



# Identifying Opportunities and Recommendations for the Integration of Advanced Reactors for Industrial Heat and Electricity Users

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## Opportunities and Recommendations: Integrating Advanced Reactors for Industrial Heat and Electricity Users

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### ABSTRACT

*Idaho National Laboratory is developing guidelines to identify and assist industrial heat and electricity decarbonization by integrating with nuclear power plants (NPPs) to provide clean, abundant, and dispatchable energy. Deliverables will contain a library of documents and models to guide various industries toward understanding nuclear technologies*

*based on their users' needs. Considerations include specific industrial hazards which impact NPP siting, heat transport requirements and associated technologies, and implementation feasibility based on site-specific demand profiles. Facility process models are based on real data obtained from a survey of baseline requirements and process information (e.g., methods, quality, quantity of required heat inputs) of industrial facilities in the United States.*

*The siting and technical data assessment will reveal opportunities for single-use nuclear integration and co-location opportunities for industries to share benefits from a single reactor. In addition to existing facilities, this "energy-park" style cooperation could include new construction like data centers which can cost-share energy investments or provide a stable demand-and-revenue stream to the investor. This paper is a summary of the current project status, and provides insights on suitable pairings for specific industries and reactor technologies.*

*Keywords: Combined heat and power, nuclear power plant, advanced reactor, industry, pulp and paper, renewables, integrated energy systems, electricity, manufacturing, ammonia*

### 1. INTRODUCTION

Worldwide, nuclear power is currently the planet's largest source for clean, dispatchable heat and electricity. For decades, nuclear power plants (NPPs) have been a valuable source of low-carbon electricity supplied to the electricity grid. In recent years, renewable energy has increased its share of electricity due to investment incentives and calls from government organizations to decarbonize the electric grid. However, electric power production contributes only part of greenhouse gas emissions. Industrial manufacturing and processing facilities burn fossil fuels for heat, steam, and electricity production. Because these processes are often based on continuous, steady-state loads, in most cases renewables are not suitable to meet these decarbonization needs. NPPs, alternatively, may be able to meet the electricity and heat load requirements of an industrial facility to replace fossil fuel combustion and decarbonize the industrial sector.

The Joint Institute for Strategic Energy Analysis (JISEA) identified key industries which could utilize nuclear energy as a power source. Fourteen target industries were identified using data from the Environmental Protection Agency Greenhouse Gas Reporting Program (GHGRP). [1] The report also identified the major types of heat use within industry. Seventy percent of energy use was classified as “indirect use,” the fuel combustion used in conventional boilers or combined heat and power (CHP). Twenty-eight percent was classified as “direct process use,” which includes process heating and refrigeration, machine drives, and electrochemical processes. One percent was classified as “direct non-process use,” and included on-site transportation, lighting and heating, ventilation and air conditioning. Conventional electricity generation was also listed under non-process direct use; however, its share (0.3%) was much smaller than CHP and cogeneration processes (37%), indicating that most industries are not generating their own electricity unless steam generation is already used to meet process needs.

The type and amount of thermal energy needed in these industries does not give a clear picture of which will be most suited to a reactor coupling. Feasibility of NPP integration may be impacted in facilities that utilize heat from byproducts or chemical reactions that are essential to a process, or that have processes that are highly sensitive to temperature or pressure changes. An NPP is readily designed to supply electricity to an industrial facility for most direct non-process energy use, including lighting and HVAC. Electricity supplied from an NPP could also serve some of the direct process use by utilizing electric heating and cooling or electric steam generation for process use.

NPP integration with industrial processes also introduces many regulatory questions. First, what will define the boundary between a Nuclear Regulatory Commission (NRC)-regulated NPP and the non-regulated industrial facility? From a technical standpoint, this will impact the heat transport methods between facilities. There is also the question of siting requirements, such as potential hazards from the NPP to the user and vice versa, that will affect the distance between facilities and therefore the heat transport requirements as well. This paper aims to explore these questions to understand the siting requirements for different industries along with the regulatory and technical implications.

The goal of this study is to perform a detailed analysis of NPP integration with potential industries, assessing each industry for technical and siting feasibility. Using high-level process information from industry partners, we will develop static and dynamic models of industrial processes to assess their suitability for different types of advanced reactors and suggest industry-specific opportunities for decarbonization. We will also utilize geospatial tools to create a general characterization of each industrial site to determine the feasibility of co-locating the reactor with the facility.

## **2. INTEGRATION OPPORTUNITIES**

In theory, an NPP can operate in place of a conventional boiler or CHP, given that it generates both steam and electricity; however, the integration is not straightforward both from a technical and regulatory perspective. NPP integration introduces technical questions such as: how will heat be transported and transferred, how will potential contamination from either side be mitigated, how does heat use on the industrial side impact the reactor? There are also industry-specific design factors that could make integration difficult. For example, pulp and paper mills were eventually determined to be not suitable for small modular nuclear reactor (SMNR) integration by the JISEA study because the chemical recovery process used in pulp making requires that the excess lignin is broken down and burned within the chemical medium. The steam generated from this “recovery boiler” is used to generate steam and electricity for other parts of the process. Removing the recovery boiler is technically infeasible without

completely altering the chemical process used for pulp making. However, some plants use natural gas or fuel oil to generate additional steam for the plant and for heat in the lime kiln, which is also integral to the chemical recovery process. These fuels could be eliminated by integrating an SMNR to supply electric heat and low-pressure steam. [2] Integrating an NPP with a cogeneration process should not be automatically eliminated as an option, especially if a single NPP can be shared between multiple facilities or integrated with the local grid. This would allow more flexibility for NPP sizing and operation, as well as provide economic benefits for the NPP and the users.

There are three NPP-industrial categories that can be considered when evaluating technological integration potential. One integration scenario is using existing NPPs and deploying some non-electrical applications and product generation using behind-the-grid connections. This concept of combined heat and power has historically been done with relatively inert products, mainly water desalination. There are now projects to co-locate hydrogen production with NPPs. [4] Another integration scenario is to introduce a new nuclear generator on-site at an existing industrial facility to create an “industrial park,” which consists of the NPP and one or multiple load customers. For these reasons, advanced reactors are promising options for process integration, and some studies have started to investigate them in detail [3] The third option would be greenfield deployment designed entirely with integrated nuclear and industrial systems. Advanced reactors, especially SMNRs and microreactors, are currently being designed and evaluated for non-electric applications.

### **3. POTENTIAL INDUSTRIES TO TARGET**

The Integrated Energy Systems (IES) group at Idaho National Laboratory (INL) is evaluating multiple industries as candidates for nuclear power integration. A survey was produced to invite partners across multiple industries to provide input and insights regarding net external loads of heat and electricity, typical plant size, decarbonization goals, nuclear integration concerns, and specific process requirements.

Ammonia is an important product in the modern food production cycle. Most ammonia produced is used in fertilizer. Ammonia synthesis involves the combination of nitrogen (easily isolated from air) and hydrogen. Hydrogen production is currently dominated by steam-methane reforming (SMR). Replacing SMR with hydrogen produced by NPPs is a direct way to significantly reduce the emissions from ammonia production, and there are multiple hydrogen production demonstrations underway at operating nuclear power plants [4] either via low- or high-temperature steam electrolysis.

Pulp and paper milling is a highly energy-intensive industry that requires the direct use of heat through steam as well as electricity loads, some of which are produced on-site. Temperature requirements for pulp and paper mills match well with even the lowest nuclear steam temperatures of nuclear reactors and plant sizes are typical of proposed SMNR sizes. [2]

Other necessary industries that are presently carbon-intensive and at higher temperatures are also being investigated, including transportation fuel production both through refining and synthesis, construction materials such as steel and cement, and chemical manufacturing across multiple sectors. Many of these technologies have processes requiring higher temperatures than those produced in existing and even prospective nuclear generators. Electrification using clean energy, heat pumps, increased recuperation, and other temperature-boosting methods that can help integrate nuclear energy are being investigated to reduce life cycle emissions. Input from survey responses along with detailed template plant engineering models will allow analysis that can identify specifically how much carbon-emitting energy can be offset through the introduction and integration of a nuclear heat generation source.

#### **4. HOW ADVANCED REACTOR TECHNOLOGY BENEFITS INDUSTRY**

The two main concerns with existing NPPs are cost and safety. Although NPPs have an exceptional safety record, [5] events like Chernobyl in 1986 and Fukushima in 2011 have damaged the public's perception of NPP safety. The next generation of nuclear reactors (called Gen IV or advanced reactors) are reactors that are technologically different from existing reactors which use light water as a coolant and are referred to as light water reactors (LWRs). Advanced reactors use non-water coolants (e.g., molten salt, molten sodium, helium) and also much safer fuel types such as the tri-structural isotropic particle (TRISO) fuel, which is tested to be safe at extremely high temperatures. These main features, in combination with other safety systems, make advanced reactors even safer than LWRs to a point where they can be passively safe (i.e., requiring no active cooling systems during an accident) or 'walk-away' safe (i.e., reactor automatically achieves a steady state without intervention) after an accident.

To address the large capital costs, and cost and schedule overruns experienced by some LWRs, advanced reactors are designed to be smaller, and in the form of standardized modules. These smaller, modular reactors, also referred to as SMNRs, enable sharing operations crew and balance of plant between multiple reactor modules, thereby reducing the cost. Given their smaller size, they are also expected to involve a larger amount of factory fabrication and cost reductions due to learning. Plants like NuScale involve integrated nuclear systems, where the reactor, steam generator, pressurizer, and other nuclear steam supply systems are all integrated into one module. This module is planned to be manufactured and assembled offsite in factories and shipped to site, where it is installed and fueled. This significantly reduces on-site labor, which is a primary cost driver. Factory fabrication also potentially improves quality due to increased precision in fabrication and assembly.

In addition to these characteristics, advanced reactors are designed with a lower power density, which reduces the amount of heat that needs to be removed from the reactor during an accident, and reduced complexity, which allows for the reduction of maintenance and surveillance, and increases reliability. These features of advanced reactors and SMNRs result in various advantages for deployment in industrial applications. In addition to increased safety and reduced cost, these advantages include 1) a smaller emergency planning zone (EPZ) and a smaller footprint, which allows the industrial facility to be closer, or even adjacent to the NPP while still not being under NRC purview and without compromising safety, and 2) more flexibility in size due to modularity, which allows for the NPP to be sized appropriately to the demands of the industrial facility.

Another significant advantage of advanced reactors is their much higher operating temperatures. While LWRs operate at temperatures of around 300–400°C, advanced reactors, especially high temperature gas reactors (HTGRs) and molten salt reactors are expected to operate above 650°C, which makes them attractive to several industrial applications. The combination of higher temperatures and lower levelized costs opens advanced reactors and SMNRs to both process heat and direct electricity supply applications.

#### **5. SITING CONSIDERATIONS**

The goal of the NPP siting process is site selection, one of the first activities in the NPP licensing process. The NPP siting process in the United States must meet NRC regulations on environmental impact, emergency preparedness, and process requirements for reasonable consideration of alternative sites. In addition to meeting regulatory requirements, selecting a site is also a business decision informed by economics and business strategy of the utility. The primary NRC regulations driving the siting process are:

- 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,” and 10 CFR Part 52, “Licenses, Certification, and Approvals for Nuclear Power Plants,” which provide pathways to licensing commercial nuclear reactors and refer to other regulations
- 10 CFR Part 20, “Standards for Protection Against Radiation,” which establishes standards for protection against ionizing radiation from the plant for public health and safety
- 10 CFR Part 51, “Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions,” which includes standards for environmental protection
- 10 CFR Part 100, “Reactor Site Criteria,” which establishes the requirements for sites where nuclear reactors are operated.

The criteria involved in site selection fall into the following categories: 1) health and safety criteria including natural and human-caused hazards, accident consequences, and operational effects, 2) ecological criteria including environmental impacts at the site due to the NPP, 3) socioeconomic criteria including the socioeconomic effects on the local population and environmental justice considerations, and 4) engineering and cost-related criteria including ease of site preparation and transportation accessibility, etc. Perhaps the most important siting consideration in the context of co-locating with industrial facilities is the safety of the NPP, which includes external hazards (e.g., explosions) from the facility. This will be the first focus of this study. It will be analyzed in detail before other criteria. A detailed description of the siting process including descriptions of the various criteria and associated regulations can be found in [6]. **Table 1** below summarizes the siting considerations related to safety.

Table 1.        **Safety considerations in NPP siting**

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**Site Safety**



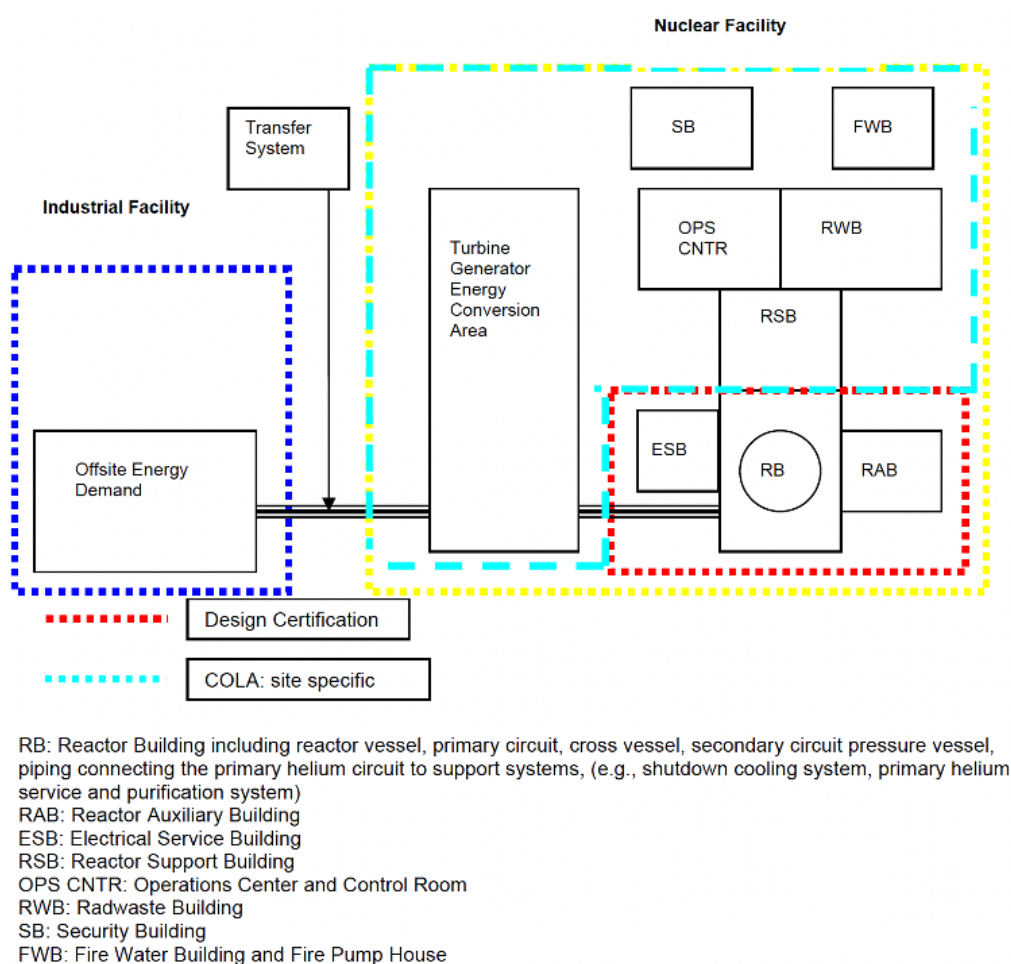
Considerations		Description
A.1	Geologic/seismologic	Hazards: Ground motion, surface faulting, liquefaction, subsidence, landslides, mud slides, tectonic and non-tectonic deformation, human activities
A.2	Atmospheric dispersion	Atmospheric dispersion characteristics of the site; can be mitigated using design and engineered safety features.
A.3	Exclusion area and low-population zone (LPZ)	Exclusion area and LPZ can be determined based on design, safety characteristics, and atmospheric dispersion characteristics of the site
A.4	Population considerations	Reactors should be located away from population centers.
A.5	Emergency planning (EPZs)	Site should not impede emergency operations. Plume exposure EPZ: 10-mi radius; ingestion pathway EPZ 50-mi radius
A.6	Security	Characteristics or development at site should not preclude or interfere with development of adequate security plans
A.7	Hydrology	Flooding Water availability Water quality (plant shouldn't impact surface and ground water quality due to effluent releases)
A.8	Industrial, military and transportation facilities	Potentially hazardous facilities within 5-mi radius and major airports within 10-mi radius Hazards: shock waves, missiles, flammable vapor clouds, toxic chemicals, incendiary fragments

## 6. POTENTIAL LICENSING STRATEGIES

Co-locating an industrial facility and an NPP involves two distinct possibilities: 1) the industrial facility is outside the NPP boundary, or 2) the industrial facility is inside the NPP boundary. Building an industrial facility inside a plant boundary might reduce the heat or electricity transportation cost, but it includes the industrial facility under NRC licensing oversight that can significantly increase the regulatory burden. When the facility is built outside the plant boundary (off site), the NPP is still required to meet NRC siting requirements introduced above as well as safety requirements resulting from being physically connected (for transferring heat, electricity, or other forms of energy) from the NPP to the industrial facility. For this case, a detailed analysis of the jurisdictional boundaries for the NRC was conducted by Moe and Hicks. [7] The analysis concluded that a regulatory basis already exists for co-locating industrial facilities with NPPs and establishing jurisdictional boundaries between them. Assuming that the facilities are connected physically, they suggest various considerations that need to be addressed. The most fundamental of these considerations are 1) all systems,

structures, and components that perform safety or risk-significant functions will be included in the NPP under NRC oversight, and 2) the interface design between the NPP and the industrial facility should ensure that the NPP is not dependent upon or adversely affected by the events at the industrial facility. The analysis also applies their recommendations for a conceptual HTGR power plant and provides notional demarcation boundaries shown in Fig. 1.

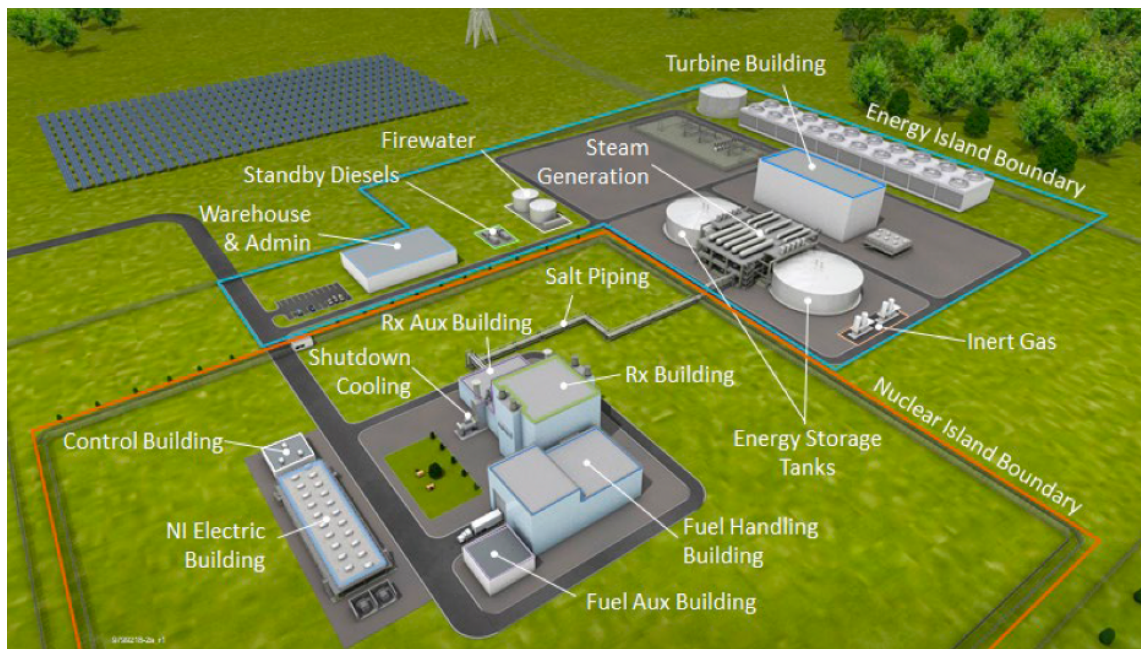
Very few precedents exist for the co-location of industrial facilities and NPPs. The first one is likely the Midland Nuclear Plant that was planned to be built in the 1970s (when the Atomic Energy Agency was the regulatory body and NRC didn't yet exist) but was halted before construction was completed. The Midland Nuclear Plant was planned to supply steam and electricity to an offsite industrial facility and was issued a construction permit. [7, 8] The project was shut down after an operation license was submitted and therefore, was never issued. A more recent precedent is the 1 megawatt (MW) demonstration scale, on-site hydrogen production at the Nine Mile Point Nuclear Station in New York, which commenced in March 2023. Hydrogen is produced on site through electrolysis using the electricity produced at the plant. In addition to the Nine Mile Point Plant, a few other existing plants are also working on hydrogen production.



**FIG. 1 NOTIONAL DEMARCATION BOUNDARIES FOR AN EXAMPLE HTGR [7]**

The first advanced reactor co-location example will likely be TerraPower's Natrium plant, which combines nuclear heat generation with thermal energy storage (TES). The Natrium plant

comprises a sodium-cooled fast reactor, which transfers heat to molten salt. The hot molten salt is transferred and stored in tanks outside the nuclear plant boundary in a TES system. Here, the primary intent for the TES system is to provide load following capability, although it can also (theoretically) provide industrial heat. The combined Natrium facility is being designed as two decoupled facilities: 1) the nuclear island (NI), which includes the nuclear reactor and primary and secondary sodium loops, and 2) the energy island (EI), which includes the molten salt loop, storage tanks for TES, and steam generation and electricity generation components. A conceptual rendering of the facility is shown in Fig. 2 below. In this figure, the NI boundary is a solid orange line and the EI boundary is a solid blue line.



**Fig. 2** CONCEPTUAL RENDERING OF THE NUCLEAR ISLAND AND THE ENERGY ISLAND IN THE NATRIUM NUCLEAR POWER PLANT [9]

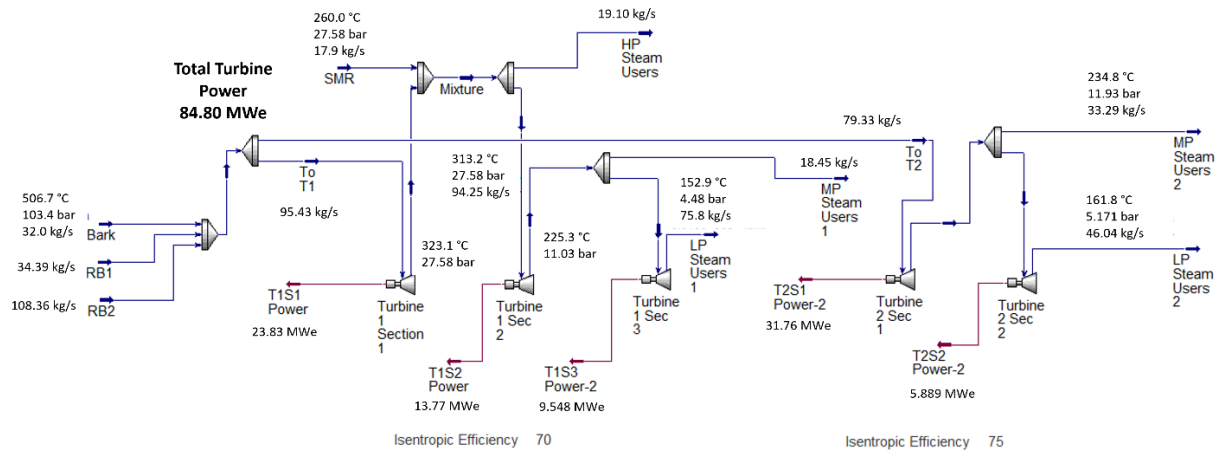
## 7. TOOLS TO ENABLE FEASIBILITY STUDIES

INL has access to licensed and open-source software which can facilitate feasibility and technoeconomic studies of industrial facilities and advanced reactor pairings. With basic information from an industrial partner on a process, we can perform a simple static and dynamic feasibility study for integration with an advanced reactor. More detailed information, like seasonal demand curves and acceptable ranges for steam quality, will improve the fidelity of the models.

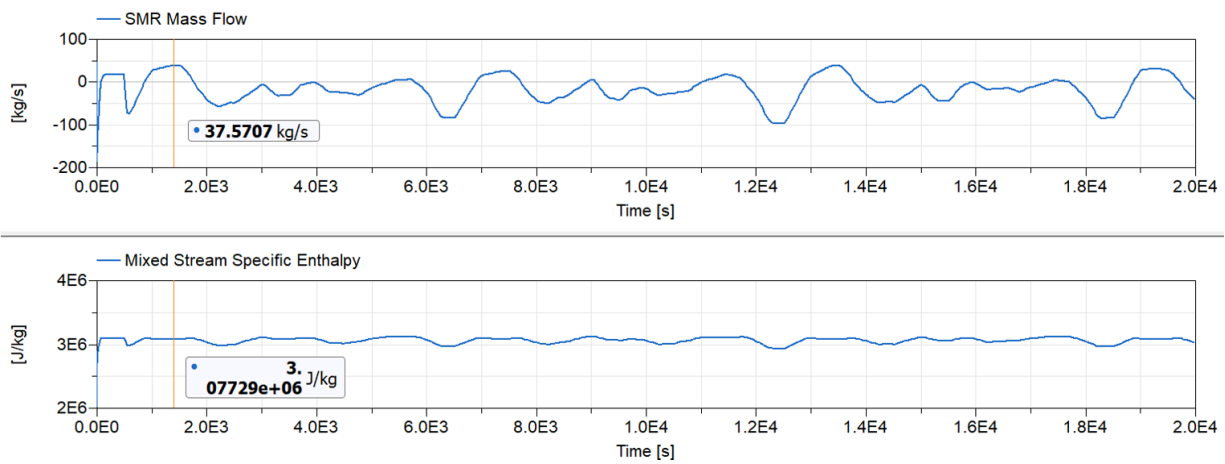
Aspen HYSYS is a powerful tool for modeling steady-state steam systems. Using data from an industrial partner, we can create a baseline model of a process and simulate the addition of steam from a reactor or a heat storage system. These baseline models provide information on how introducing or removing a steam source changes the overall steam conditions within a process. This model can also calculate the baseline steam and electricity output required from the nuclear power source. Fig. 3 is an example of one of these models, showing an SMNR steam input into the steam distribution system of a pulp and paper mill.

A dynamic analysis of the process is required for the feasibility study if the process faces dynamic steam loads or demands. A dynamic model gives information about the maximum and minimum steam and electricity requirements from the reactor, and informs the need, or the size necessary, for thermal storage integration. If the reactor is required to load follow for the industrial process, the dynamic model can also provide information on the operating impacts to the reactor. INL hosts an open-source library of models that can be used for dynamic modeling in the Modelica Ecosystem. The Hybrid/TRANSFORM library [10] contains basic components for modeling nuclear systems, including reactor models, heat transfer and storage systems, and hydrogen electrolysis.

There are two tools available to characterize potential nuclear reactor sites in the United States. The Oak Ridge Siting Analysis for Power Generation Expansion (OR-SAGE) is a process tool for siting power plants to harness geographic and population information in the United States (U.S.) to visualize the most suitable sites. OR-SAGE uses information such as availability of water, sufficient land footprint, and future projections of these criteria to characterize geographic areas based on the number of potential siting concerns. [11]



**Fig. 3** STATIC FLOWSHEET OF A PULP AND PAPER MILL STEAM DISTRIBUTION SYSTEM [2]



**FIG. 4** OUTPUT OF A DYNAMIC MODEL OF THE SYSTEM DEPICTED IN FIG. 3, SHOWING HOW THE PLANT STEAM FLOW CONDITIONS CHANGE BASED ON THE MASS FLOW RATE INJECTED FROM THE SMNR. [2]

The Siting Tool for Advanced Nuclear Development (STAND) builds on the geospatial capabilities of OR-SAGE and assists with site discovery and exploration based on the nuclear-specific priorities of a project. [12] Once the potential target industries are selected, these tools will be used to determine the typical site characteristics of that industry. Cross-referencing the locations of known producers with the geospatial and socioeconomic criteria of STAND will provide information on the feasibility of integrating these industries with advanced reactors.

## **8. NEXT STEPS**

The tools and knowledge bases for evaluating nuclear integration into industrial parks are mature but segmented. Experts exist within the nuclear field who understand with detail how existing and prospective reactors should operate in many regimes. Advanced reactor designs will increase the temperature range across which thermal energy can be extracted from a nuclear generation site without the need for heat augmentation. Industrial park operators have a similar knowledge base with regard to producing many products necessary for modern living standards: plastics, fuels, electronics, etc. Identifying decarbonization strategies within industrial parks and processes will require insights that can only come from actual operation of these parks.

The most important action going forward is facilitating effective communication of requirements and capabilities between these two historically non-integrated industries. The IES and Light Water Reactor Sustainability programs at INL are seeking partnerships to aid in industrial decarbonization efforts by partnering with existing NPPs to potentially provide decarbonized process input products (such as hydrogen, steam, or electricity produced by a dedicated process at a plant) as well as evaluating advanced reactor technologies for specific deployment scenarios. For decarbonization through the integration of nuclear energy to be successful, opportunities must continue to be identified and evaluated through collaboration of industrial park operators and nuclear experts.

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