Generation IV International Forum: Delivering Next-Generation Nuclear Systems

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GIF is a multinational co-operative endeavor organized to foster the research and development needed to accelerate the deployment of the next generation of nuclear systems.

Since its creation in 2000, GIF has identified the following six nuclear energy systems as being the most promising to meet its objectives, assuming a deployment horizon beyond 2030 (Petti et al. 2014):

- SFR
- Very high temperature reactor
- Gas-cooled fast reactor
- MSR
- Lead-cooled fast reactor
- Supercritical water-cooled reactor.

These concepts fit within the Generation IV systems depicted in Figure 1.These nuclear systems meet stringent criteria in sustainability, economics, safety and reliability, proliferation resistance and physical protection. While all six systems are certainly capable of producing electricity, they have been developed from the onset considering potential applications for their nuclear heat, particularly those systems capable of outlet temperatures ranging 700°–950° C (i.e., very high temperature reactor, gas-cooled fast reactor, lead-cooled fast reactor, and MSR), and ~550° C (SFR). Nuclear heat can be used to support hydrogen production or to provide industrial process heat to chemical processing facilities, such as petroleum refineries.

This document encompasses one section of a larger report, titled Flexible Nuclear Energy for Clean Energy Systems. The full report can be found at https://www.nrel.gov/docs/fy20osti/77088.pdf. The author(s) of each section is/are solely responsible for its content; the publication of these perspectives shall not constitute or be deemed to constitute any representation of the views or policies of any Governments, research institutions, or organizations within or outside the NICE Future initiative.

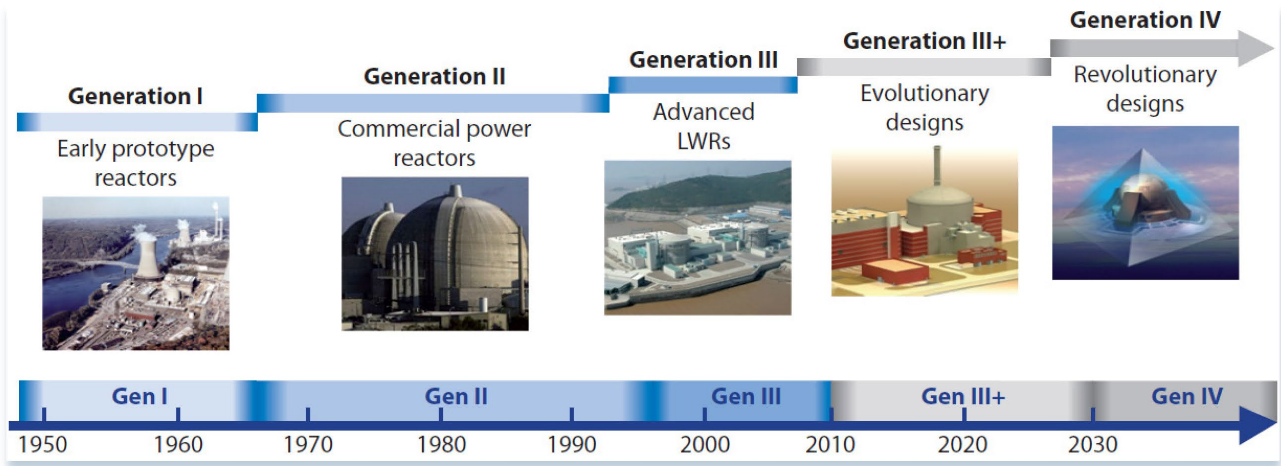

Figure 1. The four generations of reactor designs

Source: (Stanculescu 2019)

In addition to these core drivers, GIF is also increasingly recognizing the need to take into account flexibility capabilities as a specific requirement for future nuclear systems. As recommended by its Senior International Advisory Panel, GIF is progressing toward a system approach to flexibility in a broad sense, addressing operational flexibility (maneuverability, compatibility with hybrid systems, island mode operation, diversified fuel use), deployment flexibility (scalability, siting, constructability), and product flexibility (electricity, process heat).

This context was integrated into the recent update of the GIF research and development outlook (EMWG 2018) and is now taking place through a number of initiatives at the level of the GIF cross-cutting working groups (in particular for economics) and as part of the definition of research and development priorities of the six systems.

1.1 Economic Perspectives on the Flexibility of Gen-IV Systems

The GIF Economic Modeling Working Group is currently working on market issues related to the deployment of Gen IV systems (EMWG 2018); especially considering the increasing penetration of variable renewable electricity production and the importance of capital cost reductions for the future competitiveness of nuclear power.

Together with the GIF Senior International Advisory Panel, the Economic Modeling Working Group is monitoring the work being done elsewhere on the integration of renewable and nuclear energy systems to inform the research and development activities of the six GIF systems. This work resulted in the publication in 2018 of a first position paper (Bredimas 2011) with two key recommendations for GIF research and development activities:

- While flexibility is not directly identified in the original GIF goals, the six GIF systems need to ensure that flexibility aspects are an integral part of their future research and development priorities.

- Specific opportunities for cross-cutting research and development should also be encouraged. This typically includes topics such as advanced materials resistant to thermal fatigue, advanced instrumentation and control for dynamic balancing of electrical and thermal outputs, as well as efficient and flexible energy conversion systems such as the supercritical CO_2 Brayton cycle.

In addition, the Senior International Advisory Panel has further identified three strategic issues that need to be addressed in order to better integrate Gen-IV systems in future energy markets:

- Enhanced maneuverability to operate in electricity mixes that include an increasing share of intermittent energy sources. Although flexible operation may likely result in reduced revenues when participating in current liberalized electricity (energy only) markets, designers of Generation IV advanced reactors recognize that enhanced flexibility may be an essential feature in the electricity markets of the future that may value reliability, resiliency, capacity, and other ancillary services.

- Enhanced flexibility of energy products (e.g., power, heat, hydrogen, and so on). Generation IV advanced reactors are to be designed with the capability to deliver a variety of energy products, such as heat or hydrogen, in addition to traditional power. This will be beneficial from a system cost perspective while increasing the overall reliability and resilience of the energy systems and optimizing the business case for Gen IV technologies.

- Enhanced reliability of nuclear reactor operation with energy storage options. These solutions could improve the balance between base load and variable generation. Further work is needed to be assess the economic and technical implications of energy storage components.

1.2 Technical Flexibility Capabilities of Gen-IV Systems

Building on the economic and strategy assessments of Gen IV system flexibility, developers of the six system concepts are working to identify key technical areas to focus their research and development efforts. A dedicated technical workshop was organized in May 2019 in Vancouver in the margins of the 10th Clean Energy Ministerial to discuss research and development needs. A number of important findings are be highlighted in the following subsections.

1.2.1 Operational Flexibility

Overall, Gen-IV systems are expected to have load-following capabilities at least similar LWRs that implement flexibility features. However, important differences remain among the six systems.

Some Gen-IV systems, and, in particular, MSR concepts with liquid fuel, are inherently flexible. The main limitation in terms of operational flexibility would be imposed by the steam cycle. Other Gen-IV concepts, such as SFR and lead-cooled fast reactors, have in the past provided ancillary services to the grid (e.g., Phénix and Superphénix SFR reactors in France) but face technical constraints for load-following. This constraint is partly due to the fact that these reactors were initially designed without requirements for operational flexibility. In that respect, a number of research and development priorities have been identified to address this issue. For SFR, this includes:

- Redesigning the inner vessel to minimize thermal gradients

- Insertion of a backpressure to avoid changes in the level of the sodium coolant free surface
- Diversification of generated energy products generated to maintain the reactor operating at full nominal power.

1.2.2 Deployment Flexibility

Gen IV systems may face, in general, fewer siting constraints than traditional LWRs. For instance, due to their intrinsic safety features, some advanced concepts may have a smaller emergency planning zone requirements. Furthermore, the higher thermal efficiency of Gen IV systems reduces the need for an ultimate heat sink on a per-unit electricity generated basis. They can be designed for a large power range, which also supports greater deployment flexibility, as these systems can be tailored to the needs of a specific market.

In terms of construction, higher modularity and advanced manufacturing processes will also foster deployment flexibility.

1.2.3 Product Flexibility

Gen-IV systems are expected to have superior capabilities compared to LWRs in terms of product flexibility due to their higher outlet temperature. All Gen-IV systems exhibit higher reactor outlet temperatures compared to LWRs and are ideal for a wide range of process heat applications. In particular, there is a large existing and near-term market for steam at temperatures lower than 600° C. For instance, in Europe, the process heat market represents 100 GWth today, and about 50% is found in the temperature range up to 550° C (primarily in the chemical industry and for refineries) ("Cost and Performance Requirements for Flexible Advanced Nuclear Plants in Future U.S. Power Markets" 2020). In the longer term, very high temperature reactors could also offer promising opportunities for temperatures higher than 950° C (such as steelmaking, cement, and, potentially, hydrogen production) but will require additional research, particularly related to material science.

In addition to specific research and development activities, the construction of first reactor prototypes and the industrial demonstration of coupling with nonelectric applications, in particular industrial heat and hydrogen production, remain the key near-term objectives for the commercial deployment of these Gen-IV systems.

1.3 References

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