ORNL/TM-2025/3938

Assessment of NuScale SMR Steam Heat Augmentation for Chemical Plant Decarbonization

Askin Guler Yigitoglu
Scott Greenwood
Jono McConnell
Vineet Kumar
Samantha Sabatino
Luis DePavia
John Swanson
José Reyes

CRADA Final Report - NFE-24-10139

June 2025

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

External Use

ORNL/TM-2025/3938

DOE NE – Gateway for Accelerated Innovation in Nuclear (GAIN)

ASSESSMENT OF NUSCALE SMR STEAM HEAT AUGMENTATION FOR CHEMICAL PLANT DECARBONIZATION

Askin Guler Yigitoglu
Scott Greenwood
Jono McConnell
Vineet Kumar
Samantha Sabatino

in collaboration with NuScale Power
Luis DePavia
John Swanson
José Reyes

June 2025

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AEP	American Electric Power
ApCo	Appalachian Power Company
C2N	coal-to-nuclear
CHP	combined heat and power
COL	combined construction and operating license
CPP	coal power plant
DOE	US Department of Energy
EIA	US DOE Energy Information Administration
EPRI	Electric Power Research Institute
IES	Integrated Energy System
LWR	light-water reactor
NF	normalized fitness
NG	natural gas
NPM	NuScale Power Module
NPP	nuclear power plant
NPV	net present value
NRC	US Nuclear Regulatory Commission
OR-SAGE	Oak Ridge Siting Analysis for power Generation Expansion
ORNL	Oak Ridge National Laboratory
PRA	probabilistic risk assessment
PSCC	process steam conditioning and control
SMR	small modular reactor
TEA	techno-economic assessment

EXECUTIVE SUMMARY

Nearly 50% of the total energy consumed by the industrial sector in the United States is used to produce process steam with natural gas and coal-fired boilers[1]. This project conducts a techno-economic assessment of a NuScale Small Modular Reactor (SMR) coupled with a chemical plant as an Integrated Energy System (IES) where nuclear produces steam and electric power to meet the requirements of a large chemical plant.

In a 2020 study, ORNL evaluated the feasibility of using advanced SMRs, including the NuScale design, to supply energy to the Eastman Chemical Plant. However, since that report was published, NuScale received NRC approval for its uprated 77 MWe design with 56% more power and has also introduced a high-temperature, high pressure, steam heat-augmentation system, a key focus of the new study. The new study also benefits from revised capital costs, a 10-day refueling outage time, reduced plant staffing, higher capacity factors, and a site boundary Emergency Planning Zone methodology.

The study consists of a techno-economic assessment of two possible energy sources (nuclear and natural gas) in a number of steam and power generation configurations (NuScale Power Modules (NPMs), boilers and combinations of both) to satisfy the steam and power demand with the most reliable and cost competitive system. A total of 2,947.3 klb/hr of steam and 72.5 MWe of electricity are required for the demonstration case.

A range of scenarios and solutions are explored, from a 12-NPM plant (3,000 MWth)—with excess capacity and redundancy, capable of supplying a significant amount of extra power to the grid—to a 4-NPM (1,000 MWth) plant—supplemented with existing boilers or grid power for redundancy.

The study uses historical steam and power data from a chemical plant and examines the sensitivity to natural gas and grid power cost variations. Scenarios with up to two times gas and electricity costs were considered. Profitability in a 60-year time horizon was analyzed, consistent with NuScale's design life specification.

A steady-state site integration and reliability analysis was performed, and trade-offs were identified.

Key results:

- The incorporation of the NuScale power uprate and steam heat-augmentation capabilities in this analysis produced significantly more positive results compared to those presented in the 2020 report. Specifically, NuScale with steam heat-augmentation can meet the industrial steam and power requirements of a large chemical plant and provide spare capacity in a reliable, cost-efficient and flexible manner.
- Modeling results show that a 12-NPM scalable NuScale plant provides the configuration with greatest profitability, availability, and flexibility. Multiple modules enable continuous operation (no interruption when refueling) and allow capacity expansion as

[1] https://www.energy.gov/eere/ito/finding-efficiencies-process-heat

energy demand increases. In a minimalistic scenario, a 4-NPM can be used to satisfy the needs of a large chemical plant in a profitable and resilient manner with additional benefits such as reduced emissions. In all cases, a combination of NPMs and gas-fired boilers result in the most profitable system.

- A sensitivity analysis examining the impact of natural gas price fluctuations and electricity cost indicates that an IES with a NuScale plant yields increased profitability derived from excess electricity production and is resilient to rising natural gas cost.

ABSTRACT

This project performs an analysis of a NuScale Power Module (NPM) based nuclear power plant with a novel heat augmentation system for application in a commercial-scale chemical production facility. The project performs a techno-economic assessment (TEA), a steady-state site integration analysis, and a reliability analysis to help understand the functional requirements for the system, identify trade-offs, and determine the best means of integration with the facility as a reliable and cost-competitive fossil fuel alternatives.

Nearly 50% of the total energy consumed by the industrial sector in the United States is used for process heat [1]. The majority of that percentage is for steam generation from fossil-fuel boilers. Small modular reactors (SMRs) have the ability to produce steam at industrial scale for petrochemical applications.

Similarly, nearly 30% of U.S. coal-fired power plants are projected to retire by 2035 as states transition to cleaner energy sources. A 2022 DOE report [2] found that replacing unabated coal combustion with fission would reduce emissions in the surrounding region by up to 86%. This would directly improve air quality by avoiding harmful byproducts produced by fossil fuel plants that have been linked to asthma, lung cancer, and heart diseases. The same 2022 DOE report found that new nuclear power plants could save up to 35% on construction costs depending on how much of the existing site assets could be repurposed from retired coal power plants.

Additionally, the soaring energy needs of data centers are prompting the potential restarts of the Duane Arnold nuclear plant, the Palisades plant, and Three Mile Island Unit 1, with projections to be back online in 2028, subject to approval by the Nuclear Regulatory Commission (NRC). The co-location of a light-water SMR at an existing site is promising.

Elsewhere, nuclear power plants are already integrated with industrial facilities. For instance, in China, the Tianwan nuclear power plant started supplying 1.3 million lb per hour of steam to a nearby petrochemical plant in 2024. Around the world, more than 40 nuclear power plants are integrated with district heating systems.

The chemical industry requires a large supply of process heat at high temperatures. The lack of a viable low-carbon steam production option at commercial scale (e.g., >1Mlb/hr of steam) makes this challenge difficult to overcome. Compared with ORNL's 2020 report, the NRC-approved NuScale SMR has an increased power level, improved costs, reduced refueling outage time, reduced plant staffing, increased capacity factor, and is now capable of supplying higher temperature and higher-pressure steam when combined with its process steam conditioning and control (PSCC) System. These cumulative changes will affect the previously published results.

The use of a light-water SMR with steam heat augmentation offers a new clean energy option for commercial chemical plants. This study presents a detailed analysis of SMR integrated energy system requirements, an assessment of cost-effective high-temperature steam and steam heat transport losses, and revised insights on SMR siting suitability.

1. INTRODUCTION

1.1 BACKGROUND AND REFERENCE WORK

In 2020, Oak Ridge National Laboratory (ORNL) performed a feasibility study for siting an integrated energy system (IES) to meet the steam and electricity needs of the Eastman Chemical Company's facility in Kingsport, Tennessee; a producer of a variety of chemicals, fibers, and plastics [3]. The combined heat and power (CHP) system is in continuous use and consists of seventeen boilers and nineteen steam turbines. Natural gas and coal are used to fuel the boilers, with coal being the predominant source. Three of the boilers are used as back-ups. Altogether, the CHP system has an electric generating capacity of 200 MW while also generating 3,463 klb/hr of steam—approximately 93% of which is produced at 1500 psig and 7% at 600 psig. 1500 psig steam is used for electricity production only and outputs to a common 600 psig steam header. The 600 and 100 psig steam headers are used for additional electricity production, mechanical drives, and plant processes with a small fraction of the steam ultimately reduced to 15 psig. Steam available for plant processes is approximately 3,000 klb/hr at 600 psig, 680 klb/hr at 100 psig, and 100 klb/hr at 15 psig. The energy output of the CHP system accounts for over 90% of the site's thermal and electric demand.

The previous study [3] explored reactor technology options and performed evaluations and optimizations focused on meeting the facility's operational (thermal and electric demand) and reliability requirements. The study provided a useful techno-economic analysis (TEA) of IESs consisting of various small modular reactor (SMR) nuclear power technologies coupled to an industrial-scale chemical facility. The NuScale SMR (160 MWt / 50 MWe) was the only light-water SMR included in the study. Since the 2020 study was published, the NuScale SMR has been approved for a higher power rating (250 MWt / 77 MWe) and developed a heat augmentation system capable of delivering industrial-scale high-temperature, high-pressure steam. This report takes these and other updated capabilities into consideration.

However, this report does not address reactor-specific analysis such as specific reactor location, method of piping for connection to the 600 psig steam network, nor other site modifications or contractual/business arrangements for operation, construction, or related activities for realizing the integration of a nuclear plant with the Eastman facility. These attributes are critical to the integration, and it is believed that the information contained within the previously published report provides important basic understanding of a nuclear reactor. This follow-up study on the NuScale SMR design will provide a more detailed assessment regarding this integration.

The Eastman Chemical Company operating parameters present the ideal profile for this study. ORNL maintains a previously published representative "end-user" set of requirements provided by Eastman. These requirements and data were used and compared with the updated NuScale Power Module (NPM) design with steam compression and heating, updated steam pressures, temperatures, and mass flow rates to achieve process temperatures and pressures (i.e., 600 psig and 750°F).

2. SYSTEM ANALYSIS

2.1 SYSTEMS DEFINITIONS

This TEA assessment covers a representative chemical facility coupled with NuScale NPMs and a Process Steam Conditioning and Control (PSCC) system. These subsystems are described in this section to provide detailed understanding of the integrated configuration and the IES optimization requirements.

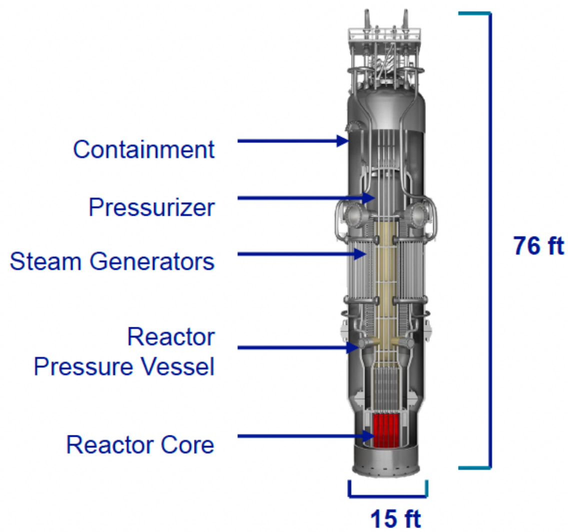


Figure 1. NuScale Power Module cutaway [4].

2.1.1 NuScale NPMs

The NuScale SMR is based on proven light-water reactor (LWR) technology, incorporates extensive use of passive safety features, meets the utility needs for standardization while also allowing flexible deployment options, and is scalable to allow 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 U.S. Nuclear Regulatory Commission (NRC) approved methodology for a modified emergency planning zone (EPZ) (e.g., site-boundary). The NuScale plant consists of multiple power units, each unit representing an independent nuclear steam supply system (NSSS) coupled to a dedicated turbine-generator system. A flexible number of power units can be configured into the plant to suit a utility's needs. The NPM produces 250 MWt (77 MWe) and is shown in Figure 1.

The recently approved uprated NPM has a much larger steam generation rate per module, 816,000 lb/hr, which generates 56% more power than the previously approved 160 MWt design. A 12-module power plant utilizing uprated NPMs generates 924 MWe, an increase of 324 MWe compared with the 600 MWe output listed in the 2020 study [3] on the same or smaller footprint. The uprated modules also include improved capital costs and the levelized cost of electricity.

NuScale has evaluated the use of steam compression and heating to achieve process temperatures and pressures versus natural gas (NG) fired heating. For the NuScale design, in which the primary cooling loop is physically separated from the secondary steam-turbine-loop, it would be technically possible to use the secondary side steam directly from the NPM. However, it is undesirable to share the same water between the nuclear power plant and the chemical facility since they have different water conditioning needs; in addition, water sharing would extend the EPZ regulatory requirements to the industrial facility. A better solution is to add an intermediate heat exchanger (IHX), sometimes referred to as an unfired boiler, to transfer the heat from the NPM steam to the industrial water stream while keeping them completely isolated from each other. An economic analysis is required to compare steam compression and heating to NG fired heating.

The following NuScale design features make it particularly well suited for providing process steam:

- The fluid inside the helical coil steam generators is not in contact with the fluid inside the reactor
- The historically low rate of fuel pin failures for the HTP-FUEL used in the NPM.
- The unique ability to isolate the main steam lines to full reactor pressure
- The passive safety of the NuScale design does not require AC or DC power to isolate the main steam line

The use of an additional IHX to further isolate the nuclear steam and the industrial steam flows.

2.1.2 Process Steam Conditioning and Control (PSCC) System Overview

Figure 2 shows a simplified flow diagram of the process steam conditioning cycle that uses NPM steam as the source of steam [4]. A portion of the NPM steam from the steam generator is sent to the turbine to generate electricity, and a second portion is sent to an IHX to transfer heat to an industrial water stream. After boiling in the IHX, the industrial steam is sent to the compression and heating system to increase the steam pressure and temperature to the nominal process pressure and temperature. The conditioned steam is then directed to the applicable chemical processing system to produce the desired product.

Thus, there are two primary independent boundaries between the nuclear material and the industrial feedwater: the helical coil steam generator in the NPM and the primary IHX. Including active radioactive monitoring equipment, this system ensures that there will be no radioactive leakage between NPM steam and industrial steam. The primary IHX is located within the site boundary and, along with the turbine generators, forms the boundary requirement to determine the EPZ. NuScale’s methodology for determining the EPZ is approved by the NRC, and with it NuScale can obtain a site boundary EPZ at most sites. Including the IHX within the site boundary, possibly proximate to the turbine generators, allows for a site boundary EPZ to be achieved.

The PSCC building, which houses any required compressors and electric heaters, need not have this limitation regarding the EPZ. The PSCC building only deals with industrial steam and thus can be located wherever makes the most sense—for example, near the nuclear plant, near the industrial facility, or somewhere in-between.

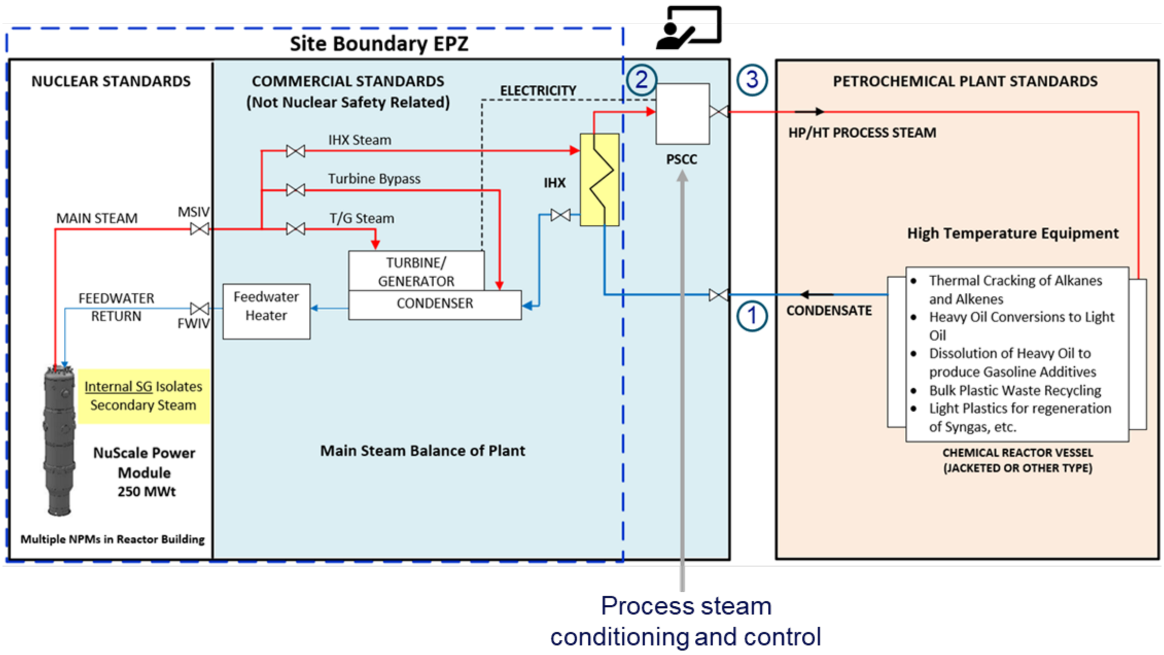


Figure 2. NPM coupled with PSCC [4].

2.1.3 Integrated System Requirements

ORNL gathered process steam and electric power requirements to conduct a TEA of a NuScale SMR plant with steam heat augmentation in support of a commercial-scale chemical plant. As a reference case, the Eastman chemical plant located in Kingsport, TN, USA, was used in this analysis as an example of a large chemical facility with numerous boilers that could potentially be powered by a NuScale SMR plant for both steam and electricity. The operational data of the power system (steam and electricity) at the facility was analyzed to establish a reasonable benchmark for the output that a nuclear power plant would need to meet the operational requirements of the facility (i.e., both total and dynamic operational demands). Figure 3 depicts the boilers and turbines, in association with the steam distribution system as they currently are at the Kingsport, TN facility.

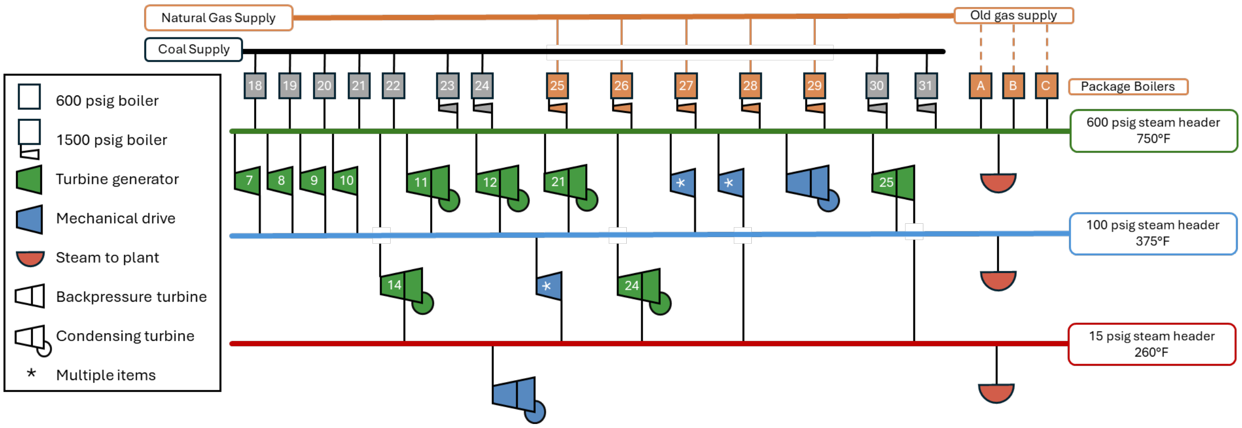


Figure 3. Eastman Tennessee operations power system.

With an understanding of the power system components, the characteristics of the components were evaluated to understand key qualitative and quantitative requirements. First, the location of the components was determined to better understand how a future power system, particularly steam lines, would need to be integrated with the overall site. As indicated in Table 1, this plant operates a mixture of coal, waste, and NG boilers located in various parts of the site (Figure 4). Therefore, it was noted that a key requirement, or at least an important item for consideration, for integration of a nuclear facility (centrally located production) is the ability to cost-effectively distribute steam to the existing steam and electricity network or account for re-engineering of the system to accommodate a new production facility.

Table 1. Building location of boilers and turbines.

Building	Fuel	Boilers	Turbines
B-83	Coal/Waste	18–24	7–12, 14
B-253	Nat. Gas	25–29	21, 24
B-325	Coal	30, 31	25
B-423	Nat. Gas	A, B, C	—

Figure 4. Location of the steam/electricity production buildings on the Eastman site (within white line).

The power system boilers were then grouped according to the likelihood that their steam production could be replaced by a nuclear power source. The logical approach to this grouping was based on coarse operational characteristics and facility purpose (not just steam or electricity output). These two features were sufficient to clearly demarcate each of the boilers into logical groups. With the PSCC system, all boilers had the potential to be replaced with NPM-supplied steam and electricity; however, there were other Eastman-specific requirements that necessitated different likelihood ratings. A low likelihood indicates that there is no current expectation that the boiler's purpose could be replaced with nuclear. Boilers 23–24 have a *low* rating because a key operational priority of those boilers is to reduce chemical waste through consuming waste as fuel. Boilers 18–20 received a *medium* rating because they are scheduled to be replaced and converted from coal to NG in the near term. If they were to be replaced with nuclear, it would not likely be until after several nuclear units were online and after replacing first the output of boilers 25–31. Boilers 25–31 received a *high rating* because they serve primarily as a base load energy source with no special constraints and are therefore aligned with a traditional base load nuclear power source. Boilers A–C received a high rating because they serve exclusively as the plant's peaking boilers as a peaking plant for steam, which is expected to be within the capabilities of NuScale's steam heat augmentation system.

Table 2. Boilers grouped for analysis according to their shared group characteristics and likelihood replacement with nuclear.

Boiler Groups	Characteristics	Replacement with nuclear likelihood
18, 19, 20	Direct to steam line, medium output variability, near term replacement timeline	Medium
21, 22	Direct to steam line, waste burners	Low
23, 24	Electricity then steam line, waste burners	Low
25, 26, 27, 28, 29, 30, 31	Base load, low output variability	High
A, B, C	Direct to steam line, high output variability	High

For each group, boiler outputs for the period of 2014–2020 were summed, and then a daily average of that group's output was calculated. A summary of the statistical behavior of each group was then calculated to provide a coarse summary of the group's operational characteristics (Table 3). To help provide insight into the groups for zero and non-zero data that may skew some information, the mean and standard deviation were calculated using only values greater than zero. The lower portion of the data provides insight into how the group operates and the variability associated with the group turning on and off. These data provide a baseline set of quantitative requirements that the NuScale system must be able to replace.

Table 3. Statistical summary of Eastman boiler output data for identified boiler groups and site electricity based on daily averaged data over the period of 2014–2020. S = steam in klb/hr, E = electricity in MW. Lower rows are unitless or as specified. Balance of electricity not created by boilers is generated by turbines between steam lines.

	Boilers 18-20 Sum		Boilers 21-22 Sum		Boilers 23-24 Sum		Boilers 25-31 Sum		Boilers A, B, C Sum		Site Electricity	
	S	E	S	E	S	E	S	E	S	E	Total Generated	From Grid
Mean ($\bar{x}$)	97.5	-	132.5	-	383.2	6.8	2823.0	62.7	26.8	-	146.0	9.8
Stand. deviation (σ)	92.1	-	70.9	-	113.7	2.0	237.0	5.3	38.7	-	11.2	3.6
Minimum	0.0	-	0.0	-	0.0	0.0	813.7	18.1	0.0	-	58.6	-0.2
Maximum	394.1	-	265.9	-	558.1	10.0	3366.2	74.8	343.5	-	166.6	31.5
Median	86.9	-	125.9	-	443.0	7.9	2838.5	63.1	11.3	-	147.5	9.2
$\bar{x}$ of data > 0	146.4	-	153.2	-	388.9	6.9	2823.0	62.7	45.0	-	146.0	9.8
σ of data > 0	74.7	-	51.3	-	104.4	1.9	237.0	5.3	41.1	-	11.2	3.6
% of data <= 0	33.4	-	13.5	-	1.5	1.5	0.0	0.0	40.4	-	0.0	0.1
Max continuous non-zero days	164	-	256	-	773	773	2191	2191	153	-	2191	2152
Max continuous zero days	60	-	60	-	17	17	0	0	27	-	0	1

2.1.4 Integrated System Configurations

2.1.4.1 Steady State

Given the results of Table 2, a steady state model of the system was developed to replace all boilers, except for the "low likelihood of replacement" boilers: boilers 21, 22, 23, and 24. The "low-likelihood" boilers' associated systems, subsystems, and production rates of both steam and electricity were assumed to be maintained. Thus, the steady-state model would incorporate a nuclear facility powered by a number of NPMs to replace the steam and electricity production of boilers 18, 19, 20, 25, 26, 27, 28, 29, 30, 31, A, B, C, as well as the grid connection.

The total system requirements were as follows:

- 2,947,300 lb/hr of steam at 600 psig and 750°F
- 72.5 MWe of electricity

To understand the energy needed to generate this amount of steam and electricity, a simple steady state model was designed using the software DWSIM. This model can be seen in Figure 5. The results of the analysis, found in Table 4, show the industrial steam production (column

12) and net electricity production rate (column 11) of a single NPM by varying the amount of steam from the NPM sent to either the IHX (column 1) or the Turbine Generator (column 9). These results show that energetically speaking, a single NPM can generate 478,500 lb/hr of industrial steam at 600 psig and 750°F. This is achieved by sending approximately 65.5% of the NPM steam to the IHX and 34.5% of the NPM steam to a turbine generator to generate electricity to drive the required compressors and electric heaters.

To quantify how many NPMs would be required to power the Eastman facility in Kingsport TN, simply dividing the requirements by these results gives the answer.

- 2,947,300 lb/hr / 478,500 lb/hr per NPM = 6.16 NPMs for Steam
- 72.5 MWe / (77 MWe per NPM – 3 MWe House Loads per NPM) = 0.98 NPMs for Electricity

This operation results in a requirement of 7.14 NPMs to supply all of the steam and electricity needed to replace the previously identified boilers and the existing grid connection. Because a partial NPM is not possible, this value was rounded up to 8 NPMs.

Table 4. Results of DWSIM analysis – Single NPM production capabilities

NPM Steam to IHX (lb/hr)	Boil. HX Area (m²)	Pump #1 (MW)	Pump #2 (MW)	Compr-essor Size (MW)	Elec. Heater Size (MW)	House Loads (MW)	Elec. Demand (MW)	NPM Steam to TG (lb/hr)	Elec. Gen. (MW)	Elec. Balance (MW)	Indust. Steam Produc. (lb/hr)
816,000	2,315	0.36	0.07	9.64	25.9	3	39.0	0	0.0	-39.0	730,500
700,000	1,968	0.31	0.06	8.27	22.22	3	33.9	116,000	10.9	-22.9	626,640
600,000	1,670	0.27	0.05	7.09	19.04	3	29.5	216,000	20.4	-9.1	537,120
534,500	1,476	0.24	0.05	6.32	16.96	3	26.6	281,500	26.6	0.0	478,500
500,000	1,373	0.22	0.04	5.91	15.87	3	25.0	316,000	29.8	+4.8	447,600
400,000	1,079	0.18	0.04	4.73	12.69	3	20.6	416,000	39.3	+18.6	358,080
300,000	912	0.13	0.03	3.55	9.52	3	16.2	516,000	48.7	+32.5	268,560
200,000	766	0.09	0.02	2.36	6.35	3	11.8	616,000	58.1	+46.3	179,040
100,000	685	0.04	0.01	1.18	3.17	3	7.4	716,000	67.6	+60.2	89,520
0	0	0	0	0	0	3	3.0	816,000	77.0	+74.0	0

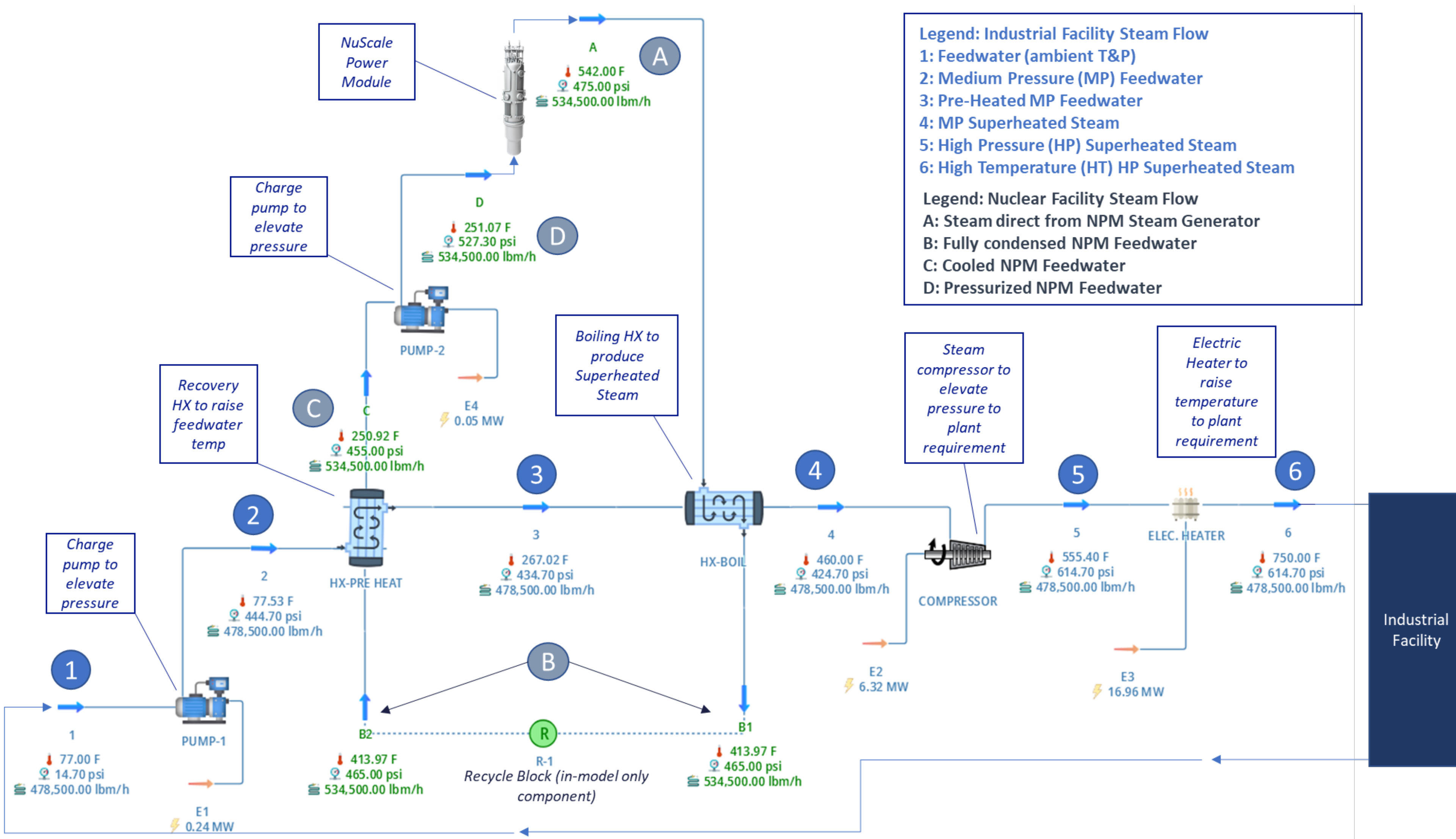


Figure 5. Basic layout of DWSIM model. The specific values for energy, temperature, pressure, and flow rate are for the balanced energy model.

2.1.5 Enthalpy Analysis

The above configuration can be analyzed using an enthalpy–pressure diagram as shown in Figure 6, which shows the enthalpy–pressure diagram of water and plots the industrial steam through each step required to reach the final pressure and temperature. Table 5 shows the numerical values that make up the figure.

Table 5. Enthalpy analysis of the industrial stream for Eastman conditions with NPMs

Stage	Description	Temperature (°F)	Pressure (psia)	Specific Enthalpy (BTU/lb)	Enthalpy Gain (BTU/lb)
1	Ambient Inlet	77.0	14.7	45	-
2	Charging Pump	77.5	444.7	47	2
3	Recovery IHX	267.0	434.7	237	190
4	Boiling IHX	460.0	424.7	1213	976
5	Compressor	555.4	614.7	1258	45
6	Electric Heater	750.0	614.7	1379	121

		% of Total
Total Enthalpy Gain (BTU/lb)	1334	
NPM Steam (Stage 3 & 4) Enthalpy Imparted (BTU/lb)	1166	87.4%
PSCC (Stage 5 & 6) Enthalpy Imparted (BTU/lb)	166	12.5%

As can be seen, the NPM steam performs the “heavy lifting” and imparts a total of 87.4% of the total enthalpy gain through the use of the IHXs. The PSCC components perform a much smaller but still important part of conditioning the steam to the final required temperature and pressure; however, they only have to impart 12.5% of the total enthalpy gain. In this case, adiabatic compression raises the temperature from 460 °F to 555.5 °F, and the electrical heaters raise it from 555.4 °F to 750 °F. It is worth noting that for other steam requirement scenarios it may be sufficient to have either a compressor or a heating system.

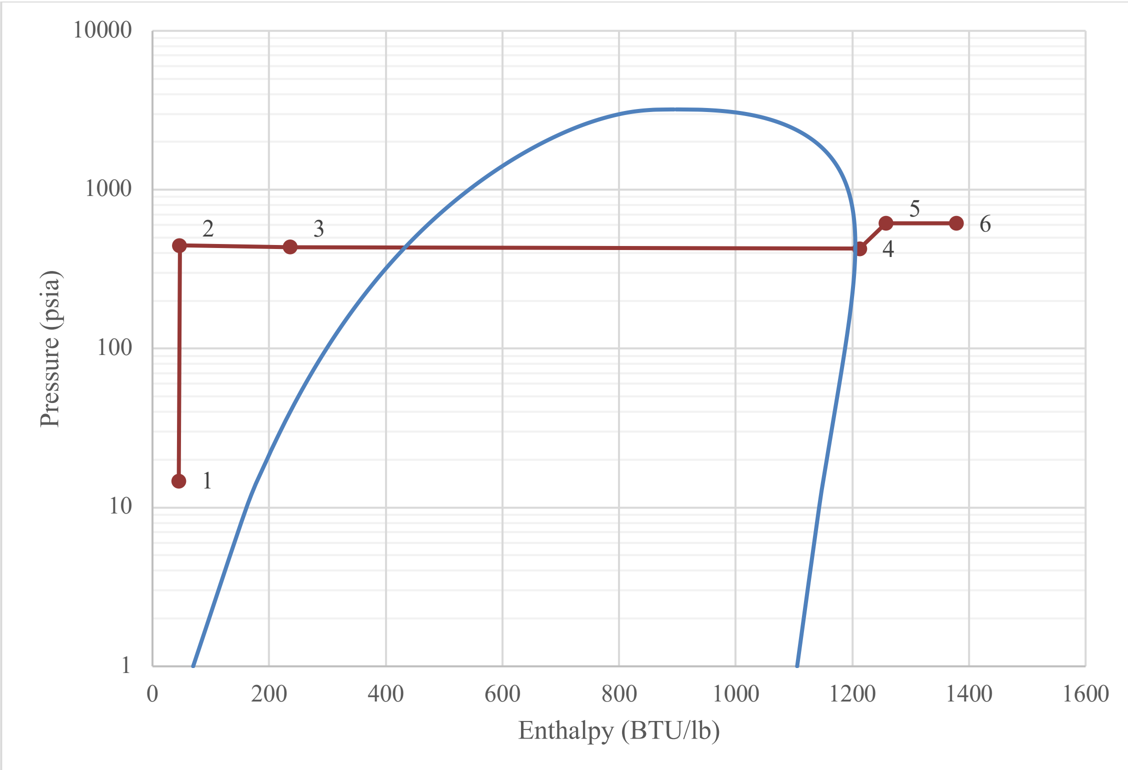


Figure 6. Pressure & enthalpy diagram for Eastman industrial stream.

2.1.6 System Layout with 8 NPMs

The NuScale modular design affords the flexibility to allocate the energy from each NPM for production of steam only, electricity, or both; therefore, there are a variety of ways to configure the 8 NPMs that would comprise the nuclear facility. The NPMs can be grouped in three different classes:

- NPMs that are completely devoted to electricity production
- NPMs that are completely devoted to steam production
- NPMs that are devoted to both steam and electricity production (Cogeneration NPMs)

Extensive analysis was performed on all possible combinations of incorporating these NPM types. Although there is some potential to lower capital equipment costs by having NPMs that are completely devoted to a specific type of production, this approach introduces tradeoffs: it lowers overall availability and demands wider operating ranges from remaining equipment, particularly during refueling or maintenance periods when online NPMs must compensate by increasing steam output. These tradeoffs made those scenarios less attractive overall. It was determined that the most promising scenario in terms of both technical viability and overall availability was the one where all required 8 NPMs are devoted to both steam and electricity production (i.e., Cogeneration). An added benefit of configuring all 8 NPMs identically is reduced operational complexity; refueling any single module leads to the same operating scenario each time.

2.1.7 Availability Requirements, including Maintenance and Refueling

The Eastman facility in Kingsport, TN, is expected to operate 24 hours a day, 7 days a week, 365 days per year without any planned plant-wide shutdowns. In fact, of the six years of data that were available, the Eastman facility experienced a single unexpected plant-wide shutdown in 2014 that lasted 9 days; this demonstrates an availability need of 99.6% between 2014 and 2020. Furthermore, this single shutdown was the first since 1998, 16 years earlier. Additionally, according to the reporting of the 2014 incident, the shutdown was caused by a loss of power from their on-site power plant. Clearly, high reliability of the power system is needed for the Eastman facility to continue its day-to-day operations.

Nuclear power in general has the highest capacity factor of any power source, averaging for the industry around 93%. NuScale has a nominal capacity factor of 95%, which includes refueling and a conservative discount factor, but the capacity factor of a dedicated smaller demand can be even higher with the inclusion of additional modules [5]. Availability of 99.98% can be achieved in a micro-grid for 77 MWe [6]. Furthermore, the nominal refueling outage for each module lasts 10 days and takes place every 18 months. Because of the nature of NuScale's modular design and operating principle, the NPMs can refuel in a staggered fashion allowing for all but one reactor to stay on-line during refueling. This feature is not present in current large nuclear reactors, for which production must shut down entirely for the length of the refueling. In the proposed 8 NPM plant with staggered refueling, this would mean refueling a single NPM approximately every 68 days (18 months divided by 8). This means that an 8 module NPM plant would be expected to operate at an N-0 (i.e., all NPMs online) configuration for approximately 85% of the time and an N-1 (i.e., all NPMs online except one) scenario for approximately 15% of the time. During this refueling period, the vast majority of routine maintenance and inspection are also planned to take place on the NPMs.

Because of the high-power availability need of the Eastman Facility in Kingsport, TN, and the inherent nature of refueling bringing a module offline, it would then seem prudent to design for an N-2 scenario. This would cover all expected scenarios, i.e., N-0 and N-1, and also cover any unforeseen scenarios that would take an NPM offline that might occur during an N-1 scenario or occur concurrently in two separate NPMs.

2.1.8 Availability Analysis – 8 NPM Plant

The 8 NPM plant was modeled including the four previously identified boilers, i.e., boilers 21, 22, 23 and 24. The boilers were assumed to operate at their nominal production for both steam and electricity. The following scenarios were modeled:

- N-0: Standard operation, all NPMs are functional, and all boilers are functional.
- N-1: A single NPM is offline, and all boilers are functional
  - This will be the case during normal refueling or during an unplanned outage of a single NPM.
- N-2: Two NPMs are offline, and all boilers are functional.
- N-3: Three NPMs are offline, and all boilers are functional.

The results of this analysis can be seen tabulated in Table 6. The boilers being taken offline for maintenance were not directly included in the results. The reason is that any boiler being taken offline constitutes a scenario less challenging than the N-1 NPM case since each boiler produces less steam and electricity than a single NPM.

The results show that during standard operation (N-0) the 8 NPM plant can provide all steam and electricity for the plant and have a surplus of 64 MWe that can be used for other processes or sold to the grid.

The results also show that during the N-1 case, e.g., refueling, the NPM based nuclear plant can still provide all steam and electricity for the plant. To achieve this, the following operational adjustments need to be made: Each remaining NPM needs to divert a small amount more of its steam from the turbine generator to the IHX, resulting in 14% more industrial steam flow per NPM. Finally, a 10.3 MWe draw from the grid is needed to balance the electrical load. This is very close to the nominal value already used by Eastman during their day-to-day operations (i.e., 9.8 MWe) and would therefore pose no problem.

Table 6. Results of availability analysis for 8 NPM facility

Scenario	No. of Cogen NPMs	Steam Generation (lb/hr)										Results
		Per NPM	NPM Total	Boiler-21 Nom.	Boiler-22 Nom.	Boiler-23 Nom.	Boiler-24 Nom.	Boiler Steam Nom. Sum	Boilers Extra Steam	Total Boiler Steam	Total All Steam	Steam Balance (lb/hr)
N-0	8	368,407	2,947,257	60,153	72,366	190,393	192,851	515,761	0	515,761	3,463,019	0
N-1	7	421,037	2,947,257	60,153	72,366	190,393	192,851	515,761	0	515,761	3,463,019	0
N-2	6	434,356	2,606,133	60,153	72,366	190,393	192,851	515,761	341,124	856,886	3,463,019	0
N-3	5	509,748	2,548,742	60,153	72,366	190,393	192,851	515,761	398,515	914,277	3,463,019	0

Scenario	No. of Cogen NPMs	Electricity (MWe)								Results
		Gen. Per NPM	NPM Total Gen.	Boiler-23 TG nom. Gen.	Boiler-24 TG nom. Gen.	Boilers Extra Electric. Gen.	Grid Electricity Draw	House Load Demand	Total Generation Less House Loads	Electricity Balance (MWe)
N-0	8	20.0	160.2	3.17	3.64	0.00	0.0	-24	143	+63.7
N-1	7	11.9	83.2	3.17	3.64	0.00	10.3	-21	79	0.0
N-2	6	9.8	59.0	3.17	3.64	3.47	28.1	-18	79	0.0
N-3	5	-1.8	-9.2	3.17	3.64	4.05	31.5	-15	18	-61.1

The N-2 scenario also shows that the NPM-based nuclear power plant can still provide all steam and power to the Eastman facility. There are a number of scenarios that can achieve this. For illustration purposes, only one is presented. To achieve the N-2 case, the following will take place: again, each remaining NPM needs to divert a small amount more of their steam from the turbine generator to the IHX, resulting in 18% more industrial steam flow per NPM compared to the N-0 case. A larger draw at 28.1 MWe from the grid is needed to balance the electrical load. This is below the maximum used by Eastman over the six years of data from 2014 to 2020, that value being 31.5 MWe. Finally, the existing fossil boilers must generate more steam, together operating at 94% of their maximum capacity, this also generates a small additional amount of electricity.

The N-3 scenario is included for completion and shows that even in this challenging and unlikely scenario the NPM based nuclear plant could still provide all the steam required if it could draw normal amounts, less than 31.5 MWe, of electricity from the grid. If for some reason the Eastman facility could draw an additional 61 MWe from the grid, for 92.6 MWe total, then this scenario is also achievable for both steam and electricity supply.

2.1.9 Fewer than 8 NPM Plant

It has been shown that an 8 NPM facility could be used to replace all “high likelihood” and “medium likelihood” for replacement boilers for the Eastman facility. However, there may be a desire to build a reduced size nuclear facility and keep more of the boilers online. If this were the case, then the steam and electricity requirements could be met by some combination of boilers and NPMs. The relationship between how many NPMs and how many boilers are needed is tabulated in Table 7, based on common NPM plant configurations, and graphically in Figure 7, which shows the relationship in terms of energy. Note that the relationship is not exactly linear because all boilers are of different sizes and capacities.

Table 7. NPMs vs. boilers needed to meet requirements

NPMs	Boilers
0	17
4	8
6	6
8	4
9	0
10	0
12	0

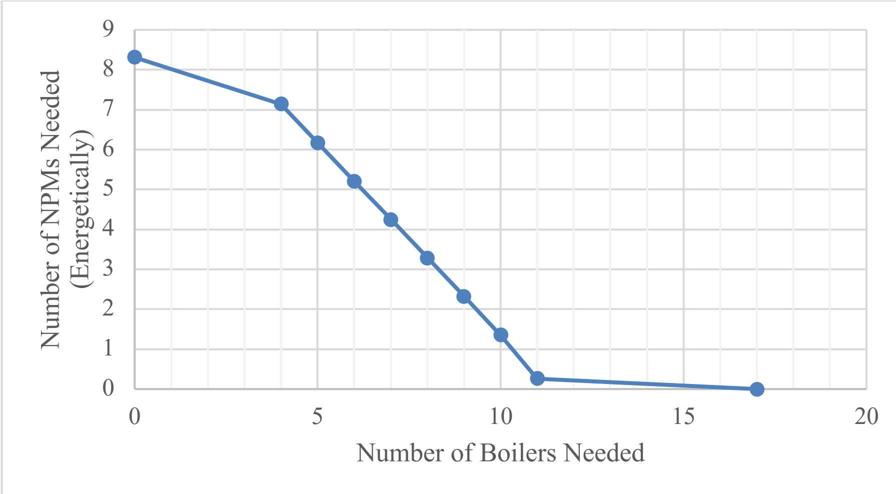


Figure 7. Trend between number of boilers needed and number of NPMs (energetically) needed when used in combination.

The zero boilers case represents the scenario where all boilers, even the “Low” likelihood boilers are replaced. The four boilers case represents the scenario where all “High” and “Medium” likelihood boilers are replaced; this is the scenario previously detailed. The five–eleven boilers case represents the scenario where the highest producing “baseload” boilers are progressively replaced, i.e., boilers 25, 26, 27, 28, 29, 30, and 31. The twelve–seventeen boilers case represents the scenario where the six smallest boilers are replaced, 18, 19, 20, A, B, and C.

This data shows that even with NuScale’s smallest standard offering of a 4 NPM facility, half of the existing boilers could be retired. Additionally, a 6 NPM facility could meet the energy requirements if only 2 more boilers were kept online beyond the “low” probability of replacement ones.

2.1.10 Thermal Efficiency – 8 NPM Plant Configuration

A typical nuclear power plant—indeed, any steam-based power plant—that is fully dedicated to electricity generation will have a thermal efficiency of around 31–33%. This means that of every 100 MW of thermal energy that is produced by the nuclear reaction only 31–33 MW of electrical energy is generated, the remaining 67–69 MW is rejected to the environment as waste heat. This efficiency is due to the inherent thermodynamics of the steam Rankine cycle that is employed to convert the temperature and pressure energy of the steam to electrical energy. It has long been known that the thermal efficiencies of cogeneration power plants, that is, those that produce both heat and power, also known as combined heat and power (CHP), can be much higher. This is because the heat can be used directly without having to be first converted into electricity.

The nominal thermal efficiency of the NuScale Power Module is 31% when it is employed in a mode that only generates electricity, i.e., 77 MWe is generated from 250 MWt. However, if the NPM is employed in a cogeneration fashion that thermal efficiency can be greatly improved.

For the 8-NPM scenario operating at standard conditions with nominally operating boilers, i.e., the N-0 scenario previously presented, the overall thermal efficiency is about 65%, a more than doubling of efficiency. Still, this can be increased to greater than 69%, if the four remaining boilers are able to operate at a reduced rate and the NPMs shift to less electricity production and more steam production. These results can be seen in Table 8. The validity of the reduced power boilers is more fully explained later in the GHG Targets section.

Table 8. Thermal efficiency of an 8-NPM system coupled with fossil fuel boilers

Condition	NPM Thermal Energy Produced (MW)	NPMs Online	Net Electricity Produced (MW)	Enthalpy Added to Process Steam (MW)	Total Net Energy (MW)	Nominal Thermal Efficiency	Thermal Efficiency Including Refueling
8-NPMs with Nominal Power Fossil Fuel Boilers	2000	8	136	1152	1288	64.4%	65.4%
8-NPMs with Reduced Power Fossil Fuel Boilers	2000	8	77	1301	1378	68.9%	69.2%
8-NPMs During Refueling	1750	7	42	1202	1244	71.1%	-

This high overall thermal efficiency represents one of the primary motivations for utilizing heat from the steam directly instead of first converting it into electricity, and this possibility should be considered when facilities look only at electrification as a method to reach their environmental goals.

2.1.11 Conclusions – 8 NPM Plant Configuration

With 8 NPMs, four already existing boilers, and the existing grid connection steam and electricity can be provided to the Eastman facility in Kingsport TN with a high degree of availability and with a high thermal efficiency. Indeed, all N-0, N-1, and N-2 scenarios can be achieved within current limitations. Presently NuScale has offerings of 4-NPM, 6-NPM, and 12-NPM facilities, but has not directly evaluated an 8 NPM plant. However, due to the modular nature of the NuScale design an 8 NPM plant would not present any technological challenge compared to NuScale's existing designs and would need simply be licensed as such. An alternative route may be that a 12-NPM plant is constructed, with the additional four modules being used in some other fashion. For example, they could be used to provide an even higher degree of availability at the Eastman site (e.g., N-3 scenarios and beyond), they could be connected to a valuable external customer such as a data center, or they could simply be used to provide more electricity to the grid.

3. PSCC SYSTEM DESIGN

3.1 COMPONENTS

For the steam augmentation scenario to be achieved, four primary pieces of equipment are needed:

- steam driven turbine electric generator,
- intermediate heat exchanger,

- steam compressor, and
- steam electric heaters.

A brief description of each subsystem is provided in the following subsections.

3.1.1 Steam Driven Turbine Electric Generator

The steam driven turbine electric generator is well understood and would simply need to be sized for the appropriate mass flow, pressures, and temperatures. In the 8-NPM scenario the mass flow variations would be around 15–20% of the total during refueling or other outages, a variation well within the capabilities of commercial steam driven turbine electric generators. These generators would be located on the nuclear site within a turbine generating building.

3.1.2 Intermediate Heat Exchanger

There are two main types of IHXs required for each cogeneration NPM.

- A primary boiling/condensing heat exchanger
- A secondary recovery heat exchanger

These IHXs would also be located on the nuclear site and could be in their own building or possibly within the turbine generator building in a separate room. The primary boiling/condensing heat exchanger would require the most area and is expected to perform the following action:

- Fully condense the NPM steam to water
- Fully boil the industrial water to steam and impart an amount of superheat.

It is desirable that the industrial steam have a certain amount of superheat so that when it reaches the compressor it is fully dry. For our calculations, we assumed 9.5°F of superheat is sufficient. This requires the heat exchanger to operate at a high thermal efficiency, i.e., +90%. Candidates of heat exchangers to fulfill these requirements would be either a plate and fin type heat exchanger or a printed circuit board compact heat exchanger.

The secondary recovery heat exchanger is much smaller in area and is utilized to improve the overall energy transfer from the NPM to the industrial water. It is expected to perform the following actions:

- Cool the NPM water to feedwater conditions
- Heat the industrial water prior to the boiler

This IHX would be liquid-to-liquid and is not expected to be a challenge, either during procurement or operation.

With the 8-NPM cogeneration case the mass flow variations would again be around 15–20% of the total during refueling or other outages, this is also not expected to be an issue with the IHXs.

3.1.3 Compression System

The compression system that is ideally situated to work at these conditions is a multistage centrifugal compressor, due to its ability to have a relatively high pressure increase and handle a large amount of flow. The compression system would be located separate from the nuclear site and outside of the EPZ. It could be proximate to the Eastman facility or somewhere in between. The compression system would be located inside a process steam conditioning and control (PSCC) building.

In the 8-NPM case the full flow of all NPMs would be combined and directed to the compression system. The flow rate, i.e., nearly 3 million lb/hr, can be processed comfortably by a single large compressor. However, given the nature of the Eastman facility and its high availability requirement, it would likely be prudent to have a redundant compressor so that one may be taken offline for maintenance every number of years. One scenario that would handle this would be to have three compressors each sized to handle 50% of the flow each.

The following are the key features related to process steam flow rate ramp-up and ramp-down for the compressors:

- Nominal to maximum: < 1 minute
- Nominal to minimum: < 1 minute
- Cold start/Shutdown: likely less than 1 hour

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

3.1.4 Electric Heating System

In the Eastman case, where the steam requires a high amount of superheat (i.e., steam at 600 psig and 750°F has a superheat of +261°F), it can sometimes be necessary to provide the extra heat with electrical heaters. The electrical heating units are envisioned to be steam circulation heaters. These would be located close to the compression system and inside the PSCC building.

In the 8-NPM case, one possible solution is for the full flow of all NPMs to go through six different trains of electric circulation heaters. Each of these trains would consist of five stages that would raise the temperature of the steam until it is at the final 750°F.

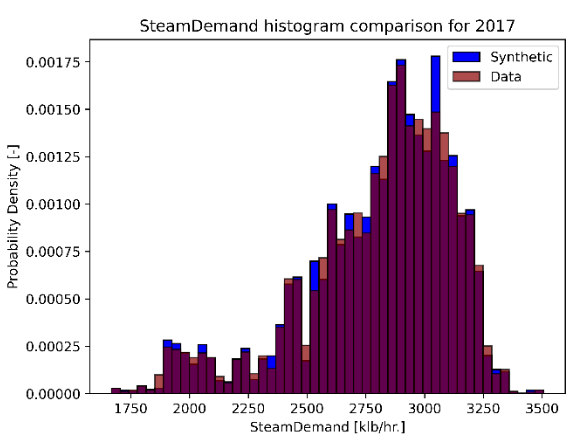
4. DEMAND FORECASTING

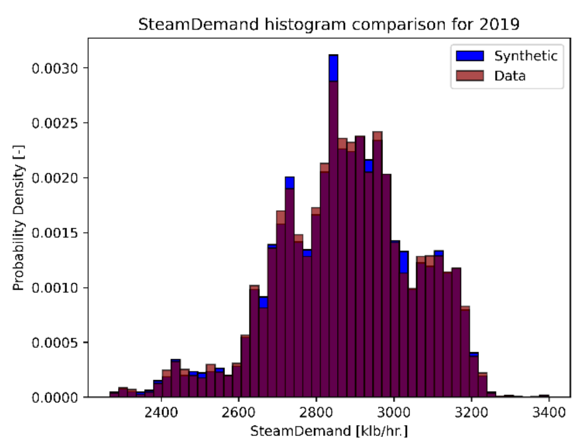
This study leverages the Holistic Energy Resource Optimization Network (HERON) [7] built upon the Risk Analysis Virtual Environment (RAVEN). RAVEN is an open-source software platform that facilitates and enhances a variety of model exploration, risk analyses, and design optimizations for nuclear reactors, energy grids, and other complex systems [8]. HERON provides a modular input deck structure which allows the user to design complex TEA of integrated energy systems including dynamic interaction of cashflows with fluctuating costs and supply/demand exchange of generated commodities (e.g. – steam, electricity, etc.).

In order to use HERON to study dispatch optimization, synthetic histories need to be generated for the time-dependent components in the model. Synthetic histories are nothing but stochastic time-dependent signals and were generated using RAVEN. The method of choice for synthetic history training is auto-regressive moving-average (ARMA). RAVEN extracts seasonality from the time signal using a Fourier detrending process and trains the ARMA model on the random component of the signal. It must be noted that only models trained using RAVEN are proper Synthetic History objects, which are used for the HERON analysis.

In the current study, ARMA models were generated for the following components: Eastman steam demand data, Eastman electricity demand data, price of electricity delivered to an industrial consumer, and NG price. For the Eastman plant, hourly-averaged time series data were provided for the years 2014–2019 for steam and electricity demands, as described in [3]. Since this study focuses on forecasting from 2025 through 2085, it was assumed that demand from 2014–2019 would be repeated for 2025–2030. For the remaining years, demand was projected by repeating five-year blocks based on the 2015–2019 data. In the absence of how the projected demand would change in the plant, this was taken to be a reasonable assumption. The ARMA model statistics for the years 2014 to 2019 are shown in Figure 8. The steam demand stays relatively constant for 2014–2019, as seen from the mean and median data (raw) values with a ~10% standard deviation (std) for every year. The higher order statistics are only noteworthy for the year 2014 where a maintenance event led to a brief plant shutdown. In general, the ARMA model fits the data well for the Eastman steam demand. The model's performance could be improved by increasing the number of clusters, which was fixed at 20 for the ARMAs generated in this study. It must be noted that the electricity demand was trained together with the steam demand given the high degree of correlation between the two quantities.

Year	rmse	mean_raw	mean_syn	median_raw	median_syn	std_raw	std_syn	kurtosis_raw	kurtosis_syn	skewness_raw	skewness_syn	sum
2014	141.02	2869.83	2869.38	2895.60	2895.03	240.11	240.46	29.83	29.60	-3.88	-3.86	2.51e+07
2015	87.95	2852.55	2852.74	2856.31	2856.91	224.95	224.62	-0.41	-0.42	-0.17	-0.17	2.50e+07
2016	108.80	2793.42	2793.58	2794.00	2793.84	222.85	222.64	0.50	0.50	-0.56	-0.56	2.45e+07
2017	106.38	2804.72	2804.35	2871.82	2873.69	318.84	318.65	0.79	0.80	-1.01	-1.02	2.46e+07
2018	88.35	2900.77	2900.68	2894.23	2894.94	224.40	224.39	-0.20	-0.20	0.07	0.07	2.54e+07
2019	108.42	2877.01	2876.91	2880.35	2880.30	177.14	177.05	0.11	0.11	-0.36	-0.36	2.52e+07





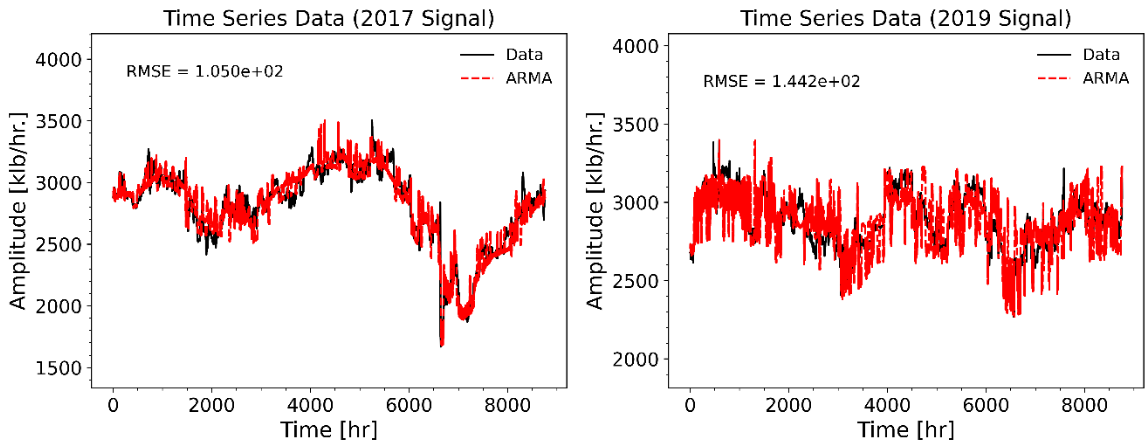


Figure 8. Statistics comparing the Eastman steam demand ARMA in klb/hr. with hourly averaged data from the Eastman plant for years 2014-2019 [3]. Also shown are steam demand histogram and time series comparisons with data for years 2017 & 2019.

For the natural gas price ARMA, the annual (reference) price forecast of natural gas (2024 prices) for the East-South-Central region, was used for the years 2025–2050. This dataset is from the U.S. Energy Information Administration (US EIA) Annual Energy Outlook 2025 [9]. A key assumption here is that the industrial price forecast for the East-South-Central region would cover an industrial consumer in Kingsport, TN, where the Eastman plant is located. The price forecast is shown in Figure 9(a). Also shown in the same figure is an upper bound in the annual price forecast for low oil and gas supply. This is factored into the sensitivity analysis in HERON and the ARMA is generated using the reference case. Due to a lack of availability of price forecast beyond 2050, the price forecast for 2046–2050 is repeated in chunks of 5 years through 2085. This assumption is reasonable given that the reference case forecast shows minimal year-on-year variation during that time period. All data were interpolated to hourly intervals and converted from $/Mcf of natural gas cost to equivalent steam production cost in $/klb using the Eastman steam demand data, in addition to the steam pressure, steam temperature, and feed water temperature, obtained from the Eastman plant data. The results of the ARMA model for the natural gas price is shown in Figure 10. Using higher-resolution natural gas price data would significantly improve the modeling of the ARMA.

The third and final ARMA model was generated for the electricity price data in $/MWh using the projected (annual) electricity prices (2024 prices) for the years 2025-2050 [9]. Similar to the natural gas prices, the price forecast for 2050 through 2085 is repeated in chunks of 5 years from 2046-2050 as the year-on-year price fluctuation is minimal for that time period, as shown in Figure 9(b). The results of the ARMA model for the electricity price are shown in Figure 11. Similar to the natural gas price data, higher-resolution electricity data would significantly improve the modeling of the ARMA.

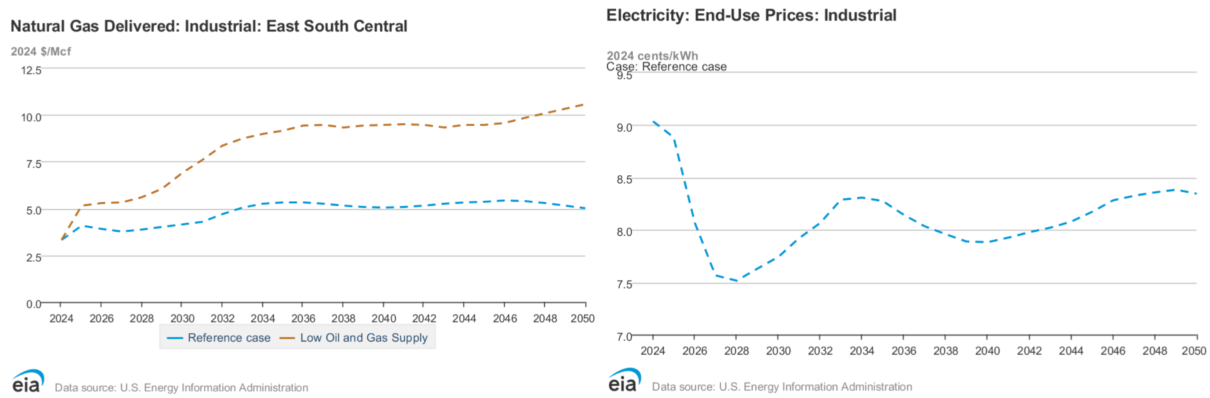


Figure 9. Annual price forecast for 2024-2050 from the Annual Energy Outlook 2025 [9] for an industrial consumer for (a) natural gas price in the East-South-Central region and (b) average retail price of electricity.

Year	rmse	mean_raw	mean_syn	median_raw	median_syn	std_raw	std_syn	kurtosis_raw	kurtosis_syn	skewness_raw	skewness_syn
2025	1.55e-02	5.76	5.76	5.76	5.77	6.33e-02	6.27e-02	-1.2	-1.19	2.55e-15	6.33e-03
2026	1.34e-02	5.56	5.56	5.56	5.56	5.49e-02	5.47e-02	-1.2	-1.20	-2.88e-14	1.11e-02
2027	9.11e-03	5.52	5.52	5.52	5.52	3.36e-02	3.35e-02	-1.2	-1.21	-4.92e-14	-5.07e-03
2028	1.49e-02	5.68	5.68	5.68	5.68	5.79e-02	5.80e-02	-1.2	-1.22	-5.23e-03	-3.92e-03
2029	1.77e-02	5.90	5.89	5.90	5.89	6.55e-02	6.51e-02	-1.2	-1.20	1.08e-14	-6.39e-03
2030	1.47e-02	6.10	6.10	6.10	6.10	5.44e-02	5.43e-02	-1.2	-1.21	-3.85e-14	-8.25e-03
2031	4.65e-02	6.49	6.49	6.49	6.49	1.71e-01	1.71e-01	-1.2	-1.20	1.27e-14	-1.49e-02
2032	3.81e-02	7.05	7.05	7.05	7.05	1.48e-01	1.48e-01	-1.2	-1.22	-5.23e-03	-3.69e-03
2033	2.28e-02	7.45	7.45	7.45	7.45	8.46e-02	8.47e-02	-1.2	-1.21	-1.89e-14	-5.41e-03
2034	9.24e-03	7.66	7.66	7.66	7.66	3.42e-02	3.40e-02	-1.2	-1.21	4.23e-14	-8.37e-03
2035	9.05e-04	7.71	7.71	7.71	7.71	3.69e-03	3.66e-03	-1.2	-1.20	4.40e-13	9.40e-03
2036	7.56e-03	7.65	7.65	7.65	7.65	2.99e-02	2.97e-02	-1.2	-1.19	5.23e-03	1.39e-02
2037	1.02e-02	7.53	7.53	7.53	7.53	4.18e-02	4.15e-02	-1.2	-1.20	-7.25e-14	9.03e-03
2038	9.47e-03	7.39	7.39	7.39	7.39	3.86e-02	3.82e-02	-1.2	-1.19	3.93e-14	4.84e-03
2039	1.73e-03	7.31	7.31	7.31	7.31	7.00e-03	6.94e-03	-1.2	-1.20	1.72e-14	-1.28e-03
2040	5.13e-03	7.33	7.33	7.33	7.33	1.99e-02	2.00e-02	-1.2	-1.22	-5.23e-03	-6.16e-03
2041	5.80e-03	7.40	7.40	7.40	7.40	2.14e-02	2.14e-02	-1.2	-1.21	4.96e-14	-6.92e-03
2042	1.20e-02	7.52	7.51	7.52	7.51	4.40e-02	4.38e-02	-1.2	-1.20	-7.80e-14	-1.43e-02
2043	6.69e-03	7.63	7.63	7.63	7.63	2.47e-02	2.46e-02	-1.2	-1.21	6.25e-14	-6.51e-03
2044	4.87e-03	7.71	7.71	7.71	7.71	1.90e-02	1.89e-02	-1.2	-1.21	-5.23e-03	-8.52e-03
2045	7.55e-03	7.79	7.79	7.79	7.79	2.78e-02	2.77e-02	-1.2	-1.20	9.13e-14	-1.42e-02
2046	2.56e-03	7.82	7.82	7.82	7.82	1.04e-02	1.03e-02	-1.2	-1.19	-1.19e-13	4.35e-03
2047	1.01e-02	7.73	7.73	7.73	7.73	4.14e-02	4.10e-02	-1.2	-1.20	-8.37e-14	1.22e-02
2048	1.59e-02	7.55	7.55	7.55	7.55	6.28e-02	6.26e-02	-1.2	-1.20	5.23e-03	1.46e-02
2049	1.42e-02	7.34	7.34	7.34	7.34	5.80e-02	5.78e-02	-1.2	-1.20	-2.22e-14	9.20e-03
2050	4.68e-02	7.54	7.54	7.54	7.54	1.73e-01	1.71e-01	-1.2	-1.20	5.00e-15	1.11e-02

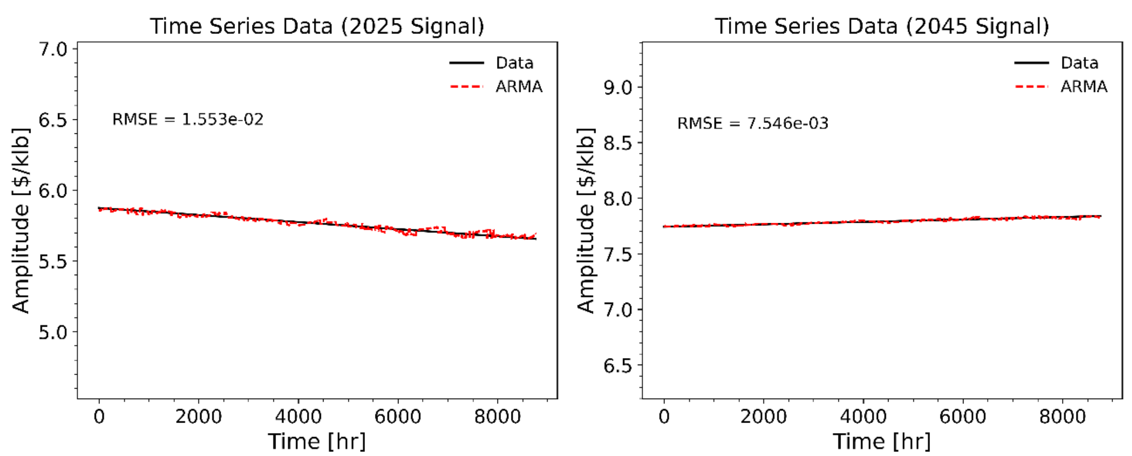


Figure 10. Statistics comparing the natural gas price ARMA in $/klb of eq. steam with monthly natural gas price data generated using the projected (annual) industrial natural gas price for the East-South-Central region for years 2025–2050 [9]. Also shown are price time series comparisons with data for years 2025 & 2045.

Year	rmse	mean_raw	mean_syn	median_raw	median_syn	std_raw	std_syn	kurtosis_raw	kurtosis_syn	skewness_raw	skewness_syn
2025	5.79e-01	84.73	84.74	84.73	84.78	2.36	2.34	-1.2	-1.20	-1.29e-14	4.97e-03
2026	3.53e-01	78.16	78.17	78.16	78.19	1.43	1.42	-1.2	-1.19	-8.71e-15	1.01e-02
2027	3.92e-02	75.41	75.41	75.41	75.41	0.16	0.16	-1.2	-1.19	1.44e-14	8.78e-03
2028	8.60e-02	75.71	75.71	75.71	75.71	0.33	0.33	-1.2	-1.22	-5.23e-03	-3.89e-03
2029	8.85e-02	76.85	76.85	76.85	76.85	0.33	0.33	-1.2	-1.21	2.89e-14	-4.53e-03
2030	1.41e-01	78.32	78.31	78.32	78.32	0.52	0.52	-1.2	-1.21	7.55e-14	-6.54e-03
2031	1.12e-01	79.93	79.93	79.93	79.93	0.41	0.41	-1.2	-1.21	1.58e-14	-1.05e-02
2032	1.64e-01	81.77	81.77	81.77	81.77	0.64	0.64	-1.2	-1.21	-5.23e-03	-1.69e-02
2033	1.57e-02	82.98	82.98	82.98	82.98	0.06	0.06	-1.2	-1.20	7.29e-13	-8.66e-03
2034	2.43e-02	82.91	82.91	82.91	82.91	0.10	0.10	-1.2	-1.20	-2.24e-13	8.24e-03
2035	9.09e-02	82.09	82.09	82.09	82.09	0.37	0.37	-1.2	-1.20	6.95e-14	1.22e-02
2036	8.25e-02	80.88	80.88	80.88	80.88	0.33	0.32	-1.2	-1.19	5.23e-03	1.88e-02
2037	4.99e-02	79.97	79.97	79.97	79.97	0.20	0.20	-1.2	-1.20	-7.67e-14	4.48e-03
2038	5.07e-02	79.25	79.25	79.25	79.26	0.21	0.20	-1.2	-1.19	-4.31e-15	7.59e-03
2039	4.67e-03	78.86	78.86	78.86	78.86	0.02	0.02	-1.2	-1.19	-3.37e-13	9.57e-03
2040	3.03e-02	79.03	79.03	79.03	79.03	0.12	0.12	-1.2	-1.22	-5.23e-03	-9.83e-03
2041	4.27e-02	79.51	79.51	79.51	79.51	0.16	0.16	-1.2	-1.21	-1.25e-13	-8.37e-03
2042	3.66e-02	80.02	80.02	80.02	80.02	0.13	0.13	-1.2	-1.21	-1.66e-13	-1.59e-03
2043	4.05e-02	80.51	80.51	80.51	80.51	0.15	0.15	-1.2	-1.21	2.26e-13	-1.96e-02
2044	7.31e-02	81.26	81.26	81.26	81.26	0.28	0.29	-1.2	-1.21	-5.23e-03	1.69e-03
2045	8.49e-02	82.30	82.30	82.30	82.29	0.31	0.31	-1.2	-1.21	4.93e-14	1.82e-03
2046	3.50e-02	83.06	83.06	83.06	83.06	0.13	0.13	-1.2	-1.20	1.20e-13	-1.30e-02
2047	2.30e-02	83.43	83.43	83.43	83.43	0.08	0.08	-1.2	-1.21	-4.82e-13	-4.82e-03
2048	1.69e-02	83.69	83.69	83.69	83.69	0.07	0.07	-1.2	-1.22	-5.23e-03	-3.10e-03
2049	2.67e-02	83.62	83.62	83.62	83.62	0.11	0.11	-1.2	-1.20	-3.17e-14	8.09e-03
2050	4.17e-02	83.14	83.14	83.14	83.14	0.17	0.17	-1.2	-1.20	2.10e-13	8.77e-03

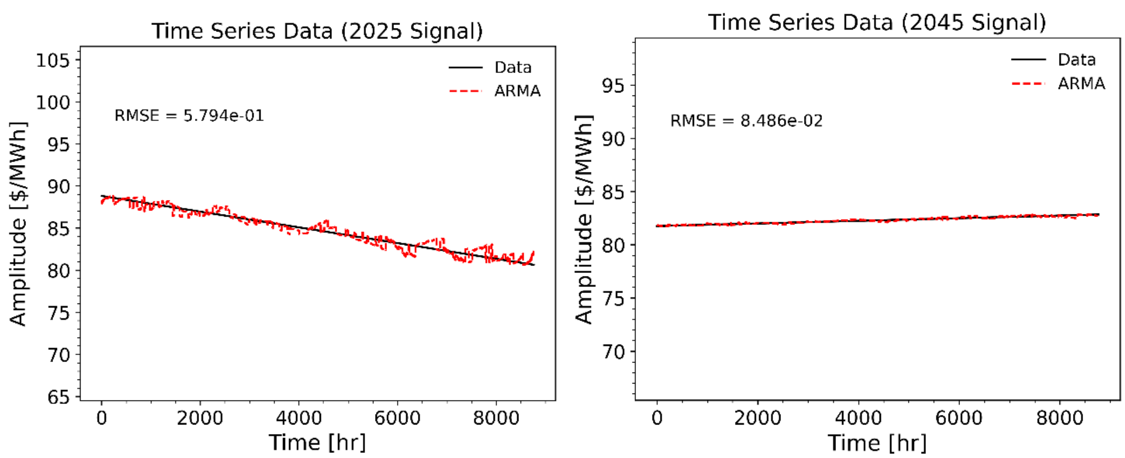


Figure 11. Statistics comparing the electricity price ARMA in $/MWh with electricity data generated using the projected (annual) electricity prices for years 2025–2050 [9]. Also shown are time series comparisons with data for years 2025 & 2045.

4.1 REGULATED ELECTRICITY MARKET

The U.S. electricity market is split into regulated and de-regulated electricity markets, with the whole of the Southeast served by regulated market entities. In regulated markets, the entities are vertically integrated, handling energy generation, transmission and distribution. In the 1990s, some states deregulated electricity systems to create competition and lower costs with independent power producers bidding into the hourly day-ahead market which are operated by ISOs/RTOs (Independent System Operator/Regional Transmission Organization). Furthermore, markets for ancillary services and capacity provide additional revenue generation avenues for utilities. A full discussion on deregulated market analysis, with a focus on the pertinent HERON analysis, can be found in [10]. The current techno-economic analysis is restricted to a regulated electricity market as the Eastman plant in Tennessee is supplied with electricity by Appalachian Power Company (ApCo), a regulated utility subsidiary of American Electric Power (AEP)

AEP is an investor-owned utility. Its Appalachian Power Company subsidiary serves parts of Virginia, West Virginia and a small footprint in Tennessee (including areas in Kingsport). Wholesale electricity rates are overseen by the Federal Energy Regulatory Commission (FERC) for transactions between utilities, while retail rates for end consumers are set or approved by the Tennessee Public Utility Commission (TPUC) for local utilities, for an independent power producer (IPP) to sell electricity to AEP or its local utility, power purchase agreements (PPAs) are typically required.

In the current analysis, it is assumed that any excess electricity generated by the nuclear power plant will be sold to AEP under a PPA. Because this analysis is restricted to a regulated market, it is assumed that price forecasts, for example reflecting increased electricity demand, are incorporated in the PPA terms. This is accounted for in the current analysis by applying a multiplier to the ARMA price in the HERON analysis. The intent is to explore scenarios where selling electricity to the grid is profitable for an NPP that produces both process heat and electricity.

5. TECHNO-ECONOMIC ANALYSIS

5.1 ECONOMIC OPTIMIZATION

The range of possible configurations is explored with HERON, a technoeconomic analysis tool which builds off the RAVEN optimization environment to allow for modular construction of IES configurations. This tool leverages the ARMA models described in Section 4 to compare the optimal balances of differing IES configurations in the presence of varying costs and demands for commodity flow like steam and electricity production and consumption.

The Eastman system is simplified to be represented by a collection of five medium-sized NG boilers (480 klb/hr steam production capacity), two larger coal boilers (600 klb/hr steam production capacity), and three smaller topper boilers (115 klb/hr steam production capacity from NG). The medium-sized NG and large coal boilers represent a subset of Eastman's current fleet of boilers which show the highest likelihood for replacement. It is assumed that forecasted emission requirements will drive the need to replace these coal boilers. Therefore, even without the presence of nuclear steam and electricity production, these coal boilers are assumed to be replaced by NG boilers of equivalent capacity. The topper boilers are included in the analysis to provide peaking capacity for steam production.

NuScale's modular design provides discrete capacity steps in the form of NPMs. The largest configuration allows for 12 NPMs at maximum capacity; however, two smaller housing configurations are available with a maximum capacity of 4 and 6 NPMs. Initial thermodynamic analysis has shown that 8 NPMs (housed in the largest plant configuration) would be sufficient to provide all necessary steam electricity demands for Eastman independently with proper redundancy. With this in consideration, these four plant configurations (i.e., 4, 6, 8, and 12 NPMs) are considered for this analysis with the addition of the null case where no NPMs are present. The range of considered configurations are listed in Table 9.

Table 9. A list of onsite power sources considered for generation of steam and electricity. Units with no cost listed are considered to be already present at the Eastman plant site and thus would only require the cost of fuel and operation and maintenance.

Energy Source	Technology	Configurations	Produces	Capacity per Unit	Overnight Cost per Unit	Reference
Nuclear						
	NPM	0, 4, 6, 8, 12	Steam or Electricity	478.5 klb/hr or 77 MWe*	$423,000,000 + PSCC	Abou-Jaoude '24 [11]
Natural Gas						
	Topper	3	Steam	115 klb/hr	-	
	Medium	0, 1, 2, 3, 4, 5	Steam and Electricity	480 klb/hr and 10.7 MWe	-	
	Large	0, 1, 2	Steam and Electricity	600 klb/hr and 13.4 MWe	$43,300,000	
***Steam and Electricity capacity are considered to exchange linearly for NPMs in hybrid production**						

The overnight cost of an NPM is assumed to be $423,000,000 by considering a 77 MWe capacity and an estimated $5,500/kWe for advanced nuclear technology deployment [11]. An economy of scale price adjustment is considered through the inclusion of the PSCC which scales to include the need for discrete changes in size and quantity of the compressor, heater, and heat exchanger components. The assumed scaling is shown in Table 10.

Table 10. Economy of scale applied through addition of PSCC cost

Number of NPMs	PSCC per NPM	Total Overnight Cost per NPM
4	$22,250,000.00	$ 445,750,000.00
6	$21,083,333.33	$ 444,583,333.33
8	$17,625,000.00	$ 441,125,000.00
12	$11,750,000.00	$ 435,250,000.00

Multiple assumptions are applied to create a conservative estimate of the performance of the nuclear technology in comparison to the NG component options. It is assumed that topper NG boilers and medium-sized NG boilers are available, and thus, do not need to be purchased. It is assumed that large NG boilers can be purchased to exactly replace the capacity of current coal boilers. The cost of large NG boilers was estimated considering that fuel cost represents ~96% of life-cycle costs for NG boilers. From this, a 40-year life and conservative fuel cost of ~$6.50 per lb of steam generated was utilized to approximate the initial overnight cost for large NG boilers. Furthermore, current industry available capacities for NG boilers suggest that 3 smaller NG boilers may be needed to replace the 2 coal boilers, losing some efficiency in terms of economy of scale. Finally, it is assumed for this study that all technology will last for the full 60-year lifetime of the nuclear power plant. Given the large dominance of fuel cost in NG cost, this is a small change, but it further emphasizes the conservative parameters of the study. Given these assumptions, it is expected that NG-focused IES configurations will perform worse than suggested by the results of this study, suggesting better performance by nuclear options by comparison.

Additional assumptions of this analysis are enumerated below:

1. A discount rate of 0.08 is taken to represent industrial technology.
2. Electricity from NPMs costs $12.20 per MWh generated.
   a. This is estimated from advanced nuclear technology deployment values expressed in [11].
3. Steam from NPMs costs $1,964 per Mlb generated.
   a. This includes operation and maintenance (O&M) as well as power generated to run PSCC components.
   b. A proportional conversion is made from NPM electricity generation cost to steam generation cost considering full capacity usage.
4. O&M cost for NG boilers is assumed to be $400 per Mlb generated.
5. Grid electricity import is capped at 35 MWe to mimic realistic demand magnitude from Eastman.
6. Selling electricity to the grid is considered in two scenarios (explored separately).
   a. Unlimited
   b. 100 MWe
      i. This represents a case of regional limitation and regulation on electricity sale.
7. A 5% loss is assumed between import and export of electricity to the grid.
   a. This adds realism and penalizes the grid selling to itself.
8. The plant is assumed to earn $10,000 per Mlb of steam consumed.
   a. This benchmark value was selected to provide positive profits for all steam production technologies in nominal economic conditions.
   b. A profitable plant is assumed to focus on competition between technologies.
9. The plant is assumed to earn $100 per MWh of electricity consumed.
   a. This benchmark value was selected to provide positive profits for all steam production technologies in nominal economic conditions.
   b. A profitable plant is assumed to focus on competition between technologies.
   c. The value selected provides a similar magnitude of profit to that of steam production to emphasize the internal changes in production cost rather than end profits.
10. Overflow steam and electricity components are present to penalize over production.
    a. These are included to help drive the optimizer to solution.
11. Fictitious steam import and additional electricity import components are included.
    a. These penalize IES configurations which cannot meet peak demands, prioritizing that the plant steam and electricity requirements are always met.

The RAVEN optimizer works to maximize NPV. No information was provided regarding the profits of the Eastman plant, so a high profit scenario was considered herein to focus analysis on the comparative competitiveness of the different IES configurations. The lack of real profit data reduces the direct meaning of the NPV for each simulated case in isolation. Instead, it is necessary to consider a comparison of the NPVs of each scenario to a base case. For this analysis, the base case of interest is the configuration that maximizes natural gas capacity and minimizes nuclear capacity (5 medium and 2 large natural gas boilers with 0 NPMs). A Normalized Fitness (NF) is produced through the normalization process described in the equation below.

$$NF = 1 + \frac{NPV_i - NPV_{NG,Full}}{NPV_{NG,Full}}$$

Where NPV_i is the maximum NPV of a specific IES configuration in a given economic condition, and $NPV_{NG,Full}$ is the maximum NPV of the fully populated natural gas configuration in nominal economic conditions. With this normalization, an NF smaller than 1 implies a less financially competitive configuration than the full natural gas configuration in nominal economic conditions.

Figure 12. NF of all IES configurations for nominal economic projections. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

displays the performance of all 75 considered IES configurations for current, nominal economic forecasting. This first analysis considers the case of unlimited grid electricity export capacity. IES configurations are represented in the manner that [4,5,2] would suggest that 4 NPMs, 5 medium-sized NG boilers, and 2 large NG boilers are present.

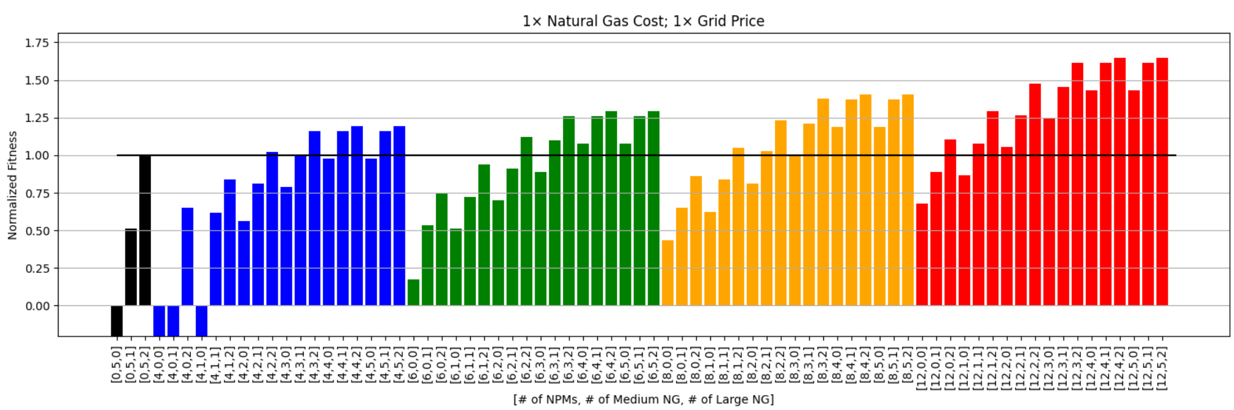


Figure 12. NF of all IES configurations for nominal economic projections. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

From these results shown in Figure 12, it is immediately apparent that hybrid NG/nuclear IES configurations are favored which provide excess capacity that can be employed to generate electricity for the grid. For this conservative estimate, the purely nuclear options are outperformed by the base case, however, there are many viable configurations, such as [12,1,2], which significantly reduce the carbon footprint of chemical plant while exhibiting a visible increase in life-time profitability of the entire IES. In this case, the maximum capacity options [*,5,2] approach the limit case of having a nuclear power plant essentially decoupled from the chemical plant and simply selling power to the grid. The same analysis is performed for the what-if scenarios of doubling grid electricity price, doubling natural gas fuel price, and doubling both simultaneous to explore the effects of supply/demand shifts or side effects of future legislation such as requiring carbon capture and sequestration. These results are provided in Figure 13,

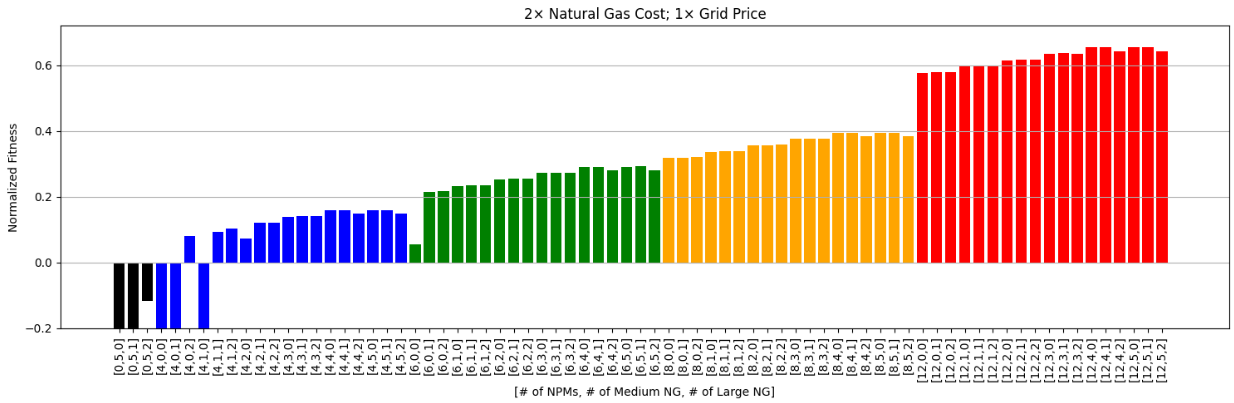


Figure 14. NF of all IES configurations for doubled natural gas fuel cost projections. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options., and Figure 15, respectively, and are normalized to the same base case NPV value as that used for Figure 12. A black horizontal line has been included at an NPV of 1.0 for better visualization of competitive options.

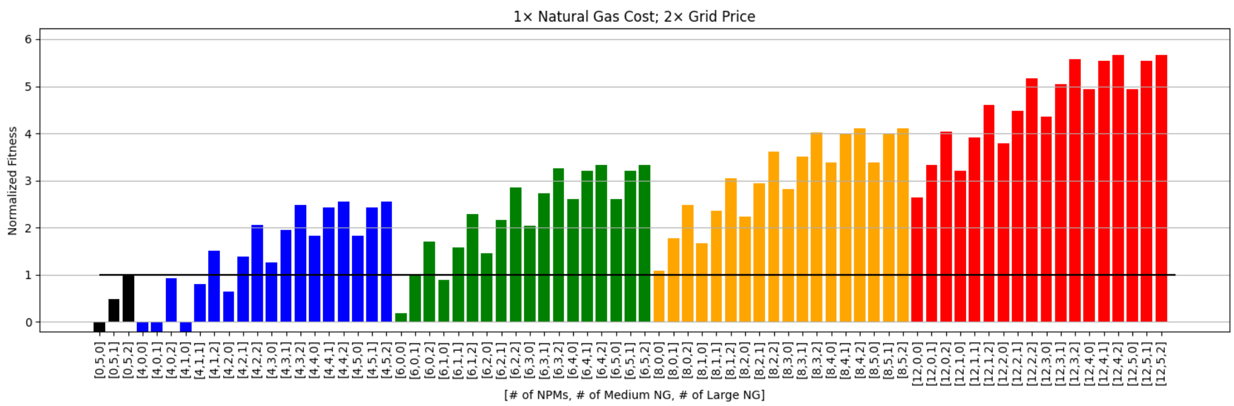


Figure 13. NF of all IES configurations for doubled electricity grid cost projections. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

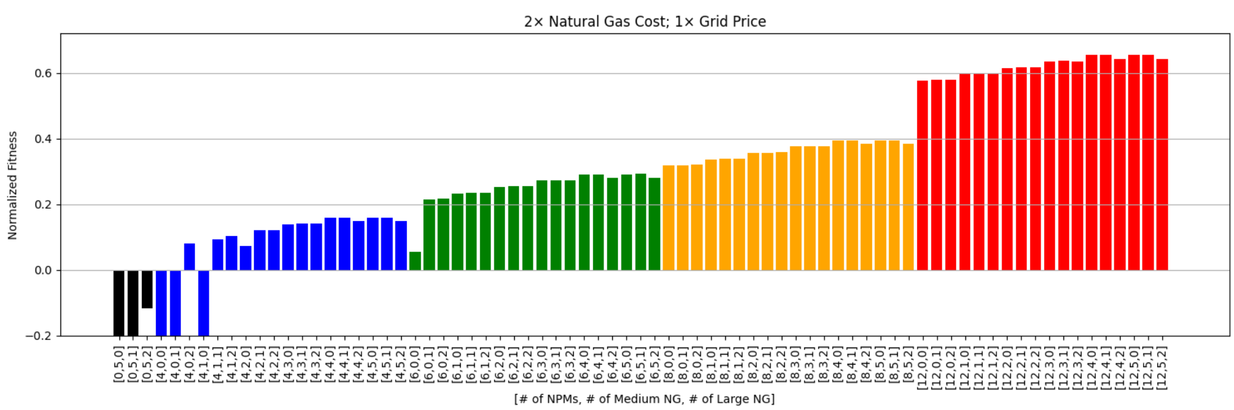


Figure 14. NF of all IES configurations for doubled natural gas fuel cost projections. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

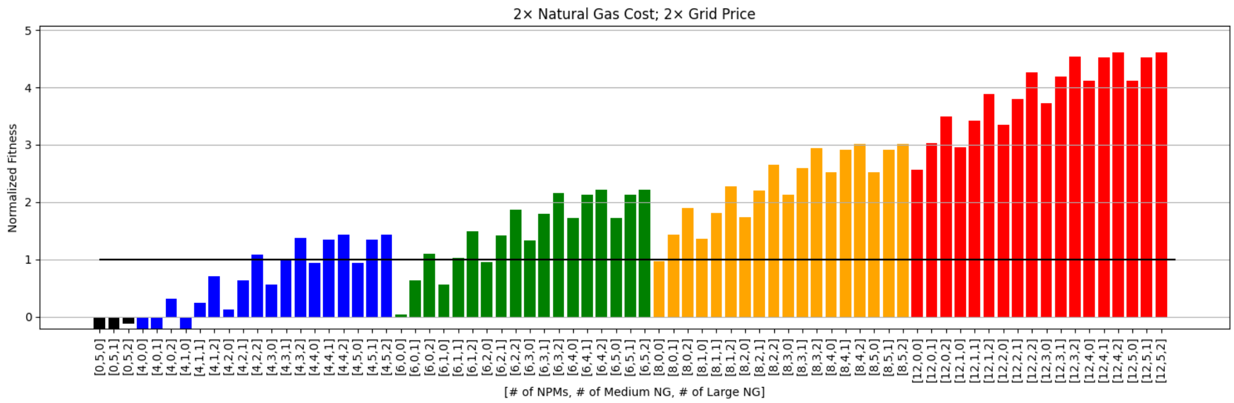


Figure 15. NF of all IES configurations doubled natural gas fuel cost and doubled electricity grid cost projections. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

The advantage of IES configurations with excess capacity is further emphasized in the conditions of increased grid electricity price. Additionally, the results shown in Figure 14 suggest that the inclusion of nuclear provides stabilization against rising natural gas prices, especially in larger nuclear configurations where plant steam and electricity demands can be completely provided by nuclear. To explore the performance of the NuScale plant options with more focus on chemical plant demand, a secondary analysis was performed with grid electricity export capacity limited to 100 MWe. These results are presented in Figure 16–Figure 19.

These results show that without excess grid sales, the 12 NPM cases are no longer able to maintain life-cycle profitability, as a significant portion of capacity is left unused. In nominal economic conditions, the base case of full NG capacity is the most economically competitive configuration; however, with a market shift to more lucrative electricity export sales, it is observed that the 4 NPM configurations with enough support from remaining NG boilers to meet plant demands becomes more competitive. These configurations, such as [4,3,0], would provide a more profitable IES with a significantly reduced carbon footprint.

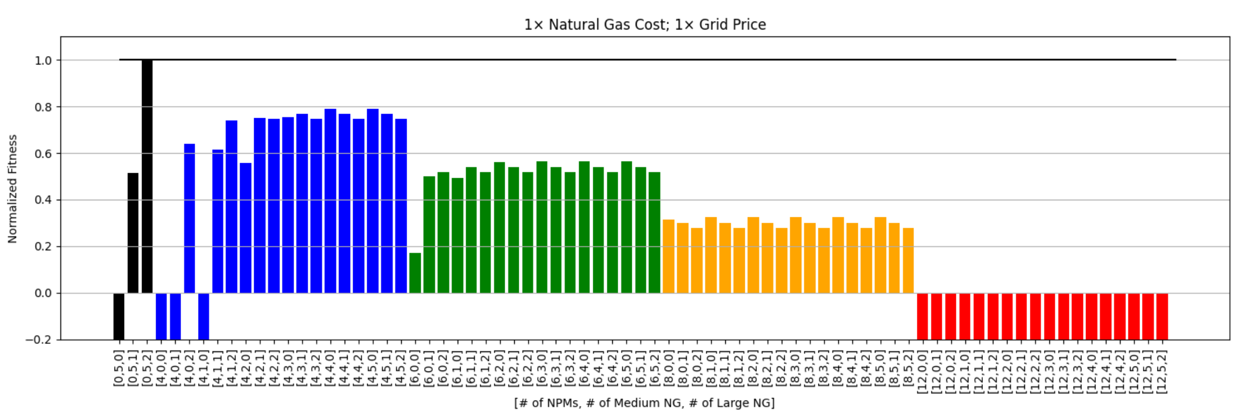


Figure 16. NF of all IES configurations for nominal economic projections and limited electricity export capacity. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

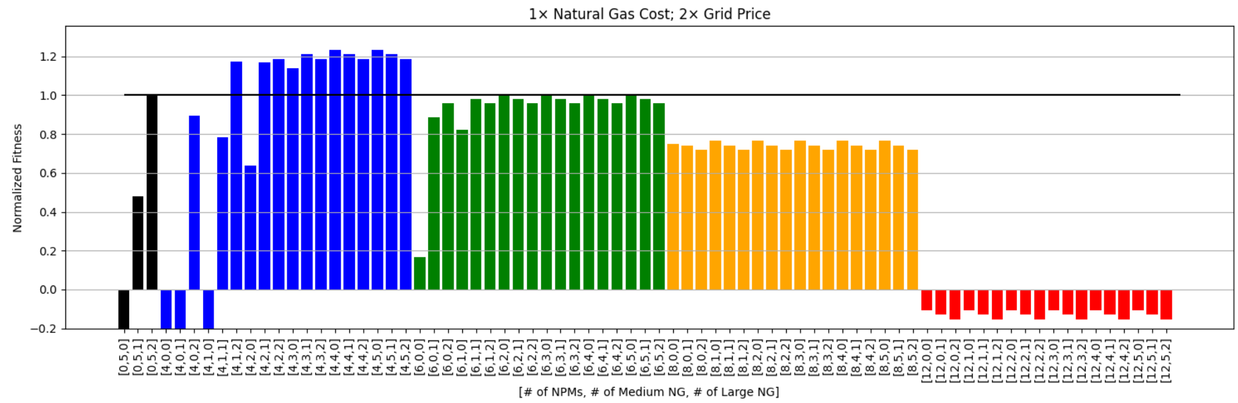


Figure 17. NF of all IES configurations for doubled electricity grid cost projections and limited electricity export capacity. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

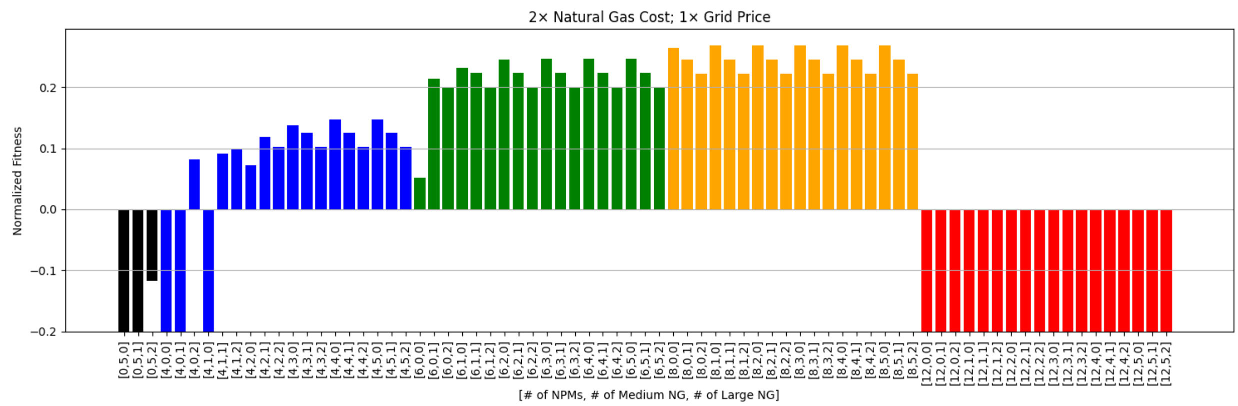


Figure 18. NF of all IES configurations for doubled natural gas fuel cost projections and limited electricity export capacity. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

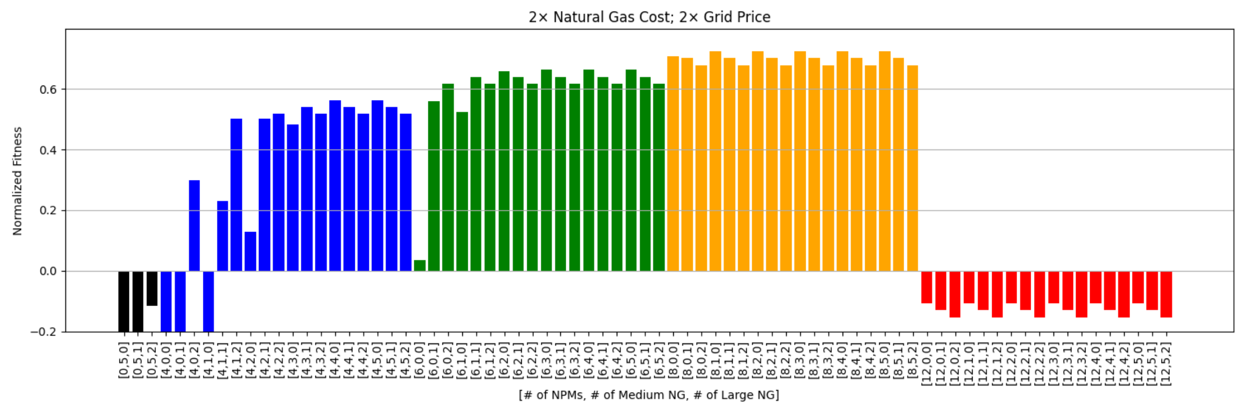


Figure 19. NF of all IES configurations doubled natural gas fuel cost and doubled electricity grid cost projections and limited electricity export capacity. Negative values are truncated at -0.2 to highlight more successful configurations; bars are colored to differentiate NPM configuration options.

The scenarios of doubled NG fuel cost shown in Figure 18 and Figure 19 display an inflection in favor of the larger nuclear options, excluding the 12 NPM case which still does not overcome its substantial initial investment without the ability to sell more excess electricity to the grid. In this case, even the full replacement of NG components with an 8 NPM configuration (see [8,0,0]) demonstrates strong competitiveness. A doubling of natural gas price is representative of the additional cost needed for carbon capture and sequestration on NG boilers suggesting that, in the wake of future legislation restricting carbon emissions, the inclusion of an 8 NPM NuScale plant would be the most competitive option [12]. It should be noted that with an increase in the cost of NG, one would expect a positively correlated change to occur in the price of electricity, given the significant dependence on NG in most current markets. This expectation suggests that the economic conditions depicted in Figure 19 are more representative of the behavioral response of a price increase in NG than that of Figure 18.

5.1.1 Technoeconomic Assessment – Observations and Conclusions

Certain observations and conclusions can be derived from the results of the TEA.
For the unlimited electricity export cases:

- [1xNG,1xElec.]
    - There are scenarios involving any size nuclear facility (4, 6, 8, or 12 NPMs) that are more profitable than the reference case [0,5,2] that will also reduce number of fossil-fueled boilers needed.
        - For 4 NPMs [4,4,1] and [4,3,2] both have NF values of 1.16 and both reduce the need of 2 boilers. 1 Medium and 1 Large in the [4,4,1] case and 2 Medium in the [4,3,2] case.
        - For 6 NPMs [6,3,1] and [6,2,2] both have NF values of ~1.11 and both reduce the need of 3 boilers. 2 Medium and 1 Large in the [6,3,1] case and 3 Medium in the [6,2,2] case.
        - For 8 NPMs [8,2,1] and [8,1,2] and [8,3,0] all have NF values of ~1.03 and all reduce the need of 4 boilers. 3 Medium and 1 Large in the [8,2,1] case and 4 Medium in the [8,1,2] case and 2 Medium and 2 Large in the [8,3,0] case.
        - For 12 NPMs [12,1,1] and [12,0,2] and [12,2,0] all have NF values of ~1.08 and all reduce the need of 5 boilers. 4 Medium and 1 Large in the [12,1,1] case and 5 Medium in the [12,0,2] case, and 3 Medium and 2 Large in the [12,2,0] case.
    - There is a scenario [12,3,2] that is near maximally profitable, 1.61 NF vs 1.65 NF, that reduces the number of required fossil fueled boilers by 2 but still achieves a 61% increase in profit.
- [1xNG, 2xElec.]
    - All nuclear scenarios benefit greatly since they are able to sell more to the grid. The more boilers available means that the more opportunities for the nuclear plant to sell electricity since the boilers will make up the steam demand
    - There are scenarios that are more profitable than the reference case that also significantly reduce the number of fossil fueled boilers needed:
        - For 4 NPMs [4,1,2] has a 1.50 NF while reducing 4 Medium Boilers
        - For 6 NPMs [6,0,1] has a 1.01 NF while reducing 6 Boilers total, 5 Medium and 1 Large.

        - For 8 NPMs [8,0,0] has a 1.08 NF while reducing all 7 boilers needed
        - For 12 NPMs [12,0,0] has a 2.63 NF while reducing all 7 boilers needed.
    - There is a scenario (i.e., [12,3,2]) that is near maximally profitable, 5.58 NF vs 5.66 NF, that reduces the number of required fossil fueled boilers by 2 but achieves a 558% increase in profit.
- [2xNG, 1xElec.]
    - All non-nuclear scenarios are reduced significantly since the cost of operating boilers increases directly due to NG price increases.
    - The reference case of zero NPMs [0,5,2] drops from 1.0 NF to -0.12 NF which implies that the chemical facility is losing money.
    - All nuclear scenarios that can meet the steam demand will be more profitable than the updated reference case.
    - The maximum profit is achieved by having 12 NPMs as more electricity can be sold to the grid.
- [2xNG, 2xElec.]
    - This scenario is deemed more in-line with realistic price behavior, since electricity prices and natural gas prices are linked because of a large percentage of electricity being produced through NG fired power plants.
    - Again, the reference case of zero NPMs [0,5,2] drops from 1.0 NF to -0.12 NF which implies that the chemical facility is losing money.
    - All nuclear scenarios that can meet the steam demand will be more profitable that the updated reference case.
    - The maximum profit is achieved by having 12 NPMs as more electricity can be sold to the grid.
    - The more boilers available translates to more profit since there are more ways to make steam and still sell excess electricity to the grid.

For the limited electricity export (100 MWe max) cases:

- [1xNG, 1xElec.]
    - If the ability to sell electricity to the grid is greatly limited, the profit potential of installing the nuclear facility is reduced and all nuclear facilities are less profitable than the reference case [0,5,2].
- [1xNG, 2xElec.]
    - All nuclear cases are more profitable than with nominal economic conditions, and specifically many 4 NPM cases can be more profitable than the reference case; however, the installation costs of more modules beyond four is not overcome due to the inability to sell more electricity.
- [2xNG, 1xElec.]
    - The reference case drops again to -0.12 NF, which makes all 4 NPM cases that can meet the steam demand as well as all 6 and 8 NPM cases more profitable. The 12 NPM case has too much over-capacity which cannot be utilized due to the limited grid export.
    - 8 NPM case achieves the highest NF since it is most appropriately sized to the needs of the Eastman facility without any excess capacity.
- [2xNG, 2xElec.]
    - Again, all nuclear cases that meet steam demand are more profitable than the reference case at -0.12 NF.

- The 12 NPM case is still the worst nuclear case; however, it has improved to being no worse than the reference case.
- 8 NPM case still achieves the highest NF.

The 8 scenarios are ranked based on the fitness values they provide, with rankings assigned as follows:

- Highest NF: 5
- Second Highest NF: 4
- Third Highest NF: 3
- Second Lowest NF: 2
- Lowest NF: 1

These rankings serve as the basis for developing Table 11.

Table 11. Ranking of IES configuration fitness (5 is best and 1 is worst)

		Number of NPMs				
	NG, Elec.	0	4	6	8	12
Unlimited Elec. Export	1x,1x	1	2	3	4	5
	1x,2x	1	2	3	4	5
	2x,1x	1	2	3	4	5
	2x,2x	1	2	3	4	5
Limited Elec. Export	1x,1x	5	4	3	2	1
	1x,2x	4	5	4	2	1
	2x,1x	2	3	4	5	1
	2x,2x	2	3	4	5	2
	Avg.	2.125	2.875	3.375	3.750	3.125

The table shows that the highest average ranked case is 8 NPMs as it is the most resilient configuration to price modulations and grid limitations.

5.1.2 Operational Reliability Assessment

Operational reliability represents the ability of the power system to balance supply and demand in real time by managing variability, ramping constraints, and flexible loads. This includes immediately following an "event" like a large power plant or transmission line failure. The overall operational reliability goal is that steam and electricity are always available to the plant since there are no scheduled outages at the Eastman Kingsport, TN site. For the remainder of the section, only the steam output will be presented; the methods can however simply be transferred to the electrical or the chemical output.

This section focuses on how larger steam generation rate per module of NPMs coupled with PSCC will affect steam reliability compared to previous study, fault tree models of the steam supply will be presented.

5.1.2.1 Steam Supply Reliability

The reliability assessment published in ORNL's 2020 study conducted by data provided by Eastman, unplanned outage data of operation-critical components (boilers and turbogenerators of the Eastman) during 10 years of operation between 2008 through September of 2018 [3]. In this assessment the CHP portfolio includes 8-NPMs for CHP with PSCC (see Section 3) coupled with 4 boilers since boilers 21-24 are burning waste and likelihood of their replacement with nuclear is low.

Steam Supply Reliability requirement defined in ORNL's 2020 study is N+1 steam generation capacity [3]. The CHP should be capable of meeting 120% of the 600-psig steam reserve. The 8 NPMs identified by TEA optimization will be assessed for its capability to meet the steam demand +20% additional capacity reliably.

The NuScale design has a benefit regarding steam output reliability. Modules are individually refueled once every 18 months. Staggered refueling ensures that only one module is offline for 10 days, while the remaining NPMs remain operational. Refueling operations are the only planned outages evaluated in this analysis.

The previous study indicated that most reliability-induced system outages were observed in the fall, between 2008 and September 2018. Without NPMs, steam supply is more vulnerable to seasonal failures because during warmer months, lower ambient temperatures reduce the demand for thermal steam while higher temperatures worsen the imbalance between thermal steam and electricity demand. However, coupling the 8 NPMs with the PSCC will minimize the dependency on ambient temperature.

Another seasonal dependency arises from the planned annual outages of coal-fired stoker boilers (Boiler 23 and Boiler 24). These outages are scheduled during the NO_x SIP Call (State Implementation Plan Call) period (May 1 through September 30), whereas the maintenance requirements for NPMs do not follow a seasonal pattern.

5.1.2.2 Probabilistic Risk Assessment of Steam Supply

The probabilistic risk assessment (PRA) fault trees were updated from the 2020 study [3] to systematically assess steam reliability from a combination of eight NPMs, boilers, and the PSCC system.

ORNL'S 2020 study evaluated 600 psig steam line supply failure using fault tree models, see Figure 20. The model captured Eastman's boilers maintenance frequencies and dependencies, steam requirement (N+1 steam generation capacity) and maintenance rules:

- Annual maintenance outages for boilers (including pulverized coal, natural gas-fired, and coal-fired stoker boilers) are conducted in compliance with Tennessee state boiler and vessel regulations. These regulations mandate that each boiler undergo inspection annually, resulting in a total of 17 scheduled outages.
- Routine maintenance is performed to minimize the downtime.
- For power system reliability, no more than one 1500 psig boiler is scheduled for an outage at any given time.

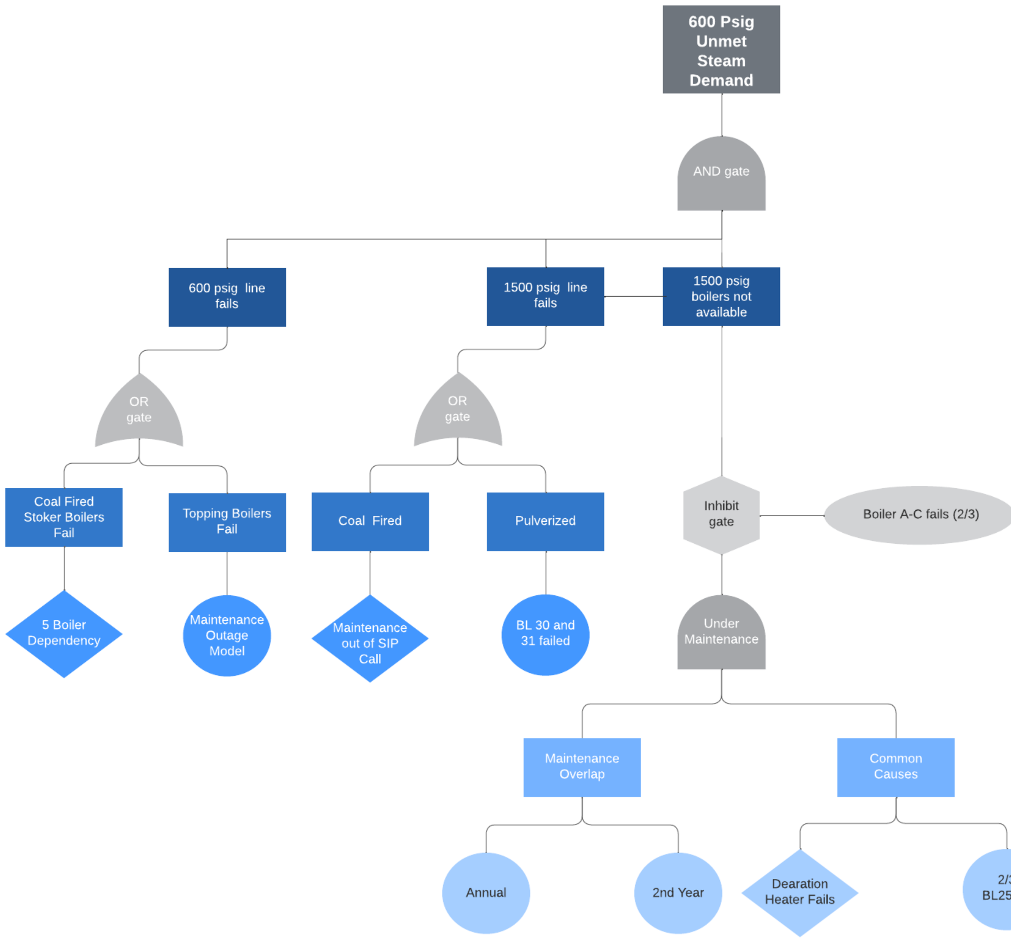


Figure 20. Fault tree model of the 600-psig steam supply [Error! Reference source not found.**].**

The fault tree model for the 600-psig steam supply failure (i.e., unmet steam demand) has been updated to include the 8-NPMs coupled with the PSCC system (see Figure 21). In this configuration, failures of the waste burner boilers (coal-fired stoker boilers) are further decomposed according to the redundancy requirement of the 1500 psig line and the maintenance requirements summarized in ORNL's 2020 study [3]. Notably, the annual maintenance for Boilers 21 and 22 should not overlap with the planned maintenance for Boiler 23 and Boiler 24 (topping boilers). In some instances, due to some repair projects on topping units such as replacing economizer or superheater tubes, the topping unit outage windows are sometimes extended for the replacement activities. This may cause Boiler 21and 22 to overlap with topping unit outages, and is assumed as a failure in the FT analyses.

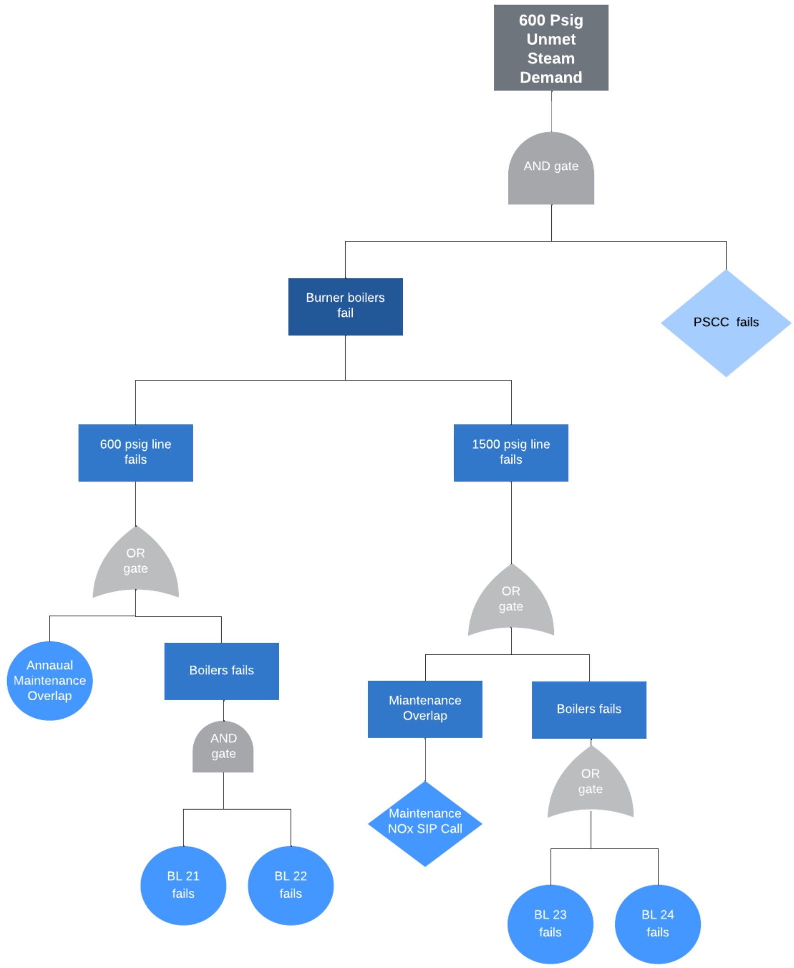


Figure 21. Fault tree model of the 600-psig steam supply for 8-NPMs, PSCC, with boilers configuration.

Figure 21 illustrates that, in the scenario where NPMs are coupled with boilers, steam supply reliability is determined by PSCC system failures, which are represented by a transfer gate. The PSCC system failure model is presented coupled with 8 NPMs in Figure 22.

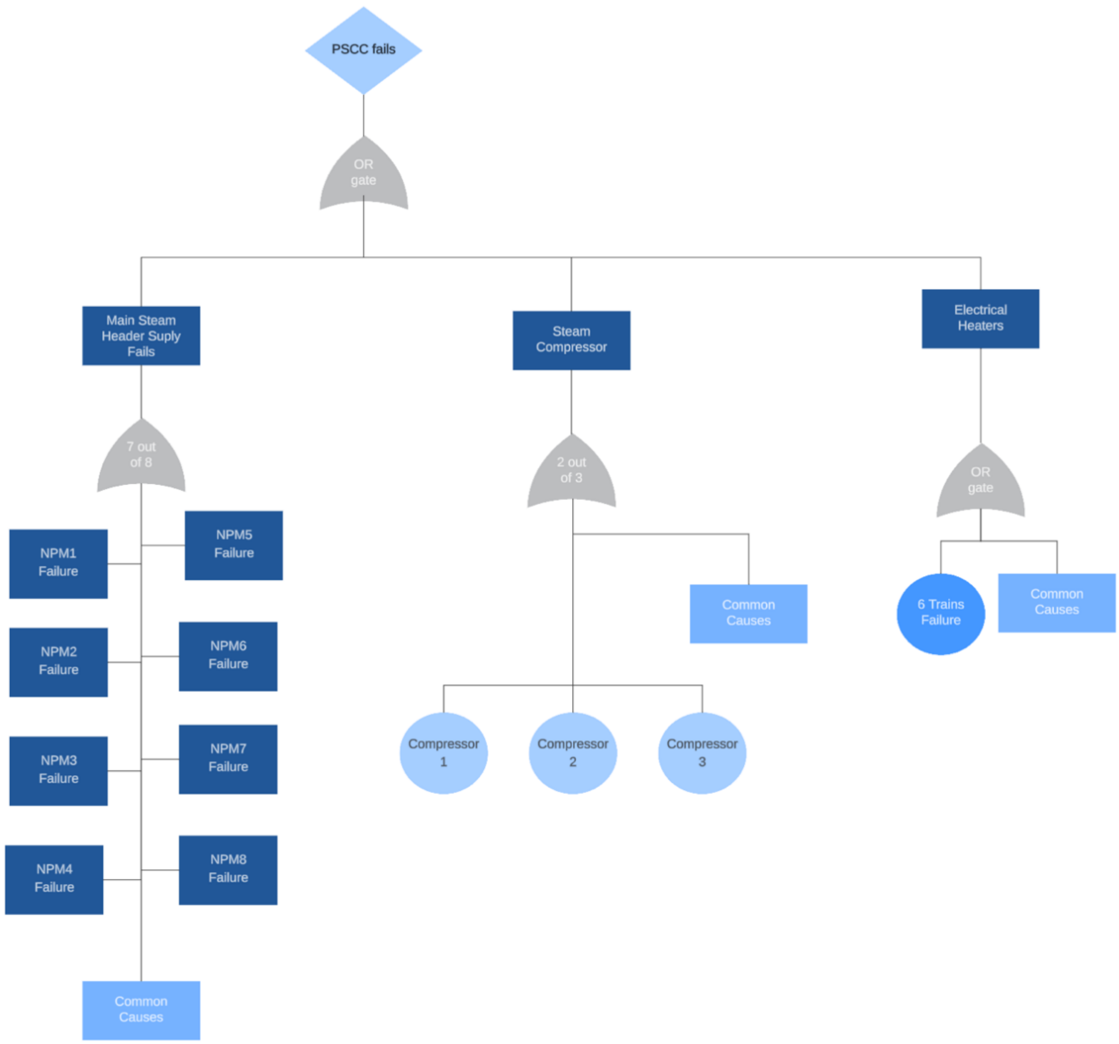


Figure 22. PSCC steam supply failure model.

The component failure data inputs for the PSCC steam supply failure model in Figure 22 are derived from industry-averaged reliability estimates. These estimates, sourced from the literature, pertain to the steam-driven turbine electric generator, intermediate heat exchanger, steam compressor, and steam electric heaters.

PRA model results indicated that 600 psig steam demand can be supplied with heating steam from 8 NPMs with 120% capacity. With one unit offline (7 out of 8 gate), the other units would provide 100% heating steam to the PSCC equipment, guaranteeing a reliable steam supply to a chemical plant.

5.1.3 Capacity Factor Comparison

In 2024, nuclear power achieved highest capacity factor of any other energy source; it produced reliable and secure power more than 92% [13], nearly twice as much as a coal (42.36%) or natural gas (59.9%) [14] plant that are used more flexibly to meet changing grid demands and almost 3 times more often than wind (34.3%) and solar (23.4%) plants.

Natural gas and coal capacity factors are generally lower due to routine maintenance and/or refueling at these facilities. Capacity factor measures a power plant's actual generation compared to the maximum amount it could generate in a given period without any interruption.

Seasonal failures have been observed in chemical plants. However, coupling the 8NPM with the PSCC minimizes the ambient temperature dependency. In contrast to coal-fired stoker boilers (Boilers 23 and 24), whose maintenance involves seasonal outages, specifically, annual planned outages that occur during the NO_x SIP Call period (May 1–September 30), NPM maintenance requirements are not season-dependent.

6. OTHER CONSIDERATIONS OF NUCLEAR ON COAL SITES

6.1.1 Staffing

Previous work in the 2020 ORNL report [3] showed an estimated staffing requirement for the NuScale based power plant. Subsequent work by NuScale on this has dramatically improved the staffing competitiveness, especially when compared to existing nuclear sites. Table 12 shows the NuScale estimated staffing requirements compared to existing nuclear power plants.

Table 12. Power Plant Staffing Requirements

Plant	Staff Per MW
12-NPM Plant	**0.29**
8-NPM Plant	**0.35**
Vogtle	0.38
Catawba	0.39
6-NPM Plant	**0.42**
Oconee	0.43
McGuire	0.45
Brunswick	0.45
North Anna	0.49
Hatch	0.52
Surry	0.56
Harris	0.79

6.1.2 Siting

In 2020 ORNL's review of the Eastman site was based on siting requirements for nuclear reactors [15]. This analysis concludes that, at this stage in the analysis, that the geography and demographics of Kingsport, TN and the site would support a nuclear plant coupled with the Eastman facility.

The Oak Ridge Siting Analysis for Power Generation Expansion (OR-SAGE) [16] restriction on siting due to population is no longer applicable to the NuScale design given NRC's approval of the NuScale Emergency Planning Zone (EPZ) sizing methodology. The EPZ methodology is only approved for the NuScale design and enables a site boundary EPZ. The chemical plant would not be burdened by an additional emergency planning requirement.

6.1.3 Hydrogen Production

The Eastman facility in Kingsport TN does contain some on-site hydrogen production, though for this study the particulars could not be ascertained. It is worth noting though that a single dedicated NPM coupled with a solid oxide electrolysis cell (SOEC) (i.e., providing both steam and electricity) could generate nearly 50 tons of hydrogen per day. This amount could be scaled up or down to meet the hydrogen demand at the site.

6.1.4 GHG targets

Carbon dioxide emissions from fossil fuel sources are well understood and many governmental organizations and private companies, including Eastman, have pledged to reduce them in the upcoming decades. Nuclear reactors generate zero CO_2 emissions from their operation. Replacing the fossil fuel boilers with steam and electricity from a nuclear plant would offer substantial CO_2 emissions reduction and help Eastman meet its environmental goals. This section evaluates the predicted reduction in CO_2 emissions for the Eastman facility in Kingsport, TN, if an 8-NPM plant were constructed and provided steam and electricity.

In the 8-NPM case previously evaluated, there was an excess of 63.7 MWe that was available during standard operation. This excess was largely because the four "low likelihood of replacement" boilers were assumed to operate at their nominal conditions; however, it is possible that they need not always operate at their nominal conditions. Indeed, the main reason for their designation as "low likelihood of replacement" is that they are involved in reducing chemical waste through consuming waste as fuel, and thus they play an important part of the normal operations of the chemical facility. However, not all of the fuel they consume is waste, but a mix of waste and coal. Unfortunately for this study the exact ratio of waste to coal for fuel could not be ascertained. Because some of the steam generated from these boilers is derived from coal, presumably that portion could be replaced by the excess energy of the nuclear plant resulting in those fossil fuel boilers reducing their energy usage and thereby further reducing the plant's CO_2 emissions.

Table 13 evaluates the reduction in CO_2 emissions that are possible by utilizing an 8-NPM power plant to supply steam and electricity. The results are also shown graphically in Figure 23. The current emissions for the Eastman plant are estimated based on the energy usage at the facility and the type of fuel used for the boilers. If the four “low likelihood for replacement” boilers are operated at their nominal steam production rates, then an 81% reduction in CO_2 emissions could be achieved.

In the reduced power case, the four boilers are operated at a reduced amount, i.e., nearly three-quarters reduced production from nominal, so reduced as to still require no grid derived electricity. In this case there is no excess electricity produced by the nuclear power plant since all the energy of the NPMs would be utilized by the Eastman Facility. This scenario results in an 93% reduction in CO_2 emissions.

Finally, if the remaining four boilers were shut off entirely, with the NPMs making up all the steam production, about 23 MWe would have to be purchased from the grid to balance the electricity requirements. In this scenario, the CO_2 emissions reduction reaches 95%. If an additional NPM were utilized (i.e., 9 NPMs total), then the total CO_2 emissions reduction in this scenario could reach potentially 100%. Because shutting off the four remaining boilers does not account for the final disposal of the chemical waste, this scenario is deemed less realistic.

Table 13. CO_2 emissions reduction by utilizing 8-NPM power plant and different boiler operating scenarios

Condition	NPM Generated Process Steam (lb/hr)	Boiler Steam (lb/hr)	Grid Electric. Purchase (MWe)	Steam Balance (lb/hr)	Electric. Balance (MWe)	CO_2 Emissions (kg/year)	CO_2 Emissions (Million Kg/Year)	CO_2 Emissions Reduction (%)
Eastman Currently	0	3,463,019	9.8	0	0	3.19E+09	3,185	0%
8-NPM with 4 Boilers Operating at Nominal	2,947,257	515,761	0.0	0	+63.7	6.17E+08	617	81%
8-NPM with 4 Boilers Operating Reduced	3,326,868	136,151	0.0	0	0.0	2.33E+08	233	93%
8-NPM with 4 Boilers shut off	3,463,019	0	22.9	0	0.0	1.64E+08	164	95%

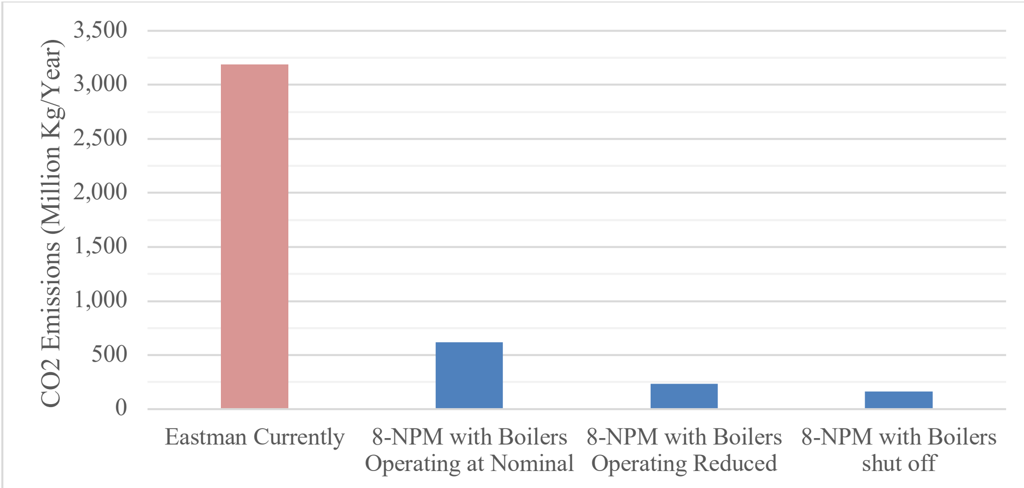


Figure 23. CO_2 Emissions reductions achievable with 8-NPM power plant.

The reduced production boilers scenario appears the most probable; therefore, a full description of its calculation is presented in Table 14.

Table 14. Eastman Chemical Plant CO2 emissions reduction using 8-NPM power plant and reduced power fossil fuel boilers.

			Coal Boilers	Natural Gas Boilers	Electricity (SRTV Grid)	Total
Conversion Factors		CO2 Emissions (KgCO2 / MWh)	326.9	180.8	406.3	-
Eastman Currently		Energy Usage (MW)	668	780	9.8	1457.8
Eastman Currently		CO2 Emissions (kg CO2/ yr)	1.91E+09	1.24E+09	3.48E+07	3.19E+09
Eastman with 8-NPM Power Plant. Reduced Operating Flow Boilers	Standard Operation (N-0)	Energy Usage (MW)	56.3	0	0	56.3
		Time at (N-0) condition (hrs/year)	7486	0	0	
		CO2 Emissions (kg CO2/ yr)	1.38E+08	0	0	1.38E+08
	Refueling (N-1)	Energy Usage (MW)	213.4	0	10.3	223.7
		Time at (N-1) condition (hrs/year)	1280	0	1280	
		CO2 Emissions (kg CO2/ yr)	8.93E+07	0	5.36E+06	9.47E+07
	Total	Total CO2 Emissions (kgCO2/yr)	2.27E+08	0	5.36E+06	2.33E+08
		CO2 Emissions Reduction (%)	-	-	-	**93%**

Notes:
Conversion factors are derived from:
2024 CO2 Emissions data https://www.epa.gov/egrid/summary-data
2023 Grid CO2 Emissions data: https://www.epa.gov/egrid/summary-data
SRTV: SERC Tennessee Valley / Eastern Power Grid
SERC: Southeastern Electric Reliability Corporation

6.1.5 Powering Data Center Scenarios

In the US around 47 GW of incremental capacity is needed to serve data center-driven load growth through 2030 [17]. Nuclear power is an attractive solution for data centers as it provides reliable baseload power with the highest nominal capacity factor of any other energy source, as mentioned in Section 5.1.3. A multi-module nuclear plant with sufficient redundancy can provide uninterrupted operations for AI and generative AI applications and users. Scalability analyses presented in Table 13 demonstrates that 8-NPM configuration is optimum to meet steam demand of the reference chemical plant. Additionally, the 8-NPM with four boilers operating under nominal condition generates an extra electrical balance of 63.7 MWe. This surplus could meet the power demands of large data centers (50 MW to 100 MW). Moreover, substituting 13 coal- and gas-fired boilers will result in 81% reduction in CO_2 emissions at the reference site. Finally, a scalable 12-NPM NuScale plant can enable continuous data centers operation while providing the flexibility for capacity expansion to accommodate growing energy demands.

The data center power scenario presented in this section requires dynamic simulation modeling of the integrated energy system, which includes NPMs, boilers, and the chemical facility, to accurately forecast demand for optimal heat and power dispatching while maintaining grid stability. A recent study [18] has identified additional challenges that need to be addressed. The dynamic simulation of the integrated energy system will serve as a basis for probabilistic risk assessment and availability modeling of the NPMs [19], ensuring the safe operation of the system configuration presented in this report

7. SUMMARY

This report presents a techno-economic assessment of NuScale NPMs replacing coal and gas boilers and coupled with a PSCC system to decarbonize CHP of a chemical plant. A steady-state site integration and reliability analysis was conducted that identified several trade-offs. The results show that incorporating the NuScale power uprate together with steam heat-augmentation significantly enhances performance compared to the 2020 report. This combined approach meets a large chemical plant's industrial steam and power demands reliably, cost-efficiently, and with spare capacity for flexibility.

This study shows that even with NuScale's smallest standard offering of a 4-NPM facility, half of the existing boilers could be retired. Additionally, a 6-NPM facility could meet the energy requirements if only two more boilers were kept online beyond the "low" probability of replacement ones. An 8-NPM facility case steam reliability assessment was conducted as a function of the plant components' reliability characteristics to determine the steam supply capacities of NPM with waste burning boilers and combinations of connections to the steam header pressure to 600 psig.

Modeling indicates that a scalable NuScale plant configured with 12-NPMs (nuclear plant modules) delivers the best overall profitability, availability, and operational flexibility. Multiple modules allow for continuous operation (e.g., refueling does not cause interruptions) and enable capacity expansion to match increasing energy demand. Even a minimal system with 4 NPMs can economically and resiliently meet the plant's needs while providing additional benefits like reduced emissions. In all cases, pairing NPMs with gas-fired boilers results in the highest profitability. The 8-NPM with four boilers operating under nominal condition generates an extra electrical balance of 63.7 MWe. This surplus could meet the power demands of even the largest data centers (50 MW to 100 MW).

Sensitivity analysis on natural gas price fluctuations and electricity costs reveals that an integrated energy system (IES) featuring a NuScale plant is more profitable due to excess electricity production and shows resilience against rising natural gas prices.

8. ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to Eastman. The authors would like to thank reviewers from our organizations for their helpful review and insightful comments on earlier drafts: John Batson III and Wes Williams from ORNL and Sarah Bristol and Amy Kozel from NuScale.

Chromalox provided technical insights on steam electrical heating systems, and Elliott-Ebara provided technical insights on steam compression systems to the NuScale collaborators.

Finally, the ORNL authors extend their appreciation to the INL HERON developers, Paul Talbot and Jacob Bryan, for their technical support.

9. REFERENCES

1. U.S. Department of Energy. "Finding Efficiencies in Process Heat." Accessed December 13, 2024. https://www.energy.gov/eere/ito/finding-efficiencies-process-heat.
2. U.S. Department of Energy. "Could Nations' Nuclear Power Plant Sites Support New Reactor Builds?" Office of Nuclear Energy, September 9, 2024. Accessed June 29, 2025. https://www.energy.gov/ne/articles/could-nations-nuclear-power-plant-sites-support-new-reactor-builds.
3. Greenwood, Michael Scott, Guler Yigitoglu, Askin, Rader, Jordan D., et al. "Integrated Energy System Investigation for the Eastman Chemical Company, Kingsport, TN Facility," ORNL/TM-2020/1522, 2020. https://www.osti.gov/servlets/purl/1643929.
4. NuScale Power. "NuScale Small Modular Reactor Integration for Hydrogen and Ammonia Production." WP-178373, Rev 2. February 25, 2025. Accessed June 29, 2025. https://www.nuscalepower.com/hubfs/Website/Files/Technical%20Publications/nuscale-small-modular-reactor-integration-for-hydrogen-and-ammonia-production.pdf.
5. Doyle, J., Haley, B., Fachiol, C., Galyean, B., Ingersoll, D.T. "Highly Reliable Nuclear Power for Mission Critical Applications. " In Proceedings of ICAPP 2016. American Nuclear Society, San Francisco, CA, 2016.
6. Doyle, Jeremiah. "Highly Available Nuclear Power in a Microgrid Configuration for the ORNL Distribution System. " Nuclear Technology 208, no.6 (2022): 1012–26. https://doi.org/10.1080/00295450.2021.1985912.

7. Talbot, Paul W., Rabiti, Cristian, Gairola, Abhinav, Frick, Konor L., Prateek, Prerna, and Zhou, Jia. HERON. Computer Software. U.S. DOE Office of Nuclear Energy, July 28, 2020. https://github.com/idaholab/HERON. doi:10.11578/dc.20200929.2.
8. Rabiti, Cristian, et al. RAVEN user manual. No. INL/EXT-15-34123; TRN: US2216055. Idaho Falls, ID: Idaho National Laboratory, 2021.
9. U.S. Energy Information Administration. Annual Energy Outlook 2025. Washington, DC: U.S. Department of Energy. Released April 15, 2025, https://www.eia.gov/outlooks/aeo/.
10. Talbot, Paul W., et al. "Evaluation of Hybrid Flexible Plant Operation and Generation Applications in Regulated and Deregulated Markets Using HERON." INL/EXT-20-60968. Idaho Falls, ID: Idaho National Laboratory, 2020.
11. Abou-Jaoude, Abdalla, et al. "Meta-Analysis of Advanced Nuclear Reactor Cost Estimations.", Jun. 2024. https://doi.org/10.2172/2371533.
12. LAZARD, 2025, Levelized Cost of Energy +, June 2025 Report.
13. U.S. Department of Energy. "What Generation Capacity." March 30, 2025. Accessed April 20, 2025. https://www.energy.gov/ne/articles/what-generation-capacity.
14. U.S. Energy Information Administration. "Electric Power Monthly, Table 6.07.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels." Accessed June 2, 2025. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_a.
15. Nuclear Regulatory Commission. "10 CFR Part 100—Reactor Site Criteria." n.d. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/.
16. Omitaomu, Olufemi A., et al. "Methods and System for Siting Advanced Nuclear Reactors and Evaluating Energy Policy Concerns." Progress in Nuclear Energy 148 (2022): 104197.
17. "AI, Data Centers and the Coming U.S. Power Demand Surge." April 28, 2024. https://www.goldmansachs.com/pdfs/insights/pages/generational-growth-ai-data-centers-and-the-coming-us-power-surge/report.pdf.
18. Talbot, Paul et al., "Navigating Integration: Key Challenges for Data Centers, Nuclear Stakeholders, And Utility Operators. " Idaho National Laboratory, Technical Report, INL/RPT-25-87663, 2025. https://csdet.inl.gov/content/uploads/45/2025/10/Navigating-Integration-report.pdf.
19. Muhlheim, Michael et al. "Risk-Informed Decision-Making and Reconfiguration using OPRA." ORNL/SPR-2023/3078. Oak Ridge, TN: Oak Ridge National Laboratory, 2023. https://www.osti.gov/servlets/purl/2076185.
20. Electric Power Research Institute. "Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities (Siting Guide)", EPRI Technical Report 3002023910, 2022.

APPENDIX A. NUSCALE PRODUCTION FOR A GENERIC CHEMICAL PLANTNUSCALE PRODUCTION FOR A GENERIC CHEMICAL PLANT

APPENDIX A. NUSCALE PRODUCTION FOR A GENERIC CHEMICAL PLANTNUSCALE PRODUCTION FOR A GENERIC CHEMICAL PLANT

Table A-1. NPM steam outlet parameters presents the nominal full power operating conditions for a single NPM. It can produce 8883 metric tons of steam per day (816,000 lbm of steam per hour) at 283 °C without heat augmentation. Table A-2 shows that a large number of petrochemical processes have process temperatures that can be met using NPM outlet steam.

Table A-1. NPM steam outlet 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 (MPa)	3.28
Steam Energy (MWt/MMBtu)	250/852

Table A-2. Temperature ranges for various petrochemical processes compatible with LWR steam

Chemical	Process	Process Temp (°C)
Ethylbenzene	Friedel-Crafts Alkylation	90-240
Ethylene Oxide	Air Epoxidation	270-290
Acetic Acid	Multiple	50-250
Cumene	Friedel-Crafts Alkylation	175-225
Cyclohexane	Transformation of Benzene	210
Terephthalic Acid	Amoco Process	200
Vinyl Acetate	Vapor-phase Reaction	175-200
Ethylene Glycol	Hydration and Ring Opening	50-195
Butyraldehyde	Oxo Process	130-175
Adipic Acid	Air Oxidation	50-160
Bisphenol A	Phenol with Acetone	50
Ethylene Dichloride	Direct chlorination of ethylene	20-70 or 100-150
Ethylene Dichloride	Oxychlorination of ethylene	200-300
Phenol	Rearrangement of Cumene Hydroperoxide	30
Urea	Reacting CO_2 with Ammonia	190-200
Ammonium Nitrate	Vacuum Evaporation	125-140
Ammonium Sulfate	Ammonia treatment in with sulfuric acid	60
Phosphoric Acid	Wet process	75-80
Nylon 6 and 6.6	Electrolysis of Brine	280-300
Polyester	Polymerization	200-290

A.1 NPM STEAM HEAT AUGMENTATION

Many chemical processes require large quantities of steam at high pressures 6.9-13.8 MPa (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 A-1 shows a range of process temperatures for a broader set of higher temperature applications.

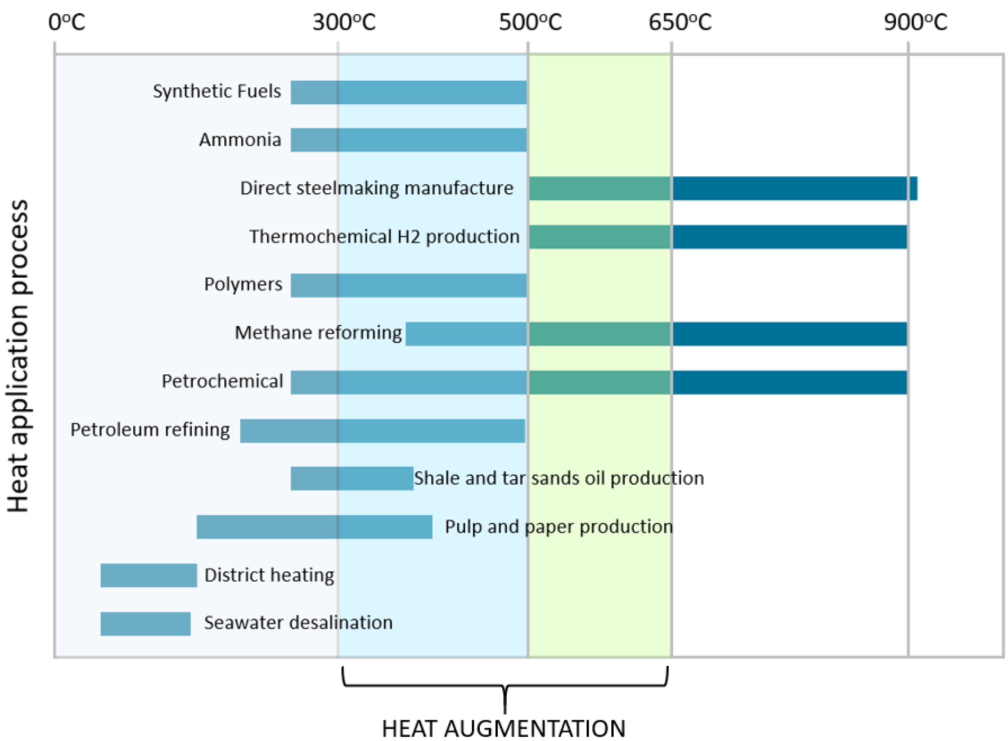


Figure A-1. Process heat opportunities for NPM steam using heat augmentation systems.

As shown in Figure A-1, the temperature requirements for several process heat applications can be met using 300 °C steam from a typical light water reactor. Temperatures above 300 °C have generally been considered outside the range of the nominal steam conditions for a light water reactor. However, by adding commercially available steam compression systems to the NPM balance of plant, steam temperatures of ~ 500 °C and pressures of 6.9MPa can be readily and economically achieved. To achieve high pressures and 650 °C steam temperatures using existing technology, both steam compression and electric heating systems would be needed. Improvements to compressor materials for higher temperature-pressure applications would reduce the need for electric heating. This section presents an overview of a method for generating high temperature and pressure process steam using compression and heating.

Commercially available steam compressors are highly efficient and capable of large volumetric flows and high pressures. Compressing a gas causes an increase in both pressure and temperature. However, manufacturers typically design their compressors to maximize gas pressure increase while minimizing the corresponding temperature increase. This includes maximizing compression efficiency and adding compressor cooling systems. For NPM steam heat and pressure augmentation, it is desirable to optimize the compression system to raise both steam temperature and pressure to achieve the target outlet conditions.

There are several advantages to this method of steam heat augmentation. It provides a clear double radiological separation of nuclear reactor coolant; first via the SG to generate NPM steam, and secondly via the IHX to generate the industrial process steam. This separation also allows the industrial process steam to be controlled chemically to best suit the industrial user. The entire balance of plant is commercial grade. The steam side of a NuScale plant is non-safety related with no risk-significant structures, systems, and components [20]. There are no augmented design requirements from a regulatory perspective. The balance of plant is Seismic Category III (non-safety). There is no high temperature-pressure nuclear safety piping and equipment. This extends the longevity of the reactor, reduces high temperature reactor materials, and the corresponding plant costs.

Figure A-2 presents the pressure-enthalpy diagram for the process steam. It shows that the process fluid enthalpy change is predominantly governed by the enthalpy imparted by the NPM to the IHX through a very efficient phase change process. After generating superheated steam, only a relatively small change in enthalpy is required to raise the temperature of superheated steam from 283 °C/2.9 MPa to 500 °C/6.9 MPa. The NPM does the "heavy lifting" in this scenario.

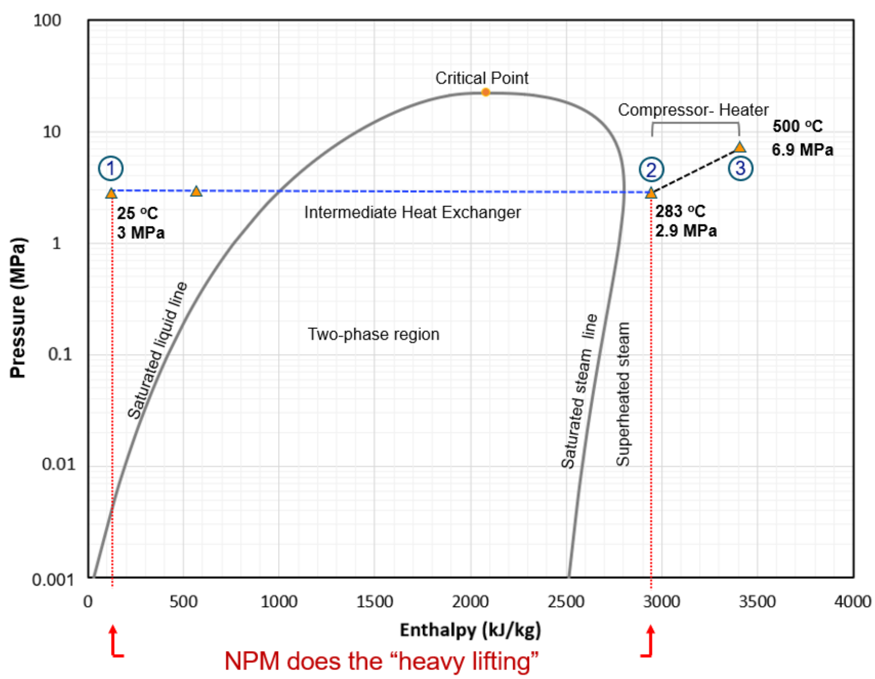


Figure A-2. Pressure-Enthalpy diagram for process heat

For this study, a DWSIM model (Figure A-2) was created to estimate a variety of steam production rates at corresponding pressures, temperatures and NPM electrical power outputs. The analysis was based on a compressor (operating at 75% isentropic efficiency) and heaters (operating at 90% thermal efficiency), which are typical values achievable in commercial systems. Some assumptions in this analysis were that the industrial water started at ambient temperature and pressure (25°C and 0.1 MPa) and that the NPM water returned to the NPM at standard feedwater conditions (121°C and 3.6 MPa). A Global Heat Transfer Coefficient of 1500 W/m²k was used to model the IHX. Total heat exchange area needed was 1400 m².

Table A-3. Estimates of Maximum Steam Production Rates as a function of Steam Pressure and Temperature. summarizes the maximum steam flow rates for an output temperature of 500 °C (932 °F) and 6.9 MPa (1000 psia). It shows that a single NPM whose outputs, both steam and electricity, are fully dedicated to augmented steam production, can produce 180,000 kg/hr (400,000 lb/hr) and a 12 NPM plant can produce 2.18 million kg/hr (4.8 million lb/hr). The NuScale flexible modular design makes it possible to assign one or more NPMs to produce steam for the petrochemical process and other NPMs to produce electricity for the power grid. The conditions used for this model show the high-temperature, high-pressure steam production capability of NuScale SMRs at industrial scale flow rates. The actual flow rates for a specific configuration will depend on the required process pressures and temperatures. They are not limited to the range used in this example and the results will vary with vendor specific compressor performance.

Table A-3. Estimates of Maximum Steam Production Rates as a function of Steam Pressure and Temperature. (Results will vary with vendor specific compressor performance.)

Number of NPMs	Steam Mass Flow at 6.9 MPa 500°C (x10^6 kg/hr)	Steam Mass Flow at 1000 psia 932°F (x10^6 lb/hr)
1	0.18	0.4
2	0.36	0.8
3	0.54	1.2
4	0.73	1.6
5	0.91	2.0
6	1.09	2.4
7	1.27	2.8
8	1.45	3.2
9	1.63	3.6
10	1.81	4.0
11	2.00	4.4
12	2.18	4.8

Figure A-3 presents the same results as Table A-3 in graphical form and also shows how a NuScale plant can be configured to accommodate a large range of steam production rates while simultaneously generating electric power. For example, the point located at the black circle O, shows that a plant with 12 NPMs could be configured to produce 1.2 million kg/hr of steam at 500°C and 6.9MPa and simultaneously produce 414 MWe of electricity that could be made available to the industrial facility or sold to the grid in any proportion.

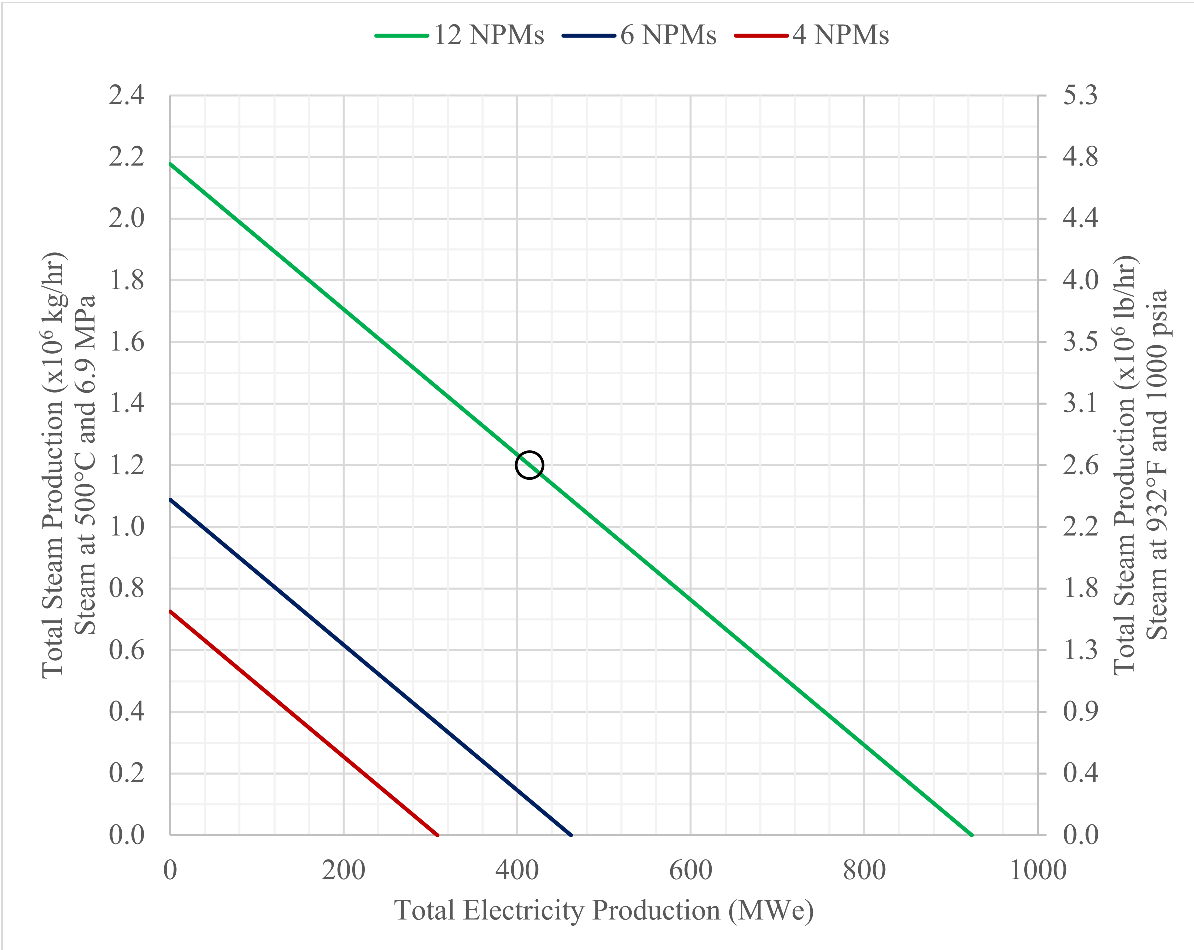


Figure A-3. Sliding Scale of NuScale Plants simultaneous Steam and Electricity Production. The black circle, Om represents an example scenario where a 12 NPM plant produces both 1.2 million kg/hr of steam at 500°C and 6.9 MPa and 414 MWe of Electricity simultaneously.