AISTech 2023 — Proceedings of the Iron & Steel Technology Conference
8–11 May 2023, Detroit, Mich., USA
DOI: 10.33313/387/023

Nuclear Energy as a Pathway to Decarbonization for Modern Steelmaking Plants

Herbert Lam, James Wikston, Neil Tannyan

Hatch Associates Consultants Inc.
1600 W Carson St. Pittsburgh, PA, USA, 15219
Phone: +1 412 497 2000

ABSTRACT

Recent developments in new advanced and small modular reactors (SMRs) are paving the way for a new source of carbon-free energy. Nuclear power will be a key energy source for the Iron and Steel industry to support DRI + EAF plant configurations with reliable carbon free electricity. This paper will provide an overview of the leading nuclear SMR technologies being developed and how they can be applied and implemented in an EAF based steel plant which requires a very high electrical load. In addition, the paper will highlight key considerations when selecting a nuclear technology to support your operations.

INTRODUCTION

Traditional Iron and Steel production is highly carbon intensive, and in the Americas and Europe is gradually being replaced with energy intensive EAF's and in order to reduce carbon emissions in the industry. In addition to a reliable and stable energy source for powering EAF's, hydrogen based DRI will require very high energy to produce hydrogen using electrolyzers. As an example, an hydrogen based DRI plant with 2 EAF's producing about 3 million tons per year of steel requires about a Gigawatt of electrical power. Nuclear power holds great potential to provide electricity and heat required without the generation of greenhouse gas (GHG) emissions.

Listed below are examples of how nuclear energy can be utilized to support decarbonization at a DRI / EAF plant:

- Emission free electricity to support GHG reductions through electrification for mechanical drives, heating, transportation and others.
- Industrial heat production without any GHG emissions
- Power for an onsite electrolysis process to generate emission-free hydrogen than can be directed used in the DRI process
- Provide power for carbon capture, utilization and sequestration technologies that can be integrated into the DRI process for non-hydrogen based DRI processes

Despite the many operational nuclear power plants around the world, the deployment of the technology to support industrial applications has not yet been done. Conventional nuclear power plants have been large utility scale power plants; however, a new generation of designs are being brought to market

Reactors are being designed in new ways that provide safer and more economical options by leveraging passive safety features while making them smaller than conventional nuclear power plants. The current development of small modular reactors (SMRs) holds great promise for the iron and steel industry by supporting ongoing decarbonization goals.

OVERVIEW OF NUCLEAR POWER TECHNOLOGIES

SMRs are being developed as the next generation of nuclear technologies to provide safer and more economical designs. The smaller size allows for reduced CAPEX for new nuclear and leverages modular components that are pre-fabricated and shipped onsite to be installed. The modularization of an SMR allows for savings in cost gained through continual production of the same modules and reduced construction times for the plants [1].

In addition to the current trend to make nuclear power plants smaller, many commercialization efforts are ongoing to advance different reactor technologies. The following section outlines the main reactor design that are currently being commercialized by various vendors.

Pressurized Water Reactors

Pressurized Water Reactors (PWR) are a type of Light Water Reactor (LWR) which use light water as both the coolant and moderator [1] [2]. PWRs use a closed, pressurized water loop that circulates between the reactor core and heat exchangers. Heat from the heat exchangers is then transferred to water in a secondary system to produce steam to drive to a steam turbine [3]. As the cooling water is kept at a high pressure (150 atm), water in the reactor core, can reach 325°C without boiling [2]. Figure 1 shows a schematic of a general PWR.

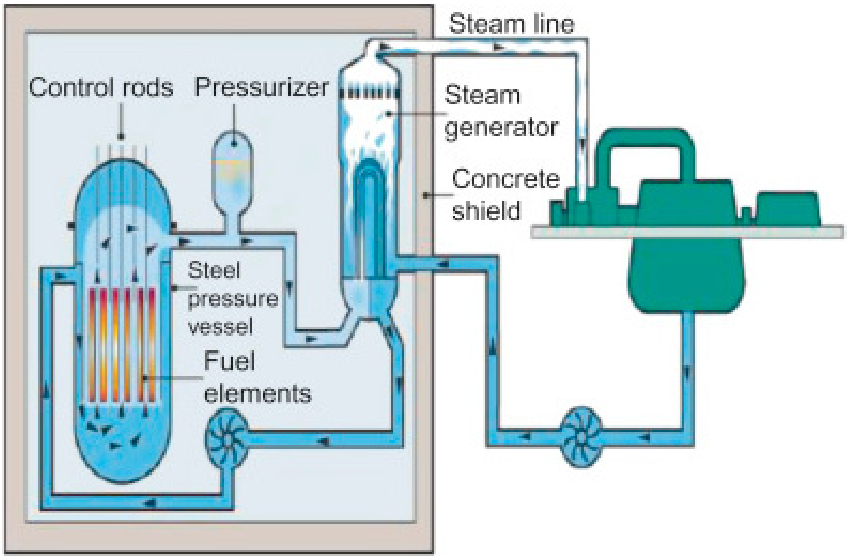

Figure 1. Pressurized water reactor.

The PWR design emerged from WWII research for submarine propulsion units, with the first American submarine with nuclear power unit launching in 1955 [2]. Westinghouse then adopted this technology for US Navy submarines, eventually developing it for power generation use. In 1960, the first commercial PWR was the Yankee Rowe nuclear station, which had a capacity of 185 MW. Over the decades, PWRs have become the most common nuclear reactors, with 300 operating reactors worldwide by 2020, providing approximately 67% of the world's nuclear energy capacity [4].

Since the first PWR in 1955, advances in PWR technology have occurred in many ways. Generation II PWR designs evolved to increase their security, effectiveness, and generation capacity, the latter mainly by increasing the size of the main reactor components and number of coolant systems [4]. Generation III and III+ designs going forward are focusing on improved efficiency and safety, which is achieved by the inclusion of passive safety systems and increased redundancies [4].

While most PWR based SMRs are still in the design phase, significant advances in the development of PWR SMRs have taken place in recent years. Each vendor is approach PWR SMRs in different ways leveraging new ways to enhance safety and reduce costs. Key features include passive safety for the BWR to leverage natural circulation and/or gravity to provide decay heat removal. PWR SMR designs being commercialized include the NuScale VOYGR in the US, NUWARD by EDF in France, and the Rolls-Royce SMR in the UK [5].

Boiling Water Reactor

Boiling Water Reactors (BWR) are a type of Light Water Reactor (LWR) which also use light water as a coolant and moderator. Unlike PWRs, the water in a BWR reactor core is meant to boil (under a pressure of 75 atm and boiling point of 285°C), which generates steam to directly drive a steam turbine [2]. Condensed steam from the turbine is then recycled back into the reactor core. Figure 2 shows a schematic of a general BWR [2].

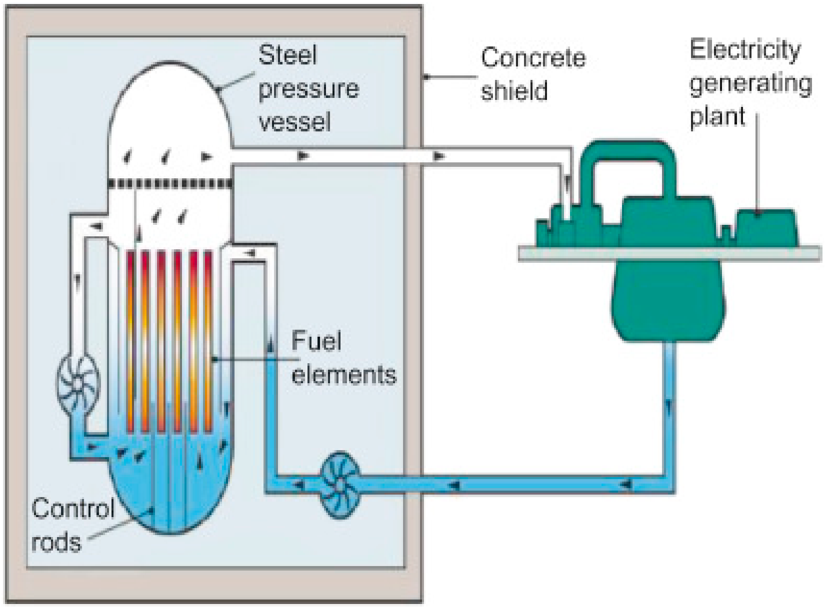

Figure 2. Boiling water reactor.

The first BWR was built in the US in 1952, and was an experimental reactor called Borax I. This reactor design was upgraded to Borax II then Borax III in 1954, the latter becoming was the first nuclear electricity supplier in the US, with a capacity of ~2 MW [2]. Subsequently, General Electric Co. adopted the BWR technology to develop the Dresden Nuclear Power Plant, which had a generating capacity of 210 MW and began operation in 1960 [2]. Over the decades, BWRs have become the second most common nuclear reactors, with 69 operating reactors worldwide by 2020, providing approximately 16% of the world's nuclear energy capacity [4].

Similarly to PWRs (which are also Light Water Reactors), BWR development and optimization is still ongoing, despite being many decades old technology. Latest advances for develop a SMR based on a BWR has been based on downsizing the reactor to improve the economics and leveraging passive safety features to use natural circulation and gravity to cool itself without operator intervention.

The BWRX-300 (870 MW(th) / 270-290 MW(e)) designed by GE-Hitachi Nuclear Energy (GEH) in the US and Japan has been selected by Ontario Power Generation for the Darlington New Nuclear Project and Tennessee Valley Authority for the Clinch River Nuclear SMR Project [5] [8] [9].

High Temperature Gas Cooled Reactor (HTGR)

High Temperature Gas Cooled Reactors (HTGR) operate at high temperatures, are moderated by graphite, and are cooled by flowing helium gas (refer to Figure 3). HTGRs use a particle-like fuel particles called TRISO fuel, which consists of uranium fuel coated with carbon and ceramic based materials [10]. The TRISO fuel can withstand high temperatures without melting in a nuclear reactor so it can act as the containment of fission products without the need for expensive containment of a conventional nuclear power plant. For HTGRs, there are 2 main reactor core configurations, the pebble-bed core and the prismatic block core [11].

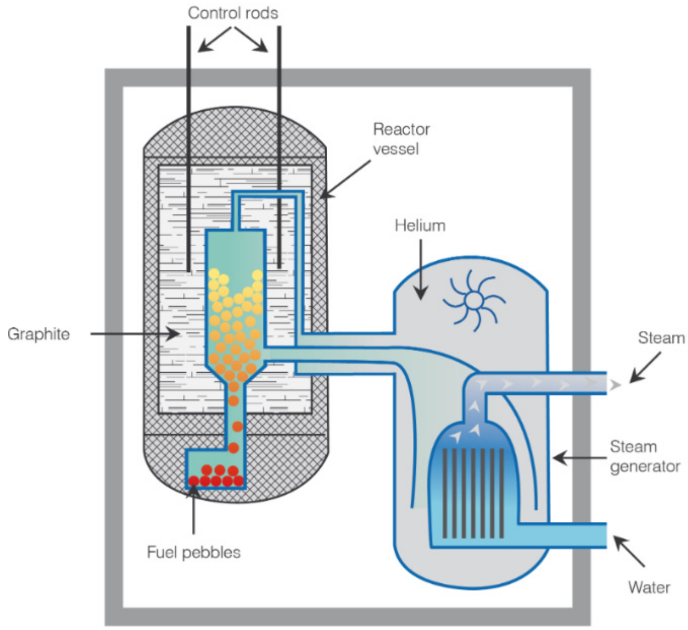

Figure 3. High Temperature Gas Reactor. [14]

Core outlet temperatures range between 700 – 950 °C (or greater than 1000°C in future reactors), which make HTGRs attractive for supplying heat to energy intensive industrial processes that currently rely on fossil fuels [11] [12].

Notable safety features of a HTGR include the inherently negative temperature coefficient of reactivity that stabilizes the reactor as temperature increases in the core. In addition, the TRISO fuel with high thermal capacity in the core with a graphite moderator and inter helium coolant allow for passive heat removal of decay and residual heat without equipment actions operator intervention [12].

The HTGR concept was first developed at Oak Ridge National Laboratory in the US in 1947. Early prototype reactors then began operation in the 1960's, and includes the Dragon Reactor in the UK (20MW(th), 1966-1975), the Peach Bottom plant in the US (150 MW(th), 1966-1974), and the AVR Juelich in Germany (46 MW(th), 1969-1988) [15] [16] [17]. Notably in the US, the Fort St. Vrain power plant began operation in 1979, with a much larger generating capacity of 842 MW(th) [16].

Demonstration project for HTGRs in operation today include the HTTR in Japan, the HTR-10 in China, and the newly operational HTR-PM in China, which was reported to reach full power in December 2022 [18].

HTGR are being adapted for SMRs to improve the economics and support industrial applications.

- The Xe-100 (200 MW(th) / 82.5 MW(e)) by X-energy is a major vendor for this technology [5]. To aid the development of HTGRs in the US, the Department of Energy selected the Xe-100 to be part of the Advanced Reactor Demonstration Program (ARDP) to support demonstration of the technology by 2027. The ARDP includes a cost share arrangement of approximately US$1.1 billion [17]
- Another notable HTGR SMR vendor in North America is Ultra Safe Nuclear Corporation (USNC). Their demonstration MMR unit is planned to be deployed at Canadian Nuclear Laboratories in Chalk River, with operation beginning in 2026 [5]. MMR output can be 15 or 30 MW(th), and 5 or 10 MW(e) [5].

Sodium Fast Reactors (or Liquid Metal Fast Reactors w/Sodium)
Fast reactors in the past have been developed to address concerns with uranium fuel shortages. Thermal neutron reactors rely on fission of the uranium-235 isotope that requires moderation of neutrons and slow them down to initiate fission. Fast reactors can accept a wider range of fuels to generate electricity and potentially create a closed fuel cycle using spent fuel from today's current commercial reactor fleet [12].

Sodium Fast Reactors (SFR) have become the most common approach for a fast spectrum reactors with liquid sodium as the primary coolant; this allows the coolant to operate at lower, near atmospheric pressures and high temperatures (coolant outlet around 500 – 550°C) [12] [6]. Additionally, the liquid sodium coolant allows for high power density and low coolant volume fraction. Despite the oxygen-free environment of SFRs (which prevent corrosion), sodium's high chemical reactivity with water and air require SFRs to have a closed and isolated coolant system [20].

Notable safety features include a reasonable margin before coolant boiling, near atmospheric operating pressure in the primary system, a long thermal response time, and an intermediate sodium system between the power conversion system, and the primary system containing radioactive sodium [20].

The two main design variants of SFRs are loop-type and pool-type. In loop-type SFRs, the primary heat exchanger is in a separate vessel from the reactor core. In pool-type SFRs, the primary heat exchanger and reactor core are in the same vessel, immersed in a single pool of liquid sodium. See Figure 4 below for a high-level schematic of loop-type and pool-type SFRs [6].

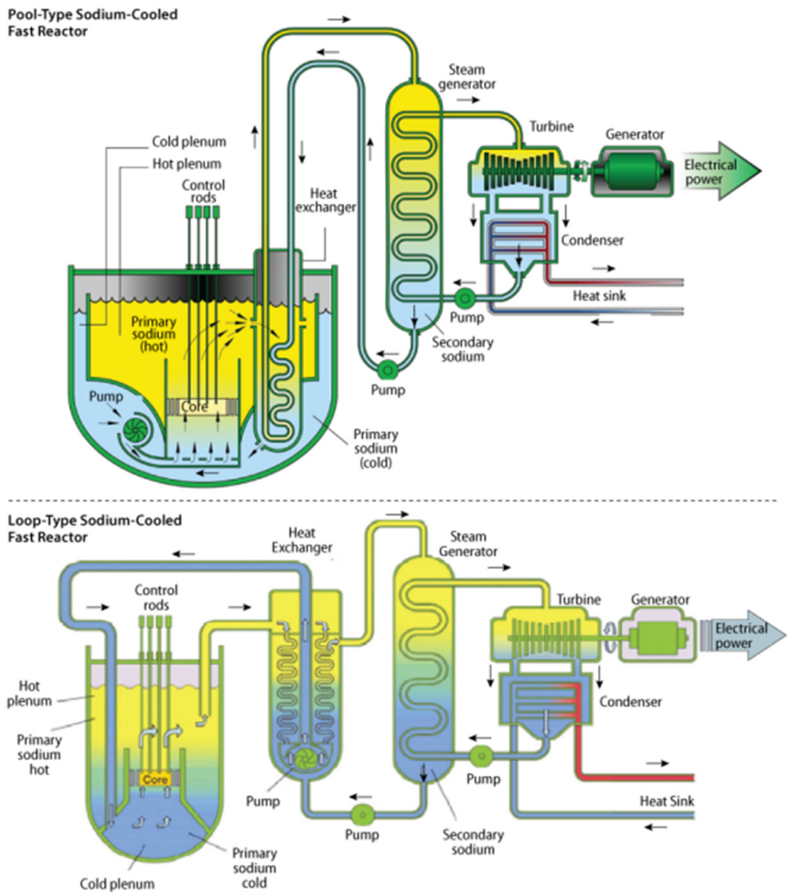

Figure 4. Sodium Fast Reactor.

Along with HTGRs, SFRs are considered as one of the most technologically mature "advanced" reactor concepts [6]. The first SFR developed was the 1.4 MW(th) EBR-I in the Unites States, which reached first criticality in 1951 and shutdown in 1963 [21]. Following the EBR-I, over 20 SFRs ranging from 10 to 3000 MW(th) were built across the world in the US, France, Russia, the UK, Japan, India, Germany, Kazakhstan, and China [21]. Currently, there are 8 Fast Nuclear Reactors (FNR) operating worldwide, 7 of which are experimental or demonstration SFRs [22]. Regarding actinide management, the SFR is widely considered as the one of the nearest-term deployable reactor type [20].

The reprocessing of used fuel and 'blanket assemblies' (of uranium around the reactor core) is a key piece of the FNR (including SFR) fuel cycle, and is an area of FNR technology undergoing development in new designs. Typically, aqueous reprocessing is used for recovered plutonium, and is recycled back into the core [22]. However, recent advances towards integrated core designs and away from core and blanket designs suggest new electrometallurgical processes (i.e., pyroprocessing) to reprocess used fuel, and removes the need to separate plutonium from other transuranic and fission products. This advancement can help improve FNR operation by closing the fuel cycle and simplifying waste management [22].

In the US, numerous companies are developing SFRs; notable examples include:

- General Electric-Hitachi (GEH) has developed the PRISM concept for a compact modular pool-type reactor based on the EBR-II reactor in the US. PRSIM modular reactor has an output of 840 MWt / 311 MW. [23]
- TerraPower founded by Bill Gates has developed the Natrium concept with GEH that uses a molten salt as a secondary coolant that can generate steam or store it to allow the power output to vary between 30% to 150% [23]. TerraPower was also selected for the US DOE Advanced Reactor Demonstration Program [24].

- ARC Clean Technology is developing the ARC-100 a 100 MWe / 286 MWth pool type sodium cooled reactor. The technology is based US EBR-II reactor (62.5 MWth) that was licensed from GEH for this design [24].

Molten Salt Reactors
Molten Salt Reactors (MSRs) use molten chlorine or fluoride salts as a coolant or as a fuel. Salt-cooled MSRs use molten salt to flow over solid fuel and cool the core, and salt-fueled MSRs contain the reactor fuel as dissolved in the molten salt. MSR design can vary considerably, as they can be fast reactors or thermal reactors, they can utilize different molten salts, etcetera [6]. MSR outlet temperatures range from 700 – 1000°C, which make MSRs suitable for providing energy to heat intensive industrial applications. Notable features of MSRs is their ability to be refueled while operating at full power (which reduces reactor downtime and safety risks associated with refueling), a drain tank failure mechanism consisting of a “freeze-plug” that is only possible in fluid fuel reactors, and the fact that molten salt is generally not violently reactive with air or water (unlike liquid sodium) [25]. Figure 5 shows a high level schematic of an MSR.

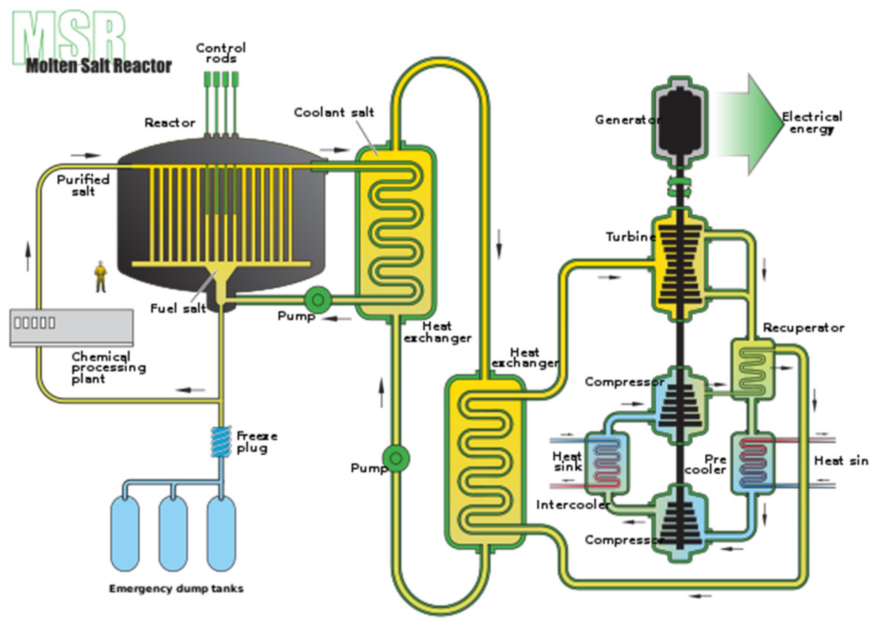

Figure 5. Molten salt reactor.

MSR development began in the U.S during the 1940s and 1950s for military aircraft propulsion, despite nuclear aircrafts never being deployed. The 2.5 MW(th) Aircraft Reactor Experiment (ARE) used fluoride molten salt with dissolved uranium fuel, and successfully demonstrated high-temperature operation in 1954 [26]. During the 1950s and 1960s, Oak Ridge National Laboratory in the US developed two demonstration MSRs, which were moderated by graphite and were thermal neutron spectrum [27]. By the 1970s, a detailed design of a 1000 MW(e) MSR was developed, which was then followed by a halt in US MSR work and development for a few decades to focus on the SFR. Interestingly, SFR R&D on pyro-reprocessing was also useful for developing safety and non-proliferation measures of molten salts, as well as for transportation and dissolving methods of molten salt.

Ongoing work in MSR technology includes the development of the Molten Salt Actinide Recycler and Transmuter (MOSART) in Russia, the FUJI concept in Japan, the FHR in the US, and numerous MSR SMRs being developed worldwide [27] [25] [5].

Current R&D include the assessment of safety features, resolving issues related to materials, improving core design, etc. [28].

MSRs are being actively developed to be commercialized by many vendors across the world. Notable companies include:

- Kairos Power’s FHR leverage TRISO fuel with a molten salt as a coolant leverage instead of dissolving the fuel in the molten salt. Leveraging the safety benefits of TRISO and molten salt [30].
- Terrestrial Energy’s Integral Molten Salt Reactor (IMSR) builds upon the work at ORNL with dissolving a standard low-enriched uranium in a fluoride salt. The IMSR leverage a reactor unit with the molten salt and graphite moderator in a larger containment vessel that can be sealed and swapped every 7 years [31] .

CONSIDERATIONS FOR THE DEPLOYMENT OF NUCLEAR ENERGY FOR A STEEL PLANT

Technology Screening of Nuclear Energy Technologies for Deployments to Support DRI +EAF Plants

As highlighted above, there are many competing SMR technologies that are being developed and the type will be a key decision in the deployment. Each technology has its own benefits and drawbacks that need to be evaluated to meet the needs of a DRI and EAF plant. There are many different aspects to be considered across multiple dimensions to be able to select a technology. Hatch has worked with many industrial users to evaluate SMR technologies and have developed a evaluation framework. The key considerations included in the evaluation are technology compatibility, technology readiness level, vendor readiness level and a levelized cost of electricity evaluation (LCOE).

Technology Compatibility Assessment

Based on the desired end use of the energy from a nuclear reactor, key technical requirements should be developed to support the reactor technology screening. Each technology has some inherent limitations that need to be considered and made incompatible for the intended application. A key of SMR criteria needs to be established to be able to screen out technology that are not capable of meeting the technical requirements.

Technology Readiness Level

Some of the SMR technologies being developed is based on reactor technology that hasn’t been deployed commercially yet, but hold promise to provide safer and more economical options for the future. Most of the SMR technologies that have not been developed still have significant research and experiments have already been completed that provide the groundwork for the ongoing commercialization effort ongoing by the technology vendors. The technology readiness level (TRL) of SMR technologies being evaluated should be considered when selecting a technology that can be deployed. Hatch leveraged a TRL assessment methodology that is similar NASA’s TRL assessment framework for their space program [29]. The assessment ranges varied based on the work completed for each technology through a spectrum of technology development steps from basic principles being established all the way through to commercial status with 9 defined levels.

Vendor Readiness Level

In addition to evaluating the maturity of the SMR technologies, a vendor readiness level (VRL) should be similarly assessed for any nuclear technology vendors. Hatch has developed an assessment framework that considers a VRL evaluation on a 5 point scale rating system based on the following elements:

- Corporate capability and financial strength
- Supply chain including engineering, procurement and construction capabilities of the vendor or partners
- Regulatory approval status
- Technology development status
- Client engagement status
- Stakeholder engagement status

Levelized Cost of Electricity (LCOE)

In order to compare various options that impact both the capital expenditure (CAPEX) and operating expenditure (OPEX), a levelized cost of electricity is typically calculated to compare various different generation options. The LCOE is calculated based on certain assumptions that need to be developed for each particular case being evaluated to select a nuclear technology and compare against other technologies. Key areas of focus for the nuclear projects in the LCOE that need to be compared with similar assumptions are the reliability of the nuclear power, long project life of a nuclear power plant, and benefit of the emission free energy from nuclear.

Multicriteria Decision Analysis for Nuclear Technologies

Decision-making is a complex issue, strongly characterized by conflicting aims, that often results in a situation when there is a trade-off between equity and efficiency. Multiple criteria or multicriteria decision analysis (MCDA) is the collective name of approaches and methodology that support decision making by taking into account multiple criteria in an explicit and transparent way. A strong MCDA tool will bring together the TRL, VRL and LCOE calculations that were conducted for each nuclear technology will lead to a better understanding of the question, and more consistent decision making. The selection of the required MCDA framework is dependent on the need and the complexity of the objective of the analysis.

Nuclear Energy Integration Considerations With a DRI + EAF Plant

EAFs have a very challenging load profile to provide generation due to the rapid load fluctuations every minute. Load variations for an EAF can be very challenging even for traditional grid supply and usually requires installation of equipment to compensate for power quality. These power quality issues can be particularly challenging for nuclear reactors that supply power directly to a EAF. Careful analysis of the anticipated electrical load is required to select the appropriate equipment that may include compensation capacitors, harmonic filters, energy storage and sometimes flicker mitigation equipment.

An alternative approach would be able to leverage a grid interconnection to manage the load fluctuations in parallel with nuclear technology. A discussion with the local utility will be required to assess capability of the local grid to support the load fluctuations.

Siting of the Nuclear Reactor
Having a nuclear facility on an industrial site will require clear designation and separation of nuclear-related and non-nuclear related infrastructure. Several key areas that will need to be analyzed to site a SMR within an DRI + EAF plant include:

- The site that the SMR will be located will also need to be demarcated and physically separate from other industrial facilities on site.
- Site access and layout needs to be considered when siting an SMR to consider flows of personnel, material, goods, fuel, waste etc. through the site.
- Emergency planning zones (EPZs) within the site that will consider site-specific factors, nearby population, accessibility, emergency response teams and their ability to respond to all anticipated emergency scenarios. Traditional nuclear had EPZs of up to 10 miles that is being proposed to be reduced 0.25 miles with new SMR design approaches that would make it more manageable for an EAF + DRI plant.
- Permitting considerations such as potential impacts to ecology, water resources, land cover, wildlife, cultural resources, etc.
- Any existing regulatory approvals in place for the EAF + DRI plant would need to be reviewed and potentially amended or revised to accommodate an SMR co-located at the facility.

An alternative approach that could be leveraged would be to locate a SMR plant at another location and leverage a grid wheeling arrangement to deliver electricity for the EAF + DRI plant. The approach should be leveraged to assess impacts of different site locations on the plant performance, licensing, permitting and economics along with the grid wheeling fees to do a cost/benefit analysis.

Ownership and Operation of the Facility
An organization assessment for ownership and operation of a SMR should be analyzed to determine the best strategy from a commercial and technical standpoint. A power purchase agreement or operation and maintenance (O&M) agreement with a qualified party could be used to reliably and cost-effectively manage a SMR.

Waste Management
Spent nuclear fuel as high level waste has been stored and managed safely in the commercial nuclear reactor fleet within the United States. SMR vendors have incorporated concepts to safely store spent fuel within their plant designs on site. The spent fuel stored onsite will be transferred by the US Department of Energy to a consolidated storage facility that is being developed in accordance with the Nuclear Waste Policy Act of 1982 [29].

Decommissioning
Many power plants across the US have been safely decommissioned in the past. In accordance with US regulations, the licensee for a operating SMR plant must establish a financial mechanism (trust fund or guarantee from parent company) to ensure there will be sufficient funds available to decommission the plant at the end of its life. The status of the decommissioning funding must by reported to the NRC every 2 years[30].

Community Engagement
Siting a nuclear facility in a community needs careful consideration and a well thought out community engagement strategy. Effective communication and early engagement with stakeholders are key considerations to ensure the necessary community buy-in is achieved.

ECONOMICS OF SMRs

SMRs are still an emerging area of development with many vendors still developing their technologies for their demonstration projects. The economics of SMRs have been reported to be competitive with combined cycle gas turbine power plants. Vendors have provided various ranges for their LCOEs that are still being fine tuned and experience with reference data will be gathered as the projects are deployed in the US and around the world.

The Inflation Reduction Act (IRA) also provided additional financial benefits for investing in SMR technologies through the Clean Energy Production Tax Credit (PTC) of up 1.5 cents per kWh sold and the Clean Energy Investment Tax Credit (ITC) of up to 30% of the cost of the SMR technology. Additional bonuses for the tax credits can be achieved by meeting US domestic content requirements or if the facility is located in an energy community or a brownfield site (as defined by the Environmental Protection Agency).

CONCLUSIONS

Carbon emission free energy is a necessity to support green steel and nuclear energy will be a critical technology for the future. New advances in the SMRs and reactor design are enabling a new generation of reactors that can be deployed for EAF + DRI projects with enhanced safety and viable economics. Each site and situation is unique and requires a site specific analysis to select the best approach to deploy a SMR. While there are challenges to implementing SMRs in a DRI-EAF plant, this energy source has the most potential for a carbon free energy supply.

REFERENCES

1. "What are Small Modular Reactors (SMRs)?," 24 November 2021. [Online]. Available: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs. [Accessed 28 February 2023].
2. International Atomic Energy Agency, "Water Cooled Reactors," [Online]. Available: https://www.iaea.org/topics/water-cooled-reactors#:~:text=Light%20water%20reactors%20(LWRs)%20are,directly%20in%20the%20steam%20turbine.. [Accessed 21 February 2023].
3. P. Breeze, "Chapter 4 - Water-Cooled Reactors," in *Nuclear Power*, 2017, pp. 33 - 44. DOI: https://doi.org/10.1016/B978-0-08-101043-3.00004-3.
4. G. J. Suppes and T. S. Storvick, "Chapter 8 - The Future in Nuclear Power," in *Sustainable Power Technologies and Infrastructure*, 2016, pp. 247 - 343. DOI: https://doi.org/10.1016/C2014-0-04843-5.
5. P. Fernández-Arias, D. Vergara and J. A. Orosa, "A Global Review of PWR Nuclear Power Plants," *Applied Sciences,* vol. 10, no. 13., p. 4434, 2020. DOI: 10.3390/app10134434.
6. International Atomic Energy Agency, "Advances in Small Modular Reactor Technology Developments," 2022. [Online]. Available: https://aris.iaea.org/Publications/SMR_booklet_2022.pdf. [Accessed 21 February 2023].
7. "TVA Board Authorizes New Nuclear Program to Explore Innovative Technology," 10 February 2022. [Online]. Available: https://www.tva.com/newsroom/press-releases/tva-board-authorizes-new-nuclear-program-to-explore-innovative-technology. [Accessed 28 February 2023].
8. "OPG advances clean energy generation project," Ontario Power Generation (OPG), 2 December 2021. [Online]. Available: https://www.opg.com/media_releases/opg-advances-clean-energy-generation-project/. [Accessed 28 February 2023].
9. S. Şahin and H. M. Şahin, "Section 1.20.4.8.6 Very high temperature reactor," *Comprehensive Energy Systems,* vol. 1, pp. 795 - 849. https://www.sciencedirect.com/topics/engineering/high-temperature-gas-reactors, 2018.
10. "Very-High-Temperature Reactor (VHTR)," GEN IV International Forum, [Online]. Available: https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr. [Accessed 21 February 2023].
11. "World Nuclear Association Image Library: High Temperature Reactors," World Nuclear Association, 29 January 2016. [Online]. Available: https://world-nuclear.org/gallery/reactor-diagrams/high-temperature-reactor.aspx. [Accessed 21 February 2023].
12. Office of Nuclear Energy , "3 Advanced Reactor Systems to Watch by 2030," Energy.gov, 12 April 2021. [Online]. Available: https://www.energy.gov/ne/articles/3-advanced-reactor-systems-watch-2030. [Accessed 23 February 2023].
13. Nuclear Energy Agency, "High-temperature Gas-cooled Reactors and Industrial Heat Applications," 2022. [Online]. Available: https://www.oecd-nea.org/jcms/pl_70442/high-temperature-gas-cooled-reactors-and-industrial-heat-applications. [Accessed 28 February 2023].
14. I. Hill and D. Jacquemain, "Dragon Project," Nuclear Energy Agency, [Online]. Available: https://www.oecd-nea.org/jcms/pl_51567/dragon-project. [Accessed 21 February 2023].
15. I. Hill, "High-Temperature Gas-Cooled Reactors," Nuclear Energy Agency, [Online]. Available: https://www.oecd-nea.org/jcms/pl_20497/high-temperature-gas-cooled-reactors#:~:text=High%2Dtemperature%20gas%2Dcooled%20reactors%20(HTGRs)%2C%20also,once%2Dthrough%20uranium%20fuel%20cycle.. [Accessed 23 February 2023].
16. "Reactor Database: AVR Juelich," World Nuclear Association, [Online]. Available: https://www.world-nuclear.org/reactor/default.aspx/AVR%20JUELICH. [Accessed 21 February 2023].

17. “China's demonstration HTR-PM reaches full power,” World Nuclear News, 9 December 2022. [Online]. Available: https://www.world-nuclear-news.org/Articles/China-s-demonstration-HTR-PM-reaches-full-power. [Accessed 21 February 2023].
18. X-energy, LLC., “Congress Appropriates ~$1.1B Dollars to X-energy’s ARDP Project with Historic Legislation Recognizing Clean Energy Supply as vital to US Infrastructure and Economic Health.,” 15 November 2021. [Online]. Available: https://x-energy.com/media/news-releases/congress-appropriates-1-billion-dollars-to-x-energys-ardp-project. [Accessed 28 February 2023].
19. D. A. Arostegui and M. Holt, “Advanced Nuclear Reactors: Technology Overview and Current Issues,” EveryCRSReport.com, 18 April 2019. [Online]. Available: https://www.everycrsreport.com/reports/R45706.html#_Toc7446180. [Accessed 21 February 2023].
20. “Sodium-Cooled Fast Reactor (SFR),” Gen IV International Forum, [Online]. Available: https://www.gen-4.org/gif/jcms/c_42152/sodium-cooled-fast-reactor-sfr. [Accessed 21 February 2023].
21. G. Flanagan, “Historical Perspective for Fast Reactors,” Oak Ridge National Laboratory, 26 March 2019. [Online]. Available: https://www.nrc.gov/docs/ML1914/ML19148A764.pdf. [Accessed 21 February 2023].
22. “Fast Neutron Reactors,” World Nuclear Association, August 2021. [Online]. Available: https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx. [Accessed 21 February 2023].
23. World Nuclear Association, “Fast Neutron Reactors,” August 2021. [Online]. Available: https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx. [Accessed 1 March 2023].
24. US Department of Energy, “U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program,” 13 October 2020. [Online]. Available: https://www.energy.gov/ne/articles/us-department-energy-announces-160-million-first-awards-under-advanced-reactor. [Accessed 1 March 2023].
25. GE Hitachi Nuclear Energy, “GE Hitachi Nuclear Energy and ARC Nuclear Announce Steps to Further Collaboration to Commercialize Advanced Small Modular Reactor,” 28 August 2017. [Online]. Available: https://www.ge.com/news/press-releases/ge-hitachi-nuclear-energy-and-arc-nuclear-announce-steps-further-collaboration. [Accessed 1 March 2023].
26. N. Touran, “Molten salt reactors,” Whatisnuclear.com, [Online]. Available: https://whatisnuclear.com/msr.html. [Accessed 21 February 2023].
27. C. W. Forsberg, P. F. Peterson and H. Zhao, “An Advanced Molten Salt Reactor Using,” in *2004 International Congress on Advances in Nuclear Power Plants (ICAPP '04)*, Pittsburgh, 2004.
28. “Molten Salt Reactor (MSR),” Generation IV International Forum, [Online]. Available: https://www.gen-4.org/gif/jcms/c_9359/msr. [Accessed 23 February 2023].
29. “Molten salt reactors,” International Atomic Energy Agency, [Online]. Available: https://www.iaea.org/topics/molten-salt-reactors. [Accessed 21 February 2023].
30. Kairos Power, “Technology,” [Online]. Available: https://kairospower.com/technology/. [Accessed 1 March 2023].
31. Terrestrial Energy, “IMSR Technology,” [Online]. Available: https://www.terrestrialenergy.com/technology/. [Accessed 1 March 2023].
32. NASA, “Technology Readiness Level,” 1 April 2021. [Online]. Available: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level. [Accessed 28 February 2023].
33. U.S. Nuclear Regulatory Commission, “High-Level Waste Disposal,” 12 March 2020. [Online]. Available: https://www.nrc.gov/waste/hlw-disposal.html. [Accessed 27 February 2023].
34. U.S. Nuclear Regulatory Commission, “Backgrounder on Decommissioning Nuclear Power Plants,” 17 October 2022. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/decommissioning.html. [Accessed 27 February 2023].
35. “Light Water Reactor Technology of the Next Decade,” Frontiers, [Online]. Available: https://www.frontiersin.org/research-topics/41589/light-water-reactor-technology-of-the-next-decade#overview. [Accessed 21 February 2023].
36. T. Seko, D. R. Wilkins, S. Sugino and J. Kani, “Modern Technology Applied in Advanced BWR (ABWR),” *Journal of Nuclear Science and Technology,* vol. 25, no. 11, pp. 837 - 847. DOI: https://doi.org/10.1080/18811248.1988.9735937, 1988.
37. GE Hitachi, “BWRX-300,” GE Hitachi, [Online]. Available: https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/bwrx-300. [Accessed 21 February 2023].

38. H. L. Brey, “The Evolution and Future Development of the,” September 2003. [Online]. Available: https://www.ipen.br/biblioteca/cd/genes4/2003/papers/1194-final.pdf. [Accessed 21 February 2023].
39. International Atomic Energy Agency, “STATUS OF INNOVATIVE FAST REACTOR DESIGNS AND CONCEPTS,” October 2013. [Online]. Available: https://aris.iaea.org/Publications/booklet-fr-2013.pdf. [Accessed 21 February 2023].
40. N. Voit, “Five of the World’s Leading Small Modular Reactor Companies,” C3, 9 January 2023. [Online]. Available: https://c3newsmag.com/five-of-the-worlds-leading-small-modular-reactor-companies/. [Accessed 21 February 2023].
41. “Molten Salt Reactors,” World Nuclear Association, May 2021. [Online]. Available: https://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx. [Accessed 21 February 2023].
42. C. Fang, R. Morris and F. Li, “Safety Features of High Temperature Gas Cooled Reactor,” *Science and Technology of Nuclear Installations,* 2017. DOI: https://doi.org/10.1155/2017/9160971.

