DECENTRALIZED ENERGY SYSTEMS FOR SMART GRID APPLICATIONS

A Thesis

by

ARMANDO BLANCQ CAZAUX DEL BOSQUE

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Chair of Committee,	Efstratios N. Pistikopoulos
Co-Chair of Committee,	M.M. Faruque Hasan
Committee Members,	Styliani Avraamidu
Head of Department,	Efstratios N. Pistikopoulos

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ABSTRACT

A symbiosis of Renewable Energy Sources with an Alternative Energy Source is necessary to satisfy the ever-changing energy demands. Solar and wind energy are taken into consideration, yet the intermittency of both present problems when integrated into the electric grid. Different Storage systems such as: Lithium-Ion Battery, PSH, and CAES are considered for optimization for charge and discharge of energy as well as Dense Energy Carriers like Hydrogen to control the fluctuations of solar and wind, as well as to store and deliver the energy to the end-user. However, using Renewable Energy Sources to produce Dense Energy Carries can result in a very complicated process. Alternative Energy Sources helps solve the intermittency and hydrogen production problem by producing electricity and hydrogen on a consistent basis; Nuclear Energy aided by Natural Gas and Biomass. The end goal is to Satisfy the current and future energy demand in the Residential, Commercial, and Industrial Sectors of the State of Texas. The methodology to follow consists of analyzing the current data for the energy profiles in Texas in the three sectors. The data is going to be used to come up with a (MILP) mixed integer linear programming optimization method to best optimize the energy sources to meet the electric demand in the 3 sectors in Texas while minimizing costs, CO2 emissions, and water consumption. By the end of this research it is expected to determine costs, water usage, CO2 emission, and energy sources to utilize in the system as well as being able to satisfy the demand in the Residential, Commercial, and Industrial sectors in Texas.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

Part 1, faculty committee recognition

This work was supervised by a thesis committee consisting of Assistant Research Scientist Dr. Styliani Avraamidu and Professor Efstratios N. Pistikopoulos of the Department of Energy and Professor M.M. Faruque Hasan of the Department of Chemical Engineering.

Part 2, student/advisor contributions

All work for the thesis was completed by the student, under the advisement of assistant research scientist Dr. Styliani Avraamidu from the department of Energy. The data analyzed for Biomass in section 4 was based by the data provided by Postgraduate Researcher Julie Cook from the energy institute. Ph.D. students Cory Allen and Rahul Kakodkar from the energy institute aided in the development of the sets, parameters, variables, constraints, balancing equations, objective function, and optimization code found in section 4.

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1. INTRODUCTION AND MOTIVATION

1.1. Energy Overview and CO2

With population growth the demand and need for energy is increasing. According to the United Nations, the current human population is around 7.6 billion, and it is expected to grow to 8.6 billion by the year 2030, and almost 10 billion by the year 2050 (UN 2017).

Increasing population will increase energy production. According to the EIA (Energy Information Administration) the need for energy usage will increase by at least 50%. (EIA 2010-2050)

The energy sources available for energy production and to meet current and future energy demands are two: alternative energy sources (AES) and renewable energy sources (RES). AES includes coal, oil, natural gas, and nuclear. RES include wind, solar, hydroelectric, geothermal, and biomass.

Currently, coal, oil, and natural gas are the leaders in energy production, yet the excess use of these fossil fuels releases greenhouse gases to the atmosphere creating global warming. Greenhouse gases trap heat in the atmosphere. Examples of these gases are nitrous oxide, fluorinated gases, methane, and carbon dioxide. The percentage of each gas released to the atmosphere by the burning of fossil fuels is shown in the figure below (the data corresponds to the year 2019):

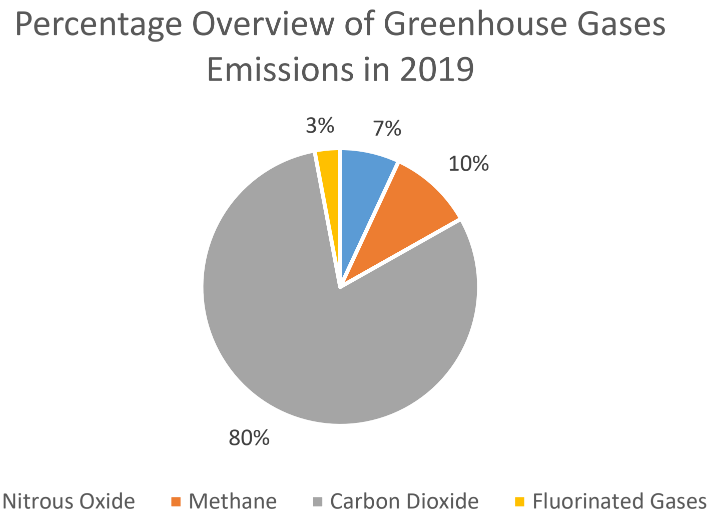


Figure 1, Percentage Overview of Greenhouse Gases Emission in 2019 EPA (adapted from 3)

Carbon dioxide happens during the combustion/burning of coal, oil, natural gas, solid waste, and wood. Methane is released by producing and transporting fossil fuels such as coal, natural gas, oil, and organic waste from livestock. Nitrous oxide is produced mainly from agriculture, industry, and combustion. Fluorinated gases include several chemicals known as High Global Warming Potential Gases for their hazardous potential; these gases are normally emitted in smaller quantities. Reduction of these gases is a top priority for the U.S. government.

These gases are emitted during daily human activities in different sectors, such as residential, commercial, industrial, grid-electricity, and transportation sectors. In the following chart, a percentage of CO2 emission per sector can be seen for the year 2019:

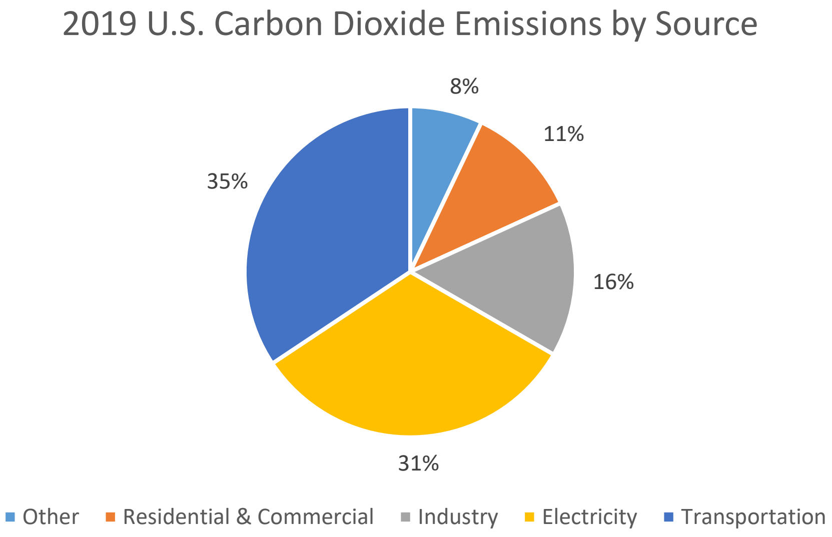


Figure 2, 2019 U.S. Carbon Dioxide Emissions by Source (adapted from 3)

The Primary Energy consumption in the U.S. comes mainly from natural gas and petroleum, both sources produce CO2 in their processes. In the pie chart below is the energy consumption for the year 2019; latest data available by the EIA.

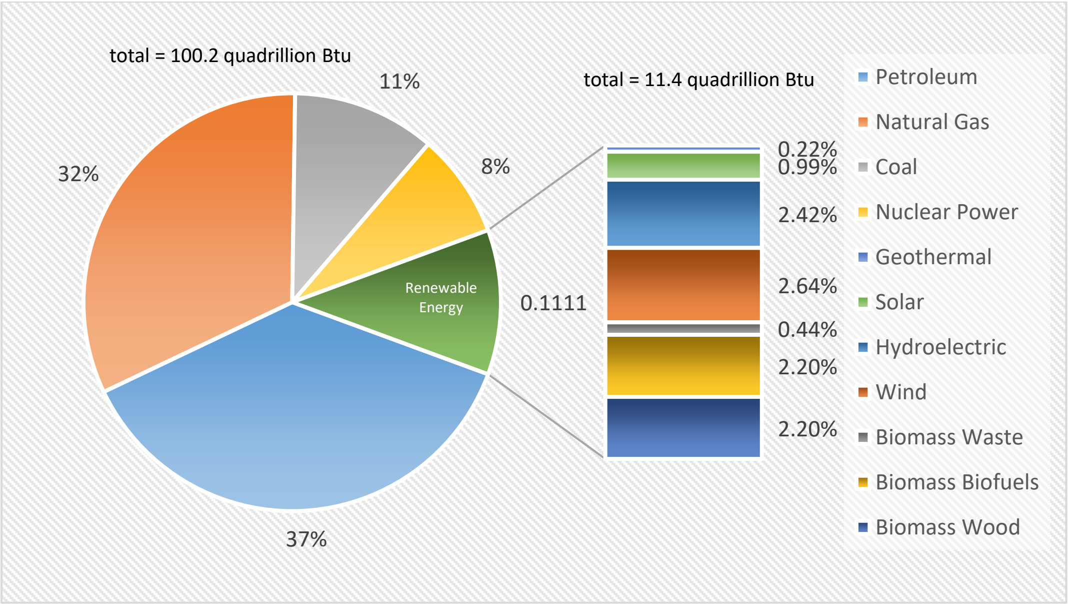


Figure 3, U.S. primary energy consumption by energy source, 2019 (adapted from 4)

The figure below (Figure 4) explains the relationship between the energy produced by the different sources in the U.S. and the End-Use sectors; transportation, industrial, residential, and commercial, in 2019. The transportation sector is not a focus on this paper, yet it is part of the figure.

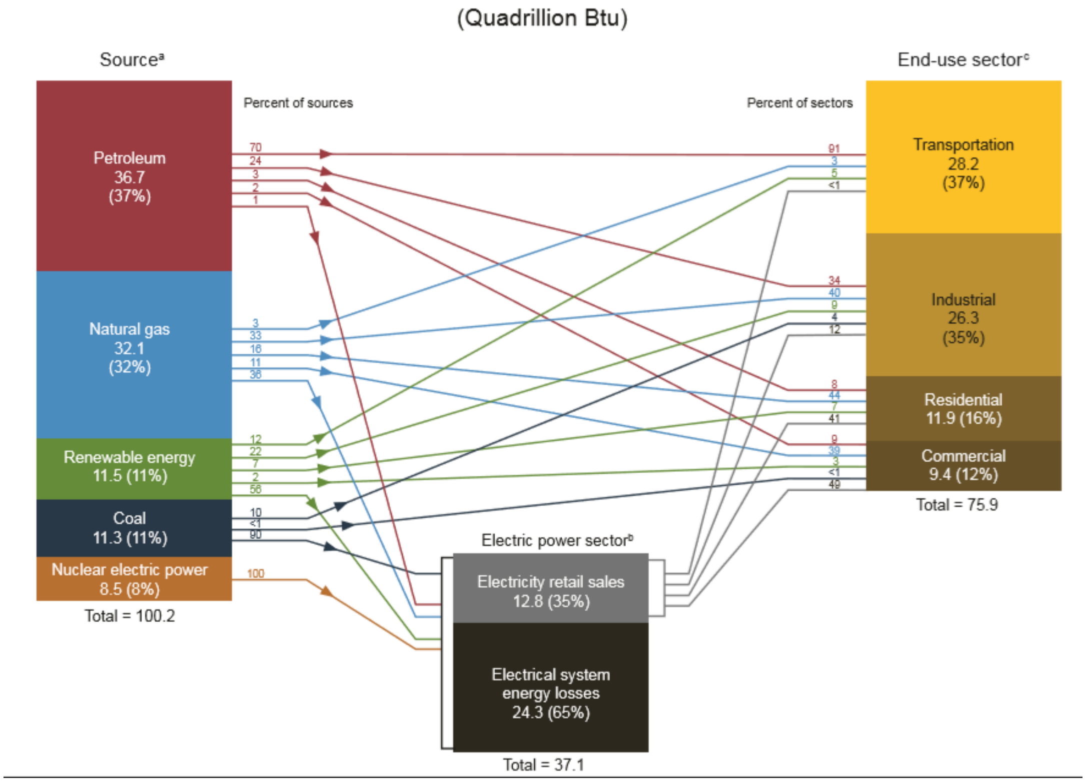


Figure 4, U.S. energy Consumption by Source and Sector, 2019 (reprinted with permission from 4)

The figure above clearly shows what sector each energy source supplies energy. In the case of petroleum, the majority (70%) of the oil produced goes to the transportation sector, while the other 30% goes to the other 3 sectors. In the case of natural gas, the majority goes to the industrial and electricity generation sector (approximately 35% respectively). Renewable energy and coal also aid for electricity production, and in the case of renewable energy it mainly focuses on supplying energy to the industrial and residential sector. Nuclear Power comes in last, providing energy only to the electric power sector to power the different sectors.

1.2. Increasing Energy Demand

As mentioned before, the world population is increasing every year and with it, energy demands. Taking the United States as an example, the U.S. Energy Information Administration (EIA) projects that by 2050, in the best economic growth case scenario, they will deliver more than 90 quadrillion BTU of energy to the end-use sectors (residential, commercial, industrial, and transportation). The Figure below shows that projection:

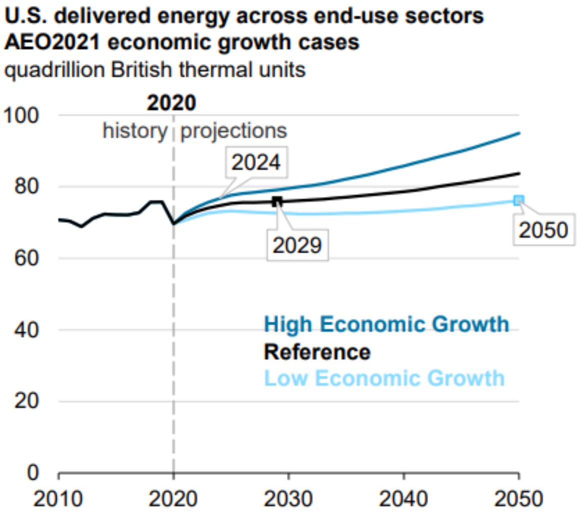


Figure 5, U.S. delivered energy across end-use sectors Annual Energy Outlook 2021 (reprinted with permission from 77)

As energy delivered to the end-use sectors increases, so the electricity used by these sectors also increases. The figure below (Figure 6) shows the projected electricity use by each sector by the year 2050. When compared to the year 2020, the electricity use increases almost 25% for each sector.

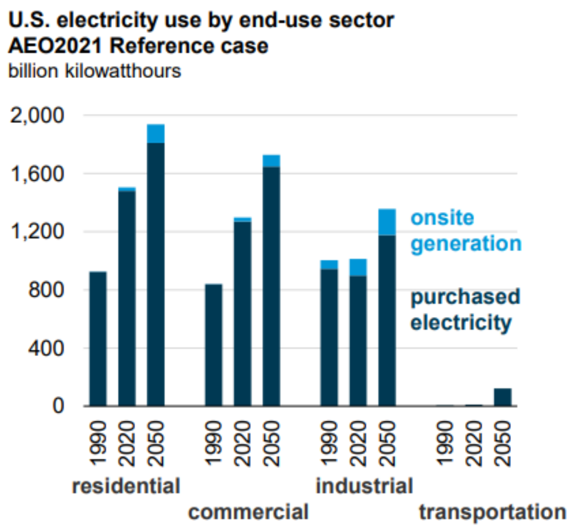


Figure 6, U.S. Electricity use by end-use sector Annual Energy Outlook 2021 (reprinted with permission from 77)

To satisfy current and future energy demands of the three different sectors some energies to consider are renewable energies like solar, wind, and biomass, but the intermittency of solar and wind create the need to build better and cleaner energy storage systems and clean ways to send that energy to the final users. RES can meet the energy demands, but they will require a very big portion of the land in the U.S. to do that. This solution is infeasible and will do more harm than good. Adding biomass and alternative energy systems like natural gas and nuclear are going to help with intermittency, diversification of the energy portfolio, and hydrogen production. Given that biomass, nuclear, and natural gas uses water, it is also important to minimize the water needed to keep the power plants running. The water used is normally taken from nearby bodies such as rivers and lakes and drying those out will bring future problems for water consumption for humans, animals, and industries.

2. OBJECTIVES

The first objective of this work is to develop an optimization model to optimize how much energy coming from energy resources such as solar, wind, biomass, nuclear and natural gas is needed to be produced to satisfy the current and future energy demands in Texas. The second objective is to utilize the demand collected and optimization results to choose the best energy sources to meet the current and future energy demands in the three different sectors combined (residential, commercial, industrial) in the state of Texas. The remaining objectives are focused on analyzing the following: environmental impacts such as the water and carbon footprint and the costs involved in this model and the best optimization network for minimizing it.

3. PROBLEM DESCRIPTION

3.1. Energy Transition and Energy System Engineering

Energy transition is necessary to reduce global warming and CO2 driven by population growth. Smart cities are being researched and developed to make cities more efficient and sustainable due to energy consumption in buildings accounting for almost 40% of the world's energy resources and emitting 1/3 of emissions (EIA 2020, IEA 2019).

The shift to low-carbon energies to reduce emissions started with renewable energies such as wind, solar, hydroelectric, geothermal, and biomass to generate electricity and heat. During the last years, the penetration of (RES) Renewable Energy Systems (from production to distribution) into the grid has increased and will continue to increase dramatically in the future (Huai Su et al, 2020).

The goal is to have a stable energy supply to meet customer demands (Pistikopoulos et al, 2020), using different energy sources including those of solar and wind. It aims to improve the system flexibility by connecting it to the power grid and reduce greenhouse emissions to the atmosphere (Sennai Mesfun et al., 2020).

Unfortunately, renewable energies have intermittent properties, solar energy works best during the day, while wind energy works best with wind speed. This makes it difficult to operate in the electric power grid (H. Su et al, 2020). Hydroelectric and geothermal depend on geographic location. Biomass has ethical problems because it competes against crops for energy or food production (A.L. Gusev et al, 2020).

To be able to solve this complex problem a generic framework developed by scientists known as Energy Systems Engineering is going to be implemented. This new framework has been used before and has been successfully applied to optimize design and operation in various sectors in the industry. The main idea behind this framework is *the design and operation of energy intensive processes in a more efficient and economic manner through mathematical optimization (*Pistikopoulos et al, 2019) This approach will help with the integration of all the possible energy combinations to achieve the best cost, the least CO2 emission, the least water consumption, and the highest efficiency possible. More about the methodology of Energy Systems Engineering is going to be discussed in the Methodology section.

The system will require precise infrastructure (supply chain optimization) to produce energy and deliver it to the end user. The following are going to be needed: construction of new power plants, construction of new energy storage devices, conversion of cooling technology after water usage for current power plants, costs, and environmental impacts (Pistikopoulos et al, 2019). Multi-objective optimization programming methods are going to be used. Taking in consideration the following constraints: ability to build new power plants, storage units, cooling technology conversions, energy generated by each power plant, energy allocated within the system, energy stored, and energy released from storage devices (Pistikopoulos et al, 2019).

Since water is taken into the equation, one of goals is to reduce costs and water during power generation while satisfying energy demands (Pistikopoulos et al, 2019).

3.2. Renewable Energy Intermittency

To solve the intermittency, the uncertainty in load behavior, a storage optimization method is needed. Integrated Energy Systems (IES) is crucial for Energy Systems Development (ESD) that integrates renewable energies, energy demands, transportation methods, and supply chain efficiency. Aiming to solve all these problems. Energy storage combats RES intermittency (Solar and wind). One option is to design an effective supply chain network of dense energy carriers (DEC) like hydrogen (Pistikopoulos et al, 2019).

Another strategy is to utilize small batteries for distributed applications; for larger applications batteries can be expensive (Pistikopoulos et al, 2019). There is an uncertainty in load behavior for the different sectors, and for batteries to solve the problem and charge/discharge energy at the correct time, optimal scheduling and demand forecasting needs to be done (H. Karami et al, 2020).

Finally, Mechanical storage systems such as: PSH (pumped storage hydroelectricity) and CAES (compressed air energy storage) are already developed technologies at the utility-scale (Pistikopoulos et al, 2019). These types of systems are one of the most sustainable and efficient today (Montaser Mahmoud, et al, 2020). Nonetheless they face a location constraint for their construction (Pistikopoulos et al, 2019).

Going back to DEC (chemical based), chemical compounds such as Hydrogen, are the most efficient for storage and transportation. Chemical energy can be stored in chemical compounds using renewable power in water electrolysis to produce hydrogen (Pistikopoulos et al, 2019), or nuclear power plants electrolysis with a little help of natural gas (A.L. Gusev et al, 2020). They are easily transportable, capable of storing more energy than batteries, higher energy capacity, geographically flexible, and can store and transport any source of energy from excess supply areas to demand locations (behave as Energy Carriers) where they are converted to electricity (Pistikopoulos et al, 2019).

Given that the best place for renewable energy placement is away from the cities, DEC based on Hydrogen is useful. Yet Hydrogen has a constraint in volumetric capacity because as a gas it needs to be stored in conditions of very high pressures (350-700 bar) and as a liquid in conditions of very low temperatures (-235 Celsius). Given its characteristics, hydrogen is used to produce ammonia and methanol, two chemicals capable of storing and transporting hydrogen more efficiently for larger distances and periods of time (Pistikopoulos et al, 2019).

Ammonia is stored as a liquid under a slight pressure of 10-20 bar or at a low temperature of -33 Celsius. Methanol on the other hand, is already in liquid form. Both chemicals come with higher production costs than hydrogen. Integrating HAM (Hydrogen, Ammonia, and Methanol) for storage and transportation increases efficiency and reduces costs. Ammonia and methanol mitigate storage costs of hydrogen, while hydrogen and methanol together alleviate the additional energy burden of producing ammonia even though its network was most optimal as an individual (Pistikopoulos et al, 2019).

3.3. Symbiosis for Hydrogen Production

Hydrogen fuel has little impact on the environment. The world demand for hydrogen is increasing, and renewable energies and nuclear energy are going to help meet the future demand (A.L. Gusev et al, 2020). A symbiosis of nuclear and renewables is needed to produce hydrogen, and clean and effective resources needed to produce huge volumes of electric and thermal energy (A.L. Gusev et al, 2020). Several industries are interested in hydrogen technologies, such as: Confectionery industry, Vehicles, Oil refining, Metallurgy, Heat (A.L. Gusev et al, 2020).

Today more than 95% of hydrogen comes from natural gas. The use of effective development of environmentally friendly energy sources to produce Hydrogen energy is being highly investigated for huge volumes of electricity and heat. This can be achievable using non-renewable sources such as natural gas or nuclear energy (A.L. Gusev et al, 2020).

Hydrogen based technologies include fuel cells, transport systems, and storage systems. Largest hydrogen consumers include oil refining, ammonia production, methanol production, and ferrous metallurgy. Below is a graph showing Largest Hydrogen consumers in the industry by percentage (A.L. Gusev et al, 2019):

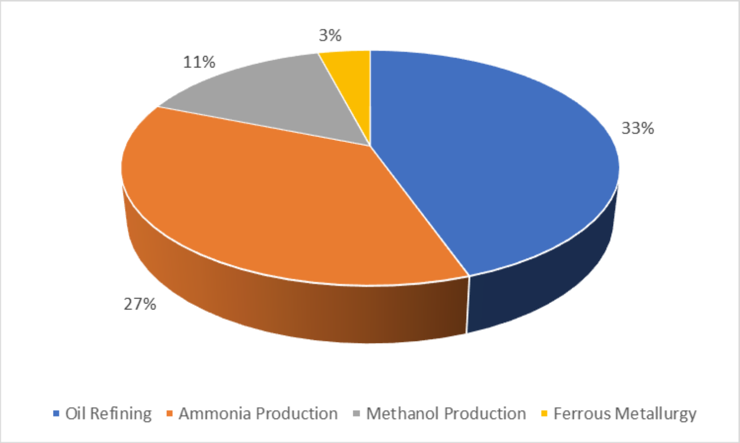


Figure 7, Largest Hydrogen consumers in the industry (adapted from 27)

Hydrogen depends on availability and efficiency of the use of the following resources: water and energy, production costs, energy capacity, and environmental impacts (A.L. Gusev et al, 2020). Hydrogen cannot be produced by only using RES since the scale of solar and wind farms (or any other) to meet the demand will lead to negative environmental impacts at the regional and global level, and the amount of hydrogen produced is small compared with the hydrogen produced using natural gas or nuclear power (Gusev et al., 2019).

Integrating alternative energy sources such as coal, oil, natural gas, and nuclear, is useful to tackle intermittency with RES and increase the generation of electricity and heat, as well as to increase hydrogen production. Given the high emissions of coal and oil, only natural gas and nuclear are taken into consideration. One example is the Finish government, who is working on simulating future scenarios where the country is based on nuclear power and wind energy, as well as the inclusion of efficient heat pumps and electric boilers for energy conversion (Sanna Syri et al, 2018).

Nuclear Power Plants (NPP) can produce hydrogen in several ways with minimal emissions: radiolysis, electrolysis, high temperature vapor electrolysis, hybrid thermochemical splitting water, thermal chemical breakdown of water, and using natural gas for heat production by steam reforming (A.L. Gusev et al, 2019).

3.4. Symbiosis for Energy Production

Solar, wind, and nuclear power are the main sources that emit the least greenhouse gases. To transition to a clean hydrogen world, we need to develop these technologies and use them in a symbiosis. Nuclear energy will provide stable power to produce electricity, heat, and hydrogen at the same time renewable energies are used. Nuclear energy will increase renewables efficiency, this is called a (HES) Hybrid Energy System. HES generates way less emissions than fossil fuels (A.L. Gusev et al, 2019). Gas pipelines can be used to store and transport hydrogen (A.L. Gusev et al, 2020). It is also important that hydrogen is generated from clean resources to prevent global warming. Nuclear energy can support countries manufacturing industries for fuel, fertilizers, steel, plastics, and chemicals (A.L. Gusev et al, 2019).

3.5.The State of Texas

The state of Texas is chosen in this paper due to the wealth of energy sources available. Texas also is a leader in energy production, providing 1/5th or more of the energy produced at the national level. Oil and natural gas are currently the main energy resources found in Texas, followed by coal. It also produces energy coming from clean renewable sources; it is the top producer of electricity coming from wind energy in the U.S, and a leader in solar energy. Also, uranium based Nuclear power plants can be found in the south. The latest data shows that Texas is the second most populated state in the nation, just behind California. It is the 6th state of the nation in terms of consumption of energy per capita and the 3rd energy supplier. The industrial sector, as shown in the figures of this section, is the largest energy consuming in Texas, which includes the processes used for oil refining and manufacturing industries.

The Texas climate directly affects the amount of renewable energy captured for electricity generation. Warm, moist, humid, and subtropical climates sweep across the state. Semi-arid climate resides in central and western Texas, and arid in the west. Freezing temperatures during winter, and hot temperatures during summer.

It is the second highest electricity producing state in the country, with natural gas supplying more than half of the electricity in 2019. Wind-power generation has been increasing in the past 2 decades, in 2019 it provided more than 1/6th of Texas' electricity. Electricity coming from Nuclear power is also part of the Texas energy portfolio, with 1/10th of the electricity coming from this source. Texas is the largest electricity consumer in the U.S. whose power goes to the residential sector, commercial sector, and industrial sector.

Renewable energy is strongly present inside the Texas energy portfolio. 1/5th of the electricity comes from renewable energies such as wind and solar. Currently, wind energy generates most of the electricity, coming from clean sources, with more than 28,800 megawatts of wind capacity installed by 2019. More wind farms are under construction each year. The western part of Texas is good for solar energy due to high levels of direct solar radiation. It is the 6th solar power producing state, and as solar photovoltaic panels technology is improved and cost efficient, the installed capacity grows each year. In 2019, it had more than 3,100 megawatts of solar installed capacity.

The state is a great choice thanks to its policies for promoting and encouraging renewable energies for electricity production. In 2005 The Public Utility Commission of Texas mandated that by 2015, 5% (5,880 megawatts approximately) of the electricity generating capacity comes from renewable sources. By 2025, 10,000 megawatts must come from renewable energy, a goal that was crushed in 2009 thanks to the generating capacity of Texas' wind farms (source: EIA 2020).

3.6. Best Locations for Utility Scale Power Plants

3.6.1 Solar Power Plant

To analyze the best location to place a Solar PV utility-scale system in Texas, NREL has a database that helps to make that decision. The map below shows the annual average of (Global Horizontal Irradiance) daily total solar resource using 1998-2016 data covering 0.038-degree latitude by 0.038-degree longitude (4km x 4km)

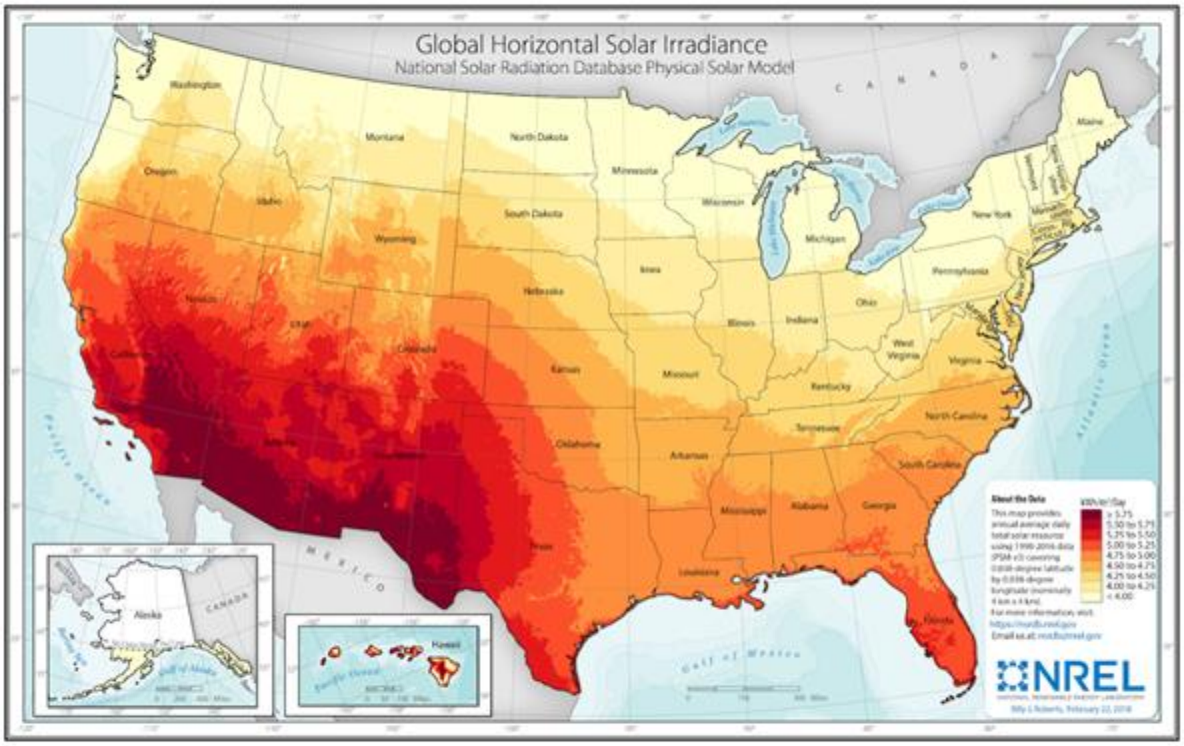


Figure 8, U.S. Global Horizontal Solar Irradiance Map (reprinted with permission from 42)

3.6.2 On-Shore Wind Power Plant

The state used in this research is the state of Texas. To have a better understating of the best geographic location in Texas is to build the future Wind Farms, graphs containing the average annual wind speed in Texas at 30 meters and 80 meters above the ground are analyzed below:

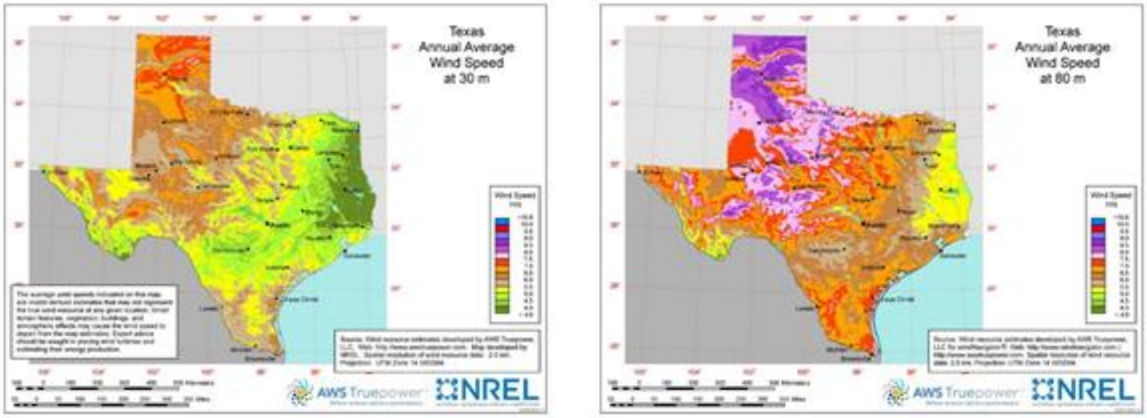


Figure 9, Texas Annual Average Wind Speed at 30m and 80m (reprinted with permission from 43)

The graphs below show the potential Wind Capacity at 110 meters and 140 meters Hub's Height. The data was collected from the year 2014.

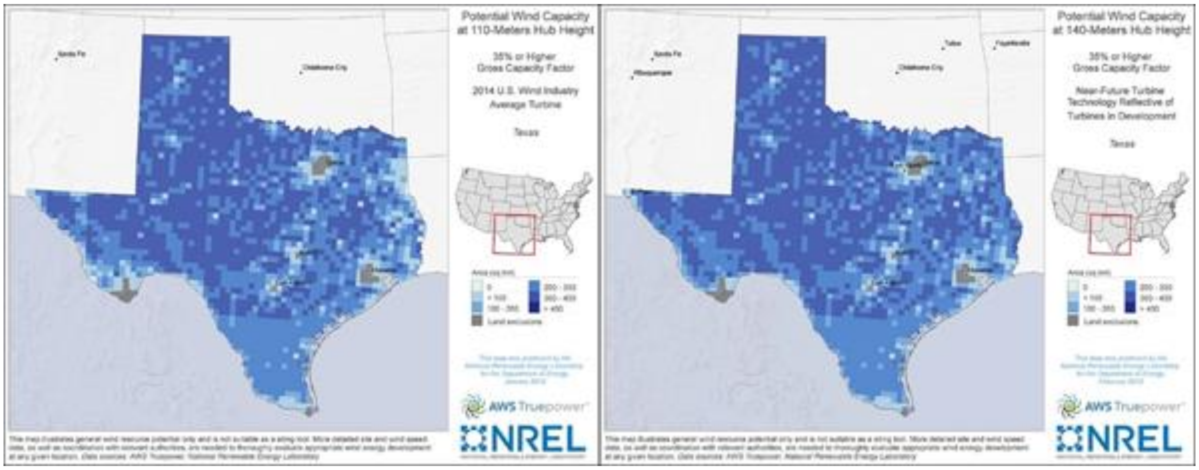
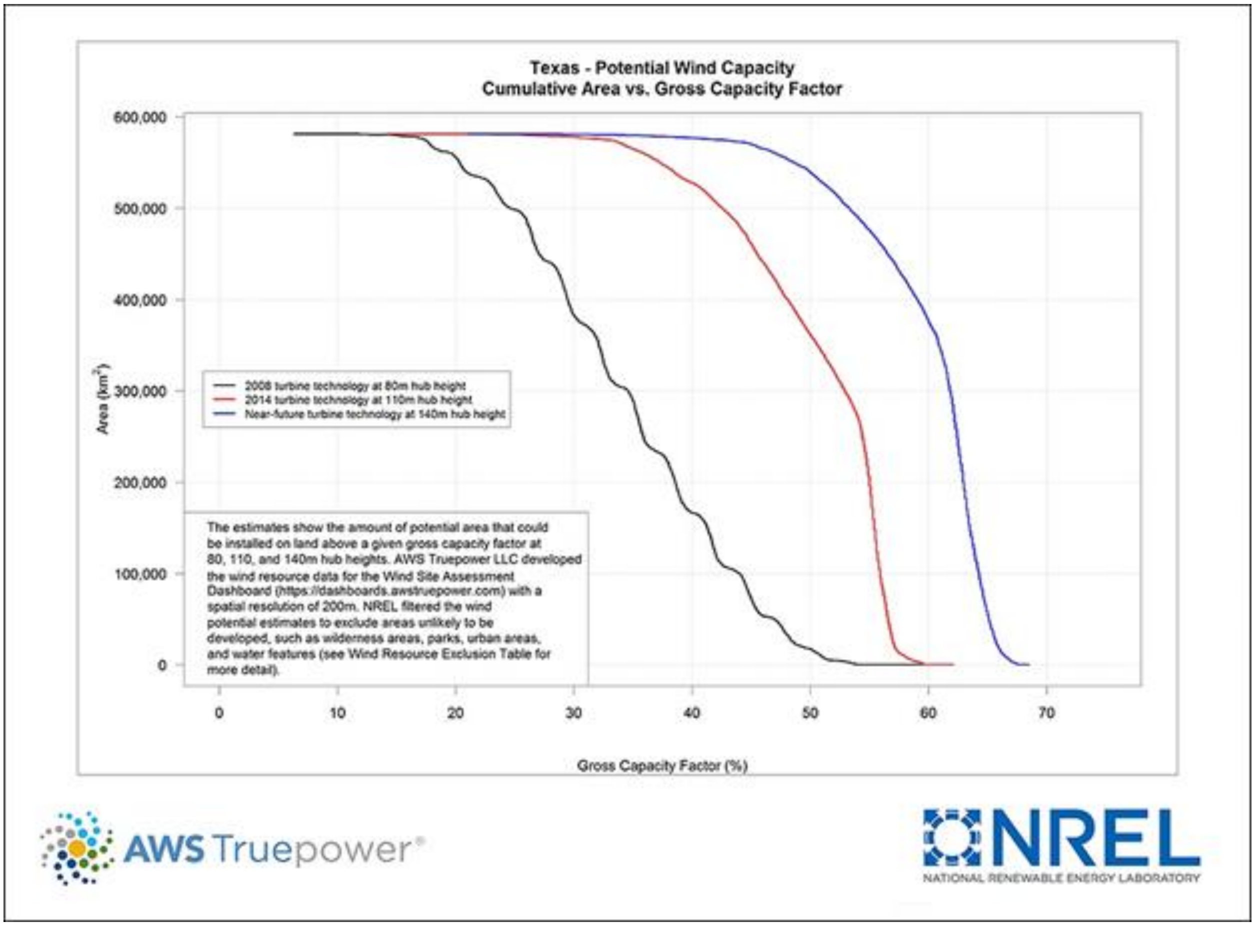


Figure 10, Texas Wind Capacities at 110m and 140m Hub's Height (reprinted with permission from 43)

Finally, the following chart shows the potential Wind Capacity in Texas given the available land for installation for hub heights of 80m, 110m, and 140m with a capacity factor equal or greater than 35%.



The estimates show the amount of potential area that could be installed on land above a given gross capacity factor at 80, 110, and 140m hub heights. AWS Truepower LLC developed the wind resource data for the Wind Site Assessment Dashboard (https://dashboards.awstruepower.com) with a spatial resolution of 200m. NREL filtered the wind potential estimates to exclude areas unlikely to be developed, such as wilderness areas, parks, urban areas, and water features (see Wind Resource Exclusion Table for more detail).

Figure 11, Texas Potential Wind Capacity (reprinted with permission from43)

3.6.3 Nuclear Power Plant

According to the US nuclear regulatory commission, the country has the following working power reactors (last reviewed in July 2020): 31 BWR and 63 PWR.

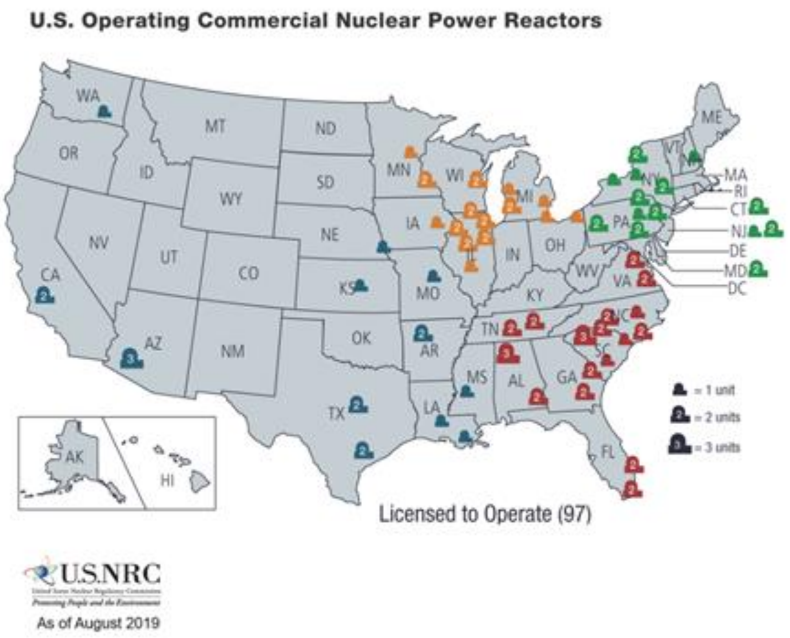


Figure 12, U.S. Operating Commercial Nuclear Power Reactors (reprinted with permission from 44)

Nuclear's main fuel source is Uranium. In Texas there are a few places where Uranium can be extracted, the following map shows the Uranium districts in the U.S.

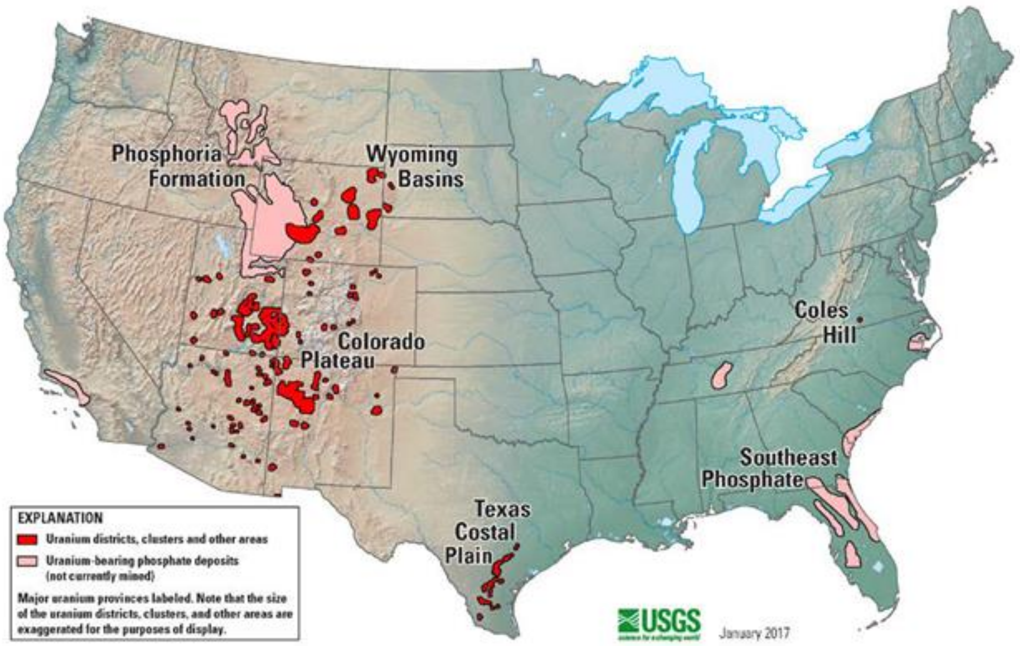


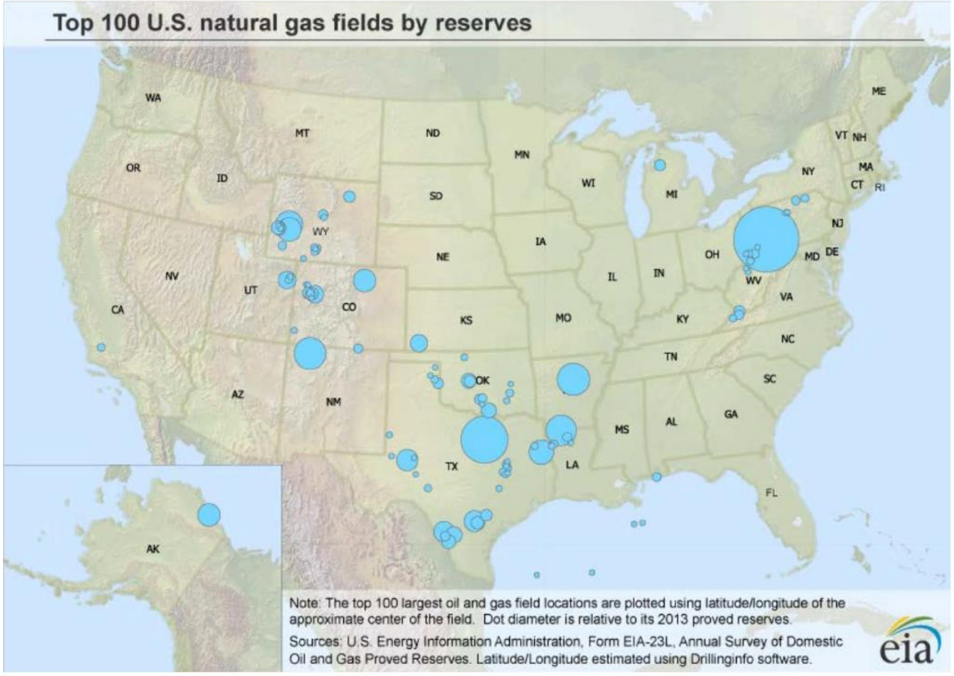
Figure 13, Uranium Resources in the U.S. (reprinted with permission from 62)

Another important aspect to consider when choosing the best location to place a Nuclear Power Plant, is the water resource since NPPs in the U.S. require water to operate, building one next to a body of water is ideal. The map below shows all the lakes and reservoirs in Texas.

Figure 14, Water reservoirs in Texas (reprinted with permission from 45)

3.6.4 Natural Gas Power Plant

The geographic distribution of the top 100 U.S. natural gas fields by proved reserves (as of December 31, 2013) is shown by the Energy Information Administration in Figure 15. As seen in the figure below, Texas has numerous oil/gas reserves from which natural gas can be extracted, focusing more on the Mexican border near Laredo, and near the city of Dallas.


Top 100 U.S. natural gas fields by reserves

Note: The top 100 largest oil and gas field locations are plotted using latitude/longitude of the approximate center of the field. Dot diameter is relative to its 2013 proved reserves.

Sources: U.S. Energy Information Administration, Form EIA-23L, Annual Survey of Domestic Oil and Gas Proved Reserves. Latitude/Longitude estimated using Drillinginfo software.

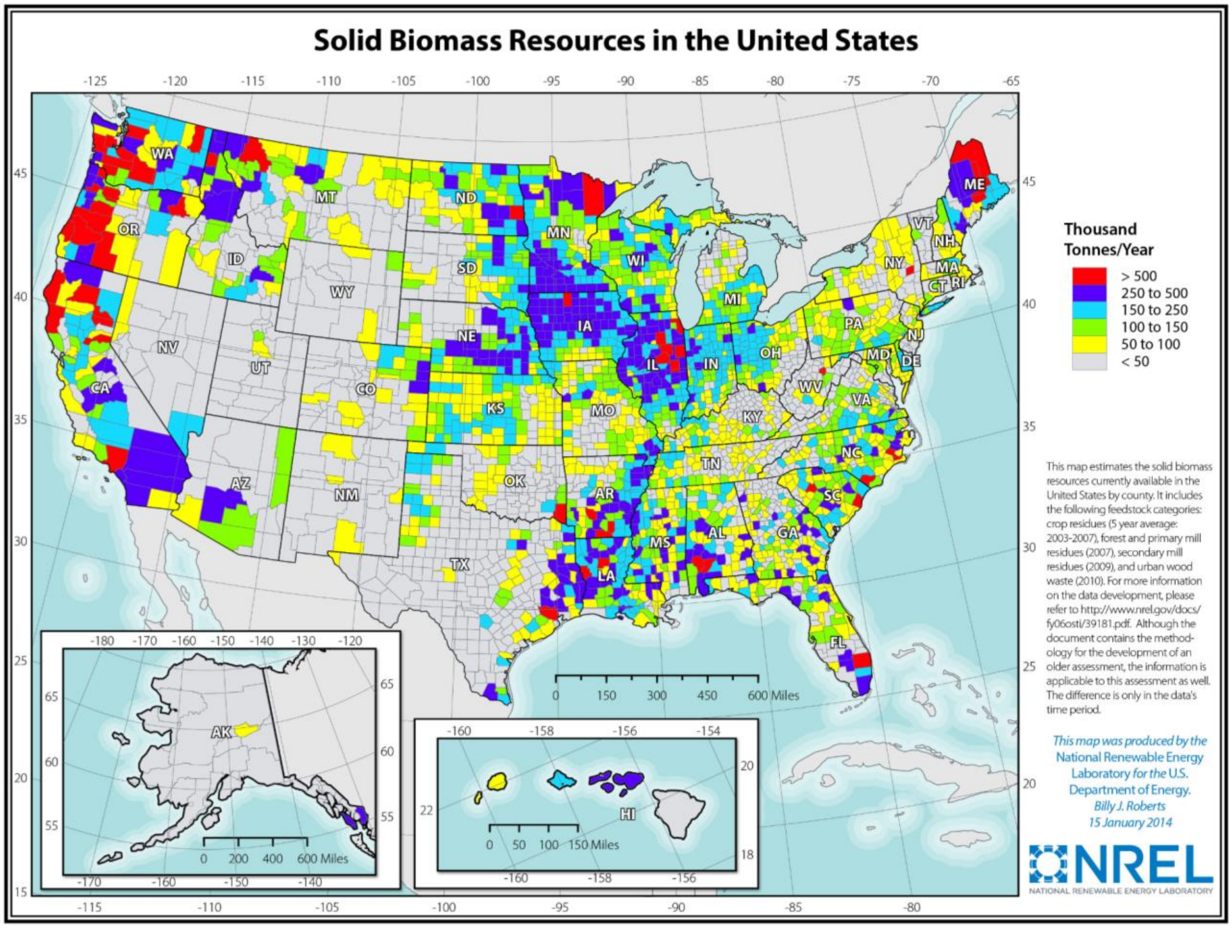
Figure 2. Geographic distribution of the top 100 U.S. natural gas fields

Source: EIA 2015

Figure 15, Top 100 U.S. Natural Gas fields by reserves (reprinted with permission from 62)

3.6.5 Biomass Power Plant

The figure below (Figure 16) is a map that shows an estimate of all the solid biomass resources currently available in the U.S. by county. It includes the following feedstock categories: crop residues, forest, primary mill residues, secondary mill residues, and urban wood waste. For this thesis, the focus will be on crop residues. According to the National Agricultural Statistics, crop residues include: corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, dry edible beans, dry edible peas, peanuts, potatoes, safflower, sunflower, sugarcane, and flaxseed. The focus of this work is in corn (maze). According to the map, the best state for biomass production capacity in general is Iowa and the surrounding states.



Solid Biomass Resources in the United States

This map estimates the solid biomass resources currently available in the United States by county. It includes the following feedstock categories: crop residues (5 year average: 2003-2007), forest and primary mill residues (2007), secondary mill residues (2009), and urban wood waste (2010). For more information on the data development, please refer to http://www.nrel.gov/docs/fy06osti/39181.pdf. Although the document contains the methodology for the development of an older assessment, the information is applicable to this assessment as well. The difference is only in the data's time period.

This map was produced by the National Renewable Energy Laboratory *for the* U.S. Department of Energy.
Billy J. Roberts
15 January 2014

Figure 16, Solid Biomass Resources in the U.S. (reprinted with permission from 49)

4. METHODOLOGY AND MATHEMATICAL MODELS

4.1. Component I: Superstructure Representation and Demand of The Model

Based on the information and energy profiles discussed, and the methods being used to achieve the objectives, several sets of variables are going to be used. A superstructure representation of the model is presented below to satisfy the desired outputs for the different sectors (Residential, Commercial, and Industrial) which will be represented as a whole with the variable "Power (Load)" using the following primary energy sources: Solar, Wind, Nuclear, Natural Gas, and Biomass. Figure 17 below shows the superstructure:

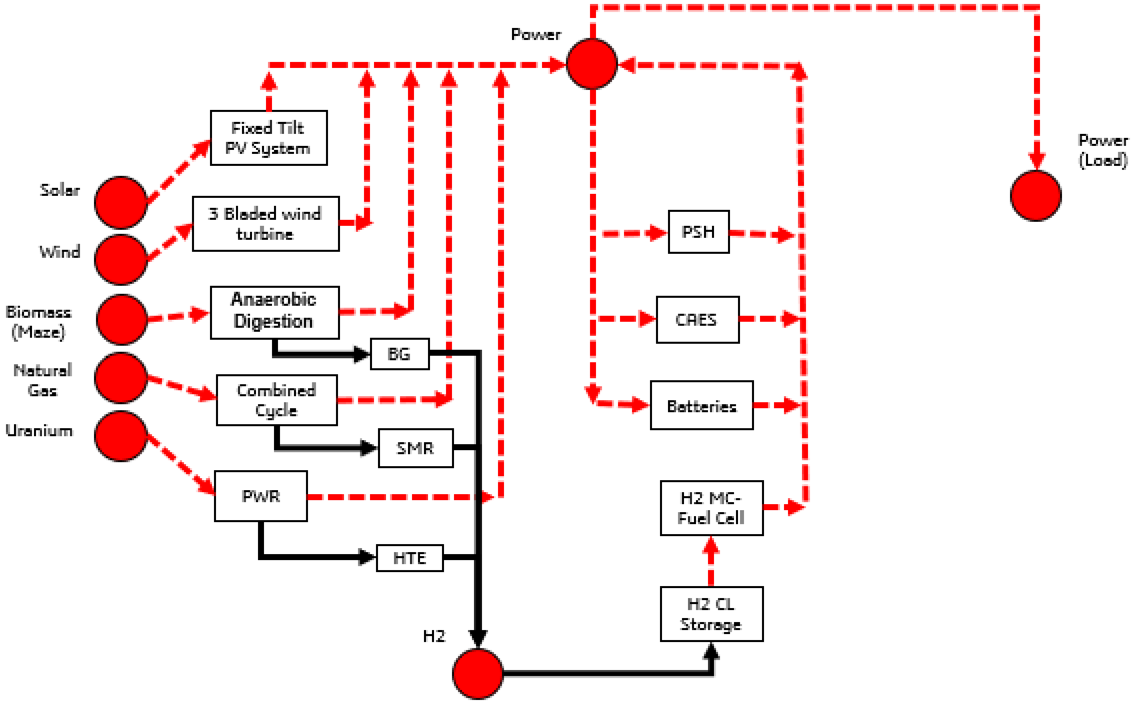


Figure 17, Energy Systems Superstructure

The optimization problem is going to consist of a Multi-Objective Mixed-Integer Linear Programming Optimization method defined with the following objectives:

- Minimize Costs
- Minimize CO2 Emissions
- Minimize Water

It is going to be utilized for three different scenarios: Variable demand, Fixed Demand for the Industrial sector, and Variable demand for a residential community, as well as three more scenarios using the variable demand in Texas as a base. Scenario 4 minimizes carbon emissions, meaning that the values for water consumption and costs are considered 0. Scenario 5 minimizes costs, meaning that the values for water consumption and carbon emissions are considered 0. Finally, scenario 6 minimizes for water consumption, meaning that the values for carbon emissions and costs are considered 0.

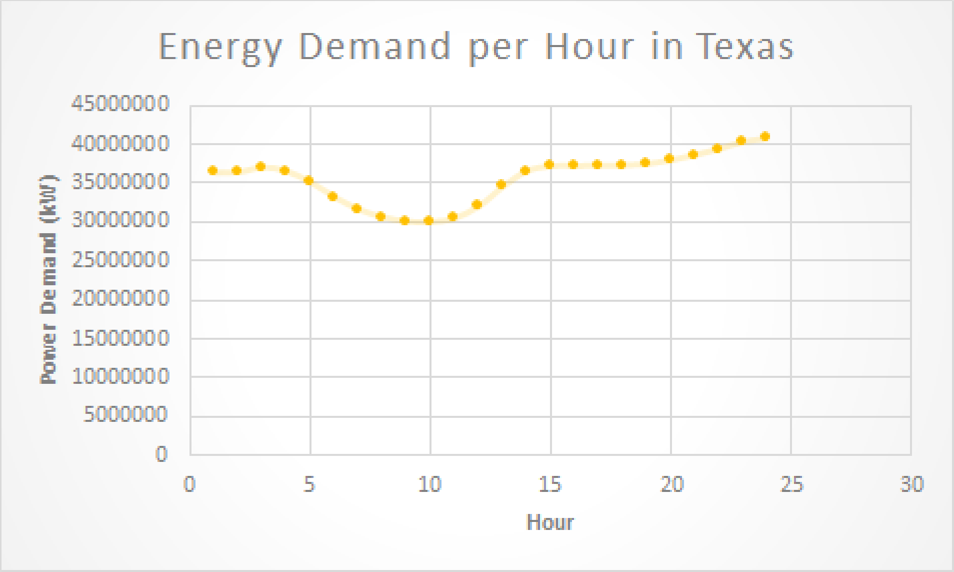


Figure 18, Hourly Energy Demand in Texas for one Day (Scenario 1: Variable-Demand)

For Scenario 1: The Energy Demand for the state of Texas was taken from the ERCOT database found on the Energy Information Administration website and it was analyzed for 1 day: March 15 2021. The values for each hour can be seen in Figure 18 above. The website for the database is the following:

(https://www.eia.gov/opendata/qb.php?category=3389948&sdid=EBA.TEX-ALL.D.H)

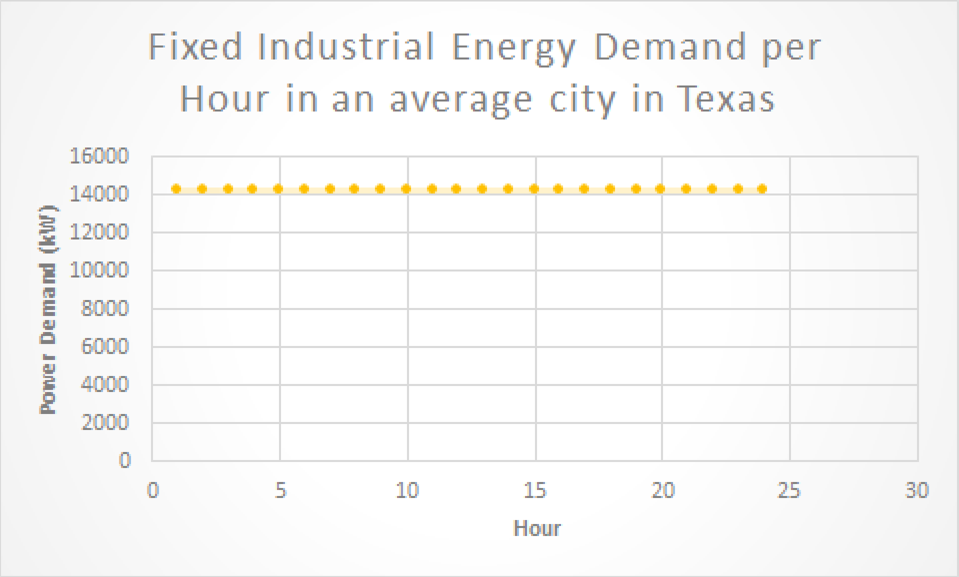


Figure 19, Industrial energy demand per hour in an average city in Texas (Scenario 2: Fixed-Demand)

For Scenario 2 (figure 19): The Energy Demand for the state of Texas was based on the ERCOT database used in the 1srt scenario. The value chosen for the fixed demand is 14,248.15 kilowatts and it was obtained by multiplying the highest demand in scenario 1 time 0.35 which is the percentage of energy consumed by the industry sector in the U.S. which that same value is going to be assumed for the state of Texas. The product of that value is then divided by 1,000 to simulate the consumption in 1 average city in Texas, instead of the whole state like in scenario 1.

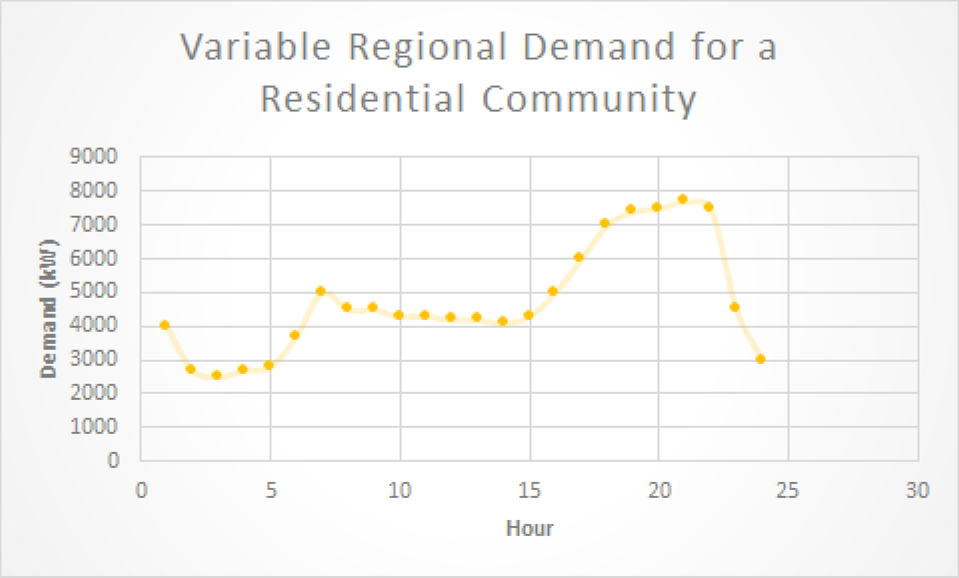


Figure 20, Hourly Energy Demand (Scenario 3: Variable Regional Demand for a Residential Community)

For scenario 3 (figure 20), the demand is analyzed from a regional residential community in a new urban area situated in North China (Xiong'an) given the lack of data for the state of Texas (Zhihao Chena, et al.). Since the analysis is just for a residential area and not a whole state, the demand values in kilowatts are much lower than the first 2 scenarios.

4.2. Component II: Process Data

The following data is taken into account for Solar, Wind, Nuclear, Natural Gas, and Biomass energy sources: Type of energy production technology, plant capacity, carbon dioxide emissions one-time, carbon dioxide emissions on-going, amount of water withdrawn, electric efficiency, ramp rates, and levelized cost of energy.

The following data is taken into account for Hydrogen, Pumped Hydroelectric, Compressed Air Energy Storage, and Lithium-Ion Batteries storage systems: energy storage capacity, carbon dioxide emissions, water consumption, storage efficiency, ramp rates, and levelized cost of energy storage.

4.2.1 Solar Energy

According to NREL, there are two possible types of Solar Ground-mounted systems configurations that can be considered as possibilities for this analysis: fixed-tilt and one-axis tracker. For the baseline model, a 100-MW, 1,000-Vdc utility-scale system using 72-cell, multi-crystalline 19.1%-efficient modules from a Tier 1 supplier and three-phase central inverters is considered for this research. *(U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018, NREL).*

PV systems produce CO2 during the upstream and downstream process, which are process non-combustion related, such as the construction of the power plant. This type of emission is Carbon Dioxide one-time, and its value for the PV system is 1,667.8 kilograms per kilowatt. For the on-going carbon dioxide emissions of solar PV systems, the value is 0, making them a clean source of energy production. Another value that is 0 is the amount of water consumed during the energy production using solar panels fixed tilt configuration (Ashlynn S. Stillwell et al., 2011). The electric efficiency of the PV system is known to be 23% for this case (Aggarwal, V. (2021, April 21)). Since solar panels depend on the radiation coming from the sun to produce electricity, it is very difficult to always ensure a sunny day 24/7, so given that the sun sets for 8 hours a day, clouds pass by blocking the sun, tropical storms happen, among other unpredictable variables, the ramp rate ranges from 0% to 100%.

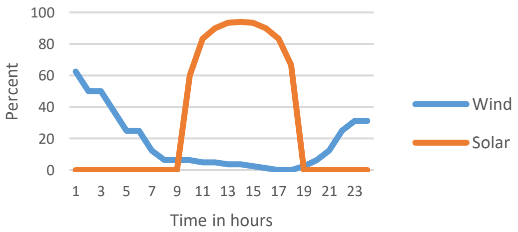


Figure 21, Solar vs Wind Capacity Factors during 1 day (adapted from 41)

Let’s take for example data from Amarillo, Texas given its Solar potential, in the figure above it can be seen that solar energy is present during the day from the morning to evening, while it is absent at night time, which makes sense. This means that it has greater capacity factors during the day. The Capacity factor values of Solar energy can be seen in table 3 (Pistikopolous et al., 2020.).

Lastly, the Levelized Cost of Energy for fixed-tilt solar panels is $0.08363 dollars per kilowatt-hour (Lazard, v.12.0, 2018).

4.2.2 On-Shore Wind Energy

The turbine used for this calculation is the one used by NREL in its report -Wind Turbine Design Cost and Scaling Model Report 2006- a Three-Bladed, Upwind, Pitch-controlled, Variable-Speed wind turbine. The turbine Farm used is of 50MW in capability. *(Wind Turbine Design Cost and Scaling Model Report, NREL, 2006).*

Wind energy produces carbon dioxide one-time during the upstream and downstream process just like the case with solar energy, which are process non-combustion related, such as the construction of the power plant. The value for the Wind system is 641.4 kilograms per kilowatt. For the on-going carbon dioxide emissions, in contrast with that value of solar PV systems, this value is 0.00141 kilograms per kilowatt-hour. A value that is 0 is the amount of water consumed during the energy production process (Ashlynn S. Stillwell et al., 2011). The electric efficiency for the 3 Bladed turbine ranges from 30-45% (Renewable Energy Supplier). Just like the case with solar panels, wind energy is unpredictable. Wind energy depends on wind speed, yet not every day or at every height, there is enough speed to move the giant blades constantly during the day everyday to produce energy. For this reason the ramp rates also range from 0% to 100%.

In the case of wind energy, data from Amarillo, Texas shows that it has its peaks during nighttime and early morning, as can be seen in the figure 21. Wind energy has greater capacity factors at night. Such values of wind energy can be seen in table 3 (Pistikopolous et al., 2020.).

Lastly, the Levelized Cost of Energy is \$0.0750 dollars per kilowatt-hour (Lazard, v.12.0, 2018).

4.2.3 Nuclear Energy

There are 2 main types of Nuclear Power Plants (NPP) operating in the U.S.: PWR (Pressurized Water Reactor Power Plant) and BWR (Boiler Water Reactor Power Plant). For this analysis, a Nuclear Power Plant with Pressurized Water Reactor is being considered, with a capacity of 1000MW (Nuclear Power Plant life extension cost development methodology, EPA, 2018).

When comparing Nuclear energy with Solar and Wind, Nuclear produces less carbon dioxide across the Upstream and downstream process combined. The value for these two processes is 525 kilograms per kilowatt. For the on-going carbon dioxide emissions, in contrast with that value of solar PV and wind turbine systems, this value is 0.0106 kilograms per kilowatt-hour, way more than the values of solar and wind combined. For the case of water consumed, Nuclear power uses a great amount of water for its steam processes and cooling technologies, with a total of 1.5 liters per kilowatt-hour (Ashlynn S. Stillwell et al., 2011). The electric efficiency of a Pressurized Water Reactor (PWR) Nuclear Power Plant (NPP) is 37% (World Nuclear Association).

In contrast with that of renewable energies, Nuclear power plants are a very steady source of energy. Most current nuclear plant technologies are designed to perform power maneuvers in the range of 50−100% RTP (Rated Thermal Power), and can ramp power as fast as 5% RTP/min.

Normal operations as base load is always 100% RTP, yet if the need arrives, 5% RTP/min evolutions can happen. (International Atomic Energy Agency Nuclear Energy Series, IAEA 2018).

From historical and operating data, the capabilities included in the design of some Nuclear Power Plants (NPP) are:

- A power (load) cycle between 100% and 20% RTP, sometimes daily:
- A power (load) cycle over a smaller range more frequently, or over a larger range less frequently.
- When power cycling, a ramp rate of 2% RTP per minute.
- Power adjustments of up to ±5% RTP, in the AGC mode.
- Power adjustments of up to ±2% RTP within 30 seconds in the AFC mode.
- No flexibility at certain times, such as during fuel conditioning or at the end of a cycle (in PWRs).
- A minimum power for extended low power operations of 20–40% RTP.

For the analysis in this report, a ramp rate value of 2% is going to be used.

(International Atomic Energy Agency Nuclear Energy Series, IAEA 2018)

Lastly, according to the University of Texas at Austin LCOE calculation, a Nuclear Power plant in Texas has a Levelized Cost of Energy of $0.14624 dollars per kilowatt-hour (LCOE SBS. Energy Institute | The University of Texas at Austin).

4.2.4 Natural Gas

For Natural Gas, there are two possible processes: Combined Cycle (CC) or Combustion Turbine (CT). Natural Gas Combined Cycle (NGCC) is going to be used in this report. According to the EIA, most of the installed capacity of natural gas-fired combined-cycle units comes from power blocks that have capacities of 600 MW to 700 MW. In 2017, two-thirds of the power blocks installed that year were 600 MW or higher. So a value of 600MW of plant capacity is utilized in this report (Power Blocks in Natural Gas, EIA 2019).

Natural Gas Combined Cycle produces less carbon dioxide across the Upstream and downstream process combined than Nuclear, Solar, and Wind energy. The value for these two processes combined is 166.39 kilograms per kilowatt. For the on-going carbon dioxide emissions, it produced way more than any other form of energy recently analyzed, given that the Combined cycle relies on combustion processes where burning of some form of matter is involved. The on-going and CO2 emissions related to combustion processes of the NGCC is 0.4159 kilograms per kilowatt-hour. NGCC also consumes water in the open-loop cooling process, with a total value of 0.4 liters per kilowatt-hour (Ashlynn S. Stillwell et al., 2011). The plant efficiency is that of 62.22% (Pistikopoulos et al., 2019). For ramping rate, a value of 8% is considered for this analysis (Miguel Angel Gonzalez-Salazar et al., 2018).

Lastly, according to the University of Texas at Austin LCOE calculation, a Natural Gas Combined Cycle Power plant in Texas has a Levelized Cost of Energy of $0.09812 dollars per kilowatt-hour (LCOE SBS. Energy Institute | The University of Texas at Austin).

4.2.5 Biomass

There are two ways to produce Biomass: direct-fired or direct combustion, and through Anaerobic digestion. Since direct combustion produces high amounts of carbon dioxide, among other harmful gases, Anaerobic digestion is going to be used for this report.

Biomass using Anaerobic digestion does not produce carbon dioxide one-time, yet it does produce carbon dioxide throughout the lifetime of the process. The correct term for Biomass using Anaerobic digestion is Biogas. Biogas produces 0.30093 kilograms of carbon dioxide per kilowatt-hour (Valerio Paolini et al., 2018), among other dangerous chemicals such as methane, but for this report methane emissions are going to be ignored, yet they should be considered in future analysis. According to the NCBI, this crop based energy production process consumes an amount of 2.38 liters per kilowatt (Li, J., Xiong, F., & Chen, Z. 2021). According to the IEA Bioenergy, the electric efficiency of a biogas plant using energy crop digestion is 37% (Bioenergy from Energy Crop Digestion) while the ramp rate has a value of 8% (Miguel Angel Gonzalez-Salazar et al., 2018). Lastly, the process has a Levelized Cost of Energy of $0.08 dollars per kilowatt-hour and the plant has a capacity of 500 kilowatt (Bioenergy from Energy Crop Digestion).

4.2.6 Hydrogen Production, Storage & Conversion

Hydrogen is an energy carrier that can be used to store massive amounts of energy for grid resilience and security and it is a critical feedstock for most of the chemicals industry. But the demand for Hydrogen in different sectors of the industry has been growing more and more with each year. The U.S. Department of Energy developed the H2@Scale Initiative to increase the production of Hydrogen using all resources in the nation, including nuclear power (Energy.gov. 2020). Hydrogen production will be done through HTE, SMR, and BG processes while being stored using Hydrogen Fuel Cells.

4.2.6.1 Hydrogen Production Using Nuclear Power

Nuclear plants today can produce high quality steam at lower costs than natural gas boilers. Yet, it is even better when high steam is electrolyzed and split into pure hydrogen and oxygen. One 1,000 MW nuclear reactor can produce 200,000 tons of hydrogen per year. With ten nuclear reactors with the same capacity, they can produce 1/5th of the current hydrogen used in the United States. Nuclear energy can provide energy to produce hydrogen, fuels, fertilizers, steel, plastics, and more (Energy.gov. 2020).

There are different methods to produce hydrogen from nuclear energy, one of them is High Temperature Electrolysis (HTE). HTE has an operating temperature range of over 600 degrees Celsius and uses electricity and heat to produce hydrogen. The electrical efficiency of electrolysis increases by up to 25% at higher operating temperatures. The method focused on this analysis is that of Solid Oxide Electrolysis Technologies (SOEC), even though this is not a mature technology, the future of SOEC can lead to cost-effective hydrogen production using HTE (The Technical and economic potential of the H2@scale concept within the United States, NREL, 2020). In the case of producing 1 kilogram of hydrogen through HTE, an energy input amount of 66.667 kilowatts-hour per kilogram is required, with a production efficiency of 50.20% (Resource Assessment for Hydrogen Production, NREL, 2020). A current High Temperature Electrolysis plant has a hydrogen production capacity of 734,000 kilograms of hydrogen per day with a levelized cost of $2.93 dollars per kilogram of hydrogen produced (T. Ramsden et al., 2009). The water required to produce 1 kilogram of hydrogen using electricity from nuclear power is 0.1365 liters (Andi Mehmeti et al., 2018).

4.2.6.2 Hydrogen Production Using Natural Gas

Natural Gas can produce Hydrogen by using Steam Methane Reforming. According to the Energy Government, Steam Methane Reforming is where most hydrogen produced today in the United States is made. It is a mature production process in which high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic—that is, heat must be supplied to the process for the reaction to proceed (Natural Gas Reforming. Energy.gov.).

In the case of producing 1 kilogram of hydrogen through SMR, an energy input amount of 45.833 kilowatts-hour per kilogram is required, with a production efficiency of 73% (Resource Assessment for Hydrogen Production, NREL, 2020). efficiency of 48.30% (Resource Assessment for Hydrogen Production, NREL, 2020). From NREL’s Technical Report “Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using H2A Production Model, V2” Steam Methane Reforming can be combined with carbon capture, but for this report, carbon capture is going to be ignored. The current plant capacity without Carbon Dioxide Sequestration can produce an approximate of 341,000 kilograms of hydrogen per day with a levelized cost of $1.32 dollars per kilogram of hydrogen (T. Ramsden et al., 2009). For each kilogram of hydrogen produced, an SMR plant generates 10 kilograms of Carbon Dioxide (N. Muradov). The water required to produce 1 kilogram of hydrogen using natural gas as feedstock is 0.328 liters (Andi Mehmeti et al., 2018).

4.2.6.3 Hydrogen Production Using Biomass

The way to convert Biomass to Hydrogen is through a process called Biomass Gasification (BG). According to the Energy Government; this conversion pathway is a mature technology that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products, without combustion. Because growing biomass removes carbon dioxide from the atmosphere, the net carbon emissions of this method can be low, especially if coupled with carbon capture, utilization, and storage in the long term. Gasification plants for biofuels are being built and operated, and can provide best practices and lessons learned for hydrogen production (Biomass Gasification. Energy.gov.).

In the case of producing 1 kilogram of hydrogen through BG, an energy input amount of 67.22 kilowatts-hour per kilogram is required, with a production efficiency of 48.30% (Resource

Assessment for Hydrogen Production, NREL, 2020). From NREL's Technical Report "Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using H2A Production Model, V2" a biomass gasification plant with a capacity of producing 140,000 kilograms of hydrogen per day is used, which is the plant analyzed in this report. This same plant has a levelized cost of $1.61 dollars per kilogram of hydrogen produced. The energy input for biomass gasification comes from feedstock which can include residues, solid waste, food waste, paper, or plastic (T. Ramsden et al., 2009). The water required to produce 1 kilogram of hydrogen using corn stover as feedstock is 4.545 liters (Andi Mehmeti et al., 2018). Given that this process converts biomass into hydrogen without the need of combustion, the emissions are going to be assumed to be 0 (Hydrogen Production: Biomass Gasification. Energy Gov).

4.2.6.4 Hydrogen Storage: Cryogenic Liquid Storage

Electricity can be converted into hydrogen by the 3 processes described above: High-Temperature Electrolysis, Steam-Methane Reforming, and Biomass Gasification. That hydrogen can later be stored and then converted back into electricity to send to the grid. Hydrogen can be stored in a variety of ways and quantities.

The Energy Storage Association states that small amounts of hydrogen (up to a few MWh) can be stored in pressurized vessels, or solid metal hydrides or nanotubes can store hydrogen with a very high density. Very large amounts of hydrogen can be stored in constructed underground salt caverns of up to 500,000 cubic meters at 2,900 psi, which would mean about 100 GWh of stored electricity. Batteries are preferably used for small scale hydrogen storage, while Pumped Hydroelectric and Compressed Air for large scale (ESA, 2021).

Another method to store Hydrogen for transportation after it's made is the one that Air Liquide, a French multinational company which supplies industrial gases and services to various industries, follows. They store hydrogen in composite tanks or bottles by putting the hydrogen under a great amount of pressure, at 700 bar, to be able to store it in a 125-liter tank (ALE, 2017). Storing Hydrogen inside a Tank is one of many ways to preserve H2. To achieve this, once Hydrogen is produced it needs to follow three steps: compression, cooling, and expansion, so it can be transformed to liquid state and stored at Cryogenic temperatures. This type of H2 storage is known as (CLHS) Cryogenic Liquid Hydrogen Storage (Elizabeth Connely et al., 2019). According to the Department of Energy of the U.S. current facilities require an energy input of 10-20 kilowatt-hour per kilogram of Hydrogen stored. The storage capacity of an actual CLHS ranges from 6,000 kilograms per day to 200,000 kilograms per day. For this analysis a plant with storage capacity of 27,000 kilograms per day is going to be used. A 27,000 kilograms per day liquifier for Hydrogen Storage has a levelized cost of around $2.75 dollars per kilogram (Elizabeth Connely et al., 2019).

4.2.6.5 Hydrogen Fuel Cells for Electricity Conversion

Hydrogen Fuel cells are becoming popular due to their high efficiency for generating electricity, environmental reliability, and multi-usage. They can be used to store energy and when combined with an electrolyzer they can convert electricity to storable energy and then re-convert it to electricity when needed (W. Smith, 1999). Fuel cells systems can generate electricity at efficiencies up to 60%. They can also be stacked up on each other to increase the power produced for different applications. In the case of utility-scale, fuel cells can have a power capacity ranging from 1-200 MW (U.S. Department of Energy, Fuel Cell Technologies Office.)

For the case of this report, Molten Carbonate Fuel Cells are going to be used since they are good for utility-scale applications (MCFC, 2021). One module of MCFC has a capacity of 300 kilowatts, but if staked they can reach up to 3 Megawatts. The efficiency of these Fuel Cells is

47%, the Carbon emissions are 0.44521 kilograms per kilowatt-hour while the water consumption is an average of 204.4122 liters per hour (FuelCell Energy, Inc. 2010). The levelized cost for this technology for fixed electricity price is $0.103 dollars per kilowatt-hour Shabbir (Ahmed et al., 2016).

4.2.7 Pumped Storage Hydroelectric

Pumped Storage Hydroelectric (PSH) is a Mechanical Energy Storage system that stores energy by pumping water from a lower to a higher reservoir and then releasing it back through the connection, passing through a turbine(s), which generates electricity. This technology is typically used for grid-scale storage.

PSH includes waterways, reservoirs, pumps, and electrical generators. It has a typical power range up to 3,600 MW and typical energy range up to 40 GWh. PSH is very efficient in ensuring renewable energy supply is smoothed out over periods of peak energy demand. Solar and wind energy require availability of certain climatic conditions to ensure uninterrupted supply, which is not always present (ESMAP 2015). It can store the electricity generated by renewable resources and supply it during peak load demand (Storage cost and performance characterization report, U.S. Department of Energy, 2019). For this report, a PSH plant with capacity of 3,000 MW was chosen.

According to the Energy Magazine, the efficiency of the storage system ranges from 70-85% (energy mag. 2014 & Fact Sheet: Energy Storage 2019). The ramp rate is that of 0.67% (Storage cost and performance characterization report, U.S. Department of Energy, 2019), while the levelized cost of storage ranges from $0.152 to $0.198 dollars per kilowatt-hour (Lazard LCOS v2.0, 2016). Developing the reservoirs result in considerable greenhouse gas emissions due to the upstream part of the process, for example clearing the land. The amount of emissions depends on the reservoir size, previous vegetation, and climate. The one-time CO2 emissions part of the upstream process (construction) is 35.7 kilograms of CO2 per kilowatt of hydrogen storage capacity while the continued CO2 emissions, on-going, is equivalent to 0.0018 kilograms of CO2 per kilowatt-hour of hydrogen storage capacity (Paul Denholm et al., 2004). The variable on-going energy requirement for a PSH plant per unit of installed storage capacity is equal to 0.00717 kilowatts-hour (Paul Denholm et al., 2004). Since water is required to produce energy, in the case of a plant with a capacity of 3,000 MW, 1.16883 liters per hour are needed to produce 1 kilowatt from stored energy. In the United States, the Bath County Pumped Storage Station in Virginia is a pumped storage hydroelectric power plant that has the same capacity as the one used in this report, so it can be used to support this data. This plant has a hydraulic head (h) of 385 meters (Pumped Storage in Bath County), so using a quick power (P) formula $P = 8Qh$ to solve for the flow rate (Q) in liters per hour, where 8 is a factor that accounts for hydraulic and electromechanical losses, the final result is the one just discussed (Quora, 2017).

4.2.8 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) is a Mechanical Energy Storage System based on using electricity to compress air and store it in underground caverns. The air is released when needed and passed through a turbine to generate electricity. It includes caverns, compressors, and generators. It has a typical power range up to 500 MW and a typical energy range from 1 GWh to 20 GWh. CAES consists of filling a cavern with compressed air during the hours when energy prices are low and then releasing the air at peak hours, and delivering it to combustion turbines, which use the natural gas for power generation (Hydrodynamics 2018). It has a typical power range up to 500 MW and energy range from 1 GWh to 20 GWh (Storage cost and performance characterization report, U.S. Department of Energy, 2019). For this report, a CAES plant with capacity of 1,000 MW was chosen.

According to the Energy Magazine, the efficiency of the storage system ranges from 40-70% (energy mag. 2014 & Fact Sheet: Energy Storage 2019). The ramp rate is that of 1.167% (Storage cost and performance characterization report, U.S. Department of Energy, 2019), while the levelized cost of storage ranges from $0.116 to $0.140 dollars per kilowatt-hour (Lazard LCOS v2.0, 2016). CAES systems require combustion to function, given that statement the system emits carbon dioxide in the following quantities: for one-time emissions (cavern development, site and buildings, plant, gas infrastructure, etc…) the value is 19 kilograms of CO2 per kilowatt of hydrogen storage capacity while the on-going emissions (Operation and Maintenance) are 0.576 kilograms of CO2 per kilowatt-hour of hydrogen storage capacity (Paul Denholm et al., 2004). The variable on-going energy requirement for a CAES plant to keep running is equal to 2.89417 kilowatts-hour per unit of installed storage capacity (Paul Denholm et al., 2004).

4.2.9 Lithium-Ion Batteries

Li-Ion batteries are a type of Electrochemical Energy Storage system that is based on charge and discharge reactions from a lithiated metal oxide cathode and a graphite anode. This battery technology is used in a wide variety of applications. The typical power range is from 1kW to 100MW, and the typical energy range is <200 MWh. A Li-Ion battery includes modules made of an assembly of cells, which are made of electrodes, electrolytes, and separators (Storage cost and performance characterization report, U.S. Department of Energy, 2019). For this report, a Li-Ion battery storage plant with capacity of 100 MW was chosen.

According to the Energy Magazine, the efficiency of the storage system ranges from 85-95% (energy mag. 2014 & Fact Sheet: Energy Storage 2019). The ramp rate of the batteries is going to be considered as 1, while the levelized cost of storage ranges from \$0.267 to \$0.561 dollars per kilowatt-hour (Lazard LCOS v2.0, 2016). Batteries in essence produce Carbon Dioxide in their value chain which refers to the processes in the start of the supply chain: mining and material extraction, conversion and refining of materials, and production of battery chemicals, cells and packs. This results in a total of emissions of 73 kilograms of CO2 per kilowatt-hour (Hans Eric Melin, 2019). The on-going value of emissions for batteries while they operate is 0.7 kilograms of CO2 per kilowatt (Quora, 2017).

4.3. Component III: MILP Model

4.3.1 Tables:

Table 1: Energy Sources CO2 emissions and Water consumption.

	Solar Energy	*On-Shore Wind Energy*	*Nuclear Energy*	*Natural Gas Combined Cycle*	*Biomass – Energy Crop Digestion*
CO2 (kg/kW) one-time	1667.8	641.4	525	166.39	0
CO2 (kg/kWh) on-going	0	0.00141	0.0106	0.4159	0.30096
Water (Lts/kWh)	0	0	1.5	0.4	2.38

Table 2: Energy Production Technologies

	Capacity (KW)	*Electricity efficiency*	*Ramp Rate*	*LCOE (\$/kWh)*

Wind turbine - 3 bladed variable speed wind turbine	50,000	30-45%	Unlimited	0.07505
Solar panel - Fixed tilt PV system	100,000	23%	Unlimited	0.08363
Nuclear Power - PWR (pressurized Water Reactor)	1,000,000	37%	2%	0.14624
NG Combined Cycle	600,000	62.22%	8%	0.09812
Biomass – Anaerobic Digestion	500	37%	8%	0.08

Table 3: Capacity Factors of Energy sources

Hour	*Wind (%)*	*Solar (%)*	*Nuclear (%)*	*Natural Gas (%)*	*Biomass (%)*
1	62.5	0	100	100	100
2	50	0			
3	50	0			
4	37.5	0			
5	25	0			
6	25	0			
7	12.5	0			
8	6.25	0			
9	6.25	0			
10	6.25	60			
11	5	83.33			
12	5	90			

13	3.75	93.33
14	3.75	94
15	2.5	93.33
16	1.25	90
17	0	83.33
18	0	66.667
19	2.5	0
20	6.25	0
21	12.5	0
22	25	0
23	31.25	0
24	31.25	0

Table 4: Energy Storage Technologies

	Storage Capacity (kW)	*CO2 (kg/kW) one-time*	*CO2 (kg/kWh) on-going*	*Ramp Rate (%)*	*Conversion Factor (kW)*	*Round Trip Efficiency*	*LCOS ($/kWh)*
PSH	3,000,000	35.7	0.0018	0.67	0.00717	70 – 85%	$0.152 to $0.198
CAES	1,000,000	19	0.576	1.167	2.89417	40 – 70%	$0.116 to $0.140
Batteries Li-Ion	100,000	73	0.7	100	0	85 – 95%	$0.267 to $0.561

Cryogenic Liquid Hydrogen Storage	27,000	0	0	100	20	40%	$2.75

Table 5: Hydrogen to Electricity Conversion Technology

	Capacity (KW)	*Efficiency*	*Conversion Factor (kW/kg)*	*Carbon Dioxide Emissions (kg/kWh)*	*Water Consumption (Lts/h)*	*Levelized Cost ($/kWh)*
MCFC (Molten Carbonate Fuel Cell)	300,000	47%	33.33	0.444521	204.412	0.1030

Table 6: Hydrogen Conversion Technologies

Resource	*Pathway*	*Conversion Factor (kWh/kg)*	*Water (Lts/kWh)*	*CO2 (kg/kWh) on-going*	*Efficiency*	*Capacity (kg/h)*	*Levelized Cost ($/kg)*
Natural gas	Steam Methane Reforming	45.833	0.328	10	73%	14,208.33	1.32
Nuclear	HTE	66.667	0.1365	0	50.20%	30,583.33	2.93

Biomass	Biomass Gasification	67.22	4.545	0	48.30%	5,833.33	1.61

4.3.2 Sets, Parameters, and Variables:

4.3.2.1 Sets:

$t \in \{1...24\}$ Time Horizon in Hours

$p \in \{1,2,3,4,5,6,7,8,9\}$ Processes

1. Solar Fixed Tilt PV System
2. 3 Bladed Wind Turbine
3. Pressurized Water Reactor Nuclear Power Plant
4. Biomass Anaerobic Digestion
5. Natural Gas Combined Cycle
6. High Temperature Electrolysis
7. Steam Methane Reforming
8. Biomass Gasification
9. Molten Carbonate Hydrogen Fuel Cell

$r \in \{1,2,3,4\}$ Resources

1. Energy
2. Hydrogen
3. Carbon Dioxide on-going
4. Water

$s \in \{1, 2, 3, 4\}$ Energy Storage Units

1. PSH (Pumped Storage Hydroelectric)

2. CAES (Compressed Air Energy Storage)
3. Li-Ion Batteries
4. Cryogenic Liquid Hydrogen Storage

q ∈ Processes + Energy Storage Units

4.3.2.2 Parameters:

Symbol	**Definition**
η	Efficiency in %
CAP	Capacity: maximum and minimum power levels at what the plant operates
RR	Ramp rate: operating level of power plant generation at one point in time minus the operating level of the power plant at a second point in time
LC	Levelized costs ($/kWh)
CO2_1	CO2 one-time (kg/kW)
CO2_2	CO2 on-going (kg/kWh)
wtr	Water consumed (Lts/kW)
cfe	Conversion factor of processes and storage units
LB	Lower bound
UB	Upper bound
D	Final demand (kW)

4.3.2.3 Variables:

Symbol	**Definition**
Continuous	

ε^{in}	Electricity going in to the storage system
ε^{out}	Electricity going out of the storage system
α	Task nameplate: energy processes and storage units capacities.
β	Task operational: operational level/capacity of the energy processes and storage units at time t in hours.
γ	Resource Operational: indicates the amount of resources being consumed or produced at a certain hour during the day.

Binary

$Y\beta$	Binary Task Operational: decision variable that indicates if the task, storage unit, or process is operational at a certain hour during the day.
$Y\alpha$	Binary Task: decision variable showing if a task, storage unit, or process is purchased.

4.3.3 Constraints and Balancing Equations:

All equations are valid during the set time horizon, being 24 hours.

Storage Units Balancing Equation:

Represents the energy balances coming from the Storage Units at time t in hours.

(Eq.1)

$$\beta_{s,t} = \varepsilon_{s,t}^{in} - \varepsilon_{s,t}^{out} + \beta_{s,t-1} \ \forall\ s\ \in Storage\ Units, t\ \in\ Time\ Horizon$$

Tasks Balancing Equations:

Represents the energy balance required to meet an energy demand at a certain time (hour) by the energy sources.

(Eq.2)

$$\sum_{s \in Storage\ Units(r)} (\eta_{s,r} * \varepsilon_{s,t}^{out} - \varepsilon_{s,t}^{in}) + \sum_{p \in Processes(r)} (\eta_{p,r} * \beta_{p,t}) = \gamma_{r,t} + D_{r,t}$$

$$\forall\, r \in Resources, t \in Time\ Horizon$$

Capacity Constraints:

Represents the task nameplate being equal or lower than the capacity of storage units and processes, being $Y\alpha$ the task binary variable indicating if a task is purchased.

(Eq.3)

$$\alpha_q \leq CAP_q * Y\alpha\ \forall\, q \in Processes \cup Storage\ Units$$

Planning and Scheduling Equations:

The operational level of the processes and storage units needs to be lower than the task nameplate capacity.

(Eq.4)

$$\beta_{q,t} \leq \alpha_q\ \forall\, q \in Processes \cup Storage\ Units, t \in Time\ Horizon$$

Binary Indicator Constraint:

The operational process and storage units need to be equal or lower than the capacity capacity of energy/storage they can produce/store. The binary variable indicates if the task is operational at a certain hour.

(Eq.5)

$$\beta_{q,t} \leq CAP_q * Y\beta_{q,t}\ \forall\, q \in Processes \cup Storage\ Units, t \in Time\ Horizon$$

Ramping Constraints:

The operational level needs to be within the ramp rate of the task. It cannot be greater than or lower than the value of the upper (equation 6) and lower (equation 7) ramp rate bounds. The binary variable is there to indicate if a task is used.

(Eq.6)

$$\beta_{q,t} - \beta_{q,t-1} \leq RR_{q} * \alpha_q * Y\beta_{q,t-1}$$

$$\forall\, q \in Processes \cup Storage\ Units, t \in Time\ Horizon$$

(Eq.7)

$$\beta_{q,t-1} - \beta_{q,t} \leq RR_{q} * \alpha_{q} * Y\beta_{q,t}$$

$$\forall\, q \in Processes \cup Storage\ Units, t \in Time\ Horizon$$

Resource Bounds Equations:

The resources need to be within the upper (equation 8) and lower (equation 9) bound values. In this case the upper bound is a big number close to infinity while the lower bound is 0. The upper bound indicates that the value can be as high as it is needed to be while the lower bound keeps all the numbers positive, except for water, which is negative if it is being consumed.

(Eq.8)

$$\gamma_{r,t} \leq UB_{q}\ \forall\, q \in Resources, t \in Time\ Horizon$$

(Eq.9)

$$\gamma_{r,t} \geq LB_{q}\ \forall\, q \in Resources, t \in Time\ Horizon$$

4.3.4 Objective Functions

Minimization Function

The equation seeks to minimize the Levelized Costs, Water consumption and Carbon Dioxide emissions from the processes and storage units.

(Eq.10)

$$min\ z = \sum \quad (LC_{q} * \beta_{q,t}) + \sum \quad (cf_{q,r} * \beta_{q,t}) + \sum \quad (co2\_1_{q} * \alpha_{q}) = 0$$

$$\forall\ q \in Processes, t \in Time\ Horizon$$

5. RESULTS AND DISCUSSION

The optimization model was coded in Python and solved/optimized using Gurobi. The model has 624 quadratic constraints, 967 continuous variables, 422 integer variables, and 299 binary variables. The results of the Multi-Objective Linear Programing Energy model are shown below.

5.1. Scenario 1: Variable Demand

5.1.1. Hydrogen Results

Figure 22 shows the amount of hydrogen produced per hour, if any, by the available technologies: Steam Methane Reforming, Biomass Gasification, and High-Temperature Electrolysis. The result shows that HTE coming from Nuclear Energy is the only technology being used to produce hydrogen with values reaching up to 13.5 kilograms of hydrogen produced in 1 hour.

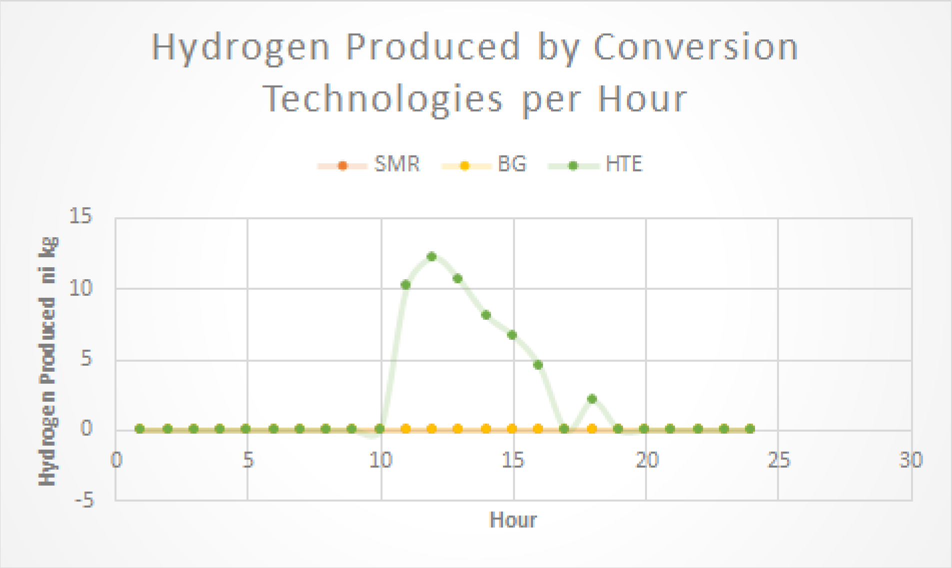


Figure 22, Hydrogen Produced by Conversion Technologies per Hour

As also shown in Figure 23, no electricity produced by Solar, Wind, Biomass, Natural Gas, and Nuclear was stored in any storage system (PSH, Li-Ion, CAES). Nuclear energy was the only energy source being used for a storage system, and it was to produce hydrogen and store it. The graph below shows how much electricity and hydrogen was incrementally stored during the day per hour, and since only hydrogen was stored, the cryogenic hydrogen system is the only one displaying any data.

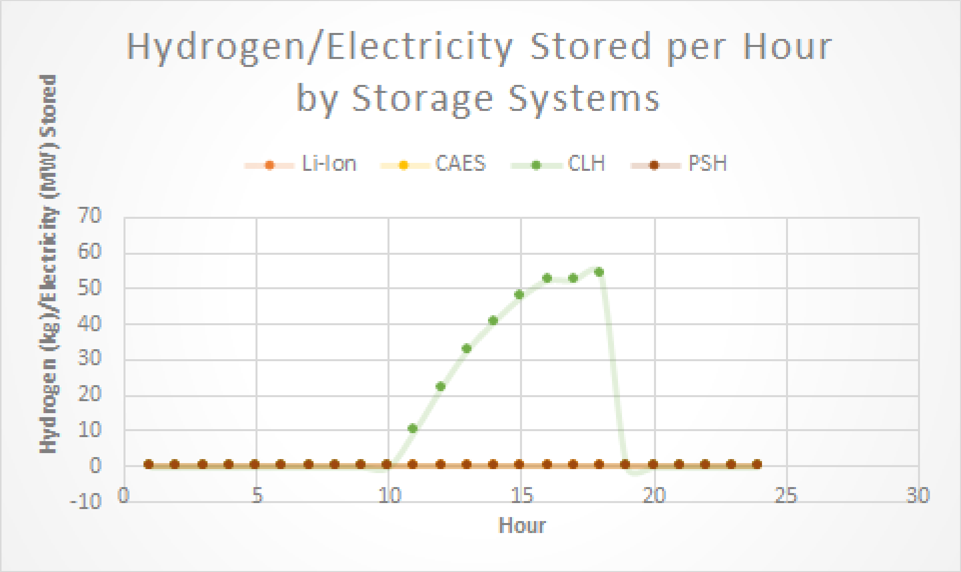


Figure 23, Hydrogen/Electricity Stored per Hour by Storage Systems

Given that Hydrogen is being produced, it needs to be stored, and the method analyzed in this report to store hydrogen was Cryogenic Liquid Hydrogen Storage (CLH). Figure 24 shows how much hydrogen was released from the storage tank at a certain time during the day, in this case all the hydrogen produced by the HTE process (54.3 kilograms) was released from the tank at hour 19 of the day to go to the next step; the fuel cell, to be converted into electricity. As also shown in Figure 24, given that no electricity produced from Solar, Wind, Biomass, Natural Gas, and Nuclear was stored in the storage systems (PSH, Li-Ion, CAES) no electricity came out from them.

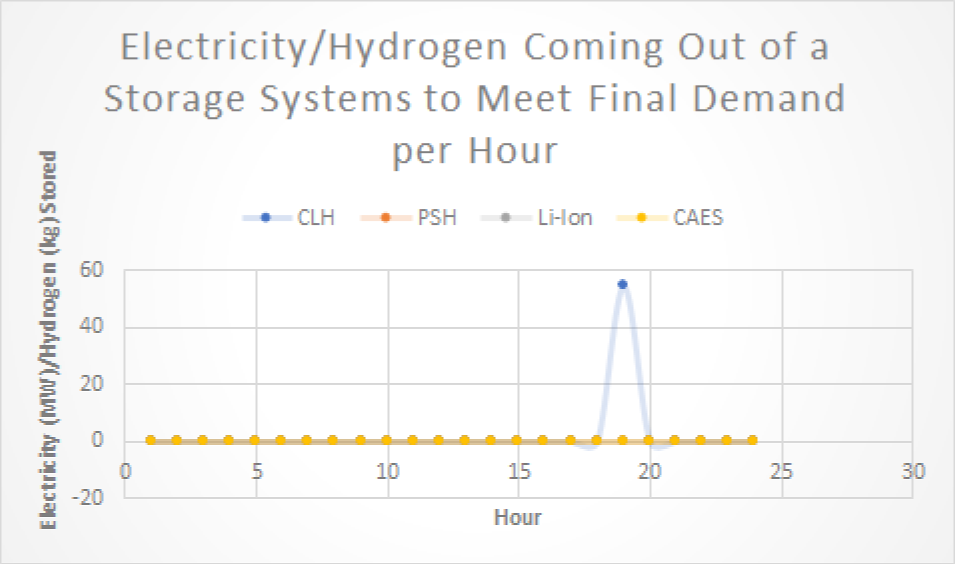


Figure 24, Electricity/Hydrogen Coming Out of a Storage System to Meet Final Demand per Hour

Figure 25 shows how much hydrogen stored was converted to electricity. In this case 54.3 kilograms of hydrogen was converted into electricity using Molten Carbonate Fuel Cells at hour 19 of the day.

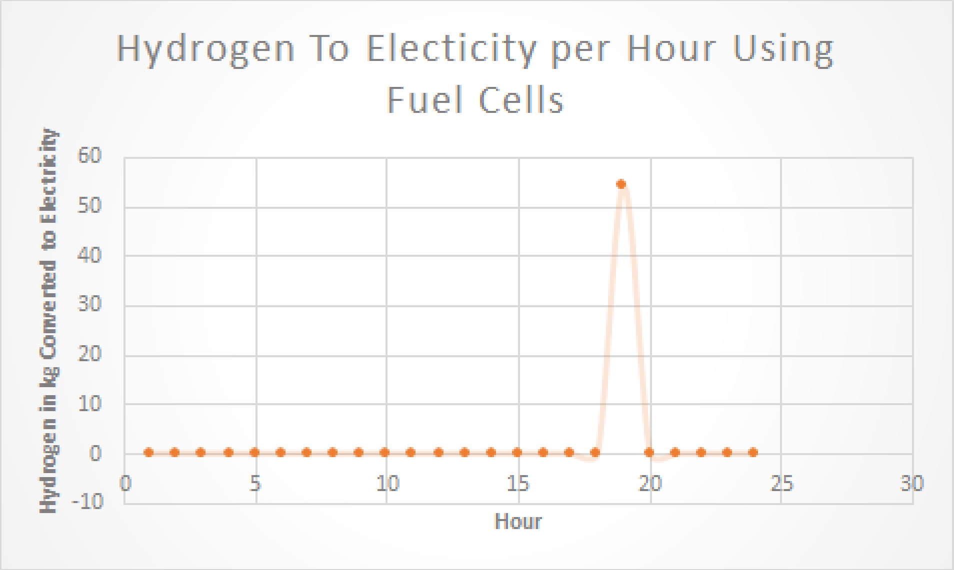


Figure 25, Hydrogen to Electricity per Hour Using Fuel Cells

5.1.2. Electricity Produced to Meet Final Demand

Figure 26 below shows the electricity produced per hour by each energy source analyzed: Solar, Wind, Nuclear, Natural Gas, and Biomass. By seeing the data in figure 26 only three of the five energy sources in the model produced electricity: Solar, Wind, and Nuclear. This means that the combination of these three sources is the most economic, the cleanest in terms of carbon dioxide emissions, and the least water consumption. As shown in the graph below, solar and wind power behave as expected. In the case of solar power, electricity starts being produced when the sun rises and stops at sunset, while wind power is the complete opposite given that at night wind-speed tends to be higher than during the day (at least for this scenario). In the case of Nuclear power, it produces energy when solar is falling and when wind is starting to rise, which in this case is from hours 17 to 21. Making the timing of Nuclear power perfect to tackle the intermittency of both solar and wind.

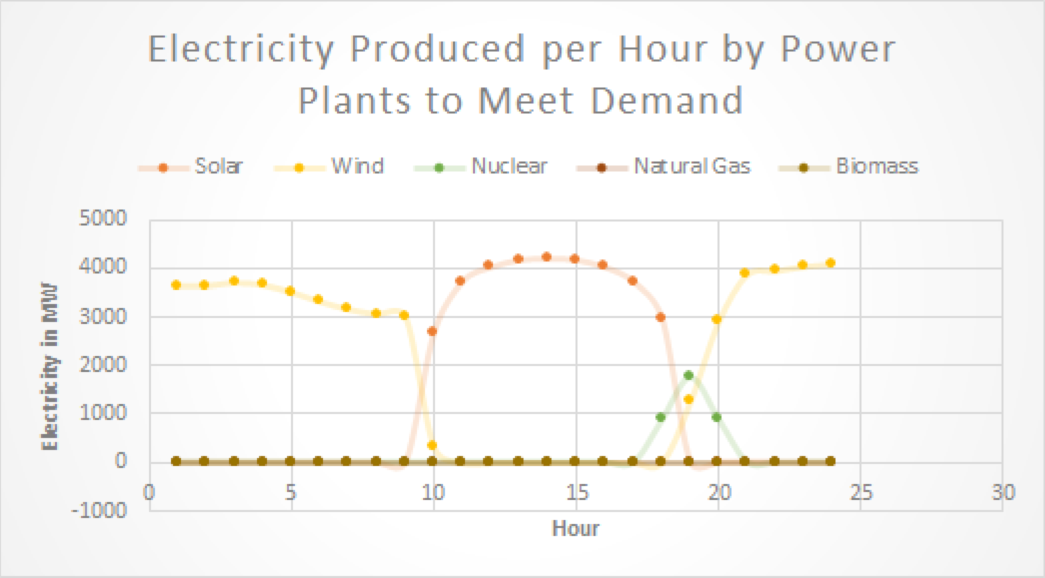


Figure 26, Electricity Produced per Hour by Power Plants to Meet Demand

5.1.3. Model Environmental Footprints

Figure 27 represents the total carbon emitted by the energy processes and storage units in the energy model per hour. As seen in the graph, from hour 16 to hour 21 there is a spike in carbon emissions, this is due to the Nuclear power and hydrogen fuel cells, given that solar and wind power emit little to none on-going CO2 emissions. By comparing this graph with that of figure 25 and figure 26, hour 19 is where the fuel cell and nuclear power respectively are most active.

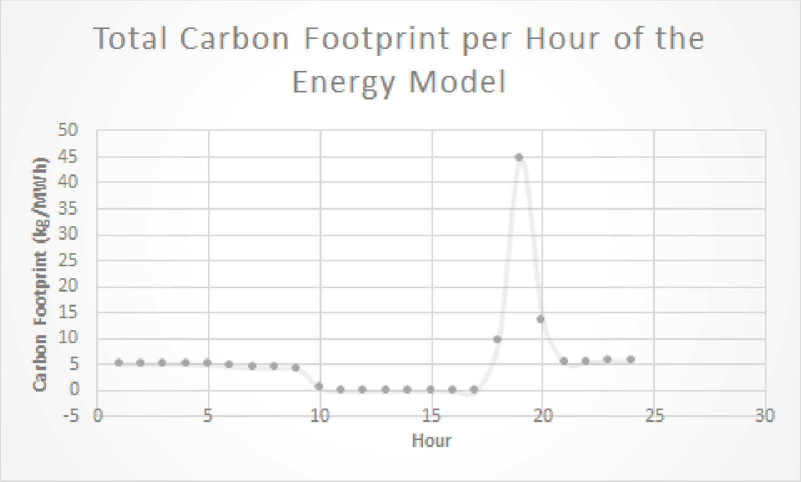


Figure 27, Total Carbon Footprint per Hour of the Energy Model

Figure 28 represents the total water consumed by the energy processes and storage units in the energy model per hour. The negative value means that water is withdrawn (taken from a water body) and then consumed, meaning not returned to its original source from where it was withdrawn. Water is being taken away from a river/lake/ocean/etc… hence the negative value.

As seen in the graph, just like in figure 26, from hours 16 to 21 there is a spike in water consumption due to the Nuclear power and hydrogen fuel cells that require water for their processes. Solar and wind power require no water to produce electricity.

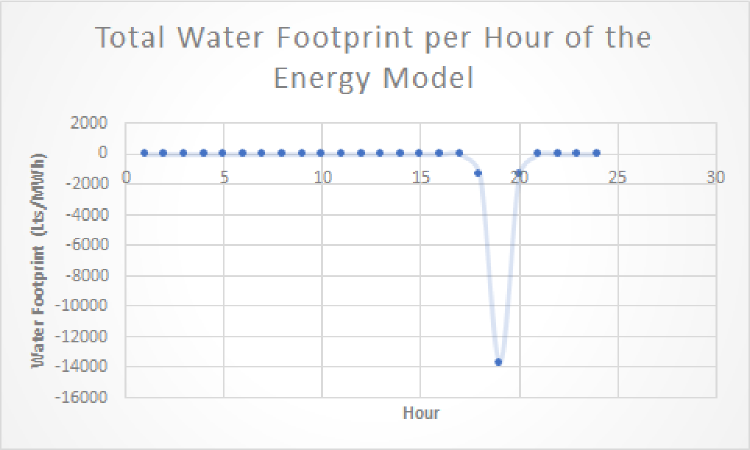


Figure 28, Total Water Footprint per Hour of the Energy Model

5.2. Scenario 2: Industrial Fixed Demand for an average city in Texas

Figure 29 below shows the electricity produced. In contrast with scenario 1, scenario 2 suggests to use only solar and wind energy, since the energy demand is much lower and just the industrial sector is considered to supply energy to 1 average city in Texas, in comparison to the first scenario where the three sectors and the whole state was involved. Given that solar and wind are the only producing energy, there is no hydrogen being produced, meaning that no hydrogen conversion technologies and storage are being used, as well as no hydrogen fuel cells. Being this the case, there is no CO2 being produced and no water being consumed.

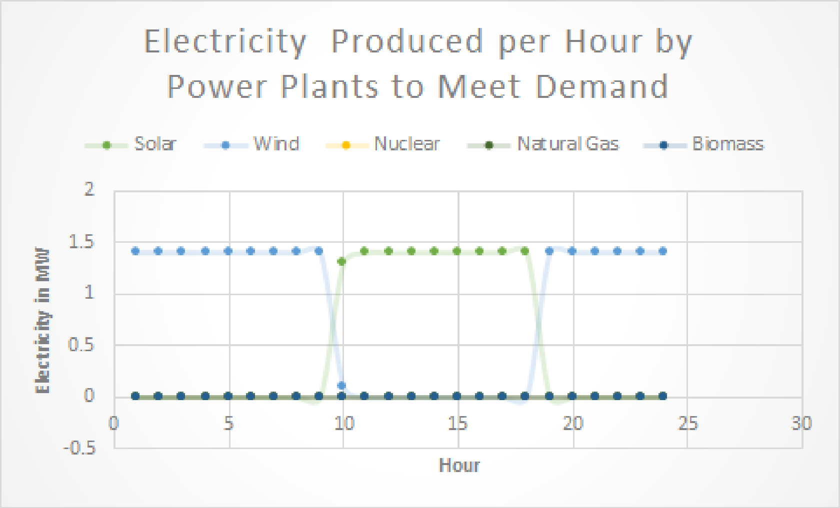


Figure 29, Electricity Produced per Hour by Power Plants to Meet Demand

5.3. Scenario 3: Variable Regional Demand for a Residential Community

Figure 30 below shows the electricity produced. This case is different from scenario 1 but similar to scenario 2, since the energy demand is much lower just like in scenario 1, solar and wind are the main electricity producers for the variable regional demand for a residential community scenario. Since solar and wind are the only producing energy, there is no hydrogen being produced, meaning that no hydrogen conversion technologies and storage are being used, as well as no hydrogen fuel cells. Being this the case, there is no CO2 being produced and no water being consumed.

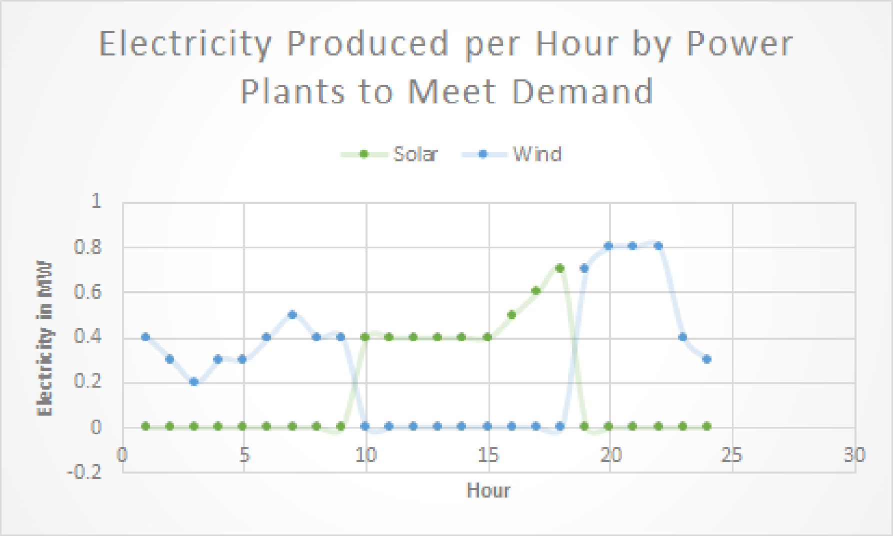


Figure 30, Electricity Produced per Hour by Power Plants to Meet Demand

5.4. Scenario 4: CO2 minimized, Water and Costs are not considered.

In the case where only CO2 is being minimized and the values of Water consumption and costs of each process is treated as 0, Hydrogen is being produced by High-Temperature Electrolysis using nuclear power plants. Figure 31 shows the amount of hydrogen in kilograms produced by HTE.

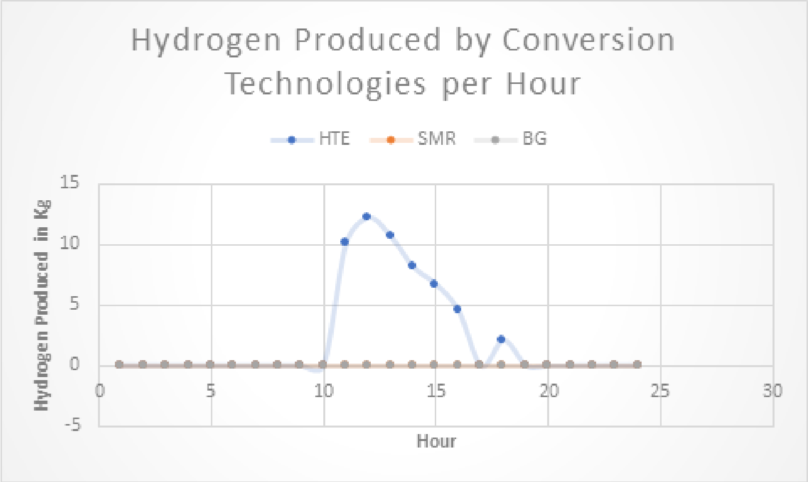


Figure 31, Hydrogen Produced by Conversion Technologies per Hour (just CO2)

As also shown in Figure 32, Nuclear energy was the only energy source being used for a storage system, and it was to produce hydrogen and store it. No electricity coming from the energy sources was stored in this case. Since hydrogen is being stored, the Cryogenic Liquid Hydrogen Storage system is the only storage system being active.

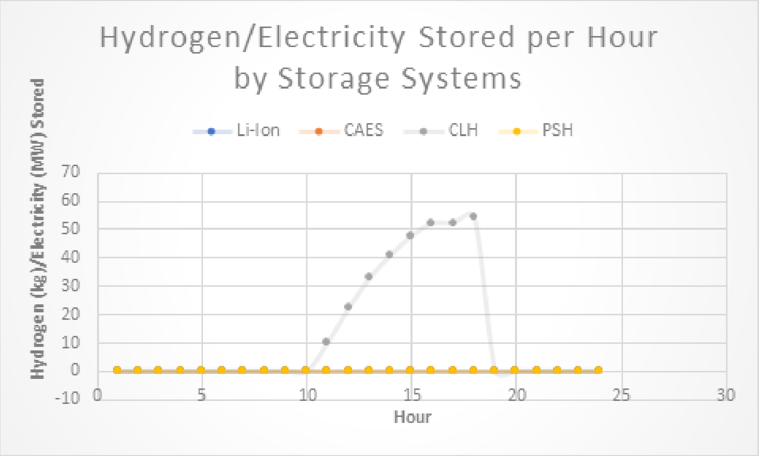


Figure 32, Hydrogen/Electricity Stored per Hour by Storage Systems (just CO2)

Same as in Scenario 1, only hydrogen is being produced, hence, only hydrogen is coming out from the energy storage systems. As seen in the figure 33 below, at hour 19 is where (54.3 kilograms) of hydrogen was released from the tank at hour 19 of the day to go to the next step; the fuel cell, to be converted into electricity.

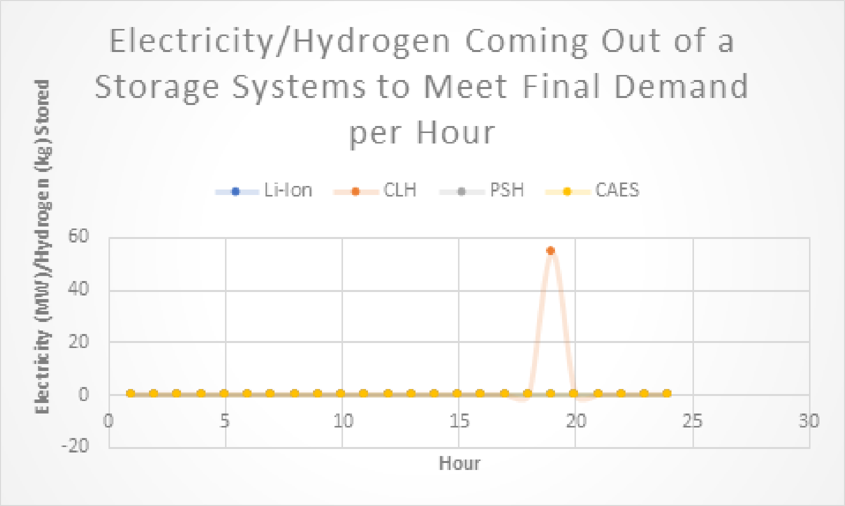


Figure 33, Electricity/Hydrogen Coming Out of a Storage System to Meet Final Demand per Hour (just CO2)

Figure 34 shows how much hydrogen stored was converted to electricity. Just like scenario 1; 54.3 kilograms of hydrogen was converted into electricity using Molten Carbonate Fuel Cells at hour 19 of the day.

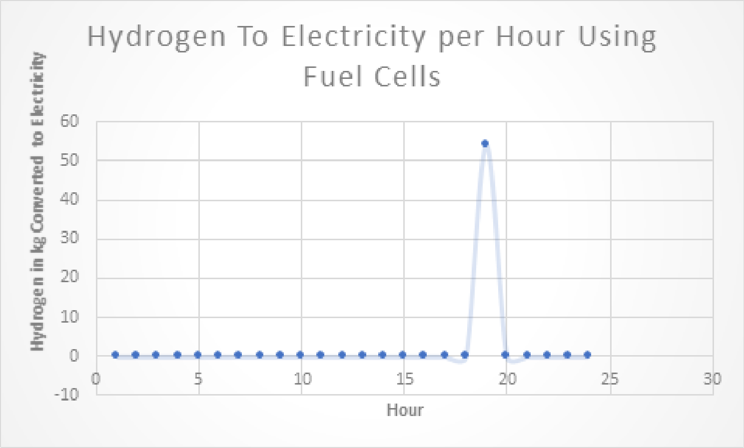


Figure 34, Hydrogen to Electricity per Hour Using Fuel Cells (just CO2)

Figure 35 below shows the electricity produced per hour by each energy source analyzed. By seeing the data in figure 35, just like in scenario 1, only three of the five energy sources in the model produced electricity: Solar, Wind, and Nuclear. This means that the combination of these three sources is the cleanest in terms of carbon dioxide emissions, without considering water consumption or costs minimization.

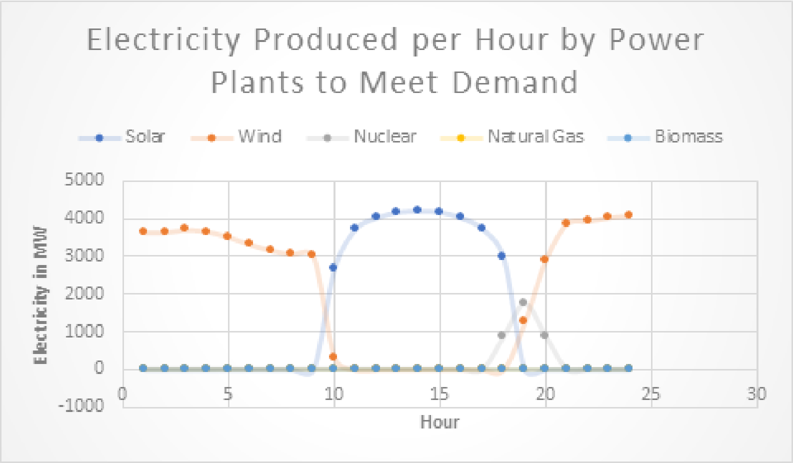


Figure 35, Electricity Produced per Hour by Power Plants to Meet Demand (just CO2)

Figure 36 represents the total carbon emitted by the energy processes and storage units in the energy model per hour. As seen in the graph, from hour 17 to hour 21 there is a spike in carbon emissions, just like in scenario 1 this is due to the nuclear power and hydrogen fuel cells, given that solar and wind power emit little to none on-going CO2 emissions.

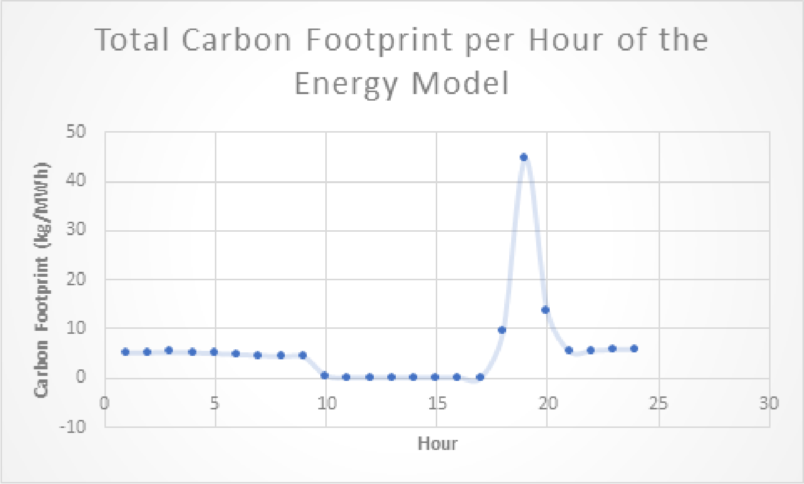


Figure 36, Total Carbon Footprint per Hour of the Energy Model (just CO2)

5.5. Scenario 5: Cost minimized, Water and CO2 are not considered.

Figure 37 below shows the electricity produced per hour by each energy source analyzed. By seeing the graph, it is different from the past scenarios, in which only nuclear energy is not being used to produce electricity. This scenario 5 only takes in consideration the minimization of costs. Given this, the combination of Solar, Wind, Biomass, and Natural Gas is the cheapest option. Nuclear power is expensive and that is why it is left out in this scenario. Natural gas in this case, is replacing the function of nuclear power at hours 17-21 to aid the intermittency of solar and wind.

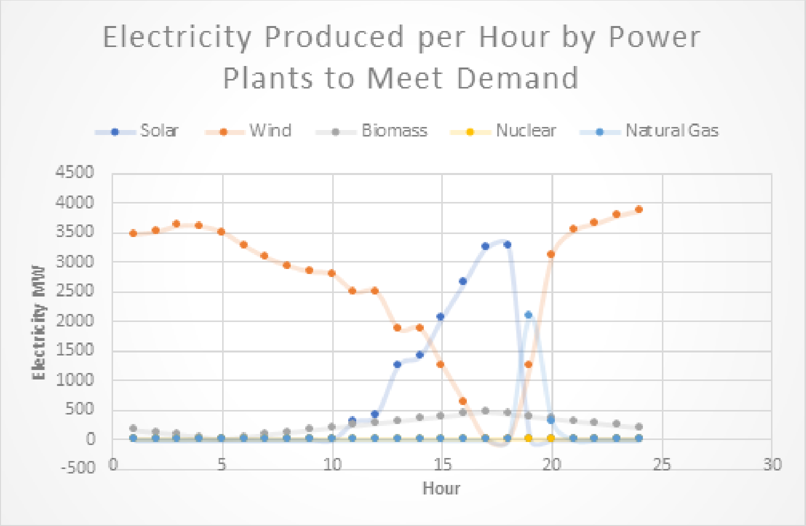


Figure 37, Electricity Produced per Hour by Power Plants to Meet Demand (just Cost)

5.6. Scenario 6: Water minimized, CO2 and Costs are not considered.

In the case where only Water is being minimized and the values of CO2 emissions and costs of each process is treated as 0, Hydrogen is being produced by Steam Methane Reforming using natural gas power plants. Figure 38 shows the amount of hydrogen in kilograms produced by SMR.

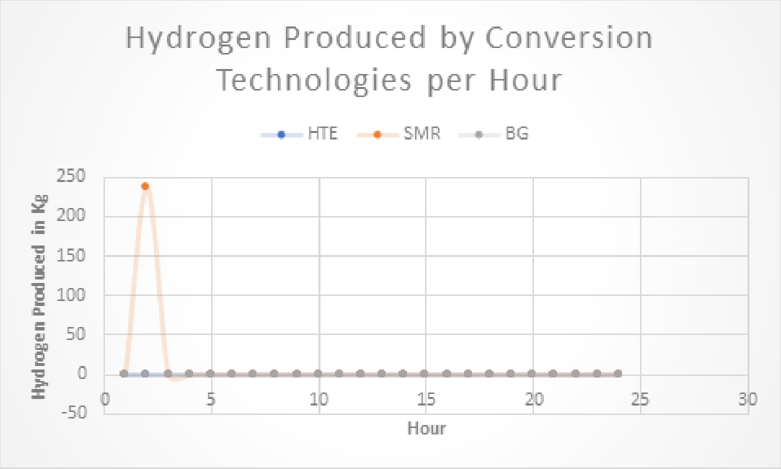


Figure 38, Hydrogen Produced by Conversion Technologies per Hour (just Water)

As also shown in Figure 39, Natural Gas was the only energy source being used to produce hydrogen and store it in Cryogenic Liquid Hydrogen Storage tanks. Since no electricity coming from the other energy sources was stored in this case, the values for Li-Ion, CAES and PSH are 0. Below it is shown that 236 kilograms of hydrogen is being stored throughout the day.

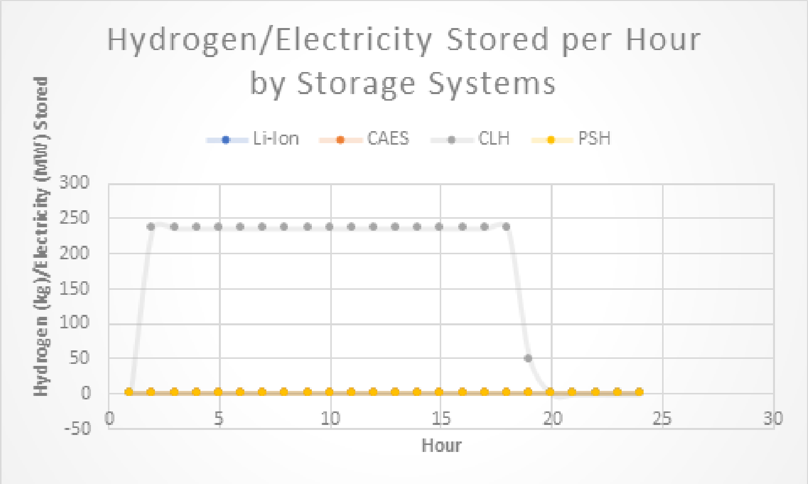


Figure 39, Hydrogen/Electricity Stored per Hour by Storage Systems (just Water)

Same as in Scenario 1, only hydrogen is being produced, hence, only hydrogen is coming out from the energy storage systems. As seen in the figure 40 below, at hour 19 is where 187 kilograms of hydrogen and at hour 20 where 50 kilograms of hydrogen were released from the tank to go to the fuel cell to be converted into electricity.

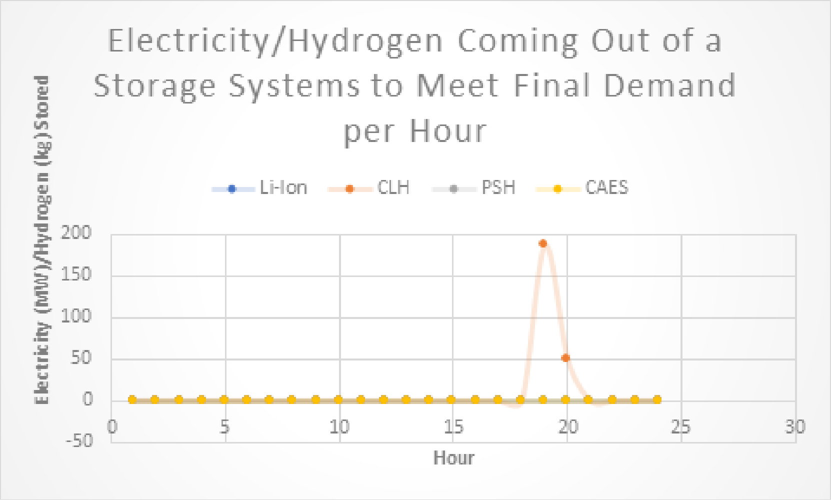


Figure 40, Electricity/Hydrogen Coming Out of a Storage System to Meet Final Demand per Hour (just Water)

Figure 41 shows how much hydrogen stored was converted to electricity. In total, around 236 kilograms of hydrogen were converted into electricity using Molten Carbonate Fuel Cells at hour 19 and 20 combined.

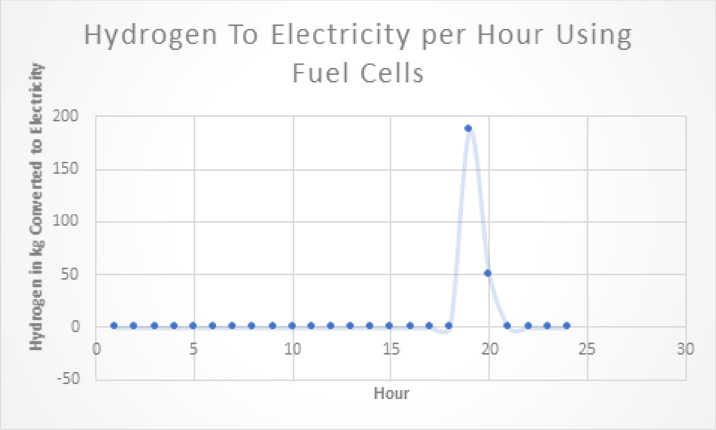


Figure 41, Hydrogen to Electricity per Hour Using Fuel Cells (just Water)

Figure 41 below shows the electricity produced per hour by each energy source analyzed. By trying to minimize water consumption, only solar and wind energy are considered, since biomass, natural gas, and nuclear power are water consuming processes. It can also be seen that at hour 2, there is an excess electricity production coming from wind energy.

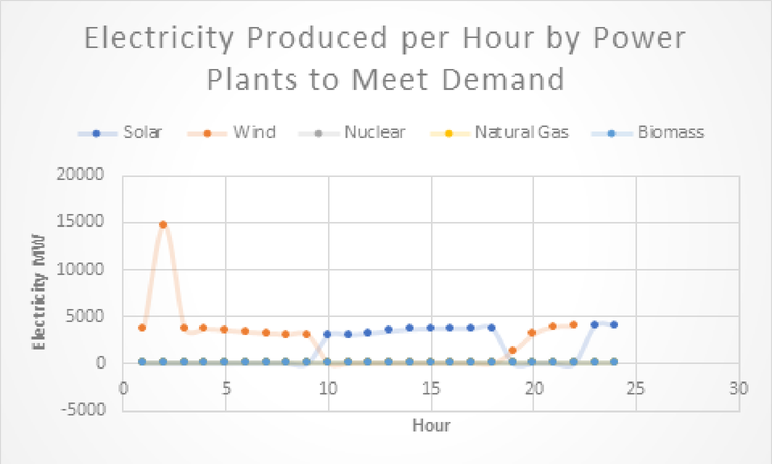


Figure 42, Electricity Produced per Hour by Power Plants to Meet Demand (just Water)

Figure 43 represents the total water consumed by the energy processes and storage units in the energy model per hour. As seen in the graph, from hour 17 to hour 21 there is a spike in water consumption, this is due to the storage system CLH and hydrogen fuel cell converting the hydrogen to electricity.

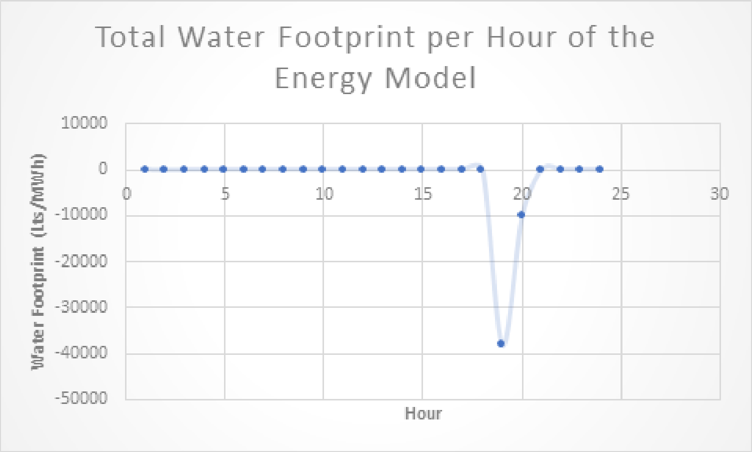


Figure 43, Total Water Footprint per Hour of the Energy Model (just Water)

5.7. Pareto Frontier Graph: Comparison between the 4 scenarios.

The Table below (Table 7) shows the total amount of Carbon Dioxide emissions, Water consumption, and Costs resulting from the four different scenarios with variable demand in Texas. Scenario 1 is the variable scenario where it is being minimized for CO2, Water, and Costs. Scenario 2 is only minimizing CO2, hence the values for water and costs are considered 0. Scenario 3 only minimizes Costs; hence CO2 and water values are considered 0. Finally, scenario 4 is minimizing for Water, hence CO2 and costs values are considered 0. Finally, all the values were multiplied by 365 to simulate the carbon emissions, water consumption, and costs involved in 1 year.

	CO2	*Water*	*Cost*
***Scenario 1**: Variable Texas Demand (VTD)*	48,654.50	-5,987,131.50	2,988,391.61
***Scenario 2**: VTD Only CO2*	48,654.50	0.00	2,988,391.61
***Scenario 3**: VTD Only Cost*	0.00	0.00	2,412,981.42
***Scenario 4**: VTD Only Water*	0.00	-17,696,441.00	6,890,783.63

Table 7: CO2-Water-Cost comparison of the 4 Scenarios

Figure 44 shows the data in table 7 as a pareto graph comparing water consumption, carbon emissions, and costs of the 4 scenarios listed before. The Y axis is the amount of water consumed, the x axis is the amount of carbon emissions, and the size of the sphere is the cost of the scenario for 1 year.

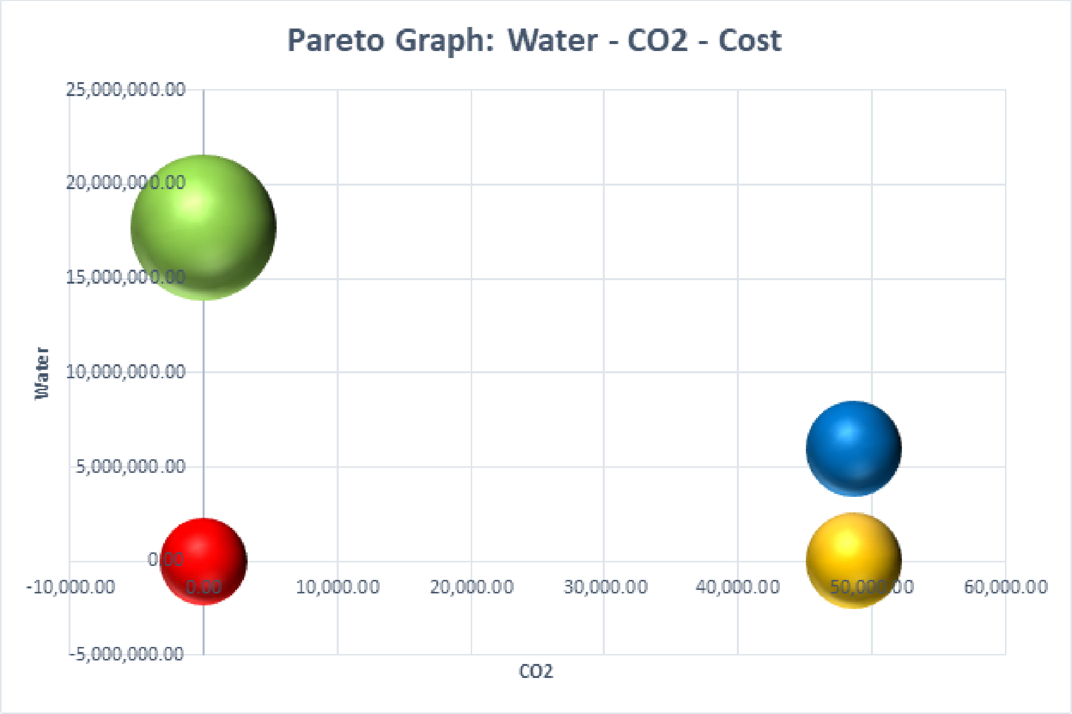


Figure 44, Water-CO2-Cost Pareto Graph Comparing the 4 Scenarios

6. CONCLUSIONS

6.1. Conclusions

In this study, a MILP (mixed integer linear programming) multi-objective optimization model is used to analyze the best energy sources to meet the hourly demand of 1 day for the different sectors combined (residential, commercial, industrial) in the state of Texas taking into consideration carbon dioxide emissions, water consumption, and levelized costs of each technology for three different scenarios.

The energy sources considered are fixed-tilt solar PV systems, 3-bladed wind turbines, pressurized water reactor nuclear power plants, natural gas combined cycle power plants, and anaerobic digestion biomass power plants. The storage systems considered were pumped storage hydroelectric, compressed air energy storage, lithium-ion batteries, and cryogenic liquid storage for hydrogen. Since hydrogen was integrated in the model, three hydrogen converting technologies were considered using different energy sources. High-temperature electrolysis powered by nuclear power, steam methane reforming powered by natural gas, and biomass gasification powered by biomass converted electricity into hydrogen to later be stored in a cryogenic tank, and then converted back into electricity using a molten carbonate hydrogen fuel cell.

After running the optimization model in python-gurobi, scenario 1 showed that the most optimal solution was the symbiosis of three energy sources: solar, wind, and nuclear energy. According to the data, Solar works best during daytime while wind works better at nighttime. There is a time where solar and wind do not produce enough electricity to meet the energy demand, in the case of scenario 1 is from hour 16 (4 p.m.) to hour 21 (9 p.m.). This is an example of the intermittency issue renewable energies present to the grid. To solve this problem, the model adds nuclear power electricity production at the times where solar and wind are lacking. As seen in figure 26, nuclear power produces electricity from hour 17 to hour 21. The model suggests a symbiosis between solar, wind, and nuclear energy to meet the final hourly demands for 1 day in Texas for variable-demand (scenario 1).

Hydrogen is also produced in this process to help meet the demand at the hours where solar and wind do not produce enough electricity. In this model, from the three hydrogen producing technologies presented in scenario 1 only high-temperature electrolysis powered by nuclear energy is used to produce hydrogen (figure 22). Since hydrogen is being produced, it needs to be stored in a cryogenic tank in liquid form. Finally, 54.3 kilograms of hydrogen were converted back into electricity using Molten Carbonate Fuel Cells at hour 19 of the day in (figure 25), where solar and wind were at their weakest in electricity production.

The model also showed the amount of carbon dioxide emitted for scenario 1 (figure 27) and water consumed (figure 28) during each hour of the process. The overall results shows that for scenario 1 the total emissions was 133.3 kilograms of CO2 emitted for each MW of electricity produced, and in the case of water consumed, the value was 154 16,403.1 liters of water consumed for each MW of electricity produced.

Scenario 2 and scenario 3 presented different results from scenario 1. For scenario 2, the demand value was estimated for the energy demand of the industrial sector for an average city in Texas using the scenario 1 demands as a basis. For scenario 3, given the lack of hourly data for a residential community in the state of Texas available online, the new urban area situated in North China, Xiong'an was analyzed. For both scenarios 2 and 3, the energy demand was much lower than for scenario 1 , and given that reason, the results given by the MILP model for scenario 2 (figure 29) and for scenario 3 (figure 30) suggested that just solar and wind energy are going to be enough to meet the demands. Since none of the alternative energy sources were used in this case, there was no CO2 emissions nor water consumption, as well as no hydrogen produced.

For scenarios 4, 5, and 6, the results were as follows. When only Carbon dioxide emissions are considered and the only objective is to minimize it, the same result is achieved in terms of hydrogen production, hydrogen storage and conversion, and energy sources as scenario 1, this is because the combination of solar, wind and nuclear energy are the least carbon emitters of the energy sources. When it comes to only considering the costs and trying to minimize them, figure 37 shows the results. In scenario 5, a symbiosis of solar + wind + biomass + natural gas is suggested by the model. Nuclear power is removed as an option given that the levelized cost of it is higher than that of the other energy sources. Finally, scenario 6 is when water consumption is being minimized and carbon emissions as well as costs are ignored (considered 0). In this case hydrogen is being produced, but in contrast with scenario 1 and 4, hydrogen is being produced at the start of the day (figure 38) using steam methane reforming given that it consumes less water than High temperature electrolysis from nuclear power plants. It is stored for several hours and then released at hour 19 (figure 39). Since the goal is to minimize water consumption, even if the demand is high, the model suggested only using solar and wind energy to meet the final demand (figure 42). Finally the water footprint is due to the use of hydrogen production, storage, and conversion.

Having analyzed the results of the model, according to the theoretical research in this paper, the best places to build/operate the power plants were also taken into consideration. According to figure 8, the best places to operate solar power plants are in the west of Texas near El Paso, Lubbock, Midland, and Amarillo given that the Horizontal Solar Irradiance is higher in those areas. For the case of wind energy, figure 9 and figure 10 show that the north of Texas, near Amarillo and Lubbock are the best places to build/operate a wind farm as long as the hub heights are 80m, 110m, or 140m tall to capture the fastest winds. For nuclear energy, it needs to be placed away from a city but close to a water body given that it uses water to produce electricity. The state of Texas is a good place for nuclear energy because uranium can be extracted in the south of the state near Austin and San Antonio (figure 13). In the case of Texas, there are a couple of nuclear power plants outside Fort-Worth and another couple outside Galveston (figure 12). Both cases are away from the main cities and next to a body of water (figure 14). Hydrogen production and storage needs to be close to the nuclear power plants.

6.2. Future Work

The project on this report has great complexity since it is trying to target all the variables in the water-energy-land nexus to be able to meet the energy demands for the state of Texas. Given its complexity, future work in many areas is going to be needed given that a lot of factors were not considered.

Future work to include for a more precise model:

- Developing hydrogen production technologies using biomass: Dark Fermentation.
- Develop a prediction model to predict the power output of solar PV and wind turbines given certain specifications.
- Find or access the following data: hourly energy demand on each of the residential, commercial, and industrial sectors of a city in Texas.
- Develop a model to predict the future energy demand on each individual sector (residential, commercial, industrial) in a city in Texas.
- Develop a model to include the best energy sources to meet the energy demand in a city in Texas according to minimizing costs, water consumption, carbon emissions, and maximizing efficiency.

- Develop a constraint to limit the land capacity of each power plant, especially that of solar and wind power plants.
- Analyze more hydrogen storage methods and include them in the model calculations.
- The storage methods in this analysis assume that the energy can be stored an infinite amount of time. In future work it is important to include a constraint that limits the time energy can be stored.
- Just like the power plants, the storage systems in this work are not confined to a specific area or land usage. In future work it is important to come up with a model that limits the area and amount of storage systems.
- For both energy sources and storage systems, a network needs to be developed. It is important to know where the energy sources and storage systems can be located to satisfy the energy needs as fast and efficiently as possible.
- The technologies in this report are already developed, new technologies need to be investigated. One example is the case of nuclear energy, where new technologies are being researched that will dramatically improve nuclear's efficiency and capacity and how the world views this technology. The new technologies being developed are Advanced Small Modular Reactors (SMRs) (Energy Gov, Advanced Small Modular Reactors), Sodium-Cooled Fast Reactor, Very High Temperature Reactor, Molten Salt Reactor (Energy Gov 2021, 3 Advanced Reactor Systems to Watch by 2030).
- Include carbon capture technologies. For example, natural gas combined cycle, biomass gasification, and compressed air storage systems can adopt carbon capture technologies to minimize or even eliminate their carbon emissions.

- Since HTE works by using ’thermal energy released from the nuclear reactors’, include a Heat equation to calculate how much electricity a nuclear power plant needs to produce to have excess heat coming from the steam to have thermal energy for High Temperature Electrolysis. For this report only the overall levelized energy is considered, not the exact excess heat a power plant needs for HTE.

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APPENDIX A

Definitions

The following terms are important to know for a better understanding of the methodology:

- **LCOE**: According to NREL, Levelized Cost of Energy (LCOE, also called Levelized Energy Cost or LEC) is a cost of generating energy (usually electricity) for a particular system. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital. This means that the LCOE is the minimum price at which energy must be sold for an energy project to break even. (NREL)
- **LCOS:** According to LAZARD, the Levelized Cost of Energy Storage (LCOS) analyzes the levelized costs associated with the leading energy storage technologies given a single assumed capital structure and cost of capital, and appropriate operational and cost assumptions derived from a robust survey of Industry participants. (Lazard LCOS v2.0, 2016). The system is focused on the utility scale transmission line system which LAZARD defines as: Large-scale energy storage system to improve transmission grid performance and assist in the integration of large scale variable energy resource generation (e.g., utility-scale wind, solar, etc.) Specific operational uses: provide voltage support and grid stabilization; decrease transmission losses; diminish congestion; increase system reliability; defer transmission investment; optimize renewable-related transmission; provide system capacity and resources adequacy; and shift renewable generation output. (Lazard LCOS v2.0, 2016).
- **Ramp Rates**: time (in seconds or minutes) that a system takes to change its output level from rest to rated power; faster ramp rates or lower response times are more valuable

(Storage cost and performance characterization report, U.S. Department of Energy, 2019). The way RR is calculated is by the difference between 2 endpoints of a 60 second interval or also between the difference of the minimum and maximum values in an interval of time (normally a second or a minute). Using the graph below as an example, the way to calculate the Ramp rates are by using the following formulas according to the calculation method preferred:

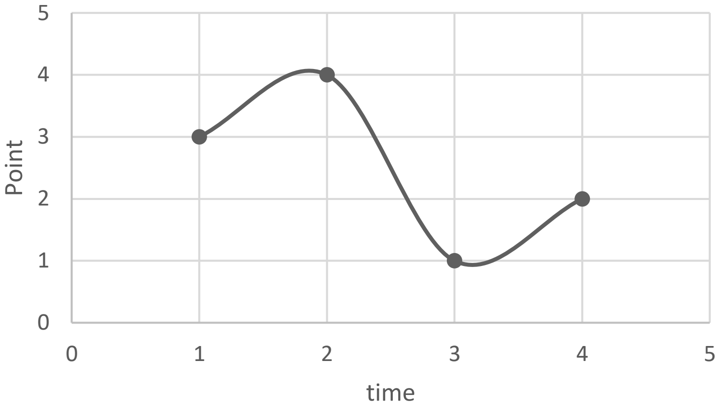

Figure 45, Ramp Rate Calculation (adapted from 35)

Methods and formulas:

- For difference between two points → $RR = (P_2 - P_3)/(t_4 - t_1)$, assuming 1 second interval between t2 and t3 → $RR = (P_1 - P_4)/1s$
- For minimum and maximum difference → $RR = (P_1 - P_4)/(t_3 - t_2)$

(João Martins et al. 2019)

- **Electric Power Capacity**: electric capacity in kilowatts at what the power plant operates in an ideal scenario.

- **Energy Storage Capacity**: maximum electricity a storage system can store in a certain at one point in time.
- **Energy Storage Efficiency**: Energy storage typically consumes electricity and saves it in some manner, then hands it back to the grid. The ratio of energy put in (in MWh) to energy retrieved from storage (in MWh) is the round trip efficiency/energy storage efficiency (also called AC/AC efficiency), expressed in percentages (%). The higher the efficiency, the less energy we lose due to storage, the more efficient the system as a whole (energy mag. 2014).
- **Carbon Dioxide CO2 emissions one-time**: emissions not related to combustion processes.
- **Carbon Dioxide CO2 emissions on-going**: emissions related to combustion processes.
- **Water Consumed**: water that the power plant or storage system uses for its operations and that is not returned to where it was withdrawn from.
- **Upstream**: refers to the material inputs needed for production. Any industry that relies on the extraction of raw materials commonly has an upstream stage in its production process (Quain, S. 2019).
- **Downstream**: is the opposite end of upstream, where products get produced and distributed. Includes elements such as distribution, wholesaling and retailing, all of which are involved in ensuring timely delivery to clients (Quain, S. 2019).
- **Fixed-tilt Solar Panel:** According to the U.S. Energy Information Administration, Solar Panels use two separate angles to gather energy from the sun that determine their orientation relative to it: the azimuth and the tilt. The azimuth specifies the compass direction that a tilted panel is facing: north, south, east, or west. The tilt is the angle from the horizontal ground. A tilt of zero degrees means that the panel is lying flat on the ground, while a tilt of 90 degrees means that the panel is perpendicular to the ground (EIA, 2018).

- **3 Bladed Wind Turbine**: Wind turns the propeller-like blades of a turbine around a rotor, which spins a generator, which creates electricity (How Do Wind Turbines Work? Energy.gov.).
- **Pressurized Water Reactor (PWR) Nuclear Power Plant**: The office of Nuclear Energy states that PWR are nuclear reactors that pump water into the reactor core under high pressure to prevent the water from boiling. The water in the core is heated by nuclear fission and then pumped into tubes inside a heat exchanger. Those tubes heat a separate water source to create steam. The steam then turns an electric generator to produce electricity. The core water cycles back to the reactor to be reheated and the process is repeated (Energy Gov, 2021).
- **Natural Gas Combined Cycle**: according to the U.S. EIA; combined-cycle units heat up fuel and use the fuel-air mixture to spin gas turbines and generate electricity. The waste heat from the gas turbine is used to generate steam for a steam turbine that generates additional electricity (EIA 2019).
- **Steam Methane Reforming**: production process in which high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic—that is, heat must be supplied to the process for the reaction to proceed (Natural Gas Reforming. Energy.gov.).
    - *Steam-methane reforming reaction:*
        - $CH4 + H2O$ (+ heat) → $CO + 3H2$. (Natural Gas Reforming. Energy.gov.)

- **High-Temperature Electrolysis**: is a method of electrolysis where steam is dissociated to H2 and O2 at temperatures between 700 and 1000°C. In electrolysis, system efficiencies increase with increasing operating temperatures. Therefore HTE is known to be more efficient than the conventional electrolysis at room temperature. As a result, the electrical energy requirement of HTE is lower than the electrical energy requirement of conventional electrolysis (Canan Acar et al., 2018).
- **Biomass Gasification**: Gasification is a process that converts organic or fossil-based carbonaceous materials at high temperatures (>700°C), without combustion, with a controlled amount of oxygen and/or steam into carbon monoxide, hydrogen, and carbon dioxide. The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen via a water-gas shift reaction. Adsorbers or special membranes can separate the hydrogen from this gas stream (Biomass Gasification. Energy.gov.).
    - *Simplified example reaction:*
        - $C6H12O6 + O2 + H2O \rightarrow CO + CO2 + H2$ + other species (Biomass Gasification. Energy.gov.)
- **Alternative Energy**: Power plants that produce energy by burning fossil fuels or by using uranium resources. Examples of this type are: Coal, Oil & Natural Gas, and Nuclear power plants.
- **Renewable Energy**: Power plants that produce energy by non-combustion processes such as: Solar, Wind, Geothermal, Tidal, Hydroelectric, and Biomass.
- **Direct-Fired System**: the process of converting biomass into energy that will in turn be used to generate electricity and/or heat. The principal categories of biomass conversion technologies for power and heat production are direct-fired and gasification systems.

Within the direct-fired category, specific technologies include stoker boilers, fluidized bed boilers, and cofiring. The biomass fuel is burned in a boiler to produce high-pressure steam that is used to power a steam turbine driven power generator (Biomass CHP Catalog).

- **Hydrogen Fuel Cells:** Fuel cells directly convert the chemical energy in hydrogen to electricity, with pure water and potentially useful heat as the only byproducts. Hydrogen-powered fuel cells are not only pollution-free, but also can have more than two times the efficiency of traditional combustion technologies (Fuel Cell Technologies Office, 2015).
- **Molten Carbonate Fuel Cells (MCFCs):** it uses a molten carbonate salt (lithium, potassium, or sodium carbonate) in a porous ceramic matrix as an electrolyte. (MCFC, 2021).

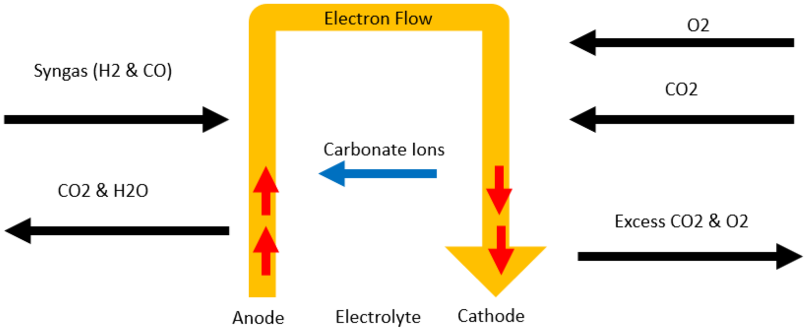

Figure 46 Molten Carbonate Fuel Cell Process (Adapted from 79)

- **SOEC (Solid oxide electrolysis cell):** SOEC feeds water into the cathode and the water undergoes water reduction reaction (WRR), which converts water into hydrogen gas and oxide ions. This hydrogen gas is later brought to purification modules to separate hydrogen gas from the remaining water. Then, the oxide ions migrate from cathode to anode and they release electrons to external circuits to become oxygen gas via oxygen evolution reaction (OER) (K. Kamlungsua et al., 2020).

- **Biomass/Biofuel Anaerobic Digestion**: Anaerobic digestion is a process through which bacteria break down organic matter—such as animal manure, wastewater biosolids, and food wastes—in the absence of oxygen.

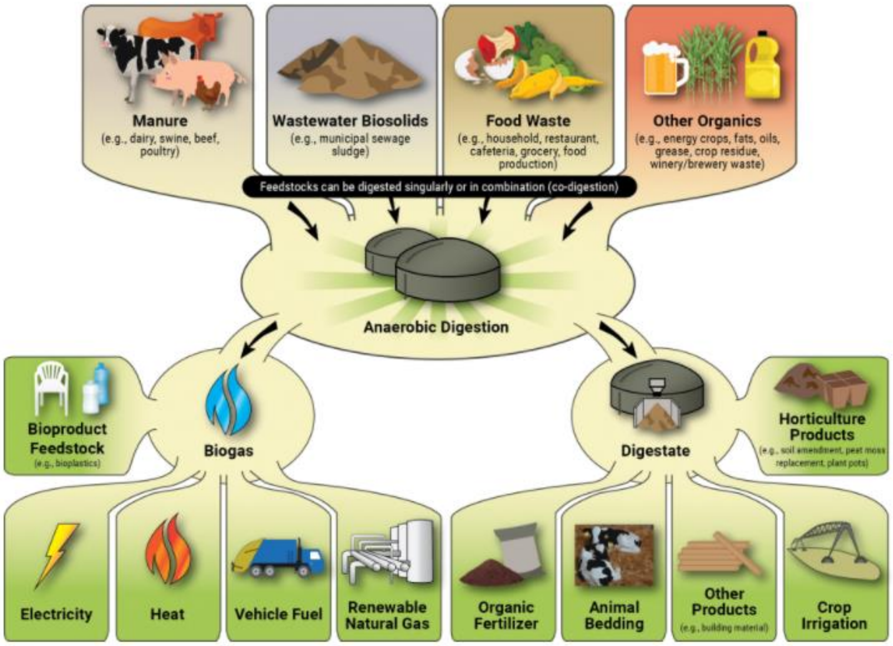

Figure 47 Anaerobic Digestion Biomass Process (reprinted with permission from 55)