Integrating Nuclear and Renewable Energy Sources

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Contents

1 Abstract

Methods of energy generation are being challenged with an effort to provide production methods that are capable of meeting needs of the present, without endangering the needs of the future. In order to address the decrease in grid stability brought on by the increasing penetration of renewable technologies, the ability to "load follow", to match the energy output to the demand, is pivotal as it helps prevent oversupplying electricity beyond the demand. The proposed design is a Nuclear-Renewable Hybrid Energy System (NR-HES). This system is comprised of a ThorCon operated molten salt reactor, renewable energy sources, and a 4-step CuCl Hydrogen Production Plant. The economic assessment of a 1 GWe NPP coupled with a 34 ton/day hydrogen production facility results in the ability to produce hydrogen at \$1.66/kg and to reduce the LCOE of the overall system. This shows that instead of relying on Greenhouse gas (GHG) emitting fossil fuels,the same reliability,affordability and flexibility can be achieved. The big economic savings of the nuclear-hydrogen facility leaves space for programs like California's goals to have 50% of its energy come from renewable energy by 2020 to be feasible.

List of Figures

List of Acronyms

GHG	Green House Gases
HES	Hybrid Energy System
HX	Heat Exchanger
LCOE	Levelized Cost of Electricity
MSR	Molten Salt Reactor
NPP	Nuclear Power Plant
NR-HES	Nuclear-Renewable Hybrid Energy System
SG	Steam Generator
SHX	Secondary Heat Exchanger

2 Introduction

With growing awareness of the environmental impact arising from conventional energy generation methods, the concern for electricity production has shifted away from simply meeting demand to integrating greater amounts of clean energy sources. Energy generation methods are being challenged with an effort to provide production methods that are capable of meeting the ever growing demand for electricity without endangering the needs of the future. Moving forward, it is essential to develop an electricity grid that can meet growing demands in a clean and sustainable manner. Ultimately, this grid should meet the following three criteria: cost effective, with low initial and operating costs; clean, with minimal carbon emissions; reliable with the ability to match energy production to the demand.

The electricity grid is a network that combines energy generation with commercial and industrial energy consumers. The grid is comprised of three main segments that include: generation, transmission and distribution, and consumption. While each segment of the grid maintains an individual and overall importance, the primary focus of this section will identify and analyze methods of energy generation.

Methods of energy generation can take on several different forms and can be split into three main categories: nuclear energy, fossil fuels, and renewable energy sources. As the grid is compromised with a mix of these three methods, it is important to analyze the advantages and disadvantages of each in order to maintain a clean and stable grid.

2.0.1 Fossil Fuels

About two-thirds of the energy produced in the US are produced from fossil fuels (1). Their low construction and operating costs along with their ability to vary electricity production has made them the main energy production source in the world. Despite their many benefits, fossil fuels are a large contributor to the production of greenhouses gases (GHG) which makes them an unsustainable energy source.

2.0.2 Renewable Energy

Renewable energy encompasses several different generating methods which includes wind, solar, geothermal, etc. These energy sources have the potential to address future energy concerns; stemming from their ability to harness energy a nigh limitless source. While renewable sources produce GHG free energy, they are far from affordable, standing as the most expensive energy sources and unreliable since their production depend on weather conditions which change frequently (3). Due to this dependence on weather, solar plants and wind farms cannot be incorporated all across the US and the rate of energy production cannot be controlled. This is especially significant for solar which produces large amounts of energy at low demand hours often leading to negative pricing of electricity which negatively impacts other energy production methods.

Figure 1 shows a characteristic plot of the energy demand in California. The blue line is the total energy demand which is predictable and steady. On the other hand, the orange line is the total demand minus the energy generated by renewables (gray) which makes the energy demand less predictable and more volatile. Thus in order to meet these changing demands, other power plants need to shut down or reduce its output when the demand drops and then quickly start up or increase its output when the demand rises again. This process is very costly and in many cases impractical.

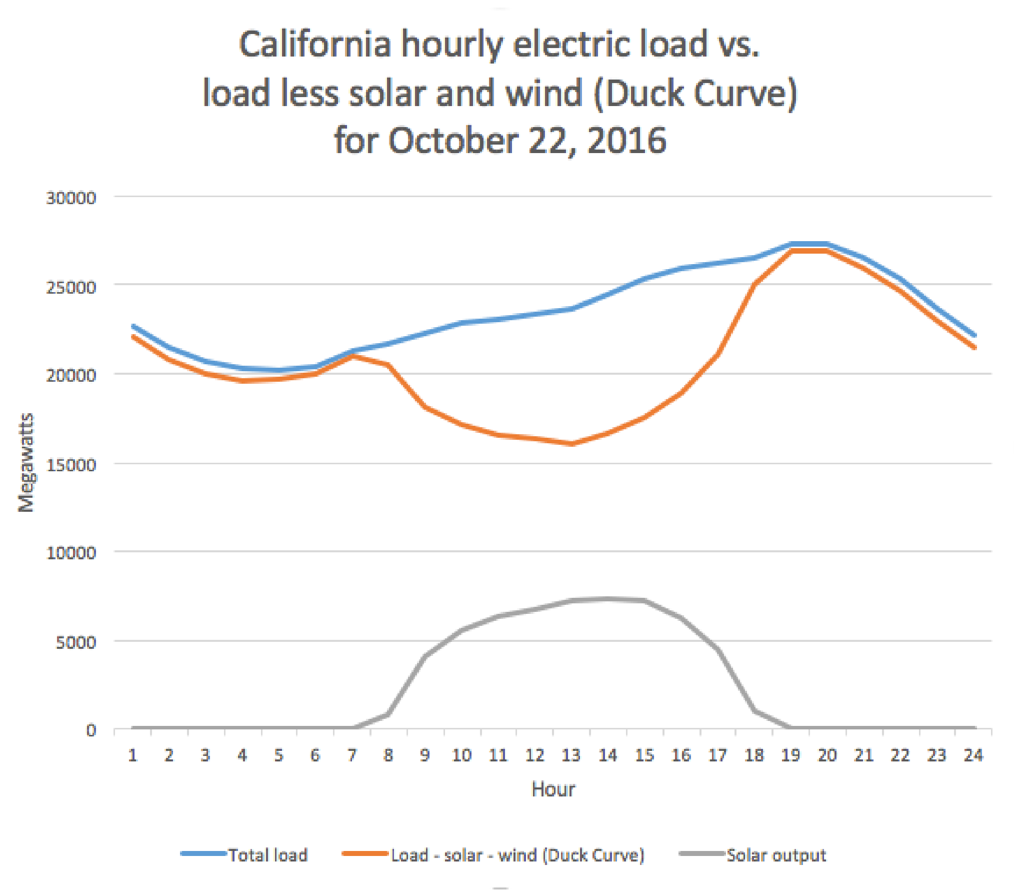


Figure 1: California hourly energy demand displaying the total load (blue) and the total load minus renewable energy generation

2.0.3 Nuclear

Nuclear energy is a reliable form of energy producing and produces no GHG. They are a base load power generation system meaning they output a near steady amount of energy throughout the day. The main drawback with nuclear power plants is that they generally hold an expensive upfront cost and the growing penetration of renewable energy has exacerbated this issue by decreasing the profitability of all base load power plants.

After analyzing the primary methods of energy production, it is evident that none of them can meet the three outlined criteria. While there are many new technologies and techniques being researched that could bolster the strength and diminish the weaknesses of these energy production methods, the clear ideal solution to the clean energy issue should use multiple energy production methods in tandem to capitalize on the benefits of each and increase reliability through diversification. This project proposes a solution to that can meet growing energy demands that meet the three previously mentioned criteria, models the performance of this solution, and then examines the financial aspects of the solution to determine if it is practical. Furthermore, this analysis places our proposed solution within California which has high renewable penetration.

3 Nuclear Renewable Hybrid Energy Systems (NR-HES)

In order to address the decrease in grid stability brought on by the increasing penetration of renewable technologies, the ability to "load follow", to match the energy output to the demand, is pivotal as it helps prevent oversupplying electricity beyond the demand.

In this case "load following" can mean two things, (1) a generating system that can vary energy supply quickly to match the demand which can lead to significant losses in efficiencies or (2) a system with a constant energy output that can divert excess energy to other systems. These other systems are referred to as secondary processes. This latter case of load following means that a system that can maintain a constant operational rate while maintaining a high thermodynamic efficiency (Bragg-Sitton et al., 2016). This analysis looks into a Nuclear Renewable Hybrid Energy System (NR-HES) which incorporates the second method of load following.

NR-HES are multi-subsystem comprised systems that consist of a "nuclear heat generating source, a turbine that converts thermal energy to electricity, a renewable energy source and an industrial process that utilizes heat and/or power from the energy sources to produce a commodity-scale product" (Bragg-Sitton et al., 2016). These type of systems are expected to provide flexible electricity generation, reduce the carbon footprint, levelize and reduce energy cost, and reduce energy system impact on water resources thus meeting the three criteria mentioned in the introduction (Bragg-Sitton et al., 2016). Our proposed design is a nuclear-renewable integrated energy system consisting of an advanced nuclear reactor, specifically a molten salt reactor (MSR), coupled with a secondary industry process—hydrogen production—and solar and wind farms. Furthermore, while our design incorporates the impact of renewable energy sources, the primary analysis focuses on the interconnection between the nuclear plant and the hydrogen production plant as shown in Figure 2. These systems are described in the following Sections.

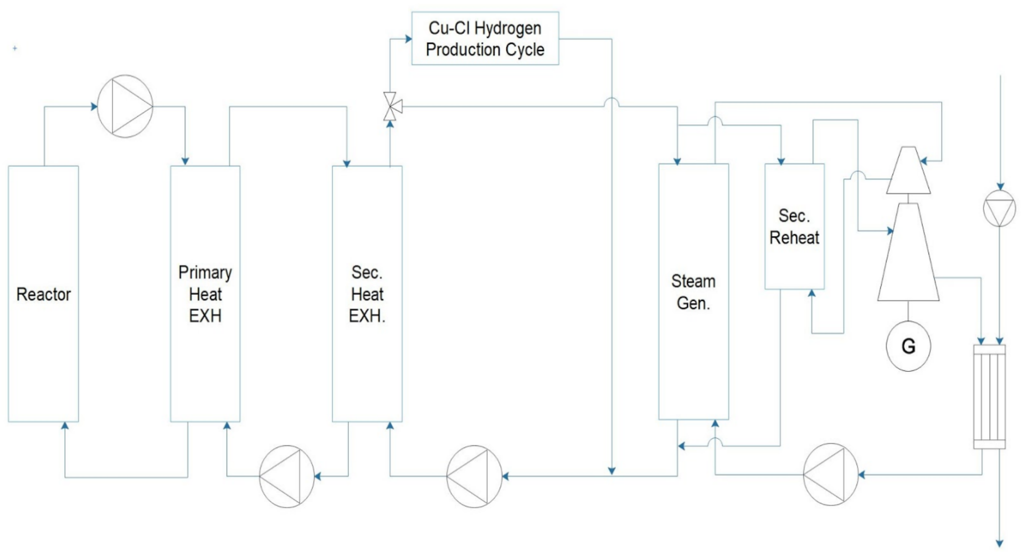


Figure 2: Block Diagram model of our design's interconnection between the nuclear power plant and hydrogen production plant

4 NR-HES System Components

4.1 Options for a Nuclear Reactor

The term conventional nuclear reactor typically refers to light water reactors (LWR) that make up the active nuclear fleet in the United States. Although these reactors have been in use since the early development of nuclear power, modern day research is focusing on developing technology that strays away from the conventional approach. This new segment of nuclear reactors are referred to as Generation IV reactors.

Generation IV reactors are important because their design focuses on advanced safety and reliability, inherent sustainability, increased assurance of proliferation resistance, and cost effective economics. Generation IV reactors include the Gas cooled fast reactor (GFR), Lead cooled fast reactor (LFR), Sodium cooled fast reactor (SFR), Molten Salt Reactor (MSR), Supercritical water cooled reactor (SCWR), and the Very high Temperature Reactor (VHTR). From the names alone, it is clear that these advanced reactors do not incorporate water as the coolant like conventional reactors. The reactor that was chosen as the basis of this research was a ThorCon designed molten salt reactor which is shown in Figure 3.

4.1.1 Molten Salt Reactor

MSR's differ from conventional and advanced reactors as its fuel and coolant are in the form of molten salt. Uranium is dissolved in a fluoride salt which allows for increased thermal conductivity and continuous fission product removal since the the fuel is in a liquid state. This reactor can also use thorium as fuel which does not breed plutonium, operates at a low pressure which decreases the risk of radioactive material escaping, and has a negative void coefficient which removes the risk of the core overheating.

The ThorCon MSR design (Figure 3) was chosen because it is a concept proven design that has been heavily researched. The ThorCon design makes use of modular reactors that are stored underground for added security. This modular design makes use of components that are easily to manufacture in a large scale which helps reduce the cost of this advanced reactor. Production of energy is split between two units that each generate 250 MWe and hold two modular reactors or cans. At any given time, only one of the cans in each unit is running while the other can is on standby for system redundancy purposes.

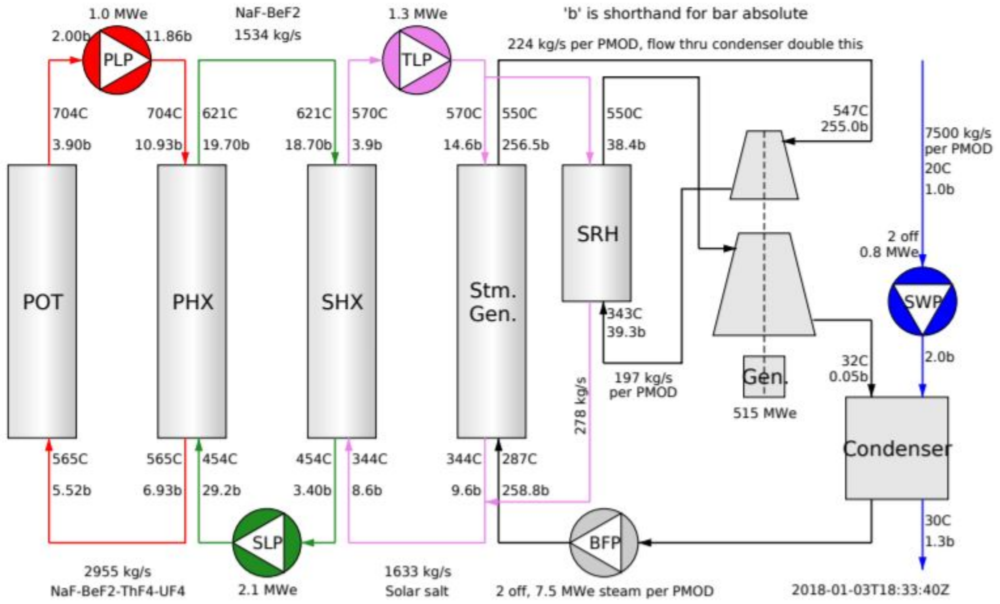


Figure 3: Block Diagram of ThorCon's molten salt reactor. (Devanney et al., 2015)

As mentioned previously, this reactor operates at near atmospheric pressure and it's designed to have three salt loops (fuel salt, secondary salt, and a tertiary salt) along with the steam loop (main and reheat). The properties of these loops and the various salt compositions are shown in Figure 4.

	Mass Flow kg/s	Hot C	Hot Bar	Cold C	Cold Bar	Fluid Mol Fractions
Fuelsalt	2994	704	10.5	564	4.0	NaF-BeF2-ThF4-UF4 76/12/9.5/2.5
Secondary Salt	1534	621	10.5	454	20.0	NaF-BeF2 57/43
Tertiary Salt	1414	598	12.0	344	1.0	NaNO3-KNO3 55/45
Steam Main	225	538	248	288	260	Water
Steam Reheat	162	538	38	343	39	Water

Figure 4: Molten Salt Reactor loop thermo-physical properties. (Devanney et al., 2015)

4.2 Options for a Secondary Process

A secondary process is a process that receives energy, from the energy generating system, in order to produce a commodity or perform a task. This is beneficial to the system because it allows the excess energy to be allocated in a way that is economically valuable. While hydrogen production was ultimately chosen for the NR-HES secondary process, several different secondary processes were initially considered.

4.2.1 Desalination Plant

Desalination is a process used for demineralization of water, making it suitable for human consumption. This technology was considered as a potential secondary process due to its ability to quickly turn on and off. The three common methods used include the use of thermal energy to boil the brine out of the water, electrical energy to dissociate salt and water ions, and pressure for reverse osmosis. Utilizing thermal energy for the process is not feasible because the MSR produces supercritical steam with temperatures too high for the desalination plant while reverse osmosis was eliminated because the pressure requirement was high for the MSR to sustain. Finally, the method incorporating electricity was not considered because it produces hazardous by-products. Ultimately, desalination was not chosen due to its incompatibility with the MSR and its potential to create unfriendly by-products.

4.2.2 Methanol Production

Methanol is a chemical usually used as a building block for producing other chemicals and material. For example, it is used in fuel for vehicles, plastics for water bottles, and paint. This technology was considered as a potential secondary process because it is an industrial process that can be ramped up and down at a fast pace and it produces a lucrative product with a high demand.

Methanol is typically produced from synthetic gas through a process called steam reforming which requires high energy input for the production process to go to completion. The process was shown to require more heat than the MSR would be capable of providing, and was thus eliminated as an option.

4.2.3 Hydrogen Production

Hydrogen is a chemical that is typically used as a building block for producing other chemical and materials. It is used for research purposes such as creating hydrogen fuel cells, gas chromatography, and explosives. Typical methods of hydrogen production include: Thermo-chemical processes, Electrolytic Processes, and Biological Processes.

The Thermo-chemical process has become of interest because they require lower temperatures to split water, about 500C-800C, and the components necessary for production are continuously recycled. Amongst the different processes proposed, the Cu-Cl thermo-chemical cycle has been selected because it is economically viable and has thermal and electrical requirements that can be provided by the MSR. Although the production cycle has not been commercially developed, it has been proven, and extensive research has been done on the system. Hydrogen production was chosen as the secondary industry process as it is compatible with the MSR's heat outputs and it produces a lucrative commodity with an increasing demand.

Cu-Cl Thermochemical Hydrogen Production Cycle

The Cu-Cl cycle for hydrogen production is the chosen secondary process and a block diagram of the production plant is displayed in Figure 5. This cycle was chosen because of its ability to produce hydrogen with the thermal input offered from the MSR. The 4 step process chosen, proceeds as follows:

Step 1: T = 80-100C

$$2CuCl(aq) + 2HCl(aq) \rightarrow 2CuCl(aq) + H_2(g)$$

The first step in the production cycle uses an electrolysis cell to yield Hydrogen Gas

Step 2: T= 60-100C

$$CuCl_2(aq) + H_2O(l) \rightarrow CuCl_2(s) \cdot H_2O(s) + H_2O$$

The second step is the process of drying the copper (II) chloride.

Step 3: T= 375C

$2CuCl_2(s) + H_2O(g) \rightarrow CuOCuCl_2(s) + 2HCl(g)$

The third step uses a hydrolysis cell to conduct hydrolysis on the copper (II) chloride.

Step 4: T= 530C

$CuOCuCl_2(s) \rightarrow 2CuCl + 12O_2$

Finally, the fourth step in the unit operation uses a oxygen decomposition reactor for the production of oxygen and recycling of Copper (I) Chloride which is used again in step 1 and therefore completes the cycle.

Now that the primary systems of the NR-HES (the nuclear and hydrogen production plant) have been identified, the NR-HES was broken down and system components (like the steam generator) were chosen. Identifying these system components helps characterize the system behavior and identifies things like how much energy can be produced or how quickly the system can adapt to changing demands in energy. Altogether, this characterization is incorporated into a code that determines the performance of the NR-HES.

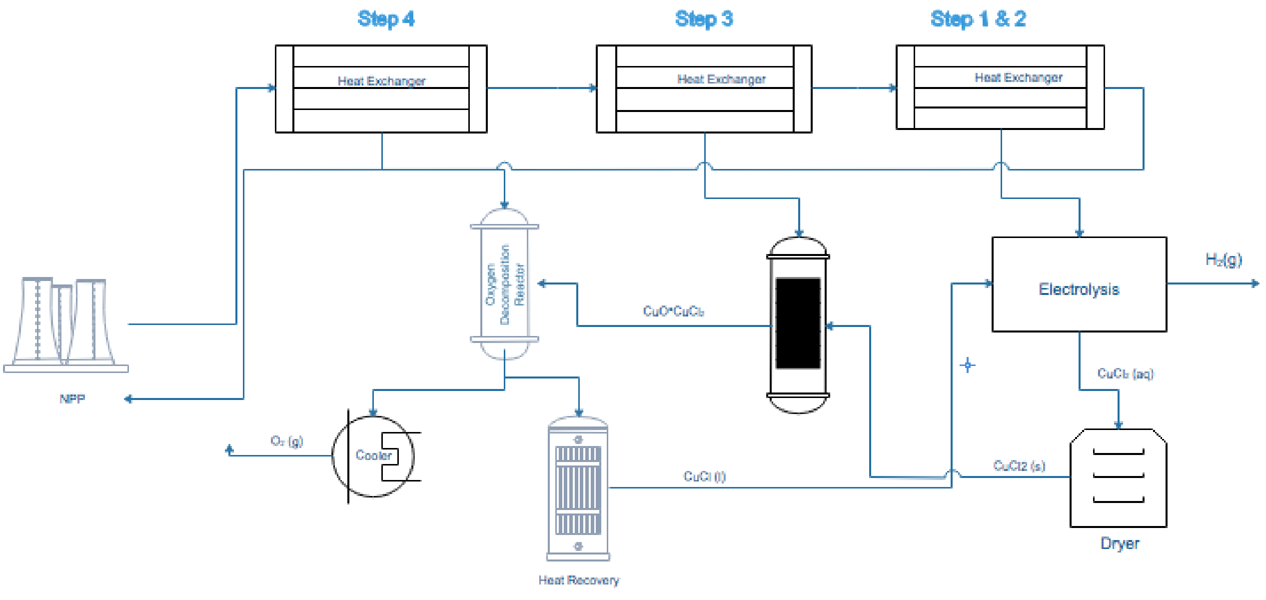


Figure 5: 4-step Cu-Cl Hydrogen Production Plant

5 Location Analysis of the NR-HES

The NR-HES was chosen to be implemented in California due to the large renewable penetration within the state. Furthermore, California has a commitment to have 50% of its energy production arise from renewables by 2030 meaning the implementation of renewable energy sources will continue to grow. In order to maintain a stable grid with the increasing introduction of renewables, California needs the NR-HES. The California electricity grid is composed of various energy production methods, the main in-state generation methods being natural gas, 49.86%, renewable energy, 27.90%, hydroelectric power, 12.31%, and nuclear energy, 9.55%, as seen in Figure 6 (ISO, 2017). These sources are not enough to satisfy the state's energy demand

and to make matters worse, these energy sources produce significant amounts of GHGs. Of the total 290,567 GWhr that the grid consumes, 46% comes from imports from the Northwest and Southwest regions as shown in Figure 7 (ISO, 2017).

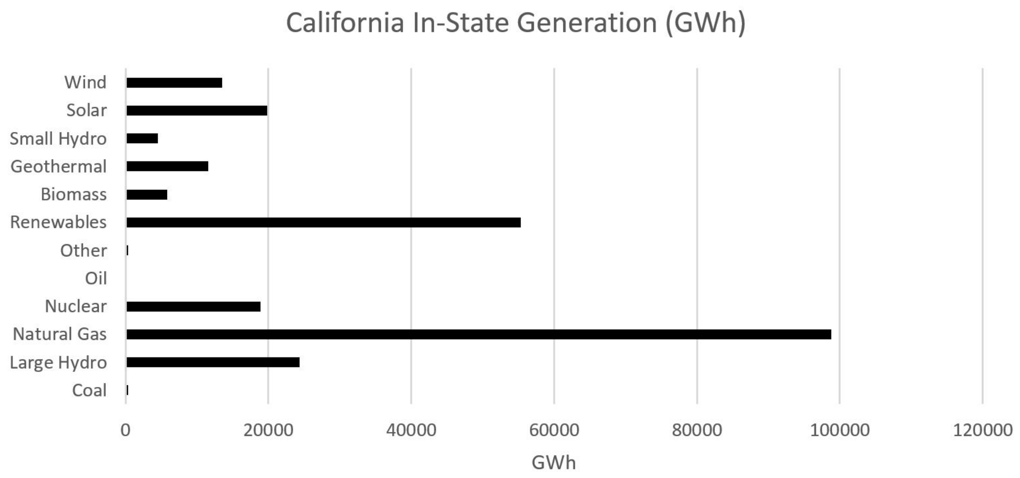


Figure 6: California In-state Generation Sources and Supply. Recreated with data from CAISO (ISO, 2017)

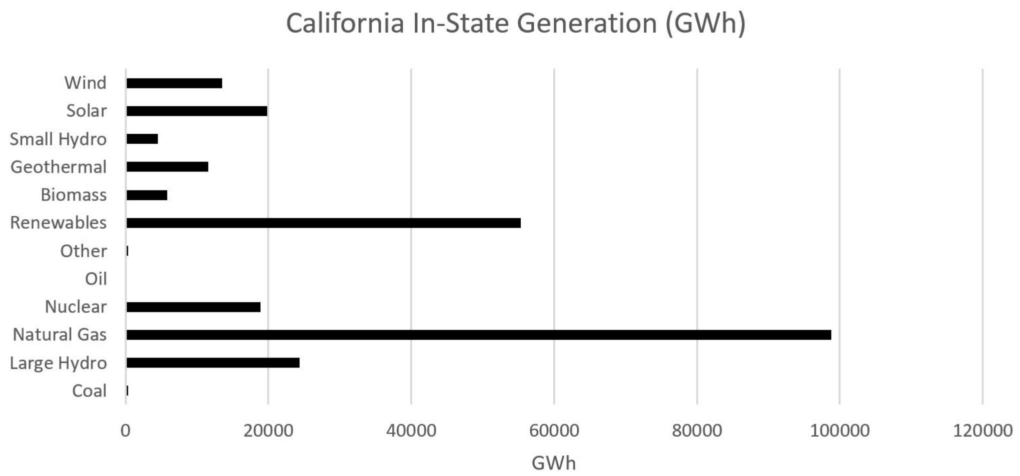


Figure 7: California Electricity Imports and Sources. Recreated with data from CAISO (ISO, 2017)

Introducing a large amount of renewable energy, particularly solar and wind energy, has a negative impact on grid management as it integrates uncontrolled generation that can be hard to predict. This issue is made worse by the fact that solar plants produce a great amount of energy throughout the day where demand is typically lower which creates a "demand well". This well has been growing as more renewables are brought onto the grid as shown in Figure 8. Current methods of energy production have to quickly ramp down and ramp up in order to accommodate this rapid change in demand.

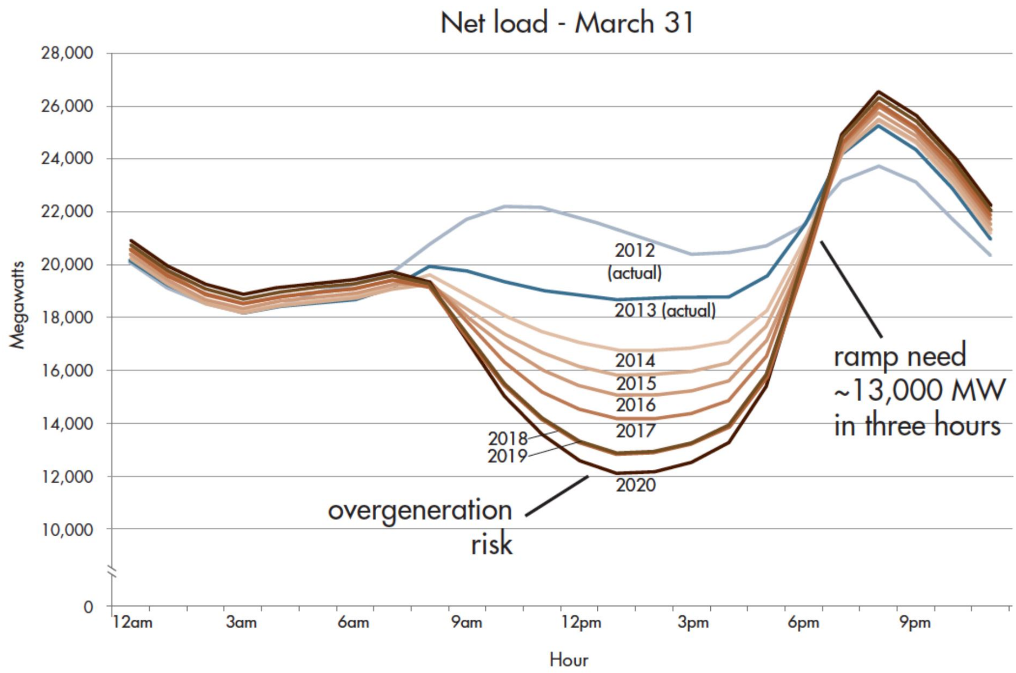


Figure 8: Daily net load showing the steep ramping needs changing over years due to renewable penetration. Taken from Idaho National Laboratories (Bragg-sitton et al., 2016).

6 Modeling the NR-HES System

6.1 MATLAB

While ThorCon's model as shown in Figure 3 provides information on the thermodynamic properties like the temperatures and pressures at every step of the energy generation side, these properties will change as molten salt is diverted from energy generation to hydrogen production. To ensure that the changes brought on by the hydrogen plant integration does not affect the functionality of the primary and secondary loop, design constraints were implemented to the integrated system. These constraints ensure that the properties of the molten salt entering and leaving the secondary heat exchanger (SHX) which connects the modified loop to the rest of the reactor stay the same in both this project's integrated design and ThorCon's MSR design.

To ensure that the molten salt inlet temperature at the SHX remains the same, molten salt exiting the hydrogen production and energy generation side was constrained to 344° C. Additionally, to ensure a consistent mass flow rate, the molten salt flowing to both energy generation and hydrogen production combine before entering the secondary heat exchanger. It is important to note that in a real system using the proposed method of load following, the mass flow rate may vary due to losses from the additional piping, valves, and turns within the hydrogen production side and the exit temperature of the tertiary loop's molten salt may fluctuate around the 344°C value.

One additional constraint was put on the steam generation loop. The supercritical steam exiting the steam generator (SG) was constrained to 550°C regardless of the amount of molten salt flow rate alloted to the energy generation side. This constraint was implemented due to concerns about component degradation and to ensure that the turbines are operating at the same temperature and pressure regime regardless of the energy demand. In order to satisfy this constraint, the mass flow rate of the steam must decrease as the amount of molten salt sent to energy production decreases. If the steam mass flow rate were to remain the same while the molten salt mass flow rate was decreased, this temperature would never be reached since there is less energy being supplied to the SG. The mass flow rate of the steam is decreased using a variable-frequency drive (VFD). From equation 1, it is clear that if the heat alloted to the SG decreases and the enthalpy stays the same since the pressure and temperature are constrained, then the mass flow rate of the steam must decrease.

$$\dot{Q} = \dot{m}\Delta h(T, P) \tag{1}$$

Unfortunately, Equation 1 is not sufficient for identifying the proper steam mass flow rate. In order to identify the mass flow rate of the steam given all the system constraints, a characterizing equation for the model's supercritical steam generator shown in equation 2 was used (Mokry 2010). This expression correlates dimensionless numbers (Nusselt, Reynolds, Prandtl) and the heat transfer coefficient (HTC) of supercritical steam in bare vertical tubes.

$$Nu_b = 0.0061 Re_b^{0.904} \overline{Pr_b^{0.684}} (\frac{\rho_w}{\rho_b}) \tag{2}$$

Implementing the data from ThorCon's model, the supercritical steam HTC expression, basic thermodynamic equations like Equation 3, and the aforementioned constraints, a MATLAB code was generated as shown in Appendix A. This code solves Equation 2 to obtain a HTC and inputs that value into Equation 3. The code iteratively solves Equation 2 and focuses on a mass flow rate until both expressions are satisfied.

$$Q = HTC * A * \Delta T \tag{3}$$

After identifying the proper steam flow rate that corresponds to the amount of molten salt sent to electricity generation, the steam flow rate is used to determine how much electricity is generated. Thus the correlation of the amount of molten salt sent to electricity generation and the amount of electricity generated is determined by this code. Figure 9 displays the percentage of molten salt versus the energy generation ratio which is the ratio between the net electricity generated and the maximum possible electricity generation. In this case,electricity generation is linearly correlated to the molten salt mass flow rate). This figure thus displays the loss of efficiency that comes from siphoning molten salt mass flow from the energy generation side. Below 40%of the mass flow rate, the electricity generation ratio rapidly falls which brings into question the economic benefit of producing electricity below the 40% mass flow rate regime. This idea will be taken further into consideration when looking into the economic viability of running at different electricity/hydrogen production regions.

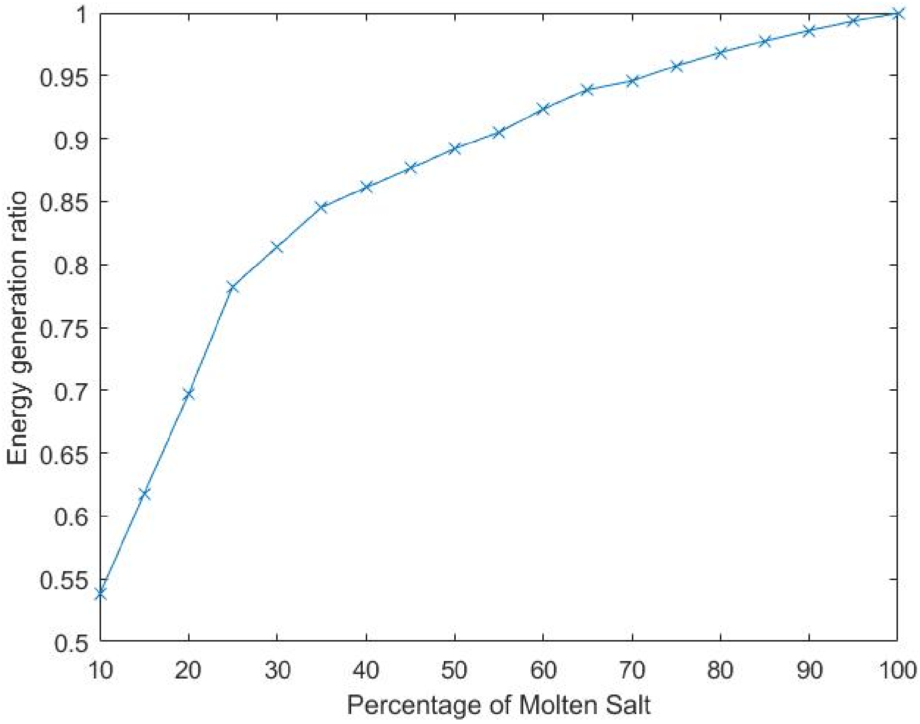


Figure 9: Percentage of molten salt sent to electricity production versus the energy generation ratio

6.2 Simulink

Simulink is an additional product on MATLAB that is designed to model dynamic systems in a graphical and interactive environment. Instead of writing thousands of lines of code to determine time dependent behavior, pre or user defined blocks can be attached to one another to characterize how a system may react. Appendix B displays with a this simplified block diagram model looks like for both the hydrogen production and energy generation side.

A Simulink model was generated using time dependent behavior of different components within the model and the thermodynamic characteristics of hydrogen production and electricity generation. These time dependent variables include valve response delay, flow stabilization, and hydrogen production ramping time while the thermodynamic characteristics analyze how much heat energy supplied by molten salt is necessary to produce a certain amount of electricity or hydrogen. A simple demand profile was put into this model to shows what the time dependent behavior of this system looks like in Figure 15. In this graph, the x axis correlates to time, in seconds, and the y axis correlates to, electricity output in MW. Rather than follow the actual demand, the electricity output is following a modified step function derived from the actual demand. A step function was chosen to circumvent issues around under-supplying electricity. Additionally, this minimizes the movement of valves and other system components which maintains more consistent operating conditions.

This model can be used to identify how much hydrogen and electricity the hybrid energy produced on a yearly basis by implementing different energy demand profiles. Additionally, the profile of the modified step function and the size of the hydrogen plant were altered to maximize the output of the integrated system.

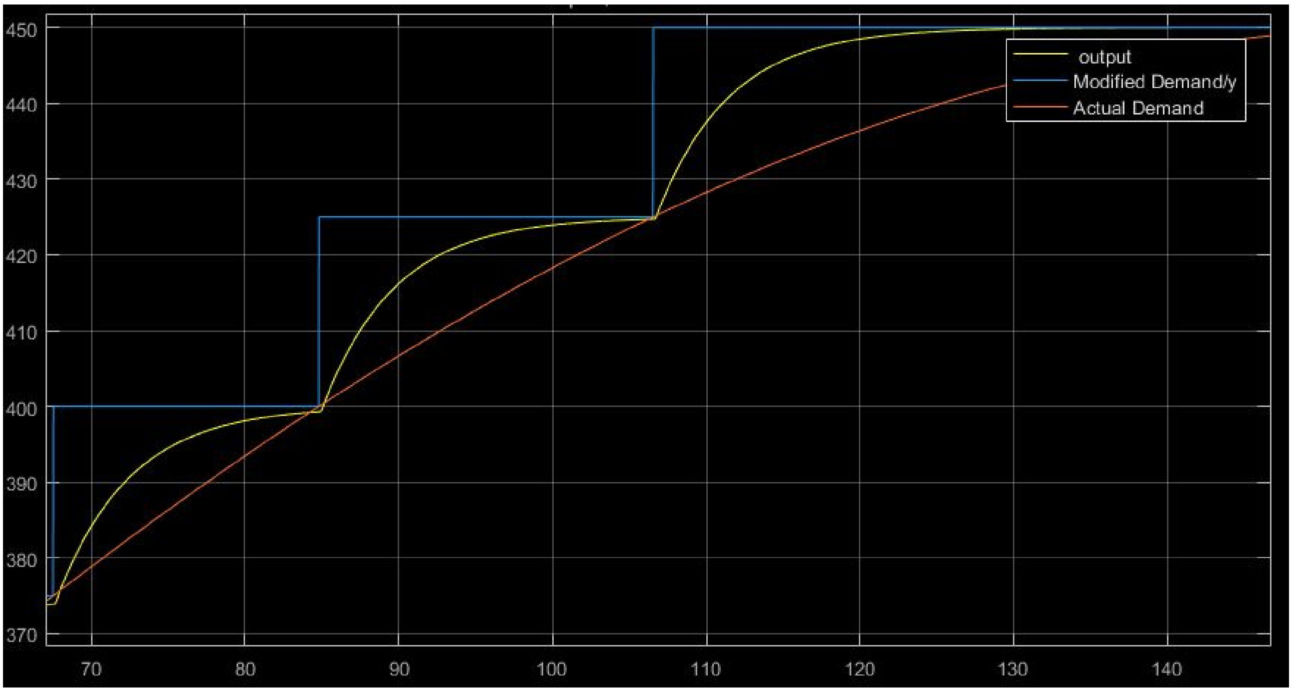
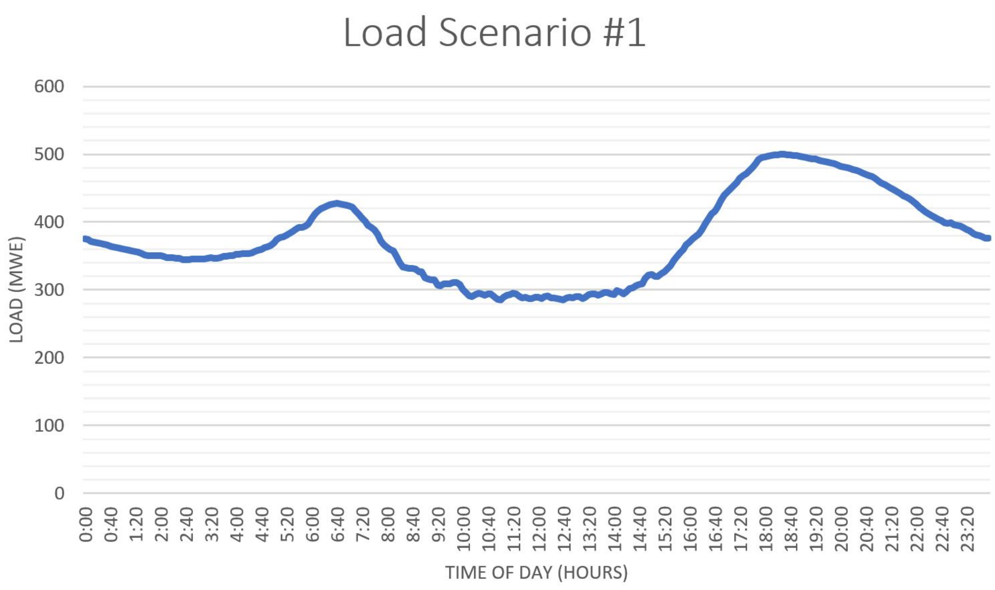
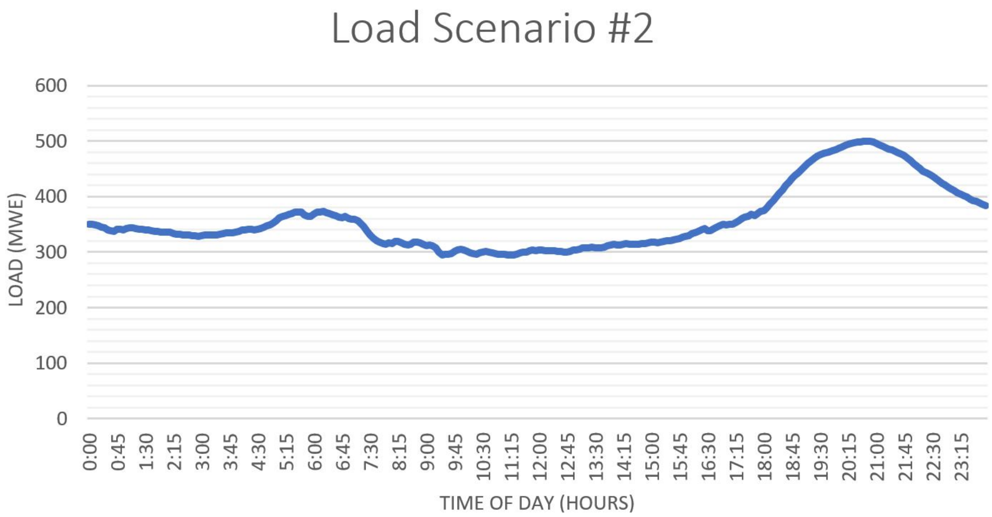


Figure 10: Graph of electricity demand and system output

6.3 Load Following Scenarios

As mentioned previously, the proposed molten salt reactor and hydrogen production plant interconnection will be placed in California and thus, the follow analysis will focus on three scenarios that reflect the state's electricity demand. These scenarios were recreated by obtaining the data from California ISO from years 2016 and 2017 (ISO, 2017) and were created with the intention to test how our MATLAB code and model will behave in a real-world deployment. The three scenarios we're created using data from February, June, and December in order to account for the differences in the demand curve throughout the year. The three load scenarios were then created by averaging total demand curve from every day in each month. From the following graphs, it is noticeable that ramping speed varies depending on the season, therefore confirming that flexible energy generating resources are needed.





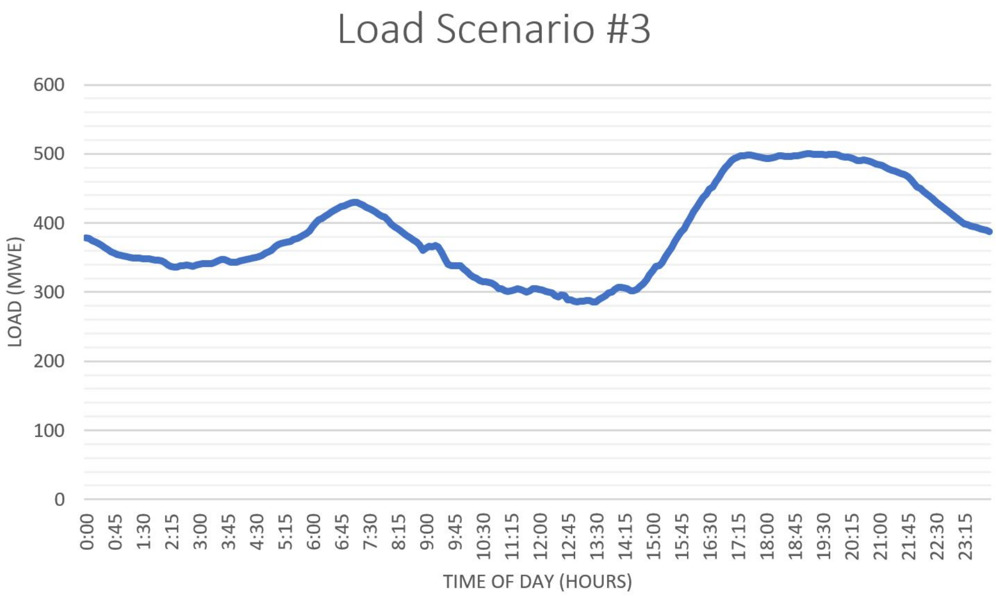


Figure 11: Load Following Scenarios recreated using data from California ISO from February, June, and December (from top to bottom)

6.4 Optimizing Simulink Model

As stated in section 5.2, the electrical output tries to follow a modified step function derived from the actual demand. This step is always greater than or equal to the actual demand to prevent underproduction of electricity. Each step is a discrete percentage (say 1% or 5%) of the total potential energy production and a new step is introduced or removed when a certain energy threshold is met by the actual demand. To determine the optimal size of these steps, load scenario #3 from Figure 11 was used as the input demand curve as it had the greatest volatility. Various demand steps were then implemented into the simulink model using this load scenario to determine the model's output and performance as shown Figure 12.

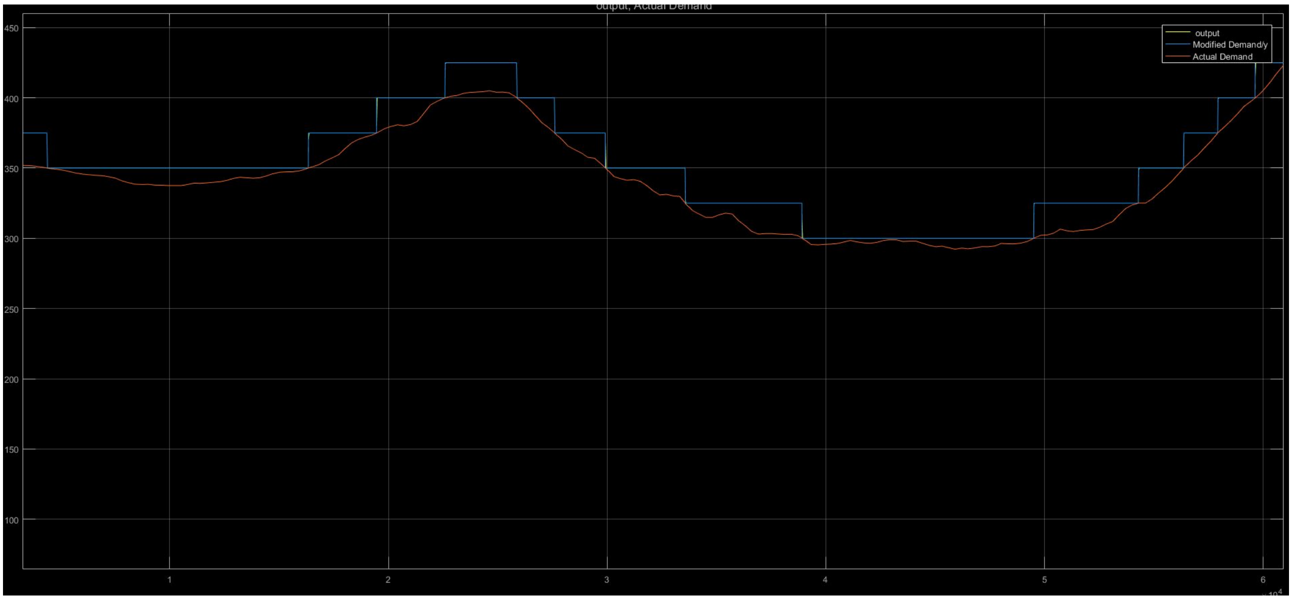


Figure 12: Graph of averaged electricity demand and modified step demand with an interval of 5%

Given that the integrated system had a short lag time when changing to a different demand interval and that the energy demand changed slowly, underproduction was not an issue in our system and overproduction was rather marginal. Table 1 displays what the overproduction the averaged scenario using different energy intervals. Smaller intervals are proven to be better as overproduction becomes a lesser issue. One additional thing to note is that this simulation assumes that information regarding changes in energy demand can be obtained almost instantly.

Energy Interval	**Overproduction MWHr**
0.1%	4.9
0.5%	25.2
1%	51.4
5%	264.9

Table 1: Energy Interval Versus overproduction in a single day using Load Scenario 3

To reiterate, load following is achieved by supplying excess energy to the production of hydrogen. Hydrogen production requires an input of about 520 degrees C for the reaction to go to completion. Thus, if the correct amount of heat input is not achieved, the reaction will not take place. To simplify these calculations, it was assumed that hydrogen production would not begin until a specific threshold was achieved. The threshold needed is maintained by the mass flow rate of the molten salt and the temperature of the hydrogen production plant. Given that there is a threshold for production, if there were only one "line" for hydrogen production, it would need 50% of the heat from the tertiary loop,given that this system can vary electrical output from 50-100%. Since energy production is the primary concern, hydrogen production would have a difficult time reaching this threshold and would produce limited amounts of hydrogen.

The solution to this issue was to create multiple hydrogen production lines within the plant. Each of these lines can take a discrete amount of energy to produce hydrogen and thus the greater the number of lines, the lesser the amount of energy that is wasted. For example, having 5 different lines would entail that each could take 10% of the tertiary loops energy. Minimum flow molten salt flow would be maintained in the lines that aren't being used and any excess energy beyond the 10% intervals would be sent to the next available line. This means that if

25% of the system's energy is sent to hydrogen production, then two lines would be operating in full production while a third line receives the remaining 5% of energy. Though energy is still being "lost", this molten salt in the third line still goes to partially heat up the production line. This allows for the third line to become fully operational in a shorter amount of time if more energy is suddenly alloted to hydrogen production.

Table 2 shows different amounts of hydrogen production in five production line scenarios where the energy interval was kept at 0.1%. While increasing the number of lines increases the amount of hydrogen produced, it is clear that this system quickly hits a point of diminishing returns. Increasing the number of lines increases the number of necessary components which would increase both the base cost of the plant and ongoing maintenance costs. For those reasons, a plant running ten production lines was chosen. Additionally, a quick analysis was done to determine the change in production at different energy intervals. Ultimately, the hydrogen production decreased the greater the energy interval. This is because energy that could have gone to producing hydrogen or preparing hydrogen production lines was lost to overproducing electricity.

Hydrogen Production Lines	**Hydrogen Production [kg]**
3	13838
5	24216
10	32173
20	36324
100	40787

Table 2: Hydrogen Production in kg depending on the number of production lines with an energy interval of 0.1%

7 Economics

In the last several years, there have been a variety of nuclear plants that are undergoing the process of permanent shutdown. For example,the Diablo Canyon power plant, which supplies approximately 10% of California's electricity is closing in 2025. These shutdowns are due to "...policy and market pressures that created a situation where the plant could not optimally operate" (Institute, 2016). Some of these factors include low natural gas prices, relative low growth in electricity demand, federal and state mandates for renewable generation (which greatly suppress prices and, from federal production tax credit, puts base-load power at disadvantage), transmission constraint and the market design itself (Institute, 2016). It is clear that for a NPP to thrive, it is important to optimize the economics in order to be competitive with cheaper energy generating sources like natural gas.

It is important to keep in mind that there is a large uncertainty when calculating the capital costs of technologies that are only theoretical concepts or that have only been proven on a laboratory scale, which is the case for both the MSR and the Cu-Cl hydrogen production cycle.

7.1 Levelized Cost of Electricity

The energy industry but more specifically the energy generation methods are evaluated by what is known as the levelized cost of electricity (LCOE). And while there are many other forms of evaluation, we will focus only in the LCOE. The levelized cost of electricity is useful to compare different generating technologies. Explained simply, the LCOE is the sum of the cost over the lifetime of the plant divided by it's energy generation. For any project to be feasible it does not only have to be technologically ready but also economically competitive with other generating sources. For this example, we calculate everything imagining we have both technologies ready for deployment and . It considers a variety of factors including "capital costs, fuel costs, fixed and variable operations and maintenance costs, financing costs and an assumed utilization rate for each plant" which results in the cost per unit of power (as a function of time) produced (ex. $/kWh) (US Energy Information Administration, 2017). As with any other measures there are uncertainties in each of the factors, especially with technologies that have only been proven theoretically or at laboratory scale. In order for a energy project to be attractive, it must be not only technologically ready, but also economically competitive. According to the US Energy Information Administration, for plants entering service in 2022, natural gas (Advanced combined cycle with carbon capture sequestration) will be the cheapest reliable method for electricity generation with an LCOE of 82.4 $/MWh (0.0565 $/kWh). This means that to be able to successfully initiate and operate a nuclear power plant project, it needs to be competitive by offering similar economic benefits. According to the same organization, Advance Nuclear Reactors are estimated to have an LCOE of 99.1 $/MWh (0.0991 $/kWh) (see Figure 12).

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System LCOE	Levelized Tax Credit[1]	Total LCOE including Tax Credit
Dispatchable Technologies								
Coal 30% with carbon sequestration[2]	85	94.9	9.3	34.6	1.2	140.0	NA	140.0
Coal 90% with carbon sequestration[2]	85	78.0	10.8	33.1	1.2	123.2	NA	123.2
Natural Gas-fired								
Conventional Combined Cycle	87	13.9	1.4	40.8	1.2	57.3	NA	57.3
Advanced Combined Cycle	87	15.8	1.3	38.1	1.2	56.5	NA	56.5
Advanced CC with CCS	87	29.5	4.4	47.4	1.2	82.4	NA	82.4
Conventional Combustion Turbine	30	40.7	6.6	58.6	3.5	109.4	NA	109.4
Advanced Combustion Turbine	30	25.9	2.6	62.7	3.5	94.7	NA	94.7
Advanced Nuclear	90	73.6	12.6	11.7	1.1	99.1	NA	99.1
Geothermal	91	32.2	12.8	0.0	1.5	46.5	-3.2	43.3
Biomass	83	44.7	15.2	41.2	1.3	102.4	NA	102.4
Non-Dispatchable Technologies								
Wind – Onshore	39	47.2	13.7	0.0	2.8	63.7	-11.6	52.2
Wind – Offshore	45	133.0	19.6	0.0	4.8	157.4	-11.6	145.9
Solar PV[3]	24	70.2	10.5	0.0	4.4	85.0	-18.2	66.8
Solar Thermal	20	191.9	44.0	0.0	6.1	242.0	-57.6	184.4
Hydroelectric[4]	59	56.2	3.4	4.8	1.8	66.2	NA	66.2

Figure 13: Estimated LCOE of different energy generating sources entering service in 2022. Taken from the US Energy Information Administration, 2017

7.2 Molten Salt Reactor Levelized Cost

When calculating the levelized cost of electricity (LCOE), staff, fuel, salt, can (reactors), and construction costs were taken into account. A 10% real discount rate was taken into account for a worst case scenario, with 5% being the average for nuclear power plants. During this study, a 32-year-old plant life was considered. Table 7.1 displays Thorcon's results for the LCOE as a function of overnight cost for a four module nuclear facility with a 1 GWe capacity. Secondary calculations showed that a single 250 MWe plant would have a cost of 35% that of a large 1 GWe plant meaning that it can produce electricity at less than 5 cents per KWh.

Plant capacity (MWe)	1000		
Plant life	32 years		
Construction period	4 years		
Capacity factor	90%		
Cost of capital	10%		
Overnight Cost	$800M	$1000M	$1200M
Reactor	0.0034	0.0034	0.0034
Fuel	0.00511	0.00511	0.00511
Salt	0.0002	0.0002	0.0002
Staff	0.00493	0.00493	0.00493
Waste	0.001	0.001	0.001
Facilities	0.01236	0.01545	0.01854
LCOE ($/kWh)	**0.02699**	**0.03008**	**0.03317**

Table 7.1 - LCOE as a function of overnight cost. (Adapted from Devanney et al., 2015)

7.3 Cu-Cl Hydrogen Production

There have been many attempts to calculate and predict the capital and working capital needed for a large scale hydrogen production plant. Since there is no real-world plant to be taken as reference, and current main production methods like steam reforming are not similar to the projected Cu-Cl cycle, literature results vary. In a study done by Ohran et al., factors like price fluctuations, federal and local governmental regulations, chemical, site, industrial buildings, off-site facilities and project indirect costs were carefully considered to provide a scaling method as a function of capacity. Our project was focused in a 1 GWe MSR and a thirty-four tons/day hydrogen production plant. Having our daily capacity permit us to use the scaling method to estimate overnight and yearly operating costs. Similar to the MSR calculations, an optimistic, base, and pessimistic case for overnight capital costs were calculated and for this examples a capital cost of 5% was considered throughout the calculations (see Table 7.2). The three different cases were created based on the base case. To take into account any extra regulatory and licensing fees, and costs arising from the physical integration of both technology, two scenarios we're calculated. One with a (1) a 10% safety margin and a (2) 50% safety margin. For the rest of the paper, we will focus only in the Base overnight and yearly operating cost scenarios.

	Optimistic	**Base**	**Pessimistic**
Nuclear (MSR)	$800,000,000.00	$1,000,000,000.00	$1,200,000,000.00
Hydrogen	$142,341,172.00	$150,229,407.00	$158,117,642.00
Total	$942,341,172.00	$1,150,229,407.00	$1,358,117,642.00
Total + 5% (int.)	$1,890,753,457.58	$2,307,869,265.32	$2,724,985,073.05
Total + 10%* + 5% (int.)	$2,079,828,803.34	$2,538,656,191.85	$2,997,483,580.35
Total + 50%* + 5% (int.)	$2,836,130,186.38	$3,461,803,897.97	$4,087,477,609.57

Table 7.2 - Overnight cost description for three different scenarios.

7.3.1 Hydrogen Plant Profitability

Before taking about the benefits on the MSR, first we looked into the hydrogen plant profitability. We looked at the operating costs per year including raw materials and distribution costs. As with any other chemical plant, there are implicit working capital needs in order to operate the plant. Because of the plant's modular construction, a 60% capacity factor was considered ultimately resulting in a thirty-four tons/day plant. Current and forecasted market prices for Hydrogen are expected to be in the range of $9-18/kg. Similarly an optimistic, base and pessimistic scenarios were calculated thus finally resulting in different net profits (see Table 7.3).

Sale Price	Scenario	Operating Cost	Cost $/kg	Profit/kg	Profit	Net Profit
10 $/kg	Optimistic	$18,920,666.67	$1.50	$8.50	$107,482,483.33	$88,561,816.67
	Base	$19,947,166.67	$1.58	$8.42	$106,455,983.33	$86,508,816.67
	Pessimistic	$20,973,666.67	$1.66	$8.34	$105,429,483.33	$84,455,816.67
16 $/kg	Optimistic	$18,920,666.67	$1.50	$14.50	$183,324,373.33	$164,403,706.67
	Base	$19,947,166.67	$1.58	$14.42	$182,297,873.33	$162,350,706.67
	Pessimistic	$20,973,666.67	$1.66	$14.34	$181,271,373.33	$160,297,706.67

Table 7.3 - Operating costs and profits for a thirty-four tons capacity hydrogen production plant at two different sale prices.

The Department of Energy has a target for hydrogen production of one to two dollars per kilogram by 2020 for thermo chemical water splitting. Our system is able to produce hydrogen at approximately 1.58 $/kg therefore meeting these targets. One reason hydrogen production is economical is because the thermal energy and electricity used in the hydrogen plant are considered to be free. These thermal energy will be accounted for when calculating the new LCOE for the molten salt reactor.

7.4 Economic Benefits of a MSR + Hydrogen System

To calculate the economic benefits of integrating both technologies, factors ranging from production to its distribution are taken into consideration. As mentioned before, in order to create a margin, three different scenarios with a capital cost of 5% we're calculated. To visualize Knowing the fixed-capital investments and the working capital for both facilities, and the profitability of the hydrogen facility, we successfully calculated the new LCOE for the the system by integrating these expenses and revenues.

First, we calculated the impact on the LCOE of having a hydrogen production facility connected to the reactor. We did this by subtracting the thermal energy lost for hydrogen production. This means that we have the same overnight costs but with less electricity generation. It can be seen from Table 7.4 and Figure 13 that the LCOE rises to $0.0439/kWh.

Facilities	Optimistic	Base	Pessimistic
MSR LCOE ($/kWh)	$0.02699	$0.03008	$0.03317
HES LCOE ($/kWh)	$0.03862	$0.04391	$0.04919
Impact	$0.01163	$0.01383	$0.01602

Table 7.4 - Hydrogen production plant impact on the MSR LCOE.

Afterwards, considering the 32 year life plant and a 4 year construction period, the operating costs and therefore the net profits were incorporated into the LCOE calculations. Figure X, represents the results of various scenarios.

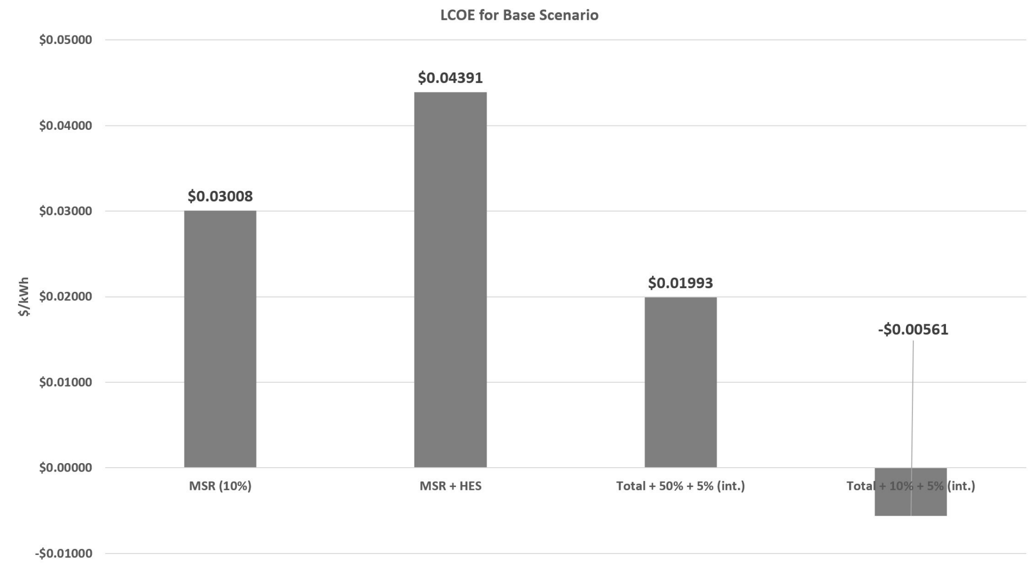


Figure 14: Resulting LCOE of the NR-HES in three different economic scenarios. (From left to right) First, the MSR alone followed by the MSR + hydrogen facility, the HES with a 50% safety margin and the HES with a 10% safety margin.

Even in the worst case scenario, were we have a 50% safety margin and selling prices of only 10 \$/kg, we obtain a LCOE of only \$0.0199/kWh compared to \$0.0300/kWh (only MSR). With these results, it has been demonstrated that the integration of a hydrogen production facility and a NPP can have economical benefits that result in a competitive energy generation system with zero greenhouse emission.

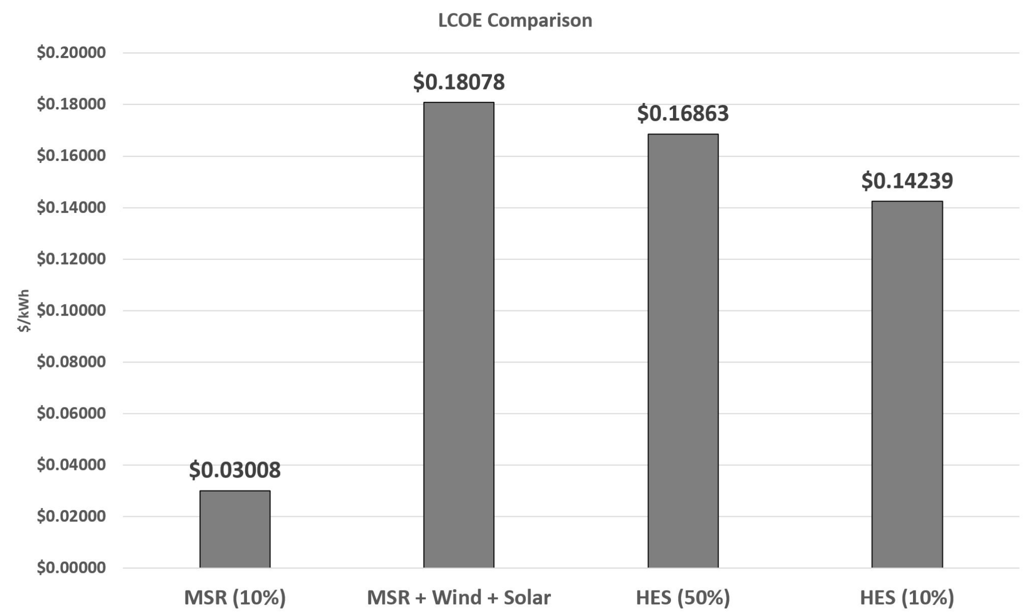


Figure 15: Resulting LCOE of the NR-HES in three different economic scenarios. (From left to right) First, the MSR + Wind + Solar followed by the HES with a 50% safety margin and the HES with a 10% safety margin.

Once having the final LCOE for our Nuclear-Hydrogen facility we integrated the benefits with the 2022 LCOE's for Wind (on-shore) and solar (photo-voltaic). Again, even in the 50% extra scenario we still manage to have savings of around \$.12/kWh (see Figure 14)

8 Future Works

There is still much space for improvement of the results resolution. In regards to the economics, in the future there is opportunity for integrating the solar and wind economics. Analysis of other types of secondary industry processes with increasing demand is another field of interest to look in the future. Heat transfer analysis and optimization within the hydrogen production facility could lead to improvements in the overall efficiency and therefore economics.

9 Conclusion

The current energy environment is varying with the introduction of new laws that require more energy generation from renewable and higher GHG emission restrictions. Renewable penetration to the markets, more specifically in California, are creating ramping times that are not suitable for base load power plants. The existing and emerging technologies are changing operating conditions and therefore clean flexible resources are required to provide electricity at all times. Due to oversupply risk and expected decreased frequency response a Hybrid Energy Systems is important and necessary for achieving a clean, affordable, reliable and therefore sustainable grid. A hybrid energy system for electricity production using nuclear, wind and solar technologies and hydrogen production using a four-step Cu-Cl thermo-chemical cycle was proposed. This work focused mostly on the integration of the hydrogen production plant and the generation IV advance molten salt nuclear reactor. The integration of a secondary industry process allows the nuclear reactor to "load follow" and to be more affordable. Economic savings will allow programs like California's goal to reach 50% energy production from renewable to be economically feasible without sacrificing reliability.

To understand the dynamics between the two technologies, the thermo-physical characteristics of the hydrogen plant and the MSR supercritical Rankine cycle we're characterized. Moreover, since the nuclear heat was delivered from the tertiary loop of our reactor, the molten salt heat transfer properties and interaction with the several steps in the Cu-Cl cycle we're analyzed. Finally an economic assessment of a 1 GWe NPP coupled with a 34 ton/day hydrogen production facility was performed. We manage to produce hydrogen within the DOE targets for 2020 at approximately \$1.66/kg. Based on the results of the integrated system it is concluded that utilization of nuclear heat, that otherwise would be wasted, for hydrogen production shows promise, however future work is still necessary as technologies are either non-existent or have only been tested laboratory scale.

10 Appendix

10.1 Appendix A

10.2 Code for the System's Thermal Properties

```
function [Tf,mw_guess,error,Q_sg,Q_egen,H_gen]=Th2(m_perc)
% Salt information %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Assume salt cp stays nearly constant throughout changing temperatures
%
%temp of salt in
Ts_in=570;
Tw_out=550;
To=Tw_out+10;
N=0;

```

```
%% Molten salt
Ts_out=344; %Temp of salt out
md_s=(1633-278)*m_perc; %m dot salt kg/s
cp_salt= @(T) 1443+0.172*T; % T in Celsius
L=5.772;

cp_salt_avg=integral(cp_salt,Ts_in,Ts_out)/(Ts_out-Ts_in);
Q_sg=md_s*cp_salt_avg*(Ts_in-Ts_out); %Q through the steam generator

%% Water
Tw_in=287;
md_w=224*2;
hw= @(P,T) XSteam('h_pt',P,T);
hci=hw(258.8, Tw_in);
hco=hw(256.5, Tw_out);
mw_guess=Q_sg/1000/(hco-hci);
%
while abs(To-Tw_out)>2 & N<30
%% Dimensionless parameters
Di=7.5/1000; %hydraulic equivalent diameter
Ai=4.4/1224; %area of one bundle
G=mw_guess/Ai; %mass flux
Df=11.5/1000;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Re = @(T,G,Di) G*Di/XSteam('my_pt',258.8,T); %Reynolds number
Pr= @(T) XSteam('pr_pt',258.8,T); % Prandtl at the constant pressure
Pr_avg= @(T) Pr_bar(T);
Nu= @(T,G,Di) 0.0061*Re(T,G,Di)^.904*Pr_bar(T)^0.684*(XSteam('rho_pT', 258.8, ...
    T+20)/XSteam('rho_pT', 258.8, T))^.564;
HTC= @(T,G,Di) Nu(T,G,Di)*XSteam('tc_pt',258.8,T)/Di;
%%
To=Tw_in+Q_sg/(Df*42*pi*L*.4915)/HTC_bar(Tw_out,G,Di)
    if To>Tw_out

            mw_guess=mw_guess+.7;
    else
         if abs(To-Tw_out) > 9
            mw_guess=mw_guess-5;
        else
            mw_guess=mw_guess-1;
         end
    end
mw_guess
N=N+1
end
Tf=To;
error=abs(Q_sg/1000-mw_guess*(hw(258,Tf)-hci))/(Q_sg/1000);
%% Dummy Energy Output
hh1=XSteam('s_pT',255,550);
hc1=XSteam('s_pT',39.3,343);
hh2=XSteam('h_pT',38.4,550);
hc2=XSteam('h_pT',.05,32);

m1=224*2;
m2=197*2;
Q_egen=((hh1-hc1)*m1+(hh2-hc2)*m2)/1000; % in MWth
eff=515/Q_egen;
effC=1-(32+273)/(550+273);
effrat=eff/effC;
%% Energy output
rat=197/224;
effC2=1-(32+273)/(Tw_out+273);
hh1=XSteam('s_pT',255,Tw_out);
hc1=XSteam('s_pT',39.3,343);
hh2=XSteam('h_pT',38.4,Tw_out);
hc2=XSteam('h_pT',.05,32);

m1=mw_guess*2;
m2=m1*rat;
Q_egen=((hh1-hc1)*m1+(hh2-hc2)*m2)/1000*eff;
Q_sg=Q_sg/10^6/md_s*(md_s+278*m_perc);

%%
```

```
H_gen=((cp_salt_avg*1633*(1-m_perc)*(Ts_in-Ts_out))/10^6)/(499.5/2); %kg/s

end
```

10.2.1 Call Function for Average Enthalpy

```
function H=h_bar(Ti,To)
Temp=Ti:1:To;
for i = 1:numel(Temp)
    X(i)=XSteam('h_pT',258.8,Temp(i));
end
H= trapz(Temp,X)/(To-Ti);
end
```

10.2.2 Call Function for Average Prandtl Number

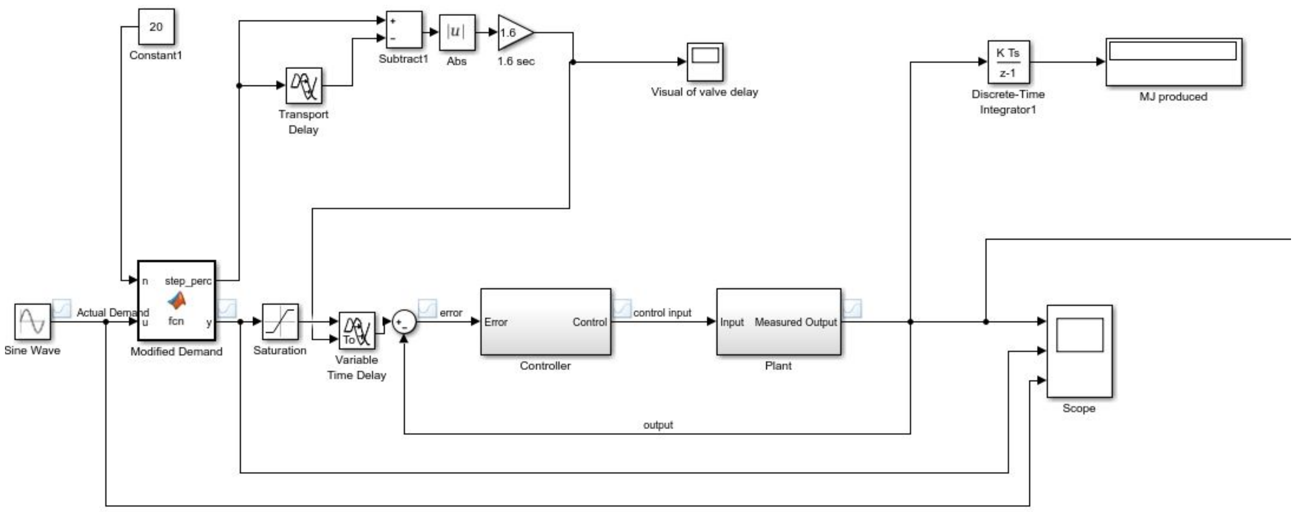
```
function PrB=Pr_bar(T)
Temp=T:1:(T+20);
for i = 1:numel(Temp)
    X(i)=XSteam('pr_pt',258.8,Temp(i));
end
PrB= trapz(Temp,X)/20;
end
```

10.2.3 Call Function for Average Heat Transfer Coefficient

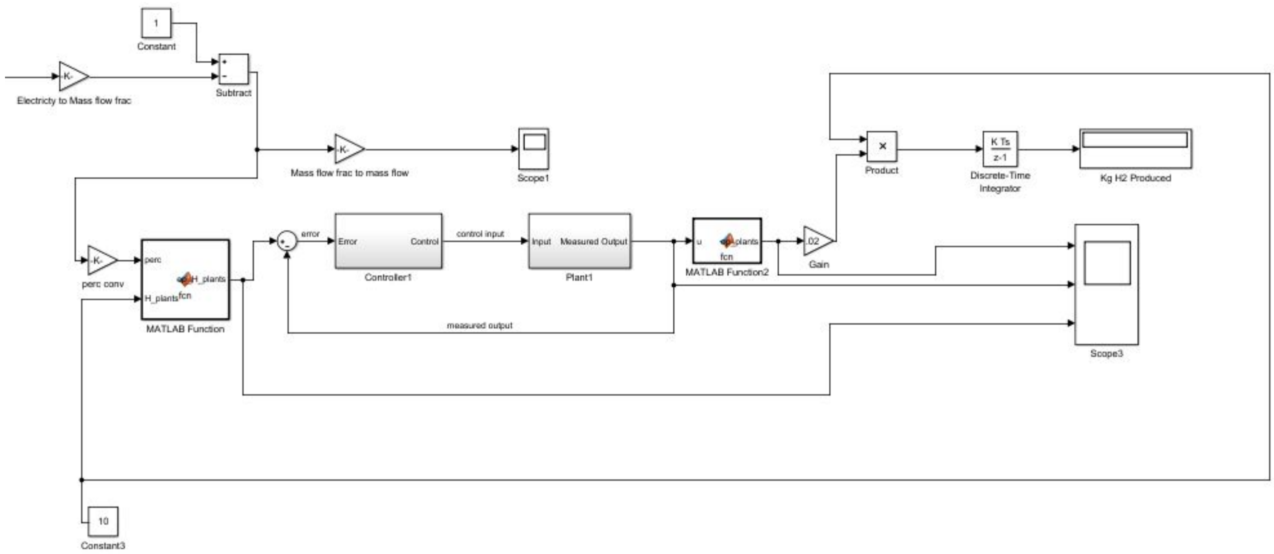
```
function HTC=HTC_bar(T,G,Di)
Re = @(T) G*Di/XSteam('my_pt',258.8,T); %Reynolds number
Pr= @(T) XSteam('pr_pT',258.8,T); % Prandtl at the constant pressure
Pr_avg= @(T) Pr_bar(T);
Nu= @(T) 0.0061*Re(T)^.904*Pr_bar(T)^0.684*(XSteam('rho_pT', 258.8, T+40)/XSteam('rho_pT', ...
    258.8, T))^.564;
HTC= @(T) Nu(T)*XSteam('tc_pt',258.8,T)/Di;
Temp=287:1:T;

for i= 1:numel(Temp)
    X(i)=HTC(Temp(i));
end
HTC = trapz(Temp,X)/(T-287);
end
```

10.3 Appendix B

10.3.1 Simulink Block Diagram for Electricity Generation



10.3.2 Simulink Block Diagram for Hydrogen Production



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