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POSITION PAPER ON NON-ELECTRIC APPLICATIONS OF NUCLEAR-HEAT

A Generation IV International Forum Priority

November 2022

Position Paper on Non-Electric Applications of Nuclear-Heat: A Generation IV International Forum Priority

GIF NEANH Task Force members

1. Background

Whilst governments around the globe seek to ensure security of energy supply, they are also committing to drastically reduce CO_2 emissions through various techniques, including the reduction of fossil fuels for energy production. Nuclear energy has the potential to play a major role in global efforts to decarbonise given its benefits around deployment flexibility (i.e., availability of reactor technologies at varying scales to support distributed or centralized demands) and product flexibility (i.e., potential to provide services beyond electricity, such as heat and hydrogen, allowing support to different energy markets).

Substantial efforts are necessary to decarbonize the electricity generation sector; nuclear energy is one of the key technological options with the potential of meeting this objective. At the same time, nuclear energy will have to be integrated into electricity grids with increasing shares of variable renewables. As a result, the current nuclear plant designs, electric utilities, plant and grid operators, and regulatory frameworks will have to adapt to allow for a significantly higher level of flexibility in electricity generation.

Moreover, decarbonisation of electricity generation alone is insufficient to meet the challenging CO_2 emission reduction targets. Energy demand from the industrial and the transportation sectors offers significant potential for further emission reduction through the direct use of nuclear-generated heat and/or process intermediates that may be produced using nuclear heat and electricity (e.g., hydrogen). Hydrogen production is of significant interest as a strategy for energy storage, direct use in fuel cell vehicles, or as a feedstock for synthetic transportation fuels. Consequently, the economics of nuclear energy systems must be reevaluated to take into account new constraints and parameters: CO_2 emission reduction towards the 2050 economy-wide net zero goal, contribution to primary heat decarbonisation, and generation of hydrogen at the required scale to reduce natural gas utilization and to meet increasing demand as a fuel and feedstock (e.g., for the production of ammonia or synthetic hydrocarbon fuels, especially for sectors that are hard to abate), or as means of long duration energy storage.

The six most promising Generation IV reactor technologies (Gas-cooled Fast Reactor, Lead-cooled Fast Reactor, Molten Salt Reactor, Supercritical Water-cooled Reactor, Sodium-cooled Fast Reactor and Very High Temperature Reactor) were selected in 2001 to meet the requirements of improved sustainability, better economics, increased safety and improved reliability, as well as a more robust approach regarding proliferation resistance and physical protection. The members of the Generation IV International Forum (GIF) are collaborating on the industrial development of the six concepts to meet these objectives through technical, institutional and organizational innovation. Since the selection of the six Generation IV systems, new challenges have arisen in the energy production sector, and the understanding of energy systems and the potential role of nuclear energy has largely evolved during the last 20 years. 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 the energy supply chains and infrastructures (i.e., from primary energy sources (mines), energy system vendors, energy producers to transportation systems and end-users).

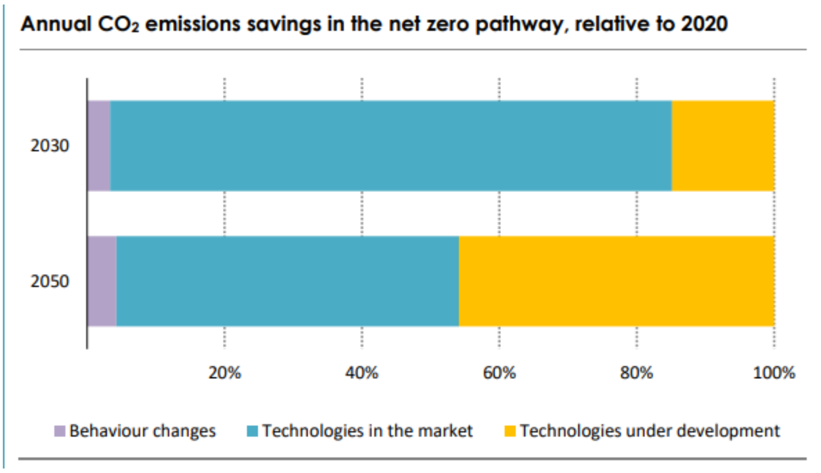

Fig. 1: CO_2 emissions reduction will require both the currently available technologies as well as those under development. Nuclear energy systems, both currently deployed and those under development, could contribute to pathways to net zero emissions. Net Zero by 2050 A Roadmap for the Global Energy Sector, Flagship report — May 2021. [1]

Nuclear energy has been used for some non-electric industrial applications for several decades [2] (e.g., water desalinisation, direct district heating), but it has faced strong economic competition, particularly from inexpensive natural gas in the absence of emission restrictions or carbon taxes. Several earlier studies in the U.S. and Europe concluded that for nuclear energy to become competitive with natural gas firing, the natural gas price would need to be significantly higher than 6.66 US$/MMBtu ($6.50 US$/MSCF) in the absence of a carbon tax (these analyses assumed heat from a high temperature gas-cooled reactor).[1] For comparison, natural gas prices are highly volatile, with current prices several times higher in many parts of the world, thus triggering strong interest in alternatives (note that some markets around the world, such as in the U.S., are still experiencing very low-cost natural gas). [3] On March 7, 2022, European prices hit an intraday high of almost $110/MMBtu before settling at $73/MMBtu for the day.[2] In June 2022 prices to ship liquified natural gas (LNG) hit their highest level in 10 years as increased quantities of LNG are shipped to Europe.[3]

The evolving energy context[4] carries uncertainties regarding future energy and environmental constraints. Policy makers need to identify options that will fit a diverse array of potential scenarios. Solutions may vary depending on geography (e.g., local, regional, national) and the desired timeline for achieving emissions reduction. Considering the magnitude of the decarbonisation challenge, no viable options can be ignored (see Figure 1). Thus, multi-criteria and multifactorial analyses will be necessary to identify the most technically promising and economically sustainable energy system solutions for each deployment region. Future energy generation systems, including nuclear technologies, will need to be designed and developed to operate within a diverse production system comprising multiple generation sources and may be expected to provide cross-sectoral support to ensure reliable, resilient energy to meet grid electricity and other diverse energy demands. Thus, the concept of an Integrated Energy System capability of supporting both electricity and heat demands becomes even more essential.

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[1] *NGNP Process Heat Applications: Hydrogen Production Accomplishments for FY2010*, January 2011, INL/EXT-11-20781, p. 11.

[2] https://www.naturalgasintel.com/european-natural-gas-prices-top-100-as-panic-buying-fuels-record-amid-war-in-ukraine-lng-recap/, March 2022.

[3] https://oilprice.com/Energy/Natural-Gas/LNG-Tanker-Rates-Soar-To-Highest-Level-In-10-Years.html, June 2022.

[4] Current observations illustrate that the future energy demand and supply scenarios are not stabilised yet. Modelling the future energy paradigm is still a key effort to be pursued.

While the criteria that were applied to drive the Generation IV technology down-selection in 2001 are still valid, the evolution of energy production and distribution systems are expected to require these technologies to support additional needs while continuing to provide reliable baseload operation.[5] Additional features that can promote the deployment of Generation IV technologies include:

- **Flexible operation:** Advanced nuclear systems should provide greater operational and product flexibility than current nuclear plants to support smooth integration into an energy mix with high shares of variable energy sources. This should be achieved without causing mismatches between demand and supply of electricity and other baseload and variable energy products (noting that the magnitude of flexibility required will depend on regional characteristics and implementation of other flexibility options, such as energy storage and demand side management);
- **Provision of high-quality heat:** While the primary energy product of nuclear plants is heat, most plants previously have been dedicated to electricity generation because the primary heat was of low value relative to what could be provided by fossil fuel combustion. As restrictions are placed on emissions and fossil fuel prices increase in many regions, nuclear technologies promise to be more competitive, particularly for higher temperature Generation IV reactor technologies.

The evolving energy landscape has led GIF to establish a Task Force on non-electric applications of nuclear heat (NEANH), as this area will have a key role in redefining the role of nuclear technologies in future energy mixes. Through this Task Force, the GIF aims to provide its signatories and other stakeholders (e.g., private industry) with the appropriate knowledge and access to novel energy system design, analysis, and optimisation tools to allow decision makers to find optimal energy system solutions for different socio-economic and geographical contexts. Future energy networks will likely be based on two main energy carriers: electricity and heat, with strong interconnections between them, e.g., in the form of heat storage or hydrogen, as depicted for the current U.S. context in Figure 2. While most traditional energy system planning and analysis tools tend to focus on a single energy use sector (e.g., the electricity market), several emerging tools allow for simultaneous analysis of energy systems that couple multiple generators and multiple energy users to provide electricity, heat, or other energy carriers, such as hydrogen. Dissemination of knowledge may be through publicly available reports, focused workshops, webinars, etc.

[5] Note that hydrogen production using Gen-IV technologies was already a significant interest and focus in the 2000s, but low natural gas prices hindered investment in advanced nuclear energy at that time. Rising natural gas prices and significant pressure to reduce environmental emissions to meet decarbonization goals have forced renewed consideration of advanced, clean energy technologies, such as advanced nuclear and hydrogen.

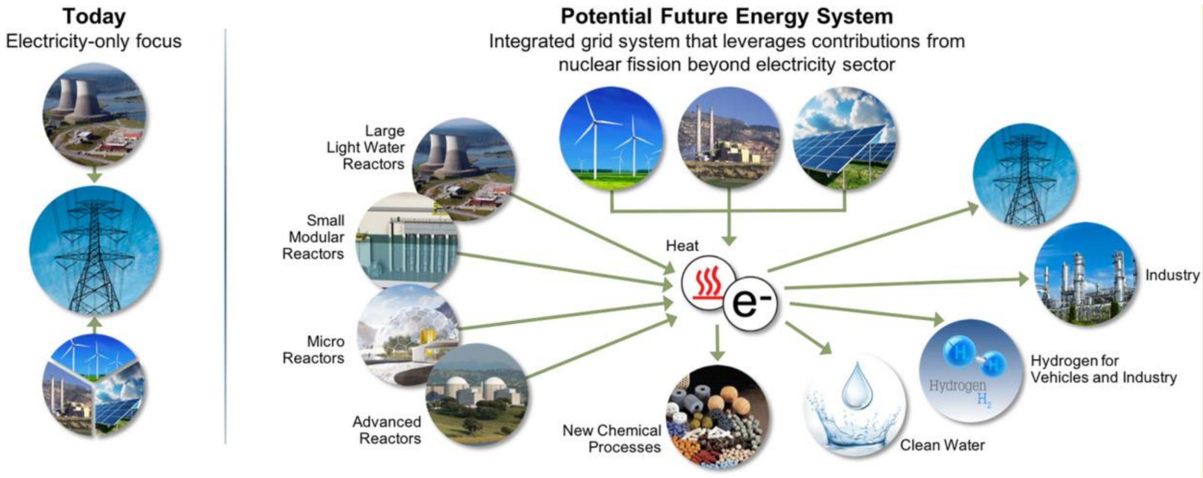

Fig. 2: Reimagining future energy systems: Overview of the US program to maximize energy utilization via integrated nuclear-renewable energy systems [4].

2. Objectives of the NEANH task force

The scope of NEANH is very broad. Initial categorization of the diverse energy system applications pertains to the definition of flexibility. For instance, as summarized in Table 1, EPRI broadens the notion of reactor flexibility beyond the capability to operate in load following or frequency following mode (i.e., operational flexibility) to include the notion of deployment flexibility and, most importantly for the topic discussed here, diverse applications beyond electricity production. This extended definition of flexibility introduces additional considerations for next generation nuclear plant designs.[6] Flexibility was further defined in the international context in the report *Flexible Nuclear Energy for Clean Energy Systems* [5], which includes a compilation of technical analyses that demonstrate the current and potential future roles for nuclear energy in providing flexibility in meeting energy demands.[7]

Attribute	Sub-Attribute	Benefits
Operational Flexibility	Manoeuvrability	Load following
	Compatibility with Hybrid Energy Systems and Polygeneration	Economic operation with increasing penetration of intermittent generation, alternative missions
	Diversified Fuel Use	Economics and security of fuel supply
	Island Operation	System resiliency, remote power, micro-grid, emergency power applications
Deployment Flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and budget
Product Flexibility	Electricity	Reliable, dispatchable power supply
	Process Heat	Reliable, dispatchable process heat supply
	Radioisotopes	Unique or high demand isotopes supply

[6] Generation IV reactors and systems were assessed to what extent and under which conditions they will be able to meet the criteria of flexibility illustrated in Table 1. This analysis was published in the GIF position paper on flexibility [9].

[7] This report, published by the Nuclear Innovation: Clean Energy Future initiative under the Clean Energy Ministerial in September 2020, includes contributions from several participating organizations and countries. The full report can be downloaded at https://www.nice-future.org/flexible-nuclear-energy-clean-energy-systems.html.

Table 1: EPRI Attributes of Advanced Reactor Flexibility and Benefits [6].

Although NEANH is an explicit concept, it is worth proposing an exact definition to ensure there is a common understanding within GIF on the boundaries of the task force. The proposed definition, as defined in the NEANH terms of reference, is as follows:

> *The NEANH include the ensemble of solutions and processes that make optimal use of the energy produced by a nuclear reactor – all or part of the heat it produces over all the extent of operational temperature and power[8] – to provide alternatives to use of fossil fuels as a source of thermal energy, and services that are complementary or alternatives to those usually provided to the electric grid. This approach is designed to optimise energy production efficiency, economics, and decarbonisation*.

At present, the primary end users of nuclear heat are the industrial and residential heating sectors. Key examples in operation include nuclear-integrated desalinisation, paper and pulp plants, and district heating. Future applications could support the very large industrial and transportation markets. Applications could include district heating/cooling; cogeneration or poly-generation; thermal energy storage, which may provide for delayed delivery of energy to coupled energy users and can support grid stabilization; using steam as a heat carrier and as a reactant in the chemical industry; production of hydrogen as a primary product, or as an intermediate product or feedstock for chemical processes; steel manufacturing; cement making; synthetic fuels for the transport sector; or stabilization of the energy grid.

The target markets to be considered for NEANH are multiple and diverse. Potential end users may be independent or may be groups of users that could connect to a heat source via a distribution network in an "energy park" type of configuration. NEANH may additionally incorporate power conversion to support the electricity grid in addition to supporting heat users. The large number of potential non-electric applications requires a specific taxonomy and techno-economic criteria to be developed to evaluate the contexts within which these NEANH approaches may be more beneficial than or complementary to heat produced through non–nuclear technologies.

3. How can Gen IV systems be employed for NEANH?

A. Processes compatible with the specific characteristics of Gen IV concepts.

Multiple methods could be used to classify non-electric applications (e.g., by function, by product). One of the possible criteria for an initial categorization of potential applications is the required process temperature. This approach is particularly well suited for Generation IV systems which, in many cases, operate with a high-temperature coolant[9] and are thus directly suitable for a wide range of applications. It is of note, however, that a lower reactor outlet temperature may be capable of supporting a higher temperature application via heat augmentation. Techniques for coupling, temperature boosting, and energy storage are important to assess the overall techno-economic feasibility, safety performance, and flexibility of such systems. Figure 3 illustrates potential nuclear-driven integrated energy systems that could

[8]Note that this definition includes low temperature sources represented by heat losses and heat arising from cooling processes.

[9] As compared with the temperatures usually reached in water-cooled generation II-III reactors.

utilize heat, electricity, and process intermediates (e.g., hydrogen) to support industrial energy demands.

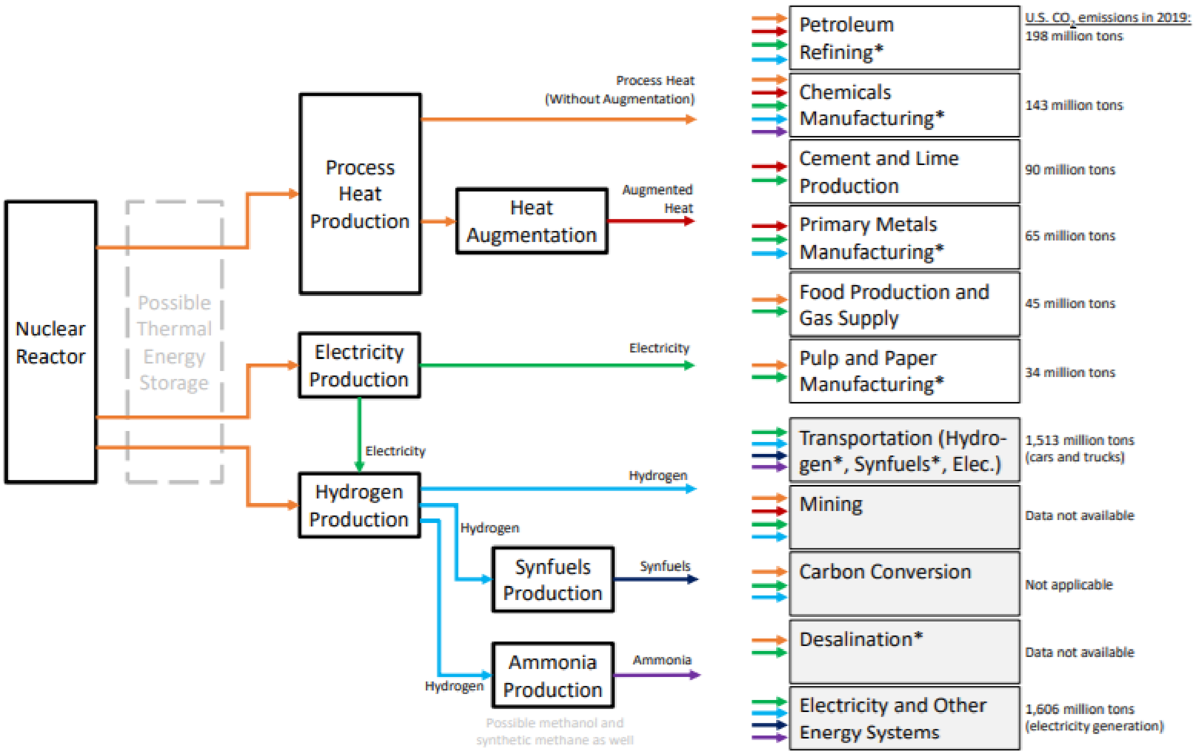

Fig 3. Linking advanced reactors and nuclear-generated products with potential use cases; note that orange arrows indicate direct process heat integration (red arrows indicate augmented heat), green arrows indicate electricity, and light blue arrows indicate hydrogen. [7]

The IAEA introduces five families of non-electric applications, as illustrated in Figure 4 [8]. Although this approach does not distinguish applications on the basis of the temperature required, it simplifies the problem and allows non-experts to capture the complexity of a variety of diverse and sometimes entangled applications.[10]

[10] As suggested in Figure 3, a nuclear system reaching very high temperatures could optimize temperature distribution and heat fluxes to satisfy different needs. However, such a scheme raises the question of technical feasibility. If shown to be technically viable, the system's reliability and operability must also be evaluated.

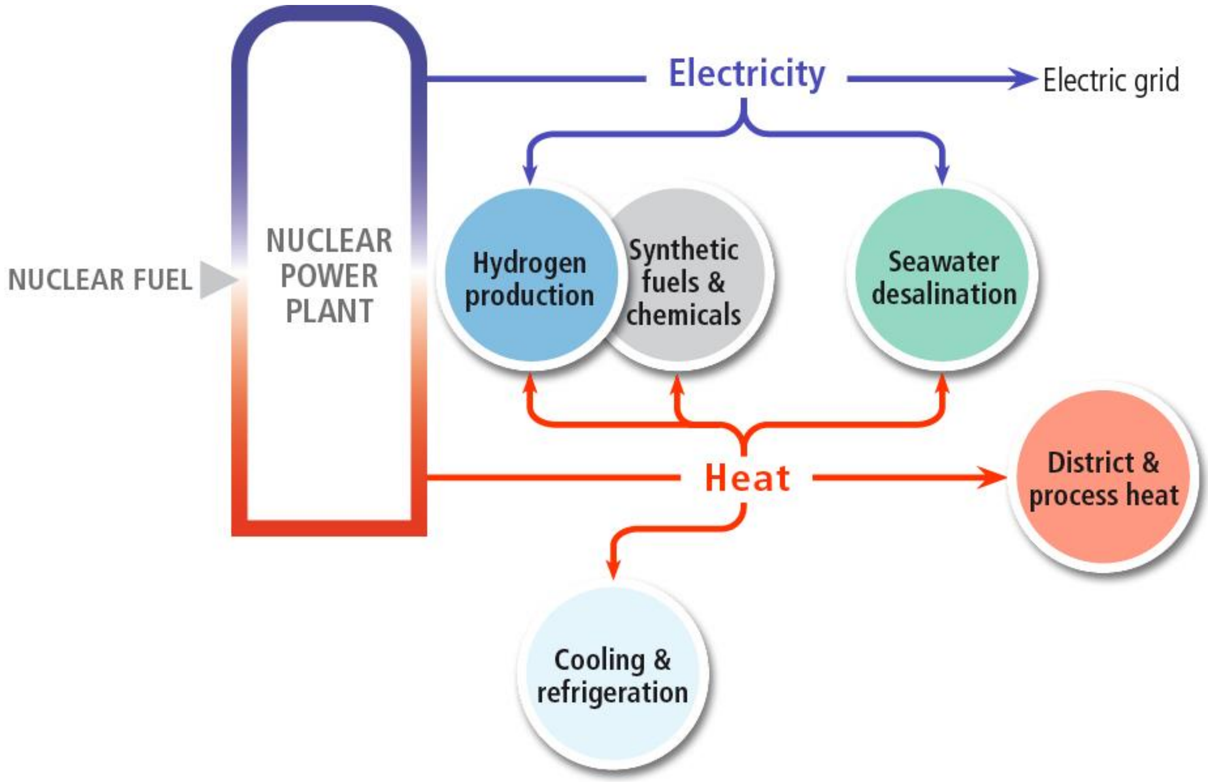

Fig 4. Five families of non-electric applications of nuclear energy, inspired from IAEA. [8]

When the candidate Gen IV systems were selected in 2001, the GIF had already identified a promising solution to be explored: the coupling of Very High-Temperature Reactors (VHTR) with large-scale hydrogen production.[11] This option anticipated the broad range of non-electric applications that may be considered for several GIF systems. Current GIF activities must consider the techno-economic, environmental and energy supply challenges on the horizon for 2050. As such, all GIF systems should be evaluated for their potential coupling with a wide range of non-electric applications, which may be prioritized by market size and potential for emissions reductions.

B. Impact of nuclear plant scale

When exploring options for possible coupling of Gen IV reactors and NEANH processes, the reactor output temperature and power level, as well as optimized coupling solutions, play a significant role in the identification of market opportunities and potential for CO_2 abatement.

Advanced nuclear energy systems are being developed over a wide range of system scales to provide flexibility in their adoption for a wide range of energy demands. Many Gen IV reactor systems would be deployed at large-scale, allowing support for centralized electricity generation, similar to current fleet nuclear systems, and also offering the potential to support large-scale industrial facilities having gigawatt-scale electricity and heat demands.

Since 2008, the nuclear sector also has experienced a renewed dynamic partially driven by the rise of Small Modular Reactors (SMRs). SMRs are defined by the IAEA as reactors with a capacity < 300 MWe, which could equate to as high as 1000 MWth. Most GIF concepts can be

[11] This led to the creation, within GIF, of a Project Management Board specifically dedicated to research and studies focusing on large scale hydrogen production coupled with a HTR/VHTR.

built as SMRs, as demonstrated in the IAEA booklet on Advances in Small Modular Reactor Technology Developments [10] that currently lists more than 70 different designs. In addition to being characterised by technological features (e.g., power scale), this class of reactors is characterised by the economic model they are based upon. The latter can be detailed as follows:

- The reduced SMR physical size should allow for increased modularization and enable increased factory manufacturing of components versus expensive on-site construction;
- The reduced power level may lead to a simpler design and create opportunities for safety and/or operational enhancements (e.g., 100% passive systems, reduced emergency planning zone);
- The potential for an increased number of SMR units to be built should more rapidly establish an improved supply chain that should lead to a reduction of construction time, cost, and improved quality versus large-scale reactors (i.e., enables economies of quantity versus economies of scale);
- The reduced power of each module opens up this class of reactors to specific markets such as geographical niches, non-electric applications, and co-generation of electricity and heat. Thus, SMRs are likely to provide a solution for decarbonizing energy-intensive industrial activities such as mining, chemical plants, hydrogen production, and steel manufacturing.
- The reduced SMR source term and worker/public dose rates typically leads to smaller Emergency Planning Zones (EPZs), which would allow co-location of SMRs with industrial or chemical facilities. This improves the feasibility and economics of co-generation deployments.

The enthusiasm for these modular reactor projects is such that there are now more than seventy designs proposed around the world, among which a significant proportion is using Gen IV technologies. However, the majority of the Gen IV classified reactors are largely in conceptual phase of design, with expected commercialisation in the early 2030s. Furthermore, it is noted that while advanced analyses provide confidence in the economics of these reactors, empirical evidence of the economics of modular systems is subject to attainment of commercial operational data.

At the same time, the nuclear sector landscape is also being shaped by the emergence of micro-reactor concepts (i.e., reactors with an output power of roughly 1 to 20 MWe). To an extent microreactors are oriented to satisfy a niche sector of power demand including remote communities, military bases, or heavy industrial installations (e.g., mining sites) in electricity/heat cogeneration. In these applications the economic criteria are balanced by the reliability and resilience of the service provided and the cost of alternative energy sources (e.g., expensive flown-in diesel fuel for generators).

C. Identification of solutions arising from a complex matrix

Identifying options to couple Gen IV reactors with non-electric applications goes far beyond solving a complex multi-criteria optimisation problem. The analyses are multi-criteria and multi-factorial (i.e., multivariable). Figure 5 illustrates the potential roles for Gen IV technologies via a 6x3x6 matrix. While the matrix shown is not fully comprehensive, this approach may be used to simplify the set of possible solutions for evaluation. This matrix corresponds to the 6 Gen IV systems at 3 levels of power and 6 NEANH process families.

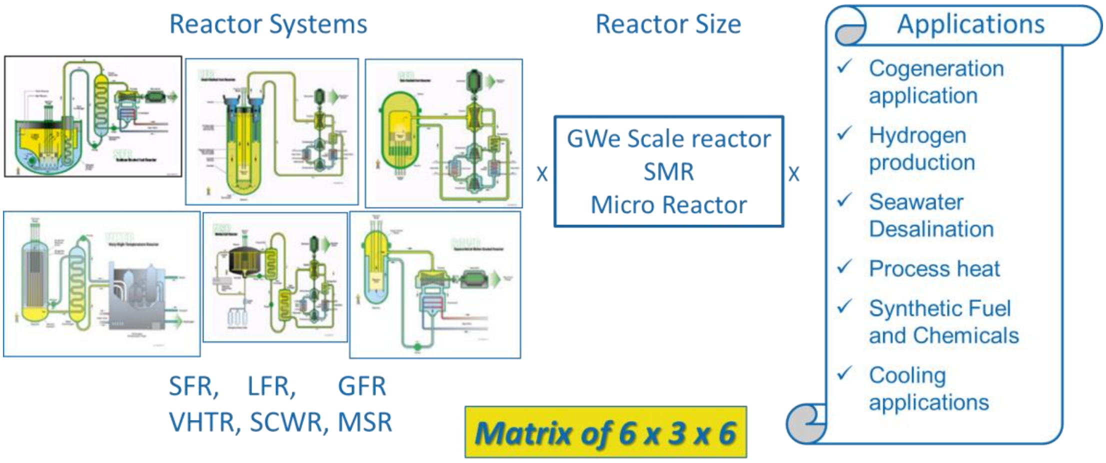

Fig. 5: Matrix of Gen IV reactor systems, scale, and applications to support identification of system options.

Although this representation of the objectives of the NEANH Task Force is schematic, it illustrates the challenges GIF faces to better understand the existing options, to propose promising co-generation approaches, and to identify the key efforts and development to be pursued to:

- remove existing technical and licensing hurdles (in particular, regarding the coupling and heat transport from the heat source to the process user while also ensuring isolation of the primary side of the nuclear system);
- identify specific requirements and specifications that the NEANH processes would impose on the operation and management of the reactor supplying the heat; alternatively, propose solutions to work around possible constraints;
- analyze the consequences of coupling a Gen IV reactor with an NEANH process in terms of safety, licensing, interoperability, reliability of coupled systems, process control, management of transients, etc.;
- analyze the technical and economic logic underpinning these complex systems from a geopolitical perspective (e.g., national policies, specific geographical contexts, need for industrial infrastructures to be developed);
- analyze the challenges of codes and regulations for colocation / coupling of NEANH with a nuclear plant;
- identify and promote the demonstration needs required to convince investors and end-users of the technical and economic performance of the proposed solutions.

Acknowledging the range of challenges or uncertainties is also important to identify suitable solutions to implementing NEANH systems. For instance, there may be additional costs, or hazards, associated with coupling reactor systems with industrial applications, both of which have distinct regulatory structures. There may also be conflicting priorities for heat between industry's needs and electricity demand. Communication will be essential to ensure that relevant parties have the data and information they need to make informed decisions. This includes technological suitability, but also an understanding of systems costs and regulatory or waste management processes.

Analyses should be conducted by mobilizing various areas of expertise from across the GIF signatories, including technical, economic, regulatory, and industrial aspects. For this reason, the NEANH Task Force was created as a multidisciplinary expert group relying on joint competencies to achieve common objectives.

4. Summary and Conclusions

To achieve a secured power system whilst meeting the constraint of net zero CO_2 emissions in 2050, all potential solutions must be considered for assessment. Some of the solutions to be deployed by 2050 are still in their infancy and require further development. This need offers great opportunities for development and innovation across all energy sectors, including the nuclear industry.

The GIF signatories agree that Gen IV systems could and should provide diversified service offers ranging from electricity to numerous heat applications at the required large scale to achieve a significant societal impact in terms of greenhouse gas emission reduction, security of energy supply, and energy affordability.

The GIF signatories are determined to utilize their collective skills, knowledge, and expertise to propose and evaluate relevant coupling and cogeneration options for the short and medium to long term. The Task Force will identify major obstacles that may arise from the energy system combinations under consideration, contribute to their resolution, and define a portfolio of realistic, technically and economically feasible NEANH solutions coupled to Gen IV reactors to help accelerate decarbonization.

Nomenclature

GenIII: Generation III reactor
GenIV: Generation IV reactor
GIF: Generation IV International Forum
IAEA: International Atomic Energy Agency
IEA: International Energy Agency
MMR: Micro Modular Reactor
NEA: Nuclear Energy Agency
NEANH: Non-Electric Applications of Nuclear Heat
NPP: Nuclear Power Plant
OECD: Organisation for Economic Co-operation and Development
PWR: Pressurized Water Reactor
R&D: Research & Development
ROI: Return On Investment
SMR: Small Modular Reactor
TF: Task Force
TRL: Technological Readiness Level
WNA: World Nuclear Association

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