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SYSTEM ANALYSIS: HYDROGEN PRODUCTION FROM NUCLEAR ENERGY

Collaborative analysis on the opportunity to produce hydrogen through High Temperature Steam Electrolysis using a High Temperature Gas Reactor

May 2025

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Abstract

Hydrogen and Generation IV (Gen IV) nuclear energy technologies have the potential to play a significant role in the clean energy transition. This report aims to explore the commercial readiness and provide a techno-economic analysis of the feasibility and economic cost of low-carbon hydrogen production using high-temperature steam electrolysis (HTSE) coupled with nuclear energy sources, specifically focusing on High-Temperature Gas-cooled Reactors (HTGRs). The report leverages insights from the Generation IV International Forum (GIF) and the Nuclear Energy Agency Working Group on Hydrogen Value Chains.

A common set of modeling inputs and baseline assumptions for a system producing hydrogen through HTSE using a 800 MW HTGR system was developed and shared with multiple international research teams, who then applied their own models and methodologies to estimate the cost and quantity of hydrogen produced. A questionnaire was also distributed to experts in the nuclear energy and hydrogen sectors to seek input on the perceived technical and commercial readiness of this system, and to understand integration challenges.

Table 1: Predicted cost and amount of hydrogen produced from select scenarios.

Model	*LCOH (USD/kgH_2)*	*LCOH with offset from O_2 sales (USD/kgH_2)*	*H_2 produced (kgH2 per year)*
CNL HESO Scenario #1	4.52	3.72	55.6 M
CEA PERSEE model	3.76	3.04	70.7 M
UKNNL literature value [1]	3.53	-	-
UKNNL model	-	-	70.4 M
IAEA HEEP	3.89	3.17	66.8 M

The modeling outputs summarised in Table 1 below suggests that the specified HTGR-HTSE integrated system could produce approximately 66 million kg of H_2 per year at costs ranging from USD 3.04 to USD 3.72 per kg on a levelized basis under baseline assumptions. LCOH values align with previous estimates from the United Kingdom for a first of a kind HTGR system [1]. The CNL HESO model explores additional scenarios beyond the baseline scenario. The expert survey showed that key barriers to integration includes regulatory uncertainty, a lack of sufficient cost data for the systems, the identification of suitable markets, and a need for a demonstration at scale. Advantages for emissions reduction and energy security are also identified.

The opportunity for nuclear hydrogen is particularly strong for applications requiring a large, continuous supply of hydrogen at a single point of consumption. No technical gaps are identified that would prevent this system from operating successfully, but significantly more work is needed to advance the readiness and certainty of an integrated system at the relevant commercial scale. While Light Water Reactors (LWRs) can already support HTSE integration, commercial Generation IV technologies may offer additional benefits and are expected to improve overall efficiency once they reach maturity. To advance commercialization, this report offers recommendations for various stakeholder groups which aim to advance technical readiness, improve cost certainty, and establish commercialisation pathways for hydrogen production from Gen IV nuclear energy systems.

Acknowledgements

This report was drafted by the members of the Generation IV International Forum's Non-Electric and Cogeneration Applications Working Group (NECA WG) in partnership with the Nuclear Energy Agency Working Group on Hydrogen Value Chains (H2 VAL WG). The report was compiled by the GIF Technical Secretariat. All NECA and H2 VAL members contributed to this report, with specific contributions provided by (alphabetical by country after listed Working Group chairs):

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The H2 VAL WG is chaired by both Julie MOUGIN of CEA in France, and Todd Knighton of INL in the United States. The valuable contributions from the H2 VAL WG and its members were essential to inform the analysis and recommendations in this report.

Finally, the scope of work and analysis within the report was informed through engagement with international partners including the International Atomic Energy Agency and the International Energy Agency's (IEA) Hydrogen from Nuclear Energy Task 44. The authors acknowledge the valuable contributions and engagement opportunities available from these networks, and especially to members of Task 44 within the IEA Hydrogen Technology Collaboration Programme.

The industrial facility photo on the cover of this report is used with permission from ThirdWay, as part of their Nuclear Reimagined initiative.

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Table of contents

List of figures

List of tables

List of boxes

List of acronyms

CCUS	Carbon Capture, Utilization, and Storage
EMWG	GIF Economics and Modelling Working Group
GIF	Generation IV International Forum
G4ECONs	GIF EMWG Economic Modeling Tool
HEEP	Hydrogen Economic Evaluation Program
HESO	Hydrogen Energy System Optimization (modeling tool)
HTGR	High-Temperature Gas-Cooled Reactor
HTR-PM	High-Temperature Gas-Cooled Reactor Pebble-Bed Module (China)
HTSE	High-Temperature Steam Electrolysis
HTTR	High-Temperature Engineering Test Reactor (Japan)
IAEA	International Atomic Energy Agency
I-S Process	Iodine-Sulfur Process (thermochemical hydrogen production)
KPI	Key Performance Indicator
LCOH	Levelized Cost of Hydrogen
LTE	Low-Temperature Electrolysis
LWR	Light Water Reactor
NEA	Nuclear Energy Agency
NECA WG	Non-Electric and Cogeneration Applications Working Group (replaces NEANH TF)
NEANH TF	Non-Electric Applications of Nuclear Heat Task Force (precedes NECA WG)
O&M	Operations and Maintenance
PERSEE	oPtimizER for System Energy managEment (modeling tool)
PMB	Project Management Board
PRIS	Power Reactor Information System (IAEA)
SMR	Small Modular Reactor
SOEC	Solid Oxide Electrolysis Cell
TES	Thermal Energy Storage
TRL	Technology Readiness Level
VHTR	Very High-Temperature Reactor
WGNT	Working Group on New Technologies (NEA)

1 Introduction

1.1 The role of nuclear energy in decarbonisation

The decarbonisation of electricity generation alone is insufficient to meet the challenging CO_2 emission reduction targets [2]. Emissions from the industrial and the transportation sectors are higher than the electricity sector, offering significant potential for further reductions through the direct use of nuclear-generated heat or process intermediates that may be produced using nuclear heat and electricity [3].

Nuclear energy has been used for some non-electric industrial applications for several decades, including as a component of early commercial systems such as the Calder Hall Nuclear Power Station which was commissioned in 1956. In recent years these systems have faced strong economic competition, particularly from inexpensive natural gas in the absence of emissions restrictions or carbon taxes. Natural gas prices are highly volatile in many jurisdictions, triggering strong interest in alternatives. Natural gas combined with Carbon Capture, Utilization, and Storage (CCUS) also faces challenges in a future decarbonized world due to lifecycle emissions associated with upstream methane leakage.

Consequently, the economics of nuclear energy systems must be reevaluated to consider new constraints and parameters. The near future will be characterized by a rapid evolution of energy supply strategies to meet increasing worldwide energy demand, while simultaneously taking steps toward life-cycle decarbonization of all energy supply chains and infrastructures.

Hydrogen is expected to play a crucial role in global efforts to achieve net zero emissions, contributing to sustainable and resilient energy systems. There is growing international momentum to scale up low-carbon hydrogen production using low-carbon electricity and heat [4]. Recent demonstration projects that couple nuclear power plants with electrolysers highlight the importance of leveraging historic R&D efforts in nuclear and hydrogen technologies into near-term innovations, thereby accelerating the production of low-carbon hydrogen.

1.2 Generation IV International Forum and the NECA Working Group

The Generation IV International Forum (GIF) is an international research and development effort with a history of cooperation among 13 countries and Euratom representing the 27 European Union (EU) members on advanced nuclear energy systems and make them available for industrial deployment by 2030.

A collaborative research and development project was launched in 2008 under GIF focused on hydrogen production using the Very High Temperature Reactor[3] (VHTR), and a dedicated cross-cutting Task Force was established in October 2021 to address non-electric applications of nuclear energy broadly. This Non-Electric Applications of Nuclear Heat Task Force (NEANH TF) concluded its term in October 2024 when the Task Force was converted into a working group as a permanent entity in GIF. This Non-Electric and Cogeneration Applications of Nuclear Energy Working Group (NECA WG) will build on the success of the NEANH TF which established a baseline knowledge of energy system design, analysis, and tools, and also established a need among GIF member countries to stay engaged in analyzing these systems.

The NECA WG is currently working to advance several initiatives to explore the opportunity for non-electric applications and hybrid systems. Including efforts to highlight relevant system configurations and conduct systems analysis with regard to key performance indicators (KPI). Throughout 2023 and 2024, the NECA WG members identified a range of KPIs of interest and developed methodology to evaluate non-electric and cogeneration systems accordingly, and

[3] In this report, the term "Very-High Temperature Reactor" (VHTR) is used almost interchangeably with "High Temperature Gas Reactor" (HTGR). While the Generation IV program initially focused on VHTR systems, current research and commercialization efforts focus on HTGR concepts broadly with lower outlet temperatures (700-850°C). HTGRs are the focus of the report. Learn more about the Generation IV International Forum at: www.gen-4.org/

quantify or qualify the status of a given system using KPIs, including:

- Technological Readiness Level (TRL),
- Market readiness and timelines,
- License readiness (including safety, regulations, codes/standards, etc),
- Geographic adaptability,
- Greenhouse gas emissions reduction potential,
- Energy availability factor,
- Energy security benefits,
- Economic viability, bankability and investment considerations,
- Supply chain,
- Scalability and ease of integration, including across multiple applications,
- Market size, and
- Sustainability

To evaluate the relevant system according to these KPIs, existing frameworks were leveraged, including the Technological Readiness Level frameworks and the Commercial Readiness Index Framework. Many of the KPIs are to be addressed qualitatively due to the complexity of the indicator, and due to regional differences.

This report has been developed by the NECA WG in cooperation with the NEA Working Group on Hydrogen Value Chains (H2VAL) to advance techno-economic analysis of coupled systems to understand the economic opportunity, readiness, and timelines for these systems. The assumptions and analysis in this report has been established in consultation with experts participating in broader activities within the Generation IV International Forum, including those of the cross-cutting Economics and Modelling Working Group (EMWG), and the Very High Temperature Reactor (VHTR) system.

In particular, this report aims to highlight the significant progress in developing and optimizing high-temperature processes for hydrogen production, and the opportunity for commercial applications. By leveraging existing modeling capabilities and expertise in the NECA WG and NEA H2VAL memberships, the report intends to highlight the importance of integrated system analysis, and the importance of reliability and flexibility in energy systems. The collaborative analysis is also expected to support analysis across similar system analysis approaches among members, and may even support future efforts related to code-to-code validation.

1.3 Why focus on High Temperature Steam Electrolysis and High Temperature Gas Reactors?

In 2002, GIF released the Gen IV Roadmap [5] which identified the following six Gen-IV reactor concepts as a focus area for cooperation under GIF: gas-cooled fast reactor, lead-cooled fast reactor, molten salt reactor, sodium-cooled fast reactor, supercritical water-cooled reactor, and very-high-temperature reactor.

The Very-High-Temperature Reactor (VHTR) features higher operating temperatures than High Temperature Gas Reactors (HTGRs) and the concept was originally envisioned by GIF to be suitable for integration with high-temperature hydrogen production or industrial process heat applications such as chemical processing facilities and petroleum refineries. The VHTR technology benefits from the operational feedback of 40 Gas Cooled Reactors and 7 HTGRs (He cooled) gained in 5 different countries.

Through a system arrangement focused on VHTR technologies, the GIF has been collaborating to advance the VHTR system. The VHTR system research involves four active projects: VHTR fuel and fuel cycle, VHTR materials, VHTR hydrogen production, and VHTR computational methods validation and benchmarks.

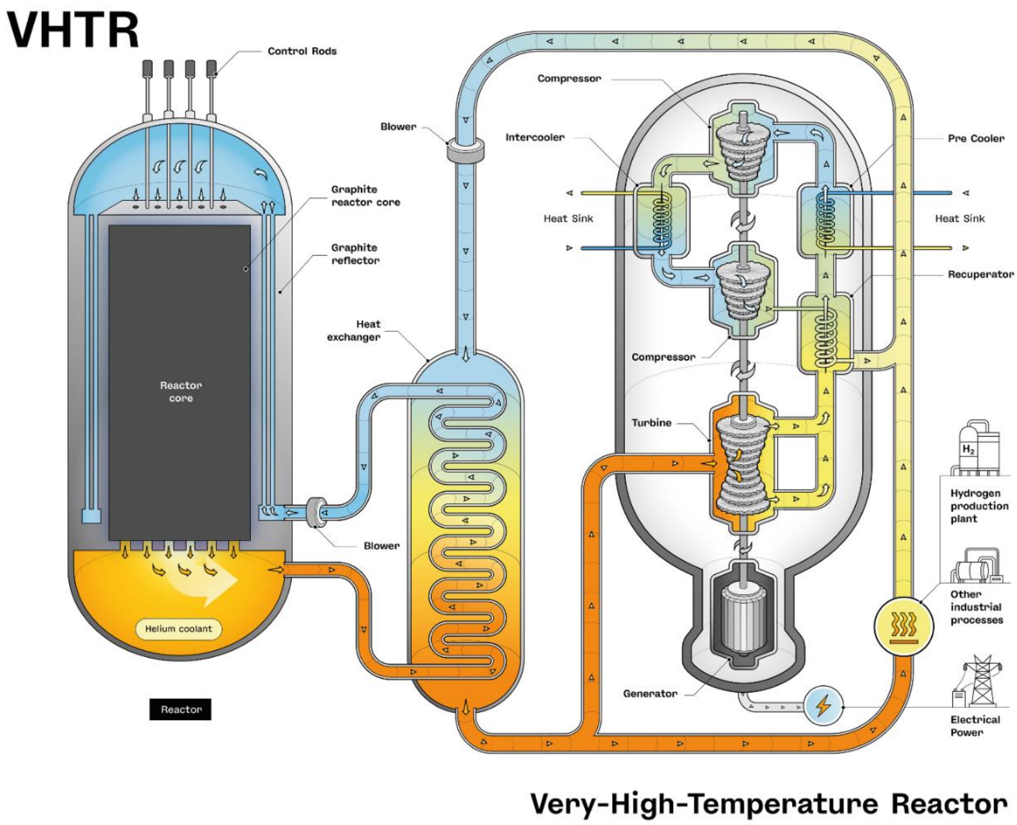


Figure 1: GIF Very-High-Temperature Reactor (VHTR) system schematic.

While the approach for VHTR at the start of the Generation IV program focused on very high outlet temperatures and hydrogen production, current market assessments and research efforts have indicated that industrial processes requiring “lower” outlet temperatures (700-850°C) have the greatest potential in the next decade while reducing the technical challenges associated with higher outlet temperatures. As a result, the focus moved from higher outlet temperature designs such as in GT-MHR and PBMR reactors to lower outlet temperature designs such as HTR-PM in China and the NGNP in the US. This broader classification of reactors is termed High Temperature Gas Reactor (HTGR), which will be used interchangeably with VHTR within this report.

There are several historical global initiatives that have explored the potential role of HTGRs for a range of non-electric application of nuclear energy, including hydrogen production, which have included engagement with end-users interested in the technology options.

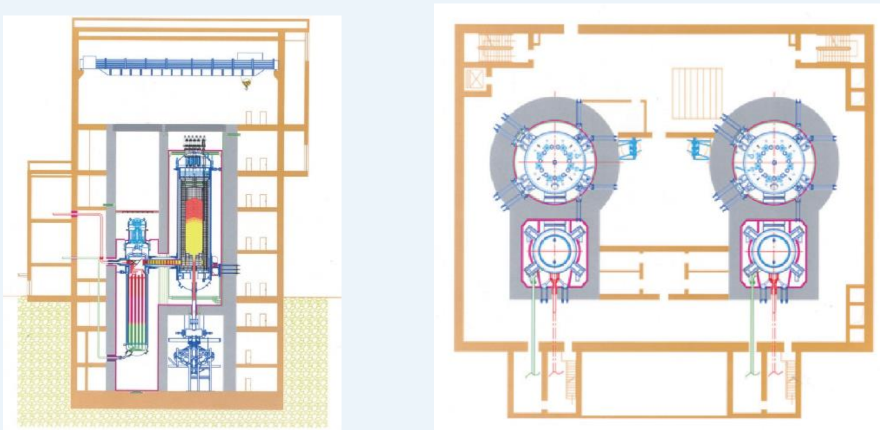
- Next Generation Nuclear Plant (NGNP) Industrial Alliance (2009-2011) – Formed to develop HTGRs and expand its industrial applications. Membership included end-users and the program led to discussions with the US Department of Energy regarding cost-sharing arrangements for a demonstration project [6].
- EUROPAIRS (2009-2011) – Evaluated coupling of HTGRs with industrial processes. This group concluded that 50% of industrial heat demand is below 550ºC and recommended strong partnerships with nuclear technology developers and end-users [7].
- ARCHER (2011-2016) – The Advanced high-temperature reactors for cogeneration of heat and electricity R&D project incorporated recent advancements into HTGR technologies in collaboration with partners in Europe, Asia, the United States and South Africa [8].

While these programs did not culminate in large-scale demonstrations or system deployment, they furthered the development of potential technologies both for energy generation and hydrogen production. It is prudent to note that these programs were being developed without the broader motivation for emissions reduction that is a key driver in pursuing these efforts today. Small and micro HTGR concepts are also being advanced at varying stages of development [9].

Box 1: The HTR-PM in China; The only commercial HTGR in operation globally.

China began research on HTGR technologies through the construction of the 10 MWth HTGR-Test Module (HTR-10) which informed the implementation of Shidao Bay High Temperature Gas-cooled Reactor-Pebble Bed Module (HTR-PM) demonstration project. In December 2023, the demonstration project successfully completed the 168-hour continuous operation assessment and began commercial operations [10].

The HTR-PM (Figure 2: The HTR-PM commercial demonstration nuclear power plant.) consists of two pebble-bed reactor modules coupled with a 210 MWe steam turbine. The thermal power of one module is 250 MWth and the helium temperatures at the reactor core inlet and outlet are 250°C and 750°C, respectively. Steam at 13.25 MPa and 567°C is produced.



(a) Front view (b) top view

Figure 2: The HTR-PM commercial demonstration nuclear power plant.

During its technology development phase China built a high-temperature and -pressure helium test loop and conducted full-scale testing of core equipment and systems. Once prototypes of key equipment were manufactured, full-scale engineering verification experiments were carried out in hot states and a helium environment, which exposed many technical problems which were solved before its service in HTR-PM.

On this basis, China completed the standard design of 600 MWe Modular HTGR named HTR-PM600 (Figure 3). This design benefits from the high safety performance of a HTGR and aims to be close to the Generation III pressurized water reactor nuclear power plant in terms of economy.

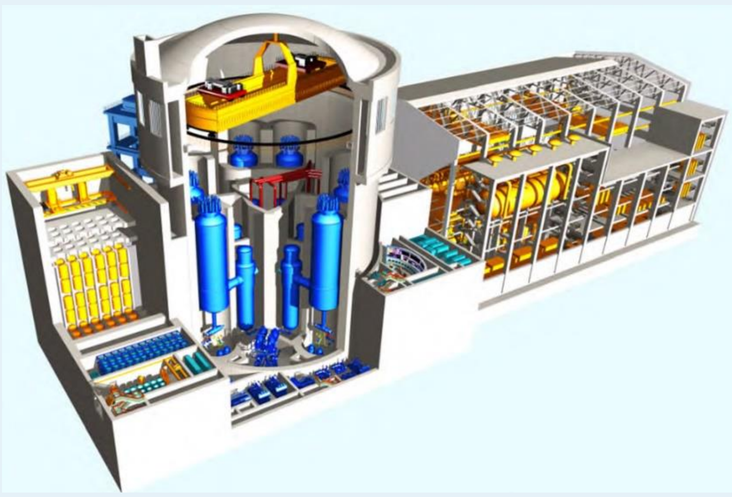


Figure 3: 3D design of the HTR-PM600 nuclear power plant [11]

In August 2024, Chinese central government approved the Jiangsu Xuwei Nuclear Cogeneration Power Plant. In the Phase I plant, one HTR-PM600 will be coupled with two HPR1000 (Hualong One) reactor units. Saturated steam from HPR 1000 heating loops will be further heated by the HTR-PM600, and supplied to the petrochemical enterprises. The expected annual output of the Phase I Project is 32.5 Mton of industrial steam and 11.5 billion kWh of electricity. This offsets 7.2 6Mton of coal and 19.6Mton of GHG emissions.

Using steam from a HTGR can reduce the electricity input requirements of hydrogen production through electrolysis due to the reduced energy requirement to separate steam versus water. Solid oxide electrolysis cell (SOEC) electrolysers, which operate at elevated temperatures (600-850°C), take advantage of the high temperature heat and steam to improve the efficiency of hydrogen production when compared to Low Temperature Water Electrolysis (LTE) [12]. The development and deployment of High Temperature Steam Electrolysers (HTSE) is a priority among GIF member countries for their potential to provide an efficient method of producing hydrogen at scale.

HTSE reduces electrical energy requirements due to the high energy content in steam and the thermodynamic benefits of higher temperatures. The plant arrangement for hydrogen production using a VHTR involves generating electricity and heating steam with high-temperature helium, integrating HTSE systems for efficient hydrogen production and recycling residual steam. Notably, the lifetime of HTSE stacks is negatively impacted by thermal cycling suggesting that a consistent supply of thermal energy from a nuclear reactor may be beneficial. HTSE still has a requirement for electricity beyond this thermal energy requirement.

While this report focuses on HTSE in particular, there are several additional hydrogen production pathways to note which could utilize the high temperature heat produced by nuclear reactors. Thermochemical water splitting processes are being explored and further developed in some GIF member countries, including the sulphur-iodine (I-S) process and the copper-chlorine cycle, while other approaches could use the steam produced by nuclear reactors as the reactant in the steam methane reformation process (See Box 2: The HTTR in Japan and hydrogen production applications. below).

The VHTR project within GIF that is focused on hydrogen production is working to advance research and development to develop and optimize these high temperature thermochemical and electrolysis water splitting processes. In particular, the members of the VHTR Hydrogen Production Project Management Board (PMB) are working to define and validate technologies and processes for coupling Gen IV systems to these processes, including through developing process flows, identifying suitable materials and catalysts, and conducting experiments to validate process parameters. The current signatories of the Hydrogen Production PMB include Canada, Euratom, France, Japan, Korea, and the United States as members, with China and the United Kingdom actively participating as provisional members.

The work within the VHTR hydrogen production project has been recently acknowledged as particularly relevant due to the momentum in GIF member countries towards the development of a global hydrogen economy, and the potential role of Gen IV reactors to enable the cost-effective production of hydrogen at scale. Currently the project has demonstrated a growing emphasis on accelerating and upscaling hydrogen production through testing, validating, and demonstrating HTSE technologies at larger scales, in advance of commercial deployment of HTSE stacks.

Finally, it is important to note that while research and other studies exploring commercial aspects of these systems typically focus on the HTGR system, lower temperature steam from a nuclear reactor, or another source, can also be used for hydrogen production using HTSE. As HTSE stacks can operate exothermically, heat can be captured from the hydrogen production process to increase the temperature of the source steam. Hydrogen production through HTSE is therefore compatible with all Generation IV reactor types as well as existing water-cooled reactors with minor variations in efficiency. Notably, utilizing HTSE with the existing reactor fleet has the potential to enable valuable operational experience to support broader adoption in the near term, and may allow the commercialization of HTSE independently from HTGR commercialization.

Box 2: The HTTR in Japan and hydrogen production applications.

The High Temperature Engineering Test Reactor (HTTR), located in Japan Atomic Energy Agency's (JAEA) Oarai R&D Institute, is the first and only HTGR in Japan. The objectives of the HTTR is to demonstrate the inherent safety features of the HTGRs technology through the design, construction and operation of the HTTR, and to demonstrate the potential of a hydrogen production using nuclear heat.

The major specifications of the HTTR are available in [13]. The HTTR is a graphite-moderated and helium gas-cooled reactor with the rated thermal power of 30 MWt. The HTTR achieved first criticality in 1998 and the world's first reactor outlet temperature of 950 ◦C in 2004. Fig. 1 shows the vertical cross-sectional view of the reactor. The reactor consists of the reactor pressure vessel (RPV), core, replaceable reflector, permanent reflector, and control rods. The reactor core consists of 30 fuel columns and 7 control rod guide columns, surrounded by 15 replaceable reflector block columns, 9 control rod guide columns and permanent reflector. The permanent reflector is fixed tightly by the core restraint mechanism. The fuel element is the pin-in-block type. The fuel compact consists of coated fuel particles dispersed in graphite powder and sintered. It is enclosed within a graphite sleeve to form fuel rods and they are inserted into the fuel rod insertion holes within the fuel block.

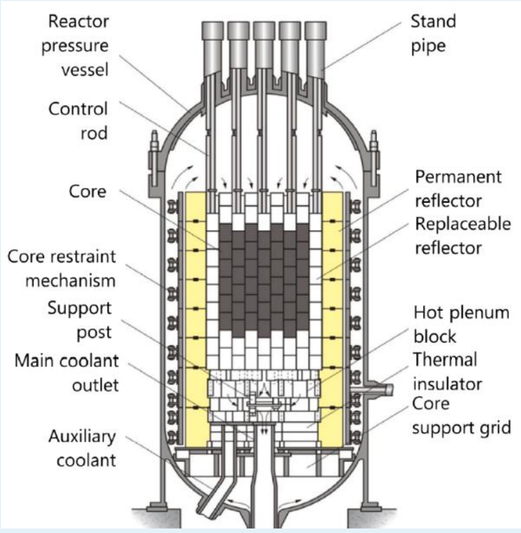


Figure 4: Vertical cross-sectional view of the HTTR reactor

Following the Fukushima Daiichi nuclear accident in 2011, JAEA applied for a permit to change the HTTR to comply with the new regulatory standards, which began in December 2013. Based on the knowledge accumulated from the various HTTR tests conducted so far, including the loss of forced cooling (LOFC) test, and the safety of HTGRs, JAEA revised the HTTR safety classification and obtained the permission to proceed with the changes in June 2020. This revision in the classification mitigated the design requirements and allowed the HTTR to restart its operation without large-scale modification work, as is the case with light water reactors.

The HTTR is carrying out LOFC tests to demonstrate inherent safety feature of HTGR, as a joint NEA international research project. In 2010 and 2022, the first test in the world to simulate the loss of all cooling functions from 30% power by simultaneously shutdown the reactor vessel cooling system which is installed to remove residual heat after reactor shutdown was conducted.

As a result, it was confirmed that the reactor power decreased automatically and that the fuel temperature remained stable without abnormal temperature change. A successful test of LOFC was completed in 2024. The test starts with 100% power, so that the effects of the different initial power on thermal hydraulic phenomena and core physics phenomena could be confirmed.

JAEA has been conducting R&D on the Iodine-Sulfur (I-S) process to develop heat-application technologies related to HTGR, which can generate high-temperature heat of 950 ◦C. A hydrogen production test facility, including all I-S process components, was constructed to verify the integrity of the process components made of industrial structural materials and demonstrate continuous hydrogen production. Fig. 2 shows a picture of the external view of the facility. The JAEA succeeded in continuously producing hydrogen for 150 h at rates of ca. 10- 30 L-H_2/h at stable operation [14].

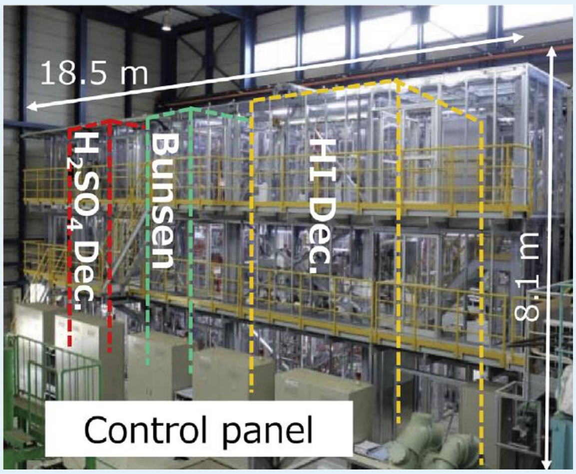


Figure 5: Photograph of I-S hydrogen production test facility

1.4 International development and progress towards HTSE and HTGR system

The following sections were provided by the country representatives to the NECA WG and NEA H2VAL WG to highlight relevant research and development to involving high temperature gas reactor systems, hydrogen production, and integration.

1.4.1 Canada

HTGR development in Canada are enabled by the VHTR research initiatives under GIF and by national and international SMR priorities. In 2018, a committee of federal, provincial, and territorial governments, as well as power utilities engaged stakeholders to outline a roadmap for SMR deployment [15], which informed the SMR action plan for Canada in 2020 [16]. A SMR feasibility study by aligned Canadian utilities subdivided the deployment strategy into streams: stream 1 – grid-scale SMR projects, stream 2 – fourth-generation, advanced SMRs, and stream 3 – micro reactors [17].

Reactor deployment in Canada is regulated by the Canadian Nuclear Safety Commission (CNSC). For HTGRs, deployment efforts include a proposed project at Atomic Energy Canada Limited's (AECL) Chalk River Laboratories as well as agreements between X-Energy and Invest Alberta, and another between X-Energy and TransAlta to study deployment opportunities of the Xe-100 in Alberta, which is one of four provinces in the Strategic Plan for the Deployment of SMRs [18].

At CNL, there are several ongoing projects supported by AECL's Federal Nuclear Science & Technology (FNST) Work Plan directly applicable to HTGRs and performed in concert with several Canadian research organizations and institutions (e.g. CANMET). Research is primarily being conducted on material science for metallic and graphite components, and TRISO fuel.

The Government of Canada released a Hydrogen Strategy for Canada in 2020 [19], which included input from hundreds of organizations including private sector, Indigenous, non-Government, and governments at all levels. The strategy specifically highlights the potential of hydrogen nuclear integration, particularly next-generation nuclear, in terms of using the electricity and thermal energy produced in high temperature electrolysis or thermochemical processes.

At CNL there are several projects supported by AECL's FNST Work Plan regarding HTSE and thermochemical cycles for hydrogen and clean fuels production targeting materials development and innovation, electrolyser testing and process optimization, and processes modeling and integration. CNL demonstrated the viability of the copper-chlorine thermochemical cycle for hydrogen production in bench-scale tests, requiring a temperature of ~530°C, and is poised to scale up these efforts. CNL's research in this area targets improving the economics of hydrogen and syngas production through use of HTSE and high temperature co-electrolysis technology.

1.4.2 China

HTGR has good safety and high temperature of outlet helium gas from reactor core, and is recognized as Generation IV nuclear energy system. Hence, HTGR has wide applications in the utilization of high temperature process heat, nuclear hydrogen production, high-efficiency power generation, space power supply, etc. Research teams from China, represented by INET from Tsinghua University, have made breakthrough progress in the development of HTGR technology. At the end of 2023, the demonstration HTGR plant (HTR-PM) successfully completed the 168-hour continuous operation assessment. In 2024, the basic design of HTGR with 600 MWth (HTR-PM600) has also been finished. In addition, a sulfuric acid chemical decomposer has been developed for the I-S process at the Tsinghua University of China which has been coupled to a helium loop. In 2023, the helium loop supplied operating heat at 900℃ and was used to test thermohydraulics of the system, and the integrity of the facility. Additionally, in 2024 HTSE for hydrogen production using HTGR has completed the design and development of four-reactor integrated module. HTSE also completed the development and operation verification of the containerized hydrogen production system, with a peak power of 12 kWe and a continuous and stable operation time of more than 100 hours.

1.4.3 Euratom

The GEMINI 4.0 project, initiated in 2022, aims to leverage the potential of HTGRs for decarbonizing energy-intensive industries through hydrogen production and cogeneration of heat and electricity. Building on the GEMINI+ project, GEMINI 4.0 focuses on demonstrating the competitive and safe provision of CO_2-emissions-free process heat and various energy products, thus expanding HTGR's role in industrial applications. A significant research goal of GEMINI 4.0 is to establish the feasibility of using HTGR systems to generate high-temperature steam for electrolysis. The project's progress is driven by foundational work from the European Nuclear Cogeneration Industrial Initiative (NC2I), which has developed the design and licensing framework necessary to adapt HTGR systems to European industrial demands.

GEMINI 4.0's activities are part of a broader transatlantic effort under the GEMINI Initiative, fostering collaboration between the U.S. and Europe to accelerate HTGR commercialization and achieve a reliable, carbon-free energy supply for the future. The GEMINI project's work packages focus on research, development, and demonstration activities that lay the groundwork for the safe and efficient deployment of HTGR technology for industrial applications.

Additional activities in Europe are dedicated to advancing R&D on hydrogen production technologies. Through the HySelect research project in the EU, electrochemistry of the hybrid sulfur cycle process was advanced in 2023 with contributions from partners in Germany, Greece, Finland, Italy, and Austria [20]. Additional research activities in the EU focuses on scaling up a range of technologies related to clean hydrogen production, including biomass gasification for distributed hydrogen production, thermochemical water splitting technologies, Photo-electrochemical and photocatalytic water splitting, and other biological and bioelectrochemical hydrogen production processes.

1.4.4 France

In France, CEA has been working on HTSE technology for over two decades, beginning with exploratory research on ceramic cells and SOFC (Solid Oxide Fuel Cell) applications. In 2005, an important program was started dedicated to the massive production of hydrogen coupled to nuclear energy, which included investigation of electrolysis and thermochemical cycles. In 2014, a lab system was put in operation at CEA that demonstrated the high efficiency achievable with this technology (84%LHV) using a heat source of only 150°C. Between 2015 and 2020, efforts focused on stack optimization and involved the installation of a pilot showing high level of reliability in the stacks. In 2021, the process was initiated to transfer the technology to a new company, Genvia, which is a joint venture between SLB and CEA, with Vinci, Vicat and ARIS as additional stakeholders. R&D continued at CEA to upscale the active area from 100 to 200 cm², and the number of cells per stack from 25 to 75, in support of targets to install ~100 GW of electrolysers in the EU in 2030. In addition, a large number of national and European projects supported CEA activities exploring different operating modes and supporting the development of multiscale and multiphysics modeling methodologies.

A stack performance of 0.94 A/cm² has been achieved at 1.3 V per cell at 700°C, representing a power of 18.6 kW and 12.6 kgH_2 per day for a stack made of 78 cells of 200 cm². This stack has been tested over durations up to 8000 hours without hydrogen production losses. Operationally, it was shown that degradation over time can be managed by adjusting stack temperature. Using a test platform, a 4-stack module has been designed, assembled and put in operation capable to operate in electrolysis, fuel cell, and reversible mode. It was found that 4 stacks behave similar to an isolated operation, and durability tests have also been successfully performed at this scale.

CEA is also studying the coupling of HTSE with nuclear reactors using its proprietary PERSEE (oPtimizER for System Energy management) modeling software [21], developed for dynamic techno-economic and environmental assessment, while optimizing operating costs. It uses Mixed Integer Linear Programming (MILP) formalism building off of the Odyssey tool which began in 2010.

PERSEE has already been used to assess the techno-economic and environmental coupling of hydrogen and nuclear energy both the TANDEM and NPHYCO projects. In TANDEM [22], PERSEE was used to conduct a techno-economic and environmental analysis of an energy hub producing electricity, heat, and hydrogen for three deployment scenarios of SMRs at different time scales (2035 and 2050), enabling the evaluation of the production costs of electricity, heat, and hydrogen, as well as the CO_2 contents of these three products. In NPHYCO, PERSEE was used to study the integration of electrolysis on the site of an existing nuclear power plant in a benchmark with three other tools (OptimHyzer, HEEP, H2Calc). The cost of hydrogen was evaluated for different levels of coupling integration (no integration, electricity integration, water integration)

1.4.5 Japan

The Sixth Strategic Energy Plan manifested a promotion of R&Ds for hydrogen production technologies using HTGR to further reduce hydrogen supply cost and efficiently produce large quantities of hydrogen to promote the usage of hydrogen towards carbon neutral society. The Japanese Government put forward development and construction of next-generation advanced reactors that incorporate new safety mechanisms on the premise of reactor safety. The basic design of the HTGR demonstration reactor is started from 2023 and will enter operation in the latter half of 2030s. The roadmap of advanced reactors is shown in Figure 6.

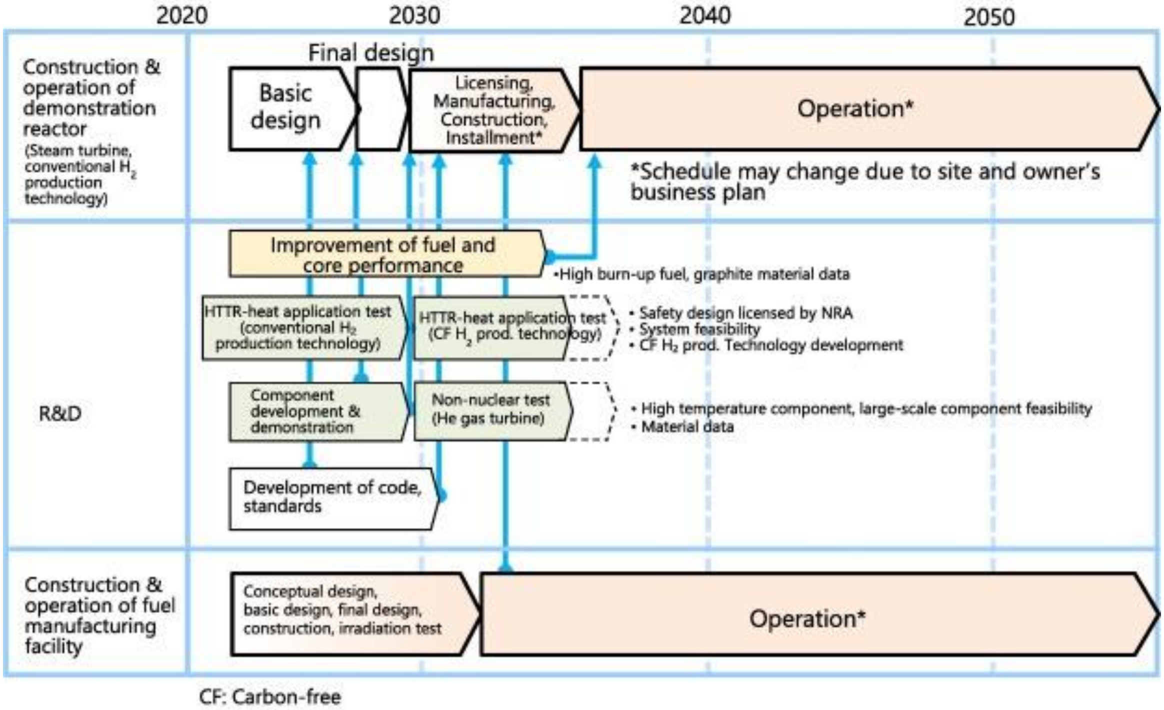


Figure 6: Technology Roadmap in Japan for Developing HTGRs

Based on this policy, JAEA initiated HTTR heat application test plan from FY2022. The hydrogen production facility is coupled with HTTR for the hydrogen production by a steam methane reforming method. The objectives of this plan are to establish a high safety coupling technology and to develop necessary equipment to connect HTTR with the hydrogen production facility. The plan is expected to be completed by FY2030. To utilize a portion of the nuclear heat extracted from the IHX as a heat source for hydrogen production, modifications of HTTR are required. In this plan, high temperature secondary helium coolant is transported from the IHX to a steam reformer through the secondary helium piping. The secondary helium is supplied to the hydrogen production facility at the flow rate of 0.637 kg/ s. The hydrogen produced by the facility is expected to be more than 800 Nm3/h in rated operation.

1.4.6 Korea

The Korea Atomic Energy Research Institute (KAERI) successfully conducted a 6kWe high-temperature electrolysis hydrogen production experiment using a helium loop, achieving a hydrogen production rate of 4.3 kg/day [23]. The results indicate that increasing the operating temperature improves hydrogen production efficiency. Specifically, the required power for hydrogen production decreased by 10% when the temperature was raised from 730°C to 770°C.

In August 2023, the Alliance for Nuclear Heat Utilization in Korea was inaugurated [24]. Its primary objective is to develop and commercialize nuclear process heat production and utilization technologies. The alliance includes 13 organizations from industry, research institutes, and local governments, including KAERI, North Gyeongsang Province, 6 plant construction companies, and 5 energy end-user companies including steel making, petrochemical industry, and hydrogen supply companies.

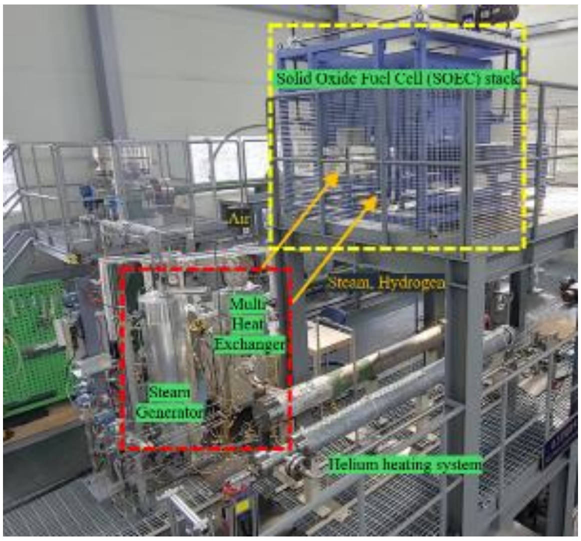


Figure 7: High Temperature Steam Electrolysis experiment facility in Korea

A significant milestone was reached in June 2024 with the signing of a business agreement for the commercialization of nuclear-based clean hydrogen production [25]. To advance this initiative, a collaborative framework has been established. By 2027, the goal is to develop infrastructure capable of producing, storing, and distributing over 4 tons of clean hydrogen daily, based on a 10MW low-temperature electrolysis system.

KAERI is developing the high temperature gas-cooled reactor for industrial process heat with five Korean companies: POSCO E&C, Daewoo E&C, Smart Power, SK Ecoplant, and Lotte Chemical. They will spend USD 32 million to develop the basic design and the business plan of HTGR for various applications by 2027. POSCO E&C, SK Ecoplant, and Lotte Chemical plan to use the HTGR in steel making, HTSE hydrogen production, and petrochemical businesses, respectively.

1.4.7 United Kingdom

Within the United Kingdom (UK), the United Kingdom National Nuclear Laboratory (UKNNL) has an active internal research program of “Nuclear to X” which is sponsoring a number of research projects aimed at producing evidence for the role of nuclear power for low carbon energy transition. Research includes several projects with university consortia (UK-HyRES, HiAct and “SusHy” Sustainable Hydrogen Centre for Doctoral Training). The main areas for research cover modeling and technoeconomic assessment (as per the recent Techno-Economic Analysis of Heat-Assisted Hydrogen Production from Nuclear Power paper [1]), digital twin development and hardware in-the-loop testing of nuclear integration and hydrogen production.

The UK is also working towards the demonstration of HTGR technology by the early 2030’s [26]. UKNNL are working with the Japanese Atomic Energy Agency on the “UKJ-HTR” project. As well as developing up the details around the reactor, building on the Japanese technology of the HTTR described in the case study earlier in this report, UKNNL is developing technoeconomic models investigating heat applications within a high-level concept design. This revolves around the concept of a ‘smart manifold’ for load-balancing of nuclear heat output against several different end-user demand cases. These include integration of district heating, hydrogen production and synthetic hydrocarbon production. Elsewhere, UKNNL is collaborating with EDF energy on the Bay Hydrogen hub, which aims to develop a best practice guide for the deployment of nuclear enabled hydrogen production against a hypothetical deployment of HTSE at a nuclear station. This project is due to complete with the publication of a handbook in 2025.

1.4.8 United States of America

The United States (US) is pursuing multiple advanced reactor technologies, via both private and public sector investment. Work under Department of Energy (DOE) investments for HTGR technologies includes fuel and fuel cycle, materials development, integration with hydrogen production, and computational methods validation and benchmarks.

In October 2020 the US DOE awarded funding to X-energy and TerraPower through the Advanced Reactor Demonstration Program (ARDP), a private-public cost share program intended to accelerate development and deployment of advanced reactor technologies. X-energy is developing the Xe-100, a 200 MWth (80 MWe) pebble bed HTGR, and is of particular interest to the NECA WG, as the initial deployment is expected to be the first grid-scale advanced nuclear reactor in North America to serve an industrial site via partnership with Dow Chemical and their site in Seadrift, Texas that plans to host a four-unit (320 MWe) Xe-100 facility to provide to provide both power and steam. Construction is expected to begin in ~2026.

The US DOE Hydrogen and Fuel Cell Technologies Office (HFTO) under the Office of Energy Efficiency and Renewable Energy (EERE) supports the development of hydrogen production technologies with the goal of reducing costs to 1 USD/kg hydrogen by 2030. HFTO has selected electrolysis as a highly promising option for carbon-free hydrogen production, with low temperature electrolysis focusing on proton exchange membrane (PEM) electrolysers and high temperature electrolysis focusing on Solid Oxide Electrolysis, which requires less energy than PEM systems. These SOE systems operate at ~700-800ºC and couple very well with both LWR and advanced nuclear reactor technologies.

The US is actively supporting multiple hydrogen production demonstration projects at three existing fleet LWR plants that will provide significant insight to future advanced reactor projects that will produce hydrogen and/or other non-electric products. Constellation was the first LWR to demonstrate collocated hydrogen production at the Nine Mile Power Nuclear Power Plant in New York using a 1.25 MWe LTE producing 560 kg of clean hydrogen per day as of February 2023.

The Constellation project is being followed by demonstration at the Vistra Davis-Besse Nuclear Power Plant in Ohio using a 1-2 MWe electrolysis system, and a third project at the Xcel Energy Prairie Island Nuclear Power Plant in Minnesota intended to support a 150 kWe HTSE system beginning in 2025.

The US DOE is also providing support for cost-shared hydrogen hub projects that will produce clean hydrogen at larger scale using a mix of renewables, natural gas (with carbon capture), and nuclear energy [27]. This is expected to include both the Mid-Atlantic Clean Hydrogen Hub (MACH2) hub, located in Pennsylvania, Delaware, and New Jersey, and the Midwest Alliance for Clean Hydrogen (MachH2), located in Illinois, Indiana, and Michigan.

1.5 Relevant existing or historical systems and analysis

There is past experience in the use of nuclear energy for non-electric and cogeneration applications, including for applications that are relevant to hydrogen production. These past examples have been characterized by the NEANH Task Force that preceded the NECA WG [28] and other international organizations such as through the IAEA’s Power Reactor Information System (PRIS) database [29]. Historical data reveals that more than 750 reactor-years of experience using nuclear energy for non-grid applications, primarily using water-cooled reactor technologies. This represents less than 0.5% of the total nuclear thermal output generated by the global fleet of over 440 reactors. The majority of this experience relates to district heating applications and desalination. Some past examples are very relevant to the study of hydrogen production from GenIV systems, including the Bruce A Heavy Water Facility in Canada.

Box 3: The Bruce A Heavy Water Facility in Canada using heat from CANDU reactors

With eight CANDU reactors and a total net electricity production of 6,288 MWe [30], the Bruce nuclear power plant in Ontario, Canada, is one of the largest nuclear facilities in the world [31]. The nuclear site's purpose was once to ensure a reliable supply of reactor grade heavy water to meet the needs of future CANDU plants [32]. Heavy water production was stopped in 1997, ending cogeneration at the Bruce site.

The Bruce bulk steam system (BBSS) was built to supply steam for the heavy water plant (HWP). The secondary heat transport system of four units at Bruce A diverted high pressure steam via a steam transformer plant to the BBSS, which became one of the largest process steam supply systems in the world, with a capacity of 5350 MWth delivered through piping of more than 6 km length. Each of the four 2400 MWth Bruce A reactors could supply high pressure steam to a bank of 6 heat exchangers (24 in total) which produced medium pressure steam for the HWP and site services. The normal capacity was approximately 1680 kg/s of medium pressure steam [33]. BBSS supplied ~750 MWth of steam to the HWP, and also supplied ~15 MWth to on-site building heating and 72 MWth to the nearby industrial park [31].

The HWP was based on Girdler-Sulphide process, which involved large quantities hydrogen sulphide requiring adequate mitigation measures to deal with potential leakage.

The HWP was planned to consist of four sub-plants, with each sub-plant composed of two enriching units, one finishing unit, and auxiliary systems. The timeline for the HWP sub-plants is shown in Table 2. The enrichment unit shown in Figure 8 concentrated the deuterium product.

Table 2: Timeline for heavy water production sub-plants

	Year entered production	***Shutdown year***	***Year demolished***
Sub-plant A	1973	1984	1993
Sub-plant B	1979	1993	1997
Sub-plant C	Cancelled before construction		
Sub-plant D	Cancelled at 70% completion		1995

During its lifetime, HWP produced 16,000 tonnes of reactor grade heavy water. Capacity of each sub-plant was planned to be 800 tonnes/annum. The plant size was approximately 960 m by 750 m. The heavy water was 99.75% pure. The production of a single kilogram of heavy water required 340,000 kilograms of feed water; thus, representing a significant heat demand by the process.

To meet HWP reliability criteria, the steam system was designed to ensure a maximum steam supply interruption of just a few minutes in winter and 4 hours in summer. Oil-fired boilers were kept on hot standby, and pumps were supplied with uninterrupted power backed by gas turbine standby generators. The HWP never suffered a loss of emergency steam. Heavy water demand was less than originally forecasted giving the BBSS significant spare steam capacity

Figure 8: Enrichment unit E4 of plant B (87 m high and 8.5 m in diameter) [31]

The Bruce Energy Centre (BEC) was established as an industrial heat supply system feeding customers beyond the HWP in the form of a 5 km long, 0.91 m diameter steam line with a 0.46 m condensate return line. BEC industries included a plastic film manufacturer, a greenhouse, an ethanol plant, an alfalfa plant, an apple juice concentration plant and an agricultural research facility, with constant steam supply guaranteed by standby oil-fired plants. The steam prices consisted of only a flat rate per thousand pounds steam delivered. The cost was significantly lower than costs of heat from burning natural gas, which is the closest competitor.

There were essentially three barriers between the end user and the nuclear plants. The steam from the heat transport system sometimes contained low levels of tritium owing to occasionally failing heat exchanger tubes, before steam transformer components were implemented. Routine sampling did not detect any significant tritium cross contamination and never exceeded the provincial limit of 7000 Bq/L. The design of the steam transformer plant prevented any steam from Bruce A from mixing with the medium pressure process steam generated for the Bruce HWP [31]. The BBSS was eventually demolished in 2006.

Although the BBSS was not directly related to nuclear hydrogen production, some of the aspects from this project could be relevant to HTGR-HTSE project, including the use of nuclear thermal energy for industrial processes on a large scale, operational considerations, safety aspects related to the toxic hydrogen sulphide gas on-site, designed barriers between the nuclear plant and the industrial heat users, and back-up systems to assure reliability of heat supply.

Through a review of existing literature, the NECA WG has also identified more than 60 studies or reports with varied analysis on global heat markets, include 12 substantive reports evaluating the opportunity to use nuclear energy for hydrogen production [28].

There are also a number of domestic and international working groups or collaborative efforts that have been established to explore the opportunity to use nuclear energy for non-electric applications and in hybrid energy systems. At least 25 relevant international or domestic initiatives have been identified, with at least seven groups focused on nuclear-produced hydrogen (including both Gen-III and Gen-IV reactor technologies).

Finally, there exists numerous modeling tools to support the exploration and evaluation of nuclear heat applications. The NECA WG members have identified 13 modeling tools with relevance to hydrogen production, desalination, and general cogeneration, which are being used to assess the feasibility, efficiency, and environmental impact of integrating nuclear technology with these various energy systems.

These analyses and available tools will be supported by existing demonstration or commercial systems, such as the HTR-PM HTGR system in China, and future systems including multiple hydrogen production demonstrations at the Nine Mile Point, Davis–Besse, and Prairie Island nuclear power stations in the United States; and various international projects across the UK, Korea, Japan, Canada, and Argentina, which are set to showcase the application of Gen III and Gen IV technologies in desalination, hydrogen production, and chemical manufacturing processes.

2 Techno-economic modeling and analysis of hydrogen production from a HTSE and HTGR system

The NECA WG was established through the GIF to, in part, perform system analysis on non-electric applications of nuclear energy focusing on key performance indicators of interest to GIF member countries. To this end, the NECA WG launched an initiative with support from partner organization to pursue a modeling task to evaluate the potential technological feasibility, commercial readiness, and financial viability of hydrogen production using HTSE coupled with HTGRs using tools and methodologies available within their home laboratories and organizations. The NEA Hydrogen Value Chain (H2-VAL) Working Group, and partner organizations represented within GIF and the NECA WG such as the IAEA, worked collaboratively to pool modeling capabilities and broaden the potential impact of this study.

The intent of this exercise was not to quantify the system with precision, but to use the range of data produced by GIF and NEA member countries to initiate a conversation on the potential role of these systems in a future clean energy mix starting from a common understanding of the system's readiness and potential feasibility, and to help identify gaps in current efforts to research and scale hydrogen production systems using nuclear energy.

A prismatic HTGR with a thermal power rating of 200 MWth has been selected as the nuclear reactor technology in the modelled scenario. It is important to note that this technology selection and associated design and operational assumptions are based on public literature and are representative of this class of technology rather than being specific to any one design being offered by a technology developer or vendor. The selected generic HTGR operates with an outlet temperature of 750°C using fuel enriched to 19.75% U235 with a refuelling timeline of 24 months. The plant is designed to have a lifetime of 40 years.

Thermal energy storage (TES) is included in the base design. The selected TES technology utilizes a two-tank system with solar salt as the storage fluid. The molten salt in the hot molten salt tank was prescribed to have a uniform temperature of 565°C.

The HTSE process uses solid oxide cells and operates with current densities on the order of 1.0 A/cm2 and has a stack lifetime of 4.5 years at a temperature of 765°C and an operating stack pressure of 1-5 bar. This temperature requirement for the HTSE stack suggests that additional electrical energy will be required to top up the energy stored in 565°C thermal storage tank. The hydrogen production plant itself is designed to have a lifetime of 35 years. The distance between the nuclear power plant and the hydrogen production site is 1 km.

Finally, the oxygen produced through the hydrogen production process is assumed to have a market price of USD 0.09 per kg at the date of commercial deployment. This is considered in the economic evaluation to offset the overall cost of producing hydrogen. This assumes the electrolysis system can sufficiently isolate oxygen from the enriched outlet airstream without additional costs and that O_2 is produced at a rate 8x that of H_2.

The complete set of modeling inputs that were developed by the NECA WG and provided to the NECA and NEA H2VAL Working Group members as guidance for their modeling activities are listed in Table 3, Table 4, and Table 5 below.

Table 3: HTGR variables provided as modeling guidance

Variable / Description	***Value***	***Unit***
Power rating	4 units x 200 (800 total)	MWth
Outlet temperature	750	deg C
Outlet pressure	7.02	MPa
Configuration	Prismatic	
Power conversion efficiency	45	%
Capacity factor	90	%
Fuel enrichment level	19.75	% U235
Refueling timeline	24	month
Plant lifetime	40	year
Years to construct	3	year
Overnight capital costs	6,000.00	USD[4]/kWe
O&M costs	25.00	USD[4]/MWh
Annual fuel costs	Not defined. Value specified by modeler	
Decommissioning & decontamination costs	Not defined. Value specified by modeler	
Annual interest rate	5	%

Table 4: Thermal storage and transport variables provided as modeling guidance

Variable / Description	***Value***	***Unit***
Intermediate heat medium temperature	565	deg C
Intermediate heat medium pressure	16	MPa
Thermal Energy Storage (TES) fluid	Solar salt	
TES configuration	Two-tank	
Levelised cost of storage	0.447	USD[4]/kWh
Distance between nuclear power plant and hydrogen production	1	km

[4] All currency values are to be expressed in 2023 USD

Table 5: HTSE variables provided as modeling guidance

Variable / Description	***Value***	***Unit***
Capacity factor	90	%
Current density	0.5 to 1.5	A/cm^2
Electricity consumption	38	kWh/kg-H_2
Thermal energy consumption	10	kWh/kg-H_2
Stack lifetime	4.5	year
Water consumption	72.6	kg/s
Feedwater temperature	185 to 225	deg C
Stack operating pressure	1 to 5	bar
Stack operating temperature	765	deg C
Stack degradation rate	1.378	%/1000 hr
Hydrogen production plant lifetime	35	year
Years to construct	3	year
Overnight capital costs	Not defined. Value specified by modeler	MUSD[4]
Annual O&M costs	Not defined. Value specified by modeler	MUSD[4]/year
Market price for secondary O_2 market	0.09	USD[4]/kg-O_2
Annual interest rate	5	%

These inputs represent a simplified scenario to provide a baseline analysis for preliminary system-level costs. Modeling was based on a basic set of assumptions, several of which may deviate from real-world conditions. These include negligible costs for hydrogen storage, water consumption, oxygen handling, and stack replacement costs. Notably, the exclusion of costs for on-site hydrogen storage may considerably impact the resulting levelized cost of hydrogen. Further refinement and detail will be necessary in future work to enhance the model's accuracy and applicability.

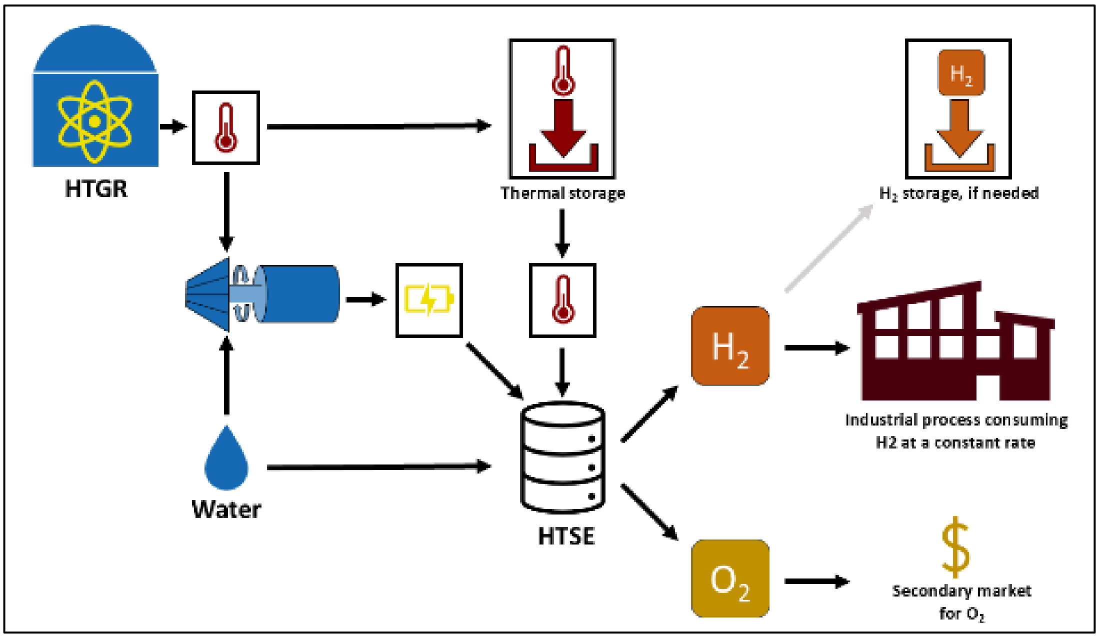


Figure 9: Schematic of proposed HTGR-HTSE scenario for the generic modeling analysis.

The scenario described above and in Figure 9 was also subject to a number of constraints or assumptions. While individual modelers may have applied additional assumptions depending on their available tools, the NECA WG prescribed the following constraints to further refine the system scenario:

- Transportation costs of the produced hydrogen, and hydrogen post processing costs are not included in the analysis. The scenario assumes that hydrogen is being produced on-site at an industrial facility, where the hydrogen is consumed directly at its point of production.
- A constant rate of hydrogen consumption is assumed, without interruption. This implies that the proposed industrial facility requires a constant rate of hydrogen for their application. Hydrogen storage may be required for periods where hydrogen is not being produced, however the costs associated with storing hydrogen are not included.
- The four HTGR units are assumed to be completely dedicated to hydrogen production. In the proposed scenario, the reactors will not produce electricity that will be sold to electricity markets. The power output of the HTGRs are fixed over its operating lifetime at 800MWth (4x200MWth).
- Oxygen gas will be sold to offset production costs of hydrogen. Oxygen gas is produced during hydrogen production from electrolysis. The scenarios consider the market value of the oxygen to offset production costs of hydrogen and assumes the perfect extraction of O_2 from the oxygen-enriched outlet gas from the HTSE. In particular oxygen is assumed to be produced at a rate that is eight times that of hydrogen by mass.
- The commercial HTGR + HTSE system will enter commercial operations in the year 2040.

With consideration for this scenario, the modellers are asked to determine the following values for the purpose of comparison with other modeling tools, and within the context of geographic specificity:

- Amount of H_2 produced in units of kg per year
- Required H_2 storage, if any, in units of kg-H_2
- Levelised cost of hydrogen produced (USD / kg-H_2), excluding distribution costs, in 2023 USD

2.1 Results from collaborative techno-economic modeling

Using the scenario described above, modeling was completed as a joint exercise with the NEA H2 VAL Working Group. Existing capabilities developed domestically within Canada, France, and the United Kingdom were leveraged to evaluate the cost and volume of hydrogen produced for this hypothetical target industrial applications. In addition, the IAEA completed the modeling exercise using the Hydrogen Economic Evaluation Program tool [34].

Notably, the GIF Economics and Modelling Working Group (EMWG) was engaged extensively throughout this study and provided tremendous support in the development of the model input recommendations and the broader scenario development. The EMWG G4ECONs tool was not equipped to evaluate the costs associated with non-electric applications of nuclear energy at this time. The EMWG may benefit from this work as a benchmark as they continue to progress efforts to update their cost estimating guidelines and G4ECONs tool.

Given the provided scenario using the recommended model inputs defined in Section 2, the modeling teams were requested to determine three values: the amount of hydrogen produced, the cost of hydrogen on a levelized basis, and the amount of storage that would be required.

A summary of the modeling results is provided in Sections 2.1.1 to 2.1.4.

2.1.1 *Modeling outputs provided by Canada*

The modeling contributions from Canada were performed using Hybrid Energy System Optimization (HESO) tool. HESO is a techno-economic energy system optimization model developed by CNL that allows energy scenario analysis of Nuclear-Renewable Hybrid Energy Systems (NRHESs). The HESO tool is formulated as a mixed-integer linear programming and solved by CPLEX Optimizer. It can be customized to satisfy hourly demands for electricity, heat, and hydrogen over one year to ensure a system with adequate supply flexibility [35]. It can help explore options for capacity planning and highlight some fundamental mechanisms associated with energy systems.

Unless otherwise stated, all costs are in 2023 U.S. dollars (USD), indicated by USD. The referenced costs in Euro are converted to USD using a conversion of 1.11 USD/Euro. All calculations were performed using HESO 3.0.

Key inputs and assumptions used in the HESO analysis for given in Table 3, Table 4, and Table 5. Additional inputs are provided in Table 6, Table 7, and Table 8. It is assumed that the HTGRs could supply the necessary heat and electricity by using a split flow system as recommended by [36]. The primary loop splits after it leaves the reactor and is recombined after it is passed through the turbine generators. With a given set of technology parameters, the HESO tool minimizes the total annualized cost subject to technology limitations and specifications to meet the hourly demand over one year.

Table 6: Reactor Key Assumptions (Canada)

Parameter	***Unit***	***Value***	***Reference***
Total capital cost (including interest during construction)	USD/kW-e	3,809	Calculated
Annual operation, per reactor	h	7884	Calculated
Annual outage, per reactor	h	876	Calculated
Fuel cost, levelized	USD/MWh-th	10	Calculated
Initial core cost	MUSD/y	19.68	Calculated
Refueling cost	MUSD/y	42.79	Calculated
Waste disposal cost	MUSD/y	0.48	Calculated

Table 7: Hydrogen Production Key Assumptions (Canada)

Parameter	***Unit***	***Value***	***Reference***
Stack cost	USD/kW-e	445	[37]
BOP cost	USD /kW-e	153	[37]
Fixed O&M cost	USD /kW-e/y	21.6	[38]
Variable O&M cost	USD /MWh-e	0.75	[38]

Table 8: Hydrogen Storage Assumptions (Canada)

Parameter	***Unit***	***Value***	***Reference***
Capital cost, above ground (750 €/kgH_2)	USD /kgH_2	832.50	GIF
Capital cost, underground salt caverns (35 €/kgH_2)	USD/kgH_2	38.85	GIF
Levelised cost of H_2 storage above ground (4-monthly cycle)	USD /kgH_2	25.4	[39]

In this exercise, the four reactors are assumed subject to staggered planned outages so that they result in a total of 90% capacity factor, as seen in Figure 10. The total thermal power available for hydrogen production ranges between 600 and 800 MWth, as seen in Figure 10 (e) below.

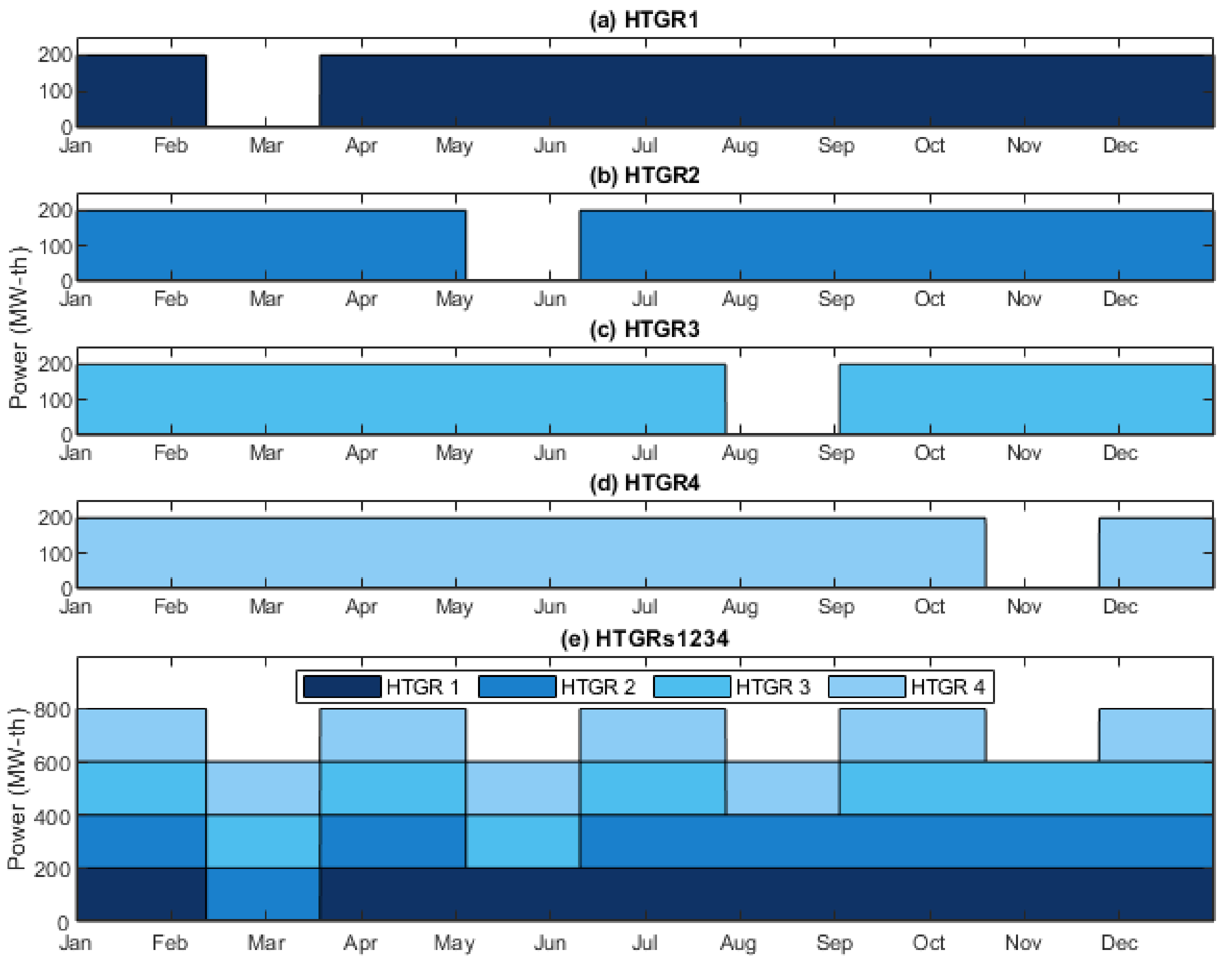


Figure 10: Available Thermal Power: (a) HTGR 1, (b) HTGR 2, (c) HTGR 3, (d) HTGR 4, and (e) HTGRs 1-4

Three scenarios are considered in this study to provide a constant rate of hydrogen supply to the nearby industrial facility without interruption, as summarized in Table 9. Note that because the amount of energy losses can vary greatly depending on storage duration, insulation, and environmental characteristics, for simplicity, perfect insulation is assumed without considering losses to the environment for hydrogen storage and TES.

Table 9: Hydrogen production and thermal storage scenarios (Canada)

Parameter	***Unit***	***Scenario 1***	***Scenario 2***	***Scenario 3***
Hydrogen production	kgH_2/h	Constant	Vary	Vary
Hydrogen supply	kgH_2/h	Constant	Constant	Constant
Hydrogen storage	kgH_2	No	Yes	No
Thermal energy storage	MWhth	No	No	Yes
Thermal power	MWth	800	800	800

The three scenarios are solved by the HESO tool to determine the hydrogen production rates, constant hydrogen supply rates, levelized costs of hydrogen (LCOH), hydrogen storage capacity, and TES capacity. Oxygen gas is sold at 0.09 USD per kilogram of O_2 to offset the cost of hydrogen production. The Hydrogen production, energy storage, and hydrogen supply are summarized and illustrated in Table 10 and Figure 11.

Scenario 1 assumes no hydrogen storage or TES and all HTGRs provide a constant thermal power of 600 MWth which is split to generate electricity of 241.4 MWe and heat of 63.5 MWth. The results in Table 10 and Figure 11 show that the system produces and supplies hydrogen at a constant rate of 6,353 kgH_2 per hour or 55.6 MtH_2 per year. This scenario resulted in a lower average capacity factor of 75%.

In scenario 2, all thermal power from all HTGR ranging between 600 and 800 MWth is used to produce hydrogen at rates of 6,353 and 8,471 kgH_2 per hour. As a result, the system produces and supplies hydrogen at a constant rate of 7,481 kgH_2 per hour or 65.5 MtH_2 per year. This scenario resulted in an average capacity factor of 90%.

Finally, scenario 3 assumes TES so that the available heat and power are used to produce hydrogen at a constant rate throughout the year. Thermal power ranging between 600 and 707 MWth from all HTGR is used to produce hydrogen and partly stored in TES, which can be used when needed. As a result, the system produced and supplied hydrogen at a constant rate of 7,481 kgH_2 per hour or 65.5 MtH_2 per year. This scenario resulted in an average capacity factor of 90%.

Table 10: Result Summary (Canada)

Parameter	***Unit***	***Scenario 1***	***Scenario 2***	***Scenario 3***
Annual hydrogen production	kgH_2/y	55,645,412	65,528,037	65,528,037
Hydrogen supply	kgH_2/h	6,353	7,481	7,481
Hydrogen storage capacity	kgH_2	0	1,397,037	0
Thermal energy storage capacity	MWh-th	0	0	131,942
HTGR capacity factor	-	75%	90%	90%
HTGR electricity and heat cost	USD /kgH_2	3.41	3.19	3.20
H_2 production cost	USD /kgH_2	1.11	1.25	1.10
H_2 storage cost	USD /kgH_2	0.00	2.03	0.00
TES cost	USD /kgH_2	0.00	0.00	2.79
O_2 revenue	USD /kgH_2	-0.80	-0.80	-0.80
LCOH	USD /kgH_2	3.72	5.68	6.29

Figure 12 (a) and (b) provide a comparative analysis of the LOCH and hydrogen supply based on three hypothetical scenarios, considering, no storage, hydrogen storage, and TES. Without any storage option, scenario 1 shows the lowest LCOH of 4.52 USD/kgH_2 with the lowest capacity factor of 75%. With storage options, scenarios 2 and 3 have higher LCOH at 6.47 and 7.09 USD/kgH_2 at the targeted capacity factor of 90%.

Produced as a byproduct, oxygen generates additional revenue at 0.80 USD/kgH_2, which helps enhance the viability of hydrogen production and storage. By subtracting revenue from oxygen, the LCOHs become 3.72, at 5.67 and 6.29 USD/kgH_2 for scenarios 1, 2, and 3, respectively.

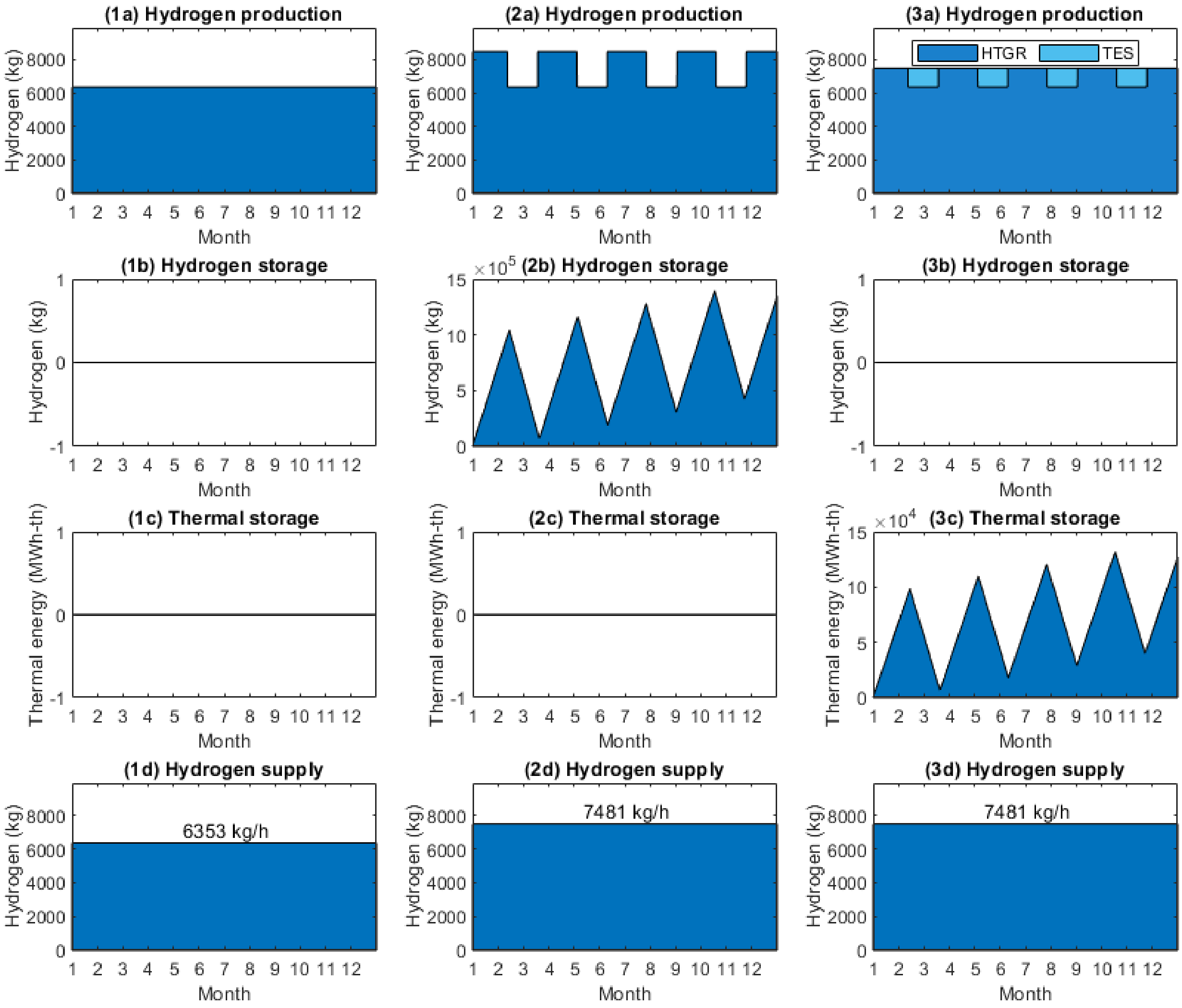


Figure 11: Hydrogen Production, Energy Storage, and Hydrogen Supply

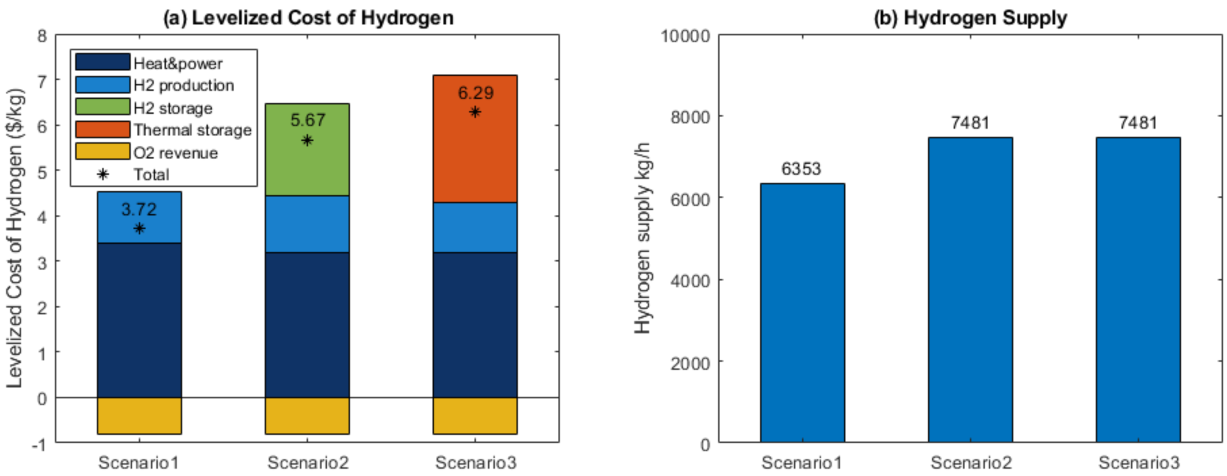


Figure 12: Levelised cost and supply of hydrogen determined using the HESO model

In conclusion, the competitiveness of hydrogen production significantly depends on the costs of energy, electrolyser, and storage. Despite the importance of energy sources and storage for hydrogen seen as a key energy alternative in future energy systems, many analyses fail to include sufficiently high resolution of the availability of energy sources and storage systems as part of the hydrogen supply chains. This study shows that all available heat and power from all HTGRs at a capacity factor of 90% cannot supply hydrogen at a constant rate without storage. With hydrogen storage, the electrolyser operates flexibly and takes advantage of all available heat and power from HTGRs. As a result, this system requires the largest hydrogen production capacity. With TES, the system takes advantage of TES to supply the required heat and power at a constant rate to the electrolyser. As a result, this system requires a smaller hydrogen production capacity. However, both hydrogen storage and TES increase the overall LCOHs.

2.1.2 Modeling outputs provided by France

For the modeling contributions from France, CEA used its PERSEE tool already introduced in Section 1.4.4. The PERSEE tool is designed to study dynamically energy systems from a techno-economic and environmental point of view but it can also be used to study such a static case. Nevertheless, it is not a financial software. There are some assumptions taken in the modeling like overnight CAPEX, applied discount rate, but inflation has to be added only in post-processing.

In addition to the modeling inputs provided in Section 2, CEA used additional assumptions including general assumptions, cost information, specific assumptions for HTGR fuel, and others. These assumptions are summarized in Table 11.

Table 11: General additional assumptions used by the CEA (France)

General Assumptions	
Project lifetime	40 years
Inflation rate	0%
Availability factors (HTGR and HTSE)	90%
Discount rate	5%
Overnight costs	Years to construct not taken into account

For HTGR assumptions, a fuel cost of 4.96 USD/MWhth is used, based on an initial fuel load of 5,500 kg per unit and an annual feed of 2,000 kg per unit at 3,660 USD/kg (aligned with IAEA assumptions), assuming a 90% capacity factor and 40-year operating lifetime.

The information provided to the CEA and summarized above and the modeling inputs listed in Section 2 were not sufficient to correctly model the HTGR in PERSEE. PEERSEE needs to know the fraction of thermal power that will not be worked on (allocated exclusively to hydrogen production) and what the impact is on the generated electrical power. This information was calculated and provided to the PEERSEE tool.

It is assumed that the HTGR's heat and electricity output aligns with HTSE requirements (38 kWhe/kg H_2 and 10 kWhth/kg H_2), with no energy losses. The reference operating point is 360 MWe for no thermal extraction (from 800 MWth at 45% efficiency), and the same Carnot efficiency ratio is assumed to apply when heat is extracted, valid only if the heat recovery fraction is low. With heat extracted at 750°C, the calculated heat recovery ratio is 11%, leading to an adjusted operating point of 89.6 MWth and 340.5 MWe (Figure 13).

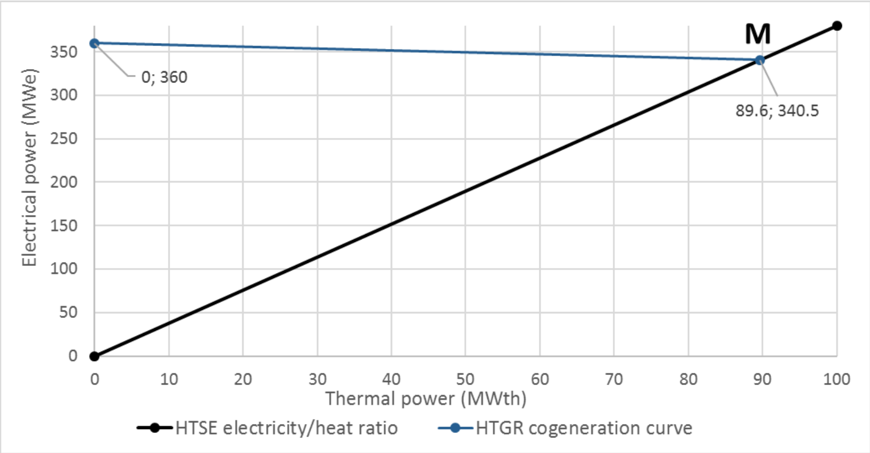


Figure 13: HTGR operation (France)

Cost assumptions for the HTSE system aligned with assumptions from the IAEA including a CAPEX of 1000 USD/kWe and a yearly OPEX of 7% of CAPEX. Notably, HTSE costs associated with stack replacement and stack degradation were not taken into account. Furthermore, a lifetime of 40 years for the HTSE system was assumed instead of 35 years and the cost of water was neglected.

The following model was implemented in PERSEE with the detailed parameters (Figure 14). This provided the optimal sizes and optimal operation. For this first simulation, since there is no temporal variation in operating conditions, heat storage and hydrogen storage are not required. The size of the HTSE is 340.5 MWe.

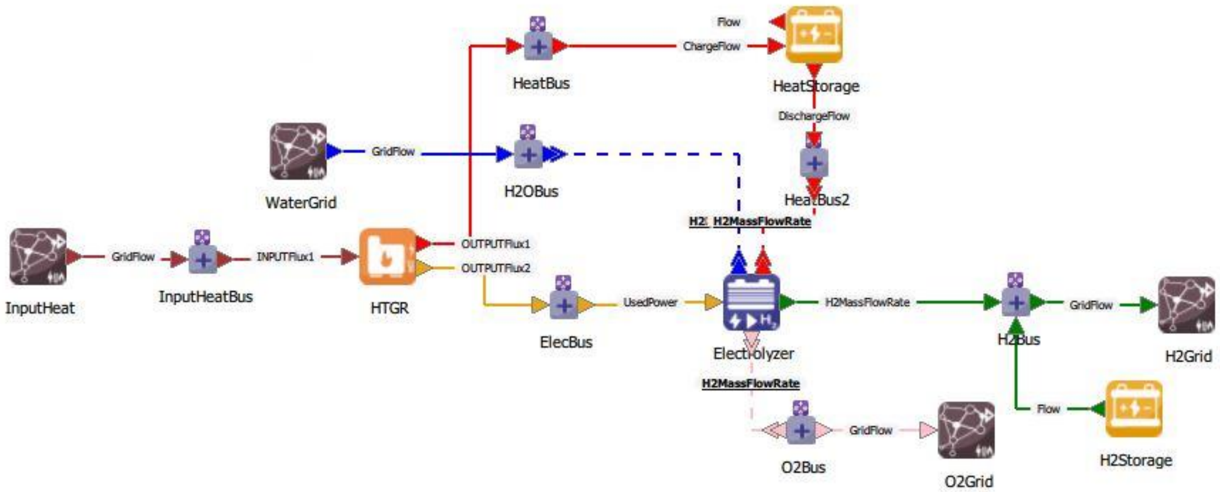


Figure 14: View of the PERSEE model (France)

This calculation resulted in the generation of 7.07e7 kg of hydrogen to be produced per year with a LCOH of 3.76 USD/kgH_2, without oxygen profit and 3.04 USD/kgH_2 with oxygen profit. The two LCOHs are shown in Figure 15.

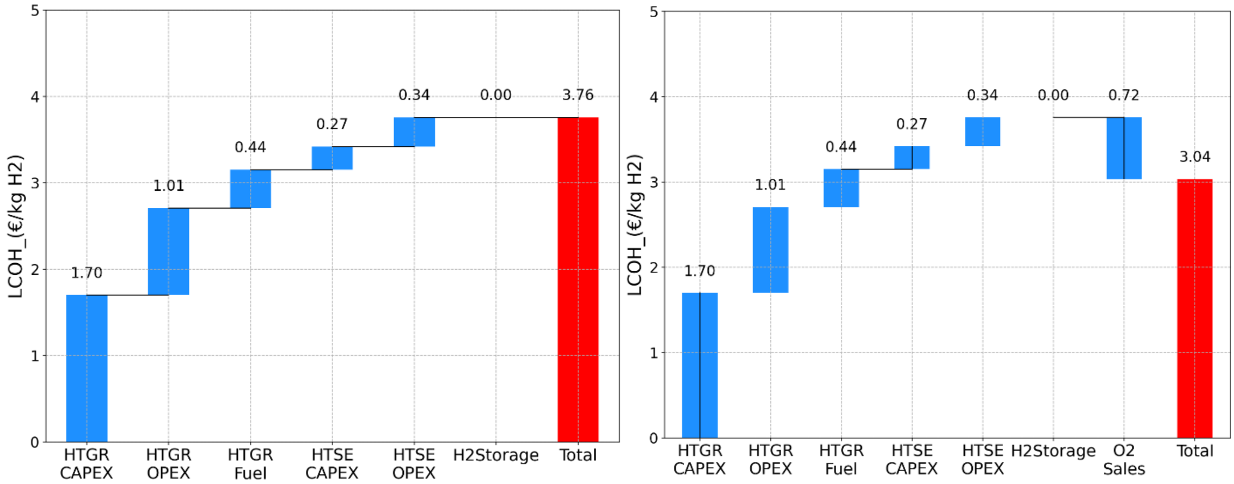


Figure 15: LCOH without and with O_2 valorization (France)

To go further in the calculation, stack degradation and stack replacement could be taken into account as well as the inflation. Furthermore, transportation could also be considered either owing to trucks or pipelines. Finally, sizing storages would make more sense if the case were dynamic.

2.1.3 Modeling outputs provided by the United Kingdom

The UKNNL has utilized their technical model of a Solid Oxide Electrolysis Cell (SOEC) stack and flowsheet to calculate the hydrogen production rate in the given scenario, and provide values for electricity, heat and water requirements for comparison.

UKNNL has developed an economic model that takes output from the technical model and uses this to calculate the levelized cost of hydrogen. Within the UKNNL modeling, costs are compared against a counterfactual which does not consider storage, this along with the fact there is limited data on storage needs means the UKNNL work does not currently consider hydrogen storage costs. This position is likely to change as UK government policy develops.

Using the input values provided as guidance by the NECA WG, model results were determined:

Table 12: Model outputs from UKNNL technical model of a SOEC stack and flowsheet

Per Stack Unit		
Stack Voltage	449.8	V
Stack Current	45.2	A
Current Density	0.558	A/cm2
Stack Electrical Duty	20319.3	W
Electrical Heater Duty	598.8	W
Balance of Plant Duty (rectifier losses, air blower, pumps, etc.)	1666.2	W
Total Electrical Duty	22584.3	W
Total Heat Duty of Low Temperature Steam	3137.1	W
Feed Water Required/Consumed	1.47608	g/s
Cooling Water Required (20°C in, 40°C out)	4.389	g/s
Feed Air Required	4.50269	g/s
Hydrogen Produced	0.16518	g/s
Specific Energy Consumption		
Specific Electricity Consumption	37.98	kWh/kg-H_2
Specific Thermal Energy Consumption	5.28	kWh/kg-H_2
Specific Reactor Energy Consumption	89.67	kWh/kg-H_2

Scale-up to 800 MWth HTGR Output		
Total Hydrogen Produced	2.478	kg/s
Stacks Units Required	15003	#
Total Water Consumption	87.99	kg/s
	316.77	m3/h

The model determined 2.48 kg of hydrogen to be produced per second requiring approximately 15,000 stack units. Each stack unit has 350 cells and an active area of approximately 80 cm2 per cell. As 15,000 stack units are required, each of the four reactors would require a minimum of ca. 38 sets of 100 stack units in order to completely meet capacity.

The current density range specified by GIF is 0.5-1.5 A/cm2. Published data from UKNNL uses a value in the middle of this range, however working with an industrial partner, UKNNL's current model is using a value towards the bottom end of the scale recommended by GIF.

The modelers noted discrepancies between the assumptions of performance provided as guidance, and the internal assumptions used. In particular:

- The electricity consumption matches closely the value provided by GIF (38 kWh/kg), this takes into account balance of plant (transformer losses and pumping) requirements etc. The GIF value is consistent with industrial values.
- The direct thermal energy consumption is significantly lower than the value provided by GIF (5.28 vs 10 kWh/kg). These differences cannot be easily explained and will require further detailed comparison between the UKNNL and GIF models.
- Water consumption is slightly higher than the value provided by GIF (87.99 vs 72.6 kg/s). In the UKNNL model most of the water is used for cooling/condensing the final hydrogen product. Again, further detailed comparison between the UKNNL and GIF models is required.

2.1.4 Modeling outputs provided by the International Atomic Energy Agency

Using the constraints, assumptions, and variables provided by this modeling exercise, the Hydrogen Economic Evaluation Program (HEEP) is used to determine the total cost of hydrogen production [34]. HEEP was developed and released by the International Atomic Energy Agency (IAEA) as a free tool which can be used to assess the economics of large-scale hydrogen production using nuclear energy. The HEEP models are based on economic and technical data, and on cost modeling which includes various aspects of the hydrogen economy including storage, transport, and distribution with options to eliminate or include specific details as required by the users.

The HEEP library models used for this modeling exercise are the HTGR510 and the HTSE04. These models were then adjusted based on the variables provided by GIF in Section 2. In addition to the modeling inputs recommended by the NECA WG, additional modeling input values were used from the HEEP library models HTGR510 and the HTSE04. The default values used in this exercise are listed in Table 13.

Table 13: Other Assumptions from HEEP Default Values

HEEP Input	***Section***	***Variable***	***Value***	***Unit***
Nuclear Generation	Power	Availability factor	100	%
Nuclear Generation	Power	Fresh fuel composition	100	% LEU
Nuclear Generation	Power	Spent fuel composition	99	% LEU
Nuclear Generation	Power	Spent fuel composition	1	% Pu

Nuclear Generation	Power	Capital cost fraction-electricity generating infrastructure	25	% of OCC_{HTGR}
Nuclear Generation	Power	Fuel cost	3660	USD/kg

Specific notable assumptions include HTGR initial fuel load of 5500 kg per unit and annual fuel feed of 2000 kg per unit based on the default HEEP libraries for the assigned power level of the reactor. A discount rate of 5% was assumed, equal to the interest rate, alongside an inflation rate of 2% and an equity-to-debt ratio of 50:50. The depreciation period was set at 40 years, with a tax rate of 0%. The HTSE overnight capital cost was estimated at 1000 USD per kWe, and its Operation and Maintenance (O&M) cost was assumed to be 7% of the overnight capital cost including the cost of the stack replacement. The HTSE's thermal and electric demand was entirely supplied by the HTGR, and costs related to hydrogen storage were excluded from consideration.

HEEP requires overnight capital costs of the nuclear power plant (OCC_{HTGR}) to be provided in USD per unit. To adjust the value provided, the following calculation was performed:

$$OCC_{HTGR} = OCC_{HTGR}\left(\frac{USD}{kWe}\right) * power\ rating(kWth) * Efficiency$$

which provided the OCC_{HTGR} to be 4.86e8 USD per unit. Operation and maintenance costs of the nuclear power plant ($O\&M_{HTGR}$) are required in HEEP as a percentage of OCC_{HTGR} (per unit). GIF provided $O\&M_{HTGR}$ as USD/MWh. To adjust the value provided, the following calculation was performed.

$$O\&M_{HTGR} = \frac{O\&M_{HTGR}\left(\frac{USD}{MWh}\right) * power\ rating(MWth) * Efficiency * 8760\left(\frac{hr}{yr}\right)}{OCC_{HTGR}(USD)}$$

which provided $O\&M_{NPP}$ costs to be 3.65% of the OCC_{HTGR} per year. It is assumed that the O&M cost provided by the NECA WG does not include the cost of fuel for the nuclear plant.

Based on an energy balance where the total amount of nuclear power generated is solely used for hydrogen production, the following calculations were performed using electricity consumption and thermal energy consumption variables provided by GIF.

$$Heat\ consumption\ (MWth) = power\ rating(MWth) * \frac{thermal\ energy\ consumption}{thermal\ energy\ consumption + \frac{electricity\ consumption}{efficiency}}$$

$$Electricity\ consumption\ (MWe) = \left(power\ rating(MWth) - Heat\ for\ H2\ Plant\ (MWth)\right) * power\ conversion\ efficiency$$

which determined that the amount of heat for the hydrogen plant is 21.17 MWth per unit and the electricity rating is 80.47 MWe per unit. As input for the hydrogen generation plant details, these values are multiplied by four to be the total values of 84.70 MWth for heat consumption and 321.88 MWe for electricity required.

Finally, for the overnight capital cost of the hydrogen generation plant, a value of 1000 US dollars per kWe was assumed. The total overnight capital cost of the HTSE (OCC_{HTSE}) was then determined through the following calculation:

$$OCC_{HTSE} = electricity\ consumption\ (KWe) * 1000\left(\frac{USD}{kWe}\right)$$

The resulting OCC_{HTSE} of 3.22e8 USD was used as input for the HEEP calculations. It is noted that hydrogen storage costs are not considered.

The hydrogen generation per unit in kg/year is one of the input parameters required in HEEP for the hydrogen cost calculations. The following equation was used to determine the amount of hydrogen generated:

$$Hydrogen\ generation\left(\frac{kg}{yr}\right)=\frac{heat\ consumption(MWth)*8760\left(\frac{hr}{yr}\right)*capacity\ factor}{thermal\ energy\ consumption\left(\frac{kWh}{kg\ H_2}\right)*\frac{1}{1000}\left(\frac{MWh}{kWh}\right)}$$

This calculation resulted in the generation of 6.68e7 kg of hydrogen produced per year. Based on this and all other input values provided and derived, HEEP determined the LCOH to be 3.89 USD/kg H_2, as shown in Table 14 and Figure 16.

Table 14: H_2 cost breakdown from IAEA HEEP (USD/kg)

Facility	*Capital Cost (Debt)*	*Capital Cost (Equity)*	*O&M + Refurb-ishment*	*Consum-able Cost*	*Decomm-issioning Cost*	*Fuel Cost*	*Facility Total*	*Less By-Product*
Nuclear Power Plant	0.82	0.79	1.18	0	0	0.49	3.28	0
Hydrogen Generation	0.12	0.12	0.38	0	0	0	0.61	0
Hydrogen Storage	0	0	0	0	0	0	0	0
Hydrogen Transportation	0	0	0	0	0	0	0	0
Total of all facilities	0.94	0.91	1.56	0	0	0.49	3.89	

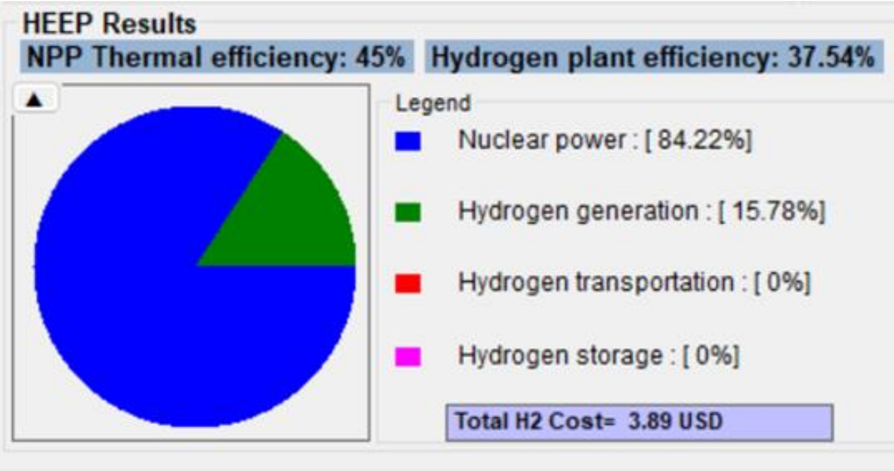


Figure 16: HEEP calculated hydrogen cost percentages from nuclear and hydrogen production facilities

As stated in the GIF modeling exercise specifications, oxygen gas will be sold to offset the production costs of hydrogen. To determine the additional profit from oxygen sale, the following calculation was performed:

$$Oxygen\ profit\left(\frac{USD}{kg\ H_2}\right)=O_2\ generation\ rate\frac{kg\ O_2}{kg\ H_2}*O_2\ market\ price\frac{USD}{kg\ O_2}$$

which determined that for every kilogram of hydrogen produced, the oxygen profit would be USD 0.72. Subtracting this from the hydrogen cost found above, 3.89 USD/kg H_2, the LCOH including oxygen profit is found to be 3.17 USD/kg H_2.

2.2 Discussion on system modeling and analysis results

To complete this pooled system modeling and analysis exercise, a set of recommended modeling inputs was shared with the respective modeling teams within the relevant GIF and NEA groups. While the system scenario and the proposed modeling inputs were useful to guide the direction of the model, they proved to be insufficient and modeling teams were required to make additional assumptions in order to complete the exercise.

In general, there was agreement that the proposed model input was appropriate for a first order collaborative analysis effort, with some discussion on appropriate values for overnight capital costs, operating temperatures and pressures, and the current density of HTSE systems. Notably, the CEA PERSEE and the IAEA HEEP modeling teams both adopted an overnight capital cost value of USD1000 per kWe, which was viewed as conservative but reasonable for this type of first order analysis. Additionally, a relatively broad range of current density was provided as a recommendation to the modelers given the range of values found in literature. Given recent research efforts, it is clear that higher current density values may impact the LCOH considerably and may be higher than originally considered.

In general, the independent models agreed relatively well based on the generic scenario and recommended model inputs provided.

This broad agreement may be an outcome of the choice of a very simple system that is easily comparable to first order by a range of different methods. As each model is optimised for slightly different applications and markets, any deviations between the models might become more evident as detailed systems are considered and compared. Members of NEA and the GIF are encouraged to pursue code comparisons bilaterally for higher fidelity systems to improve the quality of a benchmark for these holistic system codes.

For the total amount of hydrogen produced for this scenario, three of the four modeling teams agreed within 6% with an approximate value in the range of 56-71 million kilograms of H_2 produced per year.

Table 15: Amount of hydrogen produced for the specified scenario

Model	***H_2 produced (kg H_2 per year)***
CNL HESO Scenario #1	55.6 M
CEA PERSEE model	70.7 M
UKNNL	70.4 M
IAEA HEEP	66.8 M

This average annual production of approximately 66 M kg H_2 per year is a significant quantity of hydrogen to be produced at a constant rate. However, this rate of hydrogen consumption appears reasonable for some industrial applications that would consume hydrogen as a feedstock. In particular, the Korean steel making company POSCO is developing their HyREX process which intends to use hydrogen as a reducing agent for the production of steel, which will require 1 million tonnes, or 100 M kg, of H_2, per year for their first commercial plant planned for the early 2030s [40].

Notably, the modular nature of HTSE stacks is expected to be suitable for applications at this scale, assuming the HTGR can be built and constructed at the 800MWth scale prescribed above. Analysis from the US INL has attempted to quantify the learning rates for HTSE stacks given their modular nature, which suggests that the bulk of the cost reductions at a HTSE plant capacity of approximately 200 MW [41]. It is therefore recommended to demonstrate a HTSE plant at the 200 MW scale to improve cost certainty for an integrated system at 800MWe or more.

The levelised cost of hydrogen results also show relative agreement. They also appear to be approximately consistent with several recent and ongoing initiatives within GIF and NEA members countries to explore the economic opportunity to produce hydrogen using a HTGR reactor type. Specific values for levelized hydrogen costs are available in Table 16 below, as available:

Table 16: Predicted levelized cost of hydrogen (LCOH) for the specified scenario.

Model	***LCOH (USD/kgH_2)***	***LCOH with offset from O_2 sales (USD/kgH_2)***	***Notes***
CNL HESO Scenario #1	4.52	3.72	No storage assumed
CNL HESO Scenario #2	6.47	5.67	Hydrogen storage assumed
CNL HESO Scenario #3	7.09	6.29	Thermal energy storage assumed
CEA PERSEE model	3.76	3.04	No storage assumed
IAEA HEEP	3.89	3.17	Existing HEEP libraries used, no storage assumed

As CNL's HESO Scenario #1 is most similar to the scenarios used in the CEA PERSEE and IAEA HEEP models, the cost of hydrogen for this common system using the recommended modeling inputs is well constrained between USD 3.04 and USD 3.72 per kilogram of H_2.

These values approximately align with reported values in literature. Previous NEA analysis in 2022 showed an expected levelized cost of hydrogen produced through water electrolysis to be below or around USD 3.5 per kgH_2 by 2035, with the potential to achieve costs below USD 3 expected through the improved optimization of high temperature electrolysis processes [4].

In the UK, the UKNNL has written a technoeconomic paper [1] where an estimate of the levelised cost of hydrogen produced by a first-of-a-kind HTGR+HTSE system in 2040 was made to GBP 2.16/kg at 2016 prices (USD 3.53/kg at 2023 USD prices), however the methodology was quite different and described in Connolly et al. 2024. Another independent study in the UK similarly found the levelized cost of hydrogen of USD 3.8/kg using a Topsoe SOEC powered by a LWR Rolls Royce SMR.

In Europe, the GEMINI 4.0 initiative is working to evaluate the competitiveness of hydrogen produced from a prismatic HTGR system and the design and licensing framework needed to address European industry needs. Cost estimates using flowsheets developed for this project are expected to be published in 2025.

The impact of storage to the levelized cost of hydrogen is also evident based on the modelled scenarios submitted by CNL in Canada. While the addition of storage enables the integrated system to achieve the target capacity of 90%, there is a penalty in the corresponding cost of hydrogen. This may suggest that the value-maximizing solution for an integrated system may be one that avoids thermal or hydrogen storage solutions and instead pursues "market switching" to serve multiple electricity, heat, and hydrogen markets concurrently and efficiently. The business model of a given operation is therefore a critical component on the feasibility of hydrogen or hydrogen-derived products, which was explicitly missing from this analysis.

While these costs may not be directly competitive with hydrogen produced from steam methane reforming and other competing processes on a levelized basis, there are a number of cost reduction strategies that could be implemented in a system that utilizes a HTGR system at scale. One key strategy is leveraging the flexibility of an integrated system to serve multiple heat, electricity, and hydrogen energy markets simultaneously, allowing operators to optimize revenue streams while providing grid reliability services. Additional cost reductions are expected from improved economies of scale and technological advancements. As more HTSE plants are deployed, manufacturing efficiencies, modular construction, and optimized supply chains will lead to lower capital costs. Operational improvements and technical advances in electrolysis and balance-of-plant components may further enhance efficiency and durability.

Finally, the capital cost of the GenIV reactor will a significant driver of hydrogen production costs, which are not known for a commercial system. Additional refinement of the reactor-related costs will improve the accuracy of the costs of the produced hydrogen.

While a sensitivity analysis is beyond the scope of this report, it would be a useful exercise to improve the benchmark across the modeling tools used in this report and also help to systematically determine the impact of specific variables to the final levelized cost of hydrogen. In particular, it is recommended to bilaterally or multilaterally compare results of a sensitivity analysis on capital and operating cost assumptions for both HTGR and HTSE systems to understand the potential impact of the proposed cost reduction strategies for the integrated system.

3 System readiness questionnaire and assessment

The system readiness questionnaire was developed to collect expert views from industry, researchers, nuclear energy technology developers, hydrogen production technology developers, and others on the readiness of a high-temperature gas reactor to produce hydrogen through high-temperature steam electrolysis. This subjective input is intended to complement the objective results from the modeling studies.

The survey questions are available in APPENDIX 1: System Readiness Questionnaire, and has five sections:

- Introductory Information
- System Definition
- Perspectives on the technological readiness of system components
- Perspectives on the commercial readiness of an integrated system
- Additional performance indicators

The Technology Readiness Level (TRL) scale is a widely deployed metric used to assess the maturity of a technology. As the technology matures from level 1 to level 9, it moves from a scientific idea through to a fully developed application that has been deployed successfully in an operational situation.

It should be emphasized that a TRL assessment is at best a simplified measure of what is in reality a highly complex and ever changing international technological situation. Interpretation of the definitions and then using these interpretations in a TRL assessment is subjective to a degree and is challenging to apply consistently. TRL assessment also gives no indication of the amount of time, effort, or cost required to increase a technology’s TRL.

TRL values are potentially more useful for comparisons between technologies than they are when considered individually as absolute values. In all the assessments performed as part of this work, for a technology to be assigned level 9 on the TRL scale, it must be directly integrated with a nuclear power system and achieve successful commercial operation at when coupled to a nuclear power system.

The specific requirements to achieve the various levels of technological readiness vary depending on the technology area and desired assessment criteria. The 9-point scale used in this assessment is listed below, which is consistent with literature [42] [43] [44] and informed by existing TRL frameworks in related contexts.

Table 17: Technological Readiness Level (TRL) scale and definitions used in this study

TRL Level [a]	***Definition***
TRL 1	Research identifies the principles that underlie the technology. e.g., A particular application of nuclear heat has been identified showing promise for an end-user
TRL 2	Practical applications are suggested and concepts are formulated. e.g., Preliminary work is undertaken to assess the practicalities of using the low-carbon heat such as initial screening of candidate materials that would be required to make the application feasible
TRL 3	Basic components are fabricated and successfully demonstrated. e.g., Materials have undergone successful testing at the relevant temperatures and pressures and been fabricated into basic components.

TRL 4	Components are integrated into a basic system. e.g., Representative assembly sections have been manufactured and subjected to out-of-reactor tests and/or test reactor irradiation trials of individual materials/components have been conducted with limited success.
TRL 5	Basic system is successfully demonstrated at a small scale. e.g., The different components associated with, for instance, a sulfur-iodine cycle have been integrated into a simplified system and produced very small quantities of hydrogen.
TRL 6	A prototype is constructed (much more representative than the basic system). e.g., more fully integrated production system has been demonstrated, operating continuously at high capacity factors and capable of producing tons of H_2 per day.
TRL 7	Prototype is successfully demonstrated. e.g., A prototype reactor is constructed (that is not designed to be run commercially and at high capacity factors) and integrated into a heat network.
TRL 8	A system designed to meet all the reference requirements has been constructed and commissioned.
TRL 9	Actual system is successful under operational conditions.

[a] The authors acknowledge that broad TRL assessments may not fully reflect nuclear energy system readiness, as they overlook site-specific design requirements and requirements to use qualified equipment.

Extending beyond technological readiness, the questionnaire also asked experts to comment on the perceived commercial readiness of an integrated HTGR + HTSE system. A 6-point scale has been adapted from the Commercial Readiness Index framework that has been well documented by the Australian Renewable Energy Agency [45]. The framework is designed to complement the TRL index by addressing the commercial uncertainties and risks that arise during the demonstration and deployment phases of new technologies in the areas of:

- regulatory environment,
- stakeholder acceptance,
- technical performance,
- financial proposition,
- industry supply chain and skills, and
- market opportunities.

In each category, responses intend to determine the readiness of the integrated system. The full list of questions to assess the readiness in each of the above categories is available in APPENDIX 1: System Readiness Questionnaire.

3.1 Results from system readiness questionnaire

All of the answers that were provided by respondents to the system readiness questionnaire have been aggregated. In total, there were 15 responses from experts in the nuclear energy and hydrogen fields, as well as other relevant stakeholders as seen in Figure 17. Ten (10) of the respondents had more than 15 years of experience in either the nuclear energy sector and/or the hydrogen sector, with 14 participants having at least 5 years of experience in either one sector or the other. The expertise of specific researchers spanned materials development and testing, chemistry, among others.

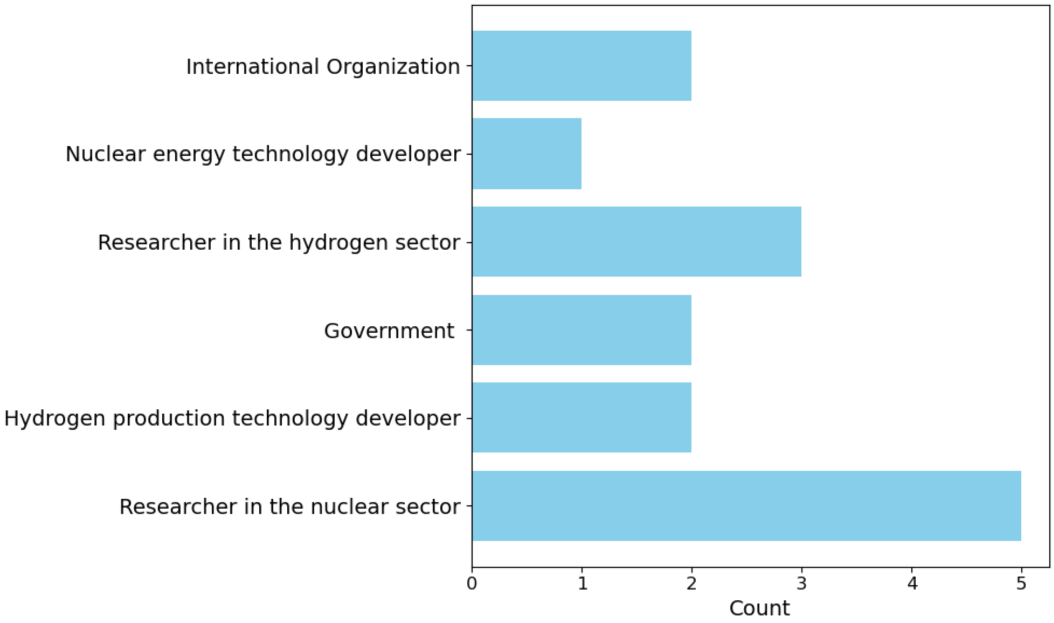


Figure 17: Types of experts that responded to the system readiness questionnaire

Respondents were also geographically located as illustrated in Figure 18, with experts completing the survey in eight (8) countries. In particular, there were four respondents in Canada, one in Czechia, two in France, two in Japan, two in Korea, one in the Netherlands, one from the United Kingdom, and one from the United States. Each expert was asked to comment on the technical readiness of a HTGR, a suitable HTSE, and the integrated combined system. Additionally, experts commented on the perceived commercial readiness and expected timelines associated with this integrated system, and commented on additional key performance indicators.

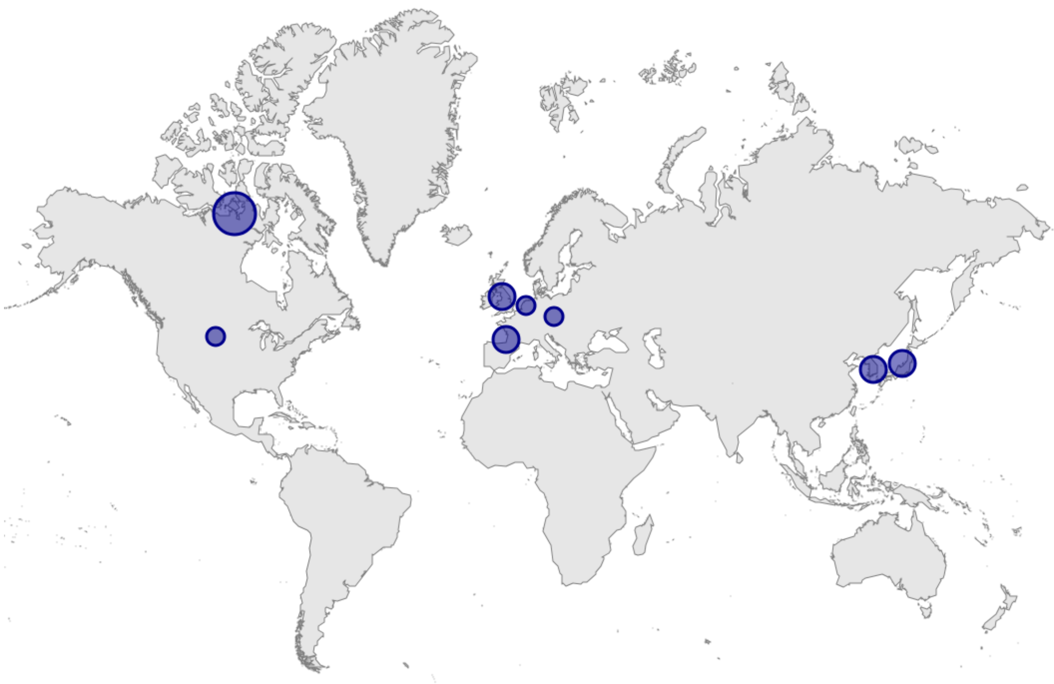


Figure 18: Geographic distribution of expert respondents to the System Readiness Survey for a HTGR and HTSE system, using the centroid of their affiliated country.

For the technological readiness of a HTGR, the respondents noted that the HTR-PM pebble-bed reactor type is already commercially operating in China. On aggregate, it is also suggested that there is sufficient progress on the development of prismatic HTGR reactor types that they could also operate commercially. While there was a range of responses based on a variety of assumptions and context, most experts suggest a high technological readiness level with a mode response of eight (8) and median of six (6).

Similarly for HTSE technologies, respondents noted that HTSE prototypes have been successfully demonstrated around the world. Some respondents also suggested that HTSE stacks are already commercially available with developers such as Siemens, Sunfire, and Bloom, although the size of HTSE stacks available commercially are not suitable for coupling with a HTGR system at this time. A mode TRL of seven (7) and a median TRL of six (6) is suggested based on expert responses for this HTSE system.

For an integrated system coupling a HTGR with a HTSE, there was a consensus agreement among respondents that the integrated system is in its infancy. Experts noted that components required for the integration are available, including suitable thermal storage solutions which have demonstrated and in operation in a number of concentrated solar power plants. However, the adaptation of these technologies to nuclear energy has not yet been completed and the concept of integrating the two is not mature. The TRL of this integrated system is therefore significantly reduced compared to the individual HTGR and HTSE components, with a mode TRL of one (1) and a median TRL of three (3).

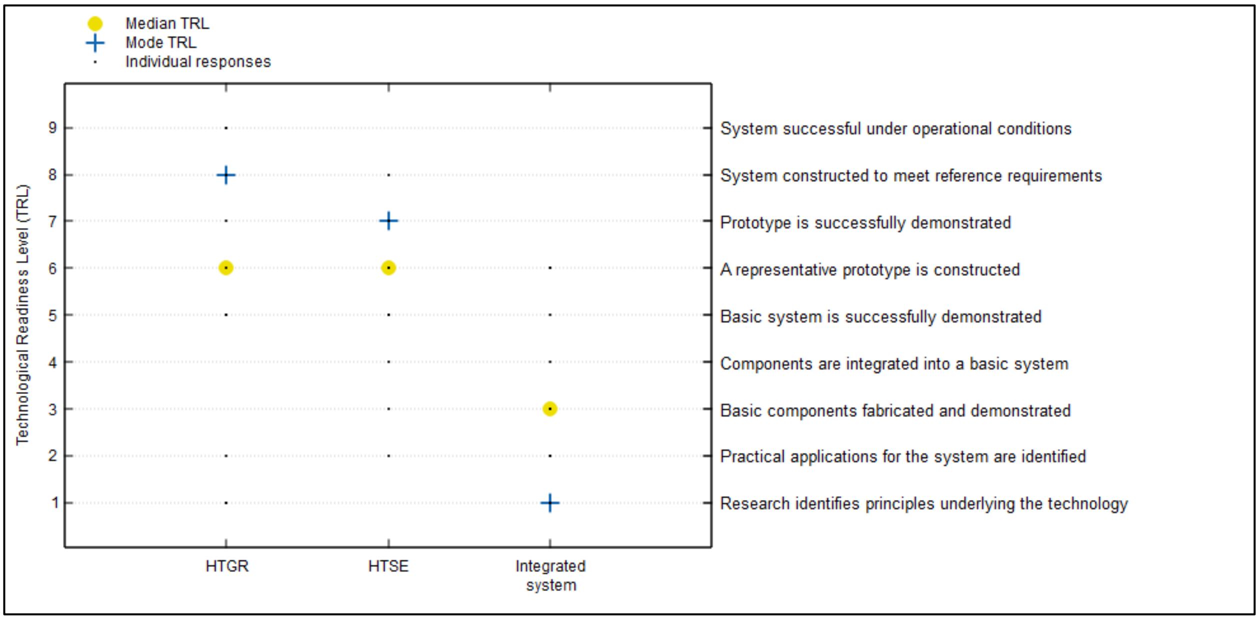


Figure 19: Aggregate questionnaire responses from experts related to the technological readiness of a HTGR, HTSE, and an integrated commercial system.

Respondents provided feedback on the readiness towards commercialization of this integrated system using the 6-point Commercial Readiness Index framework discussed above developed by ARENA and adapted for this work.

The **regulatory environment** for an integrated system where a HTGR produces hydrogen through high-temperature steam electrolysis is a clear barrier to the commercial readiness of the system according to expert responses. In particular, respondents noted that regulatory processes and their associated timelines are currently undefined, and there are specific regulatory barriers that require project specific consideration to address. Based on the responses that were not selected by experts, this also suggests that the regulatory environment has not emerged to the point that clear recommendations to address the barriers have been articulated.

While responses diverged, the mode value associated with **stakeholder acceptance** of an integrated system suggests that stakeholder support would be dependent on the specific project on interest, while broad stakeholder concerns are beginning to become understood. The responses also suggest that there is a lack of evidence and experience to inform stakeholders of the realities of a project which challenges gaining acceptance.

Related to the **cost data** associated with this system, respondents converged towards a commercial readiness indicator that suggests that cost data is available to some extent, but the key costs are based on projections with little actual data available to verify. Cost drivers associated with this integrated system are also not understood to improve judgement on long-term prospects.

Reponses focused on **revenue data** were similarly coherent among responses suggesting the largest barrier towards commercialization. Revenue data for this integrated HTGR and HTSE system is based on projections and forecasts with little or no prior data to substantiate. At the moment, revenue projections are not sound creating challenges towards commercial pricing structures for a given project.

The commercial readiness of the integrated system from the perspective of its **supply chain** yielded the largest diversity in responses. Expert responses suggest that while the supply chains necessary to commercially develop this system are taking steps toward maturity, at best, there are limited supply options available that have been proven to a useful degree. More realistically, the willingness and availability of a supply chain may depend on the specific project of interest and supply chain participants would likely need to consider the project against other projects that align with their current business models.

Finally, emerging as another significant barrier is the commercial readiness indicator associated with **market opportunities** for this integrated HTGR and HTSE system broadly. While the system appears to be a promising solution to a potential commercial opportunity, commercial trials have not definitively identified a target market to demonstrate to future investors that the technology can operate reliably and generate predictable revenue from a cost base that is understood.

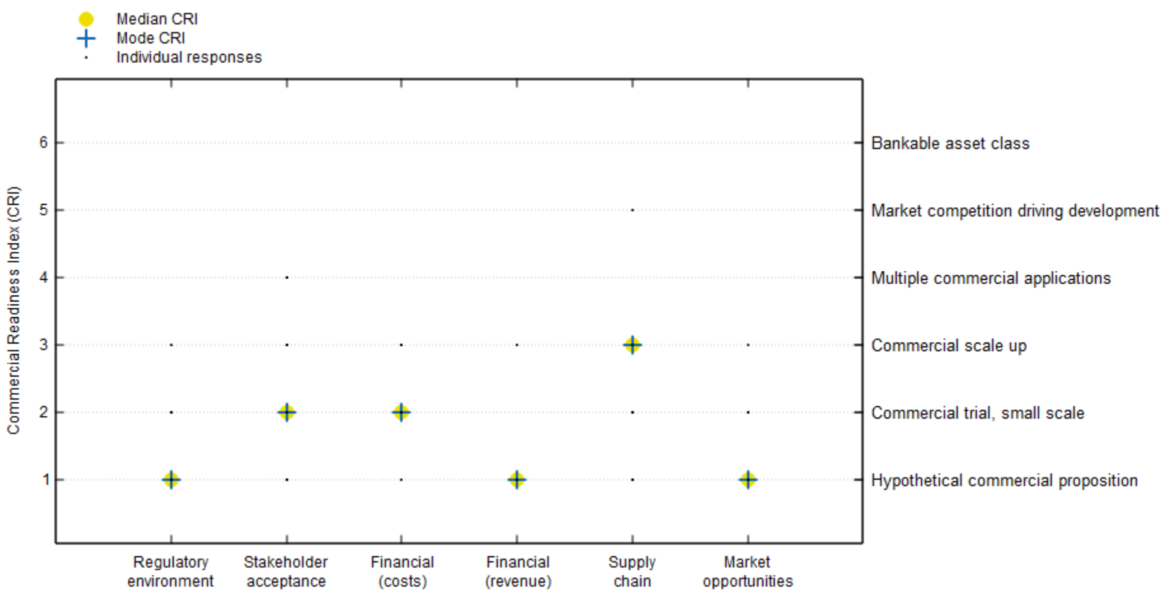


Figure 20: Aggregate questionnaire responses from experts related to the commercial readiness of an integrated commercial system coupling a HTGR with HTSE.

Experts also responded to the timelines associated with an integrated system that produces hydrogen through HTSE using an HTGR. The responses on an estimated timeline varied significantly, with the expected timeline for an integrated demonstration to be anywhere between the late 2020s and mid-2030s. Several experts projected much longer timelines with a representative commercial system expected to come online by 2050, depending on the availability of HTGR data at a demonstration scale in the near term.

For the deployment of an integrated commercial system, experts projected even greater variability in timelines, spanning from the early 2030s to well beyond mid-century. While some estimated commercialization within 10 to 20 years—pointing to 2030 or 2040—others suggested longer horizons of 20 to 30 years or more, with projections extending beyond 2050. Key factors influencing this timeline include the availability of HTGRs at a commercial scale and the time required to establish the necessary regulatory framework for HTGR/HTSE coupling at an international level.

Table 18: Estimated timelines according to questionnaire responses for an integrated demonstration and commercial system.

System	***Range in estimated timelines***
Estimates for an integrated demonstration	2026 – 2050 (Most estimates: 2028–2035)
Estimates for an integrated commercial system	2030 – 2050+ (Most estimates: 2040–2050)

Finally, experts commented on the readiness of the integrated system according to other key performance indicators, including GHG emission reduction potential, benefits of the system compared to alternatives, geographical adaptability, and scalability.

Respondents noted that the system's potential to reduce greenhouse gas emissions is significant, with significant reductions of CO_2 per ton of hydrogen produced when compared to alternatives such as hydrogen production through steam-methane reforming. The expanded benefits of the system also expands to the high energy availability factor of nuclear energy, noting a specific suitability to end-use applications that require a constant and reliable supply of hydrogen and power.

3.1 Discussion on system readiness questionnaire results

The commercial viability of an integrated HTGR and HTSE system for hydrogen production depends on more than technological maturity and high TRL values. The viability and suitability of this system is influenced by a range of factors, including regulatory frameworks, stakeholder acceptance, supply chain maturity, and market opportunities.

The commercial readiness of this system broadly depends on its suitability for specific market applications. This includes markets with a demand for reliable supply and high quantity of hydrogen typical to large industrial processes. Proximity to these industries and strong policy support are likely requirements to the success of an integrated HTGR and HTSE system within a given jurisdiction.

Despite these barriers, the system's ability to address long-term energy security, decarbonization goals, and scalability suggests that there is likely an environment where this technology will make sense and achieve commercial viability.

3.1.1 Technological readiness of an integrated HTSE and HTGR system

The HTR-PM in China represents an operating commercial HTGR. However, expert respondents to the system readiness survey suggest that HTGR technology is not commercially mature at this time. The mode and median TRL of the HTGR system was determined to be 6 and 8, respectively, according to the system readiness survey conducted in this study.

The TRL framework that is used may not account for some specificity in the nuclear energy sector. In particular, the qualification of materials and components that are required for HTGRs poses a barrier to commercial deployment of HTGRs today, which is distinct for the nuclear energy sector, if not completely unique.

The TRL of using HTSE to produce hydrogen was determined to have a median TRL of 6 and mode TRL of 7, which aligns with expectations in literature [4] [46]. While HTSE technology stacks are in nature highly modular technologies, they have not been demonstrated at a commercial scale, nor the large scale that would be suitable for a dedicated HTGR reactor.

Although experts view that there is a relatively high TRL for both HTGR and HTSE, experts view the readiness of an integrated system combining HTSE with a HTGR to be low, with a median TRL of 3 and mode TRL of 1. The process of coupling HTSE with HTGR involves combining two innovative technologies that are both working to become mature at scale, which creates significant uncertainty in a combined system. The success of an integrated system would therefore benefit from increased maturity of HTSE technologies at the relevant scale.

Compared to alternative energy sources, a large demand for hydrogen at a single point of consumption or offtake represents a potent market opportunity to use GenIV reactors to produce hydrogen using HTSE.

In general, respondents suggest that there is little evidence that this system is capable of operating at the scale required. To advance the TRL of an integrated system, it is therefore recommended to build a representative demonstration, or a commercial system, of HTSE coupled to existing LWR reactors at a suitable scale. This would allow HTSE to become a mature technology prior to coupling with a HTGR or another GenIV reactor concept, which are independently progressing towards maturity.

HTSE stacks are modular by nature, and demonstrating the integration of HTSE stacks with existing LWRs is expected to increase the TRL into a mature technology, which would then be more suitable for integration with GenIV reactor systems. Finally, as an existing LWR may already have a significant proportion of its initial capital costs paid off, this may be an effective strategy to constrain the elevated costs associated with demonstration or initial commercial units.

3.1.2 Perceived commercial readiness of an integrated HTSE and HTGR system beyond TRL

The commercial readiness of an integrated HTGR and HTSE system is defined by challenges that extend beyond technological maturity and innovation. Key barriers have arisen from the System Readiness Survey in the areas of regulatory readiness, cost and revenue uncertainties, and the suitability to a specific market. Addressing these non-technical factors is essential to advancing the system toward large-scale deployment and commercial viability.

One of the most significant barriers identified is the lack of regulatory readiness. Current regulatory frameworks are fragmented internationally, with codes and standards evolving at different rates in different regions. While some collaborative efforts, such as joint regulatory assessments across jurisdiction, show promise, there is effort required to develop precedent for a couple HTGR and HTSE integrated system. Harmonization of regulatory efforts, particularly in regions like the EU, is ideal but remains challenging due to varied national provisions and limited collaboration among nuclear regulators.

The authors recommend that regulators collaborate to share information and analysis on the considerations that are required to ensure the safety and effective licensing of this coupled system, such as through existing mechanisms including the NEA Working Group on New Technologies (WGNT). The GIF intends to support efforts by regulators to explore the risks of non-electric applications, such as to produce hydrogen using a HTGR, to help inform a pathway towards improved regulatory certainty.

Stakeholder acceptance also poses a challenge, reflecting both an opportunity and a barrier to progress. While government initiatives and policy support highlights growing interest in the role of GenIV reactors in the hydrogen economy, there skepticism associated with delivering on large-scale, integrated projects. Public acceptance therefore remains variable and tied to local contexts, and there is a need for relevant stakeholders to continue efforts to explore the potential role of heat markets in a decarbonized future.

Cost and revenue uncertainties appear to be the greatest barrier towards commercial deployment of these systems. This includes the potential for the total cost to be higher than alternatives but extends more broadly to price certainty and stability for these projects. Although modeling and projections provide a theoretical basis for its competitiveness, the absence of operational systems makes validation impossible, and the associated revenue potential is therefore speculative. Improved cost data is therefore critical. The development of specific economic models for a specific process and environment is recommended to develop a case for the feasibility of an integrated HTGR and HTSE system, on a case-by-case basis. Additional demonstrations of HTGR and HTSE technologies at scale, without integration, is also recommended to improve cost certainty for a future integrated system.

The supply chain readiness for this integrated system reveals both progress and gaps. While established supply chains may be available for HTGRs, HTSE stacks, and other individual components required for an integrated system, there is very limited experience in coupling nuclear energy with hydrogen production or other chemical processes. Moreover, the availability of components required for this system may depend on competing demands from other hydrogen production pathways, such as renewables.

Underpinning specific barriers to commercialization is the actual market demand for this system. Market opportunities were determined to be relatively promising but require significant de-risking to achieve maturity. Policies supporting net-zero emissions and the transition to low-carbon hydrogen create a favorable policy environment, but the integrated system must compete with established methods like steam methane reforming coupled with CCUS. Demonstrating a specific market for reliable, constant, and high quantities of hydrogen represent a specific opportunity for GenIV reactors to support the hydrogen economy.

Finally, it is worth noting that this system readiness questionnaire was open and available for responses for a period exceeding one year, with the first responses received in January 2024 and the final response received in January 2025. As the technological development and commercialization of both HTGR and HTSE technologies continued to advance during this time, there is a possibility that early responses have suppressed evaluations of the system's readiness compared to more recent responses.

4 Conclusion

This report highlights the opportunities and challenges associated with the development and commercialization of an integrated system combining a 800MWth High-Temperature Gas-cooled Reactor system with High-Temperature Steam Electrolysis for hydrogen production. The report includes a comparison of independently developed modeling capabilities within GIF and NEA member countries, and consolidates expert opinion on the perceived readiness of the integrated system.

The distributed modeling exercise used in this study was useful to demonstrate the similarities and differences amongst system codes in GIF and NEA member countries. The selection of a suitable scenario and modeling inputs was conducted over a period of eight months from January to August 2024 after down-selecting from a range of values used regionally for various use-cases. The scenario and full list of modeling inputs is summarized above.

A simple system using HTGRs to produce hydrogen at a large and constant rate for immediate consumption proved to be a useful initial model for comparison purposes, as the simplicity enabled the alignment of results. The 800 MW HTGR system was shown to produce between 56-71 million kilograms of H_2 per year, which is within the expected order of magnitude for some large future off-takers of hydrogen for industrial applications, such as for steel production [40]. Markets with high demand for hydrogen at a single point of consumption appears to represent a potentially competitive environment for nuclear energy to produce hydrogen.

Predicted costs of hydrogen were determined and constrained to be USD 3.04 and USD 3.72 per kilogram of H_2 when the cost of on-site storage is neglected. These values generally align with expected values in the literature, with improved costs expected for more-detailed systems with improved utilization of the available energy.

Modeling performed from the Canadian Nuclear Laboratories compares the prescribed common scenario under varying storage conditions. Including the cost of storage increased the capacity factor of the HTGR system to the intended value of 90%, but also increased over LCOH costs. This suggests that the most profitable value for an integrated system to be one where multiple markets can be served simultaneously to maximize the available energy from the reactor while minimizing the use of storage and its associated costs. Additional cost reduction strategies are expected to be implemented as technology develops for both HTGR and HTSE systems.

With respect to the perceived technological and commercial readiness of the system, the gaps identified aligned with the uncertainties present in the modeling exercise. With input from 15 experts in the nuclear energy and hydrogen sectors, this report summarizes the expected Technological Readiness Levels of a HTGR, HTSE, and an integrated system similar to the one described above, as well as the commercial readiness and expected timelines associated with the integrated system.

For a HTGR system, respondents noted that a similar system is already operating in China commercially, but not at the 800 MWth scale in the prescribed scenario. Notably, the lack of qualified materials and components for HTGRs globally inhibits its readiness as a commercially available product, which is somewhat unique to the nuclear energy industry. Similarly, for a HTSE plant, of which stacks exist commercially but not at the scale of interest in this report. In both cases, a relatively high TRL for each system was proposed, with a mode TRL of 8 for HTGR and a mode TRL of 7 for HTSE.

While these individual components suggest relatively mature technical readiness, experts were much more critical on the perceived readiness of the integrated HTGR and HTSE system. There is a lack of data suggesting that this combined integrated system is technically mature, as there are uncertainties associated with the components required for integration. A mode TRL of 1 was determined for the combined integrated system. To improve the TRL of an integrated system, it may be necessary to first increase the maturity of HTGR and HTSE technologies separately at the relevant scale.

Beyond technical readiness, a number of additional factors are required to have a commercially viable product. For this integrated system, commercial readiness was determined using an existing framework adopted from the Australian Renewable Energy Agency [45], which describes a 6-point scale to determine the Commercial Readiness Index in the areas of regulatory engagement, stakeholder acceptance, technical performance, financial proposition, supply chain, and market opportunities.

For the integrated system, the largest gaps preventing commercial adoption beyond technical aspects appeared to be in the areas of regulatory readiness, sufficient data on costs and potential revenue of this system and identifying specific markets that would be uniquely well suited to use this solution. Critically, the feasibility and applicability of this system is context-specific and largely depends on the target market that it intends to serve.

Due to these uncertainties, the predicted timelines for an integrated system varied considerably, with an integrated demonstration expected between 2028 and 2035 by most experts, and an integrated commercial system expected between 2040 and 2050 by most experts. Experts also noted that given the uncertainties involved and the ever-changing policy and energy landscape, market demand may dramatically change and accelerate these expected timelines in support of climate change targets and to address national energy security.

Generally, there appears to be no technical gaps that would prevent this system from operating successfully, but significantly more work is needed to advance the technological readiness and certainty of an integrated system at the relevant commercial scale. The following recommendations as supported by the findings and discussions within this report:

- **Bilateral benchmarking of system codes:** Members of GIF and relevant representatives of the NEA H2VAL Working Group are encouraged to pursue code comparisons bilaterally using a detailed scenario for a specific application. As each model used in this analysis is optimised for slightly different applications and markets, the differences and similarities for a detailed scenario will be essential to create a concrete benchmarking.

- **Sensitivity analysis using system codes:** Similarly, a sensitivity analysis is recommended using the modeling tools available in GIF and NEA member countries to determine the impact of specific variables to the final levelized cost of hydrogen, and improve the benchmarking across similar yet independently developed system codes. A sensitivity analysis on capital and operating cost assumptions for both HTGR and HTSE systems would be most valuable to quantify the potential impact on the hydrogen costs.
- **Consider detailed business models:** Based on the model outputs from the CNL HESO model demonstrating the impact of hydrogen storage, and learning from cost reduction strategies for hydrogen production found in literature, it is recommended to consider the business model in future analysis of this integrated HTGR and HTSE system. In particular, it is expected that an integrated system that can serve multiple hydrogen, heat, and electricity markets simultaneously may be the most valuable and represent a cost-effective solution for nuclear energy in the hydrogen economy. This approach may improve feasibility by reducing storage costs, improving energy utilization, and enhancing grid stability.
- **Value chain analysis for specific applications:** Additional analysis is recommended on specific end user applications that may be particularly well suited for a HTGR system to produce hydrogen through HTSE. Specific applications are likely to include the production of hydrogen as a reducing agent for the production of “green steel”, commercial ammonia production, large-scale production of synthetic fuels, and reducing emissions associated with existing demand for large quantities of hydrogen, including for upgrading in the oil and gas sector.
- **Scaling HTSE and HTGR separately before integration:** In general, there is significant risk associated with integrating two technologies that have not yet independently become commercially available at the relevant scale. The authors recommend prioritizing MW-scale HTSE demonstrations to validate performance, optimize costs, and de-risk the technology at the scale required to integrate with a Gen IV reactor technology. Given the learning rates available in the literature from Wendt et al, 2022, a HTSE plant at the 200 MW scale should be targeted to improve cost certainty for an integrated system with a GenIV reactor at a scale of 800MW or beyond.
- **Demonstrate integration with an existing LWR:** Similarly, a demonstration of a HTSE plant integrated with an existing LWR at scale would improve the technological readiness and commercial availability of components necessary for integrating hydrogen production with nuclear energy generally, including for Gen-IV systems. This would directly increase the TRL associated with the integrated HTGR and HTSE commercial system.
- **Support regulatory engagement on non-electric systems:** Regulators are encouraged to share information in cases where a system like this has been internally evaluated. To support this, international organizations should foster engagement amongst regulators and provide an environment for general knowledge sharing that is neutral to both technology and jurisdiction, including through existing mechanisms such as the NEA Working Group on New Technologies. The GIF is committed to support efforts by regulators to explore considerations and impacts of using nuclear energy for non-electric applications.
- **Improving data on costs:** Cost and performance assumptions remain a source of uncertainty. Additional research is needed to improve confidence in assumptions for both HTGR and HTSE systems, including overnight capital cost assumptions, operating cost assumptions, and current densities of HTSE stacks. Continuing to scale relevant experiments to the MW-scale and beyond is also expected to increase cost certainty for these systems.
- **Compare against alternatives:** The commercial viability of the system depends on market dynamics. The hydrogen market is currently dominated by steam methane reforming, which in the future will ideally be paired with CCUS. For hydrogen production with a Gen IV system

to be competitive, it must demonstrate reliable operations, cost-effectiveness, and clear advantages relative to this alternative. Incorporating lifecycle emissions, such as fugitive methane from natural gas, into comparative analyses could help identify the full scope of commercial risk in these respective systems.

The need for significant quantities of hydrogen at scale represents a compelling opportunity for integrating Gen-IV reactors with HTSE, especially in the context of global decarbonisation and energy security priorities. Based on initial analysis of these systems, there is real promise that Gen-IV reactors could support the economic and reliable supply of hydrogen for industrial applications, and to serve the future hydrogen economy broadly.

Advancing these integrated HTGR and HTSE systems will require a coordinated approach that includes refining technical assumptions, de-risking technologies through scaled demonstrations, addressing regulatory gaps, and engaging stakeholders to build confidence in the system's viability. Success will depend on addressing these gaps, while simultaneously aligning policy, market, and technological readiness to create a pathway toward commercialization. Continued collaborations among members of the Generation IV International Forum with partners such as the NEA are expected to help identify and support decision makers as they address these gaps towards a viable commercial solution for at-scale hydrogen production.

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APPENDIX 1: System Readiness Questionnaire

System readiness: Hydrogen production from high temperature steam electrolysis using a HTGR

This questionnaire is intended to collect expert views from industry, researchers, nuclear energy technology developers, and others on the readiness of a high-temperature gas reactor to produce hydrogen through high temperature steam electrolysis.

Responses will be aggregated and used to inform analysis of an integrated system where a high-temperature gas reactor (HTGR) produces hydrogen through high-temperature steam electrolysis. This analysis will also be complemented by quantitative modeling.

The NEANH Task Force intends to align this analysis with other relevant international initiatives, including the IEA Hydrogen from Nuclear Energy Task 44, the GIF VHTR Hydrogen Production Project Management Board, and work from the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (NEA). Aggregated results from this survey may be shared with these respective groups, but your name and contact information will not be shared.

The survey has five (5) sections:

- Introductory Information
- System Definition
- Perspectives on the technological readiness of system components
- Perspectives on the commercial readiness of an integrated system
- Additional performance indicators

Introductory Information

2. Name:
3. Job title: *
4. Organisation *
5. Country: *
6. Please select the category that best describes your role or affiliation *
   - Nuclear energy technology developer
   - Hydrogen end-user
   - Hydrogen production technology developer
   - Researcher in the nuclear sector
   - Researcher in the hydrogen sector
   - Government
   - International Organisation
   - Other
7. Please indicate how many years of experience you have in this field:
8. Is there anything else you would like to tell us about yourself?

System Definition

This questionnaire will seek your input on the readiness of an integrated system where a high-temperature gas reactor (HTGR) produces hydrogen through high-temperature steam electrolysis.

There are a variety of HTGR technologies with unique characteristics. For this questionnaire, we ask you to consider a single HTGR design or design class and respond to the questions accordingly. Please identify the following characteristics of your HTGR system:

9. Fuel configuration:

An example of a pebble bed fuel configuration would be the HTR-PM design by INET or the Xe-100 design by XEnergy. An example of a prismatic fuel configuration would be the HTTR by JAEA or the MMR by USNC.

- Prismatic
- Pebble bed

10. Approximate outlet temperature (°C):
11. Approximate power output (MWe)
12. Please list any additional assumptions and identify any additional defining characteristics (enrichment level, design elements, reactor name, etc).
13. The system considered in this questionnaire will include an assessment of high-temperature steam electrolysis (HTSE) technology. Please list any assumptions or defining characteristics of a HTSE technology based on your expertise.
14. Finally, this survey will complement modeling of a HTGR system coupled to hydrogen production from HTSE. Please list any modeling inputs or resources that may be useful to inform this modeling.

Perspectives on the technological readiness of system components

Using the system configuration that you defined in the previous step, please comment on the technological readiness of the following components of a HTGR system that is producing hydrogen through high-temperature steam electrolysis.

15. How would you rate the status of the **high-temperature gas reactor** nuclear energy technology that you defined in the previous step? *

- I do not know / I do not wish to answer
- Current research on the HTGR identifies the principles that underlie the technology.
- Practical applications for the HTGR have been identified.
- Basic components have been fabricated and successfully demonstrated.
- Components have been integrated into a basic HTGR system.
- The basic HTGR system has been successfully demonstrated.
- A prototype has been constructed, which is more representative than the basic system.
- A prototype has been successfully demonstrated.
- The HTGR has been constructed and commissioned; designed to meet all the reference requirements
- The HTGR is successful under operational conditions

16. Please provide additional commentary or references to support this response.

17. How would you rate the status of **high-temperature steam electrolysis technology** (HTSE)? *

- do not know / I do not wish to answer
- Current research on HTSE technologies identify the principles that underlie the technology.
- Practical applications for HTSE have been identified.
- Basic components have been fabricated and successfully demonstrated.
- Components have been integrated into a basic system.
- A basic HTSE system has been successfully demonstrated.
- A prototype has been constructed, which is more representative than the basic system.
- A prototype has been successfully demonstrated.
- A HTSE stack has been constructed and commissioned; designed to meet all the reference requirements
- HTSE is successful under operational conditions

18. Please list any assumptions that you made, and provide additional commentary or references to support this response.
19. How would you rate the status of **intermediary thermal storage technologies**? *

- do not know / I do not wish to answer
- Current research on thermal storage technologies identify the principles that underlie the technology.
- Practical applications for thermal storage have been identified.
- Basic components have been fabricated and successfully demonstrated.
- Components have been integrated into a basic system.
- A basic thermal storage system has been successfully demonstrated.
- A prototype has been constructed, which is more representative than the basic system.
- A prototype has been successfully demonstrated.
- Intermediary thermal storage technology has been constructed and commissioned; designed to meet all the reference requirements

Intermediary thermal storage technology is successful under operational conditions

20. Please list any assumptions that you made, and provide additional commentary or references to support this response.
21. How would you rate the technological readiness of **the integrated system** of a HTGR coupled to hydrogen production using high-temperature steam electrolysis (HTSE)? *

- do not know / I do not wish to answer
- Current research on an integrated system identifies the principles that underlie the technology.
- Practical applications for an integrated system of a HTGR coupled to HTSE has been identified.
- Basic components have been fabricated and successfully demonstrated.
- Components have been integrated into a basic system combining a HTGR with HTSE.
- The basic system combining a HTGR with HTSE has been successfully demonstrated.
- A prototype has been constructed, which is more representative than the basic system.
- A prototype has been successfully demonstrated.
- An integrated system of a HTGR coupled to HTSE has been constructed and commissioned; designed to meet all the reference requirements
- An integrated system of a HTGR coupled to HTSE is successful under operational conditions

22. Please list any assumptions that you made, and provide additional commentary or references to support this response.

Perspectives on the commercial readiness of an integrated system

Please consider an integrated system of the HTGR technology coupled with high-temperature steam electrolysis when attempting to quantify the below metrics. A 6-point scale has been adopted from the Commercial Readiness Index framework that has been well documented by the Australian Renewable Energy Agency, and is available online here: https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf.

23. Please rate the status of the **regulatory environment** for an integrated system where a HTGR produces hydrogen through high-temperature steam electrolysis. *

- I do not know / I do not wish to answer
- Regulatory processes are undefined. The time and cost associated with receiving an appropriate license is not known.
- Key regulatory barriers have emerged that will frequently require project specific consideration.
- Draft recommendations have emerged to address key regulatory barriers. Early developers are investing in process development to gain certification. Policy settings are currently focused on “project/technology push”.
- Key findings have been published on planning, permitting and regulatory challenges based on actual evidence. Multiple jurisdictions have experience and national standards are starting to emerge. Policy settings are moving towards “Market pull”.
- Regulatory, planning, and permitting challenges are understood and under review, yet some are still unresolved and becoming critical as market penetration increases.
- The regulatory, planning, and permitting process is documented and defined with ongoing review and refinement. Investment markets views the policy setting to be long term, robust, and proven.

24. Please provide additional commentary or references to support this response.
25. Please rate the status of **stakeholder acceptance** for an integrated system where a HTGR produces hydrogen through high-temperature steam electrolysis. *

- do not know / I do not wish to answer
- Stakeholder support or opposition is hypothetical.
- Stakeholder support or opposition is on a case-by-case basis where project developer skills create a critical success factor.
- Broader stakeholder support issues are emerging. Addressing stakeholder concerns has become a key consideration in project development timelines and future commercial uptake scenarios.
- Evidence and experience is available to inform stakeholders; increasing their acceptance.
- A transparent process using discoverable evidence is used to engage stakeholders.
- An established process is understood and expected by all parties, used to gain stakeholder acceptance.

26. Please provide additional commentary or references to support this response.
27. Related to the financial proposition of an integrated system where a HTGR produces hydrogen through high-temperature steam electrolysis, please rate the status of **cost data** for this system. *

- do not know / I do not wish to answer
- Cost data is unavailable, or cost data is based on projections and forecasts with little or no prior data to substantiate.
- Key costs are based on projections with little actual data available to verify.
- Costs data are based on projections from a single site, a comparable site, or a comparable pathway. Key cost drivers are understood enabling a broader market to judge long-term prospects.
- Key cost elements of projects are in the public domain. Commoditisation of major components is occurring.
- Cost drivers are understood with roadmaps in place to bring costs to being market competitive
- The price and value proposition of an integrated system is clear and attractive with open access to cost trends and projections based on actual project data from wide range of applications.
- The system cost of an integrated system is sufficiently reliable and competitive to drive uptake. Cost details are widely published for multiple similar applications. Global and/or local price indices have been established and reported.

28. Please provide additional commentary or references to support this response.
29. Related to the financial proposition of an integrated system where a HTGR produces hydrogen through high-temperature steam electrolysis, please rate the status of **revenue data** for this system. *

- I do not know / I do not wish to answer
- Revenue data is based on projections and forecasts with little or no prior data to substantiate.
- Revenue projections are highly discounted by investors.
- Revenue projections are being tested in a commercial context, highly discounted by investors with requirements for long term PPAs, contracts, or offtake agreements for large scale applications.
- Revenue projections are backed by commercial data. Price gaps are understood and roadmaps are in place to address them. Long term PPAs, contracts, or offtake agreements are required to secure debt.
- Revenue projections are based on proven forecasts and accepted commercial data. Greater PPA or contract optionality for large scale developers, with investors comfortable with the underlying value of the proposed system.
- Revenue forecasting is proven and accepted by finance industry with transparent benchmarking. There are examples of different forms of market participation strategies with debt finance prepared to assume risk.

30. Please provide additional commentary or references to support this response.
31. Please rate the status of the **supply chain (including skills)** for an integrated system where a HTGR produces hydrogen through high-temperature steam electrolysis. *

- do not know / I do not wish to answer
- Supply chain has not been fully considered and key elements are typically from a specialised source, often under technology proponent specification.

- Supply chain is not available or not willing to participate for many key components. Project developers typically design and procure multiple elements to their own specifications. Engineering, procuring, construction and transportation costs are often based on time and materials with high degree of risk loading.
- A project-by-project approach is used for engineering, procuring, construction and transportation providers with limited prior experience. Limited availability of key components and skills. Major supply chain participants may not support development due to conflicts with their current business model.
- Key skills have been demonstrated with replicable results. Limited supply options have been proven. “Time to build” is a key driver for future efficiencies.
- Specialisation is occurring throughout the supply chain with standards defined and supplier performance externally benchmarked.
- There are multiple supply chain alternatives with proven capability. Project and service differentiation is the key selection factor.

32. Please provide additional commentary or references to support this response.
33. From your perspective, **please identify specific supply chain gaps**. Are there any material or component requirements for this system that may limit its ability to scale up?
34. Please rate the **market opportunities** for an integrated system where a HTGR produces hydrogen through high-temperature steam electrolysis. *
    - do not know / I do not wish to answer
    - The system is a promising solution to a potential commercial opportunity. An investment case for commercial trials is supported by peer-reviewed business plans with verifiable cost, revenue, and market size estimates.
    - Commercial trials have identified a target market to demonstrate to future investors that the technology can operate reliably and generate predictable revenue from a cost base that is understood, even if still uneconomic. Market research supports estimates of local and international market sizes. The goal isn’t to maximize revenue per unit of energy but to find a balance between the trial's cost and the scale needed to show basic commercial viability.
    - The focus shifts from proving the technology's commercial viability to optimizing costs and revenue. Detailed market research exists to understand the size, interest and readiness of the market available. Post subsidy revenues cover debt and equity expectations.
    - Investment decisions are now primarily driven by market demand, with clear understanding of market segments and supply chains. Market size is confirmed by third parties. Customer engagement in the target segment plays a crucial role in investment decisions, with some support from policy incentives to encourage adoption.
    - The market now drives the investment process with minimal to no need for policy incentives. External factors may influence the pace of deployment. Market opportunities are well understood and pursued based on clear demand.
35. Please provide additional commentary or references to support this response.
36. Estimate the **timeline for an integrated demonstration** where a HTGR will be used to produce hydrogen through high temperature steam electrolysis
37. Estimate the **timeline for an integrated commercial system** where a HTGR will be used to produce hydrogen through high temperature steam electrolysis

Additional performance indicators

The final questions below are optional, and an opportunity for you to provide input on a range of additional characteristics related to the production of hydrogen from high-temperature steam electrolysis using a high-temperature gas-cooled reactor.

Please attempt to estimate the indicators, or discuss qualitatively the indicator in the context of the system.

38. GHG emission reduction potential of this system. - Attempt to quantify the GHG emissions reduction potential in units of $tCO_2(eq)$. You may assume a baseline energy supply to compare against.
39. Cost/benefit the system - This indicator involves evaluating the drawbacks of the system against the benefits. You may discuss investment, operational, and maintenance costs against the benefits such as GHG emissions avoided, hydrogen produced, or other benefits.
40. Energy availability factor - This metric measures the reliability and consistency of the system in providing energy. It calculates the proportion of time the system is functional and capable of energy production, taking into account downtime due to maintenance, refueling, or operational issues.
41. Energy security benefits - This aspect focuses on how the system may contribute to energy security relative to energy alternatives.
42. Geographical adaptability - This indicator assesses the system's flexibility and suitability across different geographical locations. It considers factors like climate, water availability, political situations, and proximity to energy demand centers.
43. Scalability - This refers to the system's capacity to be scaled up or down based on demand for energy generation and/or for the hydrogen that is produced.
44. Please identify any other performance indicators of interest that may inform the readiness or commercial viability of the system, such as business models, legal aspects, or others:

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