INL/CON-21-64721-Revision-0

FORCE Transient Physical Modeling Workshop

October 2021

Changing the World's Energy Future

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Idaho National Laboratory

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FORCE – Transient Physical Modeling Workshop

Modelica Modeling Toolset
October 5, 2021

INL/CON-21-64721

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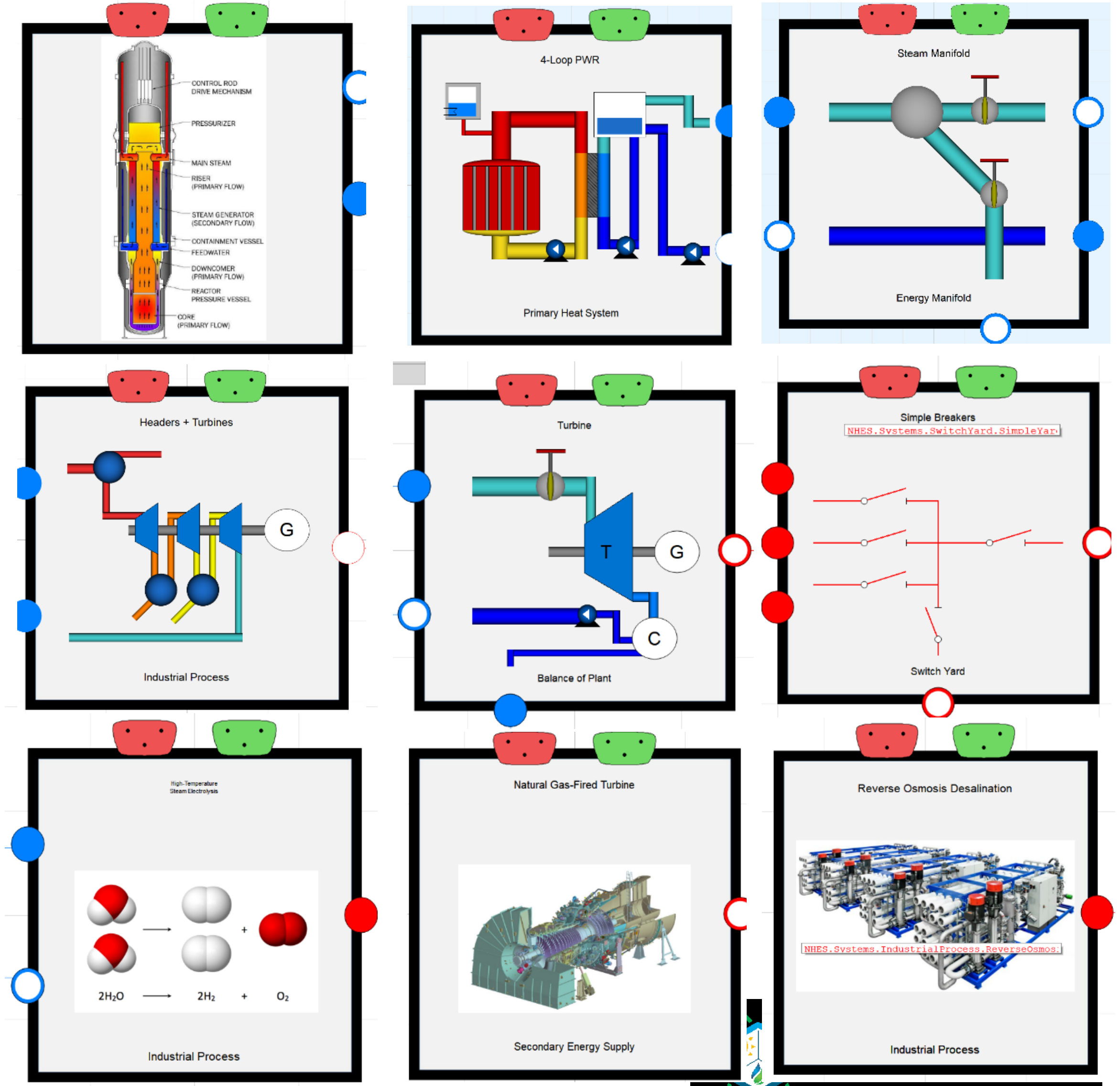
Prepared by:
Dr. Konor Frick and Dr. Daniel Mikkelson

HYBRID – What is it

- Hybrid is a collection of dynamic physical models written in the Modelica language to characterize:
  - Ramp speed
  - Thermal and electrical integration of different processes
  - Creation of novel control schemes
  - Off-demand system dynamics
  - Safety limitations based on control systems

- Adaptable
  - Object oriented with standardized connections
  - Using FMI/FMU standard, external collaboration without transfer of sensitive proprietary data or recoding of models can be accomplished
  - Components can be “hot swapped” within code.
    - Modelica was originally developed for the automotive industry as the language of choice for quick interchangeability: drive shafts, engines, transmissions, electronics, etc…

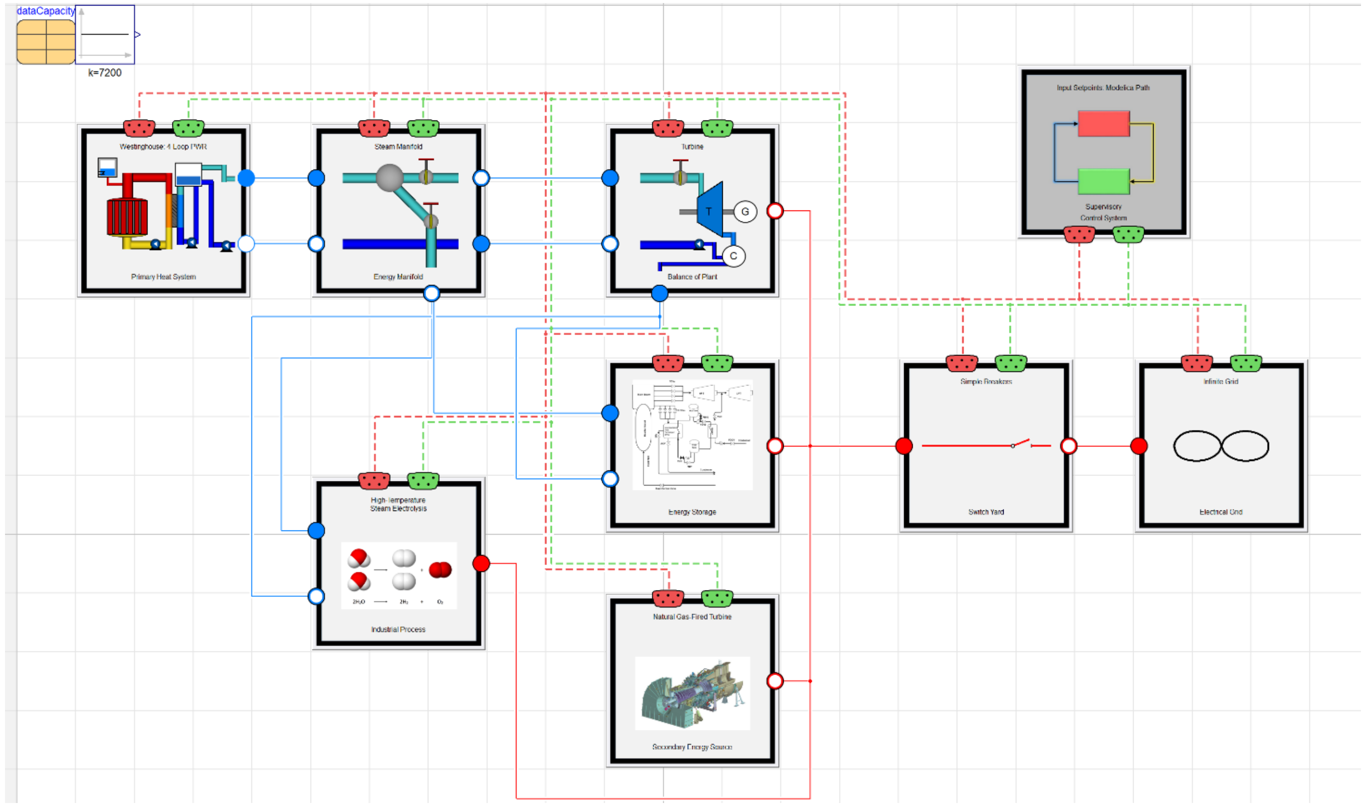
- Developed using the Commercial platform Dymola from Dassault Systems.



Integrated Energy Systems

Design Capability

- Physical models are focused on a process system basis
  - A few coupled subsystems (Nuclear plant + Gas Turbine + Thermal Storage + Grid + Ancillary Process)
  - Not a regional grid area consisting of hundreds of power plants with regional transmission lines.
- Figures of Merit
  - Demand Missed
  - System stability
    - System pressure, temperature, thermal gradients, valve positioning, etc.
  - Control strategy effects on each subsystem.
- Dispatch Points come from dispatch optimization software HERON.

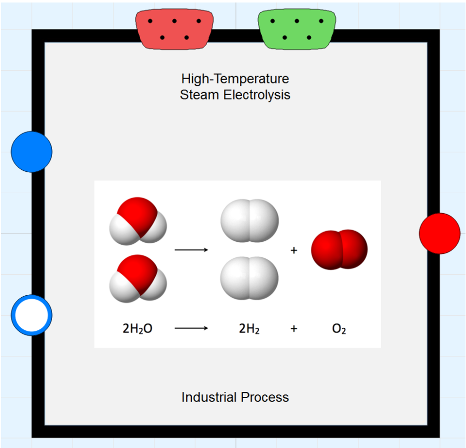


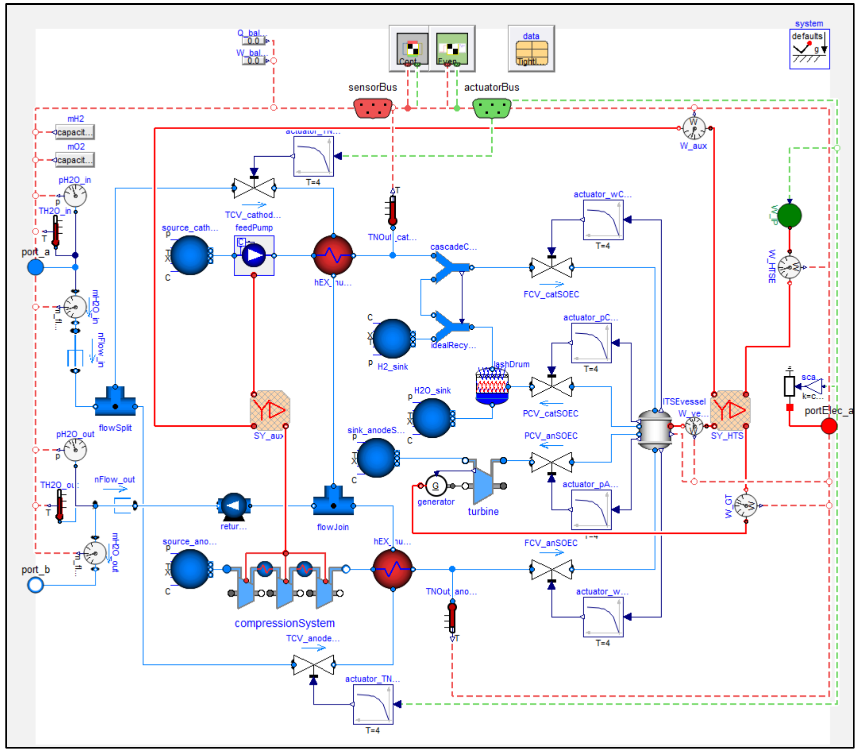
IES Integrated Energy Systems

Inter-connectability

- Creation of dynamic process models capable of modeling full plant dynamics under normal operating conditions within an Object-Oriented platform capable of quickly coupling with other dynamic process models within the same platform or via FMI/FMUs.
- Models are configured using interchangeable base classes for ease of use and adaptability of models into different configurations.
- Can be exported in the FMI/FMU standard to allow robust interoperability with industry.

Interchangeable Control System



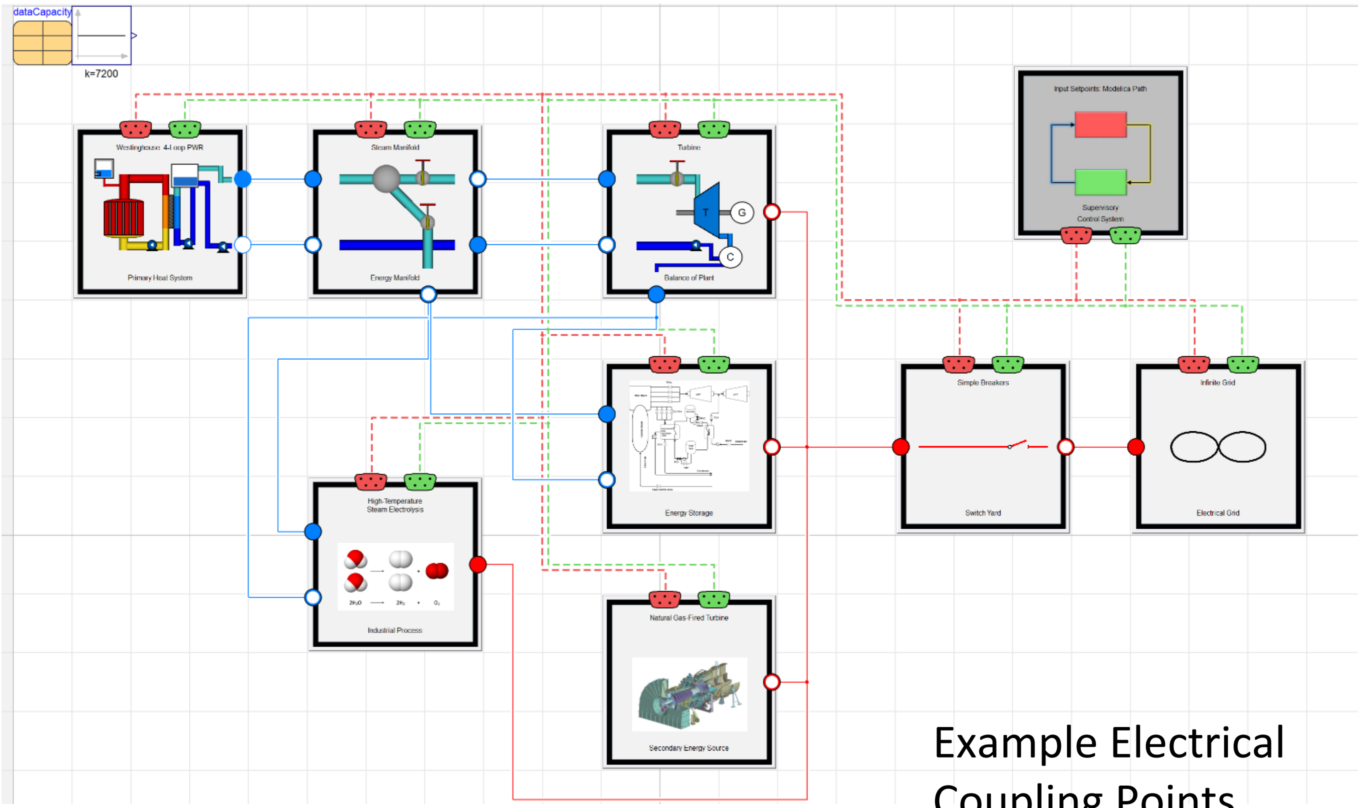


Connection points

External Inputs

- Input are System Sizing
  - Values taken from RAVEN/HERON in optimization workflow
- Control Strategies desired
  - Each subsystem has its own control strategy
- Planned Coupling methodologies
  - Supervisory control
  - Minimum electrical and heat rates for each subsystem
- Thermal and electrical demands for each subsystem through time.
  - Total demand an input from balancing authority routine

Supervisory Control



Example Electrical Coupling Points

Example Thermal Coupling Points

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Use Cases

1. Small Modular Reactor + Gas Turbine Peaker
2. HTGR + Concrete Thermal Energy Storage
3. Multi-Component Integrated Energy Storage
   - Reactor
   - Gas Turbine
   - Two-Tank Sensible Heat Thermal Energy Storage
   - Hydrogen Production

Example – Nuclear Reactor + Gas Turbine

Connection

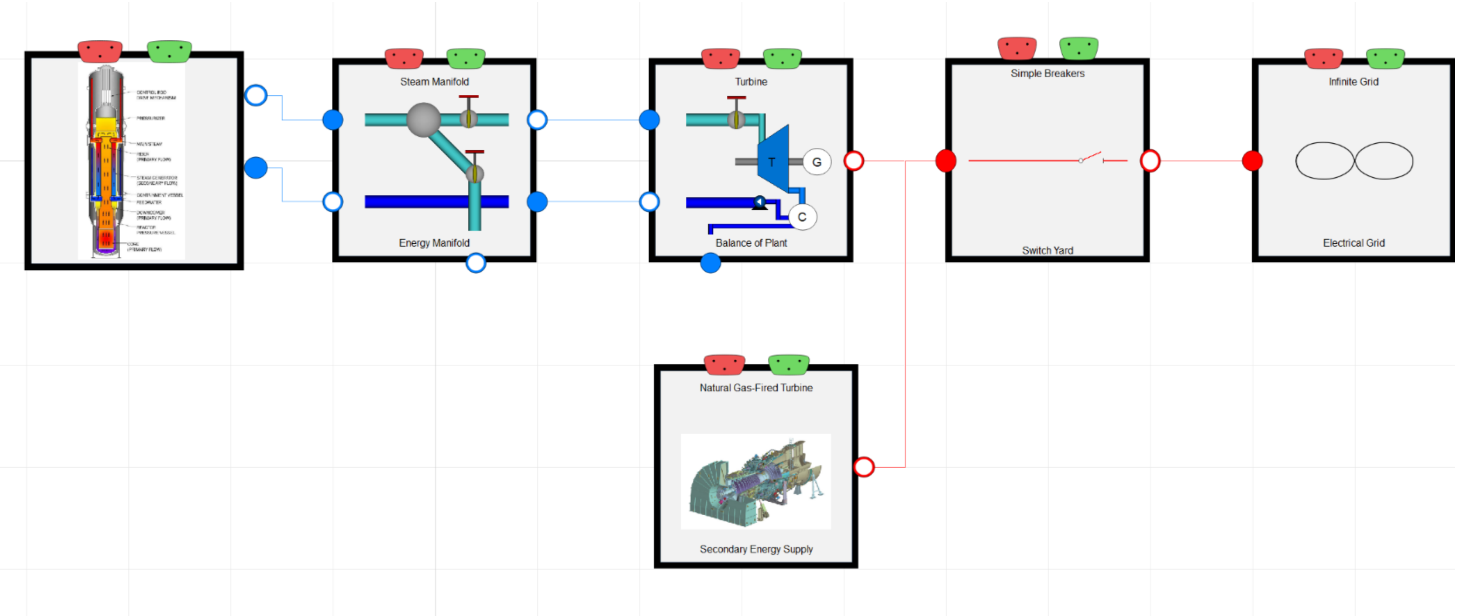
- Electrical (Via the Grid).

Libraries we need:

- HYBRID
- TRANSFORM

Control Modifications

- ISO level these inputs come from the HERON Dispatch Optimization Software

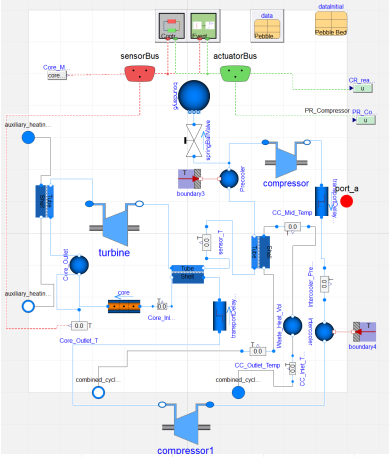


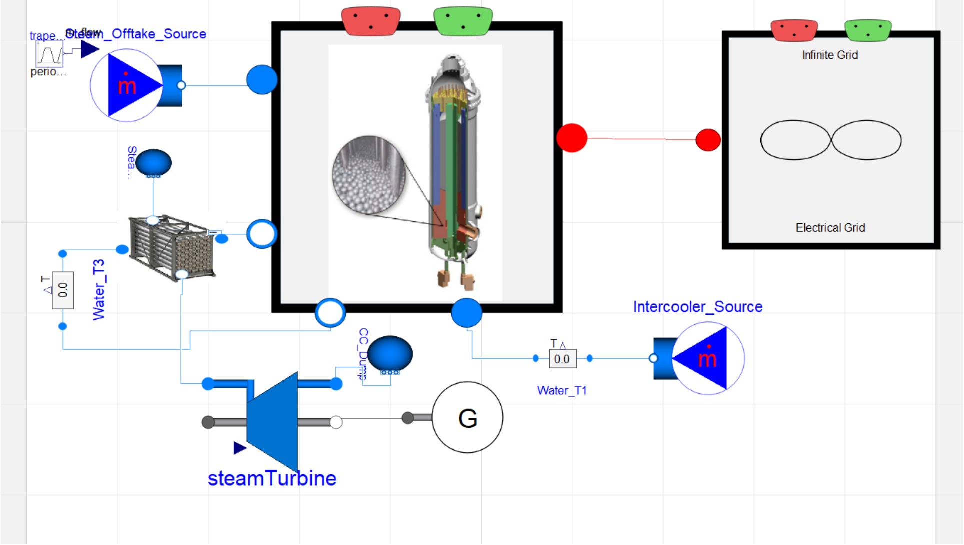
Demonstration of Gas Turbine Peaker in Dymola

Integrated Energy Systems

Pebble Bed HTGR Combined Cycle

- 648MWt nominal reactor power
- 314MWe nominal Brayton electric output
- System controllers:
  - Control rods based on coolant temp
  - System pressure based on relief valve
  - Mass flows for combined cycle portion are inputs under investigation
- Determining if using pre-turbine heat to boost temperature going into steam turbine is worth power loss





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Example

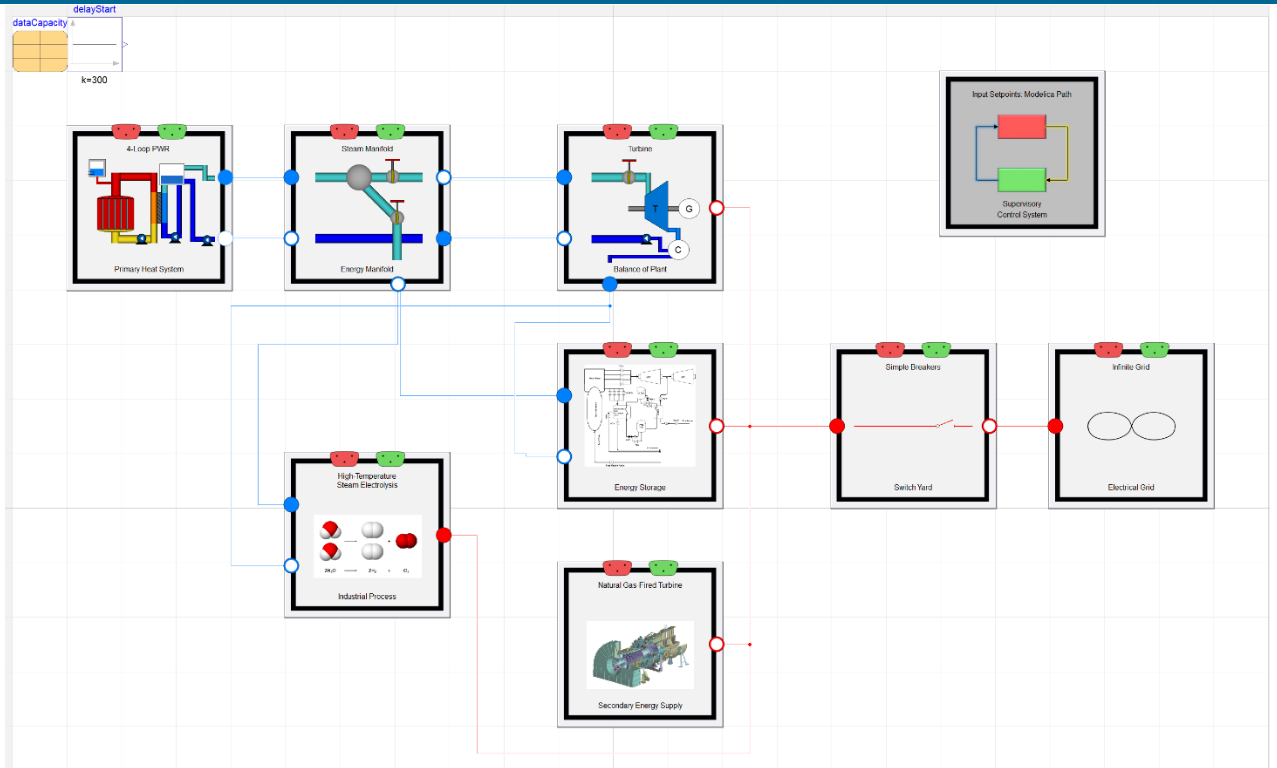
Demonstration of HTGR in Dymola

Example – Multi-Component Integrated Energy System

- Multi-component Integrated Energy System.
- Power Source = Pressurized Water Reactor
- Ancillary Process = Hydrogen Production
- Energy Storage = Thermal Energy Storage
- Secondary Energy Source = Natural Gas Fired Turbine

Case

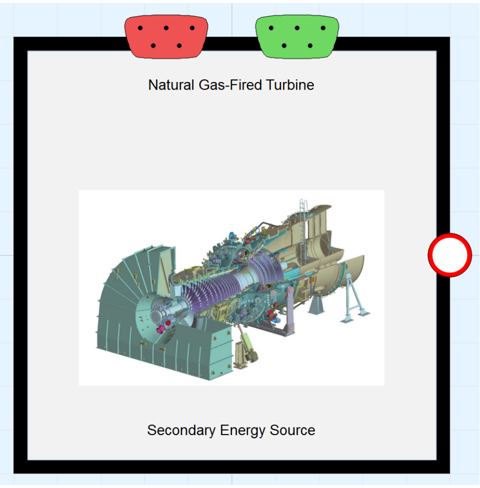
- Consider we are operating in a Microgrid with Wind Power.
- Total Microgrid Power Needs = 1200MWe

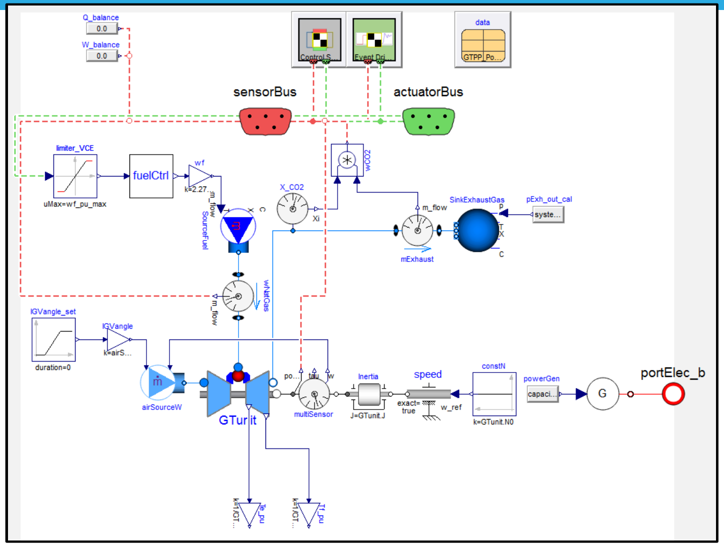


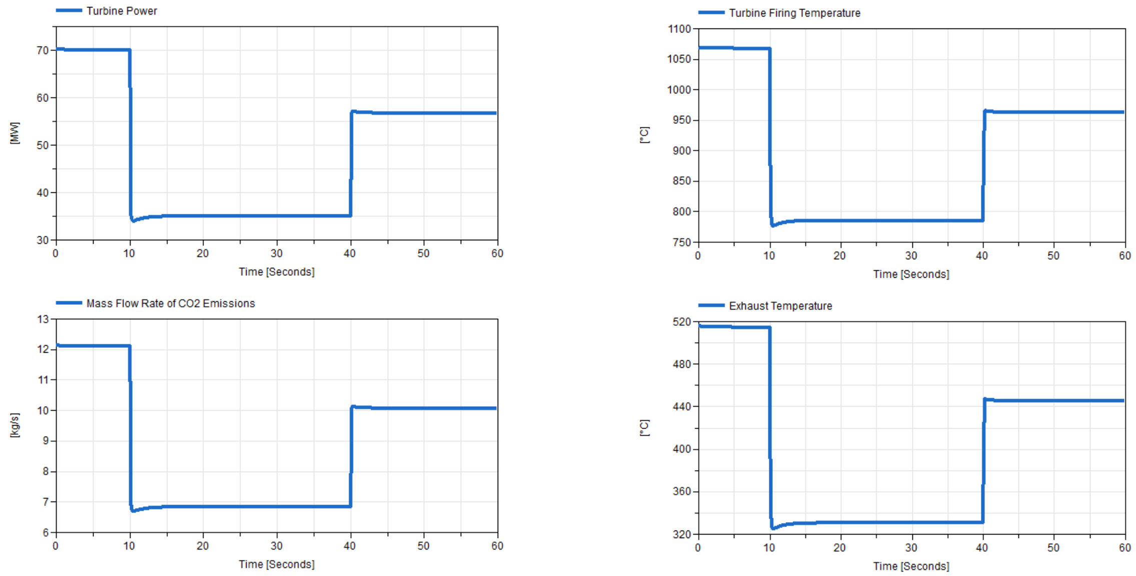
Demonstration in Dymola

Key Outputs

- Transient results of Processes
- Coupling and interaction phenomena
- Missed Demand
- Ramp Limitations based on underlying system physics (phase change, thermal time constants, valve opening speeds)
- Test platform for novel control strategies







Current Status of the HYBRID Repository

- Opensource on GitHub
  - https://github.com/idaholab/HYBRID
- In use by university partners
  - North Carolina State, Toledo, Michigan
- Automatic regression system implemented using ROOK
- Recent Additions
  - Packed Bed Thermocline Energy Storage
  - Concrete Energy Storage
  - Phase Change Material Energy Storage
  - High Fidelity Balance of Plant

Subsystems within the HYBRID Repository.

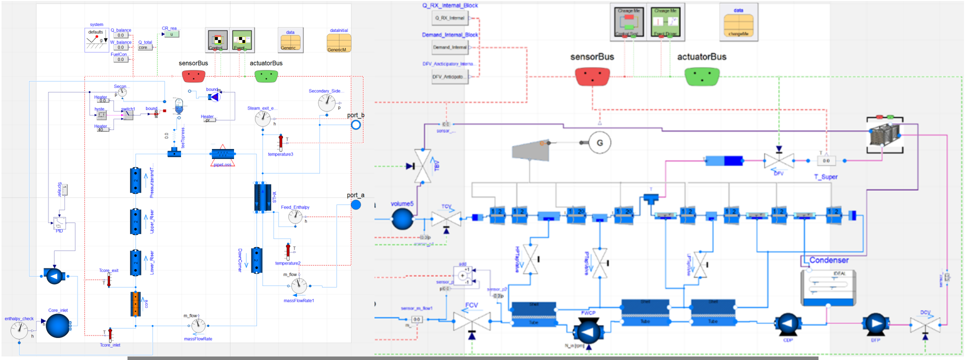
Identifier	Category	Description	Specific Example
1	Primary heat system (PHS)	Provides base load heat and power	Nuclear reactor
2	Energy manifold (EM)	Distributes thermal energy between subsystems	Steam distribution
3	Balance of plant (BOP)	Serves as primary electricity supply from energy not used in other subsystems	Turbine and condenser
4	Industrial process (IP)	Generates high-value product(s) using heat from energy manifold/secondary energy supply and electricity from switch yard	Steam electrolysis, gas to liquids, or reverse osmosis desalination
5	Energy storage (ES)	Serves as energy buffer to increase overall system robustness	Batteries, Two-Tank Sensible Heat Storage, Thermocline Packed Bed, Concrete, Phase Change Material
6	Secondary energy source (SES)	Delivers small amounts of topping heat required by industrial processes or rapid dynamics in grid demand that cannot be met by the remainder of the system	Gas turbine, Hydrogen Turbine
7	Switch yard (SY)	Distributes electricity between subsystems, including the grid	Electricity distribution
8	Electrical grid (EG)	Sets the behavior of the grid connected to the NHES	Large grid behavior (not influenced by NHES)
9	Control system center (CS)	Provides proper system control, test scenarios, etc.	Control/supervisory systems and event drivers

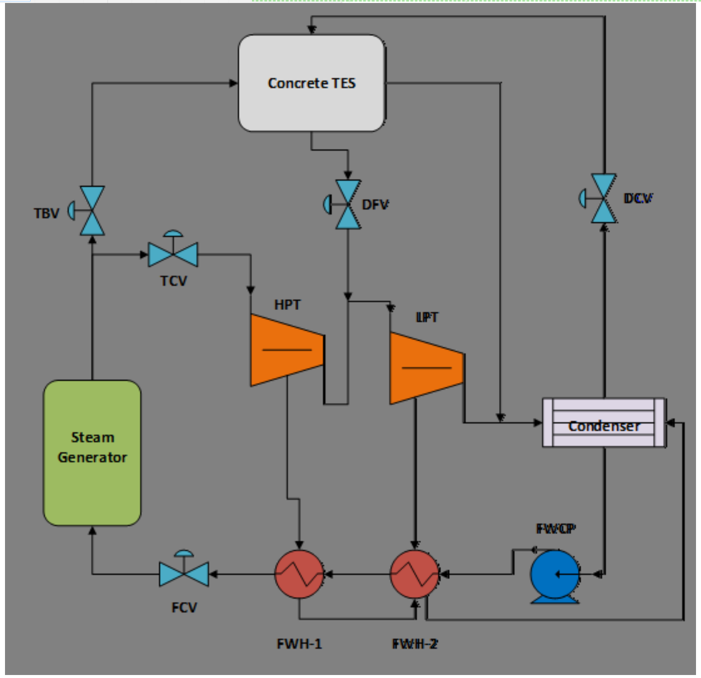
Thank you for your Attention!

Additional Slides

Energy Arbitrage SMR-CTES IES

- 160MWt nominal reactor power
- 52MWe nominal turbine power
- System controllers:
  - Control rods based on moderator Temp
  - Pressurizer heaters & sprays based on its pressure
  - TBV based on turbine power & demand
  - TCV based on steam generator pressure
  - FCV based on reactor thermal power
  - FWCP based on pressure drop across FCV
  - DCV based on turbine power & demand (only above 52MWe)
  - DFV based on anticipatory discharge signal and superheat discharge flow sensor
- Example based on part of multi-day dispatchable grid load follow scenario
- Includes "high-fidelity" reactor model, detailed stage-by-stage turbine, and dual-pipe CTES





IES
Integrated Energy Systems

Demonstration of SMR TES in Dymola

Energy Arbitrage SMR-CTES IES

- Real demand data taken from Idaho Power Company
- Net demand is calculated by removing wind and solar generation to generate demand profile
- Reactor & energy conversion system models tightly integrated to allow for about 50-125% electricity production
- Models designed specifically to capture feedback mechanisms occurring due to changing operation setpoints
- Peaking steam reintroduced upstream of a low-pressure turbine point, upstream of an imperfect moisture separator

Pebble Bed HTGR Combined Cycle

- Model is based on meeting best-available steady state designs
- Pebble-type TRISO fuel model meets approximate fuel temperature estimations from literature
- Example shown is a technology evaluation for CTES integration into a combined cycle HTGR system
- Waste heat from HTGR is passed through CTES to produce steam to turn a steam turbine
- Example shows an evaluation of efficiency improvement experienced by use of CTES in cyclical fashion

IES Integrated Energy Systems

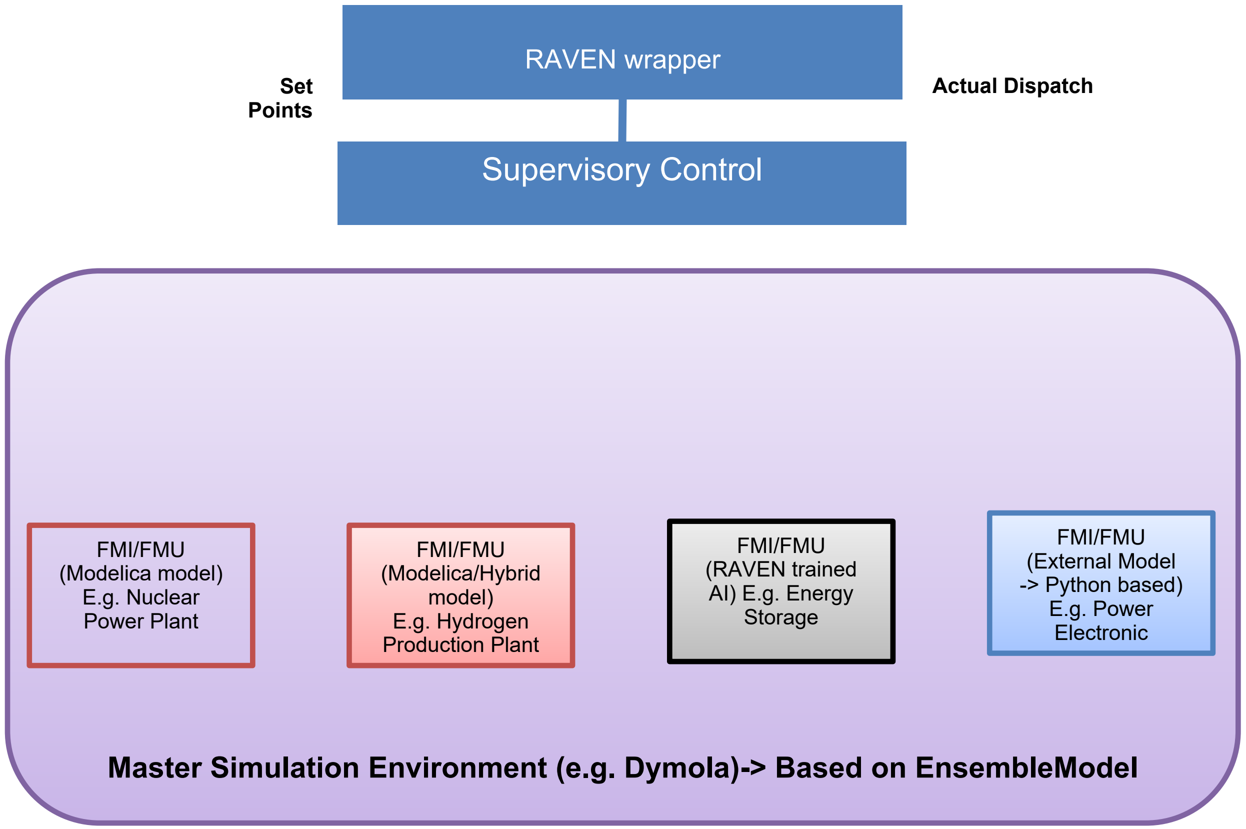
In Depth Models

Extensible Plug and Play Approach

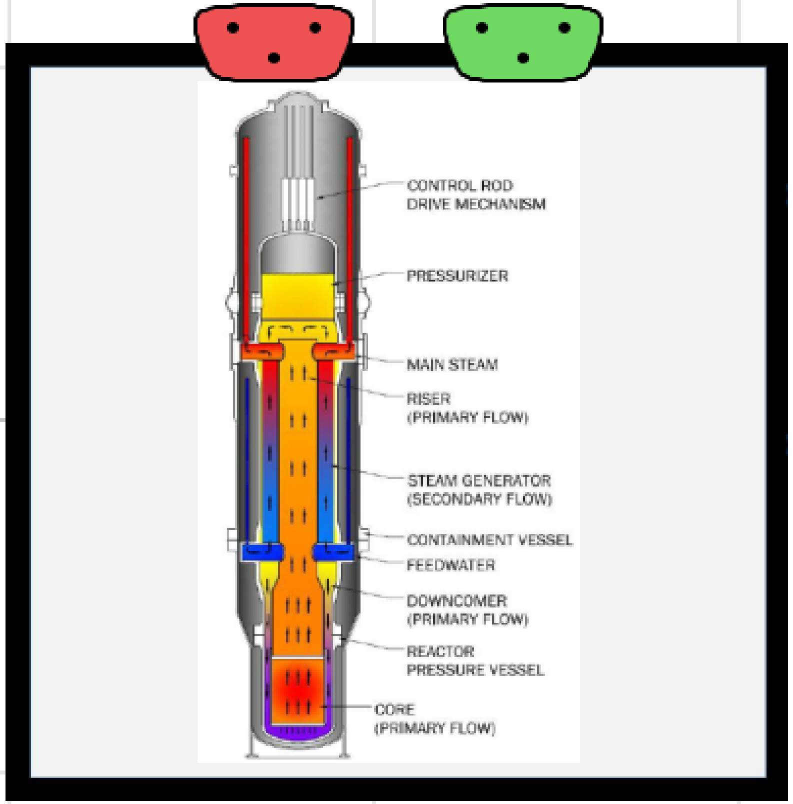
- The individual Modelica models can be exported using the FMI/FMU standard and then reconnected within an FMI importing environment.

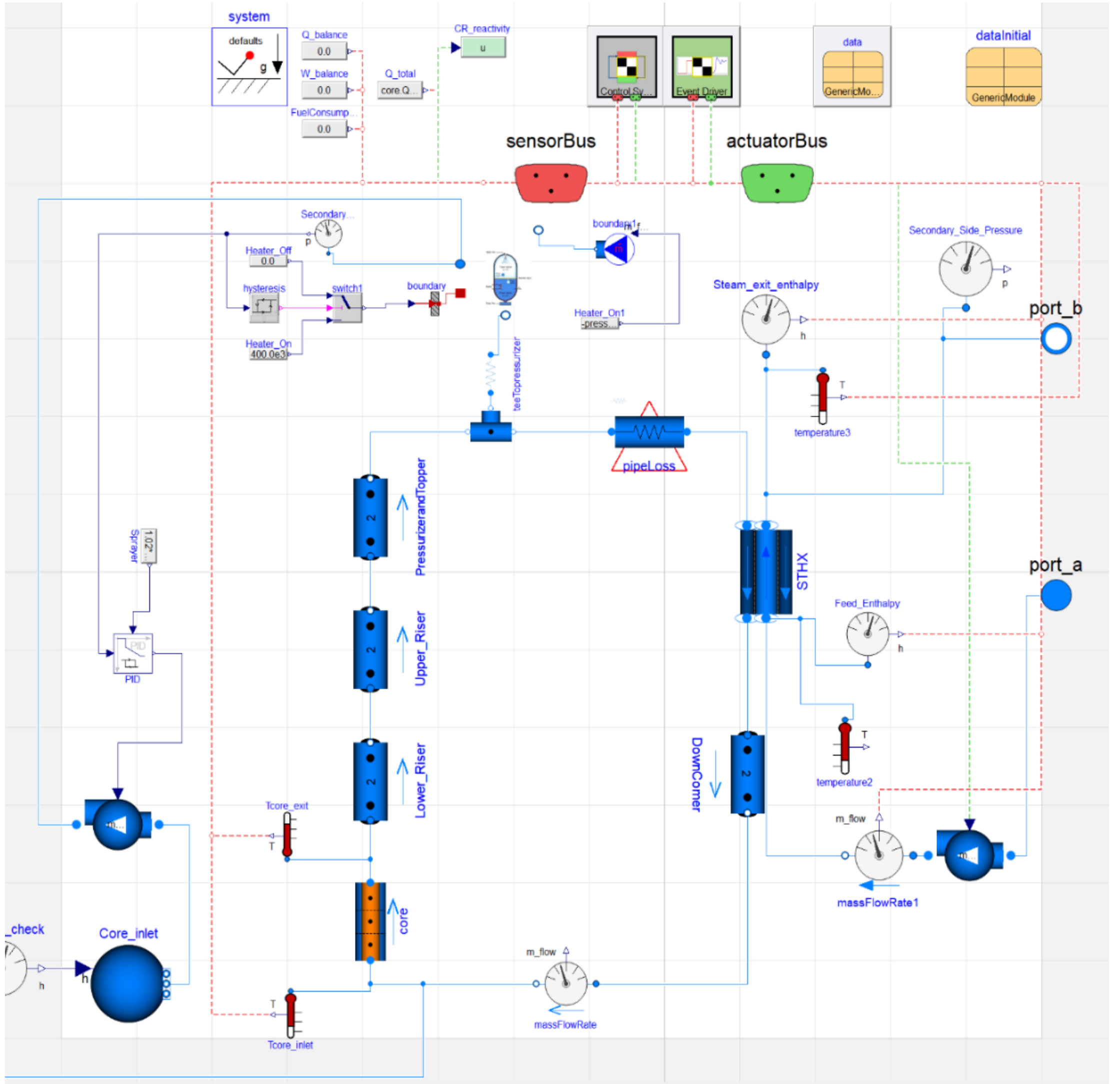
- Using a standardized templating system the interconnection of external models with modelica models can be accomplished while preserving internal physics and even proprietary information.

- Through the use of FMI/FMUS trained Raven AI's can be interconnected with existing physical modelica models.

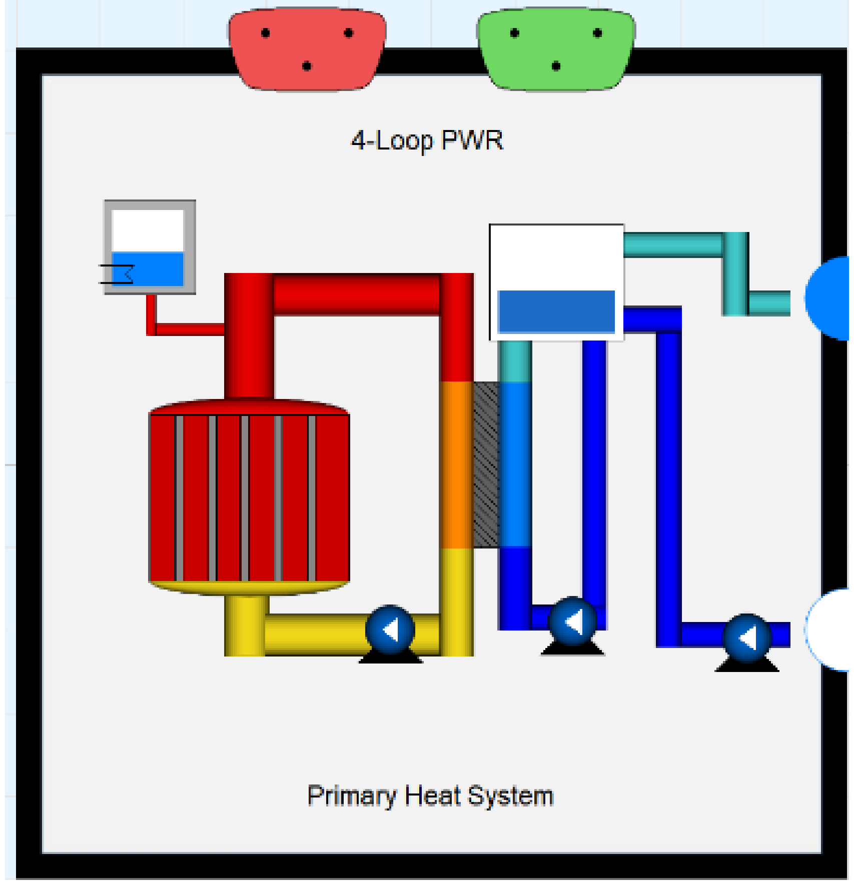


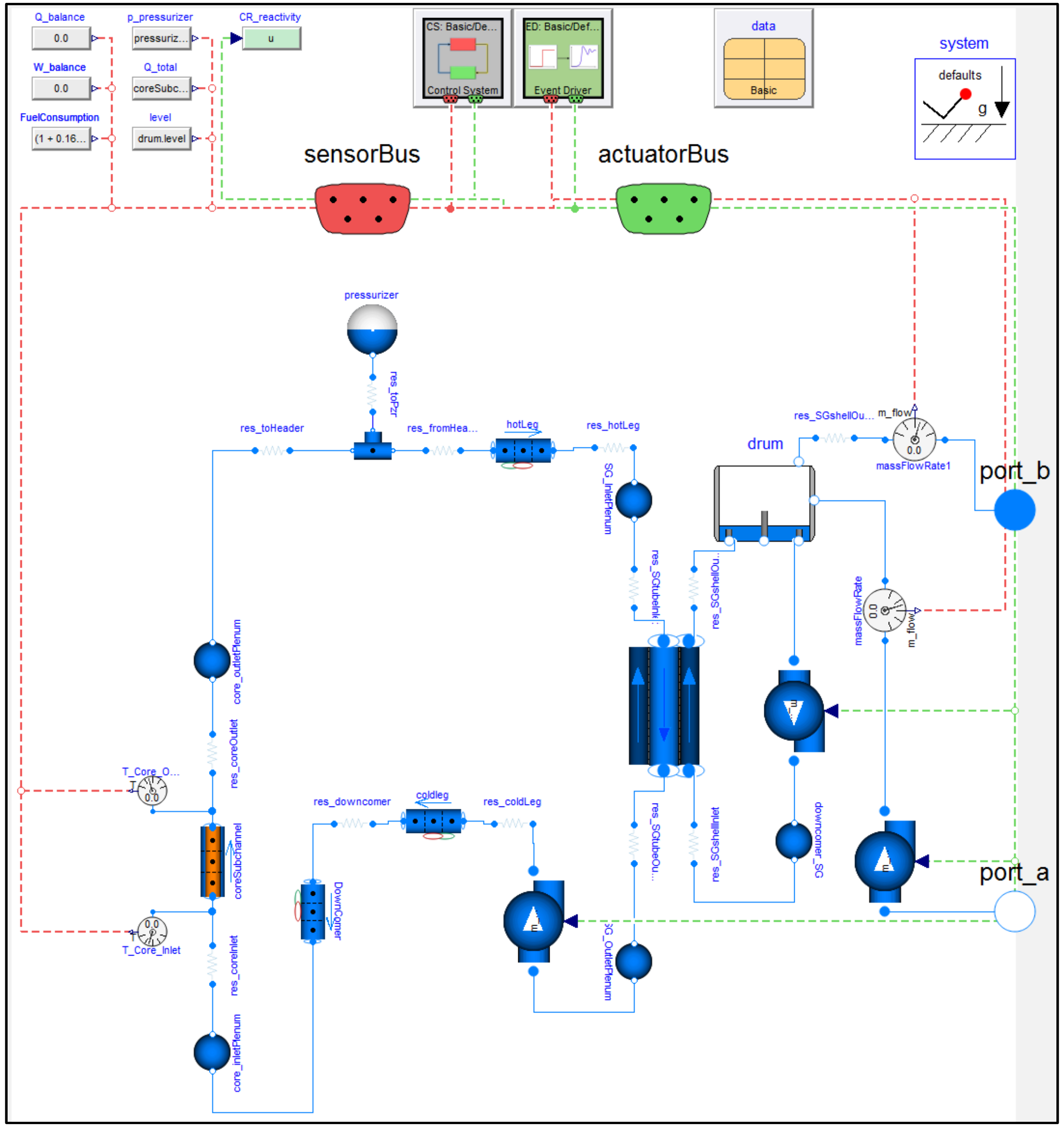
Transient NuScale style Model in the Modelica Language



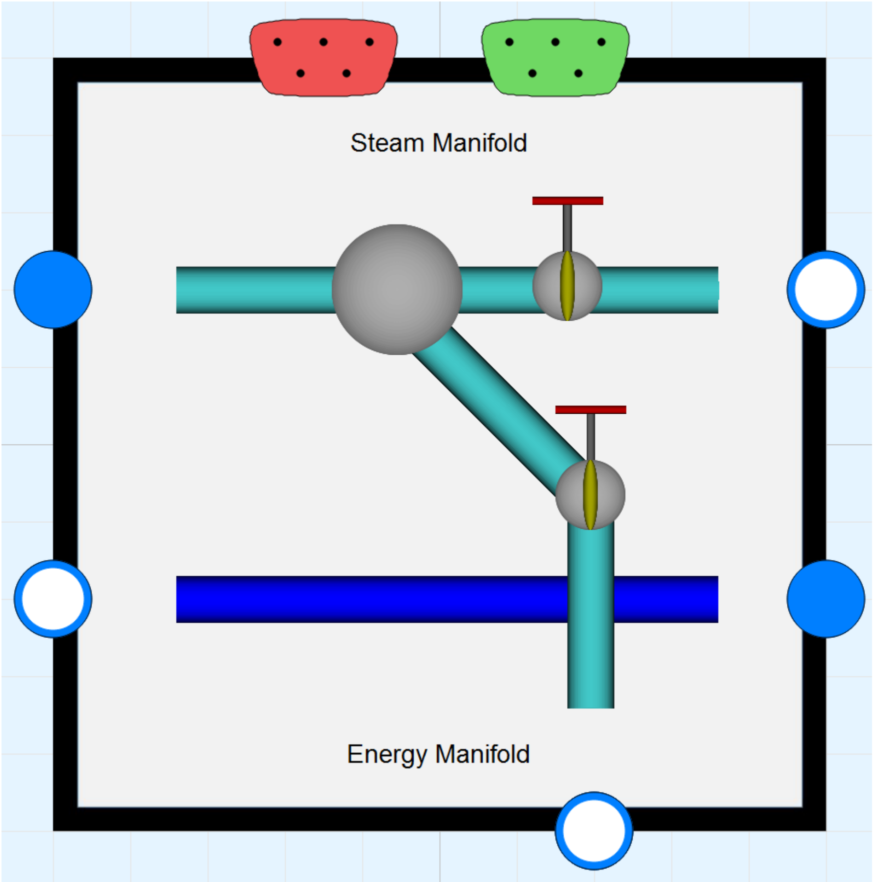


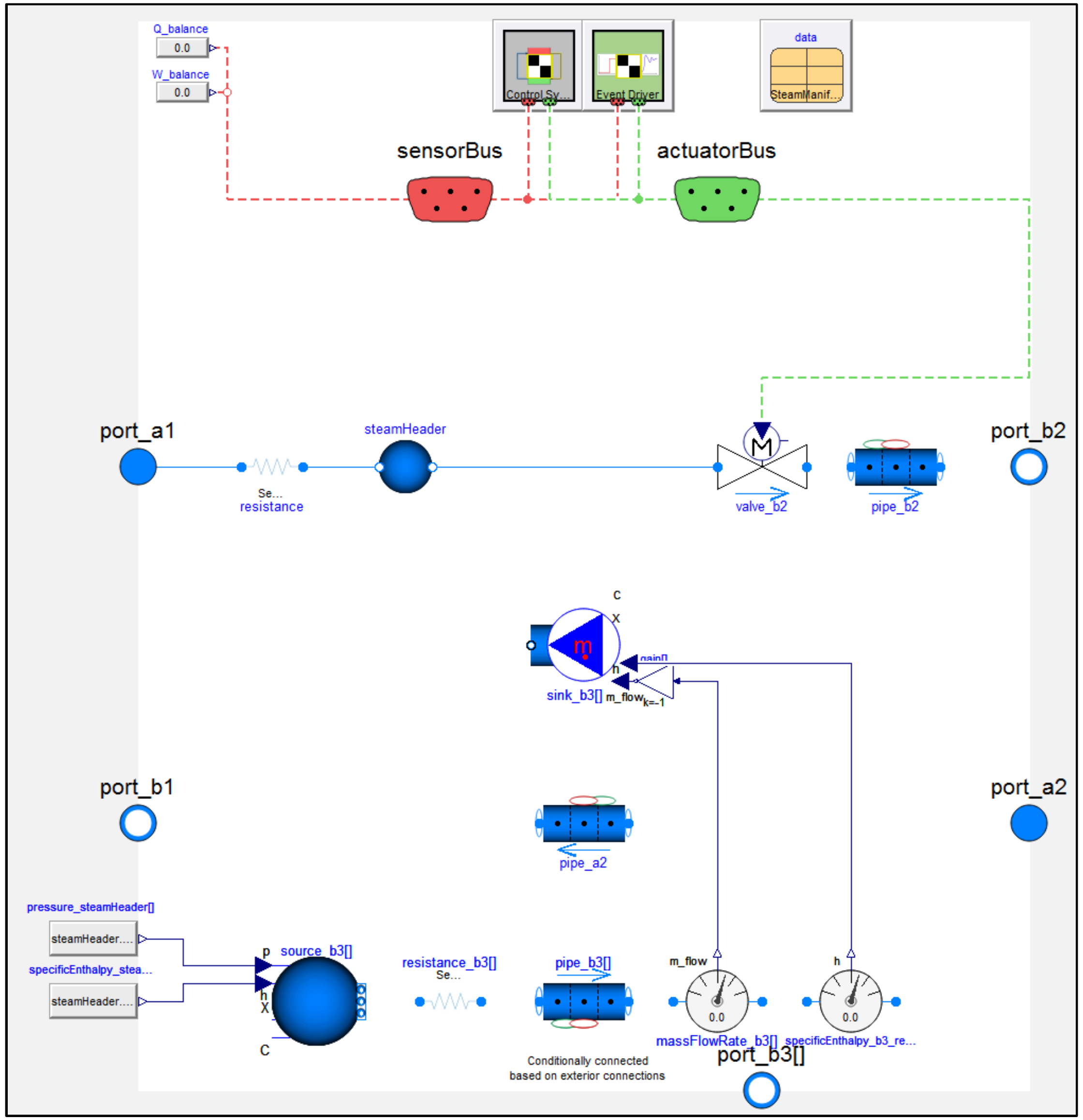
PHS– Westinghouse (WH) style: 4-Loop Pressurized Water Reactor (PWR)



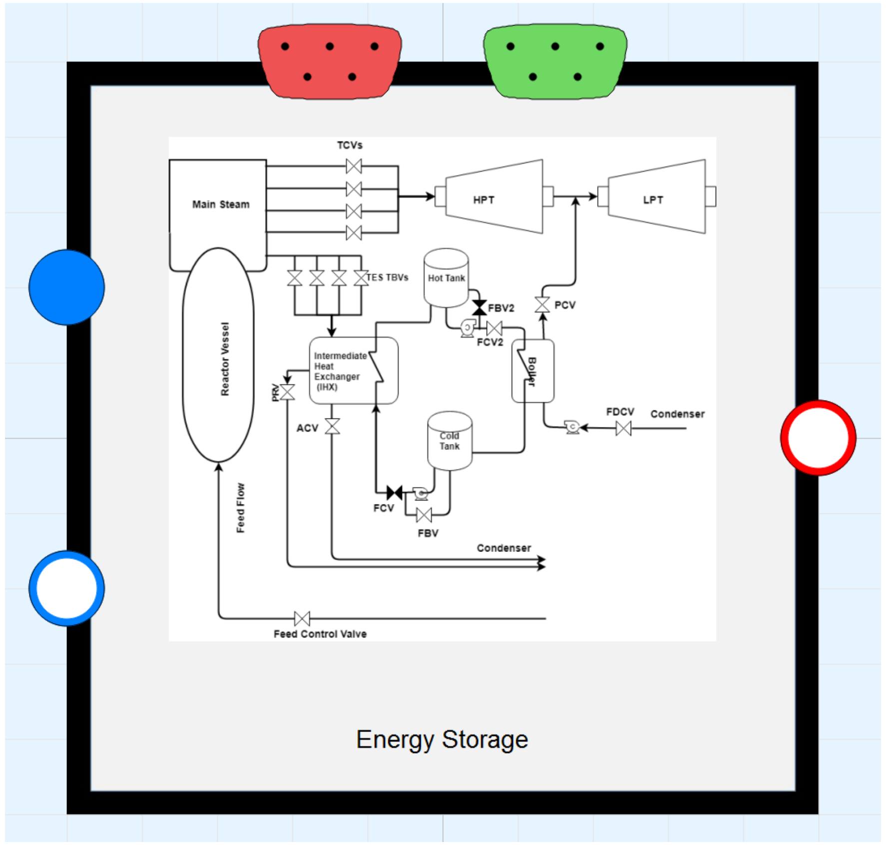


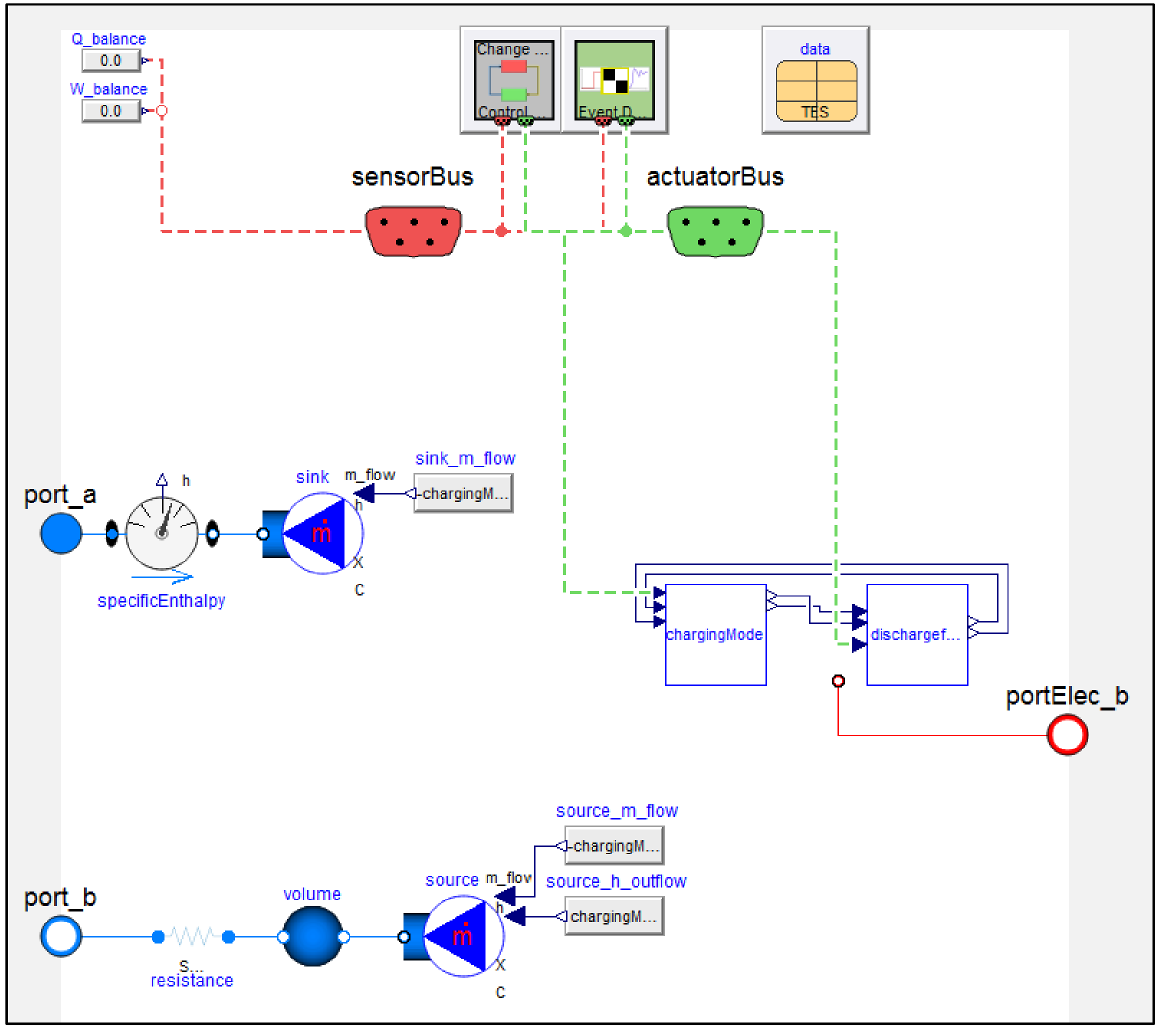
Energy Manifold



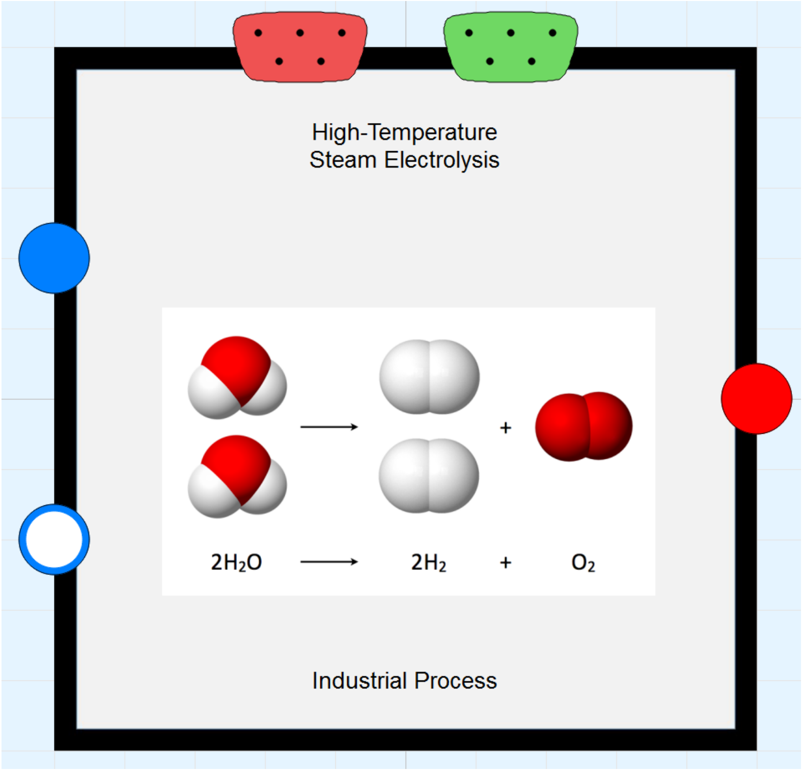


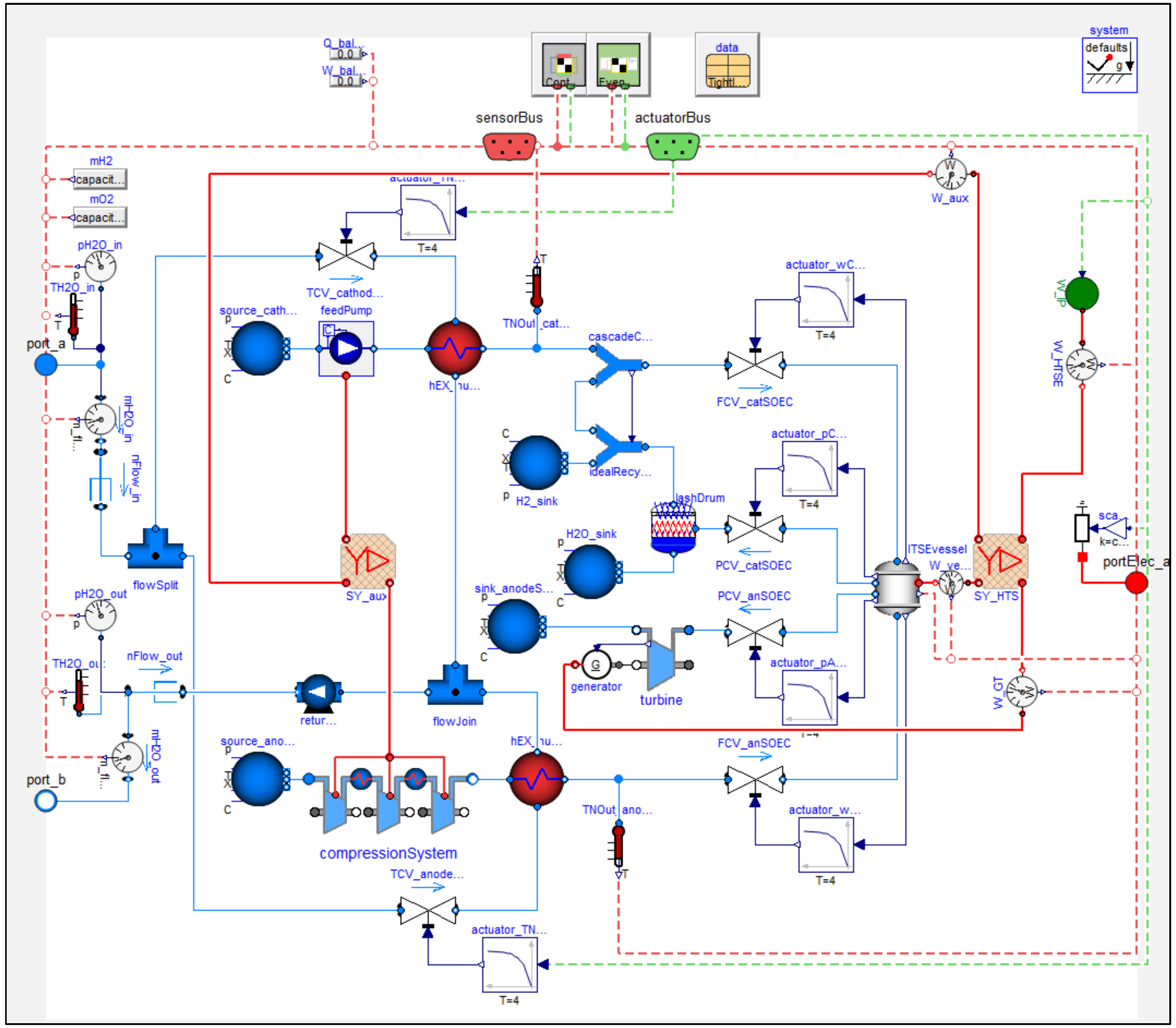
ES – Sensible Thermal Energy Storage (TES)



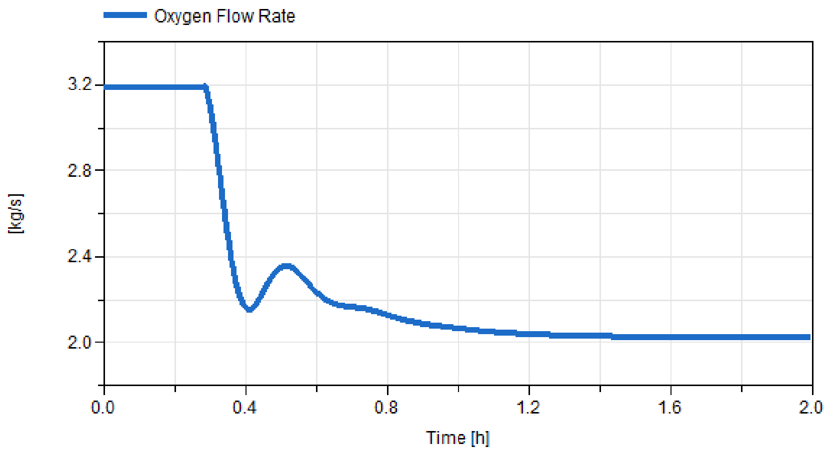


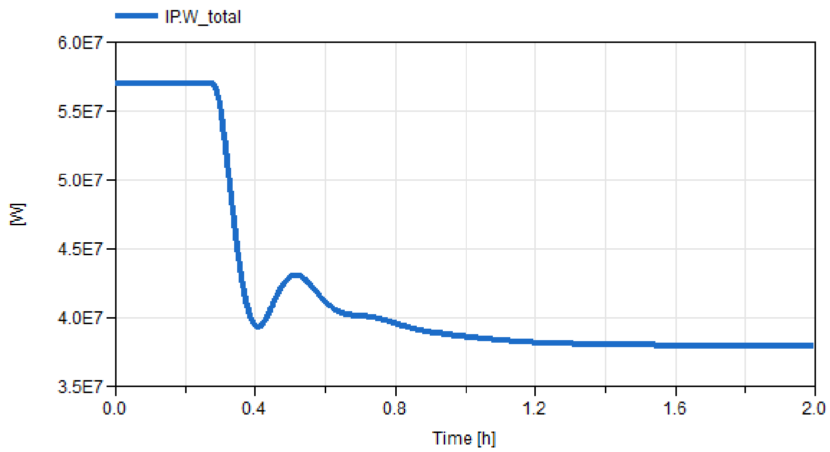
High-Temperature Steam Electrolysis (HTSE)

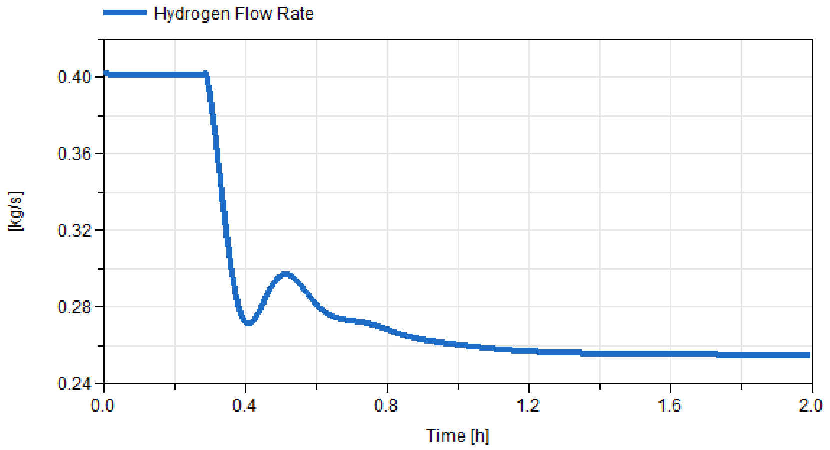


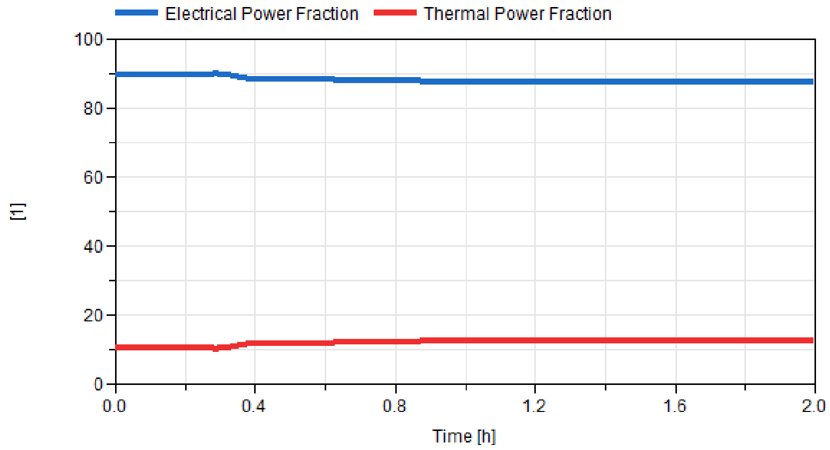


HTSE Two-Hour Simulation

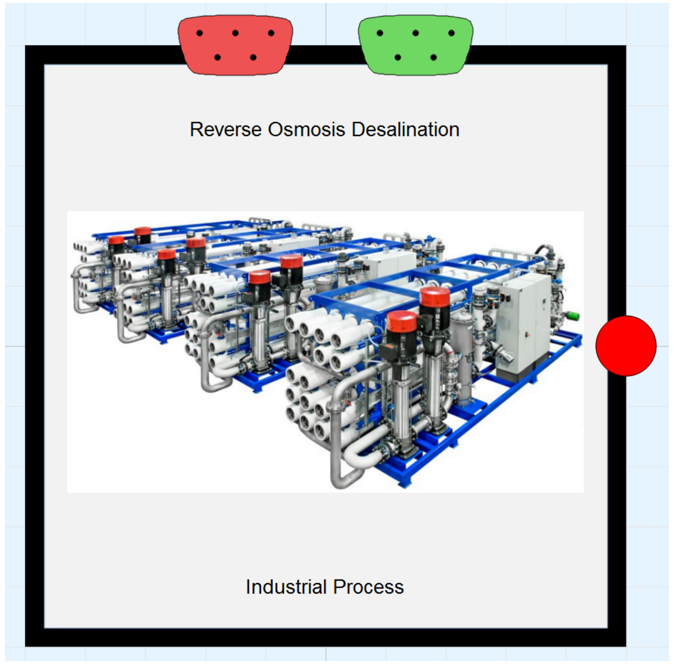


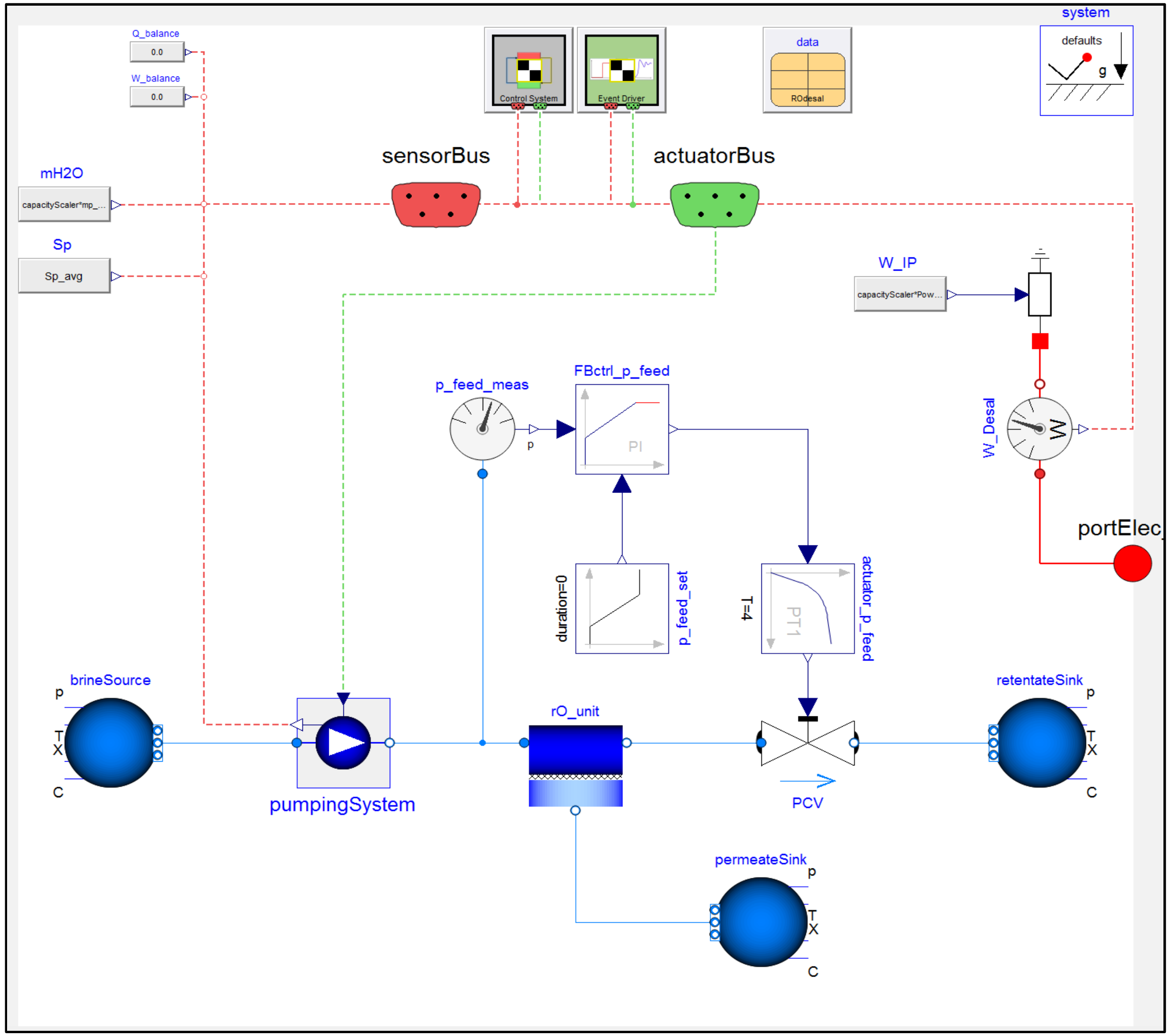




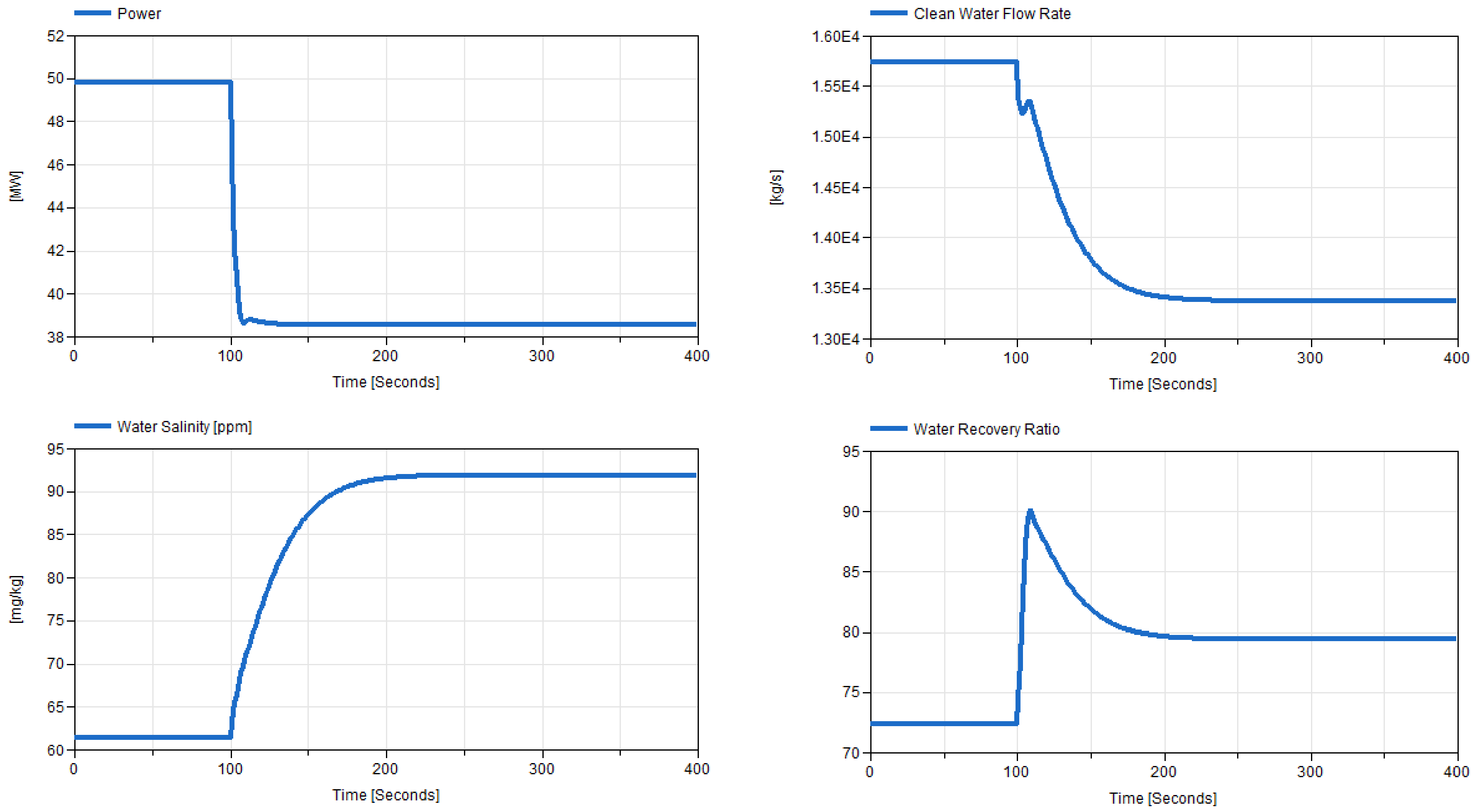


Reverse Osmosis (RO) Desalination

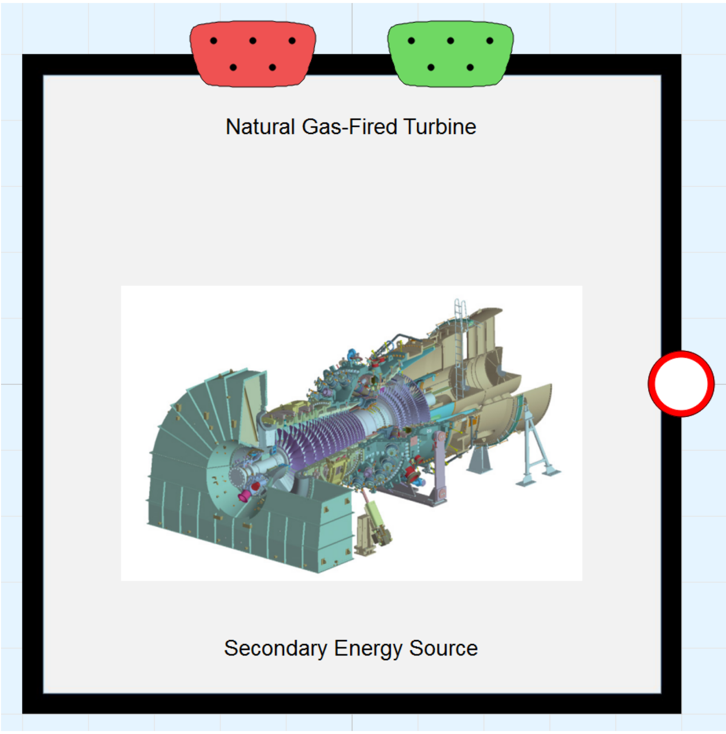


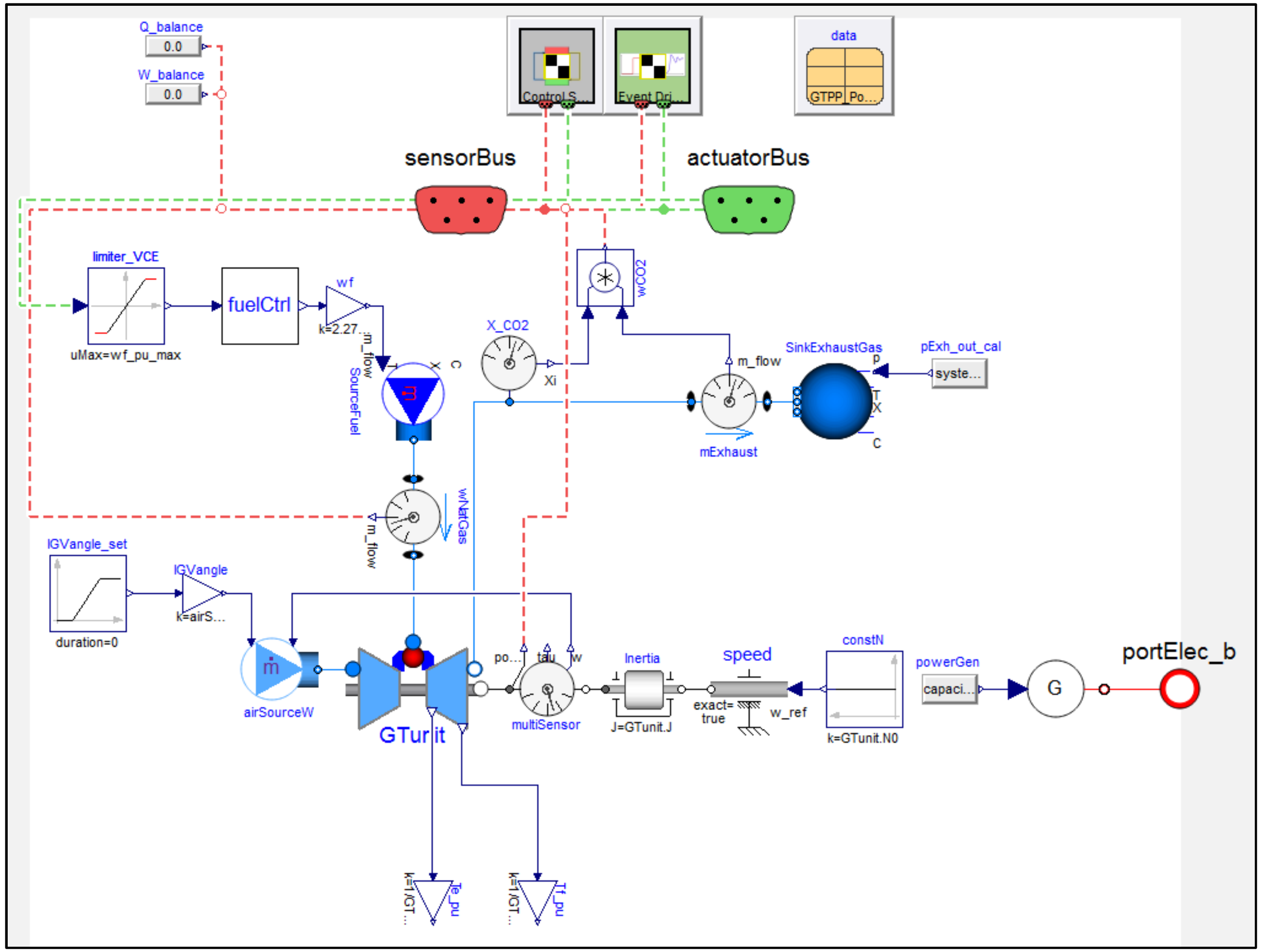


Reverse Osmosis 400 Second Run

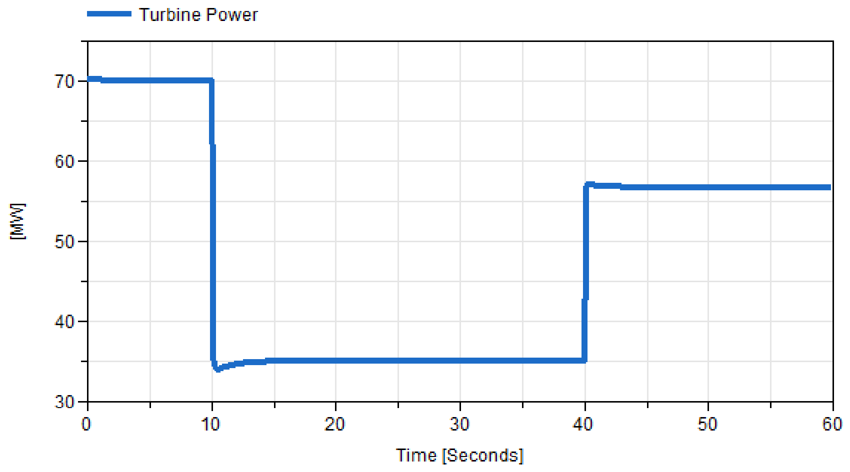


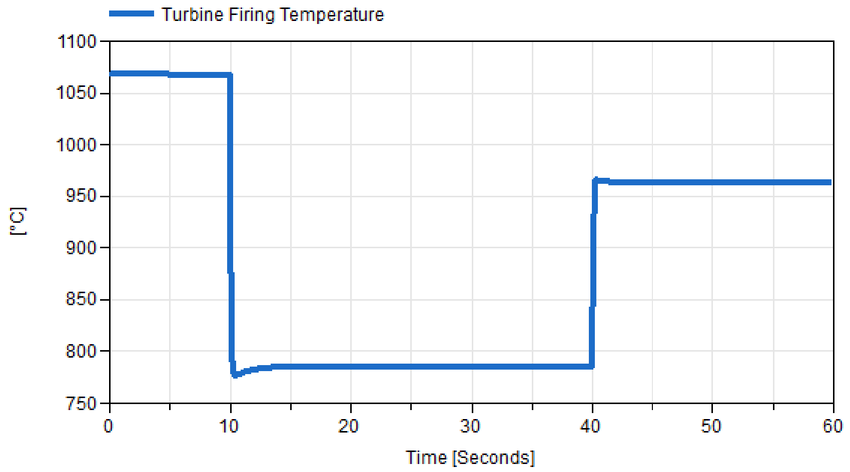
Natural Gas Fired Turbine

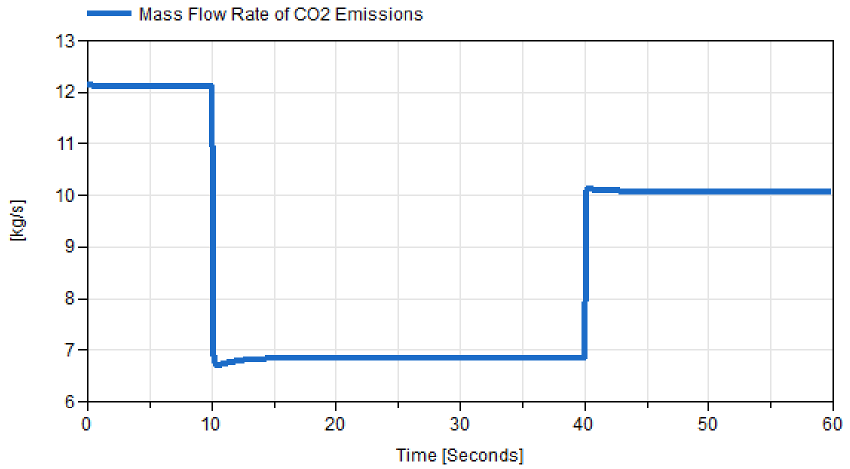


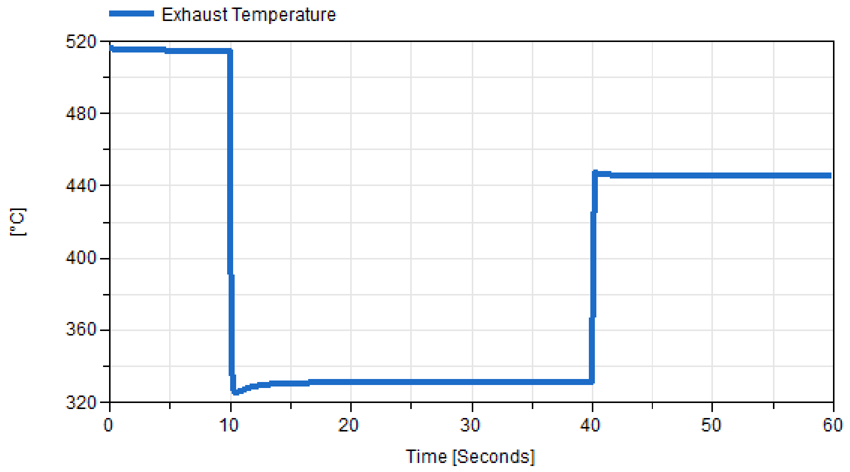


60 Second Dynamics









Simulation Capabilities/ Limitations

Subsystem		**Simulation** (All simulation times using Dymola 2018 – New CPU numbers have not been run with Dymola 2020)			
Category	Model	Settling time (min)	Stop time (s) [Interval length (s)]	CPU time (s)	CPU time/ Stop time
PHS	SMR – NuScale Style	<15	100 [1]	--	--
	WH style 4-Loop PWR	<60	10,000 [1]	33.31	0.0033
EM	Steam manifold	<60	100 [1]	0.623	0.0032
BOP	Ideal steam turbine	<60	100 [1]	0.06	0.0006
IP	HTSE	<45	3,600 [1]	11.48	0.0032
	RO desalination	<30	400 [1]	6.66	0.0166
ES	Battery	<60	100 [1]	0.006	0.00006
	Sensible TES	5–10	93,600 [1]	57.07	0.00061
SES	GTPP	1–5	600 [1]	0.067	0.00011
Integrated energy system	FY17 example: WH + HTSE + Battery + GTPP	–	352,800 [10]	5,886	0.0167
	FY18 example: WH PWR + HTSE + Battery + GTPP	–	86,400 [10]	213	0.0025

Available Literature on Models

- Literature:

1) https://www.osti.gov/biblio/1569288-status-report-nuscale-module-developed-modelica-framework. -- Frick, Konor L. Status Report on the NuScale Module Developed in the Modelica Framework. United States: N. p., 2019. Web. doi:10.2172/1569288.
2) https://www.osti.gov/biblio/1333156-status-component-models-developed-modelica-framework-high-temperature-steam-electrolysis-plant-gas-turbine-power-plant -- Suk Kim, Jong, McKellar, Michael, Bragg-Sitton, Shannon M., and Boardman, Richard D. Status on the Component Models Developed in the Modelica Framework: High-Temperature Steam Electrolysis Plant & Gas Turbine Power Plant. United States: N. p., 2016. Web. doi:10.2172/1333156.
3) https://www.osti.gov/biblio/1468648-status-report-component-models-developed-modelica-framework-reverse-osmosis-desalination-plant-thermal-energy-storage --Kim, Jong Suk, and Frick, Konor. Status Report on the Component Models Developed in the Modelica Framework: Reverse Osmosis Desalination Plant & Thermal Energy Storage. United States: N. p., 2018. Web. doi:10.2172/1468648.
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5) https://www.osti.gov/biblio/1557660-design-operation-sensible-heat-peaking-unit-small-modular-reactors -- Frick, Konor, Doster, Joseph Michael, and Bragg-Sitton, Shannon. Design and Operation of a Sensible Heat Peaking Unit for Small Modular Reactors. United States: N. p., 2018. Web. doi:10.1080/00295450.2018.1491181.
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7) https://www.osti.gov/biblio/1562960-dynamic-performance-analysis-high-temperature-steam-electrolysis-plant-integrated-within-nuclear-renewable-hybrid-energy-systems -- Kim, Jong Suk, Boardman, Richard D., and Bragg-Sitton, Shannon M. Dynamic performance analysis of a high-temperature steam electrolysis plant integrated within nuclear-renewable hybrid energy systems. United Kingdom: N. p., 2018. Web. doi:10.1016/j.apenergy.2018.07.060.
8) https://www.osti.gov/biblio/1357452-modeling-control-dynamic-performance-analysis-reverse-osmosis-desalination-plant-integrated-within-hybrid-energy-systems. Kim, Jong Suk, Chen, Jun, and Garcia, Humberto E. Modeling, control, and dynamic performance analysis of a reverse osmosis desalination plant integrated within hybrid energy systems. United States: N. p., 2016. Web. doi:10.1016/j.energy.2016.05.050.