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Overview of the Generation IV International Forum (GIF)

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Idaho National Laboratory
Chair, GIF Task Force on Nonelectric Applications of Nuclear Heat

Workshop on Non-Electric and Hybrid Applications of Nuclear Energy
Busan, Republic of Korea
April 26, 2024

Generation IV International Forum

A framework for international co-operation in research and development for the next generation of nuclear energy systems

Thirteen Member Countries Plus the EU

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Launched in 2001…

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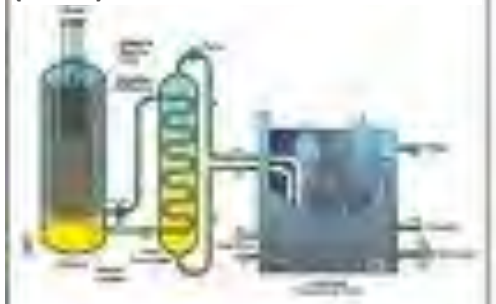
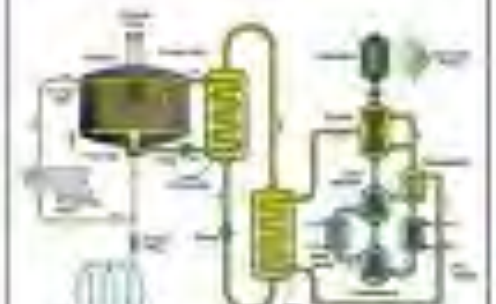
Six Generation IV Reactor Technologies

Very High Temperature Reactor (VHTR)

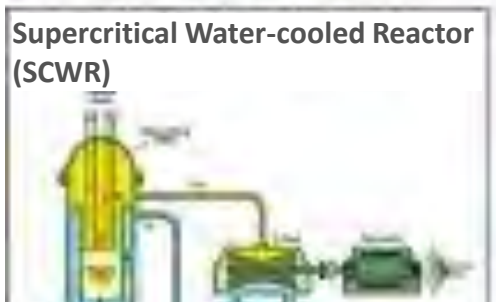


Molten Salt Reactor (MSR)



Sodium-cooled Fast Reactor (SFR)

Supercritical Water-cooled Reactor (SCWR)



Gas-cooled Fast Reactor (GFR)

Lead-cooled Fast Reactor (LFR)

Cross-cutting Collaborations

- Economics & Modelling
- Education & Training
- Proliferation Resistance & Physical Protection
- Risk & Safety
- Safety Design Criteria
- R&D Infrastructure

To achieve goals in four areas:

1. Sustainable energy with minimum waste
2. Life cycle cost advantages
3. Safety and reliability
4. Proliferation resistance & physical protection

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…aiming to be ready for industrial deployment by 2030.

Key theme for 2022 through 2024: Accelerating the Readiness of Gen IV Systems to Meet Net Zero Goals

1. Strengthening Gen IV system features for combatting climate change
   - Flexible operations and non-electric applications
2. Supporting transition from R&D to demonstration and deployment
   - Technical readiness
   - Regulatory readiness
   - Improved economics
3. Strengthening GIF relevance to industry
   - Industry engagement
   - Senior Industry Advisory Panel
4. Supporting the Gen IV talent pipeline

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History of Non-electric and Hybrid Applications of Nuclear Energy

Future clean energy systems—transforming the energy paradigm

Nuclear Energy Generation

(Light water reactors, high temperature advanced reactors, small modular reactors, etc.)

Other Energy Generation

(Variable renewables, municipal waste, fossil with carbon capture, fossil, etc.)

Integrated energy systems (IES) leverage the contributions from nuclear energy beyond electricity

Biofuel, transportation fuels | Hydrogen for transportation | Chemicals, polymers | Fertilizer, ammonia | Iron, steel, metals | Wood products, cardboard, paper | Other industrial processes | Clean Water | District heating | Flexible electricity

*Energy storage includes electrical batteries, chemicals and thermal storage.

Slide courtesy of INL Idaho National Laboratory

Past Experience—Use of Nuclear Heat

- Over 750 reactor-years of experience – accounts for less than 0.5% of the total nuclear thermal output of over 440 reactors
  - Mostly water-cooled reactors

- ***District Heating:*** 43 reactors have been used, ~500 reactor years
  - Average 5% thermal output; range 5 to 240 MWth
  - Typically, <150º C
- ***Desalination of water:*** 17 reactors have been used, ~250 reactor years
  - Mostly using thermal processes (multi-effect distillation and multi-stage flash), <130º C
- **Industrial Process Heat:** 7 reactors
  - Typically based on medium pressure steam, <250ºC

IAEA - "Opportunities for Cogeneration with Nuclear Energy" NP-T-4.1, 2017

IAEA - "Guidance on Nuclear Energy Cogeneration" NP-T-1.17, 2019

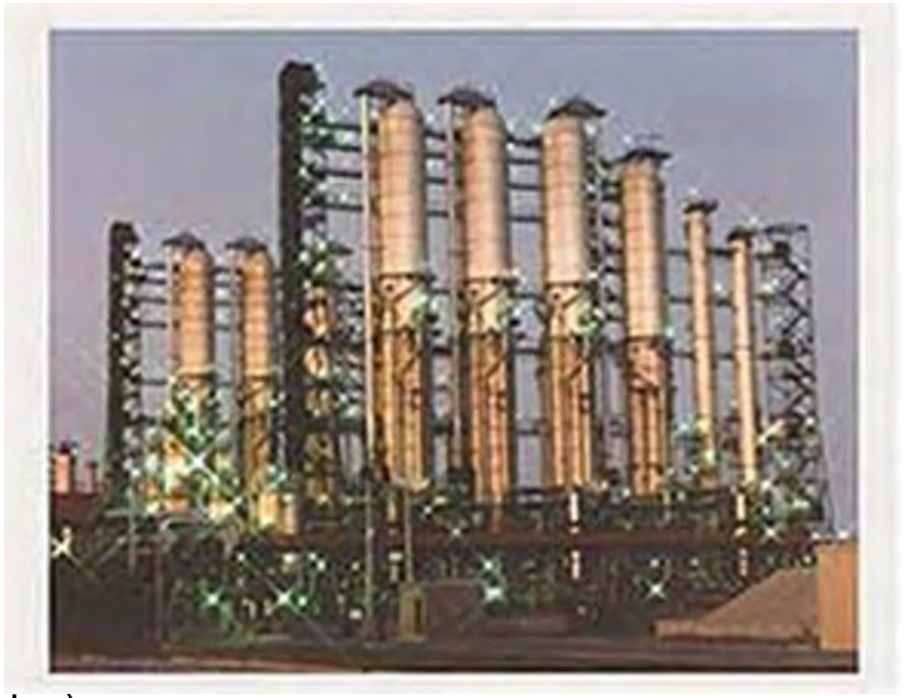
NEA – "Beyond Electricity: The Economics of Nuclear Cogeneration", 2022

Industrial process applications of nuclear heat

Country/ Reactor Type	Application	Location	Capacity of Steam System MWth	Operation
Canada, Bruce A CANDU reactors	Heavy Water Production, Bruce Energy Centre (BEC)	Onsite heavy water production Off-site supply to BEC	5,350	1981-1997
Germany, Stade PWR	Salt Refinery	Off-site	30	1984-2003
Switzerland, Gösgen, PWR	Cardboard factory	Off-site	54	1979-
UK, Calder Hall MAGNOX	Fuel plant	Adjacent site		1956-2003

Nuclear Steam System at Bruce, Canada

- **Largest nuclear bulk steam system built**
  - Medium pressure steam from 4 Bruce A reactors
- **Steam Users**
  - On-site: 2 heavy water production plants
  - Off-site: Bruce Energy Centre industrial park
    - Plastic and alcohol production, green houses
    - Cascading heat supply; Steam to condensate
- **Things to note**
  - Process plant on nuclear site
  - Contained significant quantities of H_2S gas (combustible, toxic, corrosive)
  - 3 barriers between nuclear plant and users
  - Back-up steam supply: 3 oil-fired boilers
  - Back-up power for condensate pumps
  - Different ownerships – NPP, heavy water plant, Bruce Energy Centre



Bruce Heavy Water Plant

Past initiatives with end user involvement

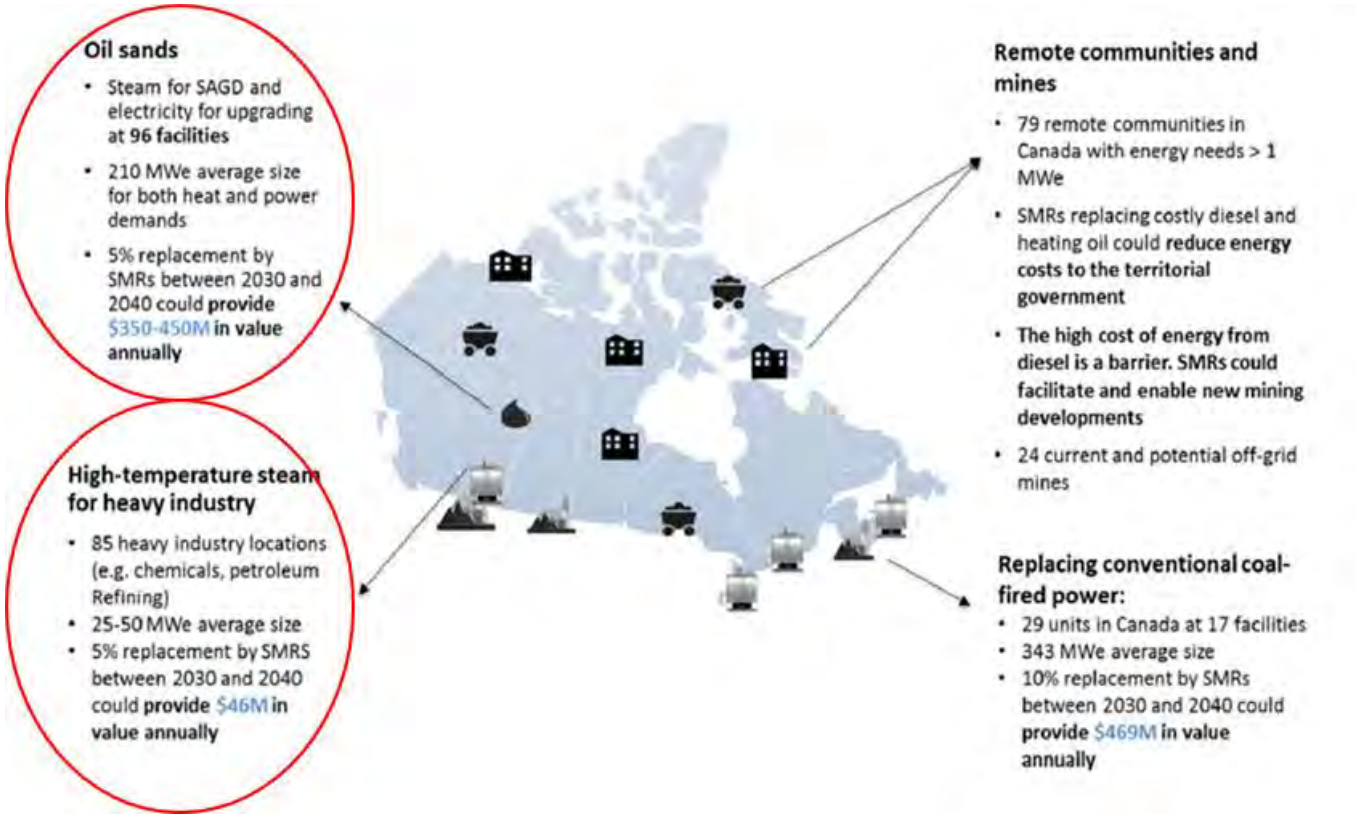
- ***Next Generation Nuclear Plant (NGNP) Industry Alliance***
  - Formed in 2010 to develop high-temperature gas-cooled reactor and expand its industrial applications
  - Members included potential end user industries
  - Several process heat applications of HTGR were examined by INL—hydrogen, ammonia, coal to natural gas, synthetic diesel using natural gas, oil sands
  - Plant Design Requirements included requirements from prospective owner/operators and end users

- ***EUROPAIRS:*** End User Requirements fOr Process heat Applications with Innovative Reactors for Sustainable energy supply
  - Funded by European Commission in 2009, evaluated potential coupling of HTGRs with industrial processes
  - 50% of industrial heat demand <550ºC — significant potential of HTGRs in replacing conventional fossil CHPs
  - Recommended strong partnership between nuclear technology developers and end users and joint technology development for coupling of reactors with industrial processes
    - Prototype demonstrations at industrial scale required to give confidence to industrial heat users

What has changed since the early 2000s?

- Policies to incentivize transition to net zero by 2050
  - Some industries considering nuclear energy option in decarbonization plans
- Worldwide development of Small Modular Reactors presents new opportunities for decarbonization
- Low-emission hydrogen production using nuclear energy is being pursued by many entities
- NEANH offers possibilities of integrating nuclear and renewable power (hybrid energy systems)

GIF set up NEANH Task Force in 2021



Canada's SMR Roadmap 2018 – Domestic Market Potential

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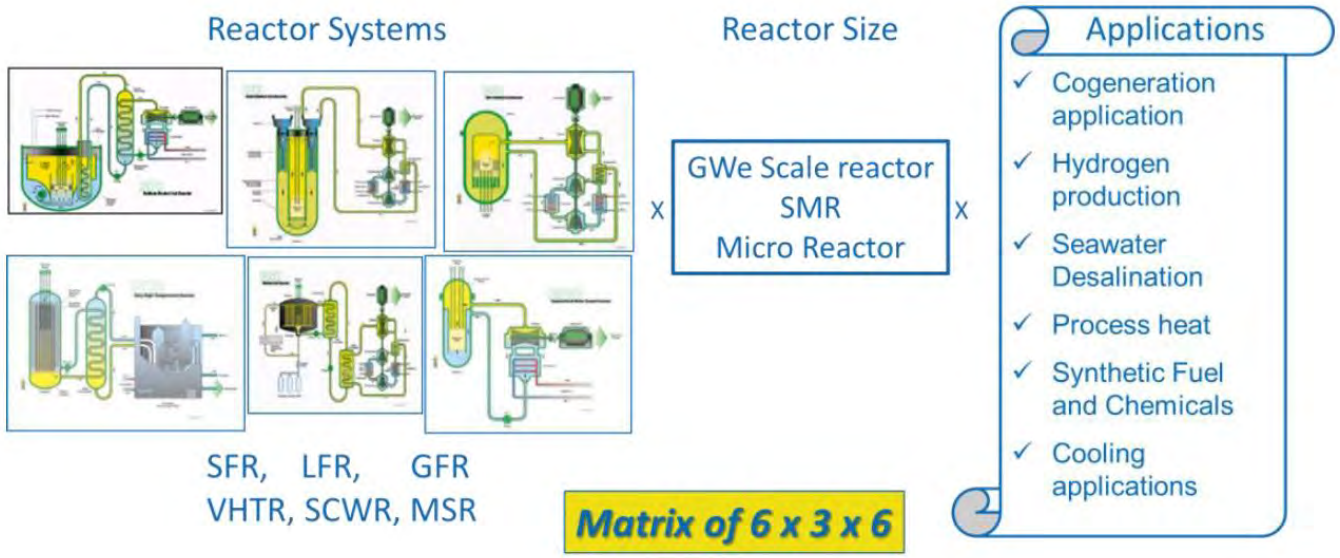
Introduction to the Task Force on Non-Electric and Hybrid Applications of Nuclear Energy

Overview of the GIF Task Force on Non-Electric Applications of Nuclear Heat (NEANH TF)

Timeline: Formed in October 2021 for an initial term of 24 months; recently extended to 36 months.

Focus: The potential of Gen IV nuclear reactors for non-electric applications, including:

- Thermal energy alternatives to fossil fuels, and
- Complementary services to the electric grid.



NEANH Membership
Australia
Canada
China
Euratom
France
Japan
Korea
Russia
South Africa (Observer)
United Kingdom
USA
IAEA (Observer)
NEA (GIF TS)

Objectives of the NEANH Task Force

1. Develop a position paper on non-electric applications coupled to GIF systems (Nov 2022).
2. Enhance the general level of knowledge of GIF members on non-grid applications of nuclear systems (July 2022, virtual workshop).
3. Develop a network to connect GIF to the high temperature community outside the nuclear field (Oct 2022, full-day workshop, Toronto; April 2024, full-day workshop, Busan).
4. Highlight relevant system configurations, and conduct systems analysis with regard to key performance indicators.
5. Provide input to decision makers, industry, licensing authorities, investors, etc. on configurations that will support achieving policy goals.

A dedicated website for the NEANH TF was launched in January 2023, available here.

Develop a network to connect GIF to the high temperature community outside the nuclear field

NEANH Workshop, Industry Panel: Energy End-Users

Panel Participants:

- Nuclear Energy Agency: Overview on NEA studies
- The Pathways Alliance / Canadian **oil sands industry**
- Dow Chemical / **chemical industry** leader
- Chevron Technology Ventures / **oil & gas, refineries**
- Ammonia Energy Association / **ammonia**
- Electric Power Research Institute / **district energy**

Key findings:

- Several end-user companies/consortia of companies have initiated studies on the utilization of nuclear energy to support decarbonization efforts.
- Companies need reliable data to support technology assessments.
- End-users do not want to operate nuclear reactors - opportunity for partnership with utilities.
- Key stakeholders need to be engaged (e.g., licensees and regulators, both nuclear and for industrial processes).

Develop a network to connect GIF to the high temperature community outside the nuclear field

NEANH members have been participating in multiple regional engagement activities:

- Sustainable Nuclear Energy Technology Platform (SNETP) forum in Gothenburg, Sweden in May 2023 Featured technical sessions and panel discussions.
- ARPA-E Nuclear Heat Workshop in Houston, USA in May 2023, Included technical and market focused presentations and breakout sessions.
- IAEA Technical Meeting on Advances in High Temperature Processes for Hydrogen Production with Nuclear Energy in Vienna, Austria in September 2023.
- Today's industry engagement workshop in coordination with the Korea Atomic Power (KAP) conference in Busan, South Korea, April 26, 2024.

Highlight relevant system configurations, and conduct systems analysis using key performance indicators (KPIs)

NEANH Database (first draft inventory completed in 2023)

- Global repository of activities relevant to non-electric applications coupled with nuclear energy systems.
  1. Studies
  2. Collaborative initiatives
  3. Past or existing demonstration projects (or relevant commercial systems)
  4. Planned demonstrations or commercial systems
  5. Modelling tools
- The database will evolve to summarize entries or systems and to characterize them using **key performance indicators.**
- Targeting end-users beyond the nuclear field, such as:
  - Hard to abate industrial sectors,
  - Licensing authorities, and
  - Investors.

Performance Indicators:
Technological Readiness Level
Market readiness
License readiness
Timelines
Geographic Adaptability
GHG emission reduction potential
Energy security benefits
Cost/Benefit ($/t CO2 saved)
Economic viability
Supply chain
Investment considerations
Scalability
Ease of integration
Market size
Sustainability

Provide input on configurations that will support achieving policy goals

NEANH engagement with regulators

- Informal discussions with regulators to help identify gaps, concerns, and timelines associated with the regulation of nuclear energy integrated with co-located non-electric applications.
- Ambitions to support regulators to help identify gaps, concerns, and timelines associated with the regulation of non-electric applications of nuclear.
- (Tentative) NEANH will develop a generic scenario through direct engagement with industry for analysis through a regulatory sandboxing initiative led by the UK Office for Nuclear Regulation.

Engagement with policy makers

- NEANH members reach a broad public audience through their participation in a wide range of conferences and other public facing venues, sharing the potential for nuclear energy to support decarbonization initiatives.
- Knowledge sharing within the monthly team meetings help NEANH members across multiple organizations/countries helps to develop an understanding of the impacts of potential policy changes and may also inform policy within some member countries.

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Ongoing and upcoming work

2024 and beyond

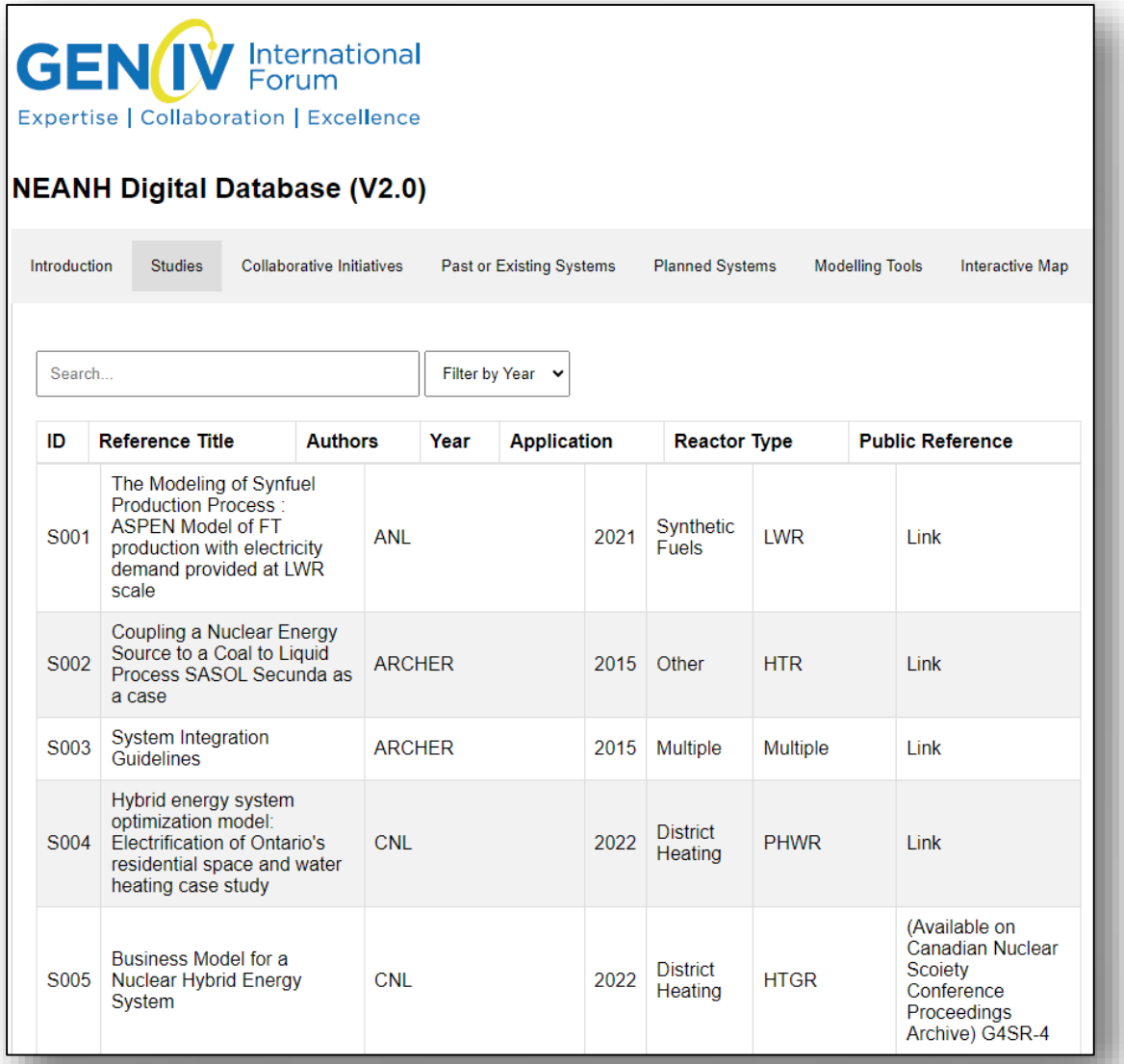
Moving forward: Transition to a digital NEANH database

NEANH intends to launch the digital database on the updated GIF site in summer 2024.

The NEANH database will be published and will evolve over time to include system summaries characterized using performance indicators.

The NEANH TF will pursue a digital database that is query-able and scalable to:

- Improve user experience
- Enable additional complexity in data structure
- Avoid version control issues associated with a flat file
- **Allow users to submit data through a web-form for review by NEANH**



ID	Reference Title	Authors	Year	Application	Reactor Type	Public Reference
S001	The Modeling of Synfuel Production Process : ASPEN Model of FT production with electricity demand provided at LWR scale	ANL	2021	Synthetic Fuels	LWR	Link
S002	Coupling a Nuclear Energy Source to a Coal to Liquid Process SASOL Secunda as a case	ARCHER	2015	Other	HTR	Link
S003	System Integration Guidelines	ARCHER	2015	Multiple	Multiple	Link
S004	Hybrid energy system optimization model: Electrification of Ontario's residential space and water heating case study	CNL	2022	District Heating	PHWR	Link
S005	Business Model for a Nuclear Hybrid Energy System	CNL	2022	District Heating	HTGR	(Available on Canadian Nuclear Scoiety Conference Proceedings Archive) G4SR-4

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Moving forward: Conduct systems analysis on non-electric and hybrid energy systems

- Throughout 2023, NEANH members selected key performance indicators to evaluate systems where nuclear energy is connected to non-electric applications.
- Key Performance Indicators intend to be measurable, and will inform analysis on:
  - System readiness
  - Gaps, or areas that more work is needed
  - The overall opportunity
- Going forward, NEANH members will aim to agree on generic NEANH system scenarios for in-depth analysis using KPIs.

Performance Indicators:
Technological Readiness Level
Market readiness
License readiness
Timelines
Geographic Adaptability
GHG emission reduction potential
Energy security benefits
Cost/Benefit ($/t CO2 saved)
Economic viability
Supply chain
Investment considerations
Scalability
Ease of integration
Market size
Sustainability

Systems analysis on non-electric and hybrid energy systems

Initial systems analysis workshop in January 2024

- The NEANH TF is working with international partners to conduct system analysis of Gen IV systems, including:
  - IEA Hydrogen from Nuclear Energy Task 44
  - GIF VHTR Hydrogen Production PMB
  - International Atomic Energy Agency (IAEA)
  - OECD Nuclear Energy Agency
- Initial focus is on a **high-temperature gas reactor to produce hydrogen through high-temperature steam electrolysis**.
- The report will communicate a simple message that clean hydrogen from nuclear is
  - (1) technically feasibility, and
  - (2) can be financially viable in some markets.
- Other systems will be considered based on stakeholder interest

Initial system Analysis workshop as part of the Joint IEA-GIF Meeting on Hydrogen from Nuclear Energy on January 23-25, 2024, at Idaho National Laboratory, Idaho Falls, Idaho, USA

Systems analysis on non-electric and hybrid energy systems

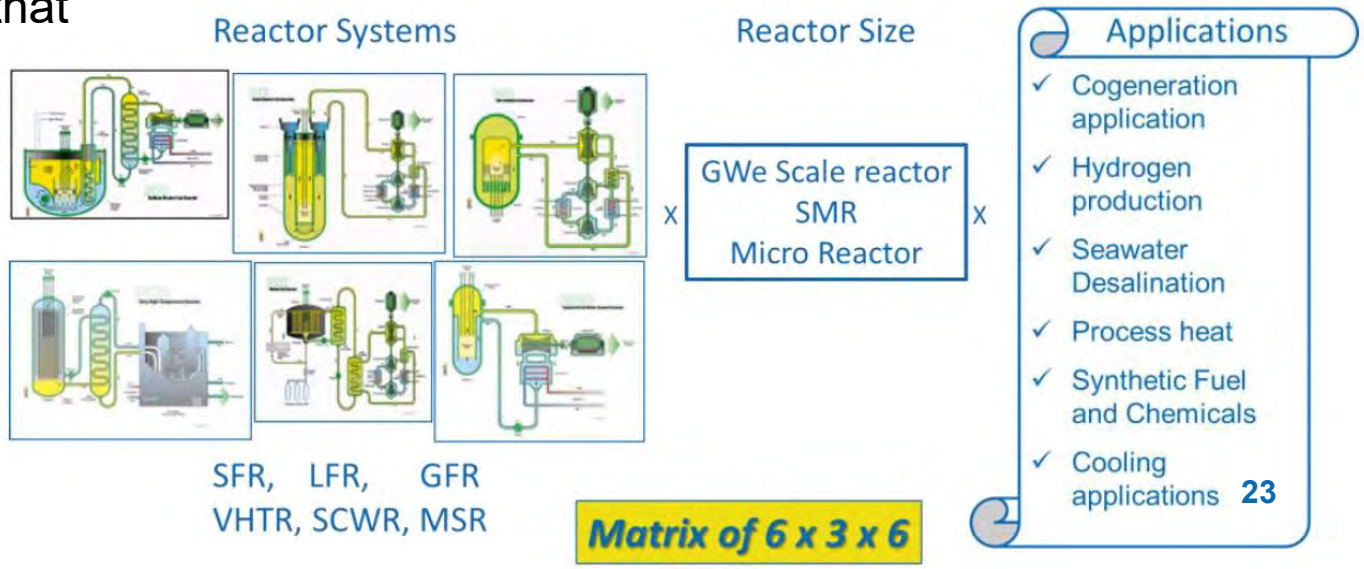
Proposed system analysis approach

Type 1 - Subjective survey of system readiness

- Leverage existing frameworks
- Seeks expert views on the status or readiness of each system
- Identifying gaps associated with specific systems
- Could identify common challenge areas that are common regardless of country

Type 2 - Objective system modelling and analysis

- Assessment of generic system scenarios using modelling tools within NEANH participating organizations



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

- Questionnaire developed to complement quantitative analysis, and crowd-source input from industry, researchers, technology developers, government, and others
- The questionnaire leverages requests quantitative input on:
  - Technological Readiness Level
  - Commercial Readiness Index
  - Timelines
- Experts are encouraged to complete the Questionnaire and circulate the link within your networks.
- Please follow this link to complete the questionnaire: https://forms.office.com/e/khU53G4x4u

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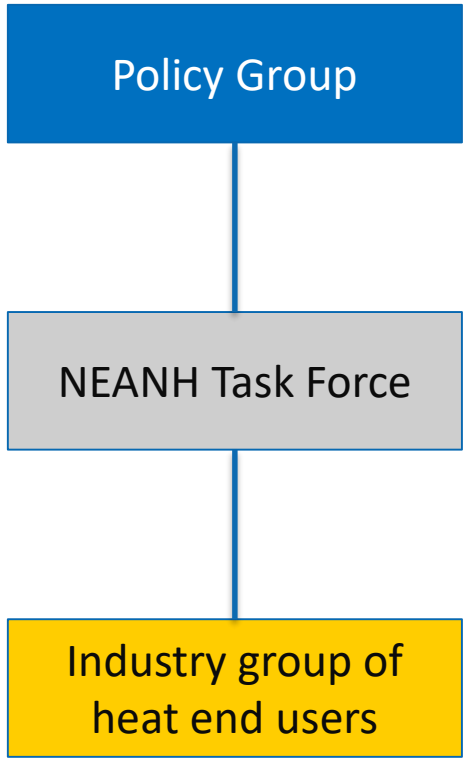
Proposal: Heat end user industry sub-group



NEANH activities the industry sub-group could support:

System analysis with respect to KPIs

- Review scenarios used for modelling
- Provide input into deliverables/reports

Regulatory Engagement

- Input into NEANH scenarios that could be used to engage regulators.

Non-Electric and Hybrid Applications of Nuclear Energy Workshop

Today's workshop will:

- Showcase GIF NEANH activities
- Build on the success of the 1st NEANH Workshop in Toronto, Canada in 2022
  - Move from a North American focus to engage Asian markets and stakeholders
- Facilitate discussions across multiple stakeholders, including:
  - Industry end-users
  - Researchers
  - Nuclear technology developers
  - Experienced operators

Organisers: Korea Atomic Energy Research Institute (KAERI) and the GIF NEANH Task Force

Hosts: Korean Nuclear Industry Association (KAIF) and Korea Nuclear International Cooperation Foundation (KONICOF)

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Thank You!

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Additional Information

Past experience in *operational* nuclear cogeneration, as summarized by Gen-IV International Forum signatory countries

- UK Calder Hall Magnox (heat supported onsite nuclear fuel plant, shut down in 2003)
- Norway Halden BWR (steam for the Saugbrugs paper factory, shut down in 2018)
- Switzerland Gösgen PWR (transport of steam over 2 km to a cardboard factory)
- Canada Bruce A CANDU (district and industrial heating, cogeneration stopped in 1997)
- Germany Stade PWR (salt refinery, nuclear plant shut down in 2003)
- Switzerland Beznau (district heating)
- Various Eastern European countries (district heating)
- >200 reactor-years operating experience with seawater desalination (mostly Japan, India, Kazakhstan; MSF, MED, RO technologies)

See *Summary Report* from the *GIF NEANH Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies*, July 2022.

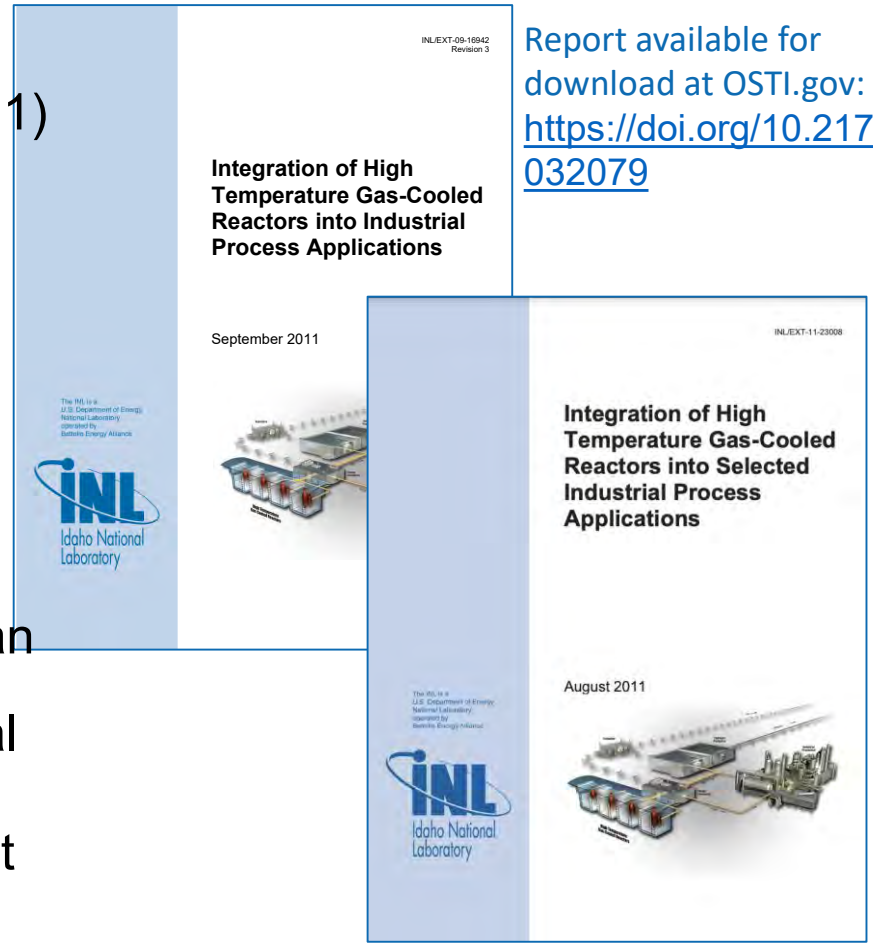
Past experience in *operational* nuclear cogeneration, reflections and lessons learned

- If possible, it is important to consider heat applications at the design phase of nuclear energy systems to avoid potentially costly retrofitting of a system exclusively designed for electricity production.
- Precedent has been established for safe, reliable operation of nuclear cogeneration systems.
- Nuclear standards and regulations have evolved since many of these systems operated and must be reviewed as a part of current efforts.

See *Summary Report* from the *GIF NEANH Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies*, July 2022.

U.S. DOE Next Generation Nuclear Plant program—key takeaways

- Cases examined for high temperature gas-cooled reactor (2011)
  - Power generation
  - Hydrogen generation using natural gas
  - Methanol to synthetic gasoline using natural gas
  - Synthetic diesel (liquid) production using natural gas or coal
  - Ammonia production using Natural Gas or Coal
  - SAGD for oil recovery
  - Coal to Natural Gas Production
- High temperature heat, electricity, and hydrogen provided by an HTGR with high temperature steam electrolysis (HTSE) offers many opportunities for integration of nuclear energy in industrial applications
- Results are highly sensitive to economic assumptions and cost inputs
- Cases should be re-evaluated in light of current technology costs, energy markets, and assumptions



Report available for download at OSTI.gov: https://doi.org/10.2172/1032079

Also see https://doi.org/10.2172/1481779