15.5%	UO_2 and MOX 14.3%	UO_2 8.5%	UCO 15.5%	UO_2 9-13%	UO_2 <20%	UO_2 3.4-9.9%	UO_2 17%
Core assemble type	Block	Block	Pebble-bed	Pebble-bed	Block	Block	Block	Pebble-bed
Design life	80 years	60 years	40 years	60 years	20 years	30 years	~ 20 years (operation time)	20 years
Refuelling cycle	18-24 months	18-24 months	Online refuelling	Online refuelling	No refuelling	N/A	---	Online refuelling
Plant footprint (m^2)	10 000 m^2	63 000 m^2 (4 reactor modules)	43 000 m^2 (for 12 reactor modules layout)	131 000 m^2 (for 4 reactor modules layout)	12 000 m^2	350 m^2	60 000 m^2	13 000 m^2
Development status	Conceptual design	Basic design	Commissionin g	Basic design	Basic design	Conceptual design	Operating	Operating
Designer	Framatome Inc.	JAEA	Tsinghua University	X-energy LLC	USNC	U-Battery	JAEA	Tsinghua University
Country	United States	Japan	China	United States	United States	United Kingdom	Japan	China

Source: IAEA, 2020; GFP, 2019; Mulder, 2019; U-battery, 2022; Venneri, 2019; Yan et al., 2018; Yan, 2017.

2.2.2. *Nuclear reactor safety features*

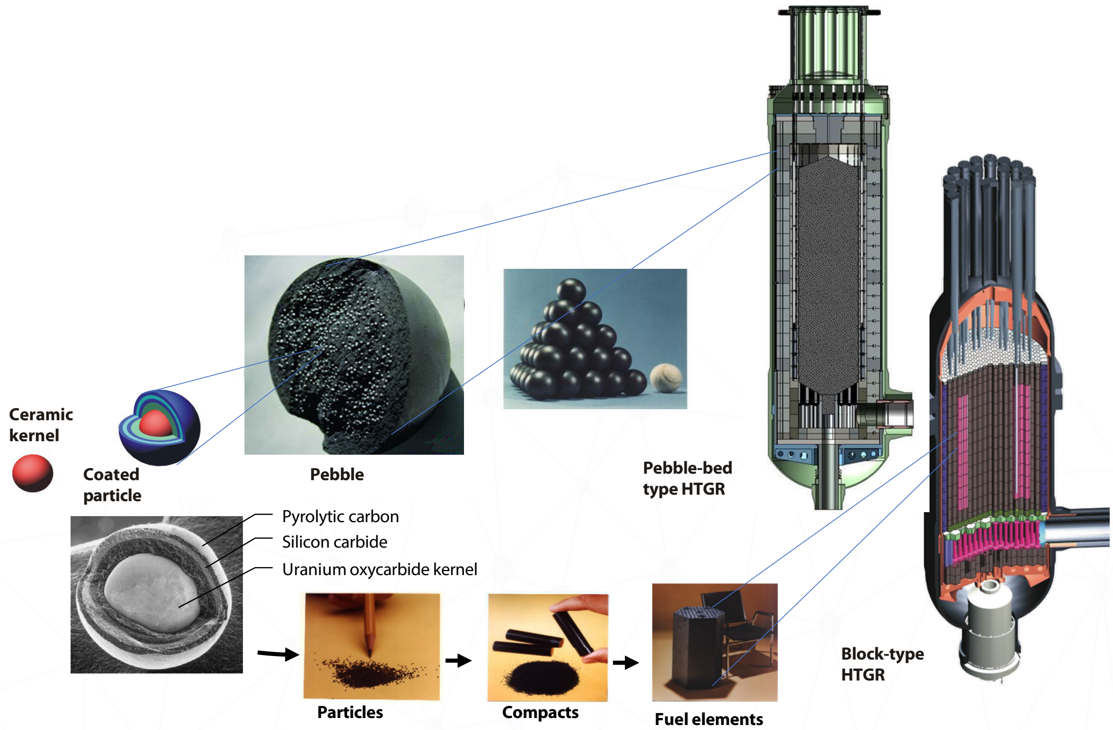
The enhanced safety features of HTGRs can be represented as follows (Ball, 2014; Fütterer et al., 2021; Gougar, 2019; Sato, 2021; Strydom, 2013; NIRO, 2021):

- **Passive safety features**: HTGRs rely on tri-structural isotropic (TRISO) coated fuel particles (Figure 2.3) with enhanced thermal resistance and confinement performance, a graphite moderator with large thermal capacity and heat transfer properties, and a chemically inert helium coolant. The combination of these features enables passive removal of decay and residual heat to the air in the event of an accident without equipment actuation or operator action, which could reduce the probability of transients with core melt conditions.
- **Reduced reliance on operator action in accident response**: Due to the low reactor power density and high thermal capacity of the graphite core structure, the reactor temperature rise after an accident is slow and the system ensures a long grace period,[2] typically more than several days or a week.
- **Robust confinement of radioactive materials in nuclear fuels**: TRISO-coated particle fuel has a high thermal resistance capable of confining the fission products to between 1 600°C and 1 800°C (latest developments). Then the reactor core can be designed such that the maximum accidental temperature in the core never exceeds the maximum acceptable temperature for the fuel.

2. Grace period is defined as the margin of time after an accident before reactor operators are required to intervene.

These enhanced safety features have been proven through various analyses and experimental demonstrations in several reactors, most recently in the Loss of Forced Cooling (LOFC) project. The LOFC project, using Japan's HTTR, has demonstrated that a loss of all functions for neutron reaction control and reactor cooling during reactor operation does not result in a serious accident or release of radioactive material (JAEA, 2022).

Figure 2.3: **TRISO-coated fuel for pebble-bed type and block-type HTGRs**



Source: Gougar, H.D., 2019.

2.2.3. *Technical maturity*

During its development over more than half a century, HTGR technology has improved, reflecting the operational experience in seven experimental and demonstration reactors. For example, TRISO fuel technology was developed based on experience with a former type of particle fuel used to operate experimental HTGRs, and its reliability has been proven through the operation of a commercial-scale demonstrator (Fort St. Vrain) as well as currently operating HTGR type research reactors (NRC, 2019; Beck and Pincock, 2011). Other examples include the magnetic bearing for helium circulators and the steel pressure vessel, which reflect operating experiences of past HTGRs and have demonstrated their reliability in operating experimental or demonstration HTGRs (NRC, 2019; Beck and Pincock, 2011). There are few significant research and development (R&D) issues left for new technology development, and remaining issues are mainly on design-specific details and on coupling technology. Therefore, the focus of current R&D activities is on licensing support and demonstrating future industrial applications and economic viability (GEMINI+, 2021; Hittner, 2017; Fütterer, 2021). These activities are being undertaken under international co-operation programs, such as the Generation IV International Forum (GIF) and the GEMINI+ initiative (see details for Section 2.4).

2.2.4. *Radioactive waste management*

The distinctive features of HTGR radioactive waste management, as compared to conventional nuclear reactors such as light water reactors, relate to the management of spent TRISO fuel and irradiated graphite waste.

As discussed above, the coating of TRISO fuel particles provides a stable and robust barrier that confines fission products within the fuel particles. This allows for long-term storage of spent TRISO fuels and their eventual disposal in a geological repository using metal or concrete casks, as is the case with spent fuel from light water reactors (IAEA, 2010; Sumita et al., 2003a). The challenge with this direct disposal method is its large disposal volume, which mainly derives from the graphite matrix and moderator associated with the fuel elements and accounts for more than 90% of the total volume (IAEA, 2010). These graphite components can be separated by core design and head-end treatment, minimising the volume of spent fuel to dispose of. TRISO fuel could also be reprocessed after appropriate head-end processes to separate the uranium oxide fuel kernels from the carbonaceous material of the coatings and from the matrix graphite. Although the basic technologies have already been established, further technological development is required for practical application in a hot cell[3] environment (Kiegiel et al., 2022; Fütterer et al., 2010; Sumita et al., 2003a).

Among other radioactive wastes that will be generated during the life cycle of an HTGR, including operation and dismantling, irradiated graphite waste derived from fuel elements or graphite moderator elements requires specific consideration due to its large volume and the long half-lives of some of the radionuclides it contains.[4] Since the radioactivity level of irradiated graphite waste from HTGRs can be kept relatively low by appropriate design and operation of the technology, such waste could be treated and decontaminated and then either handled as low-level radioactive waste and disposed of in near-surface repositories or be recycled (Kiegiel et al., 2022; IAEA 2010; Sumita et al., 2003b). With respect to volume, some preliminary studies suggest approximately 3 000 cubic metres (m^3) of irradiated graphite waste would be generated from 60 years of life cycle of a 600 MWth class block-type HTGR (Greneche and Szymczak, 2006; Kunitomi, 2016). Irradiated graphite waste is also generated from other types of nuclear reactors using a graphite moderator and, to date, over 160 000 m^3 of irradiated graphite waste has accumulated worldwide in interim storage facilities awaiting treatment and/or disposal (IAEA, 2016). Thus, in countries with accumulated irradiated graphite waste, efforts have been conducted to develop disposal facilities as well as treatment methods for the reduction in volume and re-use of graphite waste (Fuks et al., 2020).

2.2.5. *Nuclear non-proliferation and security*

Alongside nuclear safety and environmental protection, non-proliferation and nuclear security have been considered requirements in the use of nuclear energy, to be ensured at the highest level. The GIF Proliferation Resistance and Physical Protection Working Group (PRPPWG) has been working on the assessment of non-proliferation and security features of the Generation IV reactor systems, including HTGRs. Since 2017, this expert working group has been updating its initial white paper on this topic released in 2011 (GIF, 2022). As of the writing of this report, the PRPPWG said this about the proliferation resistance of HTGRs:

> [A]s a general remark, it is noted that one has to process some metric tons and tens of cubic meter quantities of TRISO fuels in order to obtain a significant quantity of nuclear material, using either grind-leach or burn-leach of electrolysis in nitric acid whose technology is still not matured at industrial level. In addition, high burnup of the spent fuel of both [HTGR] designs is also one of key proliferation resistance features due to higher order plutonium isotopes that produce decay heat and high dose rate. (Cheng et al, 2021)

3. Hot cell means shielded radiation contaminant chamber.
4. In particular, C-14 (5 730 years of half-life) and Cl-36 (3.01 × 105 years of half-life) determine the very long-term radioactivity of irradiated graphite waste.

With regard to safeguards activities, pebble-bed and block-type HTGRs have several different features due to their different fuel forms. According to the PRPPWG:

> International safeguards for [block type HTGR] can adopt item counting like [light water reactors (LWRs)]. All movements of fuels are observed by surveillance cameras. Fresh fuel storage and spent fuel storage are sealed after fuel movement. Fuel inventory in the reactor core is verified by fuel flow monitoring with radiation detectors. One of the main differences compared to LWRs is the absence of water in reactor cores. Therefore, conventional Cherenkov camera observation by [International Atomic Energy Agency (IAEA)] inspectors is not applicable.
>
> For [pebble-bed type HTGR], on the other hand, its safeguards are considered to be quasi-bulk type: No identifiers are present on pebbles. The pebbles that have achieved a predetermined burnup are discharged through discharge tubes and are led to containers in the discharge compartment as spent fuel pebbles. Diversion of Pu might be possible by using this continuous fuel loading system and discharging fuel pebbles early from the reactor core before significant buildup of even-massnumbered Pu isotopes. However, that kind of activity would be detected by adequate Containment and Surveillance (C/S) measures by IAEA safeguards. (Cheng et al, 2021)

For nuclear security features, this working group states that:

> In term of physical protection, as was mentioned in proliferation resistance, terrorists need to steal metric tons of spent fuel blocks/pebbles. The subsequent reprocessing of these spent fuel would require substantial effort in order to get a significant quantity of Pu. In addition, Pu with a high concentration of even-mass-numbered Pu isotopes, such as ^{240}Pu, ^{242}Pu and even ^{238}Pu, would not be suitable for [nuclear explosive device] fabrication; however this would provide radiological targets for theft.
>
> In case of radiological sabotage targeting power excursion, [HTGRs] are designed to achieve passive safety by the nature of its fuel that maintains the fuel temperature below fuel-damaging threshold in normal operations and even in severe accidents, including beyond-design-basis events. The consequence of using [HTGR] fuel by terrorists in Radiological Dispersal Devices (RDDs) is mitigated by the fact that the diffusion of fuel particles would be limited by their weight compared to that of finer bulk materials such as powder and liquid. (Cheng et al, 2021)

2.3. Potential benefits of HTGRs in industrial heat supply

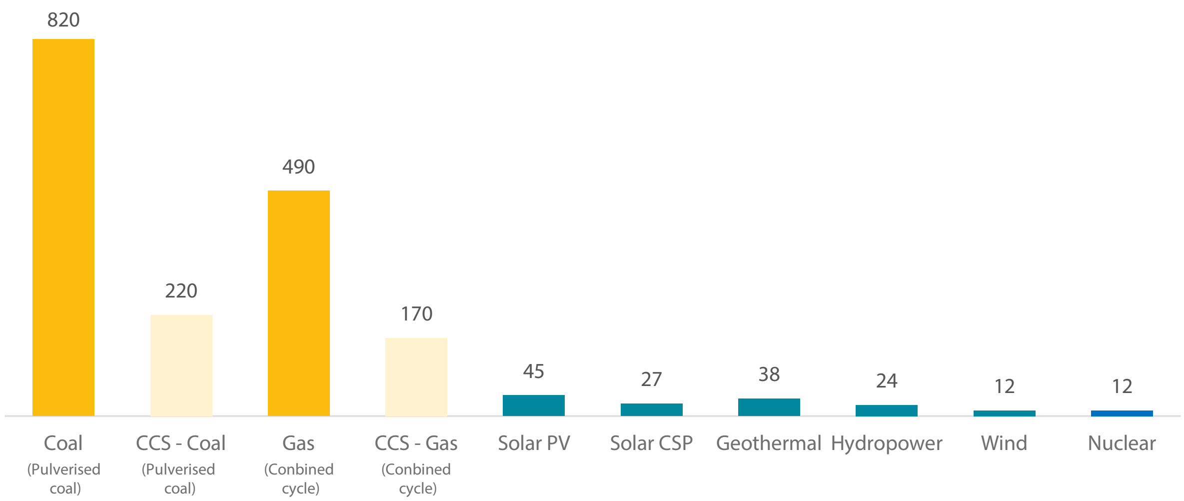
HTGRs could provide a number of benefits in energy supply for industrial sectors with the following features:

- **Low-carbon energy source**: Nuclear energy is one of the lowest greenhouse gas emitting technologies currently available.[5] Therefore, the use of HTGRs has the potential to contribute to the reduction of fossil fuel use and associated carbon emissions, not only through power generation but also process heat supply.
- **High-temperature heat supply**: HTGRs can supply heat to industrial processes in the high-temperature range. Typical HTGR concepts that are currently proposed for early deployment offer approximately 550°C to 700°C process heat. For such high-temperature heat supply, there is no low-carbon technology that can be widely deployed for industrial processes on a commercial scale today (ICEF, 2019).

5. Although many studies of greenhouse gas emissions of nuclear power plants are conducted for conventional technologies, Koltun, Tsykalo, and Novozhilov (2018) suggest that the life-cycle emissions of HTGRs are comparable or in some cases even lower than those of conventional nuclear plants.

- **Reliability and flexibility of heat supply**: Like conventional nuclear power plants, the HTGR is resilient to external conditions such as weather and can operate reliably over long periods of time. Depending on the design concept, the HTGR can operate flexibly to meet the heat demand through power control, and dynamic switching between heat, power, and thermal storage (Sadhankar, 2019; IAEA, 2020; GFP, 2019).
- **Security of supply**: Regarding fuel resources, although there is a challenge in developing capacity for mining of uranium ore and producing uranium fuel with an enrichment level above 5%[6], uranium reserves are estimated to be abundant (NEA/IAEA, 2020). The relatively stable uranium supply and the small share of fuel costs in operating costs could contribute to the security of supply and avoid large energy cost fluctuations.[7] This would also enhance energy security through the diversification of energy sources.[8]
- **Flexible deployment**: Since currently proposed HTGRs have a smaller footprint than conventional nuclear reactors and do not require a reliable water source for core cooling in the event of an accident (as discussed in Section 2.2.2), geographical constraints for installation are much smaller than those for conventional nuclear power plants (IAEA, 2020). Some HTGR designs are also scalable in multi-unit installations (NEA, 2021).

Figure 2.4: **Life cycle CO_2 emissions in g/kWh of different electricity sources**



Source: IPCC, 2014.

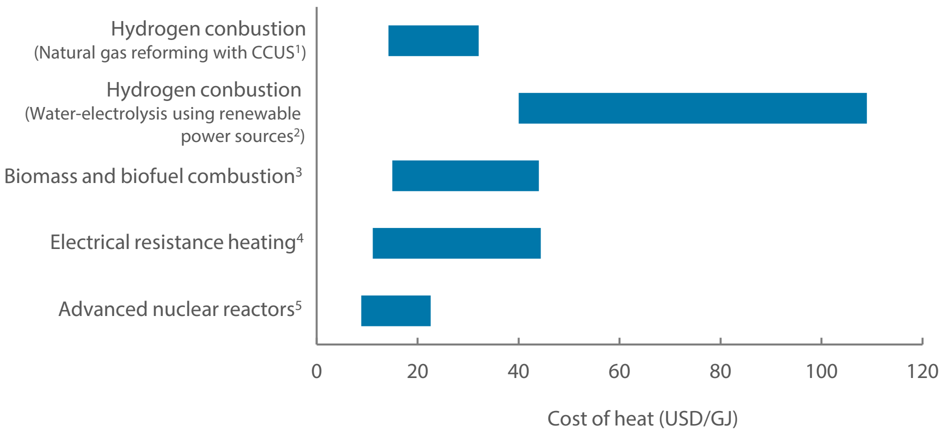
2.4. Costs of HTGRs in industrial heat supply

Although there is limited information on the cost estimation of industrial heat supply from HTGRs compared to the electricity generation of nuclear power plants, some analyses suggest there are, under certain conditions, some cost advantages over existing fossil fuels and other alternative heat sources. A study by the Committee for Analysis and Preparation of Conditions for Deployment of High-Temperature Nuclear Reactors in Poland estimates, while providing a relatively low discount rate (4%), that the cost of process heat from 165 MWth small modular HTGRs may be comparable to that of natural gas boilers, assuming a CO_2 price above EUR 20 per tonne (Wrochna, 2017). For micro modular HTGRs, the Economic and Finance Working Group of

6. The issue related to HALEU fuel production capacity will be discussed later in the Chapter 4.
7. According to IEA (2021), although there is sufficient potential land availability for bioenergy production, taking into account sustainability constraints, it could raise land-use conflictions without strict monitoring and control of land conversion.
8. In addition to uranium, HTGRs are generally also well-suited to the use of plutonium and thorium in the long run, if required (Fütterer, 2021).

the SMR Roadmap in Canada suggests that 10 or 20 megawatts electricity [MWe] micro-modular HTGRs for off-grid cogeneration for remote mining sites and communities could be competitive against conventional diesel, assuming CAD 60 per tonne CO_2 (Canadian Small Modular Reactor Roadmap Steering Committee, 2018). The Next Generation Nuclear Plant project (NGNP) Industry Alliance in the United States has estimated that process heat from an HTGR would be competitive at natural gas prices above USD 6-8 per MMBtu with no CO_2 emissions cost (INL, 2010). As an example, an analysis that compared the potential cost of HTGRs against other low-carbon heat sources, Columbia University carried out a general cost estimate in the United States of low-carbon heat sources for industrial application (Friedmann, Fan and Tang, 2019). This study suggests that while there is a large uncertainty due to the inexistence or immaturity of commercial-scale application of these technologies, the delivery cost of heat by advanced nuclear reactors, including HTGRs, could be lower than other low-carbon heat sources (Figure 2.5).

Figure 2.5: **General cost estimation of low-carbon heat source by Columbia University, 2019**



Notes: 1. Natural gas cost and CCUS capture rate are assumed to be USD 3.5/MBtu and 89%, respectively. 2. Renewable energy includes hydropower, wind power and solar PV. 3. Biomass includes wood and biofuels. 4. Electricity price is assumed to be USD 40-120/MWh. 5. “Advanced nuclear reactors” means Generation IV reactors including HTGRs.

Source: Friedmann, 2019.

2.5. National and international programmes for HTGR development

The potential of HTGRs for decarbonising industrial sectors continues to gain interest. As of 2022, China is completing the commissioning of two HTR-PM pebble-bed reactors (CNNC, 2021). At the same time, countries including the United States, United Kingdom, Canada, Poland, and Japan pursue national programmes to support the development of HTGRs for industrial heat applications, with the aim to demonstrate commercial HTGRs by the late 2020s or early 2030s. Some of these programmes have already selected reactor types or construction sites. At the point of writing this report, Xe-100 (X-energy) has been selected for the United State Department of Energy (US DOE) Advanced Reactor Demonstration Program, which aims to demonstrate the technology by 2027. The reactor will be located at the Columbia Nuclear Generating Station in the United States (X-energy, 2022). In Canada, MMR® is in stage three of four of the reactor selection process in the SMR Demonstration Project at the Chalk River site of Canadian Nuclear Laboratories, which aims to start operation in 2026 (GFP, 2021).

A detailed plan to couple HTGRs to industrial process applications as part of these demonstration projects has not yet been developed. However, the GEMINI+ initiative (2017-2020), an international partnership activity aiming to prove the industrial feasibility of nuclear high-temperature cogeneration, has proposed a design basis of HTGRs co-generating electricity and heat to industrial facilities (GEMINI+, 2021), with the plan to build a test reactor in Poland. A follow-up international joint activity is being planned by the “Sustainable Nuclear Energy

Technology Platform" (SNETP) in Europe with a focus on the licensing and demonstration of cogeneration applications of HTGRs. In Japan, heat application tests using the HTTR and planned for the late 2020s (Sato et al., 2021), will deliver further insight into the technical feasibility of coupling HTGRs with industrial installations. The Generation IV International Forum is an international collaborative research initiative for developing technology for very high-temperature gas-cooled reactors (VHTRs) through multilateral collaborative research as well as hydrogen production using high-temperature nuclear heat (GIF 2022).

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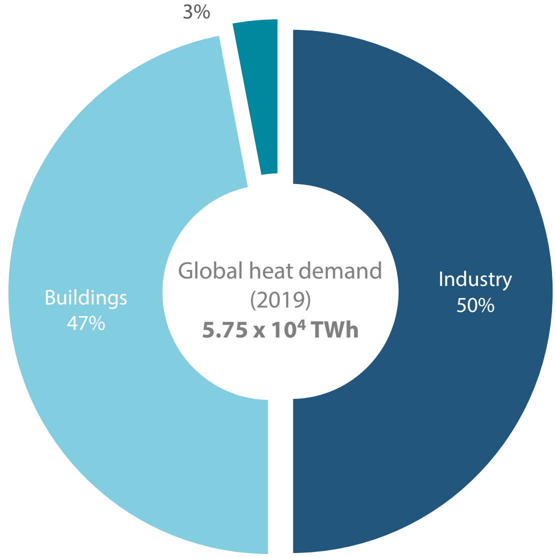
Chapter 3. **Potential industrial applications of HTGR heat**

The previous chapter provided an overview of the technological features of high-temperature gas-cooled reactors (HTGRs). This chapter will discuss a number of possible applications of this technology and explore which industrial sectors have the potential to apply HTGR heat in the near-term horizon.

3.1. **Key aspects of potential markets for HTGR heat application**

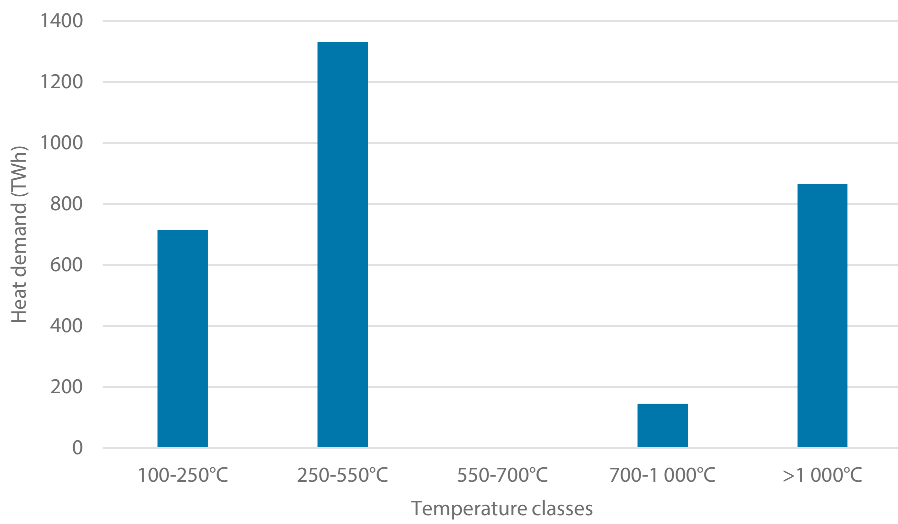
Global heat demand has been steadily increasing and has reached 207 exajoules (EJ) (5.75 x 10^4 terawatt-hour [TWh]), accounting for half of global final energy consumption (IEA, 2020). Industrial heat represents about 50% of total heat demand in 2020, around 90% of which depends on fossil fuels, a significant proportion of which requires high-temperature heat. For example, at the European level, more than three-quarters of industrial process heat demand is estimated to require temperatures above 250°C, more than half of which is in the 250-550°C range (Bredimas, 2012). It implies a huge market potential for HTGRs as high-temperature industrial heat sources.

Figure 3.1: **Global heat demand and distribution by sector**



Source: IEA, 2020.

Figure 3.2: **Distribution of heat demand by temperature class in Europe**



Source: Bredimas, 2012.

The potential application of HTGRs in different industrial sectors is mostly determined by the following factors:

- **Process temperature**: The process temperature of each industrial sector roughly informs the applicability of HTGRs. HTGR heat is uniquely suitable for temperature ranges up to 700°C in the near-term future, as discussed in Chapter 2. For higher temperature processes, further engineering is required, possibly including temperature boost methods and material development and qualification. Otherwise, HTGR heat can be used for preheating of raw materials and intermediate products, which also require appropriate system adaptation.

- **Process compatibility**: The difficulty in applying HTGRs as heat sources also depends on the type of heat supply for each process, i.e. how heat sources can be connected to the industrial processes. If the process heat is supplied via a heat transfer medium coming through steam pipes, HTGR heat can be applied with relatively small engineering modifications, for example by replacing existing steam boilers or cogeneration plants. In contrast, systems in which the heat source is closely embedded in the process will require significantly higher engineering efforts to apply HTGRs as alternative heat sources. Examples can be found in steel making using blast furnaces, production of non-ferrous metals and of ceramics with direct-fired furnaces.

- **Size of energy demand**: The energy demand of an industrial facility or a group of neighbouring facilities should be high enough to justify the deployment of a HTGR. A study carried out in the European NC21-R project (Gradecka, Kiss and Auriault, 2015) indicates that the energy demand of an industrial site in Europe is generally as high as the energy supply of one or more large HTGRs. Such facilities regularly consume more than several hundred megawatt thermal (MWth) of heat and sizeable amounts of electricity, so that relatively large reactors with several modules could be an option. For less energy-intensive industries or remote and isolated locations consuming less than 100 MWth of heat, so-called micro-modular HTGRs may be the better-suited option.

- **Time duration of heat user**: Some of the potential applications of process heat have limited asset lifetimes, such as industries dependent on resource availability. Therefore, it is important that the dedicated HTGR facility lifetime be compatible with the asset lifetime to be connected.

3.2. Potential applications of HTGRs for industrial processes

As mentioned above, the applicability of HTGR heat to each industrial facility depends on the site and process characteristics of the facility, which vary greatly from one facility to another. However, several studies have been conducted that give a general idea of the applicability of HTGR heat for individual industrial sectors. The studies include the Next Generation Nuclear Plant (NGNP) project (2006-2008, United States), the End User Requirement for Process heat Applications with Innovative Reactors for Sustainable energy supply (EUROPAIRS, 2009-2011, Europe), and various other studies on specific application of nuclear heat by the International Atomic Energy Agency (IAEA) as well as academic researchers. The NEA has reviewed these existing studies using the three major factors discussed in the previous section – process temperature, process compatibility, and plant energy demand size[1] – to assess the potential of near-term applications of HTGR heat across different industrial sectors. The following is a summary of the assessment findings.

1) **District heating** (Typical process temperature [same below] 80-150°C) (Bredimas, 2014, 2012; IAEA, 2017; IAEA, 2007)

   There is extensive experience in utilising steam from conventional nuclear power plants for commercial-scale district heating. HTGR steam can be used for this application as well. Energy demand varies depending on the size of the network (from 10 MWth to over 1 000 MWth in Europe). Since heat demand largely varies by season, HTGRs must be combined with other applications (e.g. combined heat and power) in order to achieve sufficient capacity factors. The required temperature is so low as to be supplied by a variety of other proven technologies, such as waste heat recovery, heat pumps, or conventional nuclear reactors.

2) **Seawater desalination** (70-130°C) (Bredimas, 2014, 2012; IAEA, 2017; IAEA, 2007; INL, 2011a)

   Seawater desalination is another sector where cogeneration of conventional nuclear power plants has been used on a commercial scale. HTGR steam can be used for this application as well. A typical desalination plant has a large heat and electricity demand, equivalent to several hundred megawatts thermal or more. The required temperature is so low as to be supplied by a variety of other proven technologies, such as waste heat recovery, heat pumps, or conventional nuclear reactors.

3) **Pulp and paper production** (100-400°C) (Bredimas 2014, 2012; Roudier et al., 2015; Konefal and Rackiewicz, 2008; IAEA, 2017)

   As the majority of the heat demand in pulp production is met by the combustion of process residues and waste heat recovery, there is not much room for the contribution of HTGR heat. HTGR steam could substitute steam supply that covers remaining heat demand, most of which is for the papermaking process. Some engineering consideration would be required to accommodate a large fluctuation of heat demand in this process. The required steam temperature is so low (approximately 150°C) as to be supplied by a variety of other proven technologies, such as waste heat recovery, heat pumps, or conventional nuclear reactors.

4) **Oil recovery from oil sands** (Steam-Assisted Gravity Drainage, approximately 300°C) (INL, 2011b; Konefal and Rackiewicz, 2008; IAEA, 2019, 2017)

   The steam-assisted gravity drainage (SAGD) process injects steam into the oil sands deposits to extract bitumen. Currently, steam is supplied from fuel-fired boilers or cogeneration plants via piping networks, which, as the steam conditions required are greater than 300°C and 10 MPa, could be replaced by HTGRs. A typical SAGD facility has a constant heat demand of several hundred megawatts and can accommodate one or more HTGR units, depending on the reactor concept.

5) **Oil recovery from oil shale** (Approximately 500°C) (Dyni, 2004; INL, 2011c, 2010a; Kang, et al., 2020; Speight, 2020)

1. The aspect of time duration of heat users is excluded here because the situation varied from site to site and it is difficult to assess on an industry basis.

The potential use of HTGR heat in oil recovery processes from oil shales has been studied in both ex-situ and in-situ recovery processes. In the ex-situ oil shale recovery process, oil shale ore is heated in the retort kiln to convert kerogen into shale oil and gas, and heat is provided by the combustion of char. Given the temperatures required for this chemical reaction, high-temperature steam, helium or nitrogen from HTGRs could be used to substitute heat sources. However, this would require a significant redesign of the retort kiln. The heat demand of a commercial-scale plant for this process could reach several hundred megawatts thermal or more, enough to accommodate one or more HTGRs. In-situ oil shale recovery uses steam for heating underground oil shale deposits to convert kerogen into shale oil and gas, which is then extracted. The required steam conditions are in the range of HTGR steam. However, a commercial-scale in-situ oil shale recovery site has not been developed to date due to its economic disadvantage as compared to conventional oil or gas field extraction.

6) **Oil refining** (350-550°C and 600-800°C for catalytic cracking process) (Bredimas, 2014, 2012; Chaugny et al., 2015; Konefal and Rackiewicz, 2008)

The structure of oil refining varies greatly depending on the product mix and the crude oil selected, but in general the energy demand, including heat and electricity, is high enough to accommodate energy supply from HTGR cogeneration. In terms of heat demand, although many processes are within the temperature range that is suitable for HTGR steam, the majority of the energy is provided by the combustion of by-product oil and waste heat recovery and the range that HTGR steam can supply seems limited. The availability of HTGR steam is therefore limited and requires extensive retrofitting of the energy distribution system.

Since oil refineries are large industrial consumers of hydrogen, HTGRs could contribute to decarbonisation of this sector through the supply of low-carbon hydrogen production, which will be discussed later.

7) **Chemicals production** (250-600°C and 800-900°C for naphtha cracking process) (Bredimas, 2014, 2012; IAE, 2020; IAEA, 2017; ICEF, 2019; Konefal and Rackiewicz, 2008; Wrochna, 2017)

The chemical industry has great potential for the use of HTGR heat, especially where different production units are integrated into a large chemical complex. In chemical complexes, energy demand of different chemical production facilities is aggregated, most of which is covered by external steam supply, which is usually lower than 550°C. Considering the suitable steam conditions and availability of existing steam pipe networks, HTGR steam can be used by replacing existing fuel-fired boilers or cogeneration plants. Depending on the site, heat demand is generally expected to be in excess of one or several hundred megawatts thermal, which could accommodate the output of one or more HTGRs.

8) **Soda ash production via Solvay process** (300-400°C) (Bredimas, 2014, 2012; EC, 2007a)

Soda ash production requires a lot of thermal energy for the Solvay process, which is generally supplied by steam from the cogeneration plant via steam pipelines at temperatures below about 400°C. Since the required heat conditions are in the range of HTGRs and existing steam networks are available, HTGRs can substitute the existing cogeneration plants. The heat demand of a typical soda ash plant is a few hundred megawatts thermal equivalent, which is enough to consume the output heat of HTGRs.

9) **Aluminium production** (100-300°C for alumina hydration and 800-1000°C for alumina calcination) (Bredimas, 2014, 2012; Delgado Sancho et al., 2017; IAEA, 2019; Schad, 1992)

The aluminium production process consists of three major steps: 1) aluminium hydroxide extraction from hydration of bauxite ore, 2) alumina production through calcination of aluminium hydroxide, and 3) aluminium metal production through electric reduction of alumina. At 1) the bauxite hydration step, HTGR heat can be used in the aluminium hydration step to heat caustic soda or generate process steam, which requires up to 300°C temperature. For 2) the alumina calcination, applying high-temperature helium from HTGR in combination with electric heating in a fluid bed calciner has been proposed, but it requires significant process modification. 3) The aluminium metal production step is a predominantly electric process, for which the potential contributions of HTGR would be power generation rather than heat supply.

10) **Ammonia production** (Natural gas reforming route, 600-800°C for natural gas reforming and 400-500°C for ammonia synthesis) (Bredimas, 2014; EC, 2007b; ICEF, 2019; INL, 2010b; Pattabathula and Richardson, 2016)

    The major energy-consuming steps in the ammonia production process are 1) hydrogen and nitrogen syngas production and 2) ammonia synthesis. 1) Hydrogen and nitrogen syngas production through natural gas reforming will be discussed later in the next hydrogen section. 2) Ammonia synthesis uses the Haber-Bosch method, which requires temperatures of 400-500°C. Although the process is exothermic, energy input is required to compensate for thermodynamic losses during the process, as well as to drive gas compressors, for which HTGR steam could be used. As waste heat recovery is applied throughout the process, from natural gas reforming to ammonia synthesis, engineering considerations regarding the balance of the heat supply and consumption system will be required to incorporate the heat supply of the HTGR. Although heat demand for high-temperature steam in existing production facilities is not very large (around one hundred megawatt or so), the overall energy demand, including electricity and heat from fuel burning, is equivalent to several hundred megawatts.

11) **Hydrogen production** (Natural gas reforming route, approximately 750°C) (Bredimas, 2014; INL, 2010c, 2010d; Konefal and Rackiewicz, 2008)

    Currently, the vast majority of hydrogen is produced through natural gas reforming, which requires temperatures of approximately 750°C. Given this higher temperature requirement, HTGR heat could be used for preheating input stream entering into reformers. Aside from the preheating approach, helium heated steam reforming using HTGR has been studied since the 1970s, proven and qualified under nuclear conditions though it has not yet been deployed at a commercial scale (Harth, 1990; IAEA, 2013). The typical heat demand of existing hydrogen plants is not very large but the combined heat and power application of HTGR could suit this process. It should be noted that hydrogen is expected to be produced on a large scale as a low-carbon energy carrier in the future, which will expand opportunities for HTGRs to contribute to this sector. Besides, advanced low-carbon routes of hydrogen production are under development and demonstration, which may also provide an opportunity for HTGRs to supply the input energy, as discussed further below.

12) **Lime, glass, cement, ceramics, non-ferrous metal** (800-1 500°C) (Bredimas, 2014, 2012; Delgado Sancho et al., 2017, 2013a, 2013b; IAE, 2020)

    The required process heat temperature in these sectors is much higher than the range of HTGRs. Studies suggest that HTGR heat could be used for preheating raw materials to complement heat supply, but it would still require process redesign, which may be significant in some cases, and the scale of supply may be only partial. A more detailed analysis is needed to understand potential applications of HTGR heat in these sectors.

13) **Iron and steel making** (1 300-2 500°C) (Bredimas, 2014; INL, 2011d; IAE, 2020; Kasahara et al., 2014)

    Conventional steelmaking processes (e.g. blast furnace, direct smelting) are considered impractical to apply HTGR heat because they require much higher temperatures and are incompatible with external steam supplies. Studies suggest that HTGR heat could be used for preheating of air for blast furnace. A future potential application of HTGR in this sector is the supply of hydrogen and heat for direct iron ore reduction. This is currently under development and demonstration in several countries.

Table 3.1 shows potential near-term process heat applications of HTGRs and the temperature window in which heat has to be delivered to them. In most cases, the admissible temperature window of a process is not identical to the temperature window in which a heat source will deliver its heat. This means that for optimum use of the generated heat, cogeneration of more than one energy product is necessary, such as electricity and process steam at different temperatures. For example, a previous German study proposed a system in which the thermal energy of helium gas at 850°C produced in HTGRs is consumed in three different processes of alumina production in order of temperature requirement: 1) an alumina calcination, 2) steam production for power generation and 3) a molten salt heating for bauxite reduction, with helium gas inlet temperatures of 850°C, 680°C and 419°C respectively (Schad, 1992). With an HTGR as the heat source, low-temperature processes only make sense as bottoming applications that use waste heat from other high-temperature applications, such as power generation.

In principle, any heat source could be used for any temperature range if considering the thermodynamic options of re-heating and superheating using a variety of temperature boost methods. However, the higher the temperature level (exergy) of the heat source, the lower the required engineering effort, system complexity and cost, and the higher the achievable efficiency, which is why HTGR heat is considered particularly suitable for high-temperature process heat applications.

Table 3.1: **Potential near-term applications of HTGRs in different industrial sectors**

Industry	Typical process temperatures	Possible near-term application	Notes
District heating	80-150°C	"Plug-in"	Existing steam pipelines available Bottoming applications
Seawater desalination	70-130°C	"Plug-in"	Existing steam pipelines available Bottoming applications
Pulp and paper production	100-400°C	"Plug-in"	Specific engineering efforts required (volatile heat load)
Oil sands (SAGD)	Approx. 300°C	"Plug-in"	Existing steam pipelines available
Oil shale (ex-situ retorting)	Approx. 500°C	"Plug-in"	Significant engineering efforts required for main processes redesign (retort kiln)
Oil refining	350-550°C 600-800°C (Catalytic cracking)	"Plug-in"	Specific engineering efforts required (heat system balance)
Chemicals	250-600°C 800-900°C (Naphtha cracking)	"Plug-in"	Existing steam pipelines available
Soda ash production (Solvay process)	300-400°C	"Plug-in"	Existing steam pipelines available
Aluminium production	100-300°C (Alumina hydration) 800-1 000°C (Alumina Calcination)	"Plug-in"	Specific engineering efforts required (heat system modification)
Ammonia production (Natural gas reforming)	600-800°C (Natural gas reforming) 400-500°C (Ammonia synthesis)	Preheating of feedstock	Specific engineering efforts required (heat system modification) Contribution will be limited
		Helium heated reforming	Main processes need to be redesigned (steam reformer), but technology already available
Hydrogen production (Natural gas reforming)	Approx. 750°C	Preheating of feedstock	Specific engineering efforts required (heat system modification) Contribution will be limited
		Helium heated reforming	Main processes need to be redesigned (steam reformer), but technology already available
Lime, Glass, cement, ceramics, non-ferrous metal	800-1 500°C	Preheating of feedstock	Further analysis is required
Iron and steel making	1 300 – 2 500°C	Preheating of feedstock	Further analysis is required

Industries that require a low level of engineering effort to integrate HTGR heat.

Industries that require a middle level of engineering effort to integrate HTGR heat.

Industries that require significant engineering effort to integrate HTGR heat or further analysis.

Overall, for commercially proposed HTGRs the most promising near-term and large-scale application is steam supply (typically 550°C), which is used as a commodity on many industrial sites, both as heat carrier and reactant. The market for this product is considerable in most industrialised countries. Currently, this steam is supplied almost exclusively by fossil fuel-fired boilers or cogeneration plants, thus representing a significant CO_2 abatement possibility. The availability of the existing steam networks and backup capacities also help HTGRs to take part in high-temperature steam supply to these industrial sectors ("plug-in applications"). In this respect, the preliminary assessment confirmed that district heating, seawater desalination, oil sands recovery using SAGD, chemical production, and soda ash production are in the most favourable conditions for near-term applications of HTGR heat. District heating and seawater desalination require only lower temperatures (< 150°C), so these processes could either be used as bottoming applications in cogeneration plants or use other low-carbon heat sources such as conventional nuclear power plants, waste heat recovery, or different types of heat pumps. In terms of higher temperature steam supply, the potential application of HTGR heat to chemical production and oil sands recovery has been studied extensively in Europe and Canada, respectively, due to their large market opportunities in addition to the process compatibilities discussed above. In Europe, chemical production is one of the major consumers of steam with a temperature around 500°C, typically supplied by steam networks (Bredimas, 2014). In many cases, chemical plants in Europe operate in large industrial complexes that form intense steam demand across more than 100 industrial complexes (Fütterer, 2017). For example, in Poland, the top 13 industrial sites receive steam through the steam networks from gas and coal boilers with a total capacity of 6 500 MWth, in which the majority of the sites have around 350 to 850 MWth capacity and one of the largest sites has over 2 000 MWth capacity (Wrochna, 2017). Chemical products manufactured in these sites range from saltpetre to urea, polyamide, hydrogen peroxide and ammonium sulphate (ibid.). In Canada, SAGD is the most popular technique for in-situ bitumen extraction from oil sands. In-situ recovery methods are used to recover bitumen from oil sands deposits at great depths (deeper than 75 metres below ground), which makes 80% of Canadian oil sand reserves accessible (Government of Canada, 2016). The amount of bitumen recovered by the in-situ method was 1.5 million barrels per day (bpd) in 2021 (CER, 2022), and the energy demand for in-situ SAGD facilities with such a level of production is approximately 26 GWth[2]. The estimation includes the total heat demand for the production of steam for extraction and electrical power used on-site for the brownfield production. Due to electricity grid connections and differing facility sizes, asset lives and locations, this is considered a large market opportunity to replace thermal demand with alternative heat sources. Additionally, the production from in-situ bitumen recovery is expected to increase 2.7 million bpd by 2050 (CER, 2022), equivalent to 47 GWth of heat demand.

Ammonia and hydrogen production offer a large potential for the application of HTGR heat in the medium to long-term. Demand for ammonia and hydrogen as storable energy carriers is expected to grow significantly. In a conventional natural gas reforming route to produce ammonia or hydrogen, the HTGR heat could be used for preheating of the feedstock or for a helium heated reforming process, thereby reducing fuel combustion and associated CO_2 emissions. However, this method does not reduce process-related CO_2 emissions, which are derived from the feedstock natural gas and account for about 60% of the CO_2 emissions associated with hydrogen production using natural gas reforming (Muradov, 2015). The process-related CO_2 can be reduced by the introduction of carbon capture, use and storage (CCUS), but the United Kingdom Committee on Climate Change (CCC, 2018) has warned that given the expected performance of CCUS and the significant growth for hydrogen demand in the future, unavoidable CO_2 emissions from CCUS systems could still have a significant impact on climate change. Further opportunities for HTGR heat to contribute to the production of very-low-carbon hydrogen or ammonia through High-Temperature Steam Electrolysis (HTSE) and thermo-chemical cycles routes have been suggested (IAEA, 2013; INL, 2010b, 2010d; NEA, 2010). These processes split water molecules using a combination of heat and electricity. Provided that the source of energy for heat and electricity generation is carbon-free, those processes lead to very low CO_2 emissions. Besides, these advanced processes are expected to achieve higher overall energy conversion efficiency than low-temperature electrolysis route, which is currently in commercial-scale demonstration phase (NEA,

2. According to Canada's Oil Sands Innovation Alliance, a reference in-situ SAGD facility that produces 33 000 barrels of oil (bitumen) per day requires 575 MWth for the heat and electricity for bitumen extraction. By using a simple calculation, 1.5 million bpd of bitumen extraction gives the equivalent of 26 GWth.

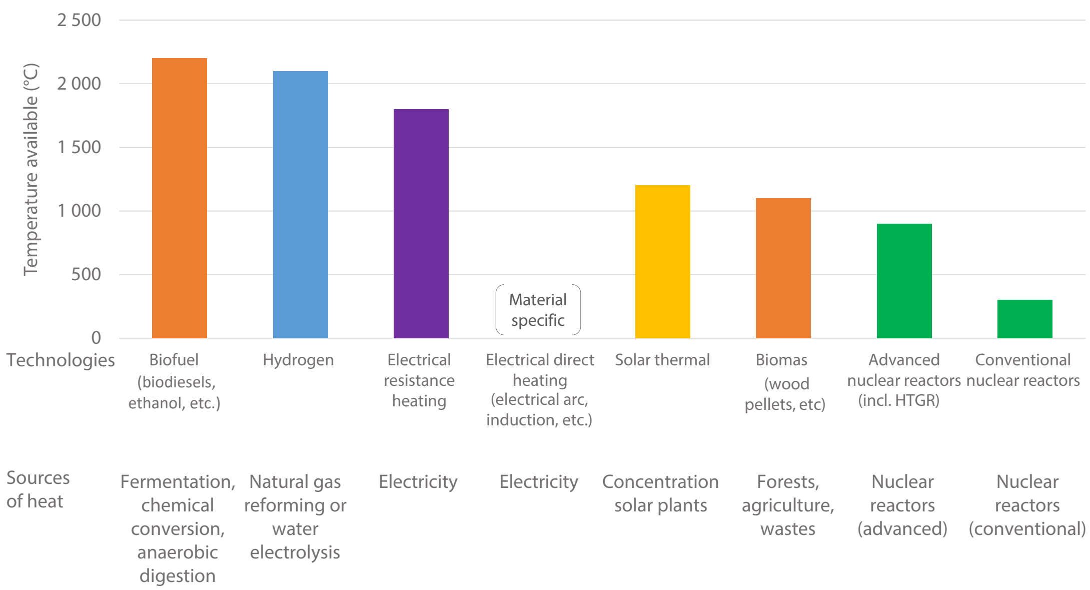
2021). However, HTSE and thermo-chemical cycle routes remain at the stage of technology demonstration and development, respectively, and should be considered as medium to long-term opportunities for HTGR. Since the required temperature for these processes is above 650°C for HTSE and approximately 850°C for thermo-chemical cycles, further development of coupling technology, temperature boost methods or increased reactor outlet temperature would be required.

It should be noted that these preliminary studies are mostly on theoretical applicability and in most cases do not consider site-specific issues, such as structural configuration, geology and topography, licensing and other constraints, and the surrounding social conditions of actual industrial facilities.

3.3. Competitiveness with other low-carbon heat providers

Actual market opportunities for HTGRs as alternative heat sources depend also on the availability of competing technologies. For the temperature range of HTGR heat supply, up to 700°C or 900°C in the future, there are several low-carbon technology options, including fossil fuel boilers with CCUS, bioenergy, concentrated solar thermal, hydrogen and synthetic fuel, and electric heating using low-carbon electricity (Figure 3.3). At the time of writing this report, all of these low-carbon and high-temperature heat supply technologies were still under development and have yet to be commercialised on an industrial scale. The availability and economy of these competing technologies relies on access to the necessary resources at the required large scale, such as cheap low-carbon electricity including renewables, suitable geological conditions for CO_2 storage, and sustainable biomass. Thus, HTGRs will be a more promising low-carbon alternative heat source in areas where access to these resources is limited. As discussed earlier, industries with process temperatures lower than 250°C can be addressed by cogeneration of conventional nuclear reactors. Conventional nuclear cogeneration is a proven technology with over 50 years and 750 reactor-years of operating experience worldwide (IAEA, 2019), and can be considered an already viable option for industrial decarbonisation for this temperature range.[3]

Figure 3.3: **Low-carbon heat technologies and temperature available**



Source: Friedmann, Fan, and Tang, 2019.

3. In all cogeneration applications of conventional nuclear reactors, heat use was only a small fraction of the reactor power and it was mostly used as a bottoming cycle application. The same approach can be applied to HTGRs.

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Chapter 4. Challenges of HTGRs for industrial heat supply

There are many studies indicating the technological maturity of high-temperature gas-cooled reactors (HTGRs) and their potential market opportunities for industrial process heat applications, as discussed in the previous chapters. However, this technology has not yet been rolled out, mainly due to the availability of rather inexpensive fossil fuel, in particular natural gas. This chapter addresses the remaining challenges to overcome before HTGRs can be used for industrial heat applications.

4.1. Ensuring safety of coupling and collocation

As discussed in Chapter 2, HTGRs are equipped with enhanced safety features and their reliability has been confirmed by the satisfactory operating results of several test reactors. In addition to the robustness of the nuclear reactor system itself, when it comes to deploying HTGRs for industrial process heat supply, the specific safety considerations associated with coupling HTGRs to industrial processes must be taken into account in design, licensing and operation.

4.1.1. Avoidance of cross-contamination

This includes preventing unintended infiltration of radioactive substances from the nuclear facility to the industrial facility and that of corrosive or other substances from the industrial facility that could affect the operation or structural integrity of the reactor. In this respect, all HTGR concepts offering potential industrial process heat supply functions propose heat transfer via at least one intermediate heat circuit with intermediate heat exchangers or steam generators/reboilers, which separate the heat distribution line to the industrial process from the primary reactor coolant circuit (IAEA, 2020). This separation, combined with the appropriate implementation of monitoring programmes, can limit or exclude contamination of radioactive, corrosive, or other harmful substances between the nuclear and the industrial plant (Verfondern, 2007; Kunitomi, 2007).

Tritium, which is mainly produced in the reactor core, may permeate the boundary of the intermediate heat exchanger into the secondary circuit due to its small particles. However, tritium contamination of the industrial processes is considered insignificant because most tritium is deposited into the graphite core structure or removed by online coolant purification; no significant tritium contamination has been experienced so far in the operation of district heat supply and desalination using conventional nuclear plants (Fütterer, D'Agata and Raepsaet, 2016; IAEA, 2019; Verfondern, 2007).

4.1.2. Management of thermal disturbance

Fluctuation in the thermal load in the industrial facilities, which is caused by the start-up and shutdown of the processes as well as malfunctions of equipment, could be transferred to the primary coolant circuit of the HTGR. The resulting temperature fluctuations in the primary coolant must be kept within the technical limits for reactor operation. The impact of such external thermal disturbances on the nuclear reactor can be avoided by controlling the primary coolant flow, maintaining a sufficient thermal capacity of the secondary circuit, and installing thermal absorbing mechanisms, such as thermal storage and external heat exchangers (Sadhankar, 2019; Ohashi, 2006; GFP, 2019). Design and HTGR licensing cases need to carefully consider how to isolate impacts to the nuclear island from the industrial facility. If changes in thermal load in the industrial facility impact the nuclear reactor operation and therefore need to be considered or included as part of the nuclear licence, this would greatly complicate the project. Heat storage technologies could be used to separate the nuclear reactor system from thermal disturbances by heat load from industrial sites. Such technologies are currently employed on a commercial scale for concentrated solar power systems up to 600°C, and advanced technologies that could operate with higher temperatures, of 750°C and higher, are under development (Forsberg, Sabharwall and Sowder, 2020).

*4.1.3. **Protection against external hazards***

In order to install HTGRs in close proximity to industrial facilities, appropriate protective measures must be taken to avoid safety-relevant impacts between the conventional and the nuclear facilities. The types and magnitudes of potential hazards depend on the characteristics of the facility or processes, and the choice and design of protective measures must comply with the industrial and nuclear regulatory requirements of respective regions. Thus, site-specific and process-specific analysis and evaluation are essential to understand the technical feasibility of coupling and locating HTGRs close to industrial facilities. For example, the types of potential events considered upon designing the Next Generation Nuclear Plant (NGNP) project in the United States were fires, explosions, vapour cloud releases that could produce fuel air mixtures, hazardous chemical releases, and combustible or toxic material propagation (IAEA, 2017). As another example, Verfondern et al. (2017) and Smith (2006) analysed the potential impact of an explosive cloud from hydrogen production on an HTGR and suggested that a safe arrangement of the HTGR and the hydrogen production facility could be achieved already with a separation distance of about 120-150 metres (m), or less than 100 m when using protective deflector berms against blast and leakage gas migration. In addition, many HTGR designs enable below-grade installation, which would further reduce mutual vulnerabilities.

4.2. **Licensing of coupling and collocation**

The distinction of the jurisdictional scope of nuclear and other industrial regulation over connected and sited facilities, and the clarification of boundary condition requirements between areas under different regulatory jurisdiction, will provide the basis for developing specific system configurations and industrial schemes for the integration of HTGRs into industrial processes. Such a regulatory scheme has not yet been established, but several studies have suggested its future viability. Examples include the work carried out within the NGNP project in the United States, which proposed distinctions and boundary conditions between nuclear-regulated and non-nuclear-regulated areas based on US nuclear regulatory requirements (INL, 2011). Furthermore, locating a HTGR close to the industrial process heat users might require special licensing and engineering considerations. Addressing these issues requires the involvement and co-operation of all relevant government agencies and industrial players, not just those involved with nuclear regulation and operation but also those with conventional industries.

A near-future initiative related to this issue is the Japan Atomic Energy Agency (JAEA) HTTR heat utilisation test, which plans to couple the HTTR with hydrogen production processes in the late 2020s to demonstrate the ability to license such systems (Sato et al., 2021). These experiences of conventional nuclear cogeneration and the result of the JAEA's test project will serve as a benchmark for future licensing activities of coupling and co-location of HTGRs and industrial processes.

4.3. **Other operational requirements**

For the HTGR to become an alternative heat source option for end users, it must meet the heat supply requirements for their processes with a high degree of availability. Typically, large industrial users need heat supplies with close to 100% capacity factor. These high capacity factors are in principle favourable for the use of nuclear power for this purpose both from a technical and economic point of view. They can be ensured by installing or maintaining existing conventional backup capacity or by using multiple units of heat sources (IAEA, 2019). Periodic outages for refuelling, maintenance and inspections on the conventional and nuclear side need to be synchronised in the system design integrating HTGRs and industrial processes. Some HTGR concepts propose online refuelling or entirely avoiding the need to refuel over the lifetime of the reactor (see Table 2.1 in Chapter 2), which means that outages are then mainly dictated by in-service inspection obligations on the nuclear site and similar requirements on the conventional side.

Depending on the end-user application, the heat supply to industrial facilities must be flexible enough to accommodate load change and fluctuations anticipated through normal process operation (IAEA, 2017, 2019; GEMINI+, 2021; Hittner, 2017). HTGRs have a higher degree of flexibility and manoeuvrability than conventional nuclear reactors (Sadhankar, 2019). It is also proposed to apply combined heat and power supply systems or to use molten salt as a secondary heat carrier with a certain storage capacity so that the systems offer flexible process heat output while keeping the reactor power constant (IAEA, 2017; GFP, 2019).

A high degree of system reliability is also essential with regards to investment protection of the end-user facilities. Insurance companies for conventional industrial facilities impose strict constraints and the consequences for a plant coupled to a nuclear reactor would need to be determined, probably on a case-by-case basis. In this respect, for example, the design requirements for the HTGR in the NGNP project, which was developed while taking into account requirements from end-user perspectives, say that the risk of events that would lead to an outage of over six months should be less than 10^{-3} per plant year and the frequency of events that would lead to faulted plant conditions less than 10^{-4} per plant year (IAEA, 2017).

4.4. Cost and schedule predictability

As discussed in Chapter 2, there is limited information available on the costs of construction, operation, and integration into industrial processes of HTGRs. Some leading demonstration projects in the United States and Canada, which aim to start operation in late 2020s (see Section 2.4), will provide important new information about the construction and operation of HTGRs. Given that HTGRs can be flexibly designed (e.g. reactor output scale, cogeneration mode) to meet the size and performance requirements for multiple industrial customers, HTGRs could potentially also cater to larger markets, potentially benefitting from economies of scale.

In addition to cost uncertainties, uncertainties related to the future timeline make it difficult for industrial sectors to include HTGRs as part of their future decarbonisation strategies (Bragg-Sitton, 2021). The major timeline uncertainties include uncertainties about the time required for licensing and construction to integrate HTGRs into industrial processes. According to Hittner (2017), most of the key technologies required for the design and licensing of HTGR heat supply systems, such as materials, equipment structures, fuel design and modelling, are already sufficiently mature to be used in industrial applications. In respect of licensing and construction lead time, the latest case of HTGR construction, HTR-PM in China, was completed within nine years from the start of the construction to the grid connection for commissioning (IAEA, 2020). Some HTGR vendors have proposed HTGR projects with a licensing and construction time of around seven years (GFP, 2019; X-Energy, 2020). However, since so far there is no project involving an HTGR combined with industrial processes that has been licensed by national regulatory bodies, completed and operated, it is not easy to obtain a confident outlook on the time required for the licensing and construction of a HTGR for industrial heat applications.

4.5. HTGR fuel supply chains

Another uncertainty is the future availability of the supply chain. One of the most pressing issues is the development of high-assay low-enriched uranium (HALEU) fuel supply capacity. HALEU fuel has uranium enrichment levels between 5% and 20%. It so far has been used only for limited applications, such as for research reactors and medical radioisotope production (NEA, 2021a). The demand for HALEU fuel, however, is expected to dramatically increase in the coming decades, along with the growing interest in advanced nuclear reactors that rely on HALEU fuel technology (see Box 1). Since HALEU fuel is not produced in sufficient amounts to allow for large-scale HTGR deployment, the development of HALEU enrichment,[1] as well as other supply chain capacity, such as reconversion, transportation, and fabrication, is crucial to support the development and

1. As of the writing of this report, only the Russian Company TENEX provides commercial HALEU enrichment services.

deployment of HTGRs. The US Department of Energy has launched an initiative to ensure the availability of HALEU fuel, including a commitment for Centrus, a US supplier of nuclear fuel and services (currently having the only licensed HALEU production facility in the United States), to demonstrate commercial-scale production by 2022 (DOE, 2021a).

Tri-structural isotropic (TRISO) fuel fabrication has been conducted in Japan and China to supply fuel assemblies for their research and demonstration HTGRs (WNA, 2021; NFI, 2022). Efforts to develop TRISO fuel fabrication capacity on a commercial scale have also been undertaken by companies such as BWXT, Nuclear Fuel Industries, Ltd., X-Energy and Ultra Safe Nuclear Corporation (WNN, 2021a, b, 2020; JAEA/NFI, 2019). Efforts in this area are also undertaken by the United Kingdom and Poland (Arnold, 2021; Sobolewski, 2021), and France has regained interest in the subject.

4.6. Stakeholder acceptance

In order to reduce the heat losses during transportation and the construction costs of transport lines, industrial process heat sources are required to be as close as possible to the heat demand sites, which can sometimes be near population centres. The coupling of the HTGR to industrial processes requires the understanding and mitigation of possible combined hazards from a nuclear reactor with, for instance, a chemical plant. Therefore, efforts have to be made to address potential concerns of using HTGRs, involving wider stakeholder perspectives than those considered for nuclear power plants, which are usually located far from industrial and residential areas and have no physical connection. Along with ensuring the highest levels of nuclear safety and environmental protection, the development of effective public communication about the advanced safety features of HTGRs, their applications in industry and their societal benefits, such as contribution to climate change mitigation, energy security, and national and local economies, will be required (NEA, 2021b).

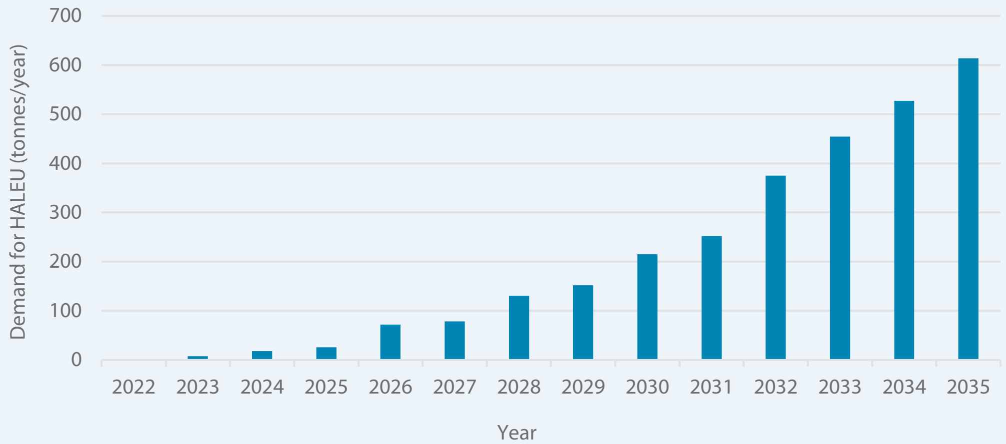
Box 1: Challenges in HALEU fuel availability

HALEU fuel is being considered in many advanced nuclear reactor concepts, including some proposed small modular reactors[2], along with several accident-tolerant fuel concepts for conventional light water reactors. This points already to a potentially rapid increase in demand for HALEU fuels in the coming decades. The Nuclear Energy Institute (NEI, 2021) projected that HALEU demand in the United States and Canada will start to increase from the mid-2020s for some demonstration projects of advanced reactors, reaching around 600 tonnes of uranium per year by 2035 (Figure B.1.1).

Downblending and reprocessing of used research reactor fuels and high-enriched uranium reserves in the United States and Russia could be used for HALEU fuel supply to support some projects in the near term (NEI, 2022). However, due to the limited availability of such uranium resources and the large potential future demand, the development of further HALEU enrichment capacity is essential. The development of HALEU production capacity requires a huge upfront investment and long lead times, several years or more, including regulatory certification (ibid.). Therefore, visibility on both the wide adoption of such advanced nuclear reactor technologies and the availability of HALEU fuel are necessary to reduce market risks and uncertainty and encourage private investment. To address these challenges, the US DOE is creating a new programme to ensure HALEU fuel availability (DOE, 2021). In addition, as the use of HALEU fuels spreads around the world, other nuclear fuel cycle infrastructure, including transport and waste management, may need to be developed and adjusted (NEA, 2021a).

2. Small modular reactors are generally defined as nuclear reactors with electrical power outputs of up to 300 megawatts. Such reactor concepts are of increasing interest due to their technical features, which enhance construction predictability, potentially reduce construction costs and delivery times, and could provide a higher level of safety (NEA, 2021a).

Figure B.1.1: **HALEU demand projection in the United States and Canada**



Notes: Data excludes demand for HALEU with an enrichment of 5%-10%. The demand year is the year in which HALEU is used for fuel fabrication, while insertion into the reactor and reactor operation will take place in a later year.

Source: NEI, 2021.

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Chapter 5. Conclusions

HTGR could be a technical solution for industrial sector decarbonisation through low-carbon heat supply as well as electricity generation

In order to achieve a carbon-neutral society, it is essential to decarbonise the industrial sector, which accounts for about a quarter of global energy-related carbon dioxide (CO_2) emissions. However, the industrial sector is a hard-to-abate sector mainly due to the lack of technology options currently available to meet high-temperature and large-scale heat requirements and the fierce competition in the commodity market. The HTGR is a mature form of technology that could provide a stable supply of high-temperature heat, supported by a long development effort, including the operating experience of several test and demonstration reactors. HTGRs could deliver heat (e.g. 550°C steam or gas at even higher temperatures) and could be flexibly designed to meet different requirements in size and performance for industrial applications (GEMINI+, 2021), which could cover a portion of the heat market and result in a reduction in fossil fuel use and greenhouse gas and other emissions. Studies (Fütterer, 2017; IAEA, 2017) suggest the market size for nuclear heat in this temperature range is of several hundred cogeneration reactors, which points to the potential for HTGRs to gain economy of scale through a fleet approach. With some penalties in efficiency, HTGRs could deliver even higher temperatures of low-carbon process heat by using temperature boost technologies, such as electric heaters and fuel-fired burners. The enhanced safety features and the flexibility in terms of design, operation and deployment enable HTGRs to meet a wide range of operating and site requirements at hundreds of industrial facilities worldwide.

The availability of steam pipeline systems connected to industrial facilities provides the nearest-term opportunities for HTGR heat application

The applicability of HTGR heat in any industrial sector depends on the characteristics of the processes and facilities used, and therefore requires process- and site-specific analysis. This report provides a preliminary assessment of the applicability of HTGR heat to each industrial sector, focusing on the process temperature range, process compatibility, and scale of site energy demand. The results suggest that sectors in which facilities are supported by external steam supply via a pipeline system represent the greatest opportunities for HTGR heat application, with the lowest technological barriers. Such sectors include district heating, seawater desalination, bitumen recovery from oil sands, chemical complexes, and soda ash production. These sectors could be decarbonised rather quickly by replacing existing fossil fuel-fired steam boilers and cogeneration plants with HTGRs in cogeneration mode where part of the nuclear heat is converted to steam and another to electricity or other energy products required on the site. Other sectors could be added at a later stage and require further efforts to integrate HTGR heat supply, such as significant process redesign, development of new technologies, and aggregation of heat demand.

The development of advanced hydrogen production and VHTR technologies could open further opportunities for HTGR heat application for low-carbon hydrogen and ammonia production

Amid efforts to achieve a carbon-neutral society, demand for low-carbon hydrogen and ammonia, as feedstock or energy carriers, is expected to soar in the next few decades; the associated energy demand to produce these commodities will be much larger and concentrated. In a first step, steam produced from HTGRs could reduce the CO_2 intensity of steam methane reforming by about 15-30% (Fütterer, 2021; INL, 2010a). However, given the large amount of remaining CO_2 emissions and the dramatic expected increase in demand for hydrogen, ammonia and synfuel in the future, a more thorough decarbonisation approach is required. This could be achieved by using HTGRs for low-carbon hydrogen production, e.g. using High-Temperature Steam Electrolysis (HTSE) or thermo-chemical cycles, which are currently under development or demonstration. For the longer term, there is potential to use the heat above 900°C that is generated by very high-temperature gas-cooled reactors (VHTRs) to further increase the efficiency and competitiveness of nuclear heat applications.

Further work needed on site- or process-specific analysis and demonstration of coupling HTGRs to industrial processes

Despite many studies indicating the ability of HTGRs to provide industrial high-temperature process heat, no HTGR has so far been connected to an industrial process for this purpose, so it is yet to be demonstrated in practice how this technology can be applied to facilities while ensuring nuclear safety. The reasons for this lie mainly in the availability of relatively cheap fossil fuels and insufficient incentives to reduce carbon emissions (Fütterer, 2021; INL, 2010b). This is currently changing and may bring HTGRs into the centre of the debate, recognising the technology as an effective means for decarbonisation of industrial applications. Discussions at the NEA workshop "High-temperature reactors and industrial heat application" in October 2021 (NEA, 2021) implied that, despite the notion that some industrial players are becoming interested in HTGR technology, uncertainties persist over a range of issues. These include uncertainties in the compatibility with existing processes and facilities, the cost and time to deployment, and regulatory implications, inhibiting industrial players from taking further steps into HTGR demonstration and deployment. Beyond the capacity of HTGRs themselves, technical and economic feasibility studies on the whole system, taking into account the coupling and collocation of HTGRs with real industrial processes and facilities, will help industrial players to clear these uncertainties and fully quantify the applicability and benefits of this technology. These studies need to be updated regularly to account for changes in economic and policy boundary conditions such as soaring fossil fuel prices, climate change mitigation and energy security. The planning and execution of demonstration projects using actual facilities is considered a way towards the roll-out of nuclear cogeneration technology with HTGRs.

Involving a wider range of stakeholders will be key to taking the next steps in development

The above-mentioned challenges cannot be addressed simply by efforts in nuclear technology research and development. Co-operation between experts in nuclear technology and interested industrial sectors is essential to understand the potential interaction between nuclear energy and industrial facilities, and to design and evaluate the overall system. At the same time, in certain countries nuclear-related topics are sometimes sensitive to discuss openly, and there are some industries that may be hesitant to engage in such topics because of the potential adverse impacts on their relationships, including with supply chain partners and local stakeholders. In this respect, research institutes that provide scientific and technological information as well as industrial associations will play an important role in bridging the gap between nuclear experts and individual companies in the early stages by sharing knowledge and possibly discussing specific matters. Needless to say, it is also essential to continue efforts to improve public understanding of the technical features and potential benefits of HTGR technology.

Clarification and co-ordination of nuclear and other industrial regulations is essential to establish a sound industrial scheme of HTGRs for industrial heat applications

The jurisdictional scope and boundary requirements of nuclear and other related industrial regulations with regard to the connection of HTGRs to industrial processes have a significant impact on the system configurations and business schemes. Although some studies have suggested such a connection is feasible with respect to nuclear safety and proposed a potential licensing pathway, there are so far no actual cases that establish a clear regulatory scheme specifically for connecting nuclear heat sources to industrial processes in close proximity. Addressing this issue requires the communication and co-operation of all relevant government agencies and industrial players in a project. Such cross-sectorial engagement from an early stage of the project planning will contribute to the effective development of industrial schemes and system configurations, resulting in the successful completion of such projects.

The timely development of a HALEU fuel supply chain is crucial for HTGR use for industrial applications

The demand for high-assay low-enriched uranium (HALEU) fuel, on which currently proposed commercial HTGRs rely, is projected to start increasing from the mid-2020s and reach a substantial level by 2035 (NEI, 2021), reflecting growing interest not only in advanced nuclear reactors but also in accident-tolerant fuels for conventional light water reactors. However, there is not sufficient supply chain capacity to support such a high level of future demand. Therefore, the development of HALEU fuel supply capacity, including enrichment, reconversion, transportation, and fabrication, is crucial to support the development and roll-out of HTGRs and other advanced nuclear technologies. Given the considerable upfront investment and lead time required to build additional or new HALEU enrichment and other relevant industrial capacities, clear prospects regarding both the widespread use of such advanced nuclear reactor technologies and the availability of HALEU fuel is necessary to reduce market risks and uncertainty and encourage private investment.

Government commitment to decarbonisation policy and the provision of predictable and effective incentive schemes is essential

In addition to building proper regulatory frameworks, governments can encourage industrial sectors to engage in the development and deployment of this deep decarbonisation technology by improving the stability and predictability of the business environment. As the industrial heat application of HTGRs has not yet been demonstrated, it will take a considerable amount of effort and investment over a long period to launch and complete the development of industrial heat applications for HTGRs before it can achieve a sizeable impact. Besides, the limited real market experience of these new applications, the high capital costs generally associated with nuclear projects, and the long asset lifetime of HTGRs and industrial facilities make the decision to invest in this technology difficult. The development of supply chains, in particular for HALEU fuel, also requires significant upfront investment and must be implemented in a timely manner so as not to impede the deployment of HTGRs and other innovative nuclear technologies. For such large long-term infrastructure investments, a government commitment that reduces risk is thus essential for the private sector and investors to engage in such projects. On a more practical level, market programmes and subsidies to support low-carbon technologies will play an important role in providing industry with visibility on the potential revenue to be earned from carbon-neutral technologies.

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High-temperature Gas-cooled Reactors and Industrial Heat Applications

Reducing industrial carbon emissions is one of the most difficult challenges on the path to net zero by 2050 due to the magnitude of greenhouse gas emissions from the industrial sector and technical requirements for heat in addition to power. High-temperature gas-cooled reactors (HTGRs) are a promising Generation IV nuclear technology that can supply process heat for a variety of industrial applications.

The Nuclear Energy Agency investigated the potential and limitations of HTGRs for industrial heat applications. This study reviews the technical features and development status of HTGRs as a low-carbon heat source and explores how this technology could meet the process heat requirements of different industrial processes. It revealed the potential industrial applications of HTGR heat in the near term as well as further opportunities in the medium to long term while identifying the remaining challenges for the industrial deployment of this technology.

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