NuScale Small Modular Reactor Integration for Hydrogen and Ammonia Production

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CONTENTS

1. INTRODUCTION

The opportunities for generating carbon-free hydrogen using nuclear power are significant [1] [2]. For the past decade, NuScale Power has studied multiple hydrogen technologies and integration pathways and remains actively engaged in the development of hydrogen technologies with major industrial partners and national laboratories. A NuScale Nuclear Power Module™ (NPM) produces sufficient power to generate 45 MT/day. A 6-module plant can produce 268 MT/day and 12-module plant 536 MT/day via Electrolysis. NuScale major investors and strategic supply chain partners with hydrogen production, hydrogen storage and hydrogen system integration capabilities include Doosan Enerbility, Samsung, JGC and IHI. These companies have deployed hydrogen production or storage facilities globally.

This white paper summarizes NuScale efforts on integrating a NuScale Power Module™ (NPM) with hydrogen production systems. Some key advantages of using a NuScale multi-module system for process hydrogen generation are:

- Industrial scale production of Steam, Electric Power and Hydrogen.
- Compatible with Electrolyzer technologies and with pathways using Natural Gas
- Steam Temperature and Pressure augmentation for higher temperature/ pressure processes.
- Flexible operation.
    - Able to ramp up/down steam and electric power output.
    - Real-time power allocation for hydrogen production, electricity or both.
- Multi-Module design for High Reliability.
    - Continuous power generation during refueling
- Site boundary EPZ provides separation between Nuclear and Commercial Plant.
    - Industrial facility in proximity of a NuScale Small Modular Reactor (SMR) but outside of emergency planning zone.
- Off-Grid dedicated power - Island Mode capability.
    - Does not require connection to the main transmission line.
- Leverages proven Light Water Reactor Technology.
    - 67 years of operating history - existing supply chain.
    - Long-term, commercially available fuel.
- Robust, Seismic Category I, Reactor Building with significant overpressure protection.
- Only NRC certified Small Modular Reactor design

1.1 Brief Overview of the NuScale Technology

The NuScale small modular reactor is based on proven light-water reactor technology with substantial improvement in nuclear safety. The innovative design is elegantly simple, incorporates extensive use of passive safety features, meets the utility needs for standardization while also allowing flexible deployment options, and is scalable to allow for incremental increases in electrical generating capacity. The robust design, small fuel inventory, and multiple barriers preventing fission product release contribute to a low probability and consequence of radionuclide release even under extreme upset conditions, thus simplifying the emergency preparedness and response, and providing a basis for reducing the emergency planning zone (EPZ). The NuScale SMR design consists of multiple NPMs, with each NPM representing an independent nuclear steam supply system (NSSS) coupled to a dedicated turbine-generator system. A flexible number of NPMs can be configured into a power plant to suit an offtaker's needs. A cutaway of the NPM is shown in Figure 1.

It consists of a 250 MWt reactor core housed with other primary system components in an integral reactor pressure vessel surrounded by a steel containment vessel, all of which is immersed in a large pool of water that also serves as the ultimate heat sink. Above the core, there is a central hot riser tube, a helical coil steam generator surrounding the hot riser tube, and a pressurizer. The helical coil steam generator consists of two independent and interleaved sets of tube bundles with separate feedwater inlet and steam outlet lines. Sets of pressurizer heaters and spray nozzles located in the upper head of the vessel provide pressure control.

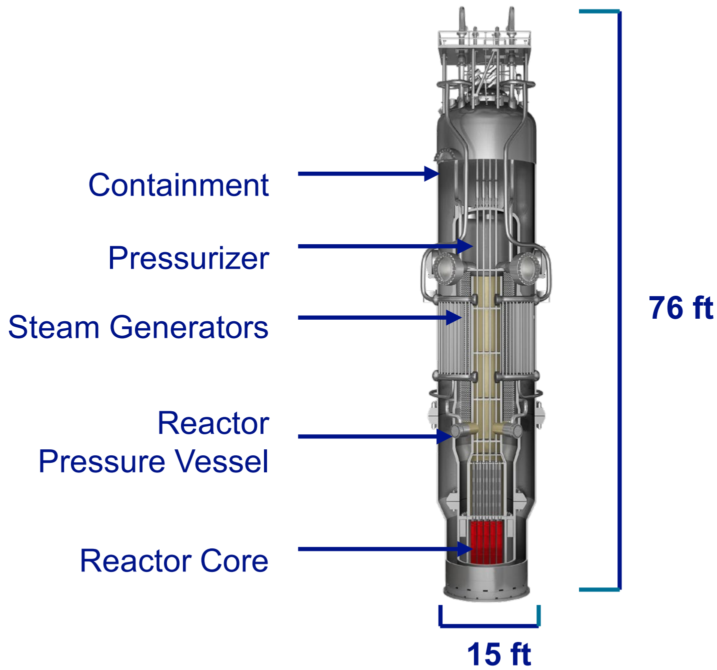

Figure 1. NuScale Power Module Cutaway

The primary reactor coolant path is upward through the reactor core. Heated water flows upward through the hot riser tube due to buoyancy forces and is turned downward at the pressurizer baffle plate. It then flows over the shell side of the steam generator, where it is cooled by conduction and convection of heat to the secondary coolant and continues to flow downward until its direction is again reversed at the lower reactor vessel head and turned upward back into the core. Coolant circulation is maintained entirely by natural buoyancy forces of the lower-density heated water exiting the core and the higher-density cooled water exiting the steam generator annulus.

The reactor vessel is enclosed in a stainless-steel containment vessel (CNV) that is nominally 76 ft (23 m) tall and 15 ft (4.5 m) in diameter. The small-volume, high-design-pressure CNV is a unique feature of the NuScale design that contributes significantly to the large safety margins and overall resilience. The CNV has been designed as an ASME Class 1 pressure vessel. As a result, it can safely contain any loss-of-coolant-accident (LOCA) that can occur inside containment. During normal power operation, the CNV atmosphere is evacuated to provide an insulating vacuum that significantly reduces parasitic heat loss from the reactor vessel.

The reactor vessel internals (RVI) support the reactor core, the control rod assemblies (CRAs), and the control rod drive shafts. The RVI channel the flow from the reactor core to the steam generators within the reactor pressure vessel (RPV).

Table 1 presents some of the key parameters for the NuScale Power Module (NPM).

Table 1. Design Features of the NuScale Power Module

Plant Parameters	
NuScale Modules 4,6,12 MW(e) gross	308 / 462 / 924
Reactor Parameters	
Reactor type	Integral PWR
Design Life (years)	60
RPV height / diameter (m)	17.7 / 2.7
Thermal / electrical capacity MW(t) / MW(e) gross	250 / 77
Coolant / moderator	Light water / Light water
Primary circulation	Natural circulation
NSSS Primary Side Pressure, MPa	13.8
Fuel type/ assembly array	UO_2 pellet / 17x17 square
Fuel Cladding Material	M5 (Framatome)
Number of fuel assemblies in the core	37
Fuel Enrichment (%)	up to 4.95
Refueling cycle	Nominal 18 months
Reactivity control mechanisms	Control rod drive, boron acid solution
Fuel Cycle Requirements	Batch size, loading pattern, and cycle length are customer driven optimization requirements
Balance of Plant	
Steam Power Conversion	Rankine Cycle with Feedwater Heaters
Steam Generators	Two Helical Coil Steam Generators with superheat
Key Safety Features	
Decay Heat Removal System Emergency Core Cooling System	No Design Basis Events cause core to uncover. Unlimited period of core cooling without Operator action, AC or DC power or water addition.
Anticipated Transient Without Scram (ATWS)	Large inherent negative reactivity feedback coefficient reduces core power to < 6% on moderator temperature.
Seismic Design (SSE) Safe Shutdown Earthquake	0.5 g ZPA
Site Boundary EPZ	NRC Approved Methodology for Calculating Site Boundary Emergency Planning Zone (EPZ)

The NPMs are located below grade in a stainless steel-lined pool of water that is contained in a Seismic Category I reactor building. Each NPM is operated in its own bay, which is approximately 6.1 m (20 ft) square by 16.2 m (53 ft) deep (Figure 2)**.** The pool provides passive containment cooling and decay heat removal. The pool also reduces and delays the release of fission products in the unlikely event of fuel, primary system, and containment vessel failure and provides radiation shielding outside containment to reduce operational exposure. The pool also enhances physical security by adding an additional barrier to fuel access.

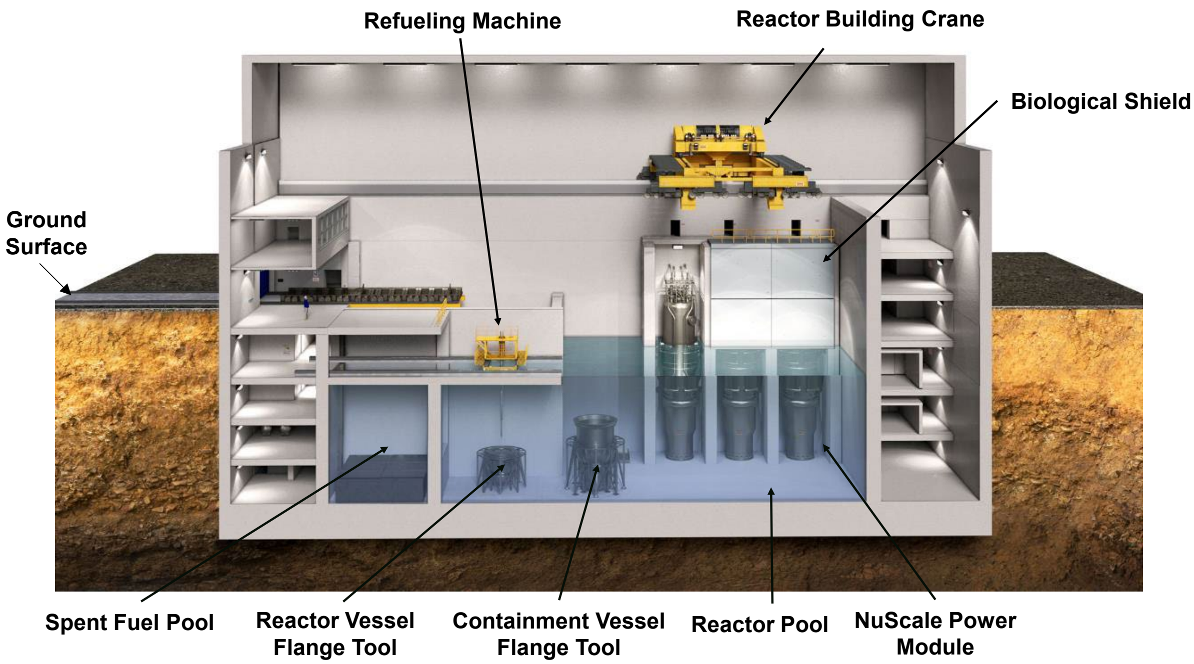

Figure 2. Reactor building cutaway for a 6 NPM plant (462 MWe)

1.2 Designed for Electric Power and 100% Steam Bypass

The NuScale SMR is the only commercial nuclear reactor design approved by the U.S. Nuclear Regulatory Commission (NRC) for off-grid operation. The NuScale NPM is designed for 100% steam turbine bypass, either to the condenser or to an industrial end user. The NuScale design uses the Rankine thermal conversion cycle to produce electricity. In the secondary circuit of each NPM, feedwater is pumped into two feedwater headers of the steam generator, where it is heated by the primary coolant and boils to produce superheated steam.

As shown in Figure 3, two main steam lines from each NPM combine into a single line and route the steam to a dedicated turbine-generator system that generates nominally 77 MWe (gross). Low pressure steam exiting the turbine is condensed and recirculated through three feedwater heater stages to the feedwater headers. The air-cooled condensers (wet cooled option shown below) are designed to accommodate 100% steam bypass of the turbine. The NPM is designed for load following using control rod motion and/or steam bypass.

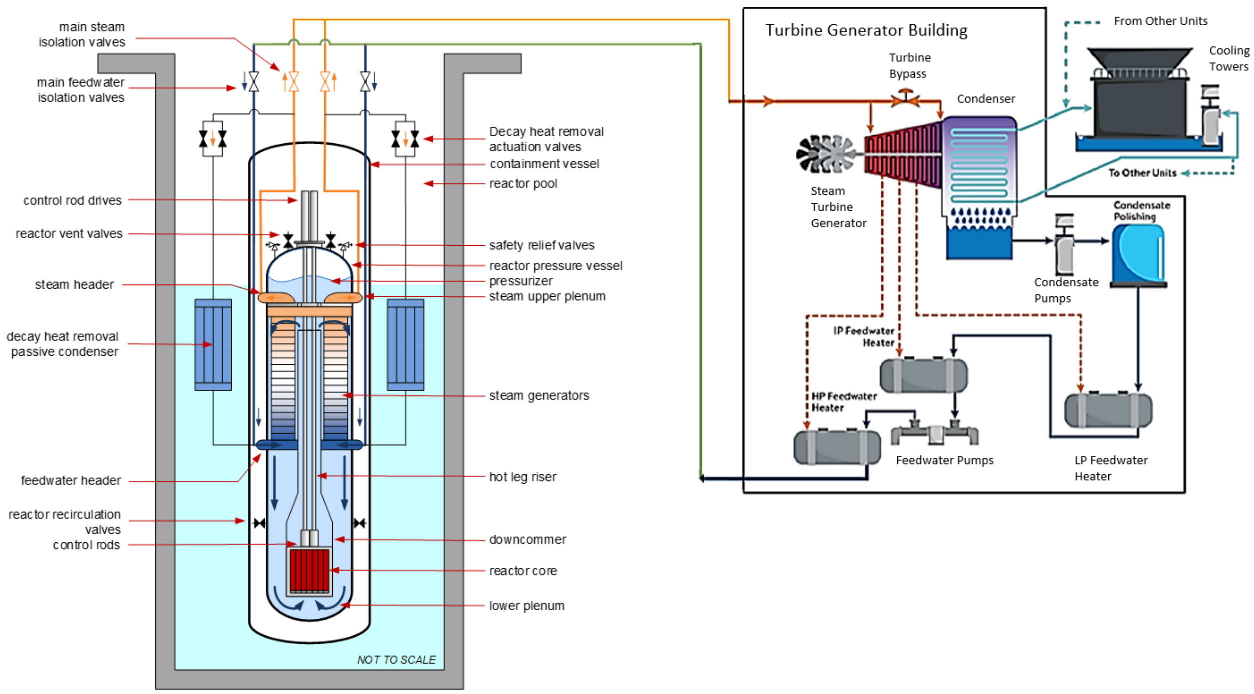

Figure 3. Thermal conversion system

1.3 Licensing

The NuScale SMR is currently the only SMR that has received design certification from the U.S. Nuclear Regulatory Commission (NRC). The NuScale Design Certification Application (DCA) was completed in December 2016. The review by the NRC commenced in March 2017. NuScale received standard design approval in September 2020 and design certification in January 2023 for its 50 MWe NPM configured as a 12-module plant. The DCA consisted of 12,000 pages of design information; requiring 2 million labor hours to prepare. It involved in excess of 50 suppliers and partners and approximately 800 people. The NRC review of the DCA was completed in 41 months, one month ahead of schedule. The review required an additional 2 million pages of supporting information and test data.

Because of its unique safety, the NuScale design has received many “first-of-a-kind” approvals from the NRC, including:

- No connection to the AC transmission grid required for safety. Regulations permits “off-grid” operation - A very important feature for providing reliable power and process heat to industrial applications.
- NRC approved control room staffing. Three operators can safely operate 12 reactors in a single control room.
- Elimination of Shift Technical Advisor (STA) position.
- Use of unique cyber resistant Field Programmable Gate Array (FPGA) based Module Protection and Plant Protection Systems.
- Approval of the NuScale Emergency Planning Zone (EPZ) sizing methodology. As opposed to a 10-mile radius EPZ, a site boundary EPZ is achievable for a power plant utilizing NPMs at most US sites surveyed.

NuScale is currently seeking standard design approval to increase its core power to 250 MWt, nominally 77 MWe per module, in a NuScale 6-module plant configuration. The SDA application and topical reports were received by the NRC in January 2023. NRC announced that it has begun it review on March 17, 2023 and that the review is expected to complete by July 2025.

1.4 Reliability

The ability to deploy an NPM-based multi-module power plant before the end of the decade and its inherent high reliability were key features recognized in the 2020 ORNL study [3]. The NuScale design has two benefits regarding power output reliability. First, it permits staggered refueling so the total plant continues to produce 847 MWe (NuScale -12) or 385 MWe (NuScale - 6) gross, even during refueling. The second benefit, particularly for the NuScale-12, is the high degree of certainty of having 1 or 2 NPMs available to produce power. This is the range of power (77-154 MWe) typically needed for facilities that require ultra-high reliability for mission-critical processes.

Operational reliability in a nuclear reactor depends on reactor scrams, which can cause shutdown. The NuScale reactor is designed to reduce the frequency of inadvertent reactor scrams compared to the currently operating reactor fleet. Energy resilience is the ability to prepare for and recover from energy disruptions. Resilient power systems minimize the effect of such costly failures. José Reyes and Daniel Ingersoll [3] assessed the energy resilience of a NuScale NPM relative to existing commercial nuclear fleet reactor scrams and noted that NuScale eliminated 70% of existing 2019 commercial nuclear fleet scrams by design. Three key factors can be attributed to the NuScale's improved performance: (1) fewer and simpler systems, resulting in fewer potential failures, 2) island mode power, and (3) a 100% steam-turbine bypass [3]. Figure 4 shows the reduction is inadvertent shutdowns relative to commercial fleet.

The expected capacity factor of a NuScale-based SMR power plant is ≥ 95%, which assumes a well-defined 10-day refueling outage for an 18-month fuel cycle and a conservatively assumed 3% forced outages. Longer fuel cycles are possible.

Jeremiah Doyle's peer reviewed paper [4] on mission-critical applications demonstrates that, because of its configuration as an independent unit and its island mode capability, a power plant utilizing 12 NPMs can provide highly reliable power to the grid. A power plant utilizing 12 NPMs has a reliability of 99.98% for 77 MWe (one NPM) and of 99.95% for 154 MWe (two NPMs) for a micro-grid over the plant's 60-year lifetime. This corresponds to a total loss of power for only four days over the 60-yr lifetime of the plant [5].

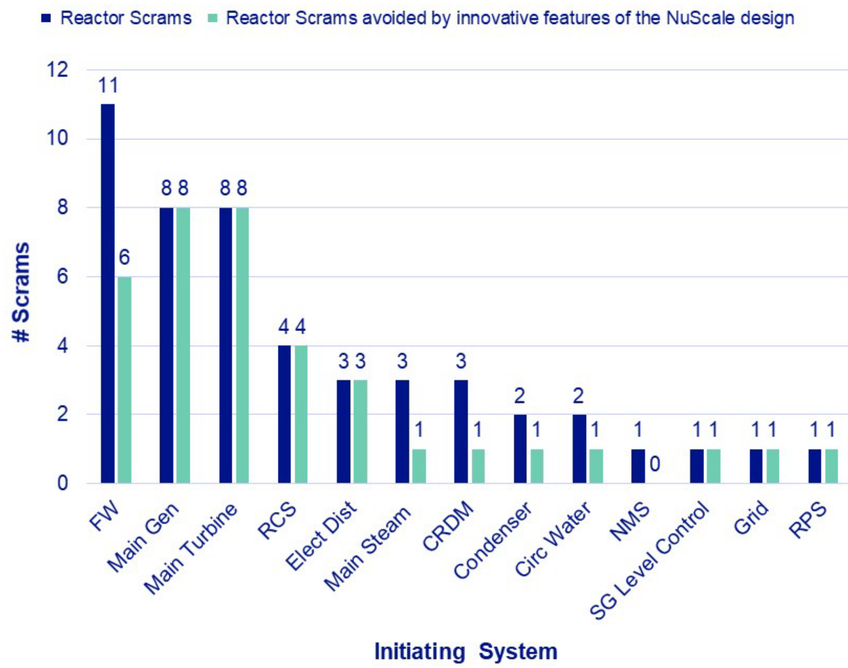

Figure 4. Reliability by Design, Figure Key: FW-Feedwater System, RCS – Reactor Coolant System, CRDM – Control Rod Drive Mechanism, NMS – Neutron Monitoring System, SG - Steam Generator, RPS- Reactor Protection System.

Figure 5 presents a comparison of conventional NPPs vs. NPM and a Multi-Module plant utilizing NPMs using IAEA data [6]. Scenarios A, B and C show conservative estimates of outages for a single NPM. Scenario D shows a key feature of the NuScale multi-module design. It can be tailored to achieve ultra-high reliability by including both off-grid and grid connected multi-module configurations. A NuScale/Oak Ridge National Laboratory (ORNL) micro-grid study showed that inclusion of a power plant utilizing NPMs reduced the potential power interruption to ORNL mission critical facilities from approximately eight hours in a year to one minute. When the macro-grid was also included, power disruption was reduced to just one-hundredth of a second per year [5].

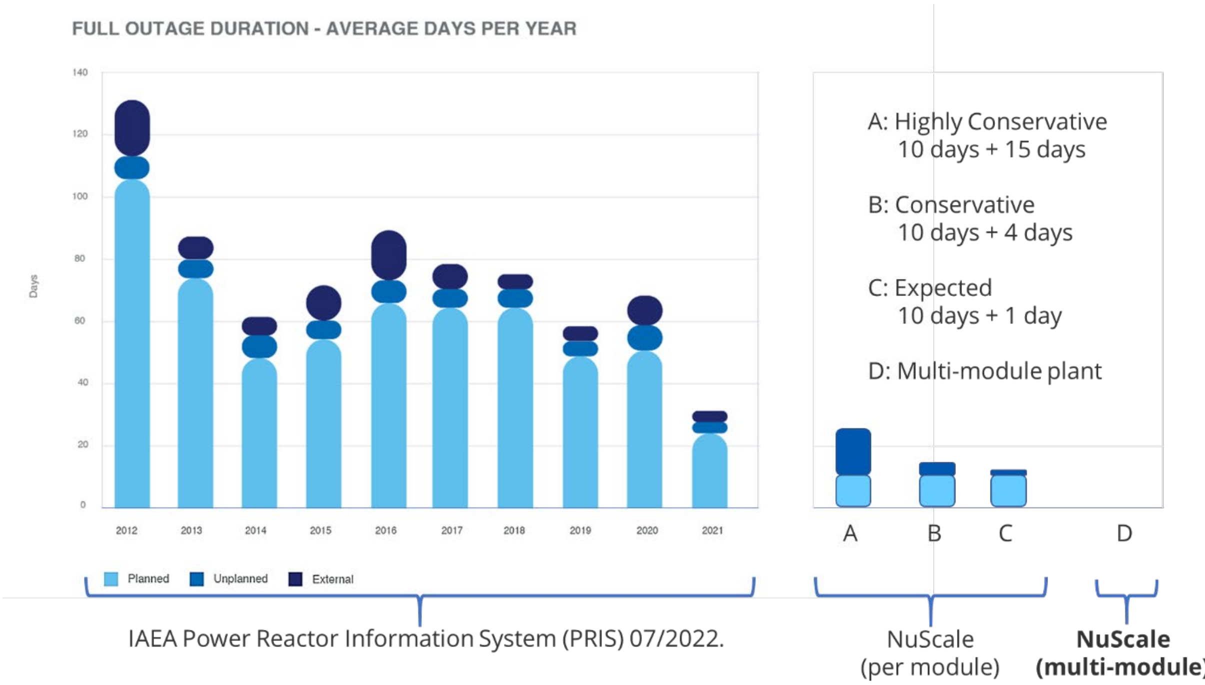

Figure 5. Full Outage Duration, Average Days/Year – Comparison Conventional NPPs vs. NPM and Multi-Module Plant utilizing NPMs.

2. PROCESS STEAM GENERATED BY A NUSCALE POWER MODULE

The following section shows that a large number of processes are within the NPM steam outlet temperature and much higher ratings are achievable through a simple, energy efficient heat-augmentation stage. Table 2 lists a variety of petrochemical processes that require process heat in the approximate range of the NPM steam outlet temperatures shown in Table 3.

Table 2. Process temperatures and annual U.S. production rates of various petrochemicals

Chemical	Process	Process Temp (°C)	2002 Production (billion lb)
Ethylbenzene	Friedel-Crafts Alkylation	90-420	13.6
Ethylene Oxide	Air Epoxidation	270-290	9.2
Acetic Acid	Multiple	50-250	6.7
Cumene	Friedel-Crafts Alkylation	175-225	7.3
Cyclohexane	Transformation of Benzene	210	3.0
Terephthalic Acid	Amoco Process	200	9.1
Vinyl Acetate	Vapor-phase Reaction	175-200	2.8
Ethylene Glycol	Hydration and Ring Opening	50-195	7.5
Butyraldehde	Oxo Process	130-175	3.1
Adipic Acid	Air Oxidation	50-160	2.2
Bisphenol A	Phenol with Acetone	50	2.3
Ethylene Dichloride		40-50	23.8
Phenol	Rearrangement of Cumene Hydroperoxide	30	5.2
Urea		190	18.5
Soda Ash		175	
Ammonium Nitrate	Vacuum Evaporation	125-140	17.2
Aluminum Sulfate		105-110	2.2
Phosphoric Acid	Wet process	75-80	26.8
Nylon 6 and Nylon 6.6	Electrolysis of Brine	280-300	2.6
Polyester		200-290	3.9

Table 3 shows that at nominal full power operating conditions, the NPM produces 8883 metric tons of steam per day (816,000 lbm of steam per hour).

Table 3. NPM feed steam parameters

NPM Parameter	***Value***
Full Power NPM Nominal Steam Production Rate, metric tons/d	8883
NPM Steam Outlet Temperature (°C)	283
NPM Steam Outlet Pressure (bar)	32.8
Steam Energy (MWt/MMBtu)	250/852

However, many chemical processes require large quantities of steam at high pressures (e.g., 1000-2000 psia) and temperatures (>500 °C). For example, Distillation (400-500 °C), Thermal Cracking (400-950 °C), Catalytic Cracking (480-815 °C), Catalytic Hydro Cracking (290-400 °C), and Catalytic Reforming (500-525 °C). Figure 6 shows a range of process temperatures for a broader set of applications.

Temperatures above 300 °C were generally considered outside the range of the nominal steam conditions for a light water reactor. NuScale's heat-augmentation system is capable of producing steam at the required high temperatures by using commercial-grade equipment. This section describes the scheme for generating high temperature and pressure process steam using steam compression and heating. Commercially available steam compressors are highly efficient and capable of large volumetric flows and high pressures. Currently there may be some material limitations for very high temperatures (>650°C).

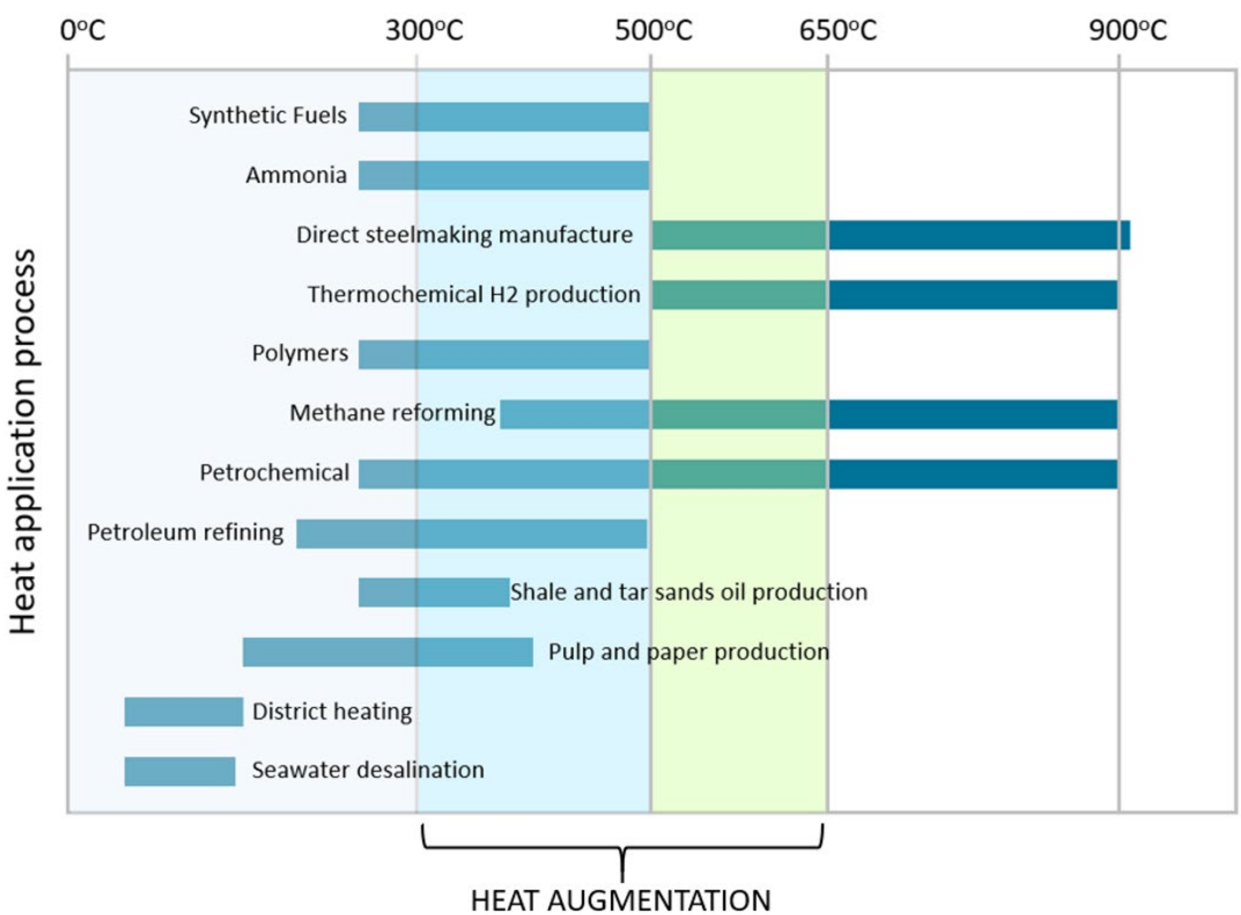

Figure 6 Processes and their corresponding temperature range. Temperatures above 300 °C are achievable through heat-augmentation.

Figure 7 shows a NuScale process steam production plant. It highlights portions of the plant that apply nuclear safety standards, commercial standards and petrochemical plant standards. In this configuration, the entire power plant, including the intermediate heat exchanger (IHX) resides within the Emergency Planning Zone (EPZ). Utilizing an IHX assures compliance with existing

NRC regulation. Key features of this configuration are:

- Only NRC-Approved Methodology that can permit a site boundary EPZ that does not extend into the petrochemical plant.
- Separation of Nuclear Reactor Coolant and Process Steam
- Commercial Grade Balance of Plant: Steam Side of an SMR power plant with NuScale NPMs is classified and approved as non-safety related with no risk-significant structures, systems, and components [7].
    - Seismic Category III (non-safety)
    - No augmented design requirements
    - Commercial Grade Components
- No High Temperature-Pressure Nuclear Safety Piping and Equipment
    - Reduces H-T materials and plant costs

The IHX will be located in the Turbine building with the EPZ. The Process Steam Conditioning and Control (PSCC) building can be located outside the EPZ. It houses the steam compressors and heaters and corresponding controls and communications systems.

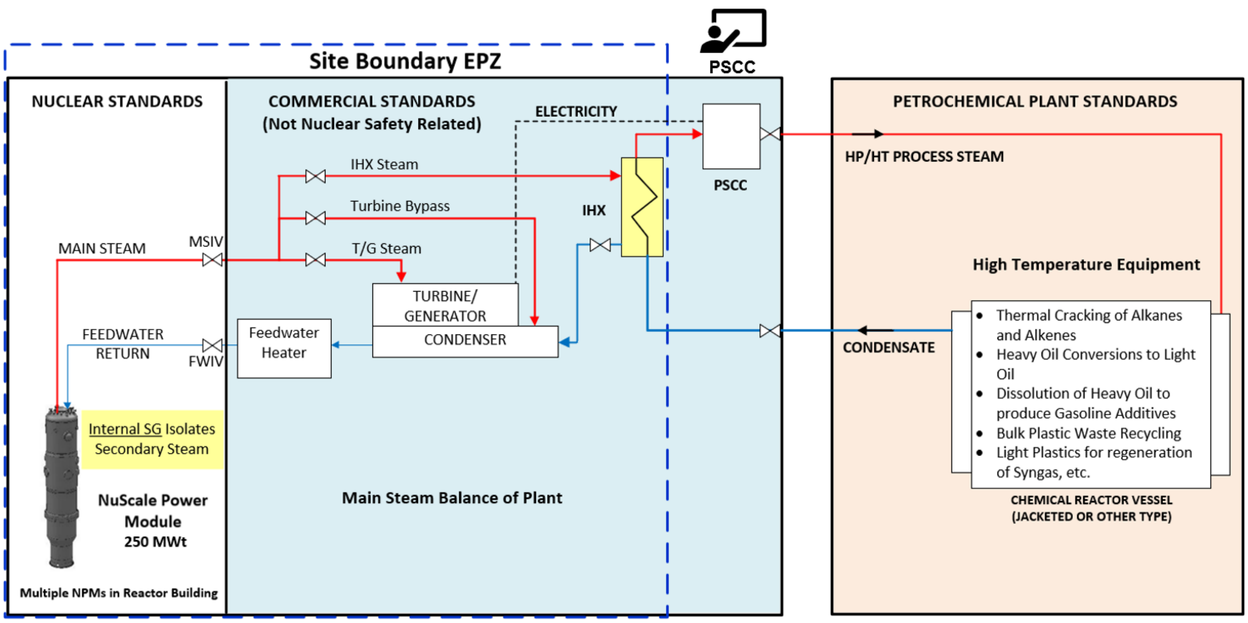

Figure 7. Schematic showing one of multiple NPMs providing heat to generate high temperature and pressure process steam at commercial scale. An intermediate Heat Exchanger IHX assures compliance with existing NRC regulation.

An SMR with NuScale NPMs provides flexible power operations. With regards to nuclear reactor operations Table 4 shows two modes of operation for an NPM. Turbine bypass permits rapid changes in power output by diverting up to 100% of the steam from the turbines directly to the condensers. Power changes using the central control rods can also be achieved.

Table 4. Flexible Power Operations for the NPM

Method	Down Power	Up Power
Turbine Bypass	100% to 20% (8 min)	20% to 100% (27 min)
Control Rods	100% to 20% (≤ 24 min)	20% to 100% (96 min)

With regards to PSCC flexible controls, the following are the key features related to process steam Ramp Up and Ramp Down:

- Nominal to maximum: < 1 minute
- Nominal to minimum: < 1 minute
- Cold start/Shutdown: Process dependent

The compressor is sized to meet requirements and the compressor steam flow and pressure are adjustable in real time with a 20% - 30% turn down capability.

3. HYDROGEN SYSTEM INTEGRATION OPTIONS

In 2014, NuScale funded the Idaho National Laboratory (INL) to perform a proprietary assessment of the use of High-temperature steam electrolysis (HTSE) for hydrogen production using NuScale Power and Heat. ASPEN HYSYS models were created and a range of simulations performed. Since then, NuScale's Integrated Energy Systems team has evaluated multiple hydrogen technologies, engaged with major industrial players and analyzed optimal integration schemes compatible with the NRC approved NuScale EPZ methodology. The following hydrogen production options have different technology readiness levels and could be integrated with a power plant utilizing NuScale NPMs.

Electrolyzer-based technologies:
- Proton Exchange Membrane (PEM)
- Solid Oxide Electrolyzer Cells (SOEC)
- High-efficiency (capillary-fed) Electrolyzers
- Other: Alkaline (AEL), Anion Exchange Membrane (AEM)

Non-Electrolyzer-based technologies:
- NuScale proprietary chemical processes
- NuScale proprietary hydrogen solid-carrier process

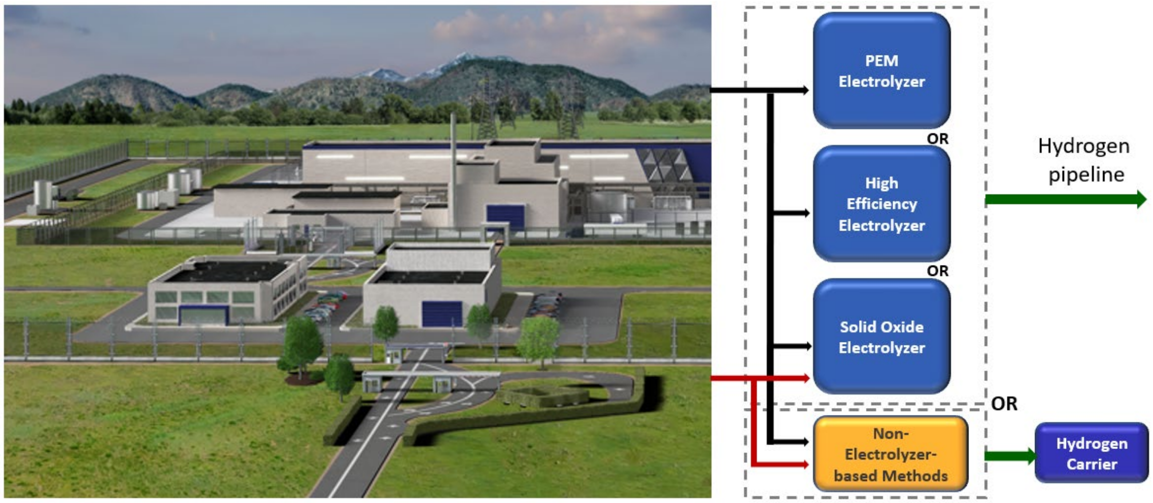

Figure 8. SMR plant with NuScale NPMs interface to a hydrogen generating facility

The NuScale's NRC approved methodology to size the emergency planning zone (EPZ) enables the location of an industrial facility to be in close proximity to the NuScale SMR. The industrial facility can be a Petrochemical plant or a hydrogen generating plant. The following section provides a brief overview of the hydrogen production technologies.

a. PEM Electrolyzer
PEM Electrolyzer based systems only requires electric power and is seamlessly interfaced with one or more NuScale NPMs. The Electrolyzer represents an electrical load and is treated in the same way as any other load in the grid. NuScale's load-following capability ensures the required power is supplied regardless of hydrogen demand variations. One example of PEM technology is HyAxiom | A Doosan Company who holds the record for the largest PEM-based power plant (Seosan South Korea) producing 50 MWe since 2020 with a capacity factor of 98%.

b. High-Efficiency Electrolyzer
Cutting-edge (capillary fed) Electrolyzers like PEM rely only on power and water (no heat or steam) and have an efficiency superior to PEM and Solid Oxide Electrolyzers. NuScale has reviewed this technology which is in development and in the process of being scaled to industrial level.

c. SOEC Electrolyzers
SOEC Electrolyzers require electricity and steam in order to achieve higher efficiency respect to PEM technology. NuScale can supply electricity and steam with the addition of an Intermediate Heat Exchanger (IHX) which resides within the well-defined site boundary EPZ. The IHX separates the NuScale secondary steam loop from the Electrolyzer feed-water system, fully decoupling the water chemistry requirements and maintaining the NuScale EPZ boundary consistent with the approved methodology. Note that SOEC Electrolyzers have evolved, the initial INL SOEC study (2014) depicts a system requiring 800 deg C. https://inldigitallibrary.inl.gov/sites/sti/sti/6303857.pdf Present day SOEC units implement advanced heat recovery systems that require only low temperature steam at 120 deg C and use built-in pre-heaters go.fuelcellenergy.com/hubfs/solid-oxide-electrolyzer-spec-sheet.pdf

d. Non-Electrolyzer-based Systems

NuScale has developed proprietary chemical processes for efficient clean hydrogen production and for hydrogen transportation in a solid inert media which is safe to handle. These patent-pending processes are undergoing development and validation in collaboration with National Laboratories.

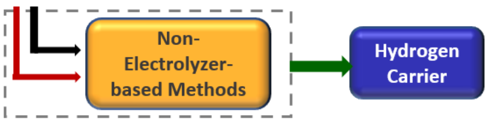

Figure 9. Conceptual Layout of a 6 NPM Power Plant Integrated with an SOEC Hydrogen Production Plant.

Figure 9 illustrates a 6-module power plant supplying electric power and steam to a hydrogen plant located at the top right corner. Studies have been done by Sandia National Labs and Idaho National Labs to determine the minimum safe distance between the plants. The image includes a "stand-off" distance between the power plant and the hydrogen production facility. The NuScale Reactor building has significant overpressure capability (5 psi) and could be safely located in as little as 150 m from the hydrogen production facility based on a hydrogen hazards analysis performed by INL. Refer to **Preliminary Process and Instrumentation Design of Advanced Reactor Integration with Refineries and Hydrogen Production Facilities**, INL, 9 January 2024. [Preliminary Process and Instrumentation Design of Advanced Reactor Integration with Refineries and Hydrogen Production Facilities (Technical Report) | OSTI.GOV]

4. AMMONIA SYSTEMS

Ammonia (NH_3) production is the largest greenhouse gas emitter in the chemical industry. In 2020, 185 million metric tons of ammonia were produced, which generated 450 million metric tons of direct CO_2 emissions, a ratio of 2.4 kg CO_2 per 1.0 kg ammonia. This demand is expected to grow ~1% per year, for a projected demand of 230 million metric tons in 2050, even accounting for potential improvements in process efficiency and fertilizer application. Between 75 and 90% of this ammonia goes toward making fertilizer, and about 50% of the world's food production relies on ammonia fertilizer. Ammonia is produced from the reaction of hydrogen (H_2) and nitrogen (N_2). More than 40% of global hydrogen production is used for ammonia production. For most existing ammonia plants, the hydrogen feed is produced on-site via the steam-methane reforming process, which uses a fossil fuel feedstock (natural gas or coal gasification). The hydrogen production process contributes to most (>90%) of the overall CO_2 footprint for ammonia [8][9][10][11]. Coupling emissions-free electrical power and process heat from NPMs to an electrolyzer system will enable reliable large-scale decarbonized hydrogen production, independent of light or weather conditions. Figure 10 shows an ammonia production system coupled with one or multiple NPMs.

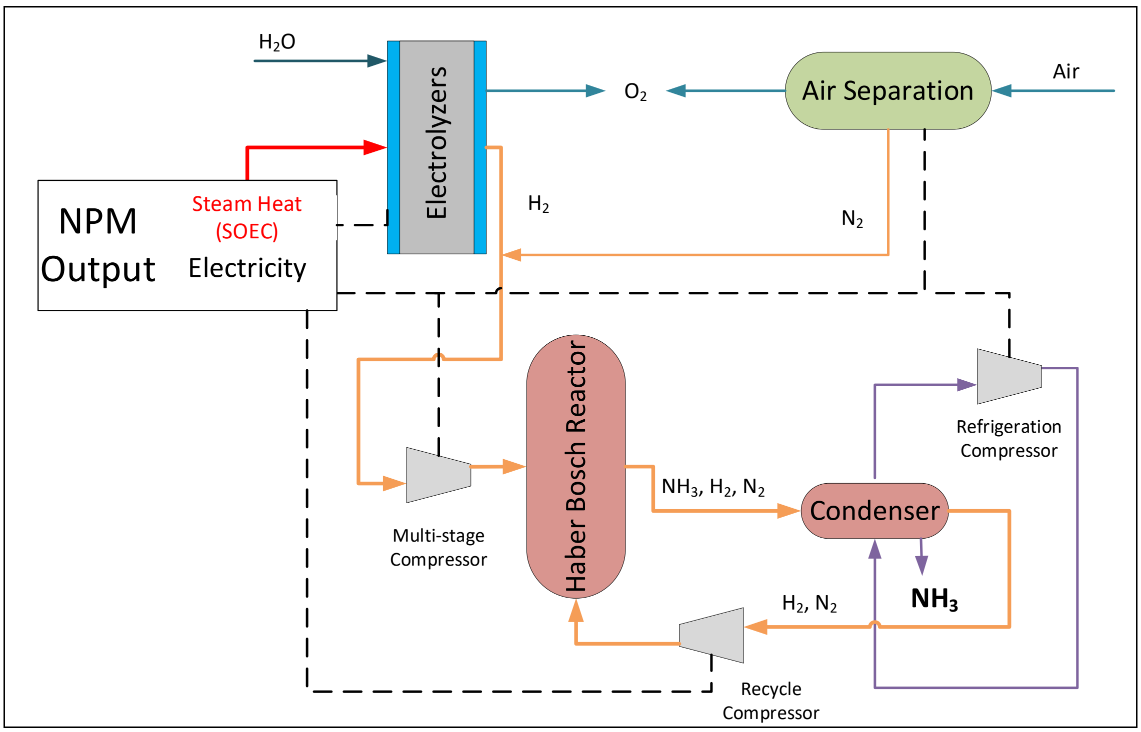

Figure 10. Conceptual Layout of a NPM coupled with Ammonia Production.

Air separation technology is used to extract nitrogen (79% of air) from oxygen (21% of air) and other trace gases. Air separation technology is mature and has been rigorously optimized. The air separation process requires electricity to power air compressors plus refrigeration if utilizing cryogenic separation technology. The ammonia synthesis reaction is exothermic once initiated, but requires temperatures of 350–550°C and pressures of 200-300 bar. The ammonia process feeds are hydrogen and nitrogen, which pass through a heterogenous catalyst bed, generating the reaction:

$$N_2 + 3H_2 \leftrightarrow 2\,NH_3$$

The process requires electricity to compress the feed gas and to power the refrigeration system to condense and cool the ammonia produced for separation and storage. Together with the air separation process and other supporting equipment, ammonia production requires ~10% of the total energy demand of an ammonia plant.

Figure 11 shows the total amount of ammonia production a plant utilizing NPMs is capable of in terms of metric tons per day based on the electrolyzer technology selected.

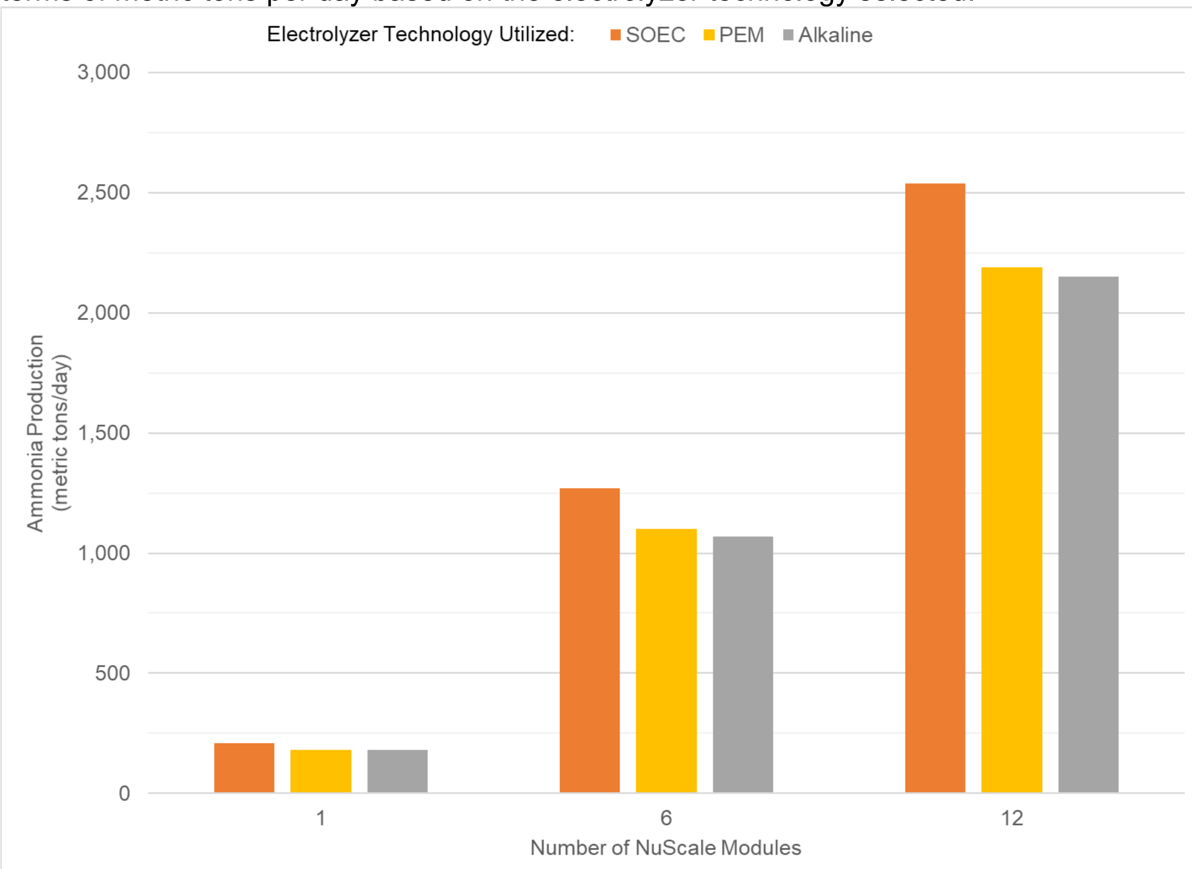

Figure 11. Total amount of Ammonia Production per in metric tons/day based on number of dedicated NPMs.
Note: Based on DOE Electrolyzer System Efficiency Targets (kWh/kg H_2) SOEC = 44, PEM = 51, Alkaline = 52

5. NUSCALE RELATED HYDROGEN AND AMMONIA STUDIES

NuScale and its investment partners continue to investigate optimal configurations for integration with hydrogen production and other industrial facilities. The following studies illustrate NuScale SMR integration approaches.

a. JGC Corporation and IHI performed a study of a NuScale SMR coupled to an SOEC Hydrogen generation facility. The published paper co-authored by NuScale was presented at the Atomic Energy Society of Japan 2024 Fall Meeting, September 13, 2024. **Evaluation for Nuclear-Hydrogen Production with NuScale VOYGR,** *Ryuki Tahara1, Keisuke Narita1, Amy Kozel2, Luis Eduardo DePavia2, Yasutomi Morimoto1, Daisuke Koike3, Paul

Boyadjian2 (1. JGC, 2. NuScale Power, 3. IHI),
https://pub.confit.atlas.jp/en/event/aesj2024f/presentation/3I02

b. A related presentation by JGC was given at the GLOBAL 2024 conference in Japan on October 8th, 2024 **Evaluation of Thermal Efficiency for Nuclear-Hydrogen Production via VOYGR™ and SOEC by Process Simulation,** JGC Corporation: Keisuke Narita, Ryuki Tahara, Yasutomi Morimoto, NuScale Power, LLC.: Amy Kozel, L. DePavia, Paul Boyadjian, https://global2024.org/

c. **NuScale collaboration for Clean Hydrogen Production with Shell Global.** The study of an economically optimized Integrated Energy System (IES) for hydrogen production using electricity and process heat from a NuScale small modular reactor (SMR) power plant was performed in collaboration with Shell and Fuel Cell Energy. NuScale Power Signs Research Collaboration Agreement for Clean Hydrogen Production | Business Wire

d. **NuScale project for Clean Ammonia in Ukraine – ongoing project.** This project involves the integration of a NuScale NPM with a hydrogen generation facility based on SOEC Electrolyzers for Ammonia production. The project was announced by US Special Presidential Envoy for Climate John Kerry at the COP27 Climate Conference in Sharm el-Sheikh, Egypt. **Nuclear Hydrogen Demonstration Analysis and Related Capacity-Building for Ukraine**, T. Lee, H. Wang and R.B. Vilim, ANL and V. Demianiuk, NT Engineering, Kiev, Ukraine, Argonne National Laboratory Report, ANL/NSE-25/1, December 31, 2024, USA-Ukraine announce cooperation on clean fuels from SMRs - World Nuclear News (world-nuclear-news.org)

e. **NuScale integrating onsite hydrogen generation powered by an SMR with industrial processes for Ammonia production**. The project is being led by Utah State University, Dr Hailei Wang and funded under U.S. Department of Energy under the Nuclear Energy University Program (NEUP). NuScale SMR is used as the power source for hydrogen and ammonia production. https://www.innovationnewsnetwork.com/green-ammonia-production-innovations-spearheaded-by-us-university/47384/

f. **An Analysis of Hydrogen Production via High-Temperature Electrolysis Using a NuScale Power Nuclear Reactor.** Performed for NuScale by Idaho National Laboratory, Richard D. Boardman et al, 2014. Early exploration study cited in section 3c in this document. Note: this reference contains previous NuScale power rating and SOEC temperature. References 4 a-d supersede this reference.

6. INTEGRATED ENERGY SYSTEM MODELING AND DYNAMIC SIMULATION

As shown in Figure 12, NuScale has developed a fully functional hydrogen simulator integrated into the NuScale Control Room simulator. The purpose is to demonstrate the ability to provide electricity and steam for hydrogen production, store the produced hydrogen (in a virtual tank) and use it when needed for conversion back to electricity in a fuel cell. This is the first hydrogen simulator integrated into a nuclear SMR. It allows NuScale to assess the integration and dynamics of different types of hydrogen production systems.

Figure 12. NuScale has Integrated Hydrogen Production Models into its Main Control Room Simulator

7. COLLABORATION WITH END USERS OF POWER, STEAM AND HYDROGEN

NuScale is interested in collaborating with end users of steam, electric power, and hydrogen to assess and optimize (i.e., energy and economic efficiency) Integrated Energy Systems (IES) capable of supporting the end user's clean energy goals at commercial scale. As such, NuScale is currently working with its research partners and industry on several techno-economic analyses (TEAs) related to clean hydrogen and clean ammonia production using a NuScale powered IES.

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