***Integrating Nuclear and Renewable Energy Sources***



*E295: Communications for Engineering Leaders*

*Round 5 Deliverable*

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1. **Overview of the Energy Industry**

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 is to 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 sustainable and stable grid.

*1.1 Fossil Fuels*

Around two thirds of the energy produced in the US come from fossil fuel production (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.

*1.2 Renewables*

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 renewables 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 all energy production methods.

*1.3 Nuclear*

Nuclear energy is a reliable form of energy producing and produces no GHG. The drawback is that nuclear power plants generally hold an expensive upfront cost and the growing penetration of renewable energy has exacerbated the this issue by decreasing the profitability of base load power plants.

After analyzing the primary methods of energy production, it is evident that utilizing one sources over the other will come with unsustainable difficulties. While there are many new technologies and techniques being researched that could bolster the strength of these energy production methods, an 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.

**2. Nuclear-Renewable Hybrid Energy System (NR-HES) - Our Proposal**

In order to address the decrease in grid stability brought on by the increasing penetration of renewables, 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 technology 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 a solar and wind farm. The constituents will be individually described below in the NR-HES(see Figure 2).

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| *Figure 2. Advanced Nuclear Reactor (ANN). The ANN is composed of several loops. In red is hydrogen production system and in yellow is the steam generator (electricity production).* |

***3.1 Advance Nuclear Reactor - Molten Salt Reactor (MSR)***

A molten salt reactor is a generation IV fission reactor and it is based on the molten salt reactor experiment carried in the 1960s at the Oak Ridge National Laboratory. This type of reactor has many advantages compared to current pressurized water and boiling water reactors where the main advantage is that it uses a liquid fuel salt rather than solid fuel rods and that it operates at higher temperatures than currently operated commercial reactors. Its passive safety and greater heat quality make it an ideal candidate as a heat supplier for a secondary process to take place, heat that otherwise would be wasted. Though safety has always been a large concern when considering nuclear power plants, this type of reactor uses liquid fuel which is inherently safer and because of its physical and chemical properties, it can shut itself down in case of an accident.

***3.2 Secondary Industry Process – Hydrogen Production***

The purpose of a secondary industry process is to divert extra energy produced by the NR-HES. Some of the considered process included methanol production, desalination, and hydrogen production. Hydrogen production was chosen based on the limited heat requirement provided by the NPP, and its current economic demand.

There are many methods to produce hydrogen, be it electrolysis, radiolysis, thermolysis, photo biological and many others. Many of these processes require extreme high temperatures to break down water into its constituents which the chosen ANN cannot supply. Because of this there has been increasing research in new production methods with lower heat requirements. For the proposed system a Copper-Chloride (Cu-Cl) thermochemical cycle (See Figure A1) was chosen due to the low heat requirements (around 530 C).

***3.3 Renewables – Solar and Wind***

The system will be fit with an industry standard Solar and Wind farm. These farms will supply energy when available and the ANN and HP will work together to allow full supply of renewables by increasing the production of hydrogen this way not oversupplying the grid. This type of system will prevent power plants from selling electricity at a loss and thus save the plant money throughout the year.

Although the concept has been increasingly researched and companies are starting to patent variations of these systems, there are no operating NR-HES in the world. While most of these patents are filed from major industry leaders such as General Electric, Hitachi, Mitsubishi and Toshiba, they are vastly different in design specifications. Some of these differences are in their design interconnections, energy generating sources, and the methods in which energy is transferred from the generating source to the industry process.

**4. Methodology for Designing the NR-HES**

A step by step selection process was used to bring together the difference pieces of the complex NR-HES. At each level, different ideas were brought to the table and a cost benefit analysis was performed to identify the most efficient or effective model. While there were countless options to shift through for new components, component compatibility helped limit the choices. For example, components that function poorly in the model’s environment such as pressures, temperatures, and secondary processes were quickly omitted. Additionally, components and systems were chosen based on available documentation, safety, and economic evaluations. For example, passive safety and availability of information were the most important aspects for choosing a NPP while economic benefits and potential for scaling were considered the most important aspects for the secondary process.

**5. System Modeling**

The purpose of this model is to create a visual representation of what the projected integration will look like. Each system is consisted of multiple parts that are primary for its individual working system; along with this, are interconnections that demonstrate their dependence on each other. Using this model permits the characterization of each component to be more straightforward. For example, when deciding on the proper location for the secondary process, it becomes non-trivial projecting how the placement of the process has a direct impact on the components before and after the system. Furthering this understanding, the model also demonstrates the process flow of each system.   
 The model was validated in multiple ways. First, the ThorCon system is a previously distinguished system that has been manipulated to fit the ongoing research. Next, the secondary process was validated through proposed iterations of previously established experiments. Finally, after characterizing each system, the integration was validated through coded thermodynamic correlations.   
 In order for the validation to be done, multiple assumptions about each system were made. For example, in order to calculate the output temperature of the steam generator, the following expression was used.

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| --- | --- |
| Nub= 0.0061Reb0.904Prb0.684()0.564 | Eqn. 1 |
|  | |

Where Nu is the dimensionless Nusselt number, Re is the dimensionless Reynolds number, Pr is the dimensionless Prandtl number, is the density of the water, and is the bulk density. (Refer to Appendix for detailed calculations)

Each dimensionless number incorporated values that is dependent on the state of the system. In order to solve this expression, the values were interpreted and further used to iteratively calculate the mass flow rate and temperature using a predetermined output temperature of 550C.   
 The model is expected to work within the scope of the specified assumptions. Once the limits of these assumptions have been surpassed, the anticipated results become dependent on the variable presumed.

**6. Results and discussion**

While the reactor is always running at 100% power, the heat extracted from the reactor is ultimately split up between hydrogen and energy generation depending on the electricity demand. For example, in times of low energy demand, more of this heat is sent to the hydrogen production than energy generation and vice versa. As heat is stored within the molten salt, managing the molten salt’s mass flow to these different processes is synonymous to managing the allotment of heat. With varying levels of heat allotment, the primary and secondary process must be able to adapt to the change

***6.1 Loss of heat transfer efficiency***

Energy generation cycles operate optimally at consistent conditions but the varying levels of heat input implement unwanted perturbations to the system. If the flow rate of molten salt to the energy generation side were to decrease and the flow rate of the water were to stay the same, the temperature of the steam would be much lower. In addition to component degradation, this decreases the efficiency of energy generation. For example, one would expect putting 50% of the maximum heat into the energy generation system would produce 50% of the maximum energy production but instead only 30% of the maximum energy is produced. To combat this, NR-HES employs variable frequency drives which allow for the control of the water’s flow rate. This allows the system to maintain the steam at a constant outlet temperature.

While this component allows for the system to run more optimally, the efficiency of energy generation still decreases as the flow rate to the electricity generation decreases. Figure 3 displays this phenomenon and these values were obtained using the aforementioned model. This is most likely due to the fact that the nusselt number from equation 1 is proportional to the reynolds number which is directly proportional to the flow rate of water (see appendix A for the correlations). Since the nusselt number is also proportional to the heat transfer coefficient (essentially the ability for something to transfer heat), a lower flow rate decreases the heat transfer coefficient. This figure can help determine the minimum percent of energy generation from the maximum that can be generated before losses due to decreasing efficiency make energy production infeasible. These bounds will help further characterize the NR-HES.

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| *Figure 3. Fraction of mass flow rate allotted to the energy generation side versus the energy generation ratio which is the net energy produced divided by the maximum energy that could be produced* |

***6.2 Difficulty in hydrogen production variability***

A rather different issue surrounds the variability of hydrogen production. In a hydrogen production plant, a specific amount of heat flow is necessary for hydrogen production to begin. This amount can be increased by increasing the size of the plant and the size of the plant determines the maximum amount of hydrogen that could be produced. To better explain the dilemma, assume a hydrogen production plant needs 50% of the system’s total heat to begin production. That means if 49% of the system’s total heat will lead to no hydrogen production and 80% of the plant’s total heat will still produce the same as if only 50% was supplied. This adds further complications since the system can only either send 0% or 50% of the molten salt flow to the hydrogen production if the system is supposed to use the heat optimally.

Adding variability can thus be achieved by creating multiple smaller hydrogen production plants that each take less of the system’s total heat in order to start production. This means that including smaller and greater numbers of hydrogen production plants leads to a greater range of the amount of molten salt flow that can be diverted. This then enhances the system’s ability to load follow. How small these hydrogen production plants should be along with how many there should be will depend on economic analysis which is the next step in this project.

REFERENCES

[1] EIA. (2017). Electricity in the United States - Generation, Capacity and Sales. Energy Information Administration. <https://www.eia.gov/energyexplained/index.cfm>

[2] California ISO (2017). Current and forecasted demand. California ISO.

http://www.caiso.com/TodaysOutlook/Pages/default.aspx

[3] Bragg-sitton, S. M., Boardman, R., Rabiti, C., Kim, J. S., Mckellar, M., Sabharwall, P., … Qualls, A. Lou. (2016). Nuclear-Renewable Hybrid Energy Systems : 2016 Technology Development Program Plan Idaho National Laboratory, (March).

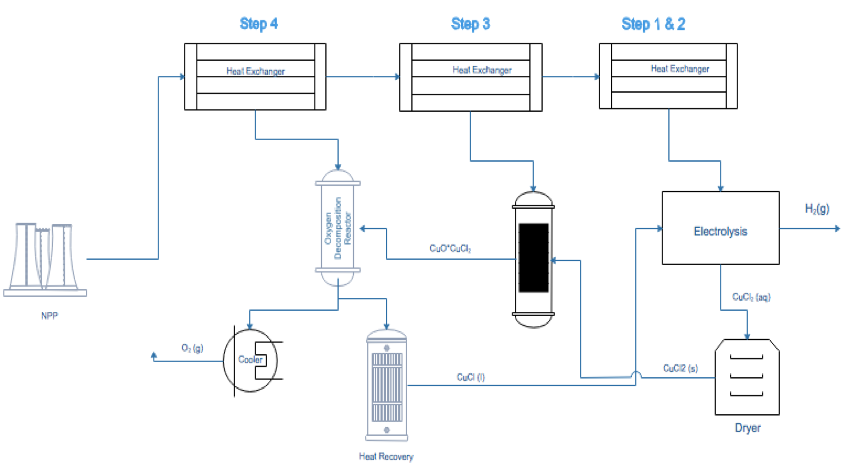
[4] IEA. (2017). World Energy Outlook 2017 - Executive summary. *International Energy Agency*. <https://doi.org/10.1016/0301-4215(73)90024-4>

[5] Engie (2016). Innovation and the energy transition.

https://www.engie.com/en/innovation-energy-transition/

APPENDIX

A.1



*Figure A1. Cu-Cl Thermochemical Hydrogen Production process. The ANN provides thermal energy to three heat exchangers this way providing heat to every step of the hydrogen production process.*

A.2

Correlations used for Steam Generator Characterization

* Nusselt Number-Nu

Nu=

Where:

- Heat transfer coefficient (W/m2K)

D - Diameter (m)

- thermal conductivity (W/mK)

* Reynolds Number- Re

Re=

Where:

- Fluid density

V - Fluid velocity

D - Diameter (m)

- Dynamic viscosity (Pas)

* Prandlt Number- Pr

Pr=

Where:

- Dynamic viscosity (Pas)

- specific heat (J/kgK)

- thermal conductivity (W/mK)

* - Density of the water and bulk (kg/m3)
* Average Heat Transfer Coefficient

h=

- Nusselt Number

- thermal conductivity

D - Diameter (m)

T2+ T1