Final Technical Report
Creation of Multiple Effect Evaporator and Combined Cycle Modelica Modules, and Optimization of Potable Water Generation from Saltwater Sources
Department of Energy, Idaho National Laboratory, System Integration
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Dr. Stephen Terry, PE, Dept of Mechanical & Aerospace Engr, NC State Univ
Dr. J Michael Doster, Dept of Nuclear Engineering, NC State University
Dr. Daniel Mikkelson, System Integration, Idaho National Laboratory

Abstract

Modelica models for a Heat Recovery Steam Generator (HRSG) and Multiple Effect Evaporator have been developed. These models have been validated against results from literature and from an actual cogeneration system on the campus of NC State University. The models are capable of connecting to other components to create multi-input, multi-output energy systems with storage, also known as integrated energy systems.

An existing 35 MW gas turbine model is connected to the HRSG model created for this project to produce 9 bar steam. The high pressure steam feeds a backpressure steam turbine from the library to generate additional electric power. 2 bar steam leaves the turbine to supply an 8 effect MEE to generate water for a community. As part of the effort, three research papers were submitted (two published in ANS Proceedings and one submitted to Applied Energy).

Introduction

Water, just like energy, is an important utility for communities, many manufacturing processes, and for generating power from traditional Rankine cycle plants (nuclear, coal, and combined cycle natural gas). The Department of Energy has identified the energy-water nexus as an important area for research [1]. As potable water sources such as aquifers are used faster than they can be replenished, new sources are needed. Seawater and brackish groundwater represent a huge source of water, but requires significant energy to treat into drinkable water.

Water treatment from contaminated, brackish, and salty waters requires more energy than surface or well fresh water. Two main technologies exist to treat salt and brackish waters in significant quantities:

1. Reverse Osmosis, which requires filtration at high pressure,
2. Multiple Effect Evaporation using a heat source in a cascading series of evaporators,

Models in the Modelica framework have been previously created for Reverse Osmosis systems. This effort has developed a Modelica model for thermal desalination capable of handling up to eight effects. Motive steam at low pressure (around several bar) is supplied to the model and purified water is output. The model is capable of interfacing with other library components (steam turbines, boilers).

The second product of the project is a Modelica model of a Heat Recovery Steam Generator (HRSG). HRSG units are frequently installed in cogeneration systems to produce steam from a source of hot air or combustion gases. The unit is essentially a boiler, but without a burner. The steam produced can be used in industrial processes, for space and water heating on university campuses and military bases, or to generate additional power via a Rankine Cycle (i.e., combined cycle generation).

The HRSG model includes superheater and economizer options. Multiple HRSG models can be coupled together to create a steam system with multiple pressures. The model can be connected to other library components, including gas turbines for input heat, steam turbines for power generation, industrial / commercial steam users, and the MEE model created. The bigger goal for the project is to allow researchers to create systems for grid independent / near independent energy parks located about military bases, large manufacturing facilities, and in small communities. Figure 1 shows how the two models fit into the larger effort of modeling energy use. The highlighted boxes indicate Modelica model additions with this project.

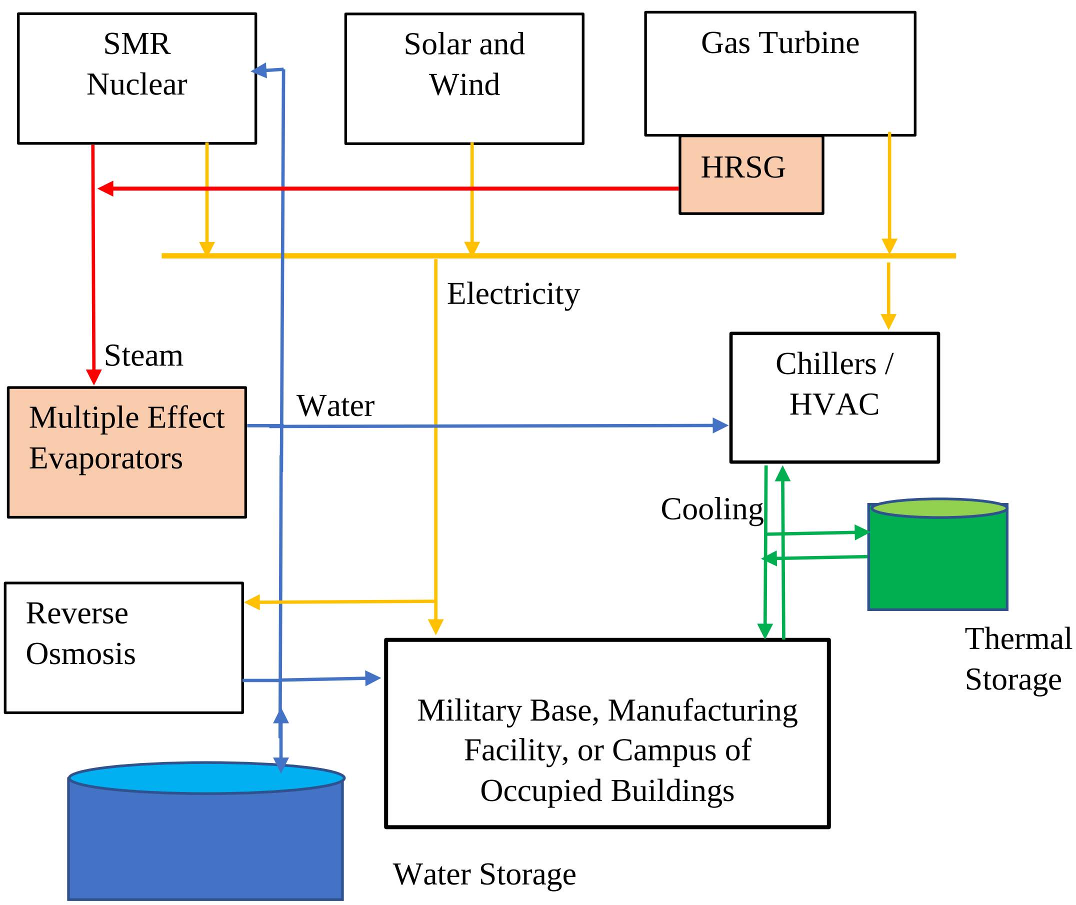

Figure 1. Schematic of Energy/Water Interdependencies for a Campus

Theory and Modeling Methodology

The simplest configuration for a HRSG is a single unit with no economizer or superheater, as shown in Figure 2. In this configuration the feed is controlled by a pump and is sent directly to the steam drum were the water mixes with the saturated liquid from the riser. This liquid is circulated down the downcomer and through the steam generator where it becomes a two-phase mixture. As the two-phase mixture exits the riser and enter the steam drum it is separated, the steam exits the drum while the liquid again mixes with the feed and recirculates. The saturated steam is sent through a pressure control valve to a sink. This valve controls the pressure of the steam drum. The feed flow rate is controlled by a three-element controller. This controller compares the liquid level in the drum to the set level, as well as the difference in feed and steam flow rates to control the feed.

The configuration with the economizer is created by adding another downcomer and heat exchanger between the feed pump and steam drum feed inlet. The economizer uses the gas exit of the steam generator as the gas inlet. The superheater is added similarly with a downcomer and heat exchanger between the steam exit of the steam drum and the pressure control valve. The superheater uses the highest temperature gas coming from the turbine then exiting to the gas inlet of the steam generator section. A natural circulation configuration with an economizer, superheater, and a feed control valve is shown in Figure 3.

A multi pressure HRSG is created by chaining several models together. In this configuration the highest pressure unit uses the highest temperature gas from the exit of the turbine as the gas inlet. The lower pressure units use the gas exit of the next highest pressure HRSG as the gas inlet, as shown in Figure 4. Each stage of the multi pressure HRSG can be configured separately. This is a possible layout for an industrial facility, such as a paper mill. The model can also be combined with other Modelica models from INL’s HYBRID library to simulate larger energy systems [2].

Shown in Figure 5 is a possible layout for a combined cycle power plant. The HRSG is configured with a gas turbine as the source of the flue gas, and a steam turbine as the steam sink and feed source. The model was created by combining several new and existing Modelica models. The existing models came from either the standard Modelica library or from INL’s HYBRID library. The heat exchanger model, pipe model and valve models used came from HYBRID. A three-element controller and a new steam drum model were created for the HRSG model.

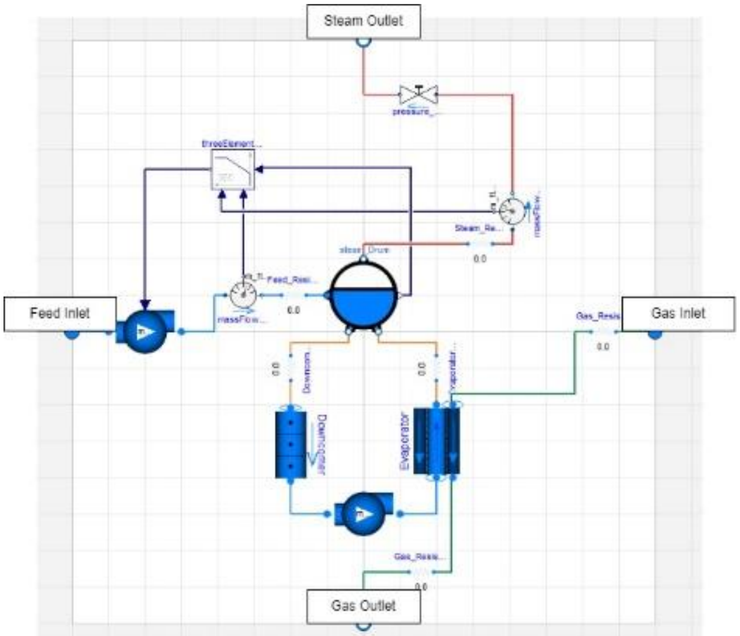

Figure 2. Simple HRSG model, with a feed pump and recirculation pump.

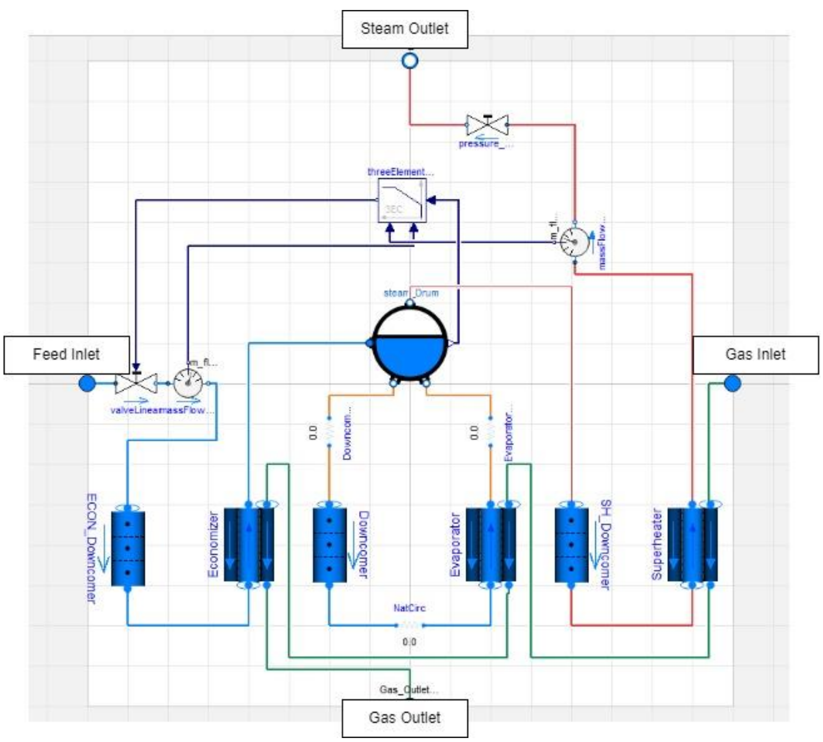

Figure 3. Natural circulation HRSG model with economizer, superheater, and control valve.

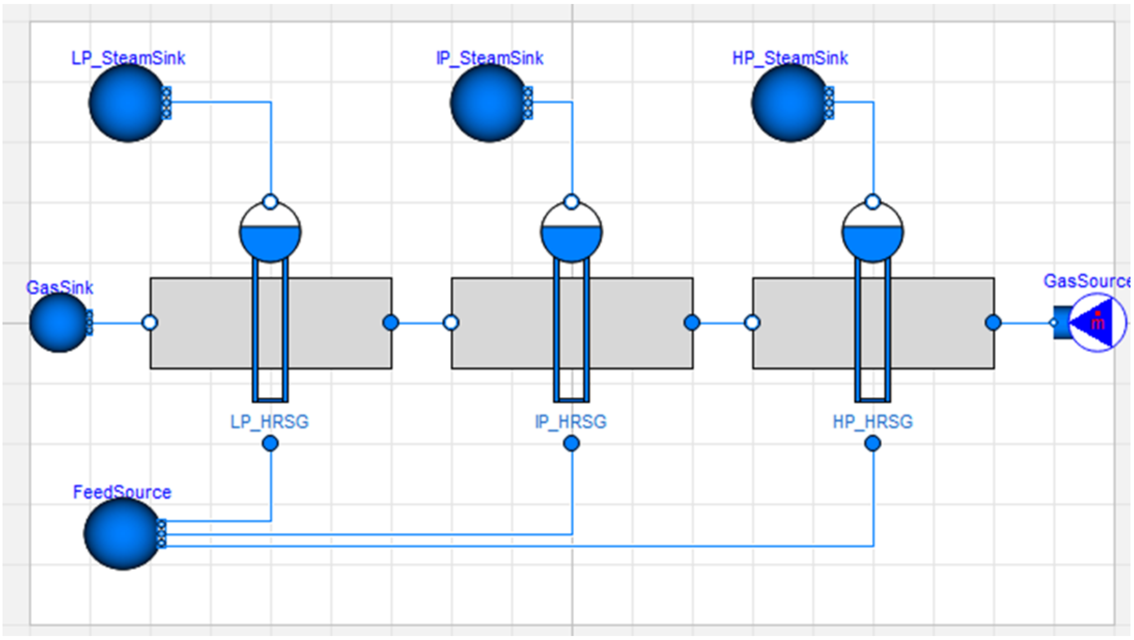

Figure 4. Multistage HRSG layout

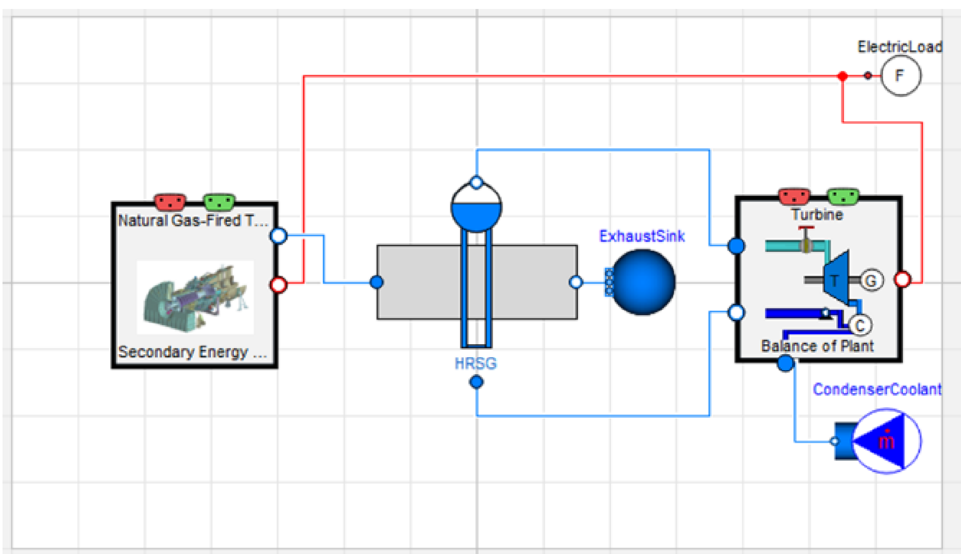

Figure 5. HRSG connected to a gas turbine model and a steam turbine balance of plant model

Data to validate the Modelica model was gathered from an existing HRSG at the Centennial Campus Cogeneration Plant at North Carolina State University (NCSU). This unit is part of a gas turbine-HRSG system that produces 5.5 MW of electrical power and up to 50,000 lb/hr of 125 psig steam for campus use. The Modelica model was set up as a single pressure unit with an economizer and driven by natural circulation. The average feedwater temperature, steam pressure, and fuel flows were taken from the operating plant. The input gas flow rate can vary over time, as shown in Figure 6. The exact geometric parameters of the plant were not available, so these parameters were chosen from a sensitivity analysis.

The results of the Dymola Modelica model were compared to the data from the actual plant. The data is plotted in Figure 7 for a period of 120,000 seconds, or 33.33 hours. The first 60,000 seconds (16.67 hours) not shown in the model was to establish a complete steady state for the model.

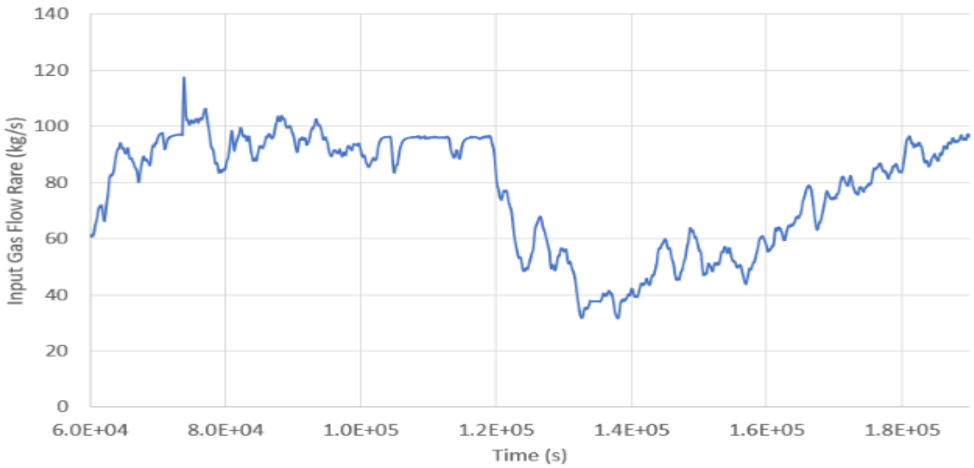

Figure 6. NC State University System Showing Natural Gas Use by the Turbine-HRSG

As can be seen in Figure 7, the actual and modeled steam output are in good agreement for most of the time considered. The modeled results do deviate from the measured actual values when there is a large drop in gas demand, and therefore steam produced. The Dymola model underpredicts the steam produced when the gas flow is significantly changed. This may be due to the large thermal mass in the systems which reduces the impact of variations. Thermal mass was considered in the Dymola model, but it is difficult to measure and match this parameter from the actual system.

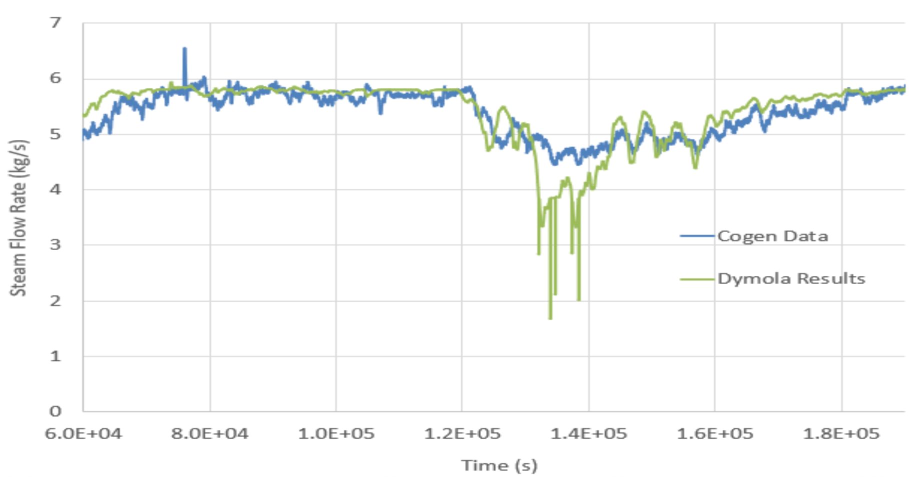

Figure 7. North Carolina State University System Performance Compared to Dymola Model

Multiple Effect Evaporators (MEE) are used in a variety of industries to gradually concentrate a liquid as it separates water from an impure feed. The desired product from the process can be the concentrated liquid or, in the case of desalination MEEs, the purified water that has been boiled off from the feed. Within an MEE, each effect acts as a single effect consisting of a two-phase volume with liquid brine and steam. The volume is connected to a dual phase heat exchanger which uses Nusselt's Theory of Condensation [4], Bromley's film boiling correlation [5] and a 1-D radial conduction model, to determine the heat rate.

All streams are at or very near saturation conditions so the temperature in each stream stays reasonably constant throughout phase change. The incoming hot stream is steam that condenses in the heat exchange and leaves as liquid condensate. The incoming cold stream is an impure feed that leaves in two streams; one liquid stream with a final higher impurity concentration and one clean water vapor stream that has evaporated off the cold stream. By accomplishing phase changes in both streams, MEEs are designed to capitalize on the large heat of vaporization of steam during the heat exchange process at relative constant temperatures.

The model is developed first as a single effect evaporator, and then multiple evaporators are chained together to create a full system by linking the output of one effect to the input of another. The shell side of each effect is a system of equations derived from the conservation equations listed below and constitute a fully transient model. The thermodynamic properties of the brine are found using the IAPWS industrial formulation for the thermodynamic properties of seawater [6]. The mixture set of equations contains a bubble rise velocity correlation, which accounts for mass transfer between the brine liquid and generated vapor.

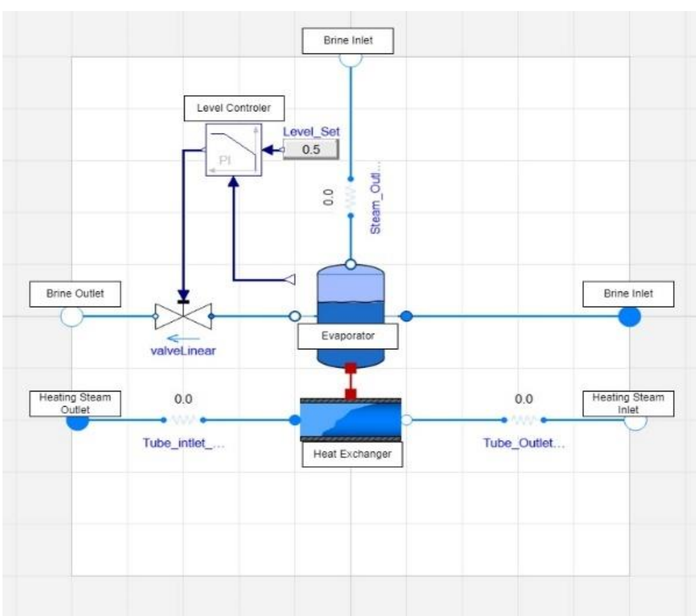

Figure 8. Single Effect Model, Inputs and Outputs.

To create an MEE system, the streams from different effects are connected so that the vapor from one effect becomes the input motive steam for the next effect. The outgoing higher concentrated liquid stream is typically the feed for a new effect to evaporate more pure water from the stream. This cascades down until the temperatures and pressures are less than what can be economically used or until a feed reaches a desired design concentration. The effects are self-feeding in this way through the system so that an MEE has two primary feeds that drive the whole system, an initial motive steam and the lowest concentration impure feed. Each effect operates with a different saturation temperature and corresponding pressure. Figure 9 shows the model in Dymola.

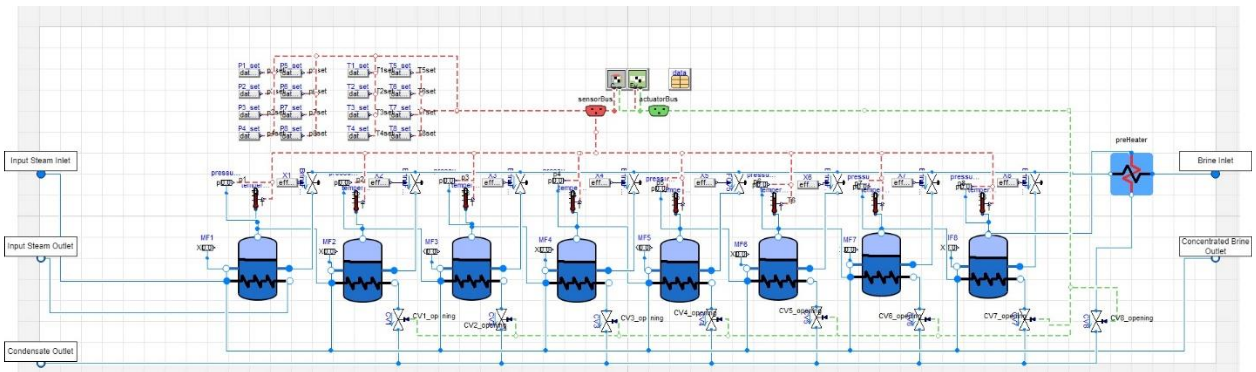

Figure 9. MEE Inputs and Output Streams

The model was tested and validated against example systems and results from literature (sources [8] through [10]). These comparisons were not meant to exactly match the literature values but to show this MED model follows anticipated trends from literature. The sources were chosen primarily on the parameters of interest and data provided which could be used to build comparable models. Many studies analyze parameters such as exergy, capital investment, pressure drops, et cetera which are not pertinent to this model. Trends discussed are generally common in MED technology and overall, the MED models developed follow the anticipated trends from four cited sources. The efficiency of these systems is measured using the Gain Output Ratio (GOR), which is the ratio of amount purified water produced to the input steam consumed.

The reference model in [7], was developed from material and energy balances for forward feed, backward feed, and parallel feed flow patterns. The study varied supplied steam flow to determine its effect on total distillate produced. From these, the GOR was calculated for the increasing steam flow. The trends, shown in Figure 10, support the literature suggesting that varying steam flow does not give a corresponding change in GOR. This is to be expected from MEE technology; adjusting the steam flowrate does not affect the intensive thermodynamic properties of the streams since the temperatures and pressures of the evaporators are not affected from the change. Adjusting the steam flowrate into the system will scale the distillate out of the system according to the GOR. Increasing the steam flow does not affect the efficiency of the system, it only achieves a difference in the magnitude of distillate produced.

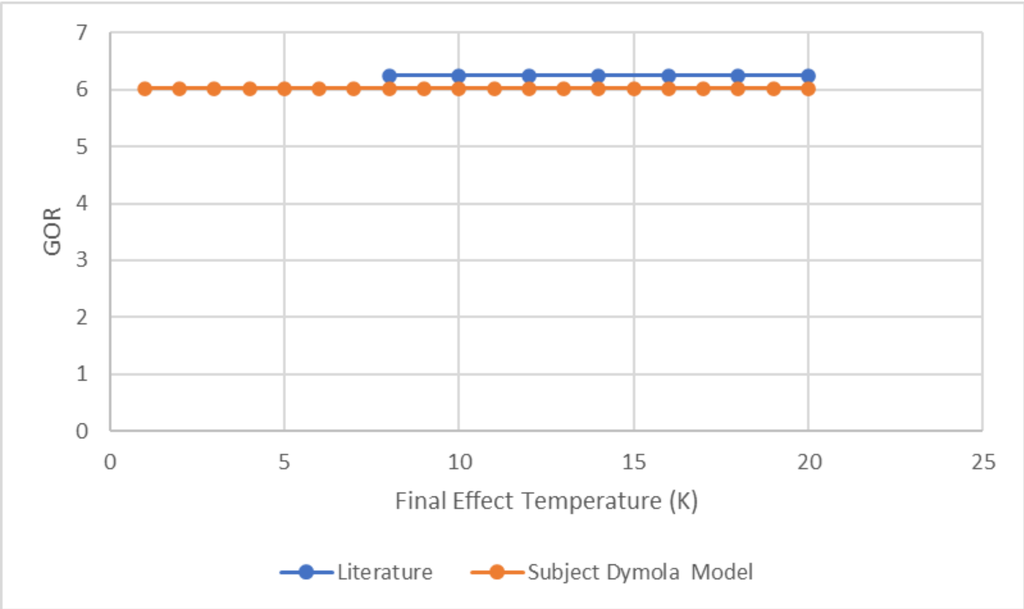

Figure 10. GOR vs. Steam Flow Rate

While increasing steam flowrate only serves to increases distillate production, increasing the number of effects in a plant will increase the GOR. This is because adding an extra effect increases the overall heat transfer area for the system and expands the opportunity flow chart for evaporation, allowing for more latent heat energy to transfer into the brine, all at the same steam input. This means, for the same steam flow rate in, the steam's heat energy is utilized through another effect to gain more output water. Each effect allows for the transfer of (most of) the original motive steam's energy through the train to generate distillate. Through each effect there are losses, of course, with the ultimate limiting factor being the diminished driving pressure and temperature as the vapor created in each effect has a lower pressure and temperature.

The increasing GOR trend with number of effects is shown in Figure 11 below. The reference literature model [8] employed a mass and energy balance alongside heat transfer equations, in in a forward feed system. The study showed that with a brine pretreatment, a higher GOR can be achieved from using a higher top brine temperature. Noticeably, while Fig. B shows the increasing GOR trend, the data line slope decreases slightly with increasing number of effects. Extrapolating the data along the line emphasizes that the increase in GOR will decrease with each new effect added. This is similar to the law of diminishing returns. This is attributed to the increasing impact of boiling point elevation in the brine which extends the necessary specific heat of the brine and saturation temperature losses of the vapor.

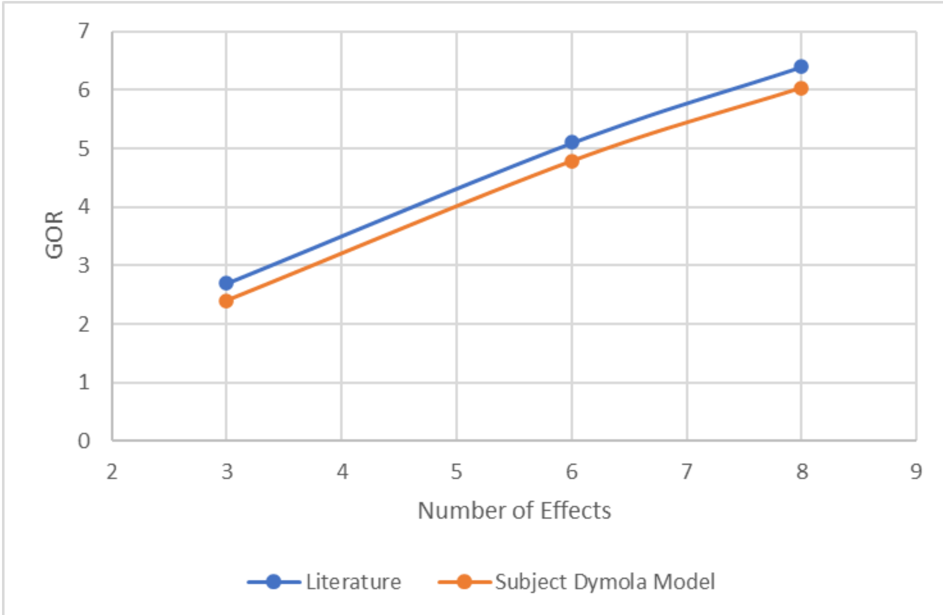

Figure 11. GOR vs. Number of Effects

The next validation comparison uses an MED model [9] based on an energy and mass balance, using both forward and backward feed configuration. The authors showed an increase in the feedwater salinity has a decreasing effect on GOR in MED technologies. This can be attributed to the increase in brine viscosity which leads to a reduced thermal conductivity and diffusion coefficient in the feed. There is also an anticipated boiling point elevation (BPE) effect that increases with salinity. This extra energy demand contributes to a decrease in GOR, along with reduced heat transfer coefficients.

Figure 12 shows how the literature model results compare to the subject Dymola model. The same trends are observed comparing the models – a decrease in GOR as the salinity increases. This trend can be attributed to the same physical phenomena discussed in the previous trend. The higher the salinity is in the plant feed, the more pronounced the BPE effect along with the associated impacts from a higher viscosity. However, the decrease in the literature model is more pronounced with salinity than the subject model. This is particularly true for salinities greater than 2%. Differences in how these models were setup (the specifics of the heat transfer surfaces, areas, etc.) could be behind these differences. Such specifics are not always provided in the literature making it difficult to compare models accurately.

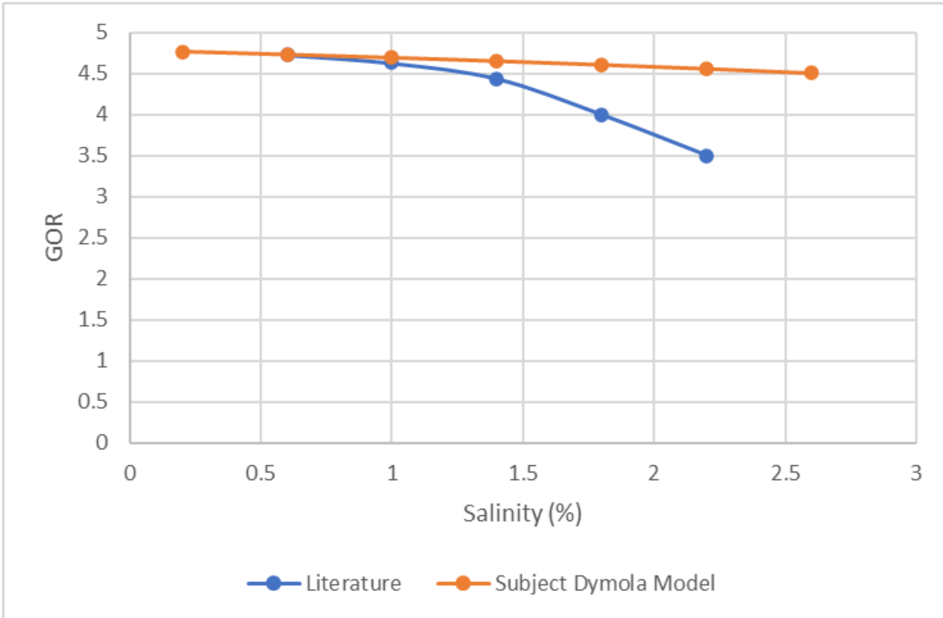

Figure 12. GOR vs. Salinity

In the fourth comparison example, the authors [10] created a mass, energy, and exergy model that was mathematically analyzed under thermodynamic and economic methodologies. The system incorporated both absorption-compression and vapor-compression heat pumps to gauge the effectiveness of innovative MED-MVC systems. Those models were seven effect MED-MVC systems where brine was fed to each effect from a common branch. This is feed pattern is known as parallel feed. The authors compared the condensation temperature of the first effect against system-wide parameters, like GOR.

Assuming a constant supply of brine feed allows the condensation temperature to vary while observing how other variables in the system respond. As the condensation temperature in the first effect is raised, the steam mass flow rate into the system must decrease to hold the same feed rate of the supply brine. A decreased steam mass flow rate into the system leads to an unequal decrease in distilled water produced from the system. The reduction of distillate production is larger than the reduction of steam flow rate, therefore the system's GOR decreases when the outlet flow rate reduction is larger than the inlet steam flow rate reduction. This is seen in Figure 13. The GOR decreases almost linearly as the first effect temperature increases from 344 to 356K. In the subject Dymola model, the GOP decreases with a similar slope from 348 to 358K.

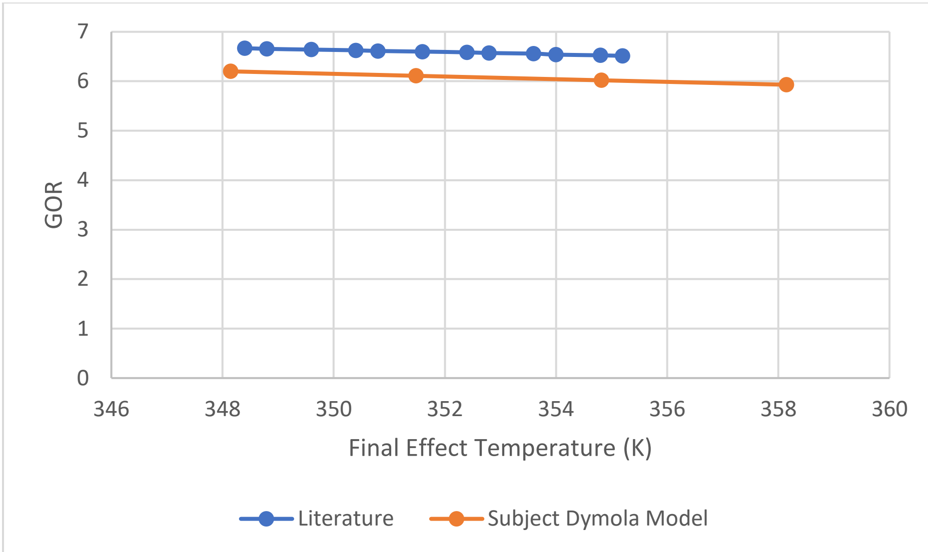

Figure 13. GOR vs. Final Effect Temperature

Results

A hybrid plant model shown in Figure 14, was constructed to incorporate the developed MEE and HRSG models coupled with gas and steam turbine balance of plant models from the NHES library. The plant acts as an IES that can produce power to the grid and freshwater. Fuel is fed to the NG turbine where the exhaust heat is captured by the HRSG. The HRSG, operating around 9 bar, fuels a steam turbine where backpressure steam at 2 bar is used as input to the MEE. The desalination model used is an 8 effect MED. The model was run to steady state and then given a power increase transient for the NG turbine power. At T=100s, the power of the gas turbine goes from 30 MW to 35 MW. T=100 and T=500 seconds are used in the results analysis as representative time stamps for the two steady state operations of the power plants.

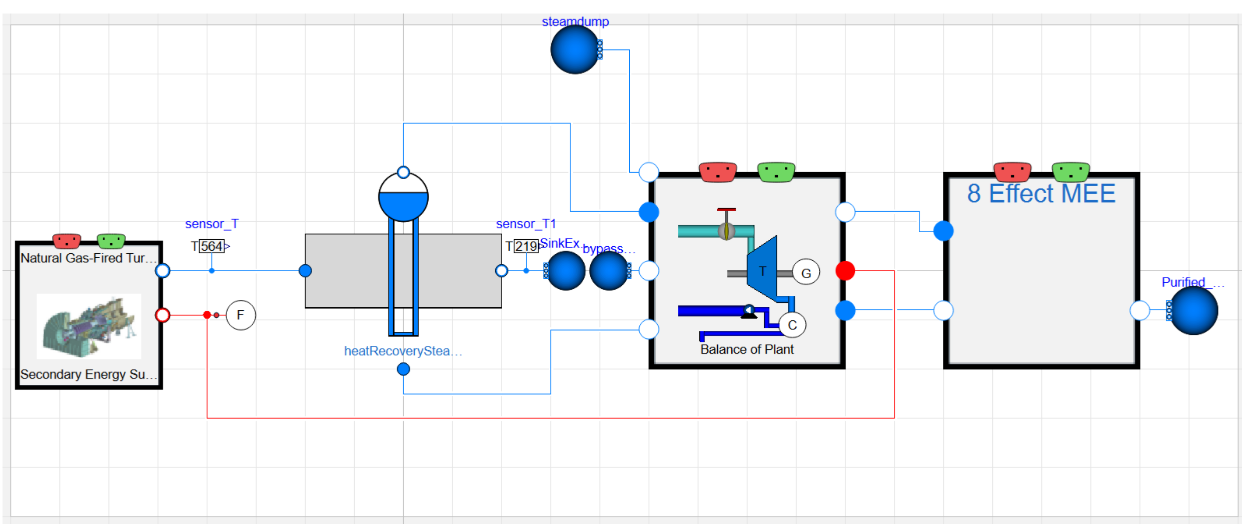

Figure 14. Dymola Subject IES Model Layout: major component icons from left to right include the GT, HRSG, ST, and 3 effect MED.

The IES results are shown in the graphs below. Figure 15 shows the power produced by each turbine. Over the runtime, the power output of each turbine gains a steady state operation. As the NG turbine receives a power increase, there is a corresponding downstream increase in the output of the steam turbine, though at less magnitude. From T=100 to T=500, the GT increases 5 MW while the steam turbine only increases 0.46 MW.

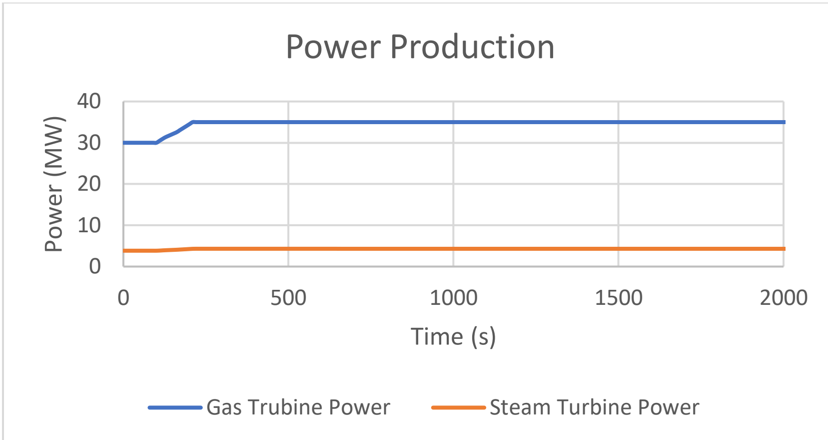

Figure 15. Power Produced by the GT and ST

Figure 16 shows the rate at which clean water was produced out of the 3 effect desalination model. Note, the flowrate trends alongside the incoming steam rate into the MED and not the power out from the turbines.

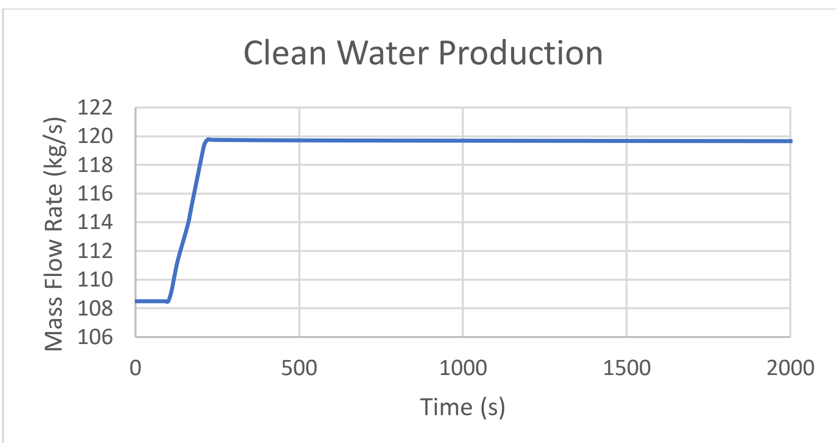

Figure 16. Clean Water Produced by the 3 Effect MED on the IES

Changing power on a gas turbine is not an atypical maneuver for a utility. Gas turbines are often used to supplement power generation on grids with a high penetration of intermittent renewable energy resources. Having a HRSG model that can be paired with a steam turbine means that a comprehensive combined cycle power plant can be modeled – the most common type of generation being installed on today's grid. The HRSG model also means smaller scale cogeneration systems for manufacturing plants, universities, hospitals, and military bases can be modeled.

Water production and power generation values are tabulated in Table 1, for different gas turbine power levels. Also shown is the power generated by the steam cycle without a MED plant. For this system the condenser pressure is set to 0.1 bar.

Table 1: Steam Power and Purified Water Production at Different Gas Turbine Power levels.

% Power	Gas Turbine Power (MW)	MED Water Production (kg/s)	Steam Cycle Power with MED (MW)	Steam Cycle Power without MED (MW)
100	35.0	119.82	4.31	9.78
90	31.5	112.02	3.99	9.02
80	28.0	103.77	3.65	8.24
70	24.5	94.56	3.28	7.40
60	21.0	84.30	6.43	6.43

Pairing the MEE with the gas turbine, HRSG, and steam turbine is useful for communities in the desert where even brackish well water might be in limited supply. These communities often employ combined cycle plants with air cooled condensers on the steam turbine side, rather than water cooled condensers. This reduces the efficiency of the steam turbine cycle because condenser pressures are much higher. Adding an MEE also reduces the efficiency of the cycle as well, but the waste heat produces useful water that can be generated as the turbine is ramped up and down, then stored to supplement that produced by RO.

Summary

The models created with this project increase the options available to those modeling IES systems. As intermittent renewable energy penetrate the market to levels where grid stability is threatened, a variety of energy storage options are critical. Thermal desalination systems can be valuable in areas where water is scarce or where the concentrated product valuable (i.e., black liquor in paper mills).

Publications

Williams, L; Solis, E; Doster, J.M.; Terry, S.D.; Frick, K; "Heat Recovery Steam Generator Models In Support of Integrated Energy Systems", 2022 American Nuclear Society Winter Meeting Transactions, Volume 127 #1, pp. 828-831, November 2022

Solis, E; Williams, L; Terry, S.D.; Doster, J.M.; Frick, K; "Desalination Multi-Effect Evaporator Models in Support of Integrated Energy Systems", 2022 American Nuclear Society Winter Meeting Transactions, Volume 127 #1, pp. 836-839, November 2022

Williams, L; Solis, E; Terry, S.D.; Doster, J.M.; "Modeling Cogeneration Systems to Produce Electrical Power and Drinking Water", submitted to Applied Energy

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