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Changing the World's Energy Future

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Static and Dynamic Modeling of Steam Integration for a NuScale Small Modular Reactor and Pulp and Paper Mill Coupling for Carbon-Neutral Manufacturing

Elizabeth K. Worsham, PhD, Idaho National Laboratory
Stephen D. Terry, PhD, PE, North Carolina State University

Abstract

Small modular reactors (SMRs) are reactor designs producing less than 300 MWe and are generally planned for deployment as multimodule nuclear power plants. The possibility of factory-manufactured, flexibly sized plants expands the opportunities for nuclear power to different communities and industries, including manufacturing plants that currently utilize fossil fuels to produce both steam and electricity. This paper examines the feasibility of coupling a NuScale SMR with a midsize pulp and paper mill in the Southeastern United States. A steady-state mill model was developed in Aspen HYSYS, based on real data from the operation of the mill, and modified it to include the SMR while maintaining steam quality requirements and making as few changes as possible to existing equipment. Dynamic plant models were also developed Dymola to demonstrate possible plant conditions, using three configurations.

Preliminary results suggest that, while SMR coupling is physically feasible, its economic feasibility is limited by the differences in steam and electricity demands. Because of limitations in the amount of steam the mill can take from the SMR, sizing the SMR for the plant's steam demand may result in an electricity deficit, or vice versa. Dynamic analyses show that the addition of a thermal storage system could reduce such deficits, but this entails its own challenges. Each plant must determine the best configuration and control scheme for itself, based on its electricity and heat needs, including the peak duration and intensity for both. Ultimately, an implementation of SMRs with manufacturing processes would benefit from partnering with a local utility to purchase excess electricity generated by the SMR. This will help manufacturing facilities meet their environmental and cost-savings goals, in addition to meeting the need for cost-effective baseload power across the United States.

1. Introduction

Growing concerns regarding the overuse (and lasting impacts thereof) of our natural resources are ushering the world into a new era. Industries are looking for alternative fuels and processes to generate power and heat. Integrated paper mills use a variety of biomass, waste residues, and fossil fuels to generate onsite energy, but those fossil fuels could be replaced by a nuclear power source to reduce the carbon output.

Small modular reactors (SMRs) are compact, factory-fabricated nuclear power plants (NPPs) that can be transported by truck or rail to nuclear power sites [1]. Unlike current NPPs, which generate 1,000 MWe or more, these small reactors only generate up to 300 MWe [1]. The United States (U.S.) Department of Energy encourages the industrial use of combined heat and power (CHP), or cogeneration [2], to increase the amount of energy extracted from a given amount of fuel, thus decreasing the carbon production. CHP can increase the heat efficiency of a typical power generation system from 40 to 80–93% and can cut the system's CO_2 release rate by half [3].

Jaskólski et al. studied the relative performance of nuclear CHP to various fossil fuels, finding that "a nuclear power plant can be a competitive combined heat and power technology even at relatively low price of CO_2 allowances… This parameter proved critical for nuclear cogeneration competitiveness." They also noted "turbine modifications required to convert a nuclear power plant to partial cogeneration mode are a low-risk investment, since they constitute only a small fraction of total capital expenditures" [4]. Current NPPs can be converted to operate in a partial cogeneration mode by extracting steam from both the low-pressure (LP) turbine bleeders and the high-pressure (HP) to LP or intermediate pressure (IP) to LP crossover pipe. Modifications of the primary cycle or nuclear reactor thermal capacity or both are not required for the conversion[4]. Similarly for an SMR, steam could be extracted from a power turbine from a NuScale plant, and in some cogeneration designs, like adding a reverse-osmosis process, normal power conversion systems could be left virtually unaltered [5].

Cogeneration is an important technology to reduce fuel consumption and CO_2 emissions. In a study of utility scale cogeneration by Rosen, "Annual uranium use by the electrical utility and related emissions decrease in all scenarios, by between 3% for low penetration of utility-based cogeneration and 35% for high penetration," and "annual emissions of carbon dioxide decrease for all scenarios, by between 13% and 47% for the electrical utility sector" [6]. Annual electricity consumption in the studied province decreased by between 3 and 30%, which also reduced electrical generation by corresponding percentages [6]. Cogeneration has the potential to significantly contribute to mitigating the utilities sector contribution to climate change.

Most importantly, nuclear cogeneration increases the utilization of the entire plant by diverting idle power and steam to produce a separate product. It is best to operate an NPP at steady state, and typically full, operation. Reactors operate at their highest economic efficiency at their maximum power because the share of fuel costs in the total generation costs are minimal, and therefore the cost of electricity generated at nuclear power plants decreases significantly when the load factor increases [7]. One well studied application for nuclear cogeneration is district heating. A study by Tulkki et al. assessed the performance of a nuclear reactor in a CHP mode to produce district heating. Operating the reactor in CHP as compared to only producing heat increased the utilization rate, because the heat-only plant would need to operate at low power during the summer when demand is low. Alternatively, the CHP plant can adjust for seasonal and daily changes in demand [8].

Traditionally, nuclear energy sources have not been considered for coupling to existing manufacturing processes because NPPs were built on a large scale (typically 1 GW or more), cost intensive, and large. Due to their smaller physical size and flexibility in electricity production, SMRs may be able to provide both power and heat to large industrial applications. Integrated paper mills are a natural fit for this application, since most mills already utilize CHP to provide large quantities of electricity and LP steam, and heat and electricity demands remain stable throughout the year [9]. High-pressure (27–40 bar) steam turns back-pressure turbines, which generate electricity while producing a pressure drop. From the authors' previous experience with paper mills, medium-pressure (10–12 bar) steam is extracted for paper drying and other uses. The remaining LP (3–5 bar) steam is used in chip digesters and other applications. A generic Sankey diagram of the steam and power demands of the Kraft process is shown in Figure 1. Pulp and paper mills were identified by Idaho National Laboratory (INL) as a target industry for greenhouse gas (GHG) mitigation, as detailed in Table 1. Although, pulp and paper mills were not considered as a candidate for SMRs as an alternative heat supply because they rely on their process byproducts for combustion fuels. However, based on previous experience and studies of pulp and paper mills, some mills utilize additional natural gas, fuel oil, or coal to supplement their steam supply and to heat the lime kilns. Replacing these fuels with an SMR is the target of this study.

There is presently interest in SMRs for hydrogen generation via electrolysis [10], in which the hydrogen can be used on its own or in further processing for high-demand chemicals like ammonia. A medium-scale hydrogen plant of about 200 tons per day of hydrogen would require six NuScale modules and provide enough hydrogen for a midsize commercial ammonia plant of approximately 1,150 tons/day, a typical distributed-scale petroleum refinery of 40,000 to 50,000 barrels/day, or a cluster of steel refining mills [11]. Locatelli et al. studied the viability of hydrogen production by alkaline water electrolysis for SMR cogeneration. They concluded that alkaline water electrolysis, as an electrical application, "is a flexible technology that can be easily coupled with SMRs." The economic viability of producing hydrogen is reasonable when the demand and price for electricity is low, otherwise it becomes more profitable to only produce electricity" [12]. This makes it a great candidate for flexible cogeneration involving an electricity demand. These cogeneration studies differ from coupling to a pulp and paper mill becausethe optimal integration requires coupling with an existing steam turbine design, and the demands are based on the operation of the plant, rather than the price of the products. The paper mill is also restricted by the SMR's steam quality and scaling ability. In this case, the cogeneration process is the incumbent process as opposed to integrating cogeneration products with an incumbent NPP, as done in previous INL technoeconomic studies for the NPP cogeneration of treated water via reverse osmosis and of hydrogen.

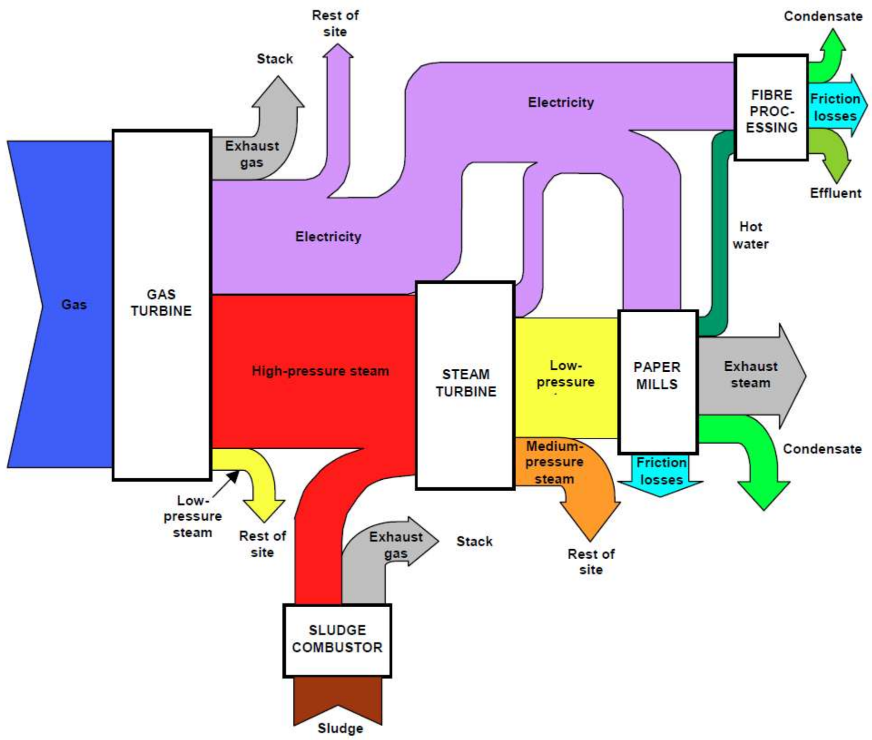

Figure 1. Generic Sankey Diagram of a pulp and paper mill [13].

Table 1. Summary of potential alternative heat supplies by target industry [14].

	Paper Mills	Paperboard Mills	Pulp Mills	
Number of EPA GHG Reporting Program - Reporting Plants in 2014	116	73	30	
Average Size of Plant (Production Rate)	1,723	4,427	474	
Reported CO_2 Emissions ($MMTCO_2e$)	32	24	12	
Fraction of Industrial-Sector GHG Emissions (%)	2	1.5	0.7	
Industry Process-Heat (Type: purpose)	Steam: stock preparation, drying		Combustion gases: electricity production	Steam: wood digesting, bleaching, evaporation, chemical preparation
Average Plant Heat Use (TJ/Day)	21.1		0.67	1.15
Process Heat Temperature (°C)	150–177		800	200

Most pulp and paper mills in the U.S. use the Kraft cycle, or Kraft chemical recovery process (described in Figure 2), to process wood into pulp and then remove impurities, such as lignin, from the chemical slurry requiring large steam demands. To generate steam, paper mills currently utilize a mix of fuels, such as fossil fuels, wood waste, and black liquor, which is a byproduct of the paper manufacturing process and contains a mixture of pulping residues and inorganic chemicals. Currently, black liquor recovery boilers reclaim these chemicals to produce heat for steam generation [5]. Alternatively, the chemicals can be gasified for a more efficient fuel for electricity production or sold to other users as fuel or chemical feedstock. This study is intended to design a carbon-neutral system, rather than focusing on zero-carbon technologies. While black liquor and wood waste are "carbon neutral" (i.e., the CO_2 released when the biomass is burned is almost the same amount as the CO_2 absorbed through photosynthesis during its growth [15]), other fuels, such as natural gas, contribute to carbon pollution. An SMR could replace traditional fossil fuels for steam generation, and the black liquor could be burned to supplement steam production or otherwise gasified and sold.

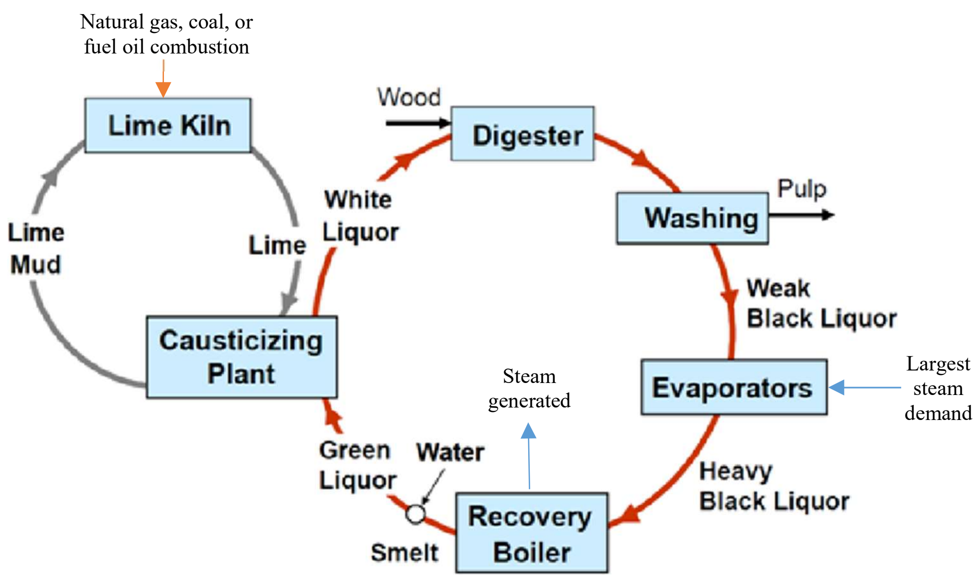

Figure 2. The Kraft chemical recovery process [16].

The major consumer of fossil fuels in the Kraft cycle is the combustion of natural gas for heat, producing the lime calcination reactions in the kiln. The calcination process releases about 0.793 kg of CO_2 for every 1 kg of quicklime produced [17]. When added to the carbon dioxide produced via combustion in boilers, the amount is significant, as emissions from the lime industry account for nearly 1% of the total amount of CO_2 produced by humans [18]. Eliminating the use of fossil fuels to produce heat would go a long way toward making the Kraft process carbon neutral.

SMRs are a good option for integration with pulp and paper mills because they can provide both heat and steam, have a small footprint and emergency planning zone that allow them to be located in close proximity to the use point, and have a long lifetime compatible with expected SMR lifetimes. The pulp and paper mill in Canton, North Carolina was built in 1908 and is still operating today [19]. An article by Greenleaf notes that 52% of North American recovery boilers were built in or before 1978, an unexpected failure would be detrimental to the entire industry, and a replacement of the boiler on its existing footprint could be upwards of USD$50 million [20]. Paper mills also experience planned outages[21] which could align with the SMR maintenance and refueling needs. The anticipation of potential failures, along with a continuing increase in market demand [22] presents an exciting opportunity for paper mills to move to lower-carbon processes and power sources on the existing property.

The larger purpose of this study is to understand how an SMR implementation affects the overall plant steam systems, what SMR size is necessary to replace the steam generated by fossil fuels, and how well can the SMR meet plant needs as steam demands vary. This will assist in determining what controls and additional equipment are needed to protect the SMR while maintaining product quality.

An important consideration for pairing a SMR with an industrial process with varying steam and electricity needs is thermal storage. Although nuclear reactors can be designed for load following, “the most economical and reliable operation is base load or producing maximum power all the time” [23]. In this case, thermal storage is beneficial by capturing excess steam during low demand, rather than releasing it from the system. For industrial applications, energy storage minimizes system costs by “moving energy use from one period of time to another” [24]. Beckmann notes that “there is even more incentive to use energy storage for NPPs than with coal-fired plants”[25]. Considering the high capital cost of a reactor island, a storage system permits the maximum use of the investment, potentially decreasing payback time. Additionally, “cyclical operation of a nuclear reactor is detrimental to its fuel elements”[25], and base load operation minimizes fuel temperature cycling. Thermal energy storage (TES) for nuclear power, including SMRs, was extensively explored in an INL report by Mikkelson et. al. According to the authors, “a TES system can be used as process heat to drive a coupled industrial process. When TES is used for industrial process heat, it can serve as a buffer between the nuclear reactor and the industrial system, allowing for better coupling between subsystems that operate with different dynamic characteristics” [26]. Thermal storage will help the plant adjust to changing steam demands and maximize reactor economics and efficiency. Excess steam and electricity could also be used for additional cogeneration, such as hydrogen generation by electrolysis, although this is not explored in this study.

SMRs are a fairly new form of technology, and limited studies have been conducted on their application. By proving the compatibility of SMRs with a large-scale manufacturing application, such coupling can be expanded to other plants and processes that utilize CHP. Additionally, after demonstrating an SMR within an integrated energy system (i.e., a system that incorporates multiple forms of energy generation such as nuclear, solar, fossil fuels), manufacturers will consider adding them to their current infrastructure, rather than undertaking a replacement that requires a complete system overhaul.

2. Material and Methods

This analysis consists of both a steady-state and dynamic component for the pulp and paper plant. The steady-state model of the plant was developed in Aspen HYSYS [27] by combining standard process operation data and single point snapshots during plant operation. Aspen HYSYS is the INL standard for steady-state process modeling. These data are specific to the plant, the study of which primarily involved utilizing SMR steam and electricity to replace fossil fuels in both a fossil-fuel-fired boiler and a lime kiln.

Developing a dynamic plant model is integral to determining the SMR performance when plant demands change. To accomplish these tasks, INL has been developing a library of high-fidelity process models in the Modelica modeling language since early 2013 called HYBRID [28, 29]. The Modelica language is a nonproprietary, object-oriented, equation-based language used to conveniently model complex, physical systems by taking multiple domains of science and quickly coupling them in a unified language. Modelica is an inherently time-dependent modeling language that allows the swift interconnection of independently developed models. Being an equation-based modeling language that employs differential algebraic equation solvers, users can focus on the physics of the problem rather than the solving technique, allowing faster model generation and, ultimately, analysis. INL utilizes the commercial Modelica Integrated Development Environment platform Dymola produced by Dassault Systems [30].

The first potential opportunity for SMR integration is the steam generation (boiler) and supply system within the pulp and paper plant, including electricity generation from the turbines. Expanding the analysis to include tertiary processes within the plant is unnecessary if the changes to the steam supply system continue to meet the required quality and demand outputs. Our analysis does not extend to SMR operations, since previous research shows that the maximum amount of steam divertible from the reactor is 50% of the total mass flow [31]; therefore, it is assumed that SMR operation will not be affected if the design uses 50% or less of the steam from each module.

In addition to the steam supply, natural gas or coal provides the heat that facilitates the conversion of $CaCO_3$ into lime (CaO) in the lime kiln. Along with the CO_2 released by fuel burning, CO_2 is released in this conversion process as well. In this study, the natural gas kilns are converted into electric ones, with the electricity provided by the SMR. Although not considered here, the capture and sequestration of CO_2 (CCS) released from the calcination process would further decarbonize the plant (i.e., reduce the total amount of CO_2 released). Paper mill CCS has previously been studied by Svensson, Wiertzema, and Harvey [32]. The authors replaced the conventional lime kiln with a plasma calcination concept and implemented CCS to capture 95 and 164 kt/a in the two integrated paper mills studied, respectively. The study includes a discussion of carbon capture and utilization as an alternative to CCS, mentioning that CO_2 can be utilized in the precipitation of calcium carbonate by water electrolysis, although the utilization would be much smaller than the mill's capture potential. The potential for carbon savings would also be dependent on the carbon output required to produce electricity for electrolysis. The authors conclude that, since only a fraction of the CO_2 captured could be utilized at the mill, CCS is the only option to handle the entire CO_2 flow. Using an SMR to provide carbon-free electricity for the mill would increase the desirability of electricity-based utilization processes like electrolysis. Although CCS may still be required to handle the CO_2 output from the mill, an SMR implementation to eliminate some fossil fuels burned in the processes could still be a desirable solution.

There are other opportunities for carbon savings within this process that were not implemented. One major opportunity is the replacement of the black liquor boilers with a black liquor gasification process. Though this was considered, studies show that the gasification process significantly impacts the lime kiln by creating a natural partition of sulfur and sodium. In the case study by Larson, the gasification system, as compared to a conventional boiler, required an estimated 44% more causticizing lime kiln capacity for low-temperature gasification and 16% more for a high-temperature gasification [33]. The gasification process would require significant, costly process changes and necessitate proprietary data and additional studies to maintain chemical balances in the plant throughout the SMR integration.

Another opportunity is the elimination of the bark boiler, which was not considered in this study because the wood waste generated by preparing the wood for the digester cannot be avoided. And while some alternative uses for the bark exist, the bark boiler was not eliminated in this study because the steam it supplies is considered carbon neutral.

3. Theory and Calculations

3.1. Development of the Steady-State Model

This model considers an actual integrated pulp and paper mill in the Southeastern U.S. All data used in the steady-state design was provided by the plant from a snapshot of the plant steam systems at their typical operating conditions. Its typical steam demand is approximately 202 kg/s, with 85% of this steam produced by carbon-neutral wood waste and black liquor. The actual amount of steam produced can vary from 40 to 110% of the typical demand value. The plant generates up to 100 MWe from two turbines to meet its electricity demands. The plant buys and sells a minimal amount of additional electricity, depending on plant demands and production factors affecting the turbine electricity generation.

Figure 3 shows the current setup of boilers, turbines, and steam users prior to SMR integration, as provided by the pulp and paper mill [9]. The 103.4 bar steam comes from four boilers: two black liquor recovery boilers producing 141.5 kg/s, one natural gas boiler producing 32.0 kg/s, and one bark boiler producing 32.0 kg/s. The steam is fed in parallel to two turbines, as shown in Figure 3. Some steam exits Turbine 2 at 27.6 bar for small secondary operations. Both turbines output medium-pressure steam at

11.1 bar and LP steam at 4.5 bar. Unused steam is sent to the condenser, about 6% of the total produced steam (about 12.6 kg/s).

As shown in Figure 3, the mill requires much more LP than medium-pressure steam. Most of this LP steam is used in the evaporator, the deaerator, and for pulp and paper drying and digesting. Some is also used to produce chlorine dioxide, a common paper-bleaching agent. Medium-pressure steam is also used in the digesting and drying processes, with a portion used for smelt recovery.

This study uses the NuScale SMR specifications for the integration models. The NuScale SMR is of particular interest to INL because the first-of-a-kind reactor will be built at INL by 2029 as a part of a carbon-free power project [34]. This was the only SMR design considered here, but further study is required to determine if other SMR designs could be more suitable for this application. To integrate the SMR, steam availability at specific pressures and temperatures must be considered.

The SMR flexibility to adjust steam and electricity output depends largely on where steam is extracted in the turbine. The power output of a steam turbine is largely dependent on exhaust pressure, therefore, if only exhaust steam is extracted, electrical and steam outputs are largely fixed at full operating power [5]. Using a controlled extraction turbine introduces limitations to the amount of steam that can be supplied due to a minimum and maximum allowable exhaust flow. Maximum flexibility is achieved by splitting the main steam flow. In a desalination application, Ingersoll showed that extracting main steam yielded the maximum possible water output of a single NuScale module for all thermal distillation cycles considered in his study.

Each NuScale SMR module can produce up to 67.0 kg/s steam per hour, with up to 50% [31] available to take off the main steam line without negatively affecting the reactor, according to a model by Frick et. al. Steam is taken from the main steam header at 34.5 bar and 307°C. This limit exists when the steam is taken off before the temperature control valve to maintain pressure control in the SMR steam generators. In this case, this point was selected so that the SMR could continue to operate as a power plant and that its highest energy steam could be provided to the process. This steam must go through an intermediate heat exchanger (IHX) to ensure that the steam used in the mill process has not been activated (i.e., made radioactive in some way) due to the SMR. The steam temperature exiting the IHX can theoretically be set to anything less than the temperature of the steam from the reactor, depending on the IHX design. A convenient option is to use 27.6 bar and 260°C as IHX design parameters to ensure compatibility with the existing plant systems. Figure 4 illustrates our proposed SMR integration, with the goal of requiring as few design changes and equipment additions as possible.

The high-pressure steam exiting the IHX does not reach the 103.4 bar from the black liquor and natural gas power boilers but could be substituted for the 27.6-bar steam exiting Turbine 1. Some steam will be diverted from the IHX to meet the mass flow criteria of the 27.6-bar steam. The rest will be diverted to the second turbine stage, along with the remaining 27.6-bar steam from Stage 1. Electricity will still be generated by onsite turbines. Developing a steady-state model enables the estimation of the makeup steam needed to replace carbon fuel sources and the power produced by the turbines.

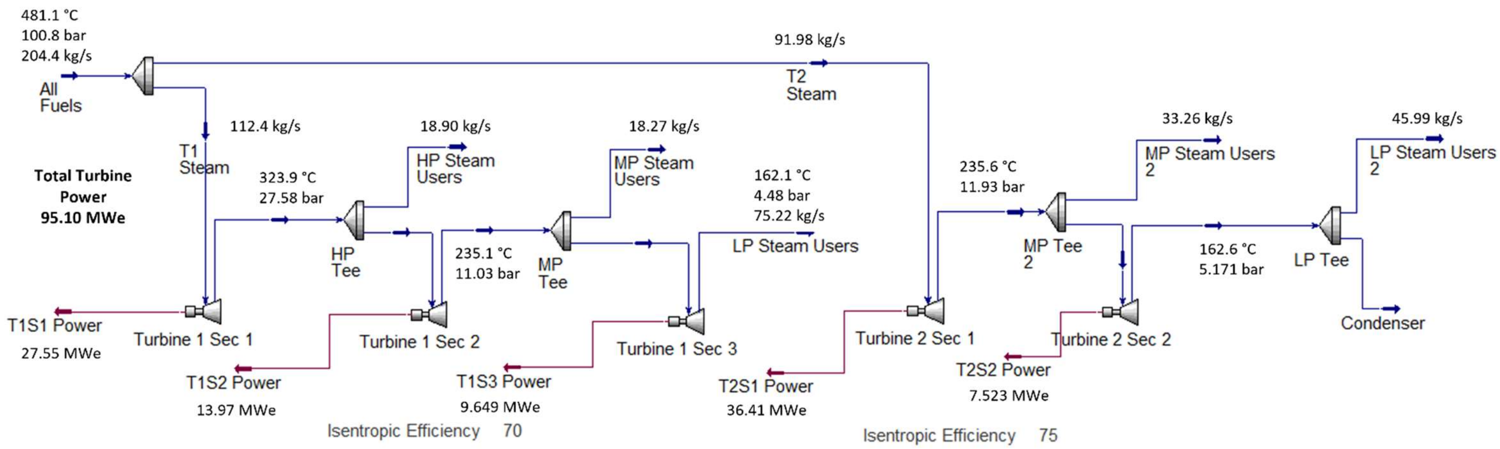

Figure 3. Steady-state model of the mill without SMR integration.

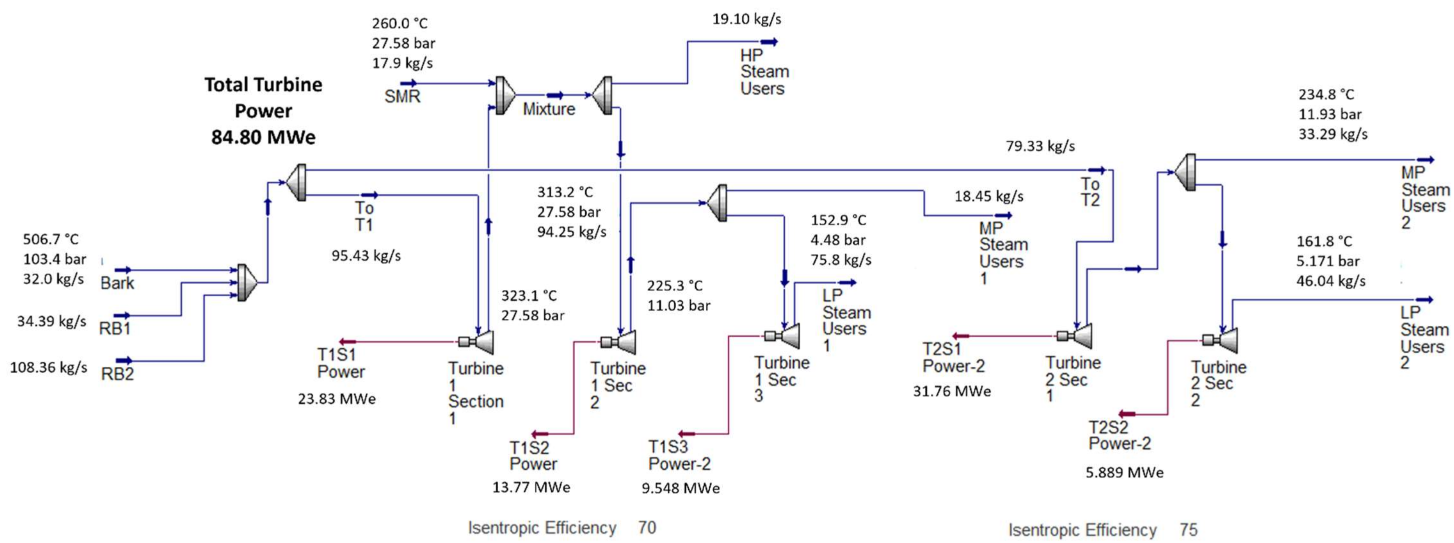

Figure 4. Steady-state model of the mill with SMR integration.

3.2. Lime

The plant analyzed in this study has two natural-gas-fired lime kilns producing a total of 477 metric tons/day of quicklime and utilizing a total of 1.13 m^3/s of natural gas fuel. These represent a significant source of carbon produced onsite and are targets for replacement with fuel-free options. The information given by the plant is shown in Table 2, along with the estimated CO_2 emissions from the lime kiln, based on the 0.79 mtons CO_2 per 1 mton of lime produced [35] and $5x10^{-9}$ mtons of CO_2 per MJ natural gas burned [36].

Table 2. Lime production and natural gas consumption at Plant A.

	Load (mtons/day)	Demand (MJ/mton)	Avg. Natural Gas Use (MJ/day)	Est. CO_2 Emitted (mtons/day)
Lime Kiln 1	181	7380	1,335,780	210
Lime Kiln 2	295	6300	1,858,500	326

An initial means of estimating the additional electrical power needed to convert the lime kilns to electricity is to simply convert the fuel energy into electrical power. An average heating value is 38,488 kJ/m^3 based on data for the Carolinas supplied by the Energy Information Administration [37].

$$Power = 1{,}335{,}780 + 1{,}858{,}500\ \frac{\mathrm{MJ}}{day} = 36.97\ \frac{MJ}{s} = 37\ MWe$$

The 37 MWe calculated via this equation is likely a conservative figure when switching from a fossil-fuel kiln to an electric kiln. Both kilns will circulate air through a heating zone and heat the product as it flows through the barrel and to the exit. A gas-fired kiln also creates water vapor during the combustion process, which essentially leaves the kiln stack as LP steam. These losses account for about 10% of the total fuel fired, based on standard steam tables, heat loss calculations, and data from the U.S. Department of Energy [38]. Therefore, assuming the same amount of air flow, the electrical power increase required for the lime kilns will likely be about 90% of the natural gas energy use, or 33 MWe. The total electrical power demand for the entire plant would then be about 133 MWe.

Although SMR integration would not reduce CO_2 emissions from the lime process itself, it would eliminate CO_2 emissions from natural gas consumption. If the plant operates at 85% capacity during the year (to account for outages and delays), 3.19 million MJ/day natural gas becomes 991 million MJ/year. By replacing the gas lime kilns with electric kilns powered by the SMR, the mill would reduce CO_2 emissions by about 50 thousand mtons/year, the equivalent of more than 123 million miles driven by an average gasoline-powered passenger vehicle [39].

3.3. SMR Sizing and Integration

The estimated 139 MWe represents the power and energy that must be generated onsite (using the proposed SMR) or purchased from the grid. In the current non-SMR system (see Figure 3), the natural gas powered boiler provides the plant with 30.9 kg/s of 103.4 bar steam for process use and power generation, requiring that 12.6 kg/s of LP steam be vented. Depending on the design selected, one or two SMR modules can generate both the power and steam lost due to the natural gas fuel removal.

Using the Aspen model, the power and steam system model with an SMR to supply steam and power predicts that the SMR will need to supply 17.9 kg/s of steam with zero venting of LP steam required. Steam from the existing recovery and bark boilers, plus the 17.9 kg/s from the SMR, can generate 84.8 MWe of power via the turbines. A single SMR module can provide up to about 33.4 kg/s of steam to the process, but since only a portion of this is needed to replace the steam lost from the gas-fired boiler, the SMR can generate over half its rated power.

$$\frac{67.0\ kg/s - 17.9\ kg/s}{67.0\ kg/s} = 73\%\ of\ steam\ to\ generate\ power * 60\ MWe = \mathbf{43.8\ MWe}$$

Therefore, the total electricity generated by the existing turbines and SMR is 128.6 MWe. This leaves the plant 10.4 MWe short, which can be purchased from the grid or generated onsite if some natural gas is fired in either the lime kiln or boiler to generate steam. However, the latter option for onsite generation would not allow for the complete elimination of fossil fuels onsite. A second SMR module can also be considered, but would produce far more power than is needed by the plant—power that could only be sold at wholesale prices.

The model was initialized based on the steady-state models from Section 3.1. The barrier to creating a higher fidelity model is that only high-level operating data were provided by the plant. Conditions and demands within the plant are varied by using proportional integral (PI) controllers. With the data available, it would be impossible to create a physically accurate system. Although the mill has provided data on steam conditions and demand, the data for actual steam demand curves, outage rates of components, losses from transporting steam, and other details are not available. However, this information is not required for this model, because as long as the steam generation system can provide an equivalent amount of steam at an equivalent quality to the original system, the additional systems and losses are the same as well. Therefore, modeling past the steam and power generation is unnecessary for a preliminary assessment of the SMR coupling.

Four steam sources were modeled, feeding into two turbines. Each source is controlled in the model by its heat flow rate in watts. The nominal values of the bark boiler and black liquor recovery boilers are based on the steady-state data provided by the plant. These sources are considered constant because their output is based on the chemical recovery process, which remains consistent even if steam demands change.

Based on data provided by the pulp and paper mill [9] turbine input steam can vary between 40 and 110% of the steady-state intake. Flows can change based on demands for medium-pressure (MP) and LP steam, as well as fluctuations in the cost of electricity. At steady state, the total steam demand from all four sources is 193 kg/s, meaning that the steam demand could vary between 77.1 and 212 kg/s. If the bark boiler and recovery boiler sources remain constant, the SMR would vary between 0 and 18.9 kg/s.

It is important to note that the SMR source is at a lower temperature than the other sources and has a lower specific enthalpy than the original natural gas source. An increased flow from the SMR slightly lowers the heat to the rest of the system. To solve this, a PI controller on either the MP or LP steam line controls the total enthalpy (mass flow rate multiplied by the specific enthalpy), rather than the mass flow rate.

4. Results and Discussion

4.1. Case 1: Baseline Plant Operations

The baseline model for the plant, as shown in Figure 5, has both the recovery boiler and bark boiler steam sources split between two turbines that each feed separate MP and LP steam streams. The first turbine also feeds a high-pressure steam stream. Each steam source is controlled by the total heat demand (i.e., the specific enthalpy of the stream multiplied by the mass flow rate). The LP stream on Turbine 1 (LP1) controls the SMR output, and the LP stream on Turbine 2 (LP2) controls the amount of steam diverted off the original steam sources and into Turbine 2. All five turbine stages are connected to provide the plant with a combined turbine electricity generation. The electricity generation of the turbines is not controlled within the model and is a result of the other requirements.

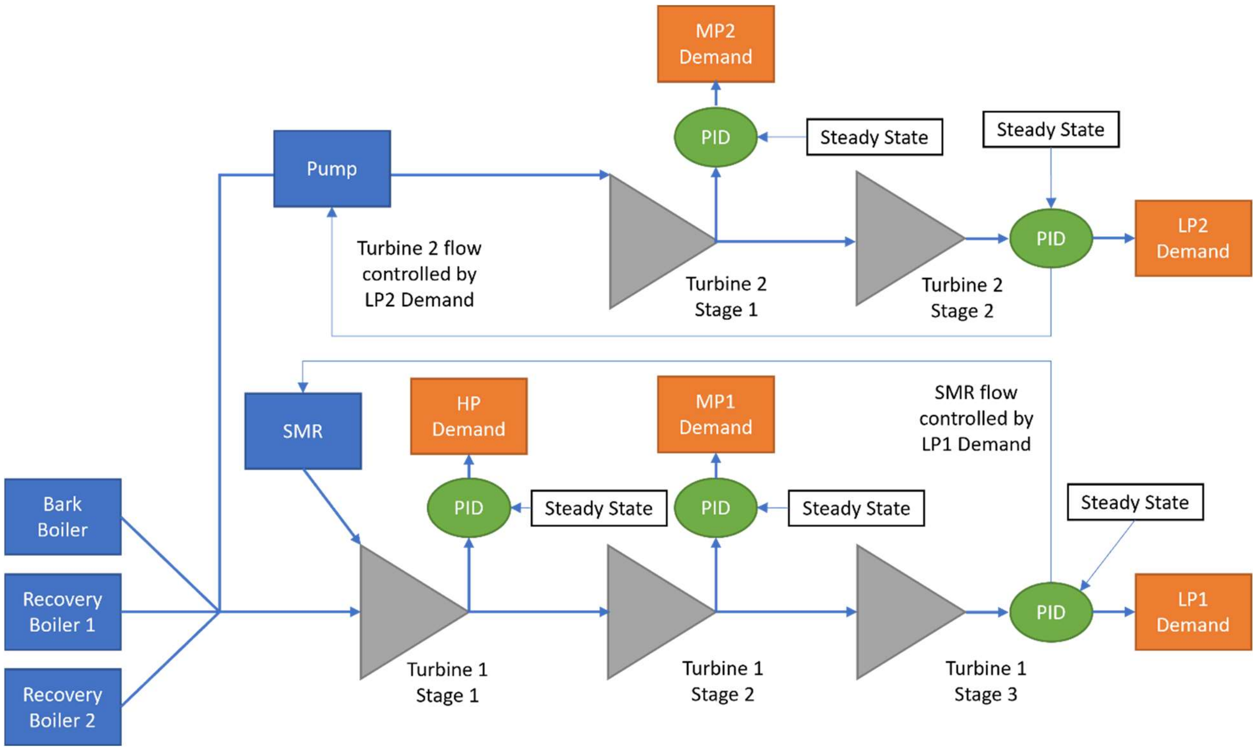

Figure 5. Baseline model of the plant built in Dymola.

The first results needed for verifying the model are the steady-state mass flow outputs of the HYSYS and Dymola models. These results are slightly different from each other. HYSYS and Dymola calculated the steady-state flow from the SMR as 17.9 and 18.4 kg/s, respectively, for a difference of 2.5%. More controlled variables entail a greater risk of variation from rounding errors and differences in the calculation methods.

The other verification point is the combined turbine power of the plant. The HYSYS model calculated the steady-state power as 84.8 MWe, while the Dymola model calculated it as 89.4 MWe, resulting in a 5.4% difference. This is mainly due to the difference in how the two programs perform turbine calculations. HYSYS uses the Peng-Robinson equation of state for fluid calculations in the turbine, whereas the Dymola turbine component uses Stodola's Law. Note that this power output is coming from the steam turbines within the plant and does not include electricity generated by the turbine within the SMR.

The mass flow rate and specific enthalpy of each stream can also be verified, thus helping identify those streams that most account for the difference. The specific enthalpy can be specified for each stream in the model in an attempt to reduce the amount of variation. Table 3 summarizes the differences between the HYSYS and Dymola model calculations. The resulting mass flow shows insignificant error, demonstrating that the heat rates calculated for all streams are identical.

Table 3. Comparison of HYSYS and Dymola steady-state models.

	Specific Enthalpy (kJ/kg)			Mass Flow (kg/s)		
	HYSYS Model	Dymola Model	Difference	HYSYS Model	Dymola Model	Difference
HP Steam	3,034	3,034	0.00%	19.01	19.01	0.00%
MP Steam 1	2,883	2,883	0.00%	18.44	18.45	0.05%
LP Steam 1	2,755	2,755	0.00%	75.80	75.83	0.04%
MP Steam 2	2,901	2,901	0.00%	33.29	33.30	0.03%
LP Steam 2	2,779	2,779	0.00%	46.04	46.07	0.07%

4.2. Case 2: Steam Demand Changes, No SMR Flow Limits

In the second case, the steam demand fluctuates without setting flow limits on the SMR; it is simply controlled by the steam demand of the LP1 stream. The model first runs in steady state to initialize itself, then the steam demand fluctuates. Figure 6 shows the complete model setup for this case.

The steam demand changes are modeled in Dymola using a trapezoidal signal. While the minimum and maximum steam demands correspond to real data from the plant, the typical rate of load changes is unknown. The signals, as summarized in Table 4, are intended to illustrate as many plant demand combinations as possible in order to visualize how much these demand changes affect the steam demands from the SMR to the mill, as well as the changes in power output from the turbines.

This dynamic analysis includes some assumptions based on the steady-state models, such as the two recovery boilers and bark boilers remaining at the nominal output. When steam demands in the plant decrease, the excess steam is vented from the plant while the chemical recovery process continues. The boiler ramp rate for an increase in steam demand is unknown, but a benefit of the SMR integration is efficiently responding to these demand changes. The SMR ramp rate is dependent on the design of the secondary side of the SMR, including the main steam offtake and heat exchanger. A TES system or steam accumulator could be included to foster quick response rates. A more detailed analysis using real-time demand curves from the plant would determine the needed response rates and the design of the secondary side. Another strategy would be to take off a consistent amount of steam from the SMR regardless of demand, and vent any excess steam as is currently the mill's strategy. While this would not help improve the thermal efficiency of the mill, it would be safe for the SMR and still achieve the goal of replacing steam from natural gas combustion. These ideas are more completely explored in the dissertation by Worsham [40].

Because the Dymola model is time dependent as well as moderated by PI controllers, a degree of error exists between the heat demand requested by the controller and actual heat demand response from the model. Figure 7 illustrates the curves described in Table 4 for each stream's demand versus the actual flow rate calculated by the model. The vertical line labels the heat flow (in MWth) of each stream at what appears to be the largest deviation of the actual flow rate from the demand rate. For all the cases, the steam demand versus the actual heat rate proved very similar, with only small differences in the two LP streams. These differences can be minimized by increasing the gain in the controllers to enable a faster response time. However, in models such as this, which feature many controlled variables, the gain can only be increased to a certain point without restricting the model calculations. Figure 7 shows that, even at a higher gain, places remain in which the actual calculation differs from the desired demand. Table 5 shows approximate values for the largest differences in each stream at the highest possible gain.

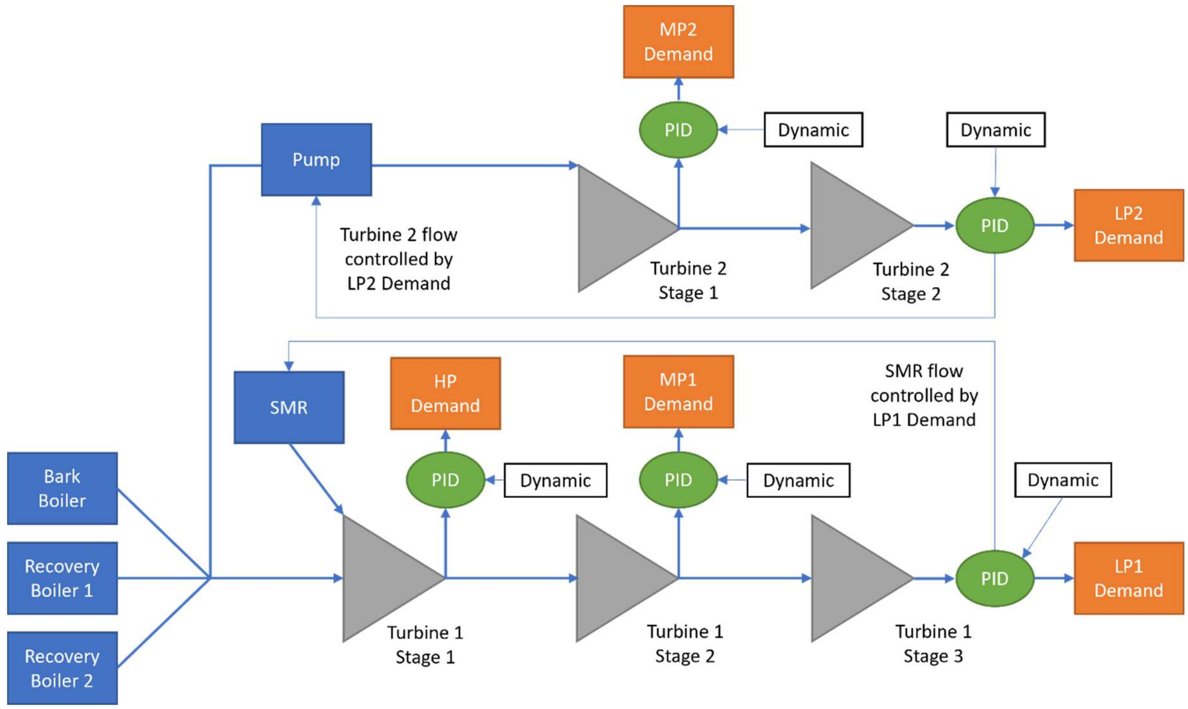

Figure 6. Case 2 model in Dymola.

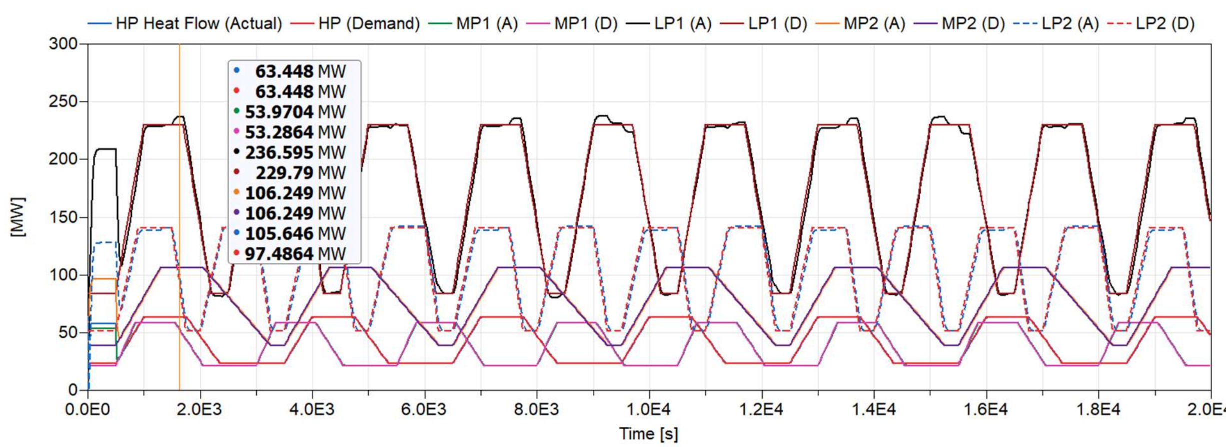

Figure 7. Heat out demand curves (D) versus actual model (A) calculations.

Table 4. Trapezoidal heat demand source curve for Case 2 and 3.

Parameter	HP Steam	MP1 Steam	LP1	MP2	LP2
Amplitude	[HP Steam Nominal Heat Demand]*0.7	[MP1 Steam Nominal Heat Demand]*0.7	[LP1 Steam Nominal Heat Demand]*0.7	[MP2 Steam Nominal Heat Demand]*0.7	[LP2 Steam Nominal Heat Demand]*0.7
Rising (s)	500	350	500	800	400
Width (s)	750	700	700	750	600
Falling (s)	600	500	500	1,200	250
Period (s)	3,000	2,500	2,000	3,000	1,500
Offset	[HP Steam Nominal Heat Demand]*0.4	[MP1 Steam Nominal Heat Demand]*0.4	[LP1 Steam Nominal Heat Demand]*0.4	[MP2 Steam Nominal Heat Demand]*0.4	[LP2 Steam Nominal Heat Demand]*0.4
Start Time (s)	500	500	500	500	500

Table 5. Heat out difference at maximum deviation from demand.

	HP	MP1	LP1	MP2	LP2
Demand (MWth)	63.45	53.29	229.79	106.25	97.49
Actual Output (MWth)	63.45	53.97	236.60	106.25	105.65
Difference	0.0%	1.3%	2.9%	0.0%	7.7%

In a more detailed study on how these steam changes affect the system, these errors could prove highly significant. In this study, however, there are only two major points of interest: the point at which all streams are at the maximum demand and the point at which they are at the minimum demand.

At these two points, the errors are very small, meaning that the data collected at these two points are as accurate as the model itself. The vertical lines in Figure 8 correspond to the selected points at which all demands are at the maximum and minimum. Table 6 shows the corresponding difference between the demand and actual output at the maximum demand. Table 7 shows the corresponding difference between the demand and actual output at the minimum demand.

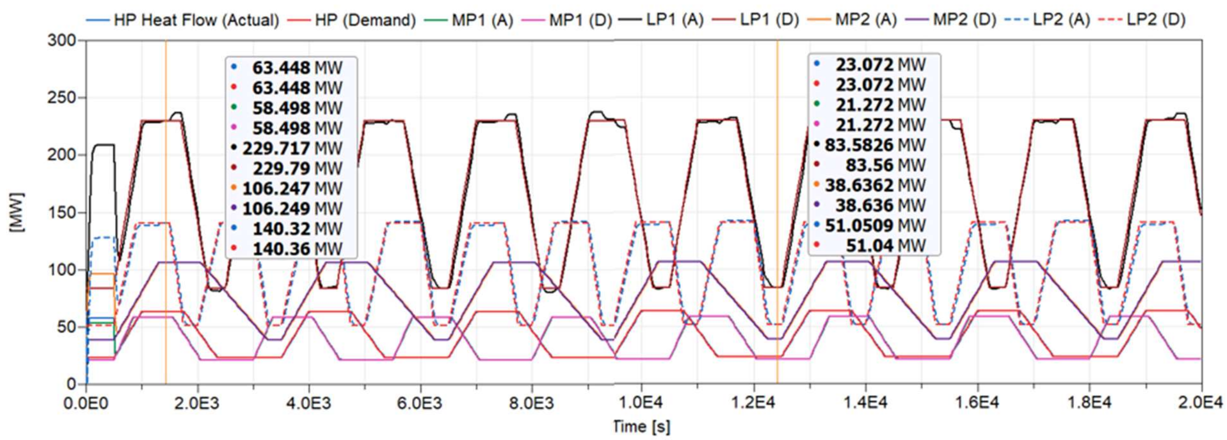

Figure 8. All streams at maximum and minimum demand.

Table 6. Error at the point of maximum demand.

	HP	MP1	LP1	MP2	LP2
Demand (MWth)	63.45	58.45	229.72	106.25	140.36
Actual Output (MWth)	63.45	58.45	229.79	106.25	140.32
Difference	0.00%	0.00%	0.03%	0.00%	0.03%

Table 7. Error at the point of minimum demand.

	HP	MP1	LP1	MP2	LP2
Demand (kg/s)	23.07	21.27	83.56	38.64	51.04
Actual Output (kg/s)	23.07	21.27	83.58	38.64	51.05
Difference	0.00%	0.00%	0.03%	0.00%	0.02%

This case is intended to show the SMR response with no limits or restrictions, and thus the results show this is a physically unrealistic case. When the steam demand for all streams is at the minimum, the SMR stream has a reverse flow of 768,000 lb/hr (97 kg/s), which would be physically impossible for the system. Even if the SMR was removed, the plant would still generate a large surplus of steam when the demands are at the minimum. This situation would require the other boilers to throttle back production or otherwise vent unneeded steam into the atmosphere.

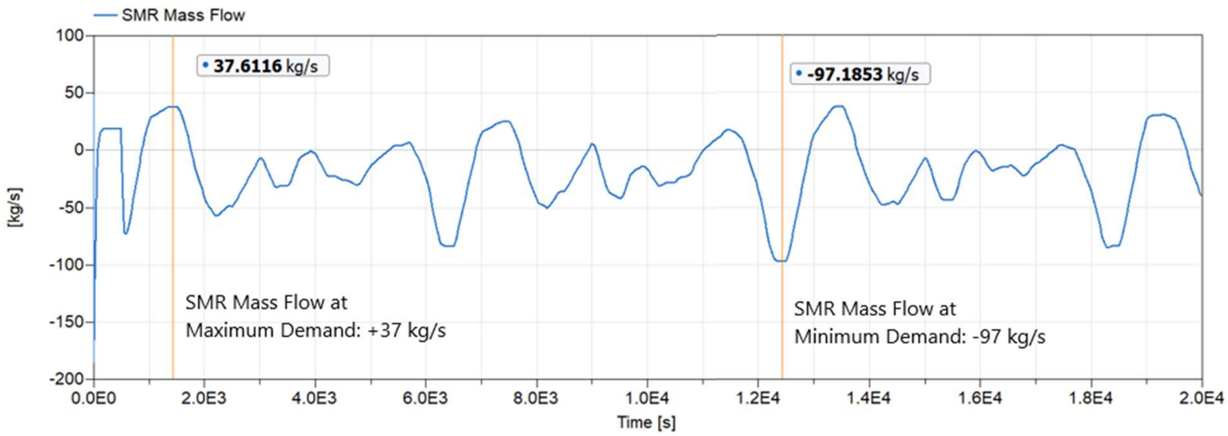

Figure 9. SMR steam flow when all demands are at minimum and maximum.

Per Figure 9, when all streams are at the maximum demand, the steam flow required from the SMR in order to meet their demands is 298,000 lb/hr (37.6 kg/s)—more than double the steady-state steam requirement. Though this is a good estimate of the possible maximum demand needing to be met by the SMR, the negative flow rates generated in this case make this configuration impossible.

While the steady-state requirement is too high for times of minimum demand in the plant, it is also well below the necessary amount of steam to meet the highest demands. The vertical line in Figure 10 indicates the mass flow for each stream necessary to meet the heat demands. This result reveals how great the demands of LP1 are compared to the rest of the streams. LP1 has a 40% higher mass demand than LP2, which is the next highest stream demand. LP1 also has the largest range of heat demands, and this range is likely the largest contributor to the swings in SMR demand as the heat demands for each stream change.

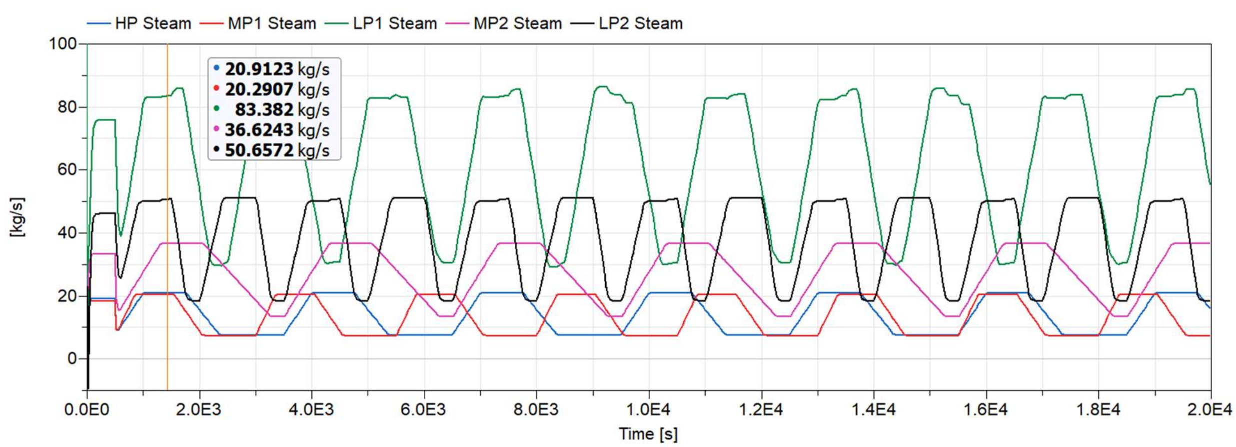

Figure 10. Steam demand of each stream in Case 2.

One last point of discussion is the change in the stream's specific enthalpy, due to the addition of the SMR steam supply (see Figure 11). Because the SMR steam contributes significantly less mass than the other steam sources, the difference is minor.

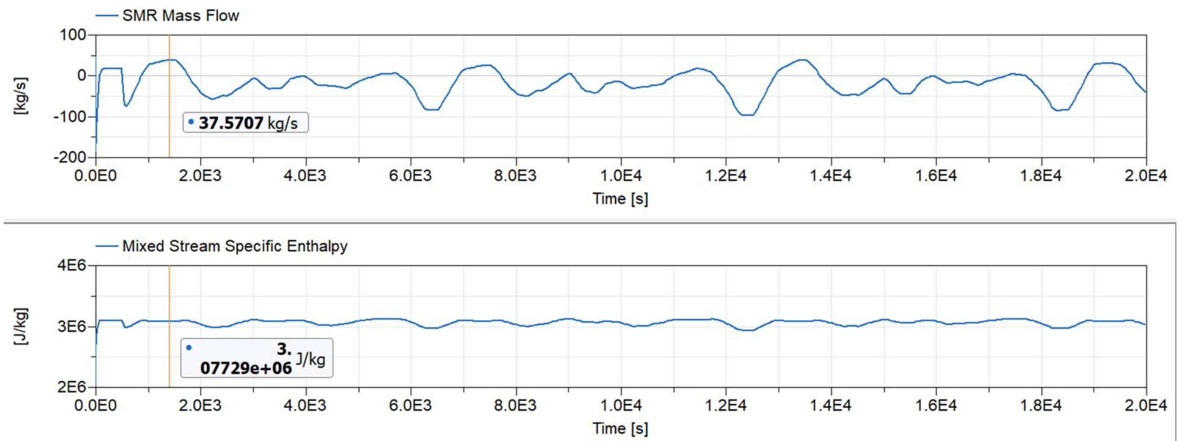

Figure 11. Specific enthalpy of steam flow versus SMR flow rate.

4.3. Case 3: Demands Change, SMR Remains at Steady-State Operation

In Case 3, the model represented in Figure 12 initializes using the demand values from Case 2, then the SMR operates at the steady-state flow rate also seen in that figure. Except for LP1, all the actual heat outputs from the stream closely match the demand curve since they are controlled elsewhere in the model. By comparing the LP1 actual curve against the demand curve, one can estimate the amount of heat wasted or amount needed to meet the plant's total demand when the SMR is running at steady-state operation. It is also known from Case 2 that LP1 has the largest individual impact on demand swings in the plant. Case 3 uses the same demand curve as Case 2.

Figure 13 shows the difference between the LP1 steam demand (blue curve) and supply (green curve). Where the green curve is above the blue curve, there is a surplus of heat that will be vented from the plant. At one point, the demands of all streams are at the maximum (110% of nominal), while the SMR is running at the steady-state flow rate. At this point, the heat deficit in the plant is 53 MWth. The combined turbine plant power is 88.4 MWe (Figure 14), which is close to the steady-state plant value of 89 MWe. Although the single SMR module cannot meet the demands of the plant, the absence of large variations in turbine power help maintain stability in plant operations.

When all the demands are at their minimum point in Figure 13, the plant produces 318 MWth of surplus heat. The combined turbine power is 101 MWe (Figure 14), which is much higher than the steady-state power value. Although keeping the SMR at the steady-state value sometimes increases the turbine power of the plant and thus decreases the amount of electricity the plant must buy to meet its electricity demands, the wasted heat decreases the efficiency of the plant, and the periods when the SMR's steady-state rate cannot meet demands will cause production and quality issues within the plant.

As mentioned in Section 1, it is most economical to maintain the SMR at steady-state operation, but this nominal value does not always meet the plant's needs in terms of demand and efficiency. One way to improve the economics and performance of the SMR integrated with the plant is to incorporate a TES system to allow for the delayed delivery of heat and electricity when plant demands increase. The addition of thermal storage would increase plant efficiency by reducing excess steam production and assisting the plant in times of peak load. However, the charging process causes significant variations in the power production of the plant, and once the storage system is fully charged, the plant will have to vent the surplus heat. The discharge process, however, keeps the electric production stable. A plant like the one studied here may not be able to sustain the swing in electricity loads because the mill relies on this electricity for its normal operations, or they may be undesirable because of increased electricity costs. Another disadvantage is that the SMR nominal load may need to be increased because steam would need to be flowing through the heat exchangers at all times. Adding the TES would also increase equipment costs and complicate the controls needed to operate the plant. The feasibility of the TES system will depend on the ability of the plant to tolerate heat and electric load swings, the plant electric power needed, and cost limitations. Apart from the TES systems suggested in this study, there are also other methods, such as concrete storage, that can be studied to find a configuration that works best for the plant.

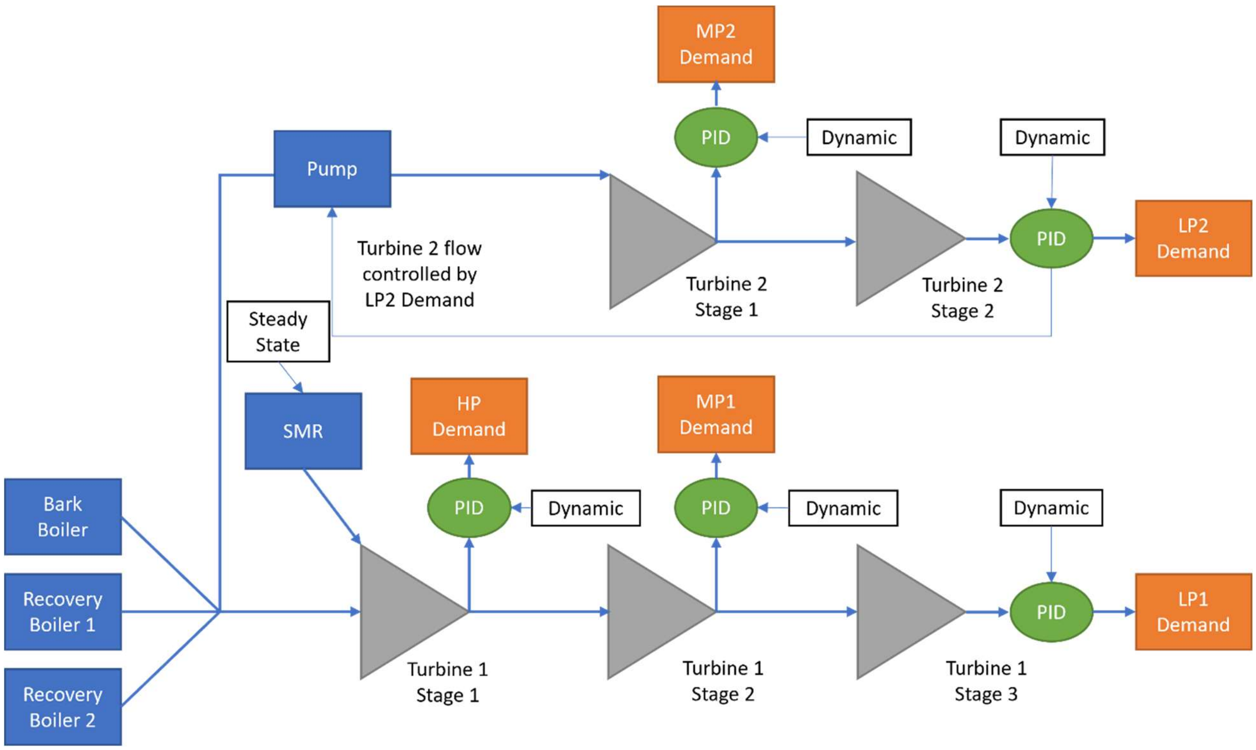

Figure 12. Case 3 model in Dymola.

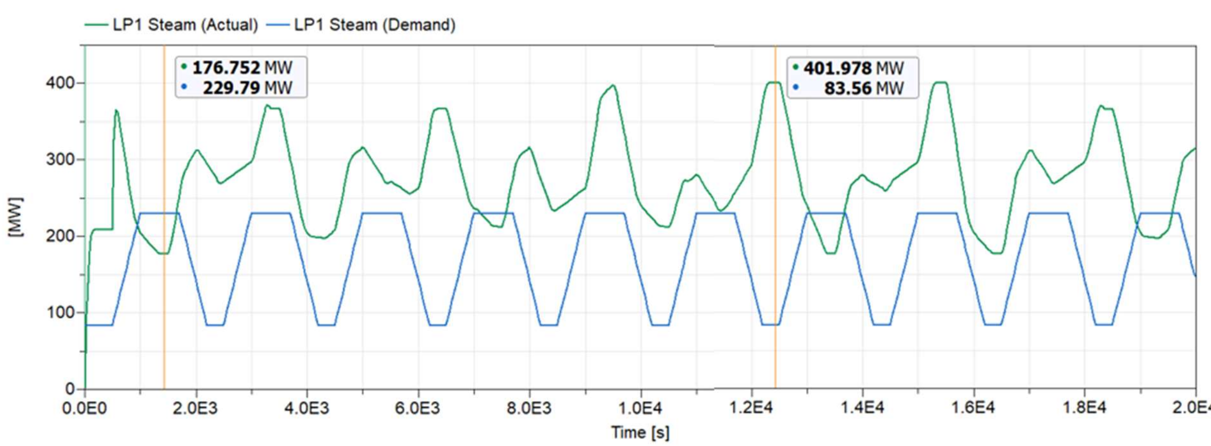

Figure 13. LP1 heat demand curve versus actual output when all demands are at the highest and lowest points.

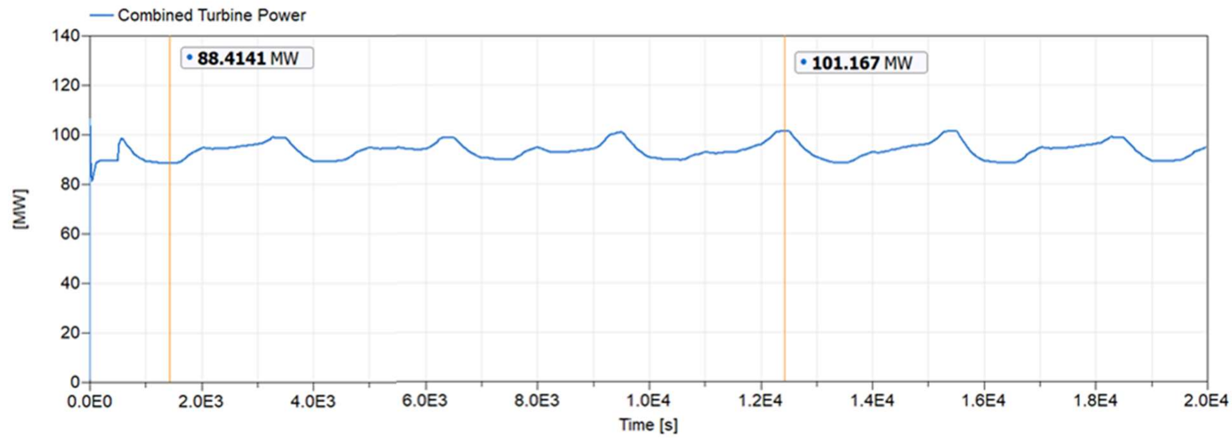

Figure 14. Combined turbine power when all demands are at the highest and lowest points.

4.4. Thermal Energy Storage Design

In the dissertation by Worsham, A thermal energy storage system (TESS) was designed for the mill to alleviate steam variations within the plant due to changes in demand. The inlet to the storage system was placed where the SMR and original steam stream is combined and the HP steam is taken off. This allows the TESS to take off as much steam as needed to meet the demands of the HP, MP1 and LP1 streams.

For a typical manufacturing application, a steam accumulator would be recommended because of the ease of integration with the rest of the system. However, there would be some challenges with sizing the accumulator if the plant does not have a regular pattern of steam peaking. Steam accumulators are also significantly more expensive than other designs explored for NPPs, including concrete, molten salt, and thermal oil storage [26]. These are all still options that any plant should explore. In this specific case, in keeping with INL program goals, a two-tank sensible heat storage system was designed for the dynamic model.

Figure 15 is a two-tank system with Therminol 66 as the heat transfer fluid. During times of low demand, steam can be redirected to an intermediate heat exchanger that passes heat to a thermal fluid, which is then stored in a "hot tank" until additional steam is needed. During times of high steam demand, the thermal fluid passes through a steam generator with feedwater on the other side. The feedwater could be preheated by other process steam before passing through the steam generator to increase efficiency.

The final design is in Figure 15, using charging steam from the combined source stream after the first Turbine 1 stage. The proposed design includes 4 hours of steam discharge capacity, with a steam outlet temperature of 200°C. The increased outlet temperature will give a longer charging time and reduce the area required in the heat exchanger. Condensate exiting the IHX could be used to preheat the feedwater entering the steam generator. The tank volume in the design is the approximate volume of Therminol increased by 10% because some mass will always be flowing through the system.

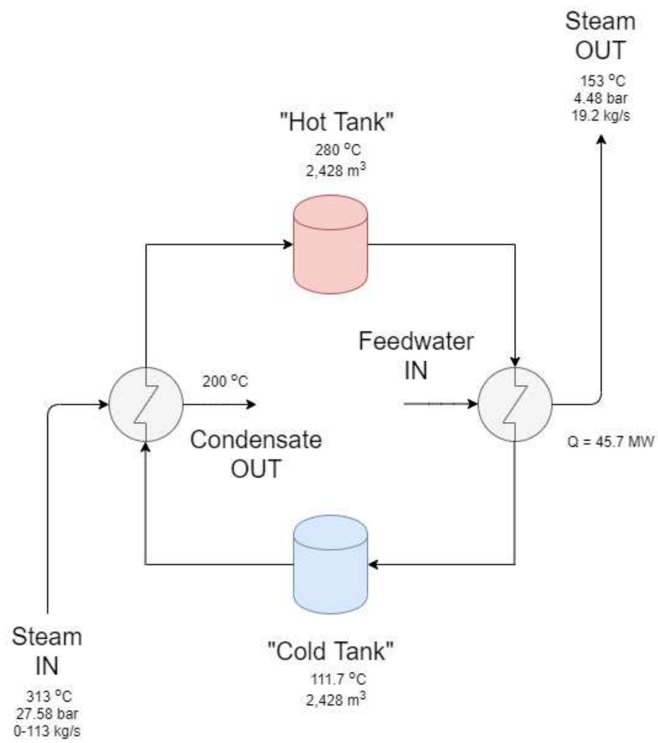

Figure 15. Proposed TES system for Plant A.

The model for Case 4 first initializes in steady state before switching the demand control for LP1 to the TES system. The TESS diverts steam from the mixed source stream (SMR, recovery boiler and bark boiler) before the HP steam stream. When steam goes through the TESS, the charging block calculates the amount of Therminol that would pass through to complete the heat transfer using the calculations from the dissertation by Worsham [40]. Once the TESS has the maximum amount of Therminol stored, the steam that goes through the TESS would be vented instead.

The demand source curve from Figure 10 is changed here so that demand only varies from the lowest point to the nominal point. If the steam flow were to go above the nominal point, the thermal storage would need to be discharged. When all the demands are at their lowest, the TESS diverts 116 kg/s of steam, as shown in Figure 16. This diversion increases the overall efficiency of the plant and allows the heat generated by the plant to be used during times of higher demand via the TESS. Figure 17 shows how the steam into the TESS changes in relation to the heat out for each stream. When the curves are not all either at the lowest or nominal demand, the flow in is in the range of 50 kg/s.

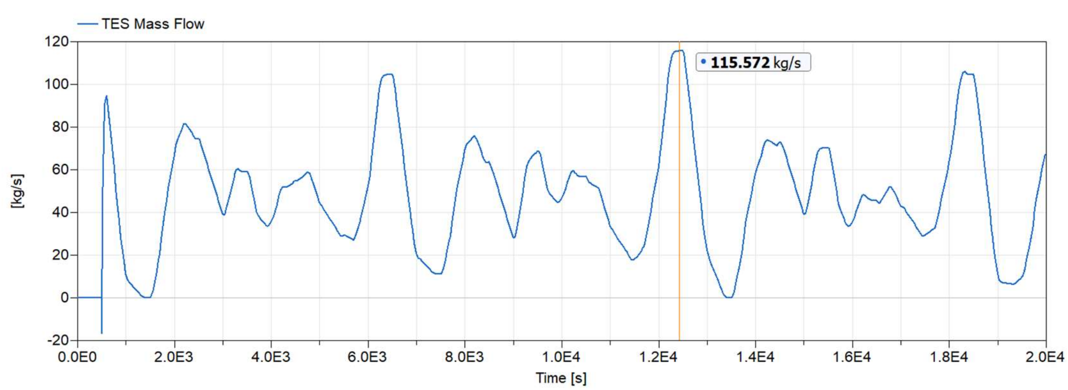

Figure 16. Steam flow into TESS when all demands are at lowest.

Using these specific demand curves, Figure 18 shows the TESS charge time. The system is fully charged at 6,200 seconds (beginning charging at 500 seconds), or 1.7 hours. The charge time will vary based on the actual demands within the plant. In this case, the plant power varies between 89.4 MW when all the streams are at their steady-state demands and 82.3 MW when the streams are at their lowest demands and the TESS is diverting the maximum amount of steam. This range is smaller than the range in Case 2.

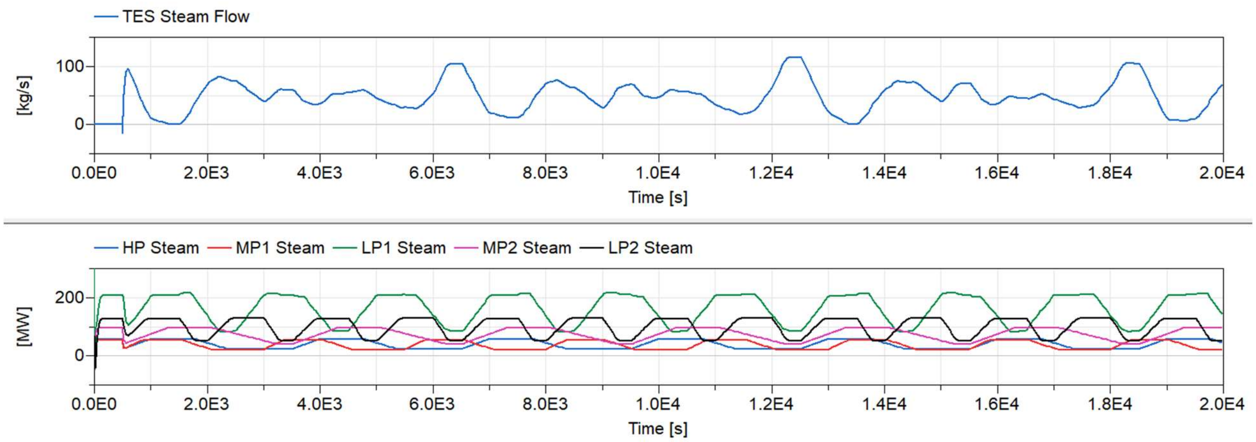

Figure 17. Steam flow into TESS versus demand curves.

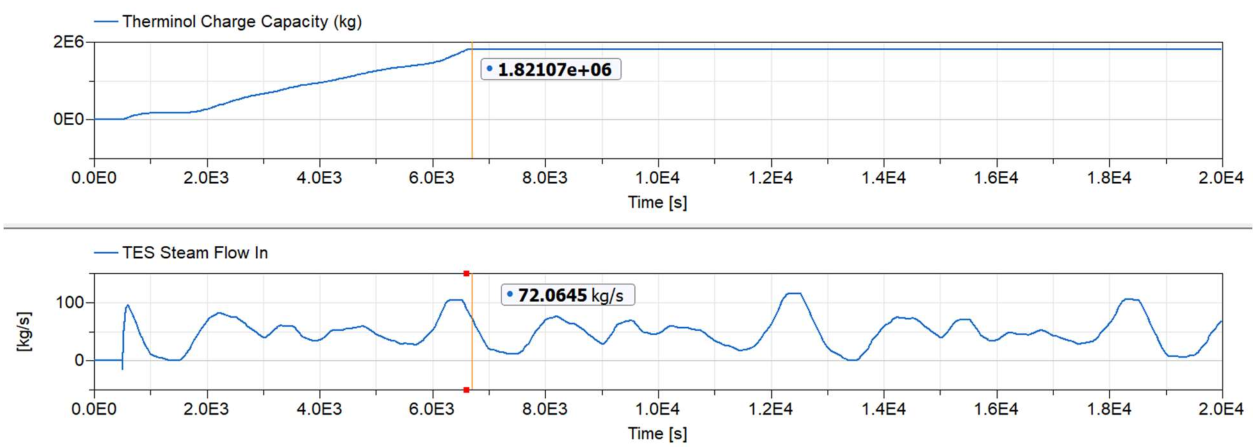

Figure 18. Charge time and instantaneous mass flow for TESS using Case 4 demand curve.

4.4.1. Case 5: Discharging the Thermal Storage System

The model for Case 5 is similar to the others in that it first initializes in a steady state. The TESS injects into the LP1 stream directly. When steam goes through the TESS, the charging block calculates the amount of Therminol that would pass through to complete the heat transfer using the calculations the dissertation by Worsham. The linear relationship is calculated from the heat transfer needed in the steam generator to bring the steam to the correct conditions depending on the mass flow rate of steam.

The difference from Figure 10 is that the demand only varies from the nominal point to the highest point, which means that TESS discharge is effectively 0 kg/s when all the demands are nominal. While this is good for model verification, realistically, there will always have to be some steam flow going through the TESS to maintain the heat exchanger.

For this specific demand curve, the TESS fully discharges at 25,000 seconds (beginning discharge at 500 seconds), or 6.9 hours, shown in Figure 19. This is longer than the design discharge time of 4 hours, because the demands are not at a maximum the whole time. In this case, the power varies very little between demands because the steam is discharged directly into the LP1 stream rather than into a turbine. The minor changes in power are due to changes in steam flow that goes out through the HP and MP1 streams. Overall, the range of power production is about 1 MW.

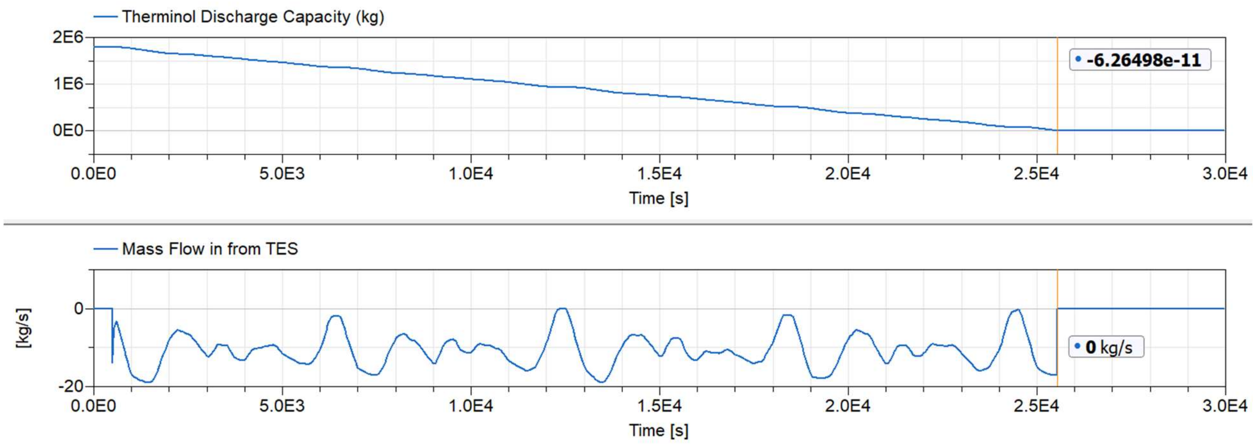

Figure 19. Actual discharge time and mass flow based on demand curve for Case 5.

5. Conclusions

The main requirements for sustainably integrating a steam source with any manufacturing plant is maintaining power and steam loads throughout the plant while adjusting to daily variations. An SMR can meet these requirements, but some adjustments to the plant will be required to increase the efficiency and cost effectiveness of the integrated system. The first adjustment would be to add a TESS. The plant's current strategy is venting excess steam at times of low demand. A TESS would increase the thermal efficiency of the entire plant regardless of an SMR integration. An additional analysis is needed to determine the optimal TESS size and how it could decrease fuel costs to the plant over time.

An SMR integration also presents potential problems in meeting steam and electricity requirements. Due to the limited amount of steam that can be taken off the nuclear steam supply in each module, it is difficult to optimize the ratio of steam to electricity provided to the plant. There are a few solutions to this, including setting up a power purchase agreement or partnership with a local utility that may already have experience with nuclear assets. This could increase plant profits and help pay back the cost of purchasing the SMR. Additionally, the benefit of the economy of multiples, as applied to additional SMR modules, may make a good economic decision for the plants. An alternative solution is to choose an SMR design specifically for process heat applications. This solution may also provide other benefits to the plant, including decreased costs and the availability of higher temperature steam. Although clustering SMRs with different industry partners has not been done in practice, the research on cogeneration presented in the introduction show that it is not only technically possible but desirable to increase utilization and improve reactor economics. Further analysis would determine the benefits of alternative SMR design integrations.

Preliminary conclusions from this work suggest that, while integrating SMRs with pulp and paper mill steam systems is technically feasible, further modeling and economic analysis would determine the most suitable SMR design for the plant and cost of modifications. The factors affecting the sizing of the SMR modules for a particular plant include fixed internal steam generation processes (e.g., the chemical recovery process of the paper mill), a large steam but small electricity demand, and differences between the SMR steam pressure and current boiler pressure. Exploring the integration of SMRs with various manufacturing sectors and different types of plant operations will frame the potential applications for SMRs while also building awareness of the technology and fostering relationships between researchers and industry leaders.

6. Acknowledgements

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