INL/CON-23-73801-Revision-0

Case Study: NuScale Integrated Pulp and Paper Mill

July 2023

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Case Study: NuScale Integrated Pulp and Paper Mill

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Agenda

- Part I: Overview, Project Purpose, and Limitations
- Part II: Steady-State Analysis
- Part III: Dynamic Analysis
- Part IV: Future Work

Project Motivation

- The Integrated Energy Systems (IES) program is researching decarbonization opportunities for industrial power systems.
- Pulp and paper mills have the potential to become carbon neutral or carbon negative because most of the fuel comes from biomass.
- As of 2020, Idaho National Laboratory (INL) was planning to use one module from the Carbon Free Power Project (CFPP) partnership between NuScale and Utah Associated Municipal Power Systems (UAMPS) for demonstration purposes.

What did I do?

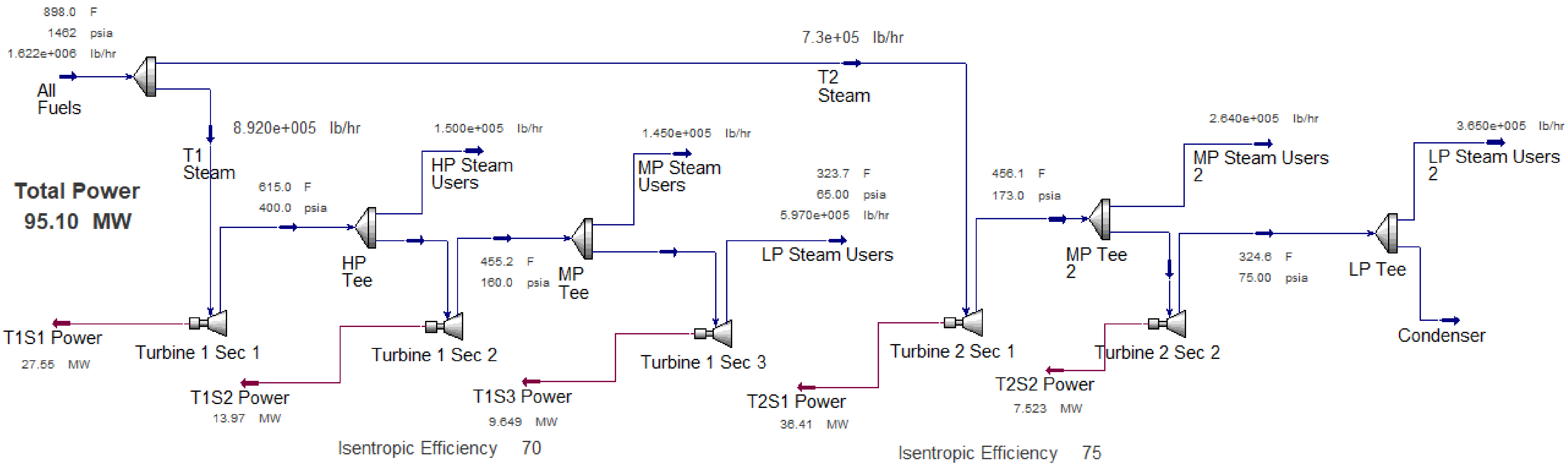
- Used steady-state data from operating paper mills in the Southeastern United States
- Modeled the plant’s steam systems from generation to end use
- Implemented a NuScale reactor to replace natural gas or fuel oil inputs
  - Determined best place to inject small modular reactor (SMR) steam
  - Calculated turbine power output changes
  - Calculated increased electricity demands by switching to electric lime kilns
  - Designed and implemented two-tank sensible heat storage

What did I not do?

- Implemented alternatives to black liquor combustion
  - Results seemed conclusive that gasification would alter the chemical process too much—out of scope
- Eliminated bark burning
  - The goal of this project was to create a “carbon-neutral” system which could include wood waste
- Used actual operating curves to predict results
  - A typical minimum/maximum flow rate through each turbine was implemented to give an idea of how rates may change throughout the plant
- Considered other nuclear power plant (NPP) designs
  - At the time, INL had more data on the NuScale design and wanted to simulate potential demonstration cases

Plant A without SMR Integration

85% of steam produced by carbon-neutral wood waste



High Pressure (HP)   Medium Pressure (MP)   Low Pressure (LP)

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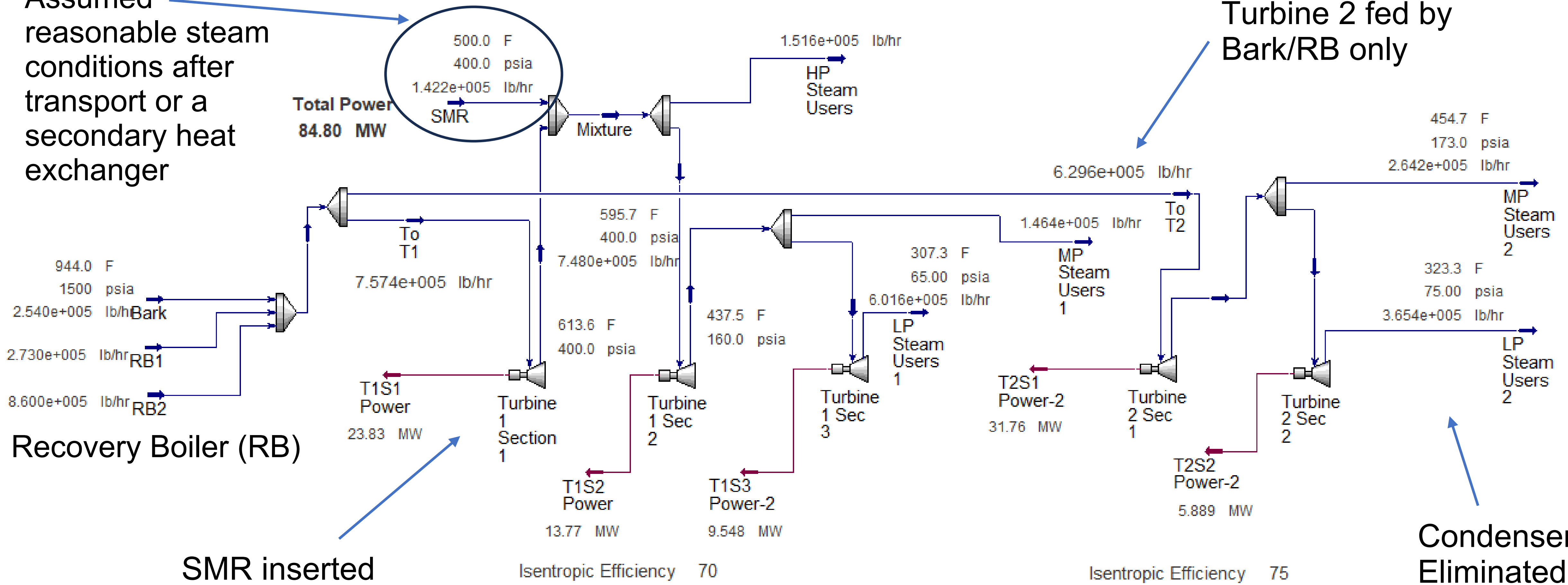
Plant A with SMR Integration

Assumed reasonable steam conditions after transport or a secondary heat exchanger

Turbine 2 fed by Bark/RB only



Recovery Boiler (RB)

SMR inserted after first turbine section

Condenser Eliminated

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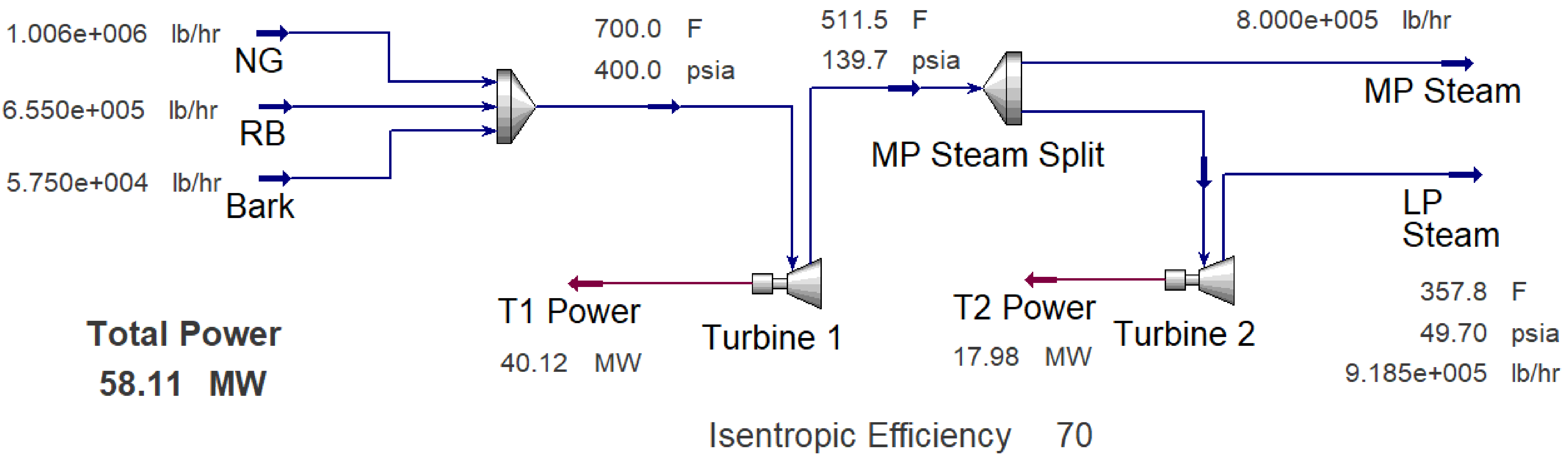
Plant B without SMR integration

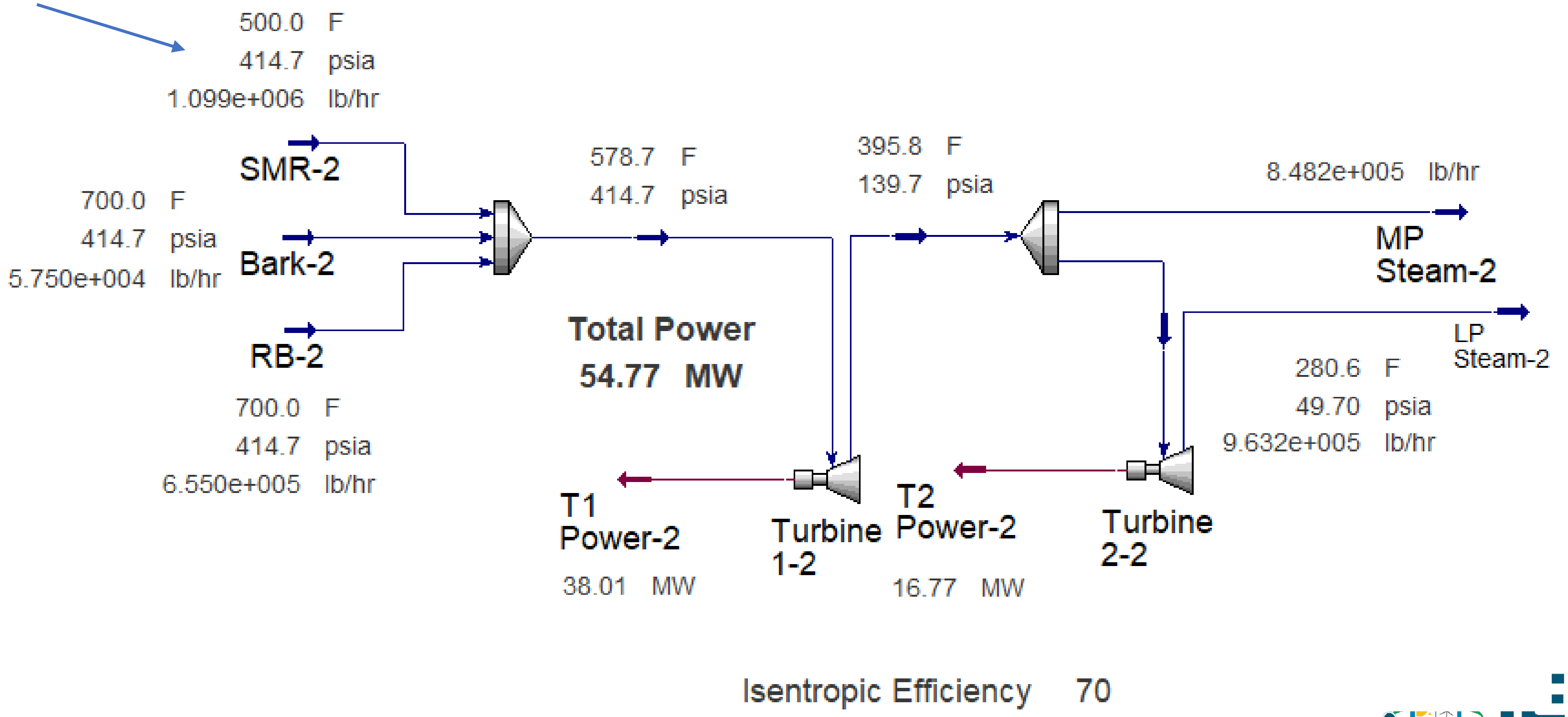
36% of steam produced by carbon-neutral wood-waste.

Recovery Boiler (RB)
Natural Gas Boiler (NG)



Plant B with SMR integration

SMR replaces NG source directly



Plant Module Sizing

	Plant A	Plant B
Original Steam Demand	1,622,000 lb/hr	1,718,500 lb/hr
New Steam Demand	1,529,200 lb/hr	1,811,500 lb/hr
SMR Steam Makeup	**142,200 lb/hr**	**1,099,006 lb/hr**
Max Steam Production per module (assuming 50% steam takeoff)	265,923 lb/hr	265,923 lb/hr
Modules Required	0.54 (**1**)	4.13 (**5**)
Est. Electricity Available from SMR*	1 – 0.5*0.54 = 0.73 *60 MW = **43.8 MW**	5 – 0.5*4.13 = 2.9 *60 MW = **174 MW**

*This is a rough estimate. We have a tool at INL now to explore how steam extractions affect the turbine performance!

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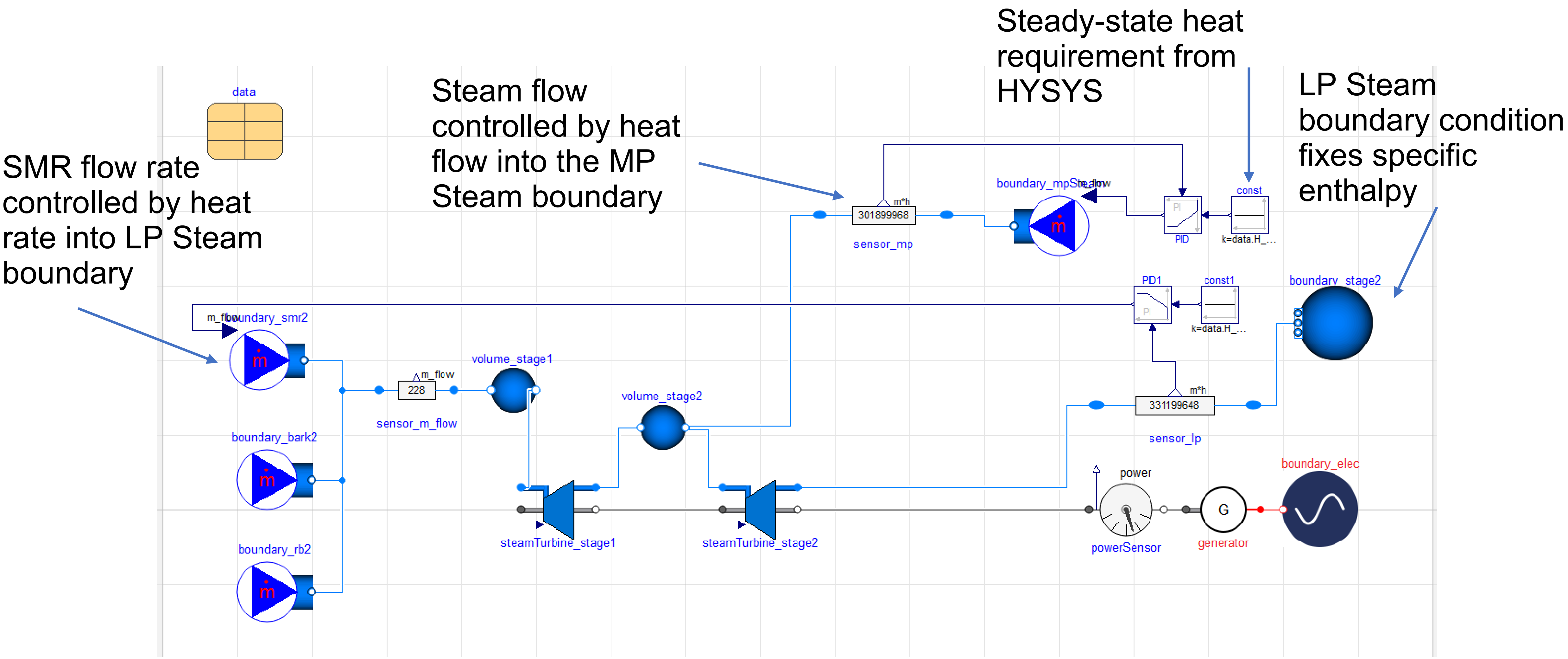
Electricity Production from SMR Integration

	Plant A	Plant B
Installed modules	1	5
Capacity required for steam demand	0.27	2.065
Electricity production from SMR	43.8 MW	174 MW
New electricity production from turbines	84.8	54.77
Additional lime kiln demand	37 MW	28 MW
Original plant demand	100 MW	83 MW
Total generation	129 MW	231
Total demand	137 MW	111
Difference	-8 MW	+120 MW

Dynamic Modeling

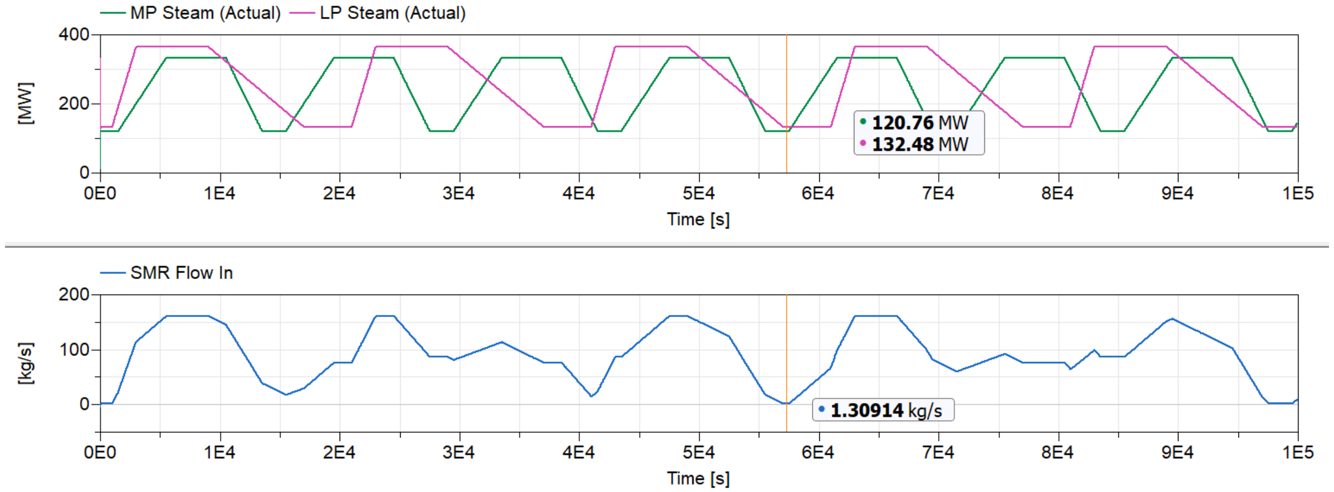
- Models in Dymola based on a steady-state initialization matching the HYSYS models.
- HYSYS: Mass and energy conservation modeling
- Dymola: Mass, energy, and momentum conservation modeling
- Limitation of only high-level operating data provided from the plants. Physically accurate system is impossible to create; models satisfy functional requirements for an illustration of plant operation

Plant B Modelica Model



Steady state flow all sources: 229 kg/s

Demand Flow Rate Strategy



Parameter	LP Steam	MP Steam
Amplitude	[LP Steam Nominal Heat Demand]*1.1 – [LP Steam Nominal Heat Demand]*0.4	[MP Steam Nominal Heat Demand]*1.1 – [MP Steam Nominal Heat Demand]*0.4
Rising (s)	2000	4000
Width (s)	6000	5000
Falling (s)	8000	3000
Period (s)	20000	14000
Nperiod	-1 (inf)	-1 (inf)
Offset	[LP Steam Nominal Heat Demand]*0.4	[MP Steam Nominal Heat Demand]*0.4
startTime (s)	1000	1500

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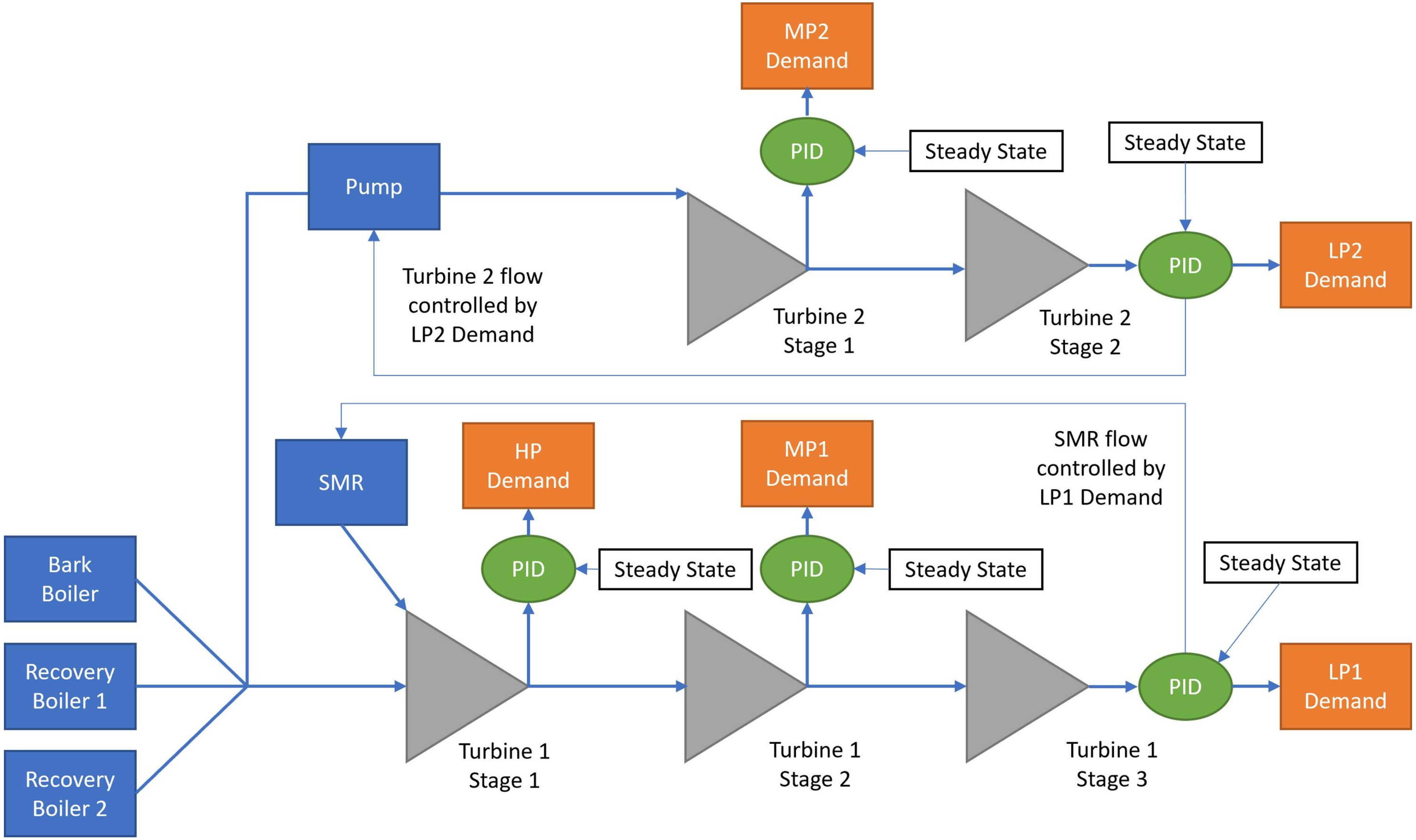
Plant A Case 1: Baseline



Initialize the model to the Aspen steady state conditions

Purpose: model verification

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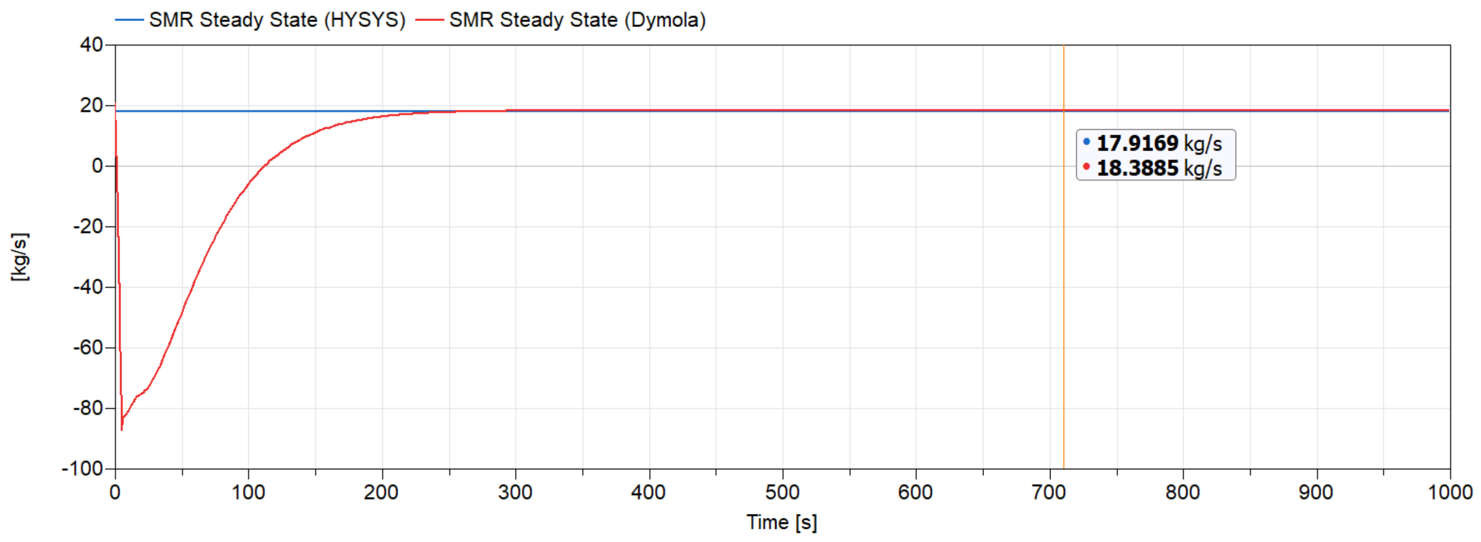
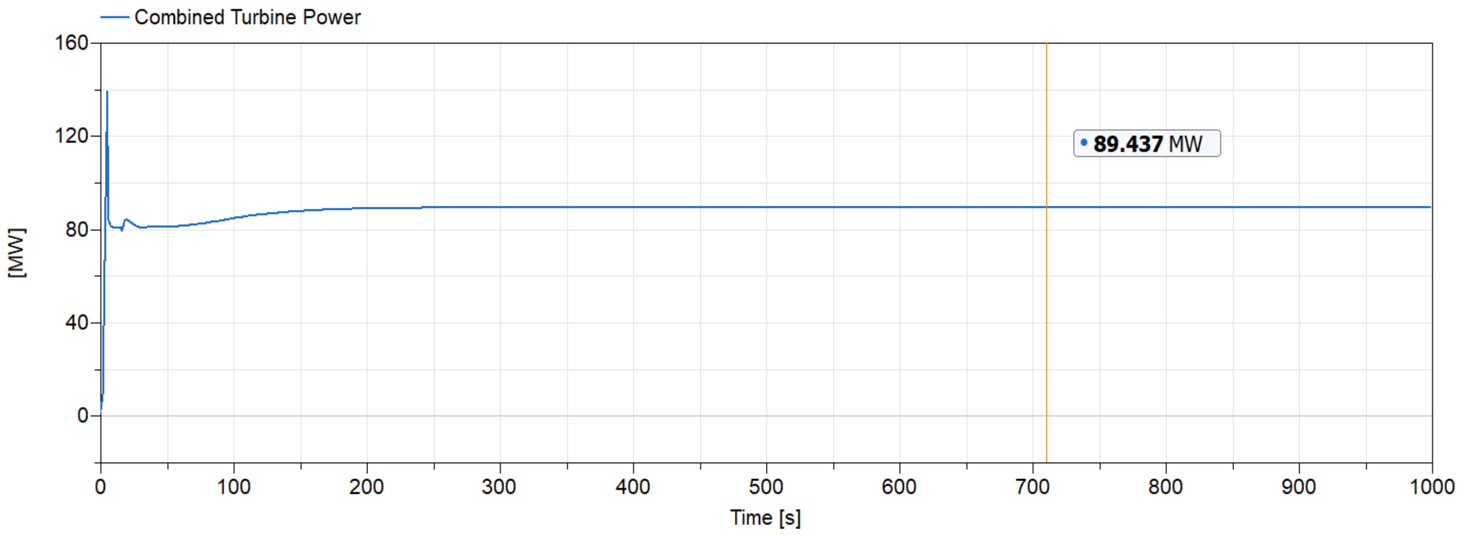
Dymola vs. HYSYS Model Results

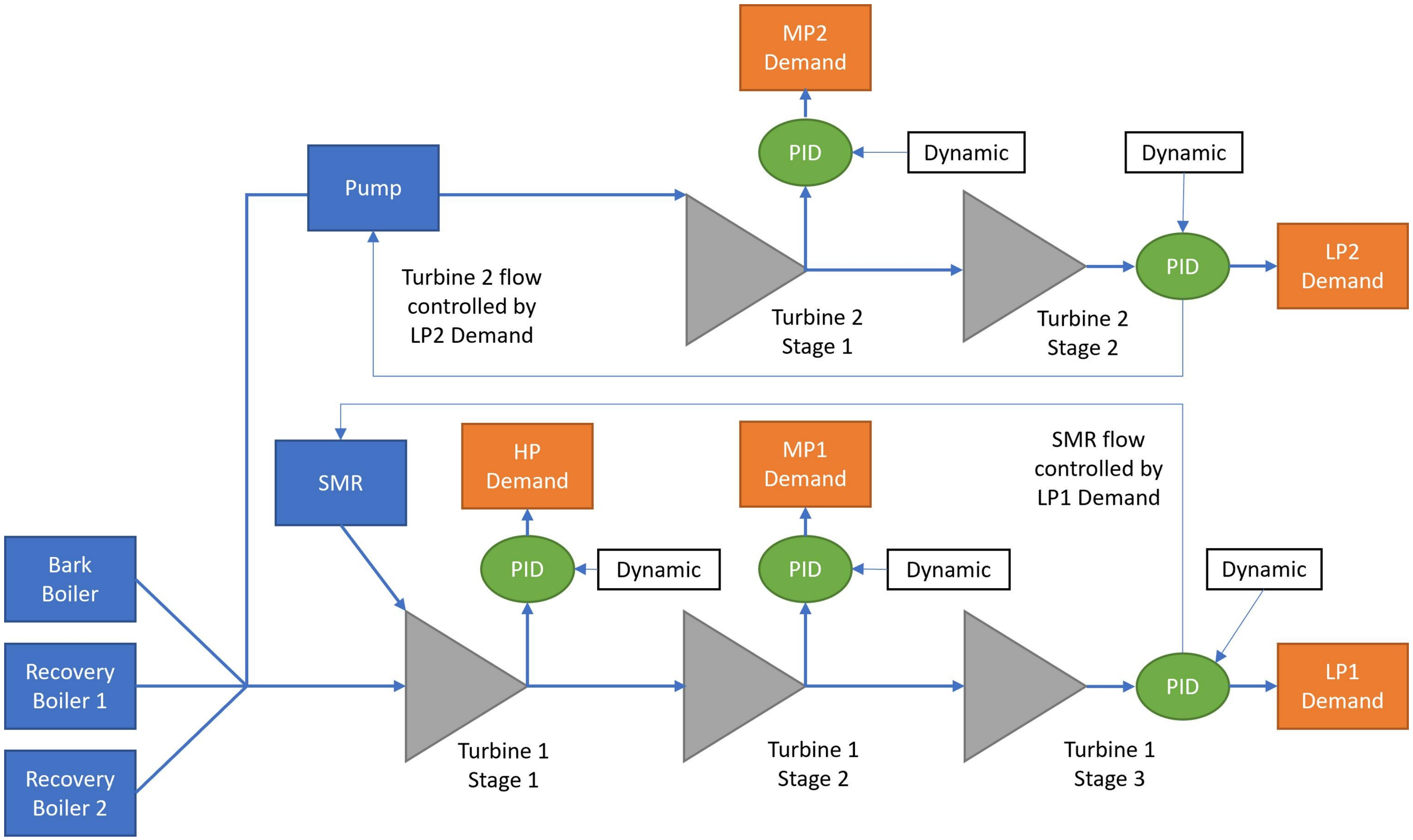




Model Verification

- Mass flow from SMR <1% error
- Power calculation 5.4% error from HYSYS
- HYSYS and Dymola use different methods to solve turbines

Case 2: No SMR Limits



The SMR ramps to meet dynamic demands.

Purpose: See how demand maximum and minimums compare to the SMR design flow rate.

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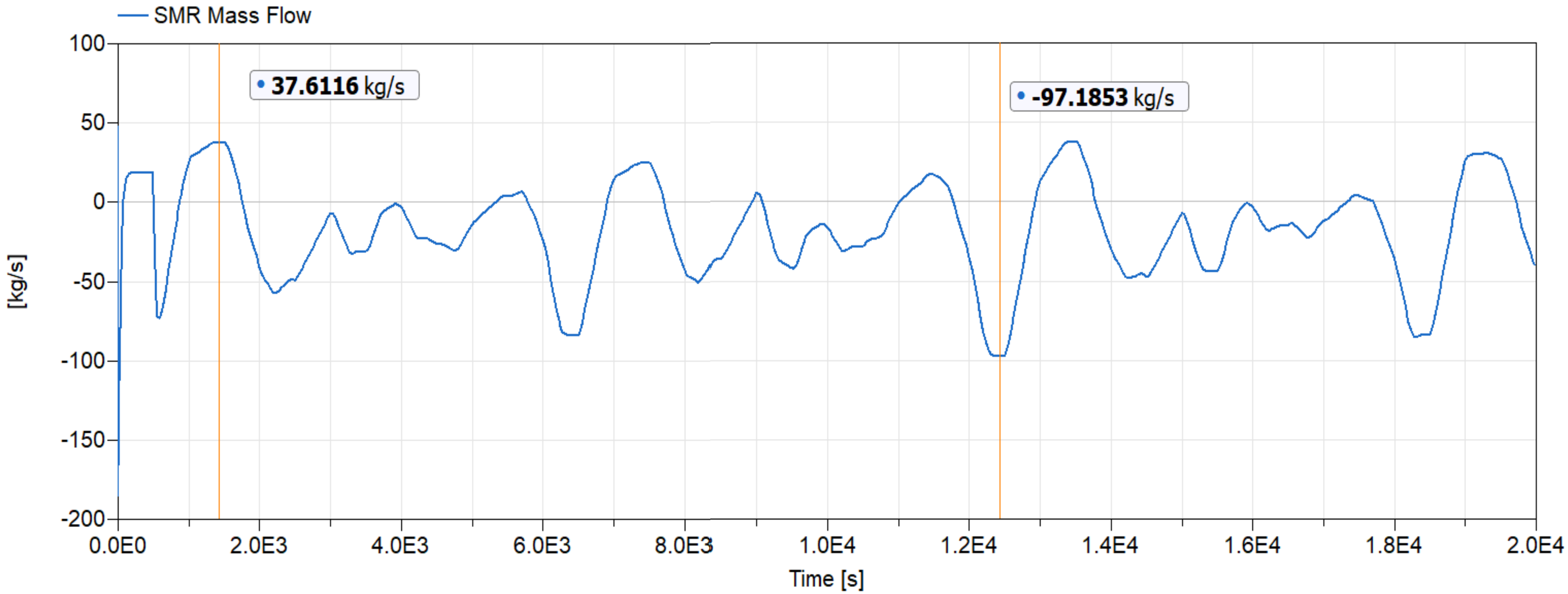
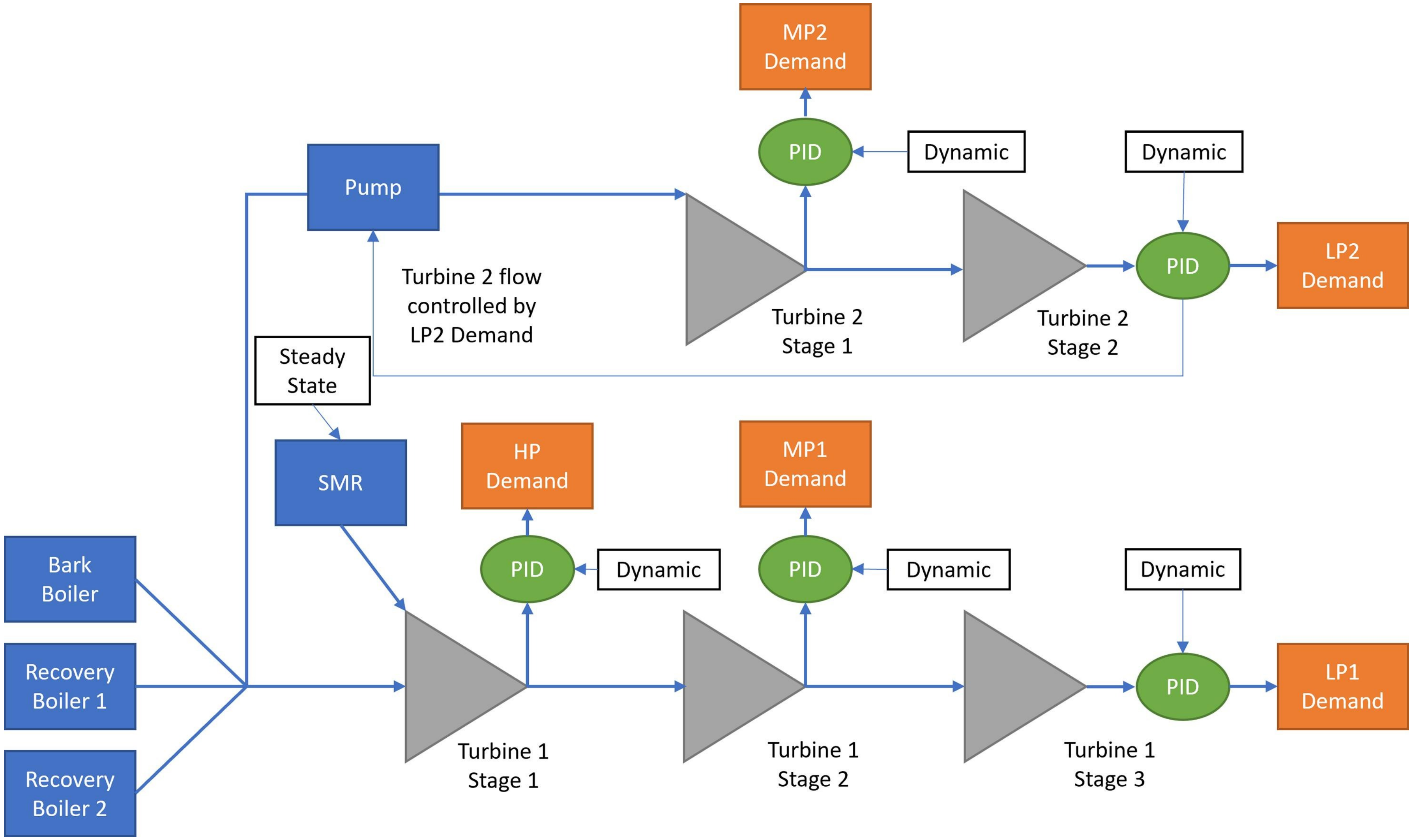
Case 2 Results

- Mass flow rate increases 110% when demand increases 10%
- Lowest demand is -97.2 kg/s – which is physically impossible – shows that SMR nominal is much too high for the lowest demand points



Case 3: SMR at Nominal Flow Rate



The SMR stays at the steady-state while demands fluctuate.

Purpose: See how power changes when SMR stays at nominal. See how heat inputs change when the SMR cannot ramp.

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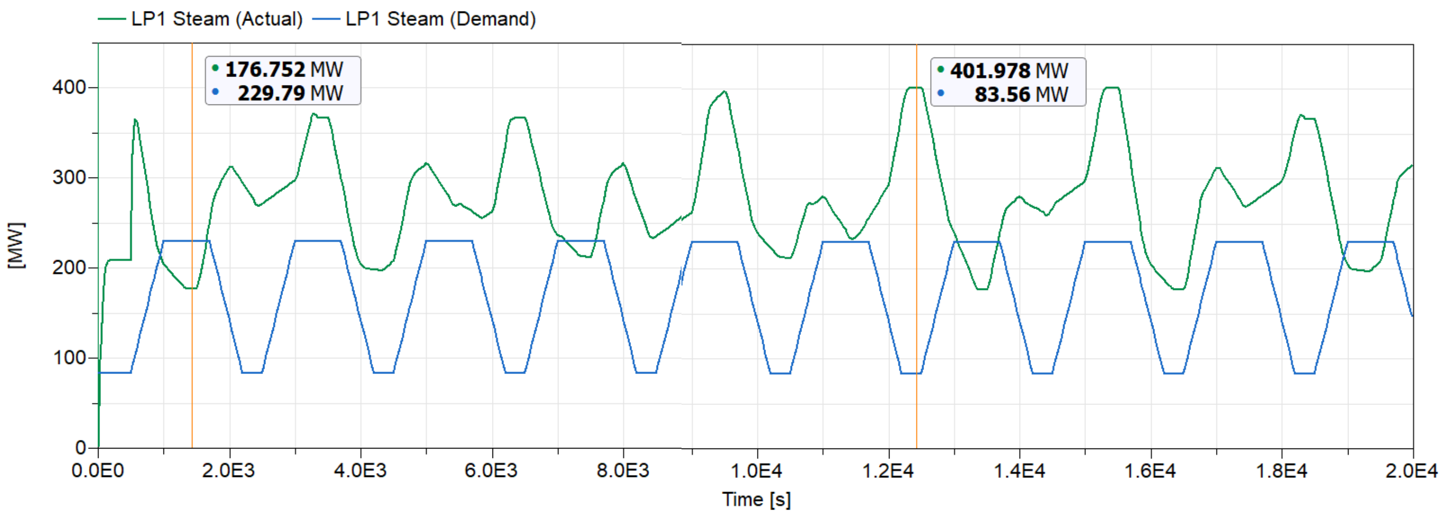
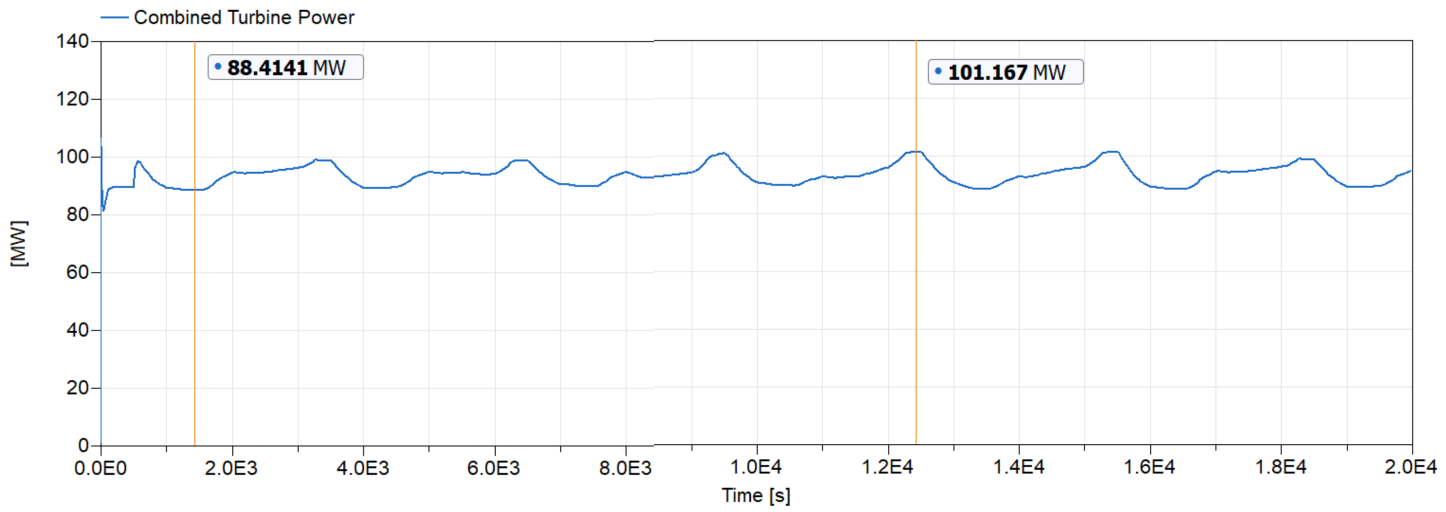
Case 3 Results: Heat





- Heat deficit at high demands is 53 MW
- Heat surplus at low demands is 318.4 MW
- Power shows small deviations with demand changes

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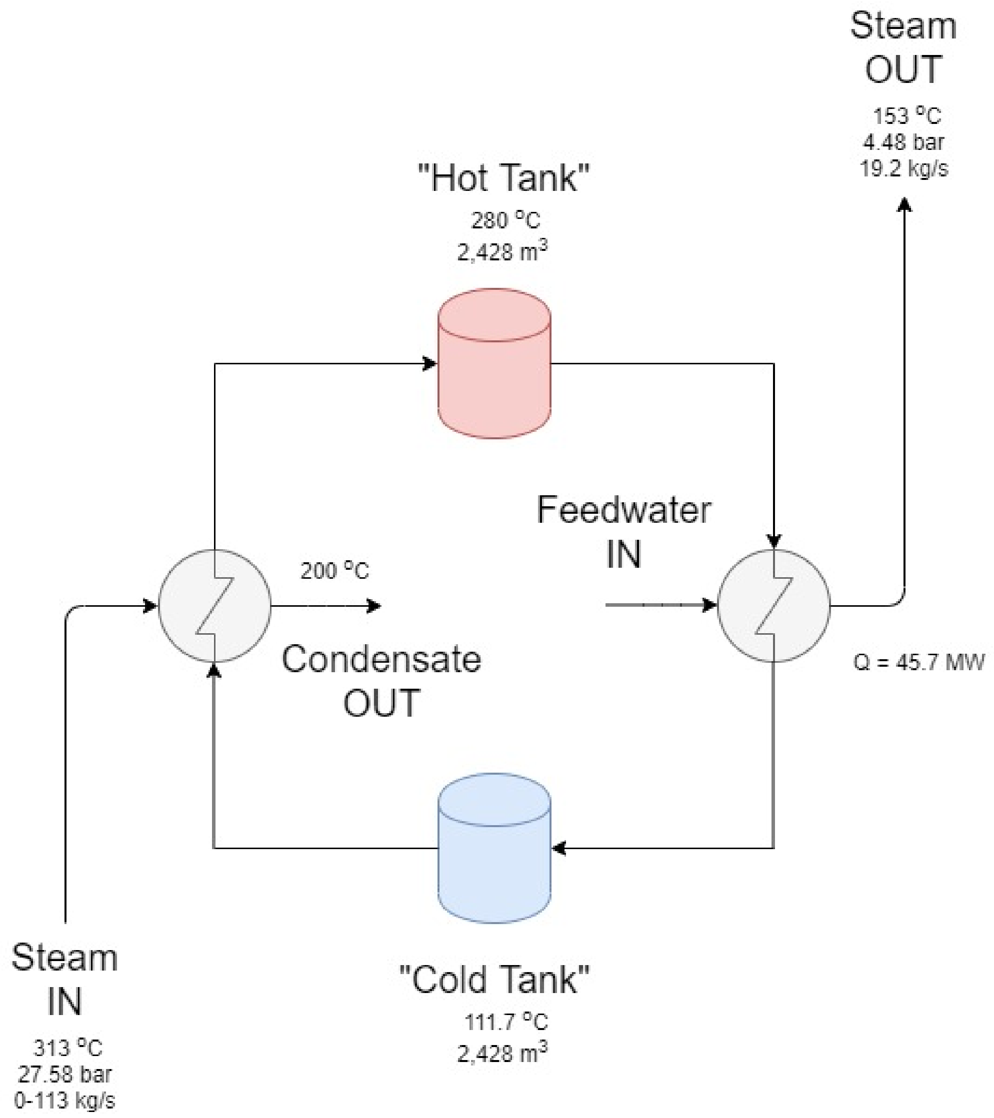
Case 4 and 5: Thermal Energy Storage System (TESS)



- Intermediate heat exchanger (IHX) passes heat from SMR steam to Therminol
- Steam generator passes heat from Therminol to feedwater
- Hot tank temperature can be higher, but trade-off for a larger IHX, more insulation needed to maintain temperature
- Discharge capacity: 4 hours
- Charge time max: 8.5 hours
- Steam flow into IHX: up to 113 kg/s
- Steam can be taken off after first turbine stage with HP steam
- Discharges after the third turbine stage in Turbine 1

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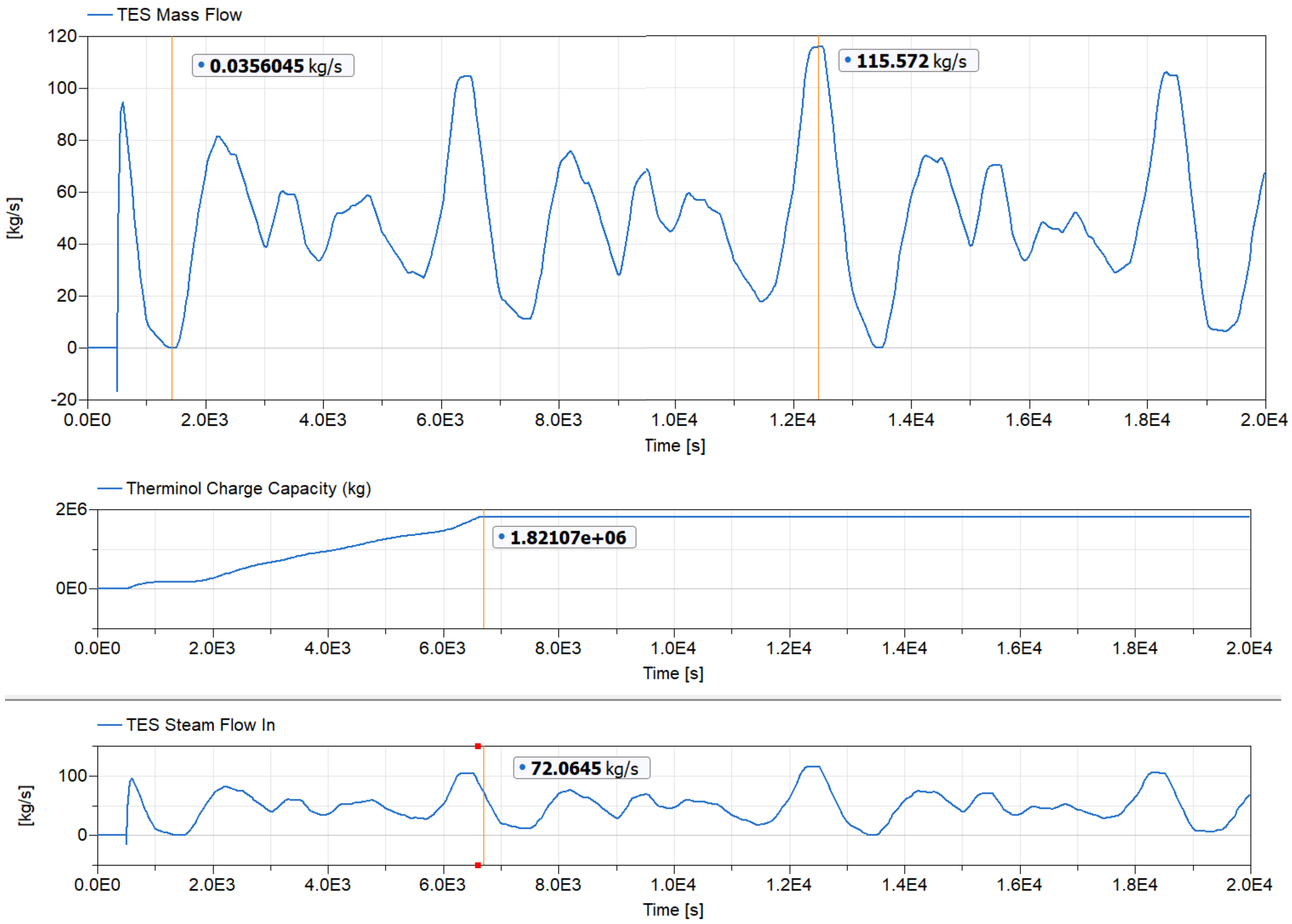
Case 4: Charging



- At nominal demand, TESS flow is essentially 0 kg/s
- At highest demand, TESS flow is 115.6 kg/s
- Charge time for this case is 1.7 hours

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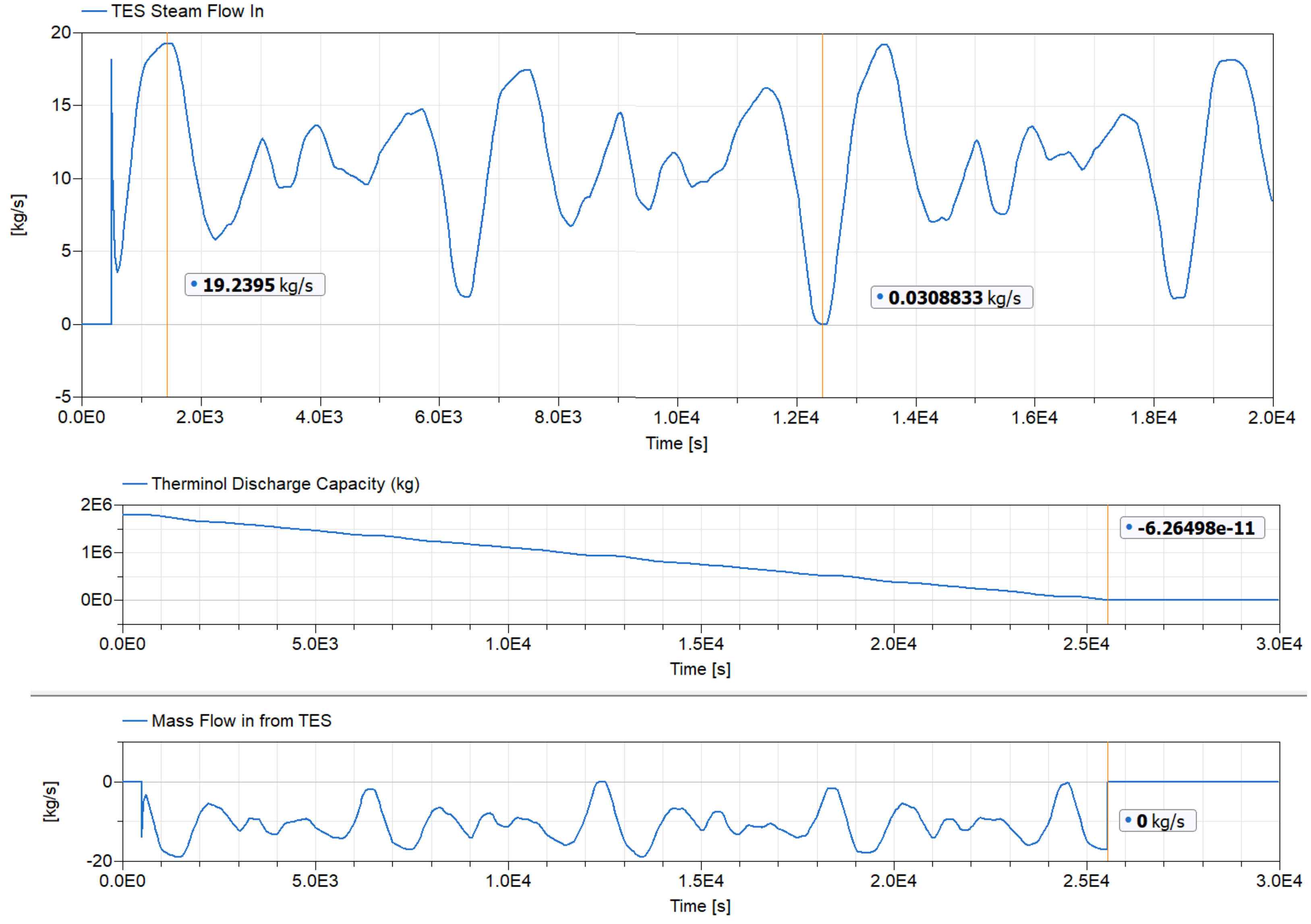
Case 5: Discharging



- At nominal demand, TESS flow is essentially 0 kg/s
- At highest demand, TESS flow is 19.2 kg/s (as expected)
- Discharge time for this case is 6.9 hours

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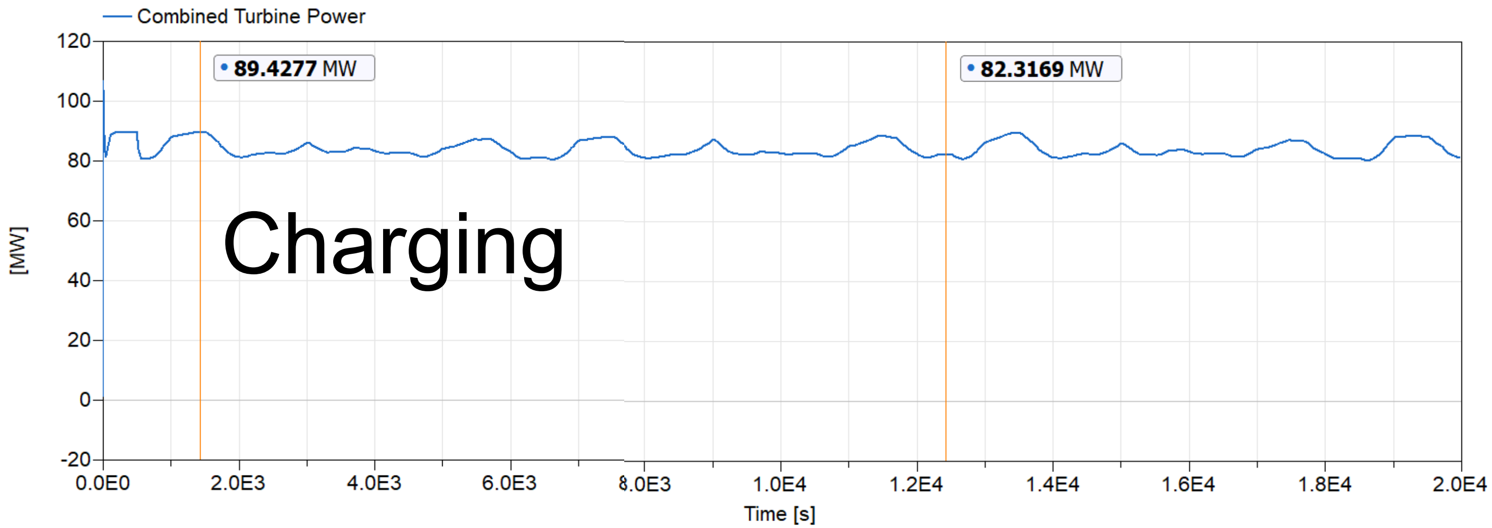
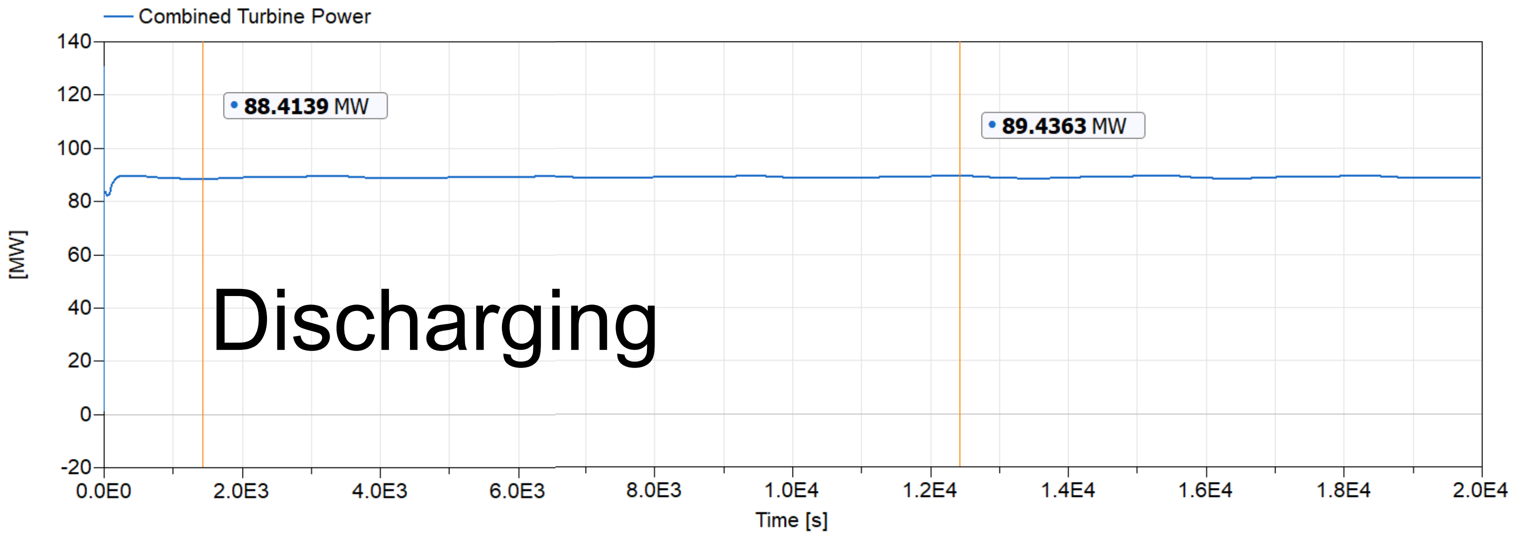
Case 4 and 5: Power Results





Turbine power varies very little during and after charge and discharge

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Conclusions

- Sizing the SMR based on steam only could result in too much or not enough electricity to meet demands
  - Other SMR designs that allow for more steam take-off could be more suitable
  - Electricity sales could increase revenue
- Running the SMR at steady state while demands fluctuate will provide the most stable electricity production and control scheme, but some heat could be wasted
  - This is essentially the current control strategy of the plant – steam is vented when not needed
- Adding thermal storage could help use heat more efficiently and would allow the SMR to run at steady-state
  - Increases efficiency of heat use and helps the plants during peak loads
  - Increases equipment and implementation costs
  - Charging prior to turbines would supply the highest quality heat, but would cause power production to drop
  - May require SMR nominal flow to increase so heat exchangers are always engaged

Part IV: Future Work

- Work with pulp and paper mills, utilities, SMR vendors, and other industries to develop financing and ownership partnerships
- Use actual plant demands to more accurately size the SMR and supporting systems
- Perform full economic analysis
  - Aspen Process Economic Analyzer can assist with the cost of components
  - Compare financing and ownership strategies
  - Include tax benefits from the Inflation Reduction Act

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Questions?

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Based on:
Full dissertation: https://repository.lib.ncsu.edu/handle/1840.20/38116
Journal article: https://www.sciencedirect.com/science/article/pii/S0306261922009175

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