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Hybrid Energy System Modeling in Modelica

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Abstract

In this paper, a Hybrid Energy System (HES) configuration is modeled in Modelica. Hybrid Energy Systems (HES) have as their defining characteristic the use of one or more energy inputs, combined with the potential for multiple energy outputs. Compared to traditional energy systems, HES provide additional operational flexibility so that high variability in both energy production and consumption levels can be absorbed more effectively. This is particularly important when including renewable energy sources, whose output levels are inherently variable, determined by nature.

The specific HES configuration modeled in this paper include two energy inputs: a nuclear plant, and a series of wind turbines. In addition, the system produces two energy outputs: electricity and synthetic fuel. The models are verified through simulations of the individual components, and the system as a whole. The simulations are performed for a range of component sizes, operating conditions, and control schemes.

Keywords: hybrid energy system; Modelica; multiple-input; multiple-output; renewable power; optimization

1 Introduction

Over the many years during which the current energy ecosystem was designed and has evolved, technological and social growth occurred slowly and environmental impact was not a primary concern. However in the current context of global climate change and economic volatility, the old energy system is far from optimal. Renewable energy sources promise an alternative that is both low cost and environmentally friendly. However, renewables also pose a challenge: they introduce significant variability in their output.

The output variability and uncontrollability of renewables require grid operators to maintain a larger spinning reserve. If a large plant is asked to reduce generation as the result of using lower-cost solar or wind, the plant has to ramp down and eventually ramp up again. This is harmful, as the cyclical loading reduces the life of the plant, or requires costly maintenance.

In addition to output variability, another concern when designing a power plant is the potential change in the cost of inputs as well as the price of outputs. In a conventional plant, there is only one input and one output. A consequence of this one-to-one energy mapping is that the plant has little control over its profitability when a price change occurs. An increase in the cost of the input, or decrease in the price of the output will most likely cause a decrease in profit. There is a clear tradeoff between using the low cost renewables and the higher level of control that conventional plants offer.

One approach for managing such tradeoffs is the development of Hybrid Energy Systems (HES). HES consider multiple energy inputs and outputs in one system. A Multiple Input Single Output (MISO) HES uses two or more energy inputs, such as nuclear and wind, and produces a single output, most often electricity. A Multiple Input Multiple Output (MIMO) system includes multiple inputs and produces multiple outputs, such as producing both electricity and synthetic fuel. Since they are capable of dynamically utilizing diverse inputs and outputs with different costs, MIMO HES provide a flexible and robust alternative for the energy ecosystem.

There are distinct advantages to having multiple energy inputs and outputs. Consider the HES architecture shown in Figure 1. This MIMO HES uses a renewable energy source (e.g., wind or solar), a nonrenewable energy source (e.g., nuclear), and a carbon source to provide both electricity and chemical products. The HES whose models are presented in this paper use the architecture illustrated in Figure 1. One proposed mode of operation when generation from renewables is high is to direct steam from the non-renewable source to the chemical plant, which requires high-temperature steam to produce synthetic fuel. The amount of steam diverted to the chemical plant can be dynamically varied so that the HES can load-follow, i.e., it can quickly react to changes in the availability of renewables or the demand from the grid. The price of electricity may change dramatically, not only during different seasons, but also during the course of a day. It is even possible that the price of electricity becomes negative, and plants must pay to dispose of the electricity they produce. Producing for a short period at negative prices may sometimes be acceptable because the cost of ramping down and ramping back up is greater than the expected loss from paying to push the electricity onto the grid [5]. Plants or MISO systems that only produce one output have little flexibility as they cannot produce another product. MIMO systems however, are more flexible. If the price for one of its outputs drops significantly, the system can produce other outputs that are still highly priced. This increased diversity allows for plant owners to generate greater and more consistent profits. Since the MIMO system does not need to cycle the non-renewable source as frequently, its performance, reliability, and capacity factor are expected to be larger than for other systems. This in turn results in an opportunity for increased renewable penetration as well as profitability for plant owners.

Although MIMO systems provide many benefits, there are also some disadvantages. Due to the increased complexity of these plants, their design, analysis, and control becomes more challenging. A second disadvantage concerns the lifespan of key components, such as heat exchangers, which may suffer from additional wear due to thermal cycling. Another concern for HES is that they have to deal with dynamic conditions that cannot be well represented in a static model. In addition, dynamic simulation is critical to controller design and optimization. To support dynamic modeling, models are implemented using the Modelica language, and simulated using Dymola [9].

In the remainder of this paper, other HES models from the literature are first reviewed. Then, models are presented for the thermo-fluid systems, electrical system, and chemical system of the HES architecture shown in Figure 1. Simulations of these models are then reported and interpreted. In addition, lessons learned throughout the model creation process are presented. Finally, concepts for future work are described.

2 Related Work

Modeling and optimization of HES is not entirely new. There are multiple examples of research being made in this area [13-15]. [15] is an example of a hybrid wind-solar energy system for small scale applications. The hybrid system does not connect with the electrical grid and therefore avoids any complications associated with having to do so, such as maintaining the same phase angle and voltage. This is another area where HES can be applied; however the systems designed for off-grid use do not help alleviate the non-renewable production of electricity that

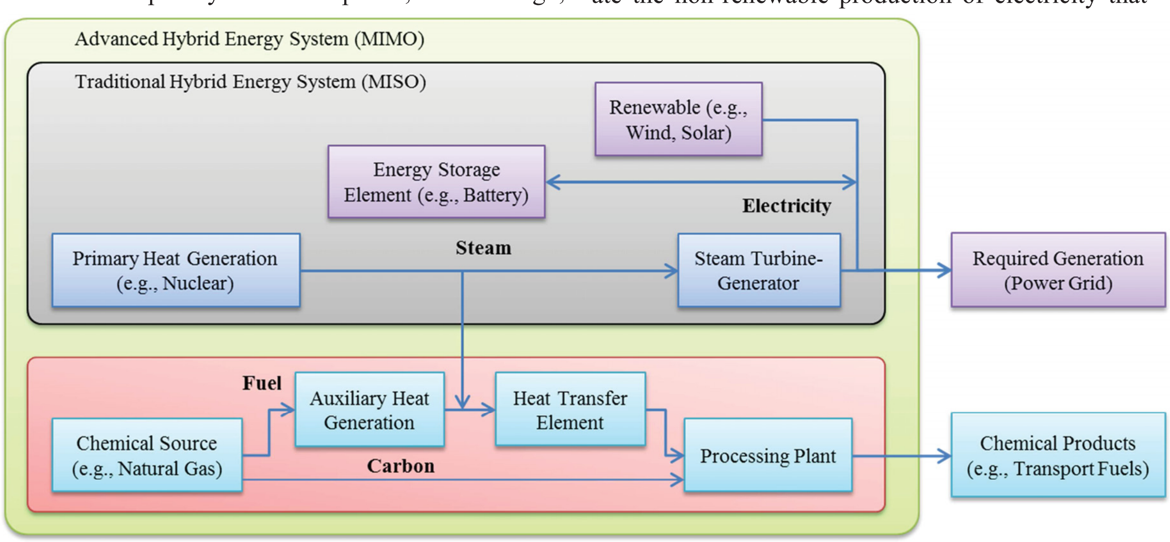

Figure 1: The architecture for an Advanced Hybrid Energy System (MIMO) [6, 7]

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dominates the electrical grid. There are examples of on-grid applications, such as [13].

In [13], the task of handling renewable generation for the purpose of connecting to the electrical grid is addressed. This system however, focuses on the control and optimization of a wind power generation plant, as compared to HES. In this case, the plant is optimized to account for dynamic changes that can occur in wind. Even so, this does not eliminate the plants dependency on there being a sufficient amount of wind to power the electrical grid. The issue of connecting a HES to the grid is discussed in [14].

In the case of [14], the HES consists of a photovoltaic, diesel, battery combination. This is used for the purpose of supplying electricity to rural Saudi Arabia. In this application, software called the Hybrid Optimization Model for Electric Renewables (HOMER) was used to evaluate and optimize the HES [12]. HOMER allows for the design of HES architectures, in a high level view. It can be used to evaluate the basic structure of HES, but does not deal with the dynamic events occurring within a system. In addition, HOMER handles loads such as electricity and thermal, abstracting the smaller components that would actually be involved in the design of a large scale plant.

There appears to be a gap in terms of designing a full scale HES plant for the purpose of connecting to the electrical grid. The previous examples show that there is potential for economic and environmental improvements from creating HES configurations, either new or from converting old plants.

3 Models

The modeling of the HES described above was divided into five main sections. The five sections are: the nuclear reactor, two steam cycles, a chemical plant, and the electrical component. These subsystems are shown in Figure 2, which shows the individual models connected to illustrate the final structure of the HES model. The nuclear reactor supplies the primary heat generation that is utilized in the first steam cycle. The steam cycles consist of one segment that extracts work from the heated steam for the purpose of generating electricity, and the other superheats steam for the chemical plant. The chemical plant takes hot steam and natural gas to produce synthetic fuel. The electrical section contains the renewable source, in this case wind turbines, with a battery and connects with the electricity generated elsewhere to power the electrical grid. The models used are from the Modelica basic library as well as the ThermoPower library, which is used for modeling of the thermo-fluid components [1].

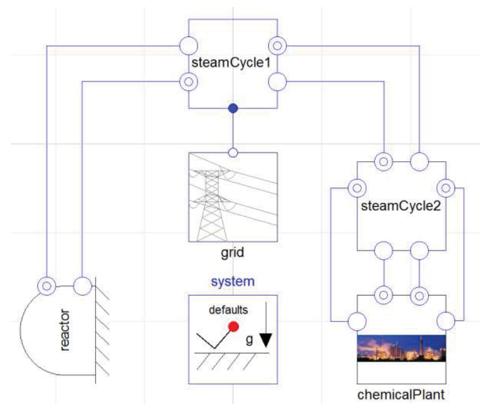

Figure 2: Top-level model for the HES

3.1 Nuclear Reactor

The nuclear reactor's purpose is to supply heat to the steam cycle. This is the largest energy input to the HES. The model for the reactor is shown in Figure 3. The model is simplified as the primary concerns are with the dynamics of the interconnected system involving the electrical and chemical components. The reactor uses a heat source that ramps from a nominal starting power to its full load. This represents a plant powering up from reduced load. This allows for a system that uses the reactor to warm up to steady state operating conditions, as compared to trying to start all of the equipment at full load. This heat transfer is applied to a pipe with water flowing through it to represent a main heat exchanger.

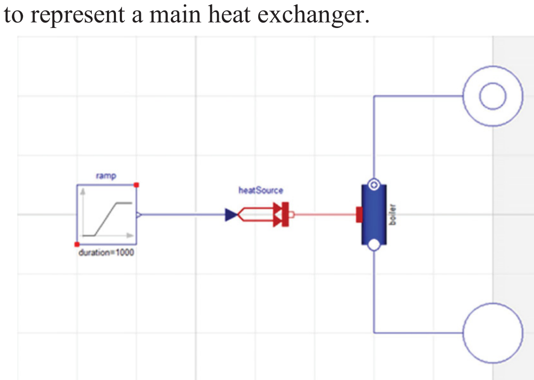

Figure 3: The model for the reactor.

3.2 Steam Cycle

The steam cycle models are responsible for capturing the transfer and distribution of energy of the thermo-fluid portion of the HES. This is broken into two segments: one whose primary purpose is the production of electricity, and the second being the superheating of steam to the chemical plant. The distinction of primary purpose is necessary due to the fact that both segments produce electricity and heat water.

The portion of the steam cycle primarily responsible for generating electricity is shown in Figure 4. There are some critical observations to note about this model. Since the HES can vary the amount of steam being utilized to produce electricity, if just one turbine were to be used there would be times where it would not be fully utilized. For this reason, multiple turbines are present for use in a cascading fashion, as in, at low power requirements, only the “60% Turbine” may be used. As the electrical demand increases, the “30% Turbine” and eventually the “15% Turbine” will also be added. Other than this, the model represents a Rankine cycle with safety components as well as a boiler to distribute steam to the chemical plant. When the power demanded from the turbines is lowered by the addition of renewable power, the flow rates through the turbines will decrease. This will cause a corresponding increase in pressure as the same amount of heat is being added to the cycle, regardless of the turbine output. To regulate this pressure, a pressure relief valve is present, but instead of venting this excess energy, the excess steam is used to heat condensate water coming from the chemical plant, thus providing it with steam. A temperature control valve is also included to more precisely control the temperature of the colder water entering the nuclear reactor.

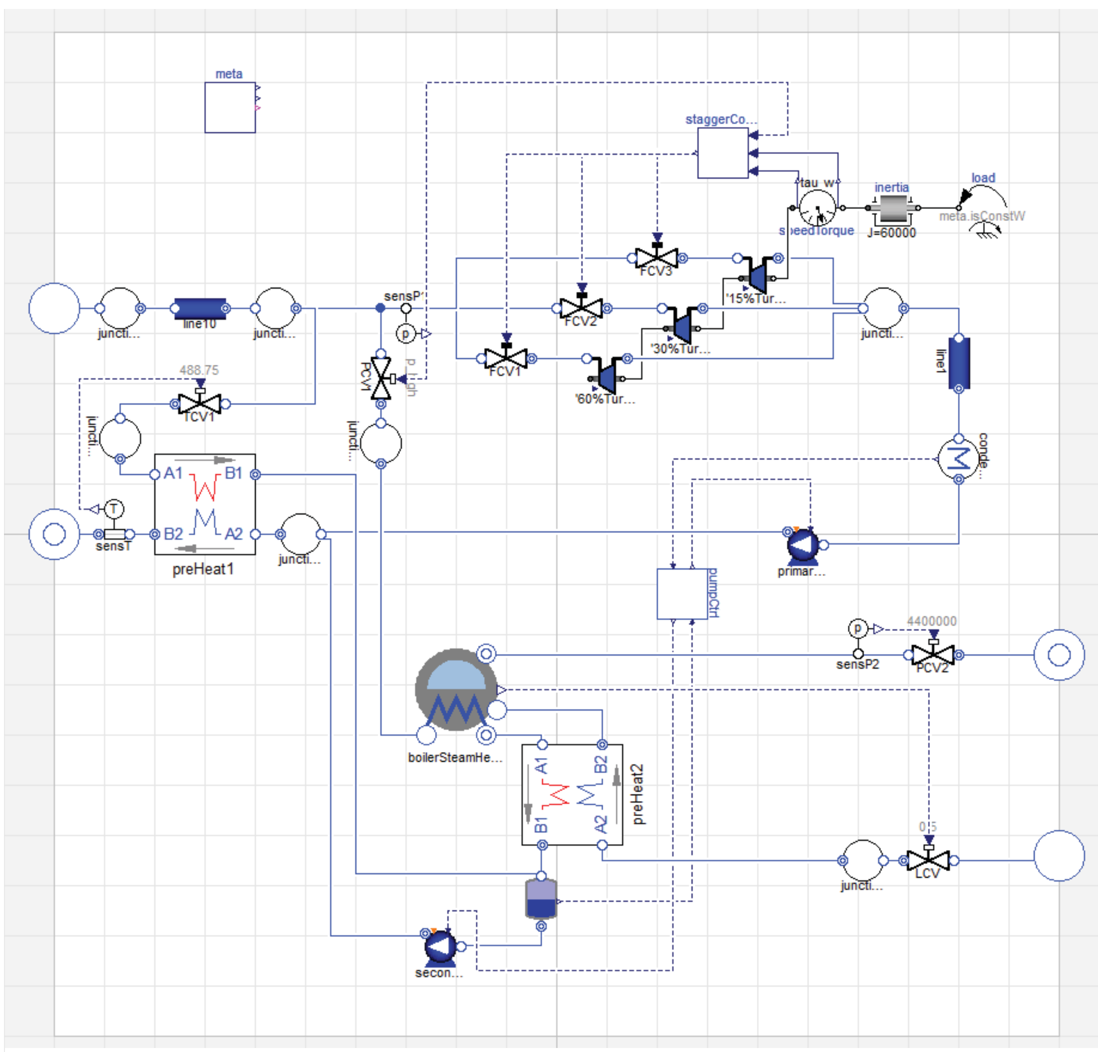

Figure 4: The model for the steam cycle whose primary function is to produce electricity.

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The model for the heat exchanger is a simplified one that is capable of simulating phase changes in the system. Other heat exchangers had been tested, such as those from the ThermoPower library and the Modelica standard library, however they did not fit the needs of this application [1, 9]. The complication in using these models is that they were not designed to allow the fluid to undergo a complete phase change. The cooling of steam to water results in significant changes in the fluid properties, such as density. This causes simulation stiffness. Often, at least one of the heat exchangers is not always in use, it is possible for the contents of that heat exchanger to cool to the saturated liquid vapor temperature, and causes corresponding stiffness.

To resolve this, a model was created that utilizes pipes with no volume. Since there is no volume, the large changes in fluid properties that occur throughout the heat exchanger are largely ignored, and only the inlet/outlet conditions of the fluid determine the heat transfer.

To capture as much detail as reasonable, the heat transfer, Q, and efficiency of the heat exchanger, η, are calculated in equations (1), (2), (3), and (4) [2, 10]:

$$Q = \Delta h_{Hot} w_{Hot} = -\Delta h_{Cold} w_{Cold} \tag{1}$$

$$\eta = \frac{T_{ColdIntlet} - T_{ColdOutlet}}{T_{ColdInlet} - T_{HotInlet}} \tag{2}$$

$$\alpha = k\left(\frac{1}{\dot{m}_{Hot} C_{p_{Hot}}} + \frac{1}{\dot{m}_{Cold} C_{p_{Cold}}}\right) \tag{3}$$

$$\frac{T_{HotOutlet} - T_{ColdOutlet}}{T_{HotInlet} - T_{ColdInlet}} = e^{\alpha} \tag{4}$$

where Δh is the change in enthalpy, $\dot{m}$ is the mass flow rate, and C_p is the specific heat of the fluid. k is the assumed heat transfer coefficient. This ignores some of the effects that are present during a phase change in a heat exchanger, however, this occurs

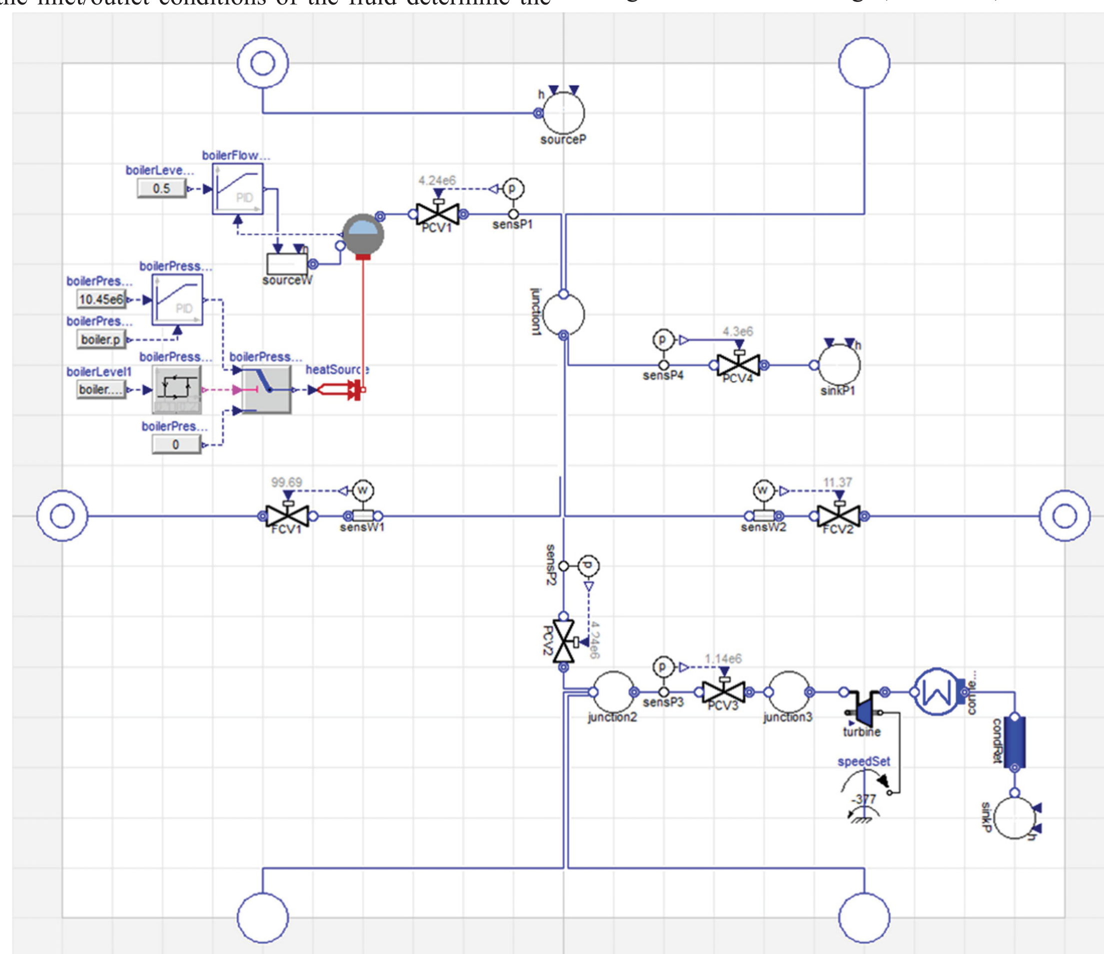

Figure 5: The model for the steam cycle that is primarily responsible for superheating steam to the chemical plant.

under conditions where capturing that change is considered insignificant. A phase change can occur when the flow rate of the hot side is small relative to the cold side. This can occur in the second heat exchanger in Figure 4, labeled preHeat2. It is expected that this condition will not change the results drastically, and the dynamics of the heat exchanger when it is not transferring large amounts of heat are not a concern currently.

Figure 5 presents the other side of the steam cycle, the one responsible for superheating steam to the chemical plant. The purpose of this model is to take steam generated from the model in Figure 4, superheat it, and then transport it to the chemical plant. There are locations where the condensate water addition and removal are represented by sources and sinks of water. This is done for simplicity instead of closing the loop of flowing water. The dynamics of the condensate water used in this system are not considered a significant concern. In addition, the justification for this is that the condensate water is merely being pumped around the system, and the power required to pump liquid water is small relative to the power produced by most Rankine cycles [10].

In the event that there is an insufficient amount of steam being transferred to the model in Figure 5, this system also has auxiliary heat production generate the necessary additional steam. Furthermore, the steam that returns from the chemical plant, in addition to excess steam produced, if any, is put through a turbine to capture energy that would have been wasted otherwise.

3.3 Chemical Plant

The model of the chemical plant is shown in Figure 6. The chemical plant model utilizes a methanol medium, and most of the sub-models perform their functions mathematically, via transfer functions, instead of using the energy based components of the water system. This is done to simplify the overall analysis, as the intricacies of transforming natural gas to gasoline and liquefied petroleum gas (LPG) are not of interest.

3.4 Electrical

The electrical model is the location where the renewable source and the electrical grid, which receives power from the HES, are included. The renewable generation for the HES under consideration is a series of wind turbines. The model uses representative data for wind speed for a location in Idaho from the Western Wind dataset, which was made available from NREL (National Renewable Energy Laboratory) [6, 11]. This data assumes a height of one-hundred meters and has wind data for every ten minute period. The year period of 2006 is used for simulations. This wind speed, v, is then mapped to rotational power, P, by equation (5) [13]:

$$P = \frac{1}{2}\rho A v^3 C_p \tag{5}$$

where ρ is the air density, A is the cross sectional

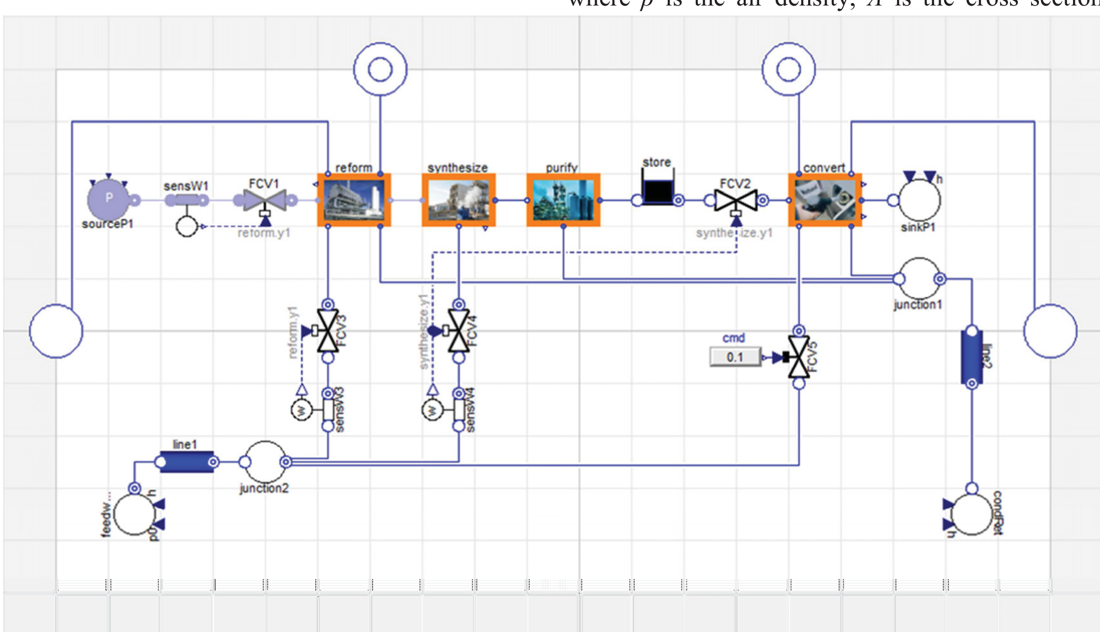

Figure 6: The model for the chemical plant.

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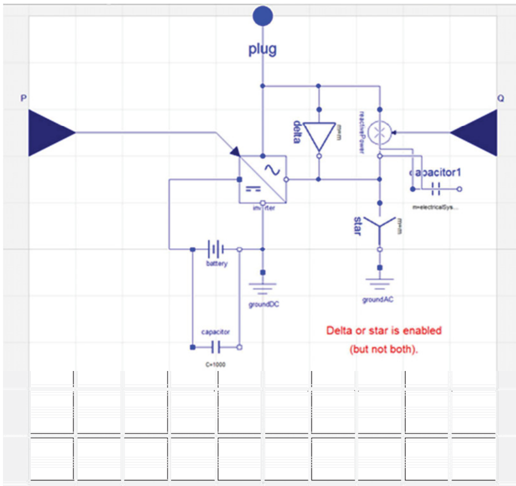

Figure 7: The model for a battery.

area of the blades, and C_p is the power coefficient. This rotational power is applied to an electrical generator, which outputs three-phase AC. It is worth noting that the models that utilize three-phase AC are done so in dq0-reference frame to improve simulation time.

In addition to the wind turbines, another notable component is the electrical battery. The model for the batteries is shown in Figure 7. The AC signal interacts with an inverter, which converts AC to DC and DC to AC depending on whether the battery is charging or discharging. The battery itself is a resistor-capacitor unit arranged in series and parallel until the necessary voltage and capacity is reached, also known as the Thevenin Battery Model [3, 8]. The overall electrical model is shown in Figure 8. The plug represents input electrical power generated elsewhere. The two batteries in Figure 8 are controlled by a grid supervisor, which dictates the real and reactive power demanded.

The electrical grid is the location where all of the electrical signals come together to power a model of the U.S. electrical grid. The outputs of the turbines from the steam cycle, as well as output from the wind turbines, each with their own battery to handle transients, are connected to the U.S. grid via a circuit breaker. This circuit breaker connects the HES to the electrical grid when it is closed. In addition, lines and substations are included to represent how the electricity would travel to the grid and include relevant losses from transmission. The lines contain inductor-resistor circuits. Thus, the losses in the resistors, as well as the dynamics from the inductors are taken into account.

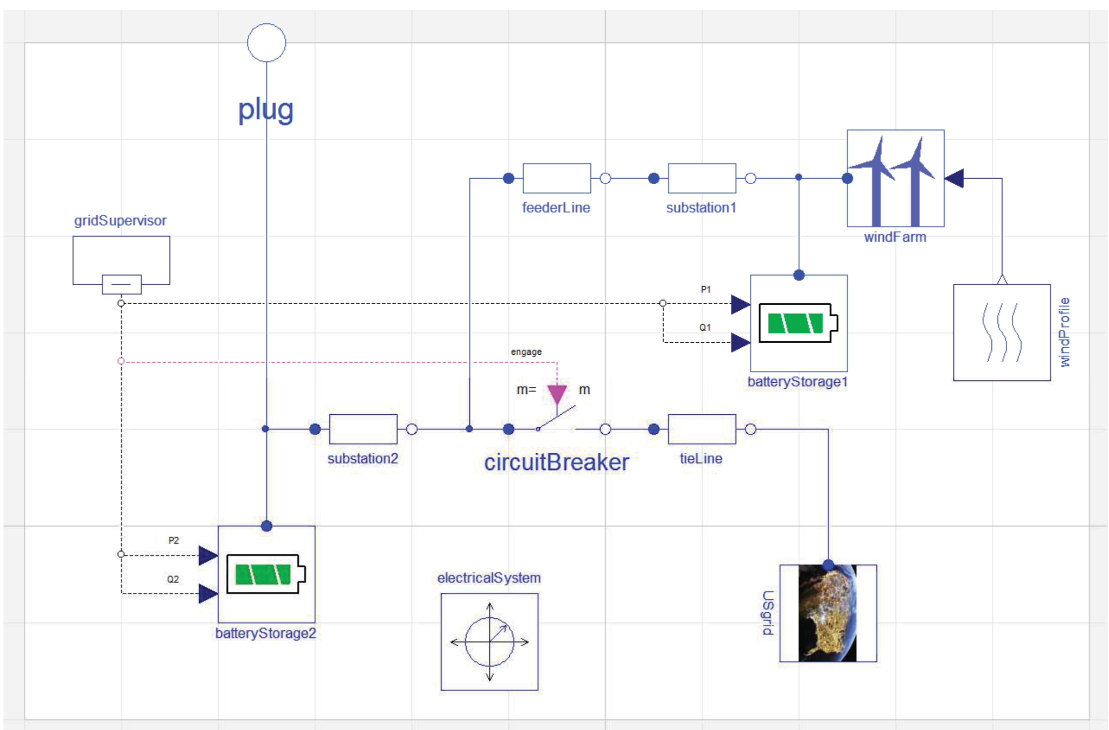

Figure 8: The electrical model, which includes the wind turbines, batteries, and the grid.

4 Simulation Results

To verify that the models created represent the system of interest, simulations are conducted. The results of these simulations are analyzed to ensure that the models behave as expected. Before combining the models and simulating the full system, individual components were tested first.

One of the first lessons learned came from the simulations of the first steam cycle. By closing the fluid loop, the simulations immediately became sensitive to various parameter values. Changes in the sizes of components in the loop cause the system to react in the form of large transients that dominate the startup period. These transients cause the simulation to be stiff and result in the simulation time increasing significantly. Attention to initial parameter values is paramount to meaningful results for this situation. This is one reason why the reactor is ramped up to load, as compared to starting at max load.

As mentioned previously, the other heat exchanger's that are considered initially resulted in simulation problems for the first steam cycle. The low flow rate of steam causes the steam to condense to liquid water, which results in a large increase of density, drastically increasing the simulation time. The change in density causes the simulation to both progress slowly, and result in the model not behaving as intended. One result of the large increase in density is that objects with a finite volume began decreasing their pressure rapidly. In some cases, this low pressure causes some components to operate in backflow. For the separator in Figure 4, this result does not make sense. A mixture of liquid water flowing from the top port into a heat exchanger is not realistic or indicative of what would normally be expected for a separator. The phase change also causes problems with the medium model used for water. The changing phase results in the properties, in addition to the density of the water, to change drastically. Since a phase change occurs, the medium model needs to be capable of varying properties, but should do so in a smooth manner so as to avoid stiffness issues.

To explore the interactions between the thermofluid systems, a simulation is conducted consisting of only the nuclear reactor, the steam cycles, and the chemical plant, represented in Figure 9. In order to capture the effect of the wind power, the load required from the turbines is reduced as if the wind turbines were connected. Assuming that the overall power that would go to the grid is set to be constant, as the wind turbines produce more power, the turbines accordingly reduce their electrical production.

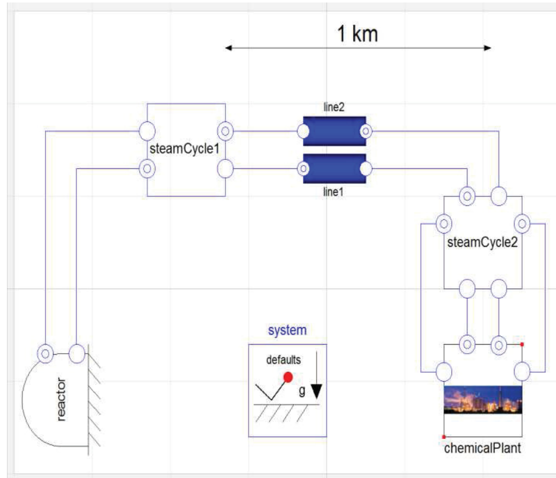

Figure 9: The model containing the reactor, the steam cycles, and chemical plant.

Conversely, as the wind turbines produce less power, more electricity is requested from the turbines.

The simulation is conducted using nominal parameter values that will cause all of the turbines to be used for at least a short period of time. Of particular interest are the flow rates of the steam through the turbines, preheater, and the secondary boiler. The results for this are shown in Figure 10. This simulation in Dymola takes approximately 45 seconds to simulate almost 14 hours of HES operation.

Figure 10 shows the result of the simulation. These results are reasonable for the conditions being simulated. Initially the system is allowed to ramp up and so no power is requested, hence causing large amounts of steam to divert toward the secondary boiler, denoted in pink. As power is requested, the flow rate of steam going to the secondary boiler decreases with a corresponding increase in flow rate through the 60% turbine, denoted in blue on the left. It quickly reaches its operating flow rate and the 30% turbine begins turning on, denoted in red. Around four hours, even the 15% turbine is at its operating flow rate. The wind turbines, based on the wind speed, begin producing significant power at four and a half hours, reducing the load requested from the turbines, and causing the 15% and 30% turbines to turn off as more steam goes toward the secondary boiler, as expected.

The simulation also catches a significant transient move close to twelve hours into the simulation. This is likely related to the low power being demanded from the turbines, with significant quantities of steam being sent to the secondary boiler. The temperature of the condensate water that would inlet to the reactor drops, causing the preheater to turn on.

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The cause of the temperature drop may be related to the temperatures in the second heat exchanger that connects to the secondary boiler.

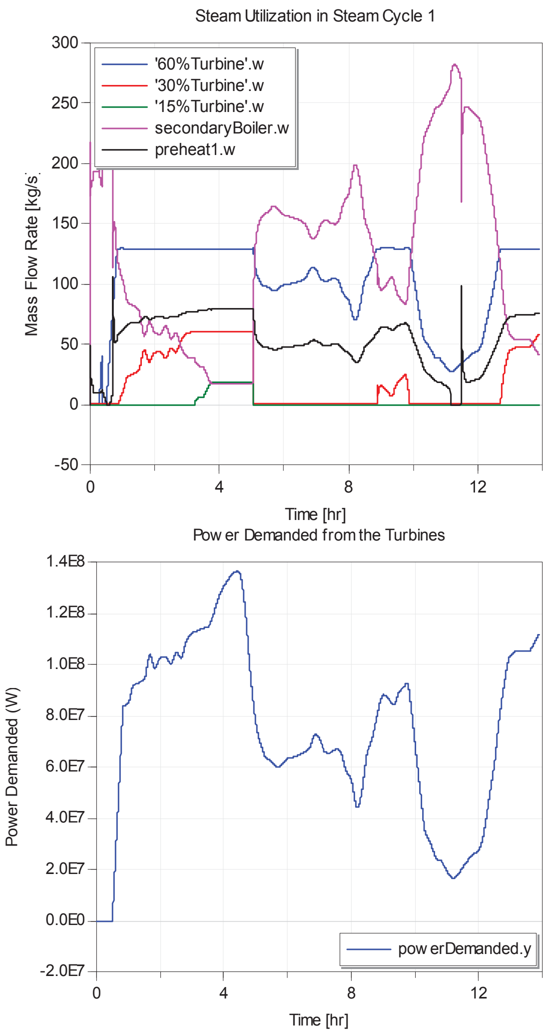

Figure 10: The results of simulation for the flow rates of the turbines, secondary boiler, and preheater1 above. Below shows the power demanded from the turbines.

5 Summary and Future Work

In summary, models for a HES that utilizes a non-renewable source (nuclear), a renewable source (wind), and a chemical plant are presented. This work shows that Modelica can be effectively used to model large complex systems, and still allow simulations of dynamic conditions. In addition to modeling the system, Modelica offers a significant advantage for evaluating control algorithms, which will likely influence the success of HES. The application of this model to determining the optimal design and control schemes will be the target of future work.

Ultimately, the economic and environmental benefits of the proposed MIMO HES described above are to be estimated in order to be optimized. The controllers and other variables, such as the quantity of wind turbines, will be optimized to maximize the profit of the HES to a plant owner. To quantify the environmental benefits of the HES so that the HES can be optimized using profit, a price per ton of CO_2 is to be used. This quantity can be a function of time or constant. This allows the decision maker to only be concerned with one thing, profit, while still having an environmental concern.

Estimating the profitability of the HES with appropriate detail is complex. It is conjectured that the profitability of a HES like the one described above is heavily reliant upon how the system is controlled. One of the HES's key features is being able to take advantage of varying conditions, including the market prices for the inputs and outputs. How the system reacts to these changes is in the control scheme. The performance of the HES may increase for a different control scheme, and still yield a negative overall profit for various reasons. For example, due to the thermal cycling of multiple components, such as the turbines and heat exchangers, the overall life of these components can be drastically reduced in practice. This will be taken into account with additional maintenance and replacement costs. These costs may cause the plant to shut down or operate at reduced capacity factors more often than a stand-alone system. This is why it is important to optimize with respect to profitability as compared to only system performance. The control scheme is not the only alternative for designing optimized HES.

In addition to optimizing the current HES, additional avenues to increase profit will be explored. One area for exploration is that of varying the architecture of the HES for potential increases in profitability. For example, it may be the case that a system that uses a core and a non-core non-renewable load will result in a superior overall profitability for the system. Testing cases such as this may also be considered, however these other architectures will also need to be optimized, making the process difficult. Other methods that can further increase the profitability of the HES will also be explored.

Another alternative is, instead of assuming constant conditions and simulating the current system under those conditions, allowing for the system to change or expand. This can also increase profit. One method that does this is Real Options Theory. Real Options Theory operates under the premise that evaluating the profitability of a design based on the average operating conditions is flawed [4]. In addition, a system will normally not stay the same throughout its life cycle, as conditions surrounding the system change, the system can be augmented in order to expand or vary how the system acts. This occurs in real life. For example, managers may elect to increase the size of a plant after it has already been built and is in operation. By taking this into account when first building a design, overall costs can be reduced with overall profitability and flexibility being increased.

6 Acknowledgments

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