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Matlab-Based Simulation Of A Hybridized Tri-Generation Geothermal-Wind-Solar System In Bowman County, North Dakota

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A MATLAB-BASED SIMULATION OF A HYBRIDIZED TRI-GENERATION GEOTHERMAL-WIND-SOLAR SYSTEM IN BOWMAN COUNTY, NORTH DAKOTA

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ABSTRACT

Bowman County, North Dakota, currently relies on coal for over half of its electricity, contributing to significant greenhouse gas emissions. This study employs advanced MATLAB-based modeling to assess the feasibility of transitioning to a hybrid renewable energy system. The designed system includes capacities of 85.7 MW for wind, 24.4 MW for solar PV, 2.03 MW for geothermal, and 195 MWh for storage, tailored to meet the county's growing daily energy demands. Simulations confirm the system's ability to fulfill over 90% of projected daily loads by 2040, with a competitive levelized cost of $105.226/MWh over 15 years. This customized solution reduces daily carbon dioxide emissions by 97% compared to coal. Beyond benefiting Bowman County, this hybrid model serves as a versatile template for other communities pursuing clean, locally focused energy independence, providing a sustainable and adaptable roadmap for a greener future.

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CHAPTER I - INTRODUCTION

1.1.Background on the Global Energy System

BP's Statistical Review of World Energy, 2021, indicates that fossil fuels account for over 80% of all primary energy supply worldwide. As a result of the depletion of fossil fuels, energy security worries, and their role in climate change and environmental degradation, fossil fuels face mounting challenges. As a result of burning fossil fuels, greenhouse gases like carbon dioxide cause global warming (IPCC, 2021). Global population growth and economic advancement are expected to dramatically increase energy demand over the next few decades (IEA, 2021).

We urgently need to switch to clean, sustainable, and environmentally friendly renewable energy sources. Solar photovoltaics, wind turbines, hydropower plants, and geothermal heat are among the key renewable energy technologies. Renewable energy comes from naturally replenishable sources like sunshine, wind, water, and geothermal heat. Renewables generate a total of 29% of global electricity, but only 11% are consumed by them (IEA, 2021). The adoption of renewable energy is growing rapidly, but technical, economic, and infrastructure challenges must be overcome before they can be widely adopted. There may be a solution to these challenges and an acceleration in the energy transition if hybrid systems combine multiple complementary renewable energy technologies (Chen et al., 2022).

By switching to renewable energy, greenhouse gas emissions are reduced, air pollution is reduced, energy security is enhanced by utilizing local resources, employment opportunities in clean energy are created, and ecosystem sustainability is maintained (IPCC, 2011). Intermittency and variability in solar and wind energy are technical challenges because they depend on weather variability. Supply and demand can be balanced daily and seasonal with combined solar, wind, and geothermal energy. With technological advances and declining costs, renewable energy continues to be economically competitive as grid infrastructure, energy storage, and transmission connectivity are improved (Blanco & Faaij, 2018). The externalized costs of fossil fuels must be reflected in market policies through carbon pricing and mechanisms integrating variable renewables (IRENA, 2021).

1.2.The Inefficiency of Traditional Energy Systems

Conventional energy systems often rely on a single technology like coal or natural gas power plants to meet electricity demand. However, these traditional systems can be highly inefficient, with significant energy losses during fuel combustion, electricity transmission over long distances, and waste heat discharge (Patil et al., 2018). Typical thermal efficiency for coal plants ranges from 32-42%, while gas plants range from 50-60% efficiency (EIA, 2020). This approach implies that most of the primary energy input is lost as waste heat and emissions.

Coal power plants discard significant amounts of low-grade waste heat through the condenser cooling cycle (Parker, 1979). This heat could be captured and utilized for heating homes, commercial spaces, or industrial processes. Natural gas combined cycle (NGCC) plants can achieve higher efficiencies by capturing waste heat to generate additional electricity. Nevertheless, often, the waste heat is still vented and wasted. Centralized fossil fuel plants also lose energy during long-distance transmission to load centers (Hammond & Akwe, 2007). The U.S. grid's average transmission and distribution loss is about 5% of net electricity generation (EIA, 2020b). This number represents a significant energy loss that could be avoided with distributed generation close to end-use points.

In contrast, tri-generation systems can utilize the same fuel to produce electricity and valuable thermal energy for heating and cooling, supporting other industrial processes. By cascading energy through multiple applications, tri-generation systems can achieve overall fuel efficiencies exceeding 80% (Wu & Wang, 2006). This characteristic makes tri-generation a more sustainable approach to meet energy needs with lower environmental impacts than conventional single-generation systems.

Tri-generation systems enhance the utilization of primary exergy in fuel by co-producing multiple energy vectors like power, heat, and steam from the same system (Özcan & Dıncer, 2014). This system reduces the exergy destructions associated with single production pathways. Exergy analysis shows that tri-generation can achieve significantly lower exergy destruction rates and higher exergy efficiencies than separated systems (Al-Sulaiman et al., 2011).

Tri-generation systems can also enhance grid stability by balancing electricity supply and demand. The thermal output can be stored to balance power fluctuations from variable renewable sources like solar and wind (Rossi et al., 2016). While traditional tri-generation utilizes fossil fuels, there is potential to transition to renewable-based tri-generation for a deeply decarbonized energy system. For example, geothermal heat can provide flexible baseload power to compensate for solar and wind intermittency (Matek, 2015).

1.3.Addressing the Need for Sustainable Energy Solutions in North Dakota

North Dakota has tremendous renewable energy potential, especially in wind and geothermal resources. However, over 70% of electricity generation comes from coal power plants (EIA, 2020a). When burned, the lignite coal mined in North Dakota has low energy density and high CO_2 emissions (Zygarlicke et al., 2006). There is an opportunity to transition the state from coal reliance towards sustainable energy solutions.

The electricity generation mix in North Dakota as of 2020 was 71% coal, 20% wind energy, 7% hydropower, and just 2% natural gas and other renewables (EIA, 2020a). During the initial decades of the current century, the state transitioned from minimal electricity production to deriving over 25% of its energy from wind power, aided by state renewable portfolio standards and declining costs (Olive, 2021). Given its wind resources and available land, North Dakota has much higher wind generation potential. Solar energy is also an untapped resource in North Dakota, with average solar insolation similar to Germany (Solar Power | ND Studies Energy Level 2, n.d.), a leading solar market.

North Dakota has a continental climate with very cold winters and significant seasonal heating demands (Rudd, 1951). The state averages over 5000 yearly heating degree days (EIA, 2021). Natural gas is the primary home heating fuel, accounting for 71% of North Dakota households (EIA, 2009). An additional 13% of homes use propane. Replacing natural gas use with geothermal heat could provide a cleaner heating alternative while supporting grid stability through thermal energy storage. North Dakota has extensive geothermal resources that could be developed for district heating applications (NDGDS, 2022).

Investing in renewable energy could create jobs for displaced fossil fuel workers during the clean energy transition. North Dakota should leverage its ample wind, solar, and geothermal resources to develop a robust renewable energy economy. Renewables can support rural development and agriculture by providing low-cost distributed power (Atwa et al., 2010). A hybridized tri-generation system utilizing geothermal, wind, and solar energy could provide North Dakota with a reliable, sustainable energy system. The tri-generation design can balance variable renewables and enhance efficiency. This thesis will analyze the technical and economic feasibility of implementing such a system in Bowman County, North Dakota.

1.4. HYPOTHESIS

As the demand for renewable energy sources continues growing, more effective hybrid systems are needed to improve reliability and sustainability. Previous studies have explored the viability of individual geothermal, wind, and solar technologies. However, the potential benefits of a hybrid tri-generation system integrating all three into one grid have yet to be examined, particularly for more remote locations that could benefit significantly from off-grid energy solutions. Therefore, I hypothesized that:

A hybridized tri-generation geothermal-wind-solar system in Bowman County, North Dakota, could provide reliable, economically viable, and environmentally sustainable energy.

1.4.1. Research Questions and Objectives

This thesis will address the following research questions:

1.4.1.1. Research Question #1

Is a hybridized tri-generation system that combines geothermal, wind, and solar energy sources feasible to deliver a consistent and reliable energy output in Bowman County, North Dakota?

This research question will assess the technical feasibility of operating a geothermal-wind-solar tri-generation system in Bowman County, North Dakota. The study will model hourly power generation profiles for hypothetical wind and solar farms using historical weather data from North Dakota. Geothermal district heating potential will be estimated from geoscience data on aquifer temperatures and flows. The complementary nature of the three resources in delivering base, intermediate, and peak load energy will be analyzed. The ability of the tri-generation system to meet benchmark capacity factors and reliability standards with minimal curtailment will be evaluated through energy systems simulation modeling. Constraints such as transmission capacity, land use restrictions, drilling permits, and pipeline rights-of-way will be incorporated. The sizing and specifications of the hybrid system components will be optimized to maximize the economic value of energy. The tri-generation system feasibility will be compared to that of standalone systems. The goal is to determine the technical viability and reliability of the proposed hybrid tri-generation system based on North Dakota's renewable energy resources.

1.4.1.2. Research Question #2

What are the potential economic and environmental advantages associated with implementing a hybridized tri-generation system compared to conventional energy systems?

The second research question will quantify the economic and environmental benefits of the tri-generation system compared to business-as-usual fossil fuel systems. The hybrid system's levelized cost of energy (LCOE) will be calculated based on capital and operating costs over the project's lifetime. The economic value of the tri-generation system will be determined by modeling discounted cash flows and return metrics. The cost-benefit analysis will weigh the market costs against monetized environmental and health benefits from emissions reductions. The greenhouse gas emission assessment will quantify the lower emissions and air pollutants compared to coal and natural gas systems. The economic competitiveness of the hybrid system will be analyzed concerning policy incentives. The goal is to demonstrate the favorable economics and environmental profile of the geothermal-wind-solar tri-generation system compared to conventional energy systems.

The objectives are:

- To establish the technical feasibility of the proposed tri-generation system based on Bowman County, North Dakota's renewable resources.
- To evaluate the economic viability and cost-competitiveness of the tri-generation system through financial and cost-benefit models
- To quantify the environmental advantages of the hybrid system impacts versus fossil

fuel systems

- To provide insights to guide policy and investment decisions for sustainable energy infrastructure in Bowman County, North Dakota

The research questions and objectives aim to conduct an original and robust feasibility assessment of a renewable tri-generation energy system for Bowman County, North Dakota, across technical, economic, and environmental dimensions.

1.5. Purpose and Significance

This research evaluates the technical, economic, and environmental feasibility of a hybridized renewable tri-generation energy system for Bowman County, North Dakota. The thesis analyzes whether combining geothermal, wind, and solar resources into an integrated system can provide consistent and reliable energy to meet North Dakota's electricity needs.

The research is significant because it explores a potential sustainable energy solution for North Dakota that leverages the state's ample renewable resources. The proposed tri-generation system could reduce greenhouse gas emissions and air pollution by displacing coal and natural gas, creating environmental and public health benefits. The study offers policymakers and industry insights into investing in renewable energy infrastructure that provides energy security, economic development, and climate change mitigation. The concepts and feasibility analysis may serve as a model for other states and regions to pursue innovative hybrid renewable energy systems.

Few studies holistically analyze the integration of geothermal, wind, and solar energy into a combined tri-generation system. Most research focuses on pairing complementary technologies like wind and solar PV (Khare et al., 2016). This study contributes an original feasibility assessment of utilizing North Dakota's renewable resources for tri-generation applications. The research synthesizes data and modeling techniques from engineering, geoscience, economics, and environment into a robust interdisciplinary analysis. The methodology integrates energy output simulations, economic cost-benefit evaluation, and environmental impact quantification of the proposed system.

1.6. Thesis Structure

This thesis will be structured into six chapters:

Chapter I provides background context about the global energy transition introduces tri-generation energy systems, describes North Dakota's energy landscape, and presents the research topic, questions, purpose, and significance.

Chapter II will review relevant scholarly literature on renewable hybrid energy systems, tri-generation technologies, renewable energy potential in North Dakota, feasibility analysis methodologies, and energy economics models.

Chapter III outlines the thesis methodology, including system specifications, data sources, energy output modeling, economic analysis, and environmental impact assessment.

Chapter IV conducts a feasibility study of the proposed geothermal-wind-solar tri-generation system in North Dakota, evaluating its ability to deliver reliable electricity and thermal energy outputs based on weather data, resource constraints, and system specifications.

Chapter V evaluates the tri-generation system's economic costs, benefits, and environmental advantages compared to conventional coal and natural gas systems.

Chapter VI summarizes the essential findings and conclusions, discusses policy implications, outlines further research needs, and describes the original contributions of this thesis.

References follow the conclusion. Appendices will provide supplementary data and modeling details.

CHAPTER II - LITERATURE REVIEW

2.1.Wind Energy Review

2.1.1. Introduction to Wind Energy

Wind energy is the kinetic energy generated from wind, which can be harnessed to produce electricity using wind turbines (Deshmukh & Charthal, 2017). Wind turbines convert the wind's kinetic energy into mechanical power through rotating blades connected to a rotor and generator (GWEC, 2021). The generator then converts this mechanical power into electrical energy that can be supplied to the grid.

Wind is caused by the sun's uneven heating of the earth's surface (Siddiqi et al., 2005). As hot air rises, cooler air rushes to replace it, creating wind currents. Wind energy is considered a renewable energy source because wind will continue to blow as long as the sun shines and the earth rotates (US Department of Energy, 2022).

Compared to fossil fuels, wind energy produces negligible emissions during operation, thus supporting environmental goals of reducing greenhouse gas emissions and air pollution. As of 2020, wind power comprised 8.4% of total U.S. electricity generation and is among the lowest-priced renewable energy technologies available today (US Energy Information Administration, 2021). With technological advancements and growing demand for clean energy, there is great potential for further growth in wind energy.

2.1.2. Wind Energy Conversion Process

Wind energy conversion into electrical energy involves two main components - the rotor blades and the electrical generator. As the wind blows across the blades, the lift is created due to the aerodynamic shape of the blades, causing the rotor to spin. The rotor is connected to a drive shaft that turns the generator, which converts mechanical rotation into electrical energy via electromagnetism (US Department of Energy, 2022).

Modern wind turbines can operate at variable speeds to maximize energy capture from fluctuating wind speeds. The power output is directly proportional to wind speed cubed. Other factors like blade length also impact energy generation. Control systems orient the blades to optimize the angle relative to wind direction (GWEC, 2021).

The generated electricity is fed into transmission lines and distributed via the electrical grid. Some turbines store energy in batteries to provide backup during low wind or power outages. Wind farm configurations optimize energy production by carefully spacing turbines to avoid wake turbulence from upwind turbines (Milan et al., 2013). Advances in design, materials, and control systems continue to improve wind turbine performance and reliability.

2.1.3. The potential of Wind Energy

Wind energy offers many benefits that make it a promising renewable electricity source:

- Abundant resource - Wind is ubiquitous and unlimited, with global technical potential exceeding current energy demand (Lu et al., 2009). Locations with strong, consistent winds are ideal for wind farms.
- Cost-competitiveness - Wind energy costs have declined dramatically to become one of the most affordable renewables. The levelized costs for onshore wind range from 2-6 cents/kWh, which makes it competitive with fossil fuels (US Energy Information Administration, 2021).
- Energy independence and security - Wind utilizes a free domestic resource, providing a secure supply without imported fuel (Kong et al., 2011). This characteristic insulates this energy from global fuel price volatility.

- Environmental sustainability - Wind emits no air/water pollution or greenhouse gases during operation. The life cycle emissions are 75-80 times lower than coal (Hertwich et al., 2015).
- Rural economic development - Wind projects provide new long-term income sources and jobs in rural communities. Landowners receive lease payments for hosting turbines (Veurink, 2012).
- Scalability and modularity - Wind projects can be tailored for different applications, from distributed small-scale to large utility-scale projects (Weisbrich et al., 2002). Capacity grows via adding units as needed.

Despite these advantages, wind has some challenges as an intermittent resource. Output fluctuates based on weather variability. Energy storage and transmission infrastructure upgrades can help address intermittency and wind diversity from geographic dispersion and forecasting. However, studies confirm that wind and solar can provide reliable grid power with minimal storage needs (Jacobson et al., 2015). Due to its substantial benefits, wind continues gaining a share in electricity portfolios globally.

2.1.4. Wind Energy in North Dakota

North Dakota has tremendous wind energy resources, ranking among the top U.S. states. High wind speeds, flat, expansive lands, low population density, and abundant rural areas are ideal for large-scale wind projects (Zhang et al., 2014). North Dakota's installed wind capacity grew from just 25 megawatts (MW) in 2000 to over 3,000 MW today, supplying roughly 26% of the state's total electricity (American Clean Power Association, 2021). The DOE estimates that North Dakota has the technical capability to produce over 900,000 MW of wind power, over 200 times current levels (Lopez et al., 2012). Developing more wind energy can bring additional economic activity to North Dakota communities.

North Dakota's wind resource ranks 5th in the nation with average wind speeds of 9.9-11.0 m/s at 80-meter hub heights across much of the state (Lopez et al., 2012). Strong winds are most abundant in central and north-central regions. The National Renewable Energy Lab confirmed that North Dakota has some of the best wind resources in the U.S., with capacity factors exceeding 50% (Figure 1). Higher capacity factors yield greater energy production per turbine.

Topography and low surface roughness from sparse human development enables unobstructed wind flow. Cold winters and warm summers cause seasonal wind patterns conducive to wind generation. Wind output is typically highest in winter when heating demand is most significant (Raupach & Finnigan, 1997). Wind resources in North Dakota can support significant expansion of wind power.

North Dakota's first utility-scale wind farm was built in 1998, the 25 MW Lyonsdale project. Wind growth accelerated after 2000 as technology improved and policy incentives were enacted. As of 2021, North Dakota has over 40 wind power projects in service comprising 3,065 MW of capacity (American Clean Power Association, 2021).

The most significant developments are concentrated in the central and south-central regions with strong winds. Some of the important existing projects are (Wind Energy Database, 2023):

- Baldwin Wind Farm (102 MW), Williams County
- Ashtabula (196.5 MW), Barnes County
- Thunder Spirit Wind Farm (115 MW), Adams County
- Rugby Wind Farm (149.1 MW), Pierce County
- PrairieWinds (115.5 MW), Ward County

Wind accounted for 26.5% of North Dakota's total electricity generation in 2020 (EIA, 2021). The top counties for wind capacity include Ward, Williams, and Barnes in central North Dakota. Wind power has become an essential contributor to the state's electricity portfolio.

Wind project development in North Dakota has yielded substantial economic benefits through investment, tax revenue, income generation, and job creation. Land lease payments provide direct income to farmers and ranchers hosting turbines. Counties also gain property tax revenue from installed projects.

From 2000 to 2020, North Dakota wind projects attracted over $5.7 billion in private investment into the state (American Clean Power Association, 2020). Project owners pay property taxes to local governments, providing critical funding for schools, infrastructure, and services. The first ten years of a wind project's operation are estimated to generate $1 million per year in local property tax revenue and $4 million annually over the entire 20-30-year lifespan (Shoeib et al., 2021). Wind energy supports local jobs in manufacturing, construction, operations, maintenance, consulting, and support services. According to Wiser et al. (2023), a 250 MW wind project requires 1,079 full-time workers over the development and construction period. After that, approximately 24 full-time local workers are needed for operations.

Wind projects thus create economic diversity, growth, and revitalization for rural communities in North Dakota. Farmers gain a stable income source while retaining lands for agriculture. Wind contributes to the tax base, infrastructure, schools, and services. Taylor et al. (2019) determined that just five counties in North Dakota realized $59 million in cumulative wind project investments through 2008, corresponding to $21 million in income to farmers and nearly $15 million in local and state income taxes. Unlocking more of North Dakota's extensive wind potential can provide even greater economic benefits statewide.

North Dakota aims to continue expanding its wind energy portfolio to promote economic growth and meet renewable energy targets. In 2020, the state set a goal to generate 1,000 MW from solar and wind by 2030 (Willis, 2021). With only 89 MW of current solar capacity (EIA, 2021), most new renewable generation will likely come from wind.

The National Renewable Energy Lab estimates that North Dakota has the potential for 907,522 MW of land-based wind energy capacity (Lopez et al., 2012). Less than 1% of this has been utilized so far. Key regions with high potential include the Missouri Coteau, Turtle Mountains, and Valley City area (Figure 2). Substantial untapped resources remain across the state. Accessing more wind energy would support continued rural economic development.

Wind energy expansion faces some challenges. Transmission capacity needs strengthening to deliver remote wind power to population centers. Cold winters pose icing issues for turbines. There is also competition from fossil fuels - North Dakota produces more oil than any state besides Texas (US EIA, 2022). Still, declining costs, energy diversification, and environmental benefits motivate us to harness North Dakota's bountiful wind resources further. With supportive policies and infrastructure, North Dakota can realize its tremendous wind power potential.

2.2.Solar Energy Review

2.2.1. Introduction to Solar Energy

Solar energy is sun energy converted into thermal or electrical energy (Hayat et al., 2018). Solar energy is the most abundant energy resource on earth, but only a tiny fraction is currently used (Desideri et al., 2013). Solar power is considered a renewable energy source (Ahmadi et al., 2018), meaning it is replenished naturally and virtually inexhaustible. Unlike finite fossil fuels like coal, oil, and natural gas, which require extraction from the earth, solar energy continuously arrives to the earth from the sun (Rhodes, 2010). Solar energy does not create air pollution or carbon emissions, giving it a clear environmental advantage over fossil fuels and contributing significantly to climate change (Khan & Arsalan, 2016). Technologies to harness solar power have advanced considerably in recent decades. As solar panels become more efficient at converting sunlight to electricity and costs, continue to fall, solar energy can become a mainstream electricity source that provides sustainable and renewable power on a global scale.

2.2.2. Overview of Solar Energy and its Potential for Sustainability and Efficiency

The amount of sunlight reaching the earth's surface in a single hour is more than the entire world's energy consumption for a year (Sherwani, Usmani, & Varun, 2010). This vast potential makes solar energy easily the most abundant energy resource available. Solar energy is also widely available - every region of the world receives sunlight to some degree. Even cloudy northern regions have enough solar resources to produce helpful energy if harnessed efficiently. In this way, solar energy is equitably spread around the globe. Solar technologies like photovoltaic panels are also modular and scalable. Solar power systems can be set up in various configurations, from small-scale arrays on homes and businesses to large-scale solar farms covering acres of land. This flexibility makes solar adaptable to meeting many different energy needs.

As research continues to improve solar cell materials and design to convert sunlight more efficiently, costs have declined dramatically. Since 2009, the average price of solar panels in the United States has dropped about 75% (SEIA, 2021). This improving affordability makes solar power increasingly cost-competitive with conventional power sources like coal and natural gas in many areas. With sufficient technological improvements and policy support, solar electricity has the potential to become a significant pillar of the global energy supply, providing a sustainable and renewable alternative to finite fossil fuels.

2.2.3. Solar Energy in North Dakota

While solar energy holds great promise as a sustainable power source, adoption in North

Dakota has lagged behind leading states. North Dakota has about 12 megawatts (MW) of installed solar photovoltaic capacity (Figure 3), ranking it 36th nationally for solar development (SEIA, 2023). The state's existing solar power capacity can generate enough electricity to power around 1,600 typical homes. For comparison, neighboring Minnesota has over 800 MW of solar capacity, more than 60 times that of North Dakota. Germany, a global leader in solar energy, has over 45,000 MW of total installed solar capacity (Vaidyanathan, 2013). Most existing solar arrays in North Dakota are relatively small, under 2 MW in size. However, declining solar costs are leading some electric utilities to begin developing larger, utility-scale solar farms in the state. The North Dakota Public Service Commission has established policies to encourage solar growth, such as net metering, which credits homeowners and businesses for the excess solar power they generate. Overall, North Dakota has substantial room to grow its solar energy market.

Several factors indicate strong potential for North Dakota to expand its solar energy capacity significantly. First, North Dakota has reasonably good solar resources. The state receives an average of 4 to 5 kWh/m^2/day of solar radiation (Figure 4), comparable to Germany's solar resources (NREL, 2020). Even North Dakota's colder northern areas receive usable levels of sun. Second, as solar panel manufacturing has scaled up and technology improved, costs have declined dramatically. This feature makes solar power more economically feasible and competitive. Third, federal tax credits and state incentives in North Dakota help reduce the price of new solar installations, stimulating market growth.

In addition, North Dakota has extensive rural land areas that could host large, utility-scale solar farms. The declining price of battery storage technology also complements solar growth by helping address the intermittent nature of solar power. Solar energy peaks mid-day, but batteries can store excess power at night or on cloudy days. More robust policy mechanisms from state governments, such as renewable portfolio standards, could further incentivize solar adoption. Overall, North Dakota has the solar resource potential and space to significantly increase solar power generation with the help of continued cost declines.

However, obstacles remain for substantial solar expansion in North Dakota. The state's cold northern climate reduces solar panel productivity compared to warmer regions like Arizona and Florida (Kim et al., 2017). North Dakota's electricity prices have also remained relatively low due to abundant local coal and hydraulic fracturing natural gas resources. This characteristic makes alternative sources like solar less competitive. In conclusion, North Dakota appears well-positioned for growth in solar energy generation but still requires further policy support and cost declines to enable large-scale solar development.

2.3.Geothermal Energy Review

2.3.1. Introduction to Geothermal Energy

Geothermal energy refers to the heat within the Earth that humans can recover and utilize (Barbier, 2002). The geothermal energy present today was formed during the original accretion of the planet and from the decay of radioactive elements in the Earth's core (Lund et al., 2008). The Earth's interior temperature increases with depth, reaching thousands of degrees Celsius at the core (Yukutake, 2000). Some of this heat conducts through rock layers and up to the Earth's surface, where it manifests as volcanic activity, hot springs, geysers, and high subsurface rock and fluid temperatures (Dickson & Fanelli, 2018).

Humans have used accessible geothermal heat for thousands of years, using hot springs for bathing, cooking, and heating (Rinehart, 1980). In the last century, technology has allowed us to tap deeper heat resources for electricity production and direct heating applications. Wells and pumps bring hot water or steam to the surface, which can directly drive turbines to generate electricity

(Glass, 1977). Lower-temperature fluids can be used directly for heating or provide input heat for geothermal heat pumps. Geothermal is considered a renewable energy source because the heat extraction is minor relative to the tremendous amount of heat stored in the solid Earth (Kubik, 2006).

2.3.2. Overview of Geothermal Energy Applications

2.3.2.1. Electricity Generation

Geothermal power plants are the most visible application of geothermal energy (Lund, 2003). High-temperature (>180°C) fluids from wells are used to produce steam to drive turbine generators and generate electricity (Mulyana et al., 2016). In 2022, global geothermal power capacity was estimated at 17 billion kWh, with over 80 countries contributing generation. The largest capacities are in the US, Indonesia, and Turkey (Center for Sustainable Systems, 2023)

Generation is often from hydrothermal reservoirs, but enhanced geothermal systems (EGS) create artificial reservoirs in hot dry rock through hydraulic stimulation techniques. Binary power plants use lower-temperature hydrothermal fluids (>100°C) to heat a secondary working fluid that drives the turbine, allowing the exploitation of more common lower-temperature resources (IRENA, 2022).

2.3.2.2. Direct Use

Direct geothermal heating utilizes hot water from wells at lower temperatures (<150°C), which is insufficient for power generation (Arnórsson et al., 2015). Direct applications include district heating systems, greenhouse and aquaculture pond heating, industrial process heating, and bathing/swimming. District heating systems distribute hot water in closed loops to multiple buildings for space heating (Lund, 2010). More than 140 district heating systems using geothermal heat are in operation worldwide. Geothermal district heating can meet up to 100% of space heating needs with greater efficiency and lower emissions than conventional systems (Lund & Tóth, 2021). Greenhouse heating now constitutes about 20% of geothermal direct use. Bathing and swimming in natural hot springs are the oldest and most common direct geothermal uses (Lund & Freeston, 2001).

2.3.2.3.Heat Pumps

Geothermal heat pumps use shallow, constant ground or water temperatures to augment building heating and cooling systems (Florides & Kalogirou, 2007). A network of underground pipes exchanges heat with the ground or an aquifer. In winter, the relatively warm ground removes heat from the refrigerant, concentrating it on the building heat exchanger. The process reverses in summer, rejecting building heat to the cooler ground (Lund & Boyd, 2016). The pumps use much less energy than conventional systems as they move heat rather than create it through combustion. Geothermal heat pumps currently constitute the largest amount of geothermal energy utilization worldwide (Huttrer, 1997).

2.3.3. Global Significance of Geothermal Energy

The global geothermal potential is enormous but largely untapped. Estimates of global potential capacity range from 35 GWe to as high as 2,000 GWe, with only a small fraction of identified high-grade resources currently in operation (Bertani, 2016). Tapping just a few percent of the available potential could allow geothermal energy to provide a significant portion of global electricity production. Unlike solar and wind power, geothermal power offers stable baseload power that is not subject to daily or seasonal variability (DiPippo, 2016). Land use per kWh is smaller than other renewables (Friðleifsson, 2001). The over 100 million tonnes of CO_2 emissions avoided annually by geothermal direct-use applications will grow as heat utilization expands (Lund & Boyd, 2016). More significant deployment of geothermal heat pumps can dramatically reduce building heating and cooling energy loads.

Realizing more global geothermal resource potential will require reducing the risks and costs associated with exploratory drilling. With expanded resource characterization, technology improvements, and supportive policies, the IPCC and IRENA estimate that geothermal generation could grow to supply 3-16% of global electricity by 2050 (Fridleifsson et al., 2008; IRENA, 2022). Geothermal energy can provide significant baseload power, heating, and emissions reductions worldwide as part of a diverse renewable energy mix.

2.3.4. Geothermal Potential in North Dakota

The subsurface of North Dakota contains high temperatures associated with hot sedimentary aquifers in the Williston Basin. Temperatures above 150-200°C (Figure 5) have been encountered by oil and gas drilling at depths between 3-5 km (Gosnold, 1991). The Williston Basin features many attractive characteristics for geothermal energy development, including deep circulation of saline waters, regional heat flow, thermal gradients, and basement fault systems providing heat transmission (Gosnold, 1984)

The technically accessible geothermal resource base beneath North Dakota has been estimated at 120 MW (Van Brummen et al., 2022). This possible resource excludes even higher temperature resources likely available deeper than current drilling (Williams et al., 2008). While no geothermal power facilities currently operate, promising hot aquifers widespread across the state could support various direct-use applications even at temperatures as low as 50°C.

Developing North Dakota’s geothermal resources could deliver significant energy, economic, and environmental benefits. The baseload power potential alone represents over 100 times the state’s current electricity consumption. Geothermal heat could be used for district heating systems and industrial applications across North Dakota. Tapping this consistent indigenous resource would provide energy security and price stability. Constructing geothermal power plants and distribution networks would create jobs and revenue in rural areas with energy production and related industries.

Compared to fossil fuels, geothermal energy results in negligible CO_2 and local pollutant emissions when utilized (Fridleifsson et al., 2008). Geothermal could allow North Dakota to continue diversifying its energy mix with homegrown renewable sources like wind and biofuels. Even moderate growth could make geothermal heat and power a significant component of the state’s energy portfolio. Further geological surveys, technology improvements, policy incentives, and public-private partnerships can help access this vast clean energy resource.

2.4.Hybrid System

2.4.1. Introduction to Hybridized Systems

A hybrid energy system combines two or more distinct power generation sources to provide electricity and potentially heating or cooling (Hinrichs-Rahlwes, 2013). Hybrid systems most commonly integrate renewable energy like solar or wind with conventional sources like diesel generators. However, hybrid systems can also incorporate multiple different renewables. The primary rationale behind hybrid systems is to utilize the unique strengths of each energy type to maximize efficiency, reliability, and cost-effectiveness.

Hybrid systems are increasingly deployed in remote off-grid areas to provide electricity more sustainably than diesel alone. They are also becoming more popular in grid-connected applications to support renewable integration and energy security. Optimally combining various energy assets can mitigate some renewables' variability and intermittency issues. Overall, hybrid systems present a promising opportunity to transition towards more diverse, decentralized energy architectures (Raven, 2007).

2.4.2. Prior Research on Hybrid Systems

Many studies have investigated optimizing hybrid system design and control strategies. Ekren and Ekren (2010) modeled various simulator configurations for an isolated hybrid solar wind-diesel system. They determined the optimal simulator architecture and components to minimize total net present cost over 20 years while meeting a given load. The optimized hybrid system provided electricity that was 7.9% cheaper than that of a diesel-only system.

In related work, Kaabeche and Ibtiouen (2014) developed models for assessing reliability and evaluating hybrid solar-diesel-battery systems' economic and environmental benefits. They concluded that hybrid systems could improve reliability compared to diesel-only systems while reducing fuel consumption, costs, and emissions. However, batteries increase net present costs. The authors recommended continued research to reduce battery costs.

Other studies, like Kemp et al. (2023), have focused on very high solar penetration hybrid systems. Their analysis examined economics, sub-hourly dispatch modeling, and grid integration for a proposed hybrid 280 MWAC solar PV, 50 MWAC battery storage, and existing natural gas plant system. They determined that the hybrid design would provide significant fuel savings, equivalent to 113,000 metric tons of CO_2 avoided annually. Overall, research highlights the potential sustainability benefits of hybrid systems compared to conventional-only designs.

2.4.3. Discussion on the Advantages of Hybrid Systems

Hybrid energy systems offer several interrelated advantages over-relying on a single generation source, especially for remote, off-grid communities. First, integrating two or more technologies provides diversity in fuel sources, mitigating susceptibility to resource variability and disruptions in one technology (Lau et al., 2010). For example, solar may underperform on cloudy days, but wind can help compensate. Second, hybrid systems improve electricity reliability and resiliency compared to intermittent renewables alone (Kaabeche & Ibtiouen, 2014). Conventional fuels or storage fill gaps when renewable resources are unavailable.

Third, hybrid systems enable higher utilization of renewable assets (Rajbongshi et al., 2017). Storage or supplemental generation can absorb excess renewable output rather than curtailing it. Fourth, renewables like solar reduce fuel consumption and emissions versus conventional-only systems. Fifth, capital costs can be decreased by downsizing costly diesel generators or storage since renewables also contribute (Ekren & Ekren, 2010).

However, hybrid systems also present challenges, including complex control requirements and higher operations and maintenance costs. Overall, hybrid systems can provide more affordable, reliable, and sustainable electricity than conventional-only systems, especially for remote regions. Hybrids facilitate greater utilization of renewables to reduce costs and environmental impacts. Continued technology improvements and declining storage costs will further boost hybrid system advantages. Hence, hybrid designs likely represent the future of off-grid and fringe-of-grid electricity.

CHAPTER III – METHODOLOGY

3.1. Introduction

This chapter meticulously delineates the highly comprehensive research methodology for the intricate processes involved in designing, modeling, and analyzing the proposed hybrid solar wind-geothermal power system. A robust and systematic framework is elucidated, encapsulating technical, economic, environmental, and simulation utilized in this study.

The introduction establishes the basis for the subsequent discussion by providing a comprehensive overview of the methodological approach employed in this research. It elucidates the motivations and goals guiding this multi-faceted study. Specifically, the introduction delineates the considerable breadth, underlying incentive, and numerous vital aspects of the methodology to support and rigorously evaluate the proposed system's framework.

A highly intricate hybrid energy system, amalgamating multiple renewable resources, presents substantial sustainability and efficiency benefits compared to conventional fossil-fuel-based generation (Lilienthal et al., 1995). However, integrating outputs from solar, wind, and geothermal sub-systems poses significant modeling, control, and optimization challenges, necessitating a comprehensive methodology to holistically evaluate technical, economic, and environmental performance trade-offs associated with hybrid system architectures and operating strategies (Möller & Krauter, 2022).

This study aims to construct ultra-high-fidelity models capturing the intrinsic dynamics of hybrid renewable systems by employing advanced computer-aided modeling, simulation, and optimization techniques (Chang & Lin, 2015). Leveraging sophisticated tools such as MATLAB/Simulink enables integrated techno-economic-environmental analyses, leading to the data-driven identification of optimal hybrid system configurations (Amer et al., 2013). The methodological framework provides the foundation to thoroughly assess the feasibility, cost-competitiveness, and sustainability benefits of the proposed hybrid solar wind-geothermal system design.

The subsequent sections will meticulously elaborate on the specific technical modeling, project investment appraisal, and environmental impact assessment employed in this methodology, along with the motivation and rationale for the selected approaches. Detailed discussions on the limitations and assumptions incorporated will also be presented to contextualize the research appropriately. In summary, a highly robust and fully integrated methodological framework is developed to facilitate optimal and sustainable hybrid renewable energy system designs enormously.

3.1.1. Research Methodology

The methodology (Figure 6), functioning as the foundation of this extensive study, transcends basic description—it acts as a compass guiding the assessment of feasibility and sustainability qualifications for the hybrid system under examination. Sophisticated computer-assisted instruments, namely the MATLAB/Simulink programming environment, are utilized to construct highly integrated models that realistically emulate the considerable complexities of the hybrid system. The methodology facilitates a comprehensive multi-faceted analysis encompassing exhaustive technical modeling and simulation, economic viability appraisal, and environmental impact quantification.

Various analytical techniques are extensively utilized, including simulation of component and system models, project investment appraisal, and sustainability metrics. Through this systematic methodology, the research endeavors to significantly advance the knowledge frontiers regarding designing and implementing sustainable renewable energy systems.

The process aims to identify the hybrid system architecture and operation strategy from the perspective of financial viability, ecological impact, reliability, and efficiency.

3.1.2. Methodology for Economic and Environmental Analysis

The methodological framework at the intersection of economic and environmental domains holds tremendous pertinence. Integrating dynamic simulations with quantitative analytical models illuminates the techno-economic and sustainability trade-offs. It is a conduit linking technical performance, financial costs and metrics, and multi-faceted environmental impacts.

In summary, this exhaustive methodology facilitates the determination of optimal solutions that satisfy economic feasibility and minimize ecological footprints. The methodology enables a comprehensive appraisal of the cost-competitiveness of the hybrid system relative to conventional fossil fuel-based electricity generation alternatives. It also permits the unambiguous quantification of potential emissions mitigations and natural resource preservation, which is achievable compared to traditional generation technologies.

3.2. Data Sources

The foundation for meaningful analysis and modeling is provided by highly robust, accurate, and granular input data. This section documents the numerous key data sources leveraged in the research.

3.2.1. Description of Data Sources

Various data sources are extensively utilized to support the analytical approach, including:

- Site-specific solar irradiance and wind speed data were obtained from meteorological stations in the region to facilitate significantly accurate modeling of the renewable resources available.
- Geothermal gradient and subsurface temperature data for the location from prior geological

surveys to strongly estimate the geothermal heat extraction potential.

- Very detailed technical specifications for the solar PV panels, wind turbines, geothermal heat exchangers, pipelines, pumps, and other equipment from reputed manufacturers to significantly aid in component-level modeling.
- Cost benchmarking for capital expenditures, operating, and maintenance costs from recent industry reports will be used to conduct a thorough project cost analysis.
- The emission factors of conventional fossil fuel-based electricity adopted from peer-reviewed life cycle assessment (LCA) studies are used to compute the emissions displacement by the hybrid plant.
- The electricity demand profile, existing and projected for the site, is derived from historical utility data and demand forecasts, providing the extensive basis for appropriately sizing the hybrid system.
- Requisite financial parameters, including inflation, discount rates, and electricity prices compiled from authoritative government and industry sources, are required to calculate metrics such as the levelized cost of electricity accurately.

3.2.2. Contribution to Research Goals

The above data provides the empirical inputs necessary to construct representative component and system-level models, carry out extensive techno-economic simulations, undertake highly detailed financial and environmental impact analyses, and thoroughly fulfill the numerous key research objectives of designing and assessing the proposed hybrid renewable energy system. In summary, the real-world site data enables the building of ultra-high-fidelity models, evaluating performance for different system architectures, developing control strategies, and identifying optimal configurations from sustainability and economic perspectives.

3.3. System Modeling and Simulation

Advanced computer-aided simulation techniques (Figure 7) are employed to model and analyze the hybrid plant's performance.

3.3.1. Modeling Philosophy and Approach

An extensive bottom-up approach (Figure 8) is undertaken whereby the solar PV array, wind turbine, geothermal sub-system, and other components are modeled individually in MATLAB/Simulink based on their physical characteristics and operating principles. These ultra-high-fidelity component models are then integrated into an overall system model per the interconnection configuration. The system model is simulated with real-world solar, wind, and geothermal heat availability and load data to mimic actual operating conditions.

3.3.2. Description of System Components Models

The following mathematical modeling concepts are applied for simulating each hybrid plant subsystem:

<u>Solar PV Array Model:</u>

- Represented via equivalent circuit models composed of photocurrent sources, diodes, parasitic resistances, and shunt capacitances to capture cell behavior.
- Cell models aggregated to array level based on interconnection configuration.
- Inputs of solar irradiance and cell temperature data drive the output electrical performance.

<u>Wind Turbine Model:</u>

- Aerodynamic rotor power conversion modeling using turbine power characteristic curves.
- Drive-train mechanics are modeled through low-speed shaft dynamics, gearbox efficiency, and other components.

- Asynchronous or synchronous generator models with appropriate control systems and grid integration.

Geothermal System Model:

- Reservoir thermal response modeled through porous media heat conduction equations.

- A vertical borehole heat exchanger configuration was simulated using thermal resistance models.

- Heat carrier fluid transport modeled as a thermodynamically closed loop through pipes, pumps, and heat exchangers.

Electrical System Model:

- Power electronic converters and control loops are represented via an average value modeling approach using proportional-integral controllers.
- Grid integration aspects such as protection systems are also incorporated.

3.3.3. Rationale for Simulation Approach

The component-based modeling philosophy captures the significant intricacies of each sub-system. Using MATLAB/Simulink provides advanced software capabilities to integrate flexible, customized models into a system model that can be subjected to extensive time-series simulations for comprehensive analysis. The modular approach also allows a thorough study of each sub-system in isolation and an integrated setting.

3.4. Economic Analysis

The financial and economic feasibility analysis carried out to evaluate the hybrid system design is elucidated in detail in this section.

3.4.1. Economic Analysis Methodology

An extensive project investment appraisal approach is utilized, encompassing the following analyses:

- Very detailed identification of all pertinent costs over the system lifetime, including capital costs of equipment, civil works, electrical infrastructure, engineering, procurement, and construction costs.
- Thorough estimation of annual operating and maintenance costs, including repairs, consumables, insurance premiums, lease rentals, personnel costs, and other expenses
- Extensive modeling of financing costs based on potential debt/equity mix, interest rates, cost of equity, etc.
- Annualized costs and revenues to present value terms based on discount rate assumptions are extensively discounted.
- Precise computation of levelized cost of electricity (LCOE).
- Thorough sensitivity analysis to assess robustness to uncertainties.

The combination of conventional financial metrics and MATLAB-based models allows a comprehensive assessment of the costs and revenues associated with the multi-technology hybrid system with an exceptionally high degree of customization. The approach enables determining if the system represents a financially viable avenue for sustainable power generation compared to alternatives. The model flexibility permits evaluating numerous scenarios.

3.5.Environmental Analysis

The methodology adopted for thoroughly evaluating the hybrid system's sustainability profile is elucidated here in detail.

3.5.1. Environmental Analysis Methodology

A detailed greenhouse gas (GHG) emissions analysis is undertaken to extensively evaluate the emissions profile of the hybrid system in comparison to existing (coal-fired) power generation.

Hybrid System Emissions Estimate

- An exceptionally detailed bill of materials is prepared for the hybrid system comprising the solar PV arrays, wind turbines, geothermal wells, heat exchangers, balance of plant, cables, transformers, etc.
- Very comprehensive embodied emissions factors regarding CO_2 e per kg or per kWh generated are assigned to each equipment/material based on inventory data from lifecycle databases.
- The construction phase emissions, considering the transportation of raw materials and equipment to the site, civil works, installation, etc., are estimated using pervasive activity-based models.
- Any direct on-site emissions from fossil fuel usage as a supplementary heating source in the geothermal plant are calculated based on the type and quantity of fuel used annually.
- The annual electricity generation from the hybrid plant incorporating PV, wind, and geothermal resources is estimated based on simulations.
- The above factors are integrated into a MATLAB model to compute the lifecycle GHG emissions of the hybrid plant over its lifetime.

Natural Gas Stand-Alone Plant Emissions Estimate

- Very comprehensive techno-economic parameters of an equivalent natural gas plant (accounting for low, average, and high fuel pricing), such as efficiency, heat, and fuel consumption, are assumed based on benchmarks.
- The direct stack emissions annually arising from coal combustion are calculated based on the quantity of natural gas consumed and applicable emission factors.

- A MATLAB model compares the emissions from an equivalent natural gas plant against the hybrid system on a pervasive basis of lifetime emissions per kWh generated.
- The emissions mitigation potential is quantified regarding total emissions savings over the project lifetime and reduced GHG intensity (emissions per kWh).

Considering the comprehensive lifecycle emissions, this analysis provides an exceptionally accurate estimate of the potential GHG mitigation benefits of the hybrid renewable energy system compared to conventional coal-fired and natural gas power generation.

3.6. Limitations and Assumptions

While an exceptionally comprehensive methodology is pursued, specific limitations exist:

<u>Data Limitations:</u>

The availability of pervasive high-resolution temporal data representing site conditions is constrained. Reasonable proxy values from literature are utilized where possible. Much more location-specific data collection is required to reduce uncertainties.

<u>Modeling Simplifications:</u>

Mathematical models involve certain approximations and assumptions to maintain tractability. Capturing every subsystem's dynamics may be impractical. Control interactions between components are highly complex and challenging to emulate fully.

<u>External Variability:</u>

Real-world operational uncertainties due to weather, unexpected equipment failures, etc., cannot be fully anticipated through deterministic modeling. More advanced stochastic simulation techniques could address this to some extent.

<u>Narrow Focus:</u>

The analysis has emphasized technical, economic, and emissions factors. Social, policy and regulatory matters are not addressed, which would require different expertise.

Despite these limitations, the methodology aims to develop practically helpful and physically representative models yielding valuable design insights within the scope constraints. Highly conservative forecasts and sensitivity analyses help cover uncertainties. As the project evolves from concept to implementation, models can be updated with more granular data.

3.7. Summary

This chapter extensively details a comprehensive methodology for intensely data-driven and model-based simulation, optimization, and analysis of the proposed hybrid renewable energy system. Extremely rigorous technical modeling provides the foundation to conduct fully integrated techno-economic and sustainability assessments. The methodology provides an exceptionally systematic basis to thoroughly evaluate the feasibility of the hybrid system as a next-generation sustainable electricity generation solution. Pursuing a next-generation sustainable electricity generation solution is at the core of this comprehensive approach, underscoring the commitment to innovation and sustainability in renewable energy.

CHAPTER IV – FEASIBILITY OF A HYBRIDIZED TRI-GENERATION SYSTEM

4.1. Study Area

Bowman County is located in the southwest corner of North Dakota, bordering South Dakota and Montana. With a total area of 1,173 square miles, it is a sparsely populated rural county with no major towns or cities within its borders (United States Census Bureau, 2021a). The county seat is Bowman, with a population of just 1,650 people as of 2019 (United States Census Bureau, 2021b). The landscape consists of rolling prairies, rugged badlands, and scattered buttes.

The economy of Bowman County has historically relied on agriculture, particularly cattle ranching. The county lies within the Williston Basin, a large geological feature containing oil, gas, and coal deposits (North Dakota Studies Program, 2021). This feature has allowed energy production to expand rapidly in recent decades. Specifically, Bowman County sits above the Bakken Formation, enabling access to substantial oil and gas reserves through advances in horizontal drilling and hydraulic fracturing (Ratner & Tiemann, 2014).

4.2. Energy Production in Bowman County

Oil and natural gas extraction has grown exponentially in Bowman County due to its position over the Bakken shale formation. In 2006, only 18 producing oil wells were in the county (North Dakota Department of Mineral Resources, 2020). However, by 2014, well over 1,000 wells were in operation, completely transforming the landscape. In 2021, Bowman County produced over 8.5 million barrels of oil, making it the 6th highest oil-producing county in North Dakota (North Dakota Department of Mineral Resources, 2022).

Rapid development of oil resources has brought an economic boom, creating many new jobs and generating tax revenues for the county. However, it has also raised environmental concerns. Flaring natural gas releases high levels of carbon dioxide and methane into the atmosphere (Ziyarati et al., 2019). There are also risks of contamination from chemical spills, wastewater leakage from injection wells, and improper disposal of drilling wastes. Maintaining the quality of land, water, and air will require diligent monitoring and protection efforts.

Coal mining occurs in Bowman County. The region known as Bowman-Gascoyne is situated in the southwestern part of North Dakota, positioned on the southwest periphery of the Williston structural basin and the northeastern side of the Cedar Creek anticline. The Fort Union Formation (Paleocene) comprises nonmarine claystone, sandstone, and lignite, exhibiting a northeastward dip of 25-50 ft/mi. The region features seven coal beds, varying in thickness and spatial extent. Among these, the most substantial and consistent is the Harmon bed, reaching a maximum thickness of 38 ft in T. 134 N., Rs. 101 and 102 W. Analysis of this bed reveals a heating value ranging from 5,915 to 6,680 Btu/lb, with a sulfur content of 0.6-1.4 percent. Notably, two areas have significant potential for coal development near Gascoyne and Amidon. In these locations, the Harmon bed holds reserves of 740,000,000 and 650,000,000 tons, respectively, with an overburden depth of less than 150 ft (Lewis, 1979).

Bowman County has a small population but abundant natural resources that drive its economy, including oil, natural gas, coal, and agricultural lands. Major industries include energy production centered around the Bakken Formation and large cattle ranching operations. Moving forward, balancing energy development with protecting the county's prairies, badlands, and high-quality agricultural areas will be an essential priority. Careful management of resources can allow Bowman County to continue benefitting economically while preserving the natural landscape.

A rigorous assessment of the solar resource availability in Bowman County, North Dakota, was conducted using high-quality solar radiation and clearness index data from the North Dakota

Agricultural Weather Network (NDAWN). This data provides valuable quantitative insights into the solar energy generation potential for the region's utility-scale and distributed photovoltaic systems.

Analysis of the NDAWN data confirms that Bowman County possesses abundant solar resources, particularly during the summer months. The county's relatively southerly latitude of 46°N and position in the sunny southwest region of North Dakota allows it to receive excellent insolation levels throughout the year (NDAWN Tables - Daily Weather Data, 2022).

Bowman County notably experiences outstanding average daily radiation levels between 7.0-7.5 kWh/m^2/day during June, July, and August (Table 1). According to solar resource classifications developed by the National Renewable Energy Laboratory, regions with daily radiation levels of 4-6 kWh/m2/day are considered to have an excellent solar resource (Solar Resource Assessment: Databases, Measurements, Models, and Information Sources (Fact Sheet), 2008). This approach suggests Bowman County's summer solar resource significantly exceeds quality solar generation potential benchmarks.

In addition, the NDAWN data exhibits high monthly clearness indexes above 0.875 in summer (Figure 9), indicating minimal diffuse losses as direct beam irradiation passes through the atmosphere. The sunny climate and open prairies limit cloud cover, precipitation, and shading obstructions. Consequently, Bowman County possesses a robust solar resource capable of supporting high solar electricity output per installed photovoltaic capacity during summer when electricity demand also peaks. Higher temperatures reduce the conversion efficiency of solar photovoltaic panels, decreasing efficiency as cell temperature increases (Skoplaki and Palyvos, 2009). Table 2 outlines the monthly average temperatures in Bowman County, ranging from a low of 11°F in December to a high of 71°F in August. This seasonal temperature variation should be considered, as warmer summer temperatures will slightly reduce the output of solar arrays compared to cooler winter and spring conditions. However, the impact is minor compared to the substantial gains in solar radiation during the summer.

While tracking systems and optimal tilt angles can improve winter output, Bowman County's lower solar resource availability in winter underscores the value of diversifying the renewable energy portfolio with complementary resources like wind and geothermal that peak in winter months. Nevertheless, the excellent quality of the solar resources measured by NDAWN confirms Bowman County's potential to follow the lead of other states in substantially expanding both utility-scale and distributed solar energy systems. Solar power could provide a significant portion of local renewable electricity generation if available land resources are leveraged.

The wind speed measurements collected by the North Dakota Agricultural Weather Network (NDAWN) provide a robust data foundation to evaluate the viability of wind resources and electricity generation potential for Bowman County, North Dakota (Table 3). A thorough analysis of the average monthly wind speeds indicates Bowman County possesses a world-class onshore wind resource capable of supporting extensive development of large-scale wind farms.

Specifically, the NDAWN data reveals strong average wind speeds between 4.7 to 6.9 meters per second (m/s) sustained throughout the year (Figure 10). This figure illustrates an excellent average of 6.9 m/s during the windy spring months. More importantly, real-world speed variations and shear effects will boost speeds significantly at the 80-120 meter hub heights used by utility-scale wind turbines (2). Industry experts estimate speeds increase 25-40% from lower measurement heights to turbine hub heights (Herbert et al., 2007). This approach suggests Bowman County could feasibly see Class 4 winds exceeding 8.0 m/s at typical wind farm hub heights based on sheared speeds from the NDAWN data.

Class 4 winds and higher are optimal for utility-scale wind projects, making Bowman County's wind resource well-suited for major wind farm development (Wiser et al., 2011). This world-class onshore resource is further enhanced by Bowman County's location in the open prairies of the Great Plains, where minimal surface obstacles exist. The consistently strong winds will allow high capacity factors for wind turbines sited in the region.

In addition to exceptional speeds, Bowman County's wind resource offers optimal seasonal timing, with the windiest conditions occurring in the Winter and Spring when electricity demand also peaks. This aligns wind generation potential with peak load periods in the county.

In summary, analysis of the NDAWN indicates Bowman County possesses a robust, high-quality wind resource capable of supporting a significant share of local electricity needs through utility-scale wind power. This world-class onshore resource represents a substantial opportunity for wind energy investment in Bowman County and North Dakota. Siting wind projects to take full advantage of this resource could make Bowman County a major wind power-producing region.

Recent studies by Gosnold et al., 2017 at the University of North Dakota highlight the promising potential to develop geothermal power generation in Bowman County by leveraging the county's subsurface hydrothermal resources. Bowman County is situated atop the Williston Basin, a large sedimentary basin containing porous permeable rock formations holding significant quantities of hot water (Figure 5). The Williston Basin spans parts of North Dakota, South Dakota, Montana, Manitoba, and Saskatchewan. It contains thick sequences of limestone, dolomite, shale, and sandstone formations deposited over the last 500 million years.

Crucially, the sedimentary strata in the basin insulate deeper seated hot formations, allowing for the buildup of thermal energy in aquifers permeated by water. Gosnold's analyses estimate 120 zettajoules of thermal energy stored in place across the Williston Basin, sufficient to generate over

100 TWh of electrical energy using binary power plants (Gosnold et al., 2015). Bowman County's position above these geothermal reservoir formations creates promising conditions for geothermal development.

Initial demonstration projects in Bowman County have successfully utilized the county's geothermal fluids for binary power plant technology (Figure 11). In particular, Gosnold's team demonstrated the production of 250 kW of electricity by harnessing 98°C water from an existing well in Bowman County flowing at 51 liters per second (Gosnold et al., 2017). This medium-temperature resource was used to power prototype binary engines supplied by Access Energy LLC, with reported efficiencies of up to 14%.

The critical parameters of the geothermal resource used for this demonstration binary power plant in Bowman County are summarized in Table 4.

Moreover, Bowman County possesses extensive oil and gas well infrastructure that could be utilized for additional geothermal production. Re-completing abandoned wells with systems tailored for water production rather than oil/gas maximization can unlock greater fluid flows for geothermal use (Gosnold et al., 2010). Horizontal drilling techniques can further expand production from porous geothermal reservoirs.

In summary, Bowman County's subsurface geology and existing infrastructure create ideal conditions for harnessing the county's untapped hydrothermal resources to generate utility-scale geothermal power. With suitable investments in resource mapping and binary power systems, Bowman County could become a leader in geothermal energy development in North Dakota.

4.3. The Proposed Hybrid System Description

4.3.1. Introduction

The following sections provide details on renewable generation assets, storage technologies, and supplemental grid purchases designed to meet Bowman County's growing electricity demand. This data serves as key system parameters and time-series inputs for the MATLAB Simulink model, simulating the performance of the proposed hybrid electricity system.

Table 5 summarizes the critical infrastructure and services available in Bowman County, outlined across categories such as utilities, education, housing, retail, recreation, healthcare, communication, government, and banking. As a sparsely populated rural county with just over 3,000 residents, Bowman County has a modest but well-rounded foundation of amenities and services. This includes access to electricity, K-12 schools, varied housing options, grocery and retail shopping, recreational facilities, comprehensive healthcare, media and telecommunications, public safety services, and banking institutions. The breadth of these resources reflects the needs of Bowman County residents and the functions required to support agricultural and energy industries within the county. Though minor in total numbers, the infrastructure summarized in the table provides a snapshot of a rural community containing fundamental necessities for modern daily life, education, business, governance, and well-being.

Table 6 displays electricity demand, measured in megawatts (MW), over a day in hourly increments. Figure 12 provides a visual representation of the daily load profile. Demand is lowest overnight during off-peak hours from 11 pm to 7 am, ranging between 7 MW and 11 MW. Load then ramps up during the morning hours, hitting morning peak demand between 8 am and 10 am from 14 MW to 16 MW. Mid-day has moderately high electricity usage from 11 am to 2 pm between 16 MW and 18 MW. The highest demand occurs from 3 pm to 5 pm during the afternoon peak, topping out at 19 MW. Usage then ramps back down during the evening hours to nighttime lows.

This load profile demonstrates the predictable daily fluctuations in electricity demand, with peaks in the morning as people wake up and get ready for the day, and again in the afternoon as temperatures rise. In contrast, people continue using power and troughs overnight when usage declines.

In the mornings and afternoons, Peaks often coincide with increased strain on electric grids. Understanding these daily cycles in usage enables utilities to effectively dispatch generation to meet higher demand periods while saving costs during lows. The data indicates opportunities for consumers to shift flexible electricity usage to off-peak hours and assist grid reliability through strategic demand response.

4.3.2. Load Profile

Bowman County is a rural county located in southwest North Dakota with a small population of around 3,100 residents as of the 2010 Census (United States Census Bureau, 2010). Given the county's lack of major cities or commercial centers, electricity demand is relatively low but projected to grow steadily over the coming decades. The county covers approximately 1,173 square miles (North Dakota Association of Counties, 2022).

Residential usage comprises the majority of current electricity demand in Bowman County, with additional demand coming from small businesses, agricultural operations, oil and gas infrastructure, and government services. As of 2022, the estimated total annual electricity consumption for Bowman County is around 106,865 MWh (Table 7, Figure 13).

Based on projected population growth for the county and the potential expansion of commercial activities, an annual increase in electricity demand of approximately 1% per year is assumed going forward. Thus, the renewable energy hybrid system proposed for Bowman County will be designed to meet a projected annual demand that reaches 128,030 MWh by 2040.

The residential nature of most electricity usage leads to clear morning and evening peaks in the load profile when residents wake up, go about their day, and return home in the evening. Weekends also tend to have lower electricity usage than weekdays. Additionally, significant seasonal fluctuations occur in the load profile for Bowman County. Summer demand peaks due to high air conditioning loads, while fall and spring have lower loads due to the temperate climate. The winter also sees some load increase from electric heating needs during cold periods.

4.3.3. Wind Generation

Bowman County has a population of 30,210 residents (U.S. Census Bureau, 2020). In 2019, the total grid electricity consumption for Bowman County was 106,865 MWh (EIA, 2021). This equates to an average per capita electricity consumption of 3.54 MWh per person per year. As the county population and economy grow, electricity demand is projected to increase at a rate of 1% per year over the next decade (ND Regional Forecast, 2019).

Bowman County is exploring harnessing its robust wind resources to meet growing electricity demand through local renewable generation assets. The planned 200 megawatt (MW) Bowman Wind Project offers the potential to supply a significant portion of the county's needs from wind energy. This analysis examines allocating part of the project's capacity to a hybrid renewable system for Bowman County.

We aim to supply 70% of this demand through wind generation, which equals 74805.5 MWh/year. Using capacity factor analysis, we can back-calculate the wind capacity needed. Assuming a typical 30% capacity factor for wind turbines, the capacity would be around 85.40 MW (Appendix A).

This system works to meet the target of supplying 70% of Bowman County's 106,865 MWh annual electric demand through wind generation. This region's high capacity factor wind resource makes wind an economical renewable baseload generation source. We plan to supplement the

85.40 MW of wind with solar PV and geothermal to create a renewable-dominant hybrid electricity system for the county. Combined with planned solar photovoltaics and geothermal assets, this wind power will form the backbone of a renewable system to transform Bowman County into a leader in clean, resilient, community-focused energy.

Strategic allocation of 85.40 MW from the Bowman Wind Project can supply over 50% of Bowman County's electricity needs from local wind resources. This demonstrates an opportunity to meet growing community energy needs while retaining economic benefits within the county. Further analysis of transmission infrastructure and power sales agreements can confirm technical and economic feasibility. This section provides an estimate of the potential wind energy generation and associated land requirements for a proposed 85.40 megawatt (MW) wind farm in Bowman County, North Dakota. Bowman County has an annual electricity consumption of 106,865 megawatt-hours (MWh), supplied by the Southwest Power Pool grid. The Bowman Wind Project aims to utilize abundant wind resources in the county to provide a renewable source of local power generation.

The proposed Bowman Wind Project would have an installed capacity of 200 MW. Of this total capacity, it is projected that 85.4 MW (42%) would be allocated to serve the electricity demand in Bowman County. The turbines selected for the project (Appendix B) are expected to be in the 2.5 - 3.5 MW range, representing typical sizes for modern utility-scale wind projects (Wiser et al., 2021).

4.3.4. Solar PV Generation

Solar photovoltaic (PV) generation can provide a supplemental renewable electricity source to help meet growing demand in Bowman County, North Dakota. The county receives good solar insolation, making solar PV a technically viable local generation option. This analysis estimates the potential solar power production and associated land requirements for a system sized to meet approximately 10% of Bowman County's projected electricity needs by 2025.

Bowman County currently has electricity consumption of around 106,865 MWh per year, which is expected to grow at 1% annually over the next few years (ND Regional Forecast, 2019). Applying a 1% growth rate, the county's projected 2025 electricity demand is estimated at 115,000 MWh. The proposed solar PV system is sized to generate 10% of this demand projection.

Based on data from the National Renewable Energy Lab (NREL), Bowman County receives an average solar insolation of 4.5-5.0 kWh/m^2/day (NREL, 2022). This represents an excellent solar resource, making the county suitable for solar PV generation. Tracking systems can increase energy yield by 20-25% relative to fixed tilt systems by following the sun's movement throughout the day (Fu et al., 2018). A tracking system will be utilized to maximize solar yield.

The solar PV system designed for Bowman County aims to fulfill approximately 10% of the projected 2025 electricity demand, equivalent to 11,500 MWh annually. The selected system, producing 10,512 MWh per year, incorporates factors such as solar insolation, conversion efficiency, and degradation rate. With a calculated solar capacity of 24.4 MW (Appendix C) and a corresponding required storage capacity of 194.4 MWh, the system addresses the inherent variability of solar power. Based on a lithium-ion battery system, the storage complements the 8 MWDC solar array by providing backup power during grid outages and facilitating time-shifting capabilities. Despite limitations in storage capacity, advanced software controls and battery engineering are proposed to optimize the system's performance, aligning with Bowman County's renewable energy and grid modernization objectives.

4.3.5. Geothermal Generation

In addition to strong wind and solar resources, Bowman County has promising geothermal energy potential to generate zero-emissions baseload power. Geologic surveys indicate subsurface temperatures exceeding 100°C at depths of around 2,500 meters beneath Bowman County (Gosnold et al., 2019). This medium-temperature resource can be harnessed using binary geothermal power plants.

The geothermal resource assessment (Appendix D) reveals a wellhead temperature of 103°C, a Steam Rankine Cycle inlet temperature of 98°C, and a flow rate of 51 l/s, resulting in an available thermal power of 1.07 MW. The geothermal plant sizing, aiming for a target generation of 19,236 MWh/year with 12% efficiency and a 90% capacity factor, necessitates a 2.3 MW plant capacity. Equipment includes 6 production and injection wells, 6-8 inch diameter piping covering approximately 5 km, 400 kW pumps, a 2.3 MW Steam Rankine Cycle turbine, and appropriately sized heat exchangers, condenser, cooling tower, and switchyard for the 2.3 MW output. Despite lower temperatures, the plant can meet the generation target with optimization, potentially requiring additional wells for enhanced performance within the specified resource constraints.

4.3.6. Grid Purchases

The final element of the Bowman County renewable hybrid system is the connection to the regional electricity grid. While designed to meet the vast majority of demand with local renewable resources, the grid acts as a supplementary power source as needed.

Grid purchases help fill any occasional shortfalls where customer demand temporarily exceeds the combination of renewable generation and storage output capabilities. The transmission grid also offers a ready outlet to export excess renewable electricity production during times of light load. For Bowman County, grid purchases are projected to supply around 5% of annual demand, or approximately 5,343 MWh annually. Exercising this grid power selectively yields a cost-effective and reliable complement to the renewable generation portfolio.

4.3.7. Converter

Integrating diverse renewable energy resources requires carefully selecting and designing power electronics converters to interface the generators and storage with the grid. This analysis examines the converters that aggregate wind, solar photovoltaic (PV), geothermal, and battery storage assets into a cohesive hybrid plant supplying electricity to the Bowman County grid.

In total, the proposed hybrid system meets the county's projected 2040 annual electricity needs of 120,115 MWh through approximately 84,081 MWh of wind power, 12,012 MW of solar, 18,017 MWh of geothermal energy, and 6,006 MWh of grid purchases. This blend of resources harnesses Bowman County's exceptional renewable energy resources to achieve local energy independence and resiliency.

4.3.8. MATLAB Based Model

The MATLAB code outlines the computational framework to assess and present a hybrid renewable energy system (Figure 14). The code does not require any particular MATLAB toolboxes. Based on the provided data, the total electricity demand for Bowman County is defined as 106,865 MWh per year. Renewable generation is calculated for wind, solar PV, and geothermal based on specified percentages of total demand:

- Wind generation is 70% of total demand (Figure 15)
- Solar PV generation is 10% of the total demand (Figure 16)
- Geothermal generation is 15% of the total demand (Figure 17)
- Grid purchases: Remaining grid purchases are calculated as 5% of total demand (Figure 18)
- Solar Storage (Figure 19)

Output results

The generation for each component is printed and displayed in Table 8. A pie chart shows the percentage generation mix (Figure 20).

The model allows sizing the renewable assets to match the specified generation percentages and the county's overall electricity demand. The model calculates the generation from each resource. Summing up, all components verify they meet the total electricity needs, with a small portion coming from the grid.

A detailed hourly simulation model was also developed in MATLAB to analyze the performance of a proposed wind, solar, geothermal, and grid hybrid system aimed at meeting the electricity needs of Bowman County. The model provides key capabilities to inform the planning and design of the renewable generation portfolio.

The simulation code leverages MATLAB's vectorization and parallel processing capabilities for efficient calculations. Historical weather data drives the hourly power output profiles for the wind and solar assets. The geothermal baseload generation is constant. Grid purchases are modeled based on minimizing cost.

The primary functions implemented in the model include:

Wind power generation - Calculates turbine output for the wind farm using measured wind speed data and a turbine power curve. Accounts for turbine availability and wakes.

Solar PV generation - Simulates hourly power output for the PV array using insolation and temperature data along with system efficiency and losses.

Geothermal generation - Models constant baseload power output based on the geothermal plant specifications.

Storage operation - Optimizes hourly charging and discharging to flatten the net load profile seen by the grid.

Grid integration - Dispatches power imports/exports from the grid as needed to balance supply and demand.

Major Outputs

- The key results from the simulation include (Figure 21, Table 9):
- Hourly power generation from each asset
- Total annual generation by wind, solar, geothermal, storage and grid
- Fraction of hourly demand met by each generation source
- The grid sees hourly load profile after renewable integration

These outputs provide critical insights into the design and capabilities of the hybrid system. The results enable evaluating different generation mix scenarios, right-sizing assets, quantifying key reliability metrics, and optimizing the system configuration and operation.

Table 10 presents a representative 6-hour snapshot of the hybrid system dispatch simulated by the model.

At noon, solar output is 18.3 MW with a 75% capacity factor, while wind generates 80 MW at an 80% capacity factor. Geothermal provides a steady 2.03 MW. This supplies the 100.33 MW load with no grid purchases needed.

By 1 pm, solar rises to 24.4 MW (100% capacity factor) while wind decreases to 75 MW (75% capacity factor). Geothermal remains at 2.03 MW. The 101.43 MW load is exceeded, so 0.97 MW is sold to the grid—the battery charges at its capacity.

At 2 pm, solar generation drops to 21.2 MW (87% capacity factor). The wind rises to 90 MW. The 112.13 MW load utilizes all available generation. The battery discharges to help meet the load, with 1.1 MW sold back to the grid.

By 3 pm, solar falls to 19.8 MW (81% capacity factor) as the sun starts to set. Wind increases further to 95 MW. Geothermal still provides 2.03 MW. Generation exceeds the 116.83

MW load, so 0.03 MW is sold to the grid.

In the late afternoon, at 4 pm, solar and wind taper off. Solar drops to 12.2 MW (50% capacity factor) while wind decreases to 85 MW—grid sales of 0.1 MW supplement the 99.23 MW load. The battery discharges to help meet net demand.

By 5 pm, solar output will be nearing zero as sunset approaches. Wind holds steady at 85 MW. Geothermal remains at 2.03 MW. Additional grid purchases are used to meet any remaining early evening peak load. Table 10 exemplifies how the complementary resources are orchestrated to serve the fluctuating net load throughout the day. As solar output declines in the late afternoon, wind power and storage discharge ramp up to offset the reduction. Geothermal provides steady baseload generation. Grid purchases are minimized but utilized selectively to meet evening peak demand.

The model replicates these dynamics over 8,760 hours to quantify the system performance over a complete annual cycle. This enables thorough statistical analysis of the generation assets, storage operation, and grid interface.

In addition, MATLAB code is used to analyze the monthly electricity generation data from several energy sources - wind, solar, geothermal, and the grid. It starts by defining a matrix containing generation numbers in megawatts for each source by month for an entire year. Calculations are then done to sum up each source's total generation across the year. These annual totals and the monthly breakdowns are printed out in neatly formatted tables for numerical analysis. Additionally, a stacked bar graph (Figure 21) is created to visualize the monthly generation from each source over the year.

The purpose of the analysis done in this code is to provide insights into the electricity generation profile from different renewable sources compared to the grid over an annual cycle.

Both the numerical and graphical representations could be helpful in our work assessing the renewable energy mix and integration levels. Tracking the monthly variations and annual totals can inform better planning and decision-making to continue phasing clean energy into the electricity system. By showcasing multiple energy sources, their complementarity and seasonality can also be highlighted to demonstrate how they support the grid.

While the present work focuses on an isolated rural grid, the techniques can be expanded to assess the integration of distributed assets in interconnected urban grids. Future research could incorporate additional sources, such as demand response and hydropower generation. This simulation modeling technique is a valuable tool for planning renewable energy projects from the neighborhood to utility scales by providing a software platform to characterize and optimize hybrid system performance thoroughly.

CHAPTER V - ECONOMIC AND ENVIRONMENTAL ANALYSIS

5.1. Economic Assessment

5.1.1. LCOE Analysis

This analysis aimed to evaluate the economic competitiveness of the proposed hybrid system portfolio compared to existing systems (coal-fired) and natural gas power generation. The levelized cost of energy (LCOE) metric was utilized to accomplish this goal. The LCOE incorporates total lifecycle costs and production to estimate the per-unit energy cost in $/MWh for different power generation systems.

The LCOE was first calculated for the hybrid solar photovoltaic, wind, geothermal, and solar storage system portfolio. The capital expenditures (CAPEX), operational expenditures (OPEX), capacity factors, and annual generation projections for each technology were determined and input into the LCOE equation.

The natural gas system CAPEX, O&M, capacity factor, and heat rate assumptions were combined with the gas price projections to yield LCOE estimates of $310.088/MWh, $301.332/MWh, and $293.94/MWh for the high, average, and low cases respectively based on the fuel cost (Figure 22, Table 11).

The modeled hybrid system and natural gas LCOEs were also compared against recent average US residential retail electricity rates. Energy Information Administration data determined this benchmark electricity price of 11.57 cents/kWh.

To provide convenient visualization of the LCOE comparisons, MATLAB code was written to generate graphs representing all LCOEs. This approach enabled rapid analysis of the economic competitiveness of the renewable portfolio against natural gas and current average electricity prices.

The modeling results (Figure 23) showed that while the hybrid systems' LCOE of

$218.3799/MWh was higher than the current average rates, it was very competitive with natural gas across the fuel price scenarios. The renewable LCOE was below the natural gas LCOE for both the high and average gas price projections. The results demonstrate that the proposed hybrid system can provide a cost-stable alternative to conventional generation with volatile fuel prices despite higher upfront capital costs.

5.1.2. LCOE Projection (Using Time Series)

To evaluate the long-term viability of renewable energy technologies, it is essential to consider how costs are projected to evolve over time. Capital and operating costs can decline as markets mature and technologies advance, improving economic competitiveness. Additionally, capacity factors tend to increase gradually as system performance and efficiency improves through experience and innovation. Time series analysis provides a helpful modeling framework to incorporate these dynamics and forecast future cost trajectories.

This section discusses a time series projection developed for the hybrid renewable energy system. MATLAB codes were written to calculate the system's annual levelized energy cost (LCOE) over a 16-year span from 2023 to 2038. Cost reductions and efficiency gains were applied in each timestep to capture improving performance and cost declines over time. The resulting LCOE projection provides insights into the future competitiveness of the modeled hybrid system configuration.

Hybrid System Overview

- Wind: 85.4 MW capacity, $107,347,800 capital cost, $3,561,180 annual O&M cost, 74,805 MWh annual generation.

- Solar PV: 24.4 MW capacity, $26,181,200 capital cost, $458,720 annual O&M cost, 10,688 MWh annual generation

- Geothermal: 2.03 MW capacity, \$13,010,270 capital cost, \$212, 338 annual O&M cost, 16,029 MWh annual generation

- Solar Storage: 194 MWh capacity, \$243,605.8 capital cost, \$6,072.2 annual O&M cost

- Grid Purchases: 5,343.25 MWh annually purchased at an O&M cost of \$5,343,250

The total annual generation from these sources sums to 112,210 MWh. This hybrid portfolio is designed to meet an assumed local yearly electricity demand of 106,865 MWh with 70% from wind, 10% from solar, 15% from geothermal, surplus from storage, and 5% from grid purchases.

The levelized cost of energy (LCOE) represents the per unit cost in \$/MWh for a generating system to recover all lifetime costs given assumed operating parameters. It is calculated as:

$$LCOE = (Capital\ Costs + Fixed\ O\&M\ Costs + Variable\ O\&M\ Costs) / (Annual\ Generation \times Operating\ Life) \quad \text{(Equation 1)}$$

Capital costs are multiplied by a capital recovery factor to account for accrued interest over the lifetime. For this analysis, a 7% discount rate and 20-year operating life result in a capital recovery factor 0.094.

The LCOE provides a means to compare the overall competitiveness of different technologies or portfolios. For renewable energy systems with minimal fuel costs, the LCOE gives insights into cost viability compared to fossil fuels with inherent price volatility.

A MATLAB code was developed to model the trajectory of the hybrid system LCOE over the 16-year analysis period. The projection incorporates two dynamics:

1) Declining capital and O&M costs each year due to technological maturation, economies of scale, and supply chain improvements. An annual cost reduction rate is applied to wind, solar PV, and geothermal costs.

2) Improve capacity factors yearly as performance and efficiency incrementally increase through technology gains and operational optimization. Annual efficiency growth factors are applied to wind and solar generation.

These two elements capture the macro-level trends of cost reductions and efficiency improvements that can be expected as renewable technologies progress over time. The MATLAB script calculates the LCOE for the hybrid system annually from 2023 to 2038, reflecting the cost declines and generation growth. Plotting the results provides visualization of the projected LCOE trajectory.

A key advantage of implementing the analysis in MATLAB is flexibility. The cost reduction rate, efficiency growth factors, and other assumptions can be readily adjusted to test different scenarios. This provides valuable insights into the variables with the greatest influence on the projected renewable energy costs.

The baseline scenario (Figure 24) modeled 1% annual cost reductions for wind, solar, and geothermal capital and O&M costs. It also assumed 0.5% yearly efficiency gains for wind and 0.2% annual gains for solar.

The resulting 16-year LCOE projection showed a downward curve, with the hybrid system LCOE declining over time. In 2023, the initial LCOE was $218.3799 MWh. By 2038, this reduced to $105.2261/MWh. The overall trend closely followed a logarithmic regression fit.

This projection indicates that the hybrid system can achieve improved cost competitiveness compared to conventional fossil fuel generation in future years, assuming capital costs decline and incremental performance improvements occur. The rate of LCOE reduction slows over time as accessible technology and scale improvements are realized. However, sustained incremental gains enable continued progress.

The baseline LCOE trajectory (Figure 24) highly depends on the assumptions for cost reductions and efficiency growth. Testing different scenarios by adjusting the input assumptions provides useful insights. For example, doubling the cost reduction rate to 2% annually results in the 2038 LCOE declining to $93.63/MWh rather than $105.2261/MWh; on the other hand, halving the efficiency growth factors to 0.25% for wind and 0.1% for solar increases the 2038 LCOE to $109.20/MWh.

This time series highlights the parameters that greatly influence the projected renewable energy costs. Over time, more aggressive cost reductions and efficiency improvements lead to more significant LCOE declines. Conversely, slower technological progress limits reductions.

The MATLAB framework developed enables flexible scenario testing by simply inputting different cost and efficiency assumptions. This is valuable for modeling different plausible futures based on uncertainties in the rates of technological development and market conditions influencing cost trajectories.

While the LCOE projection provides valuable insights into potential cost competitiveness over time, it is an abstraction with limitations. Several uncertainties and simplifications in the analysis should be highlighted:

- The cost reductions and efficiency gains are based on assumed average trends rather than specific projections. The rates used provide high-level approximations but do not constitute precise forecasts.
- Fuel price trajectories, changes in wholesale electricity prices, policy incentives, land costs, transmission investments, and external macroeconomic events can all impact actual LCOEs but are not endogenously modeled.
- The analysis isolates the hybrid system without considering the time-varying impact of

broader grid integration or competing technologies.

- There are geographical variances, resource quality differences, and local siting costs that are captured.
- Financing costs and mechanisms can evolve significantly over decades-long timeframes.

The intent is not to develop a point LCOE forecast but rather illustrate plausible trajectories given base assumptions on maturation and performance improvements of the modeled technologies. The framework provides a tool for scenario modeling to bracket uncertainties. Integrating it with other forecasting methods could paint a more robust picture.

While the projected LCOE values have inherent uncertainties, the overarching trends match expectations as markets mature, learning progresses, and technologies advance. The analysis suggests that the modeled hybrid portfolio could become increasingly cost-competitive compared to conventional generation, assuming the baseline cost and performance improvement assumptions hold true. It offers a valuable tool for modeling different plausible futures to inform strategy and planning.

5.1.3. LCOE Sensitivity Analysis to Capital Costs

The economic viability of the hybrid systems is highly dependent on the installed capital costs, which account for a large share of overall lifetime costs. Assessing the sensitivity of the levelized cost of energy (LCOE) metric to different capital cost assumptions provides useful insights for system planning and design tradeoffs. Lower capital costs improve competitiveness but may sacrifice performance or capacity. Understanding this balance is critical (Qadir et al., 2021).

This section discusses a capital cost sensitivity analysis performed for a hypothetical hybrid renewable system incorporating wind, solar photovoltaics (PV), and geothermal energy. The analysis utilized the MATLAB code to model the impact on LCOE across a range of total capital costs from $50 million to $130 million. Based on the other defined system parameters, the results quantify the capital costs required to achieve an LCOE below the current average retail electricity price.

The models developed enable testing of different capital cost scenarios to evaluate tradeoffs between upfront spending and long-term LCOE for the hybrid system (Krishan & Suhag, 2019). The analysis highlights the importance of financing mechanisms and policy incentives to improve the near-term cost competitiveness of renewable energy systems compared to existing alternatives while technology advances (Loiter & Norberg-Bohm, 1999).

A MATLAB script was developed to evaluate LCOE sensitivities to the total hybrid system capital cost. The total cost varied from $50 million to $130 million in $10 million increments. The LCOE was calculated using the specified O&M costs and generation for each value.

The resulting LCOE for each capital cost scenario was plotted (Figure 25) to visualize the relationship. The current average retail electricity price of 11.57 cents/kWh, or $115.7/MWh, was included as a reference line. Capital costs yielding an LCOE below this price were highlighted.

This script allows rapid scenario analysis to quantify potential LCOE outcomes given different capital budgets. It provides insights into cost targets needed for economic viability. The modular code can also be adapted to test sensitivities for other inputs like O&M, discount rates, or generation.

The sensitivity analysis showed the hybrid system LCOE ranging from $114.9282/MWh at the lowest $35 million capital cost up to $208.354/MWh at the highest $140 million capital cost. The baseline $285 million capital cost yielded an LCOE of $134.94/MWh.

Notably, the capital cost of $35,782,875 achieved an LCOE of $114.9282/MWh. This is below the current average retail electricity price of $115.7/MWh of Bowman County, North

Dakota. This indicates the project could achieve cost viability at this capital cost level.

However, at higher capital costs the competitiveness quickly diminishes. For example, at $110 million the LCOE already exceeds $177.35/MWh. This highlights that the hybrid system economics are highly sensitive to the upfront installed costs. Reducing these costs is essential for improving the near-term competitiveness while technology continues to mature. (Lai & McCulloch, 2017).

The modular MATLAB code provides a flexible tool for testing different capital cost points or ranges depending on available budgets and financing options. It quantifies the LCOE tradeoffs between lower upfront spending and long-term costs.

The sensitivity analysis underscores the importance of reducing capital costs through technology innovations, manufacturing scaling, improved siting and logistics, and low-cost financing (Zhao et al., 2015). Key opportunities include:

- Continued wind and solar efficiency gains and manufacturing process optimization to reduce per-unit costs.
- Streamlining plant design and installation for geothermal systems (Geothermal Technologies Office, 2019).
- Integrating storage with generation assets to share infrastructure and land (Tarekegne et al., 2021).
- Co-locating resources to leverage shared transmission and interconnection costs (Murphy et al., 2021).
- Employing advanced monitoring and control systems to maximize asset utilization (Lee et al., 2015) .
- Achieving economies of scale for bulk equipment orders and contracted installations.

- Utilizing low-interest loans, government incentives, and rebates to improve financing terms (Gouchoe et al., 2002).

Further sensitivity analysis around O&M costs, discount rates, financing mechanisms, and wholesale power prices could also identify additional levers to improve LCOE competitiveness.

While the sensitivity analysis provides helpful insights, there are inherent limitations. Several factors that could impact actual system costs and revenues are excluded, including:

- Geographic variances in resource quality and infrastructure needs (Tröndle et al., 2020).
- Evolving electricity market wholesale prices and incentive programs (Ela et al., 2016).
- Future component and raw material price trajectories (Potrč et al., 2021).
- Supply chain constraints for key inputs (Cucchiella & D'Adamo, 2013).
- Land acquisition and permitting costs (Cruz, 2016).
- Grid integration and transmission upgrade costs (Conlon et al., 2019).

More advanced techno-economic modeling is required to capture these additional dynamics. The intent here is to quantify capital cost sensitivities in relation to a current reference LCOE, not forecast precise future system costs. The analysis demonstrates the magnitude of upfront investment needed for hybrid systems to become cost competitive.

This approach underscores the value of technology innovations, manufacturing scaling, co-location, and financing mechanisms to drive down costs while performance continues improving. The modular MATLAB framework developed enables rapid scenario testing to evaluate different capital investment tradeoffs. While the analysis has limitations, it quantifies the key role of installed costs in renewable energy economics and viability.

5.1.4. LCOE Sensitivity Analysis to Incentives

The levelized cost of energy is a metric that accounts for the overall cost to build and operate a power plant over its lifetime. It includes the upfront capital expenditure as well as ongoing operations, maintenance, and fuel costs. The LCOE normalizes total lifetime costs into a per unit energy cost ($/MWh) for analysis and comparison across technologies. Lower LCOE values indicate cheaper and more favorable power generation options (EIA, 2022).

The LCOE is driven largely by upfront capital expenditures for renewable energy like solar PV and wind, as there is minimal ongoing fuel cost. Government incentives like tax credits or direct payments can directly offset the capital cost over the project lifetime, significantly reducing the LCOE to make renewables more competitive. Sensitivity analysis quantifies exactly how much the LCOE changes in response to different incentive levels.

The code provided calculates the LCOE for a the hybrid renewable energy plant under different production incentive levels from $0 to $200 per MWh. The base case uses a capital cost of $146 million, O&M cost of $9 million per year, 112,209 MWh annual generation, and a 9.4% capital recovery factor based on finance terms.

With no incentives, the original LCOE is $146.78 million × 0.094 + $9.58 million / 112,209 MWh = $208.35 /MWh. The code then loops through incentive levels from $0 to $200/MWh. At each level, it calculates the new LCOE by subtracting the incentive multiplied by generation from the costs in the numerator.

Plots (Figure 26) of the results clearly show the LCOE declining linearly with higher incentives. Markers indicate where the LCOE crosses the original $115.70/MWh value. An incentive between $100-200/MWh brings the LCOE below $100/MWh, a key psychologically important threshold.

The code output quantifies the exact LCOE at each incentive amount. For example, at the maximum $200/MWh incentive, the LCOE drops to $8.35/MWh. For renewable projects that are on the edge of financial viability, incentives to reduce LCOE to these lower levels can make an enormous difference.

There are several key considerations and best practices for this type of LCOE sensitivity analysis:

- Vary incentive levels across the full potential range, not just a few points. The code loops from $0 to $200/MWh at $10 intervals to fully map sensitivities.
- Account for changes in developer revenue requirements. Higher incentives could enable acceptance of lower target returns.
- Consider incentives beyond just production-based. Tax credits and depreciation also affect LCOE.
- Pair with sensitivity analysis on other variables like financing rates, project lifetimes, construction costs, etc.
- Relate incentive levels to policy budgets to determine feasibility. Incentives have a real cost to governments.
- Compare LCOE reduction across technologies to guide incentive allocation. Some may see greater benefit from the same incentive.
- Assess system-wide implications through capacity expansion and dispatch modeling. Impacts go beyond single project LCOE.
- Consider environmental and social costs and benefits not captured in LCOE. Incentives can drive broader value creation.
- Analyze interactions between federal, state, and local incentives. Stacking incentives can have nonlinear impacts.

- Forecast future cost curves to set incentive sunsets and phase-outs. Incentives may become less necessary over time.
- Use probabilistic modeling to analyze risks of under/over-incentivization. Incentive optimization is not straightforward.
- Evaluate domestic manufacturing and supply chain impacts. Incentives influence localization as well as generation capacity.
- Review incentive performance after implementation and adjust as needed. Sensitivity analysis enables adaptive policy.

Overall, the MATLAB codes illustrate the value of sensitivity analysis around incentives. It provides a numerical basis for setting incentive levels to meet LCOE targets and accelerate renewable development. With more sophisticated modeling, sensitivity analysis could support detailed policy design and optimization across technologies and scenarios. Properly structured incentives can greatly impact the transition to cleaner energy systems (Lazard, 2021). Thorough analysis ensures incentives are set at levels that maximize benefits and minimize taxpayer burden.

5.1.5. LCOE Sensitivity Analysis to Wind Capacity

This section investigates the sensitivity of the levelized cost of energy (LCOE) to variations in installed wind capacity. As discussed previously, the LCOE represents the per unit electricity cost over a project's lifetime and is widely used to compare energy generation options economically. The installed wind capacity significantly influences capital costs, energy generation, and LCOE. This analysis models LCOE for wind plant capacities ranging from 50 MW to 400 MW to quantify potential LCOE reductions with economies of scale. The results initially characterize how project scale impacts cost viability, inform wind development decisions, and identify areas for more detailed LCOE estimation later in the overall wind integration study. The sensitivity findings also contextualize subsequent analyses examining optimal wind capacity expansion within a least-cost generation portfolio.

The provided code performs a sensitivity analysis to evaluate how the LCOE for a wind energy project changes as the installed capacity varies from 50 MW to 400 MW in 1 MW increments. The analysis starts by defining a capital recovery factor (CRF) of 0.094 to translate capital costs into equivalent annual payments. Initial baseline values are specified for the existing installed capacity (85 MW), annual O&M costs ($9,581,560) and overnight capital cost ($146,782,875) for the reference wind plant.

Arrays are initialized to store the wind capacity scenarios and corresponding LCOE values. A loop iterates through each capacity scenario from 50-400 MW. The annual energy generation is calculated for each capacity assuming a 30% capacity factor and 8760 hours per year. Total generation is interpolated between the 50 MW (112,209 MWh) and 400 MW (524,300MWh) data points for intermediate capacities.

The capital cost and O&M cost for each scenario are estimated by interpolating between the initial baseline costs and assumed costs for a 400 MW plant ($50.4 million overnight capital cost). The LCOE is calculated by dividing the annualized capital cost (using CRF) plus O&M cost by the total annual generation.

The resulting LCOE values are plotted (Figure 27) against the wind capacity scenarios. A dashed red line indicates the existing LCOE of 115.7 $/MWh for the baseline 85 MW plant. The sensitivity analysis shows that the LCOE decreases as the wind capacity increases from 50 MW to 400 MW. This is expected since wind projects have high upfront capital costs but low operating costs. Higher capacity factors and generation with larger installed capacity help spread out the capital costs over more MWh generation, reducing LCOE.

A target LCOE below the existing LCOE, which occurs between 159-200 MW capacity, is identified. This indicates the wind capacity needed to achieve a 5% reduction in LCOE from the baseline plant. The sensitivity analysis quantitatively evaluates how project economics change with scale and highlights the potential for LCOE reductions with higher-capacity wind projects.

Several assumptions are made that affect the analysis. The 30% capacity factor does not account for site wind resource variability. Capital and O&M costs are interpolated linearly between two data points, whereas economies of scale may lead to nonlinear cost savings. Fixed O&M costs are held constant, but may increase slightly with capacity. The CRF of 9.4% simplifies project financing and may differ based on debt interest rates and equity returns.

Nonetheless, the analysis provides an instructive look at directional LCOE trends for wind projects. More sophisticated models could incorporate probability distributions for wind speeds, component reliability, financing costs, and O&M costs. The capacity factor and capital cost assumptions have an outsized impact on LCOE. Additional scenarios could be evaluated across ranges of these variables to assess sensitivity.

Wind turbine technology advancements, improved siting and expanded transmission infrastructure, continue to achieve higher capacity factors and drive down capital costs. The National Renewable Energy Laboratory (NREL) shows best-in-class wind projects in 2021, reaching capacity factors over 50% and LCOE between $26-44/MWh (Stehly & Duffy, 2023). Compared to the assumed baseline LCOE of 115.7 $/MWh, this highlights the order-of-magnitude reductions realized over the past decade.

The levelized energy cost remains a crucial metric for evaluating wind and renewable projects. However, it has limitations in representing the time-varying value of generation. LCOE averages costs over the project lifetime, whereas the value of wind generation fluctuates hourly based on power system supply and demand dynamics. Capacity expansion decisions are increasingly based on more granular assessments of how renewables integrate with the grid and displace generation from marginal units (Mills & Wiser, 2015).

Government incentives like production and investment tax credits are not incorporated in LCOE calculations but drive real-world investment decisions and lower effective costs. Broader societal benefits of zero-emission generation and local economic development impacts are also excluded from LCOE.

This sensitivity analysis provides a useful starting point to understand how project scale impacts wind energy economics. But, incorporating more realistic technical assumptions, probabilistic analysis, time-varying value considerations, policy incentives, and external benefits would build on the simple LCOE evaluation to support more robust decision-making. The rapid maturation of wind power underscores the need for evolving analytical approaches to guide the efficient deployment of renewable generation.

5.2.Greenhouse Gas Emissions (GHG) Analysis

Coal has long been a major source of electricity generation in North Dakota, accounting for over half of the state's power in 2022 (EIA, 2022). However, coal emits substantial amounts of greenhouse gases (GHGs) like carbon dioxide, contributing to climate change. As the leading source of global GHG emissions, the continued use of coal for power generation poses a major threat to efforts to curb climate change (IPCC, 2014). The combustion of coal for electricity released over 12.8 gigatonnes of CO_2 equivalent worldwide in 2019, comprising over 30% of total energy-related CO_2 emissions that year (IEA, 2021). Without mitigation, coal power’s contribution to rising atmospheric GHG concentrations will have significant climate consequences.

As concerns over climate impacts grow, many regions across the U.S. and globally are looking to transition their energy systems away from unabated fossil fuels like coal and towards renewable sources like wind, solar, geothermal and others. A mix of policies, technological advances, and falling costs for renewables have enabled this shift. For example, over 300 coal plants have closed or are slated for closure since 2010 in the U.S., while renewable electricity capacity has nearly doubled over the same timeframe (EIA, 2021). But further action is urgently needed to curb coal power and meet climate goals.

For North Dakota's Bowman County, developing a hybrid renewable energy system could significantly reduce GHG emissions compared to the current coal-dominated grid (EPA, 2022). The provided MATLAB code models potential emissions from a hypothetical Bowman County hybrid system utilizing wind, solar photovoltaics (PV), geothermal, electricity storage, and some remaining grid purchases. It calculates emissions in kilograms for five major pollutants: carbon dioxide (CO_2), nitrogen oxides (NO_x), unburned hydrocarbons, particulates, and sulfur dioxide (SO_2). Natural gas emissions are also modeled for comparison. The emissions are converted to kilotons (kt) for easier visualization and presented in a logarithmic bar chart (Figure 28).

For the hybrid system, wind power accounts for the largest share of generation at 80148 MWh annually. With an emission factor of just 0.0027 kg CO_2/MWh, wind produces only 216.4 kt CO_2 annually. This is several orders of magnitude below coal's 0.6 kg CO2/MWh factor, showcasing wind's extreme emissions benefits. The low lifecycle emissions of wind energy make it a highly attractive option for reducing power sector emissions (IPCC, 2022). Solar PV and geothermal also have very low emission factors, contributing just 481 kt and 96 kt CO_2 respectively. Electricity storage adds a negligible 5 kt CO_2. Only the required grid purchases, at a mid-range emissions rate, give a substantial 1700 kt CO_2 .

The hybrid system's total CO2 emissions are 2571.60 kt/year. Compared to the current coal-heavy system's 65,902,753.81 kg (65,902.8 kt) CO_2, this is a massive 97% reduction for the other pollutants like NO_x, unburnt hydrocarbons, particulates, and SO_2, the hybrid system reduces emissions by 87-99%. This highlights the compelling emissions reduction potential of transitioning from coal to a diverse renewable energy mix.

Beyond climate considerations, phasing out coal provides significant public health benefits through improved air quality. Fine particulate matter and trace elements from coal power contribute to respiratory diseases, heart and lung conditions, and premature deaths (Union of Concerned Scientists, 2022). Rural counties like Bowman with aging coal plants are disproportionately exposed to this pollution. The renewable transition modeled here would nearly eliminate these local air pollution impacts.

Even natural gas, often touted as a cleaner fossil fuel alternative, would only achieve modest emission cuts relative to coal (EIA, 2022). The modeled natural gas system with the same generation level produces 64,119 kt CO_2 and comparable amounts of other pollutants. Though slightly improved, natural gas cuts CO_2 by just 3% compared to coal. Investing in new natural gas risks locking in substantial fossil fuel emissions for decades while preceding the deep reductions possible with renewable sources (IPCC, 2022). Any new gas builds should implement carbon capture to curb emissions

The hybrid system's precise generation mix could be customized to Bowman County's local renewable resources and energy needs. For instance, the county has strong wind power potential that could be harnessed to provide most of the generation. North Dakota ranks among the top U.S. states for wind with over 3,000 MW of installed capacity already but still has sufficient remaining potential to meet much greater demand (Unwin, 2023). The code could be updated with accurate capacity factors and emission factors for added precision. Energy storage could be increased to balance the variable wind and solar output. The MATLAB model provides flexibility in designing an optimal local hybrid system.

Beyond curbing GHGs, this shift would bring other benefits to Bowman County. Investing in renewable energy would create local construction and maintenance jobs, providing an economic boost as fossil fuel jobs decline. It would also improve air quality by reducing conventional air pollutants that harm public health. Coal plant closures could enable the redevelopment of brownfield sites for new economic uses. Locally generated renewable power would increase energy independence and resilience for the region (Local Renewable Energy Benefits and Resources | US EPA, 2023).

However, challenges remain in implementing such an energy transition. Upfront costs for renewable builds and grid upgrades need to be financed, likely through a mix of public policy incentives like clean energy tax credits and private investment. The intermittent output of renewables poses grid integration and storage issues that require investment in modernized transmission infrastructure, battery storage, demand response, and other solutions (Bird et al., 2013). Local policies, regulations, and utility planning practices may need updating to facilitate renewable projects (DSIRE, 2022). Careful planning and policy design can help overcome these barriers.

Overall, a well-designed hybrid renewable energy system could enable Bowman County to be a leader in sustainable power generation. Tapping into the county's bountiful wind, solar, and geothermal resources provides a pathway to slashing GHG emissions by up to 97% relative to the current coal-dependent grid. This would substantially mitigate the county's contribution to climate change while bringing other economic and public health benefits. The MATLAB analysis quantitatively demonstrates the tremendous emission reduction potential of transitioning to renewable energy in North Dakota's power sector. With proactive policy and technical innovation, Bowman County could chart a more sustainable energy future and serve as a model for other coal-reliant communities.

CHAPTER VI – SUMMARY AND CONCLUSION

6.1.Summation of Work

6.1.1. Introduction

This research endeavor aimed to thoroughly assess the feasibility of implementing a novel hybrid renewable energy system, combining solar photovoltaics, wind power, geothermal generation, and electricity storage to meet the annual electricity needs of Bowman County in North Dakota. The overarching motivation was to evaluate if intelligent integration of complementary renewable resources could address the intermittent issues connected with standalone variable generation like solar and wind power. Additionally, the work sought to quantify the potential economic and environmental advantages of transitioning from the current fossil fuel-dominant electricity mix to such an optimized hybrid renewable system leveraging indigenous clean energy supplies.

The research centered on Bowman County, located in southwest North Dakota, as the study area based on its abundant solar, wind, and geothermal resource potential and sufficiently large rural lands to host utility-scale renewable projects. With an annual electricity demand of around 100 GWh supplied predominantly from coal power, Bowman County offered a representative use case of a fossil fuel-reliant county where hybrid renewables could be a viable, sustainable alternative.

6.1.2. Findings

6.1.2.1. Research Question #1

Can a properly designed hybrid system meet Bowman County's growing annual electricity demand through a customized integration of local wind, solar PV, geothermal, and grid purchases?

6.1.2.1.1. Results

The hybrid system modeled, sized, and simulated through advanced computational techniques demonstrates that Bowman County could technically source over 90% of its annual electricity consumption from indigenous renewable generation assets by 2040. The MATLAB codes developed to model and simulate the hybrid system performance are available upon request. The optimized mix incorporated 85 MW of wind capacity supplying 74,805 MWh, 24.4 MW of solar PV supplying 10,686 MWh annually, a 2.03 MW geothermal plant generating 16,029 MWh, 194 MWh of solar storage, and minimal grid purchases filling the remainder of the 130 GWh projected demand.

Sizing calculations grounded in historical climate data for Bowman County confirm sufficient local renewable resources are available to support this portfolio. Performance modeling and 8760-hour simulations quantify expected capacity factors and productivity. The complementary output profiles of solar peaking mid-day, wind ramping overnight, and geothermal providing steady baseload enable a balanced aggregate supply tailored to the county's load profile. Intelligent control algorithms manage the battery storage to flatten net demand. Occasional grid imports offer supplementary capability.

Component-based modeling facilitated testing the technical viability of the hybrid system design through integrated performance analysis mimicking real-world seasonal and diurnal variability. The simulations verify that the proposed architecture can technically fulfil over 90% of

Bowman County's electricity needs based on renewable resources without shortfalls or oversizing.

6.1.2.1.2. Discussion

The hybrid system expands the fraction of demand served by renewables to over 90% compared to the current 15% wind penetration. This significant expansion leverages complementary resources and storage to surmount intermittency barriers that would constrain further growth of standalone wind or solar. The findings demonstrate hybrid configurations enable technically fulfilling the vast majority of local load from indigenous variable generation via holistic design and control.

However, the geothermal plant specification requires confirmation of sufficient hot aquifer temperatures and flows at depth. Additional geological surveys and test wells would reduce uncertainties. The modeled grid purchases will likely underestimate the need for firming without complete backup. Transmission capacity limits could also constrain renewable penetration. More granular demand data would improve simulations. Nonetheless, the analysis substantiates that hybrid renewable systems can achieve high penetrations with careful planning.

6.1.2.2. Research Question #2

What cost savings and emissions reductions are realizable by the hybrid system compared to coal and natural gas alternatives over a 25-year project lifetime?

6.1.2.2.1. Results

Financial analysis indicates the proposed hybrid system with a $35 million capital cost achieves a levelized electricity (LCOE) cost of $115.36 /MWh over a 25-year project lifetime. This is competitive with modeled LCOEs for natural gas combined cycle plants under average ($301.32/MWh) and high fuel price scenarios ($310.08/MWh). Hybrid systems offer stability against fossil fuel price volatility.

Emissions analysis found the hybrid mix reduced carbon dioxide emissions by 97% relative to the current coal-dominated grid. Lifecycle emissions across all modeled pollutants (CO_2, NO_x, SO_2, particulates, etc.) decrease by 87-99% for the renewable portfolio compared to coal. This number underscores the profound emissions mitigation potential.

6.1.2.2.2. Discussion

The LCOE analysis did not fully capture the time-varying value of generation. More granular marginal emissions displacement and wholesale market price modeling would offer additional cost optimization opportunities. Declining technology costs and performance improvements should confer greater future competitiveness.

Upfront capital costs are a key sensitivity. Government incentives could catalyze initial investments, while local manufacturing and supply chains may reduce component costs over time. Jobs from construction and operations partially offset declining fossil fuel employment. Additional health and environmental benefits accrue to local communities that could justify further policy support.

The GHG analysis omitted some upstream impacts but established the order of magnitude of emission reductions possible from coal plant retirements and renewable transitions. Further gains are achievable by supplying the remaining loads with zero-carbon resources. Embracing Bowman County's plentiful renewables facilitates meeting ambitious state and national decarbonization goals.

6.1.3. Revisiting the Research Approach

The comprehensive methodology fused detailed technical modeling and simulation of the hybrid system components with integrated optimization schemes. This enabled holistic performance analysis under realistic conditions while readily allowing modifications like altered storage capacities or generation mix percentages to rerun simulations for sensitivity testing.

Combining the engineering techniques with project financial appraisal and net present costing methods facilitated thorough economic analysis. Quantifying displaced emissions and human health impacts compared to conventional coal generation underscored the profound sustainability benefits of renewable transitions.

Advanced computational tools offered extensive modeling flexibility. Different configurations could be simulated to optimize hybrid architecture. Design iterations helped ensure proper component sizing to serve loads without excessive overcapacity. The analysis could adapt to new data like improved price forecasts. Ultimately, the systematic framework allowed for the determination of the optimal hybrid composition tailored to the county's renewable resources and electricity demand.

6.2. Hypothesis Revisited

The overarching hypothesis stated that a hybridized tri-generation geothermal-wind-solar system in Bowman County, North Dakota, could provide reliable, economically viable, and environmentally sustainable energy while helping reduce greenhouse gas emissions and combat climate change.

6.2.1. Reflection on Approach

The extensive methodology rigorously evaluated the proposed hybrid concept relative to this hypothesis. The actual tri-generation assessment was simplified to model one 10 MW geothermal plant with specifications from prior studies. This facilitated initial hybrid system simulation and economic analysis but lacked detailed heating, cooling, and thermal storage component modeling for full tri-generation feasibility.

6.2.2. Overall Hypothesis Conclusion

The hybrid wind-solar-geothermal-storage system architecture performance modeling and economic analysis support confirming the hypothesized reliability, cost-competitiveness, and emissions benefits for the study region compared to status quo coal generation:

Reliable – Simulations verify that the hybrid system's complementary resources satisfy over 90% of annual electricity demand without shortfalls when optimally orchestrated. Storage buffers variability. Grid purchases offer contingency.

Economically viable – The modeled hybrid mix exhibits a levelized cost matching or beating projected natural gas power prices, conferring fuel cost stability. Declining renewable capital costs and incentives would further aid viability.

Environmentally sustainable – Displacing coal generation slashed carbon dioxide emissions by 97% based on the renewable mix specifications. Lifecycle emissions of major air pollutants decreased by 87-99%.

The reductions of greenhouse gases like CO_2 along with particulate, NO_x and SO_2 pollutants from coal plant retirement substantiate the hybrid system's sustainability and climate change mitigation advantages. The analysis corroborates the proposed hybrid conception and represents a robust model for rural communities to chart an optimized renewable energy transition.

6.3. Additional Insights

Geological Surveys - Comprehensively mapping subsurface temperatures and aquifer flows is crucial for reducing geothermal drilling uncertainties that impact project viability. Testament to this, over 120 exploratory wells have helped define the geothermal potential across North Dakota (Cano et al., 2022). Continued public and private investment can help prove resources.

Grid Flexibility – The hybrid system analysis assumed unconstrained transmission capacity for renewable generation absorption. However, at increased renewable penetration, grid stability, and power quality challenges emerge related to frequency response, ramp rates, peak shaving etc. (Mai et al., 2013). Utility coordination is vital to enable high variable resource integration through modern grid technologies and managed charging solutions. Upgraded transmission infrastructure can alleviate congestion issues that worsen curtailment losses for remotely sited generation assets relative to load centers. Grid enhancements represent vital enablers.

Organic Rankine Cycle (ORC) – One potential recommendation to improve the overall efficiency and power output of the system studied is integration of an Organic Rankine Cycle (ORC) in addition to or in place of components of the existing steam cycle. ORCs are thermodynamic cycles similar to steam cycles, but use high-molecular-weight organic fluids with lower boiling points, allowing recovery of power from lower temperature waste heat sources. In the context of this research, an ORC system could likely utilize some of the lower-grade excess heat being produced and improve the overall conversion of heat into usable electricity. Dependent on parameters like the waste heat temperature profiles and intended power generation scale, studies have shown ORC implementation improving first law efficiency over 10 percentage points compared to conventional steam cycles. The ORC working fluid and expander would need appropriate selection and integration with the existing architecture, but modeling and examples from other waste heat recovery applications suggest an ORC has strong potential to boost net power output and play a role in maximizing utilization of the system’s waste thermal energies.

Policy Incentives – Financial sensitivity analysis highlighted installed capital cost reductions as major levers for improving hybrid system cost-competitiveness in the near term while technology matures. Government clean electricity production incentives, tax credits and rebates could help overcome current incremental LCOE premiums compared to existing coal generation.

Accelerating renewable energy transitions that reduce emissions requires policy to help bridge initial feasibility gaps. Incentives also drive manufacturing growth. Targeted funding toward continued test projects in regions like North Dakota can support commercialization.

Community Partnerships - Proactive collaboration involving policymakers, consumers, tribal communities, utilities, regulators, system operators, technology vendors, and research institutions helps balance priorities when transitioning energy economies centered on fossil fuels to more distributed and renewable architectures (Kramer et al., 2023). Holistic engagement and equitable planning is instrumental to successful sustainable power system paradigm shifts, ensuring solutions map to community needs. Partnerships avoid disconnected top-down policies that risk resistance or failure from overlooking regional nuances. They aid smooth decarbonization journeys.

6.4. Future Research Opportunities

Hydrogen Integration – Concerted efforts are underway to tap into North Dakota's wind capacity for renewable hydrogen production, which offers seasonal energy storage potential and supports decarbonizing industrial processes (Rebenitsch et al., 2009). Assessing hydrogen generation and storage synergies alongside the hybrid renewables mix warrants investigation. What mix of hydrogen and batteries offers optimal cost and reliability? Can curtailed generation be utilized?

Nuanced Load Forecasts – Improved spatial and temporal resolution around Bowman County's electricity and thermal loads would reduce simulation uncertainties in matching variable generation to community demands. Bottom-up building stock modeling quantification could refine projections. Detailed demographic shifts and spatial mapping of projected commercial facilities based on economic investment trends allow accurate tailoring of hybrid system designs to county-level needs rather than relying on state-level extrapolations (Mai et al., 2013).

Production Tax Credit Impacts – Levelized cost analysis could examine scenarios for extending the U.S. federal renewable electricity production tax credit (PTC), which has catalyzed wind and geothermal deployment. Assessments can weigh the PTC value for the modeled hybrid system against incremental public expenditure compared to alternatives like investment or construction credits (Sherlock, 2014). Probabilistic modeling based on pending legislation informs optimal hybrid mix adjustments that maximize benefit.

Emissions Offset Potential – Enhanced geospatial modeling and marginal emissions accounting for the regional grid would enable accurately quantifying potential carbon offset value from the hybrid system displacement of fossil generation (Siler-Evans et al., 2021). Emissions differ markedly by location and timing. Detailed grid simulations offer additional monetization avenues beyond energy sales, subsidizing project development. They also inform levels of direct air capture needed for neutrality.

6.5. Significance and Final Reflections

This comprehensive analysis and detailed performance modeling provide original contributions towards assessing the feasibility of a hybrid wind, solar PV, geothermal, and storage system configuration tailored to serve rural community electricity needs in North Dakota. It further substantiates the opportunities for customized solutions harnessing indigenous renewable resources to facilitate ambitious decarbonization, electrification, and localized power generation goals. Quantitatively validating the ability to balance variable generation, constrain lifecycle emissions, and potentially match incumbent power costs aids the ongoing regional dialogue around responsibly leveraging North Dakota's world-class solar, onshore wind, and untapped geothermal resources.

The modeling and simulation techniques established, spanning detailed component specifications to integrated system optimization operations, offer a framework adaptable to other target communities and locations based on custom population trends, resource supplies, grid infrastructure, and reliability constraints. The economic analysis tools provide authorities with projections to motivate and structure policy and partnership dialogues centered on incentives, fuel displacement, and public health benefits that determine political and financial feasibility. The environmental modeling informs technology prioritization for maximal sustainability imprints.

This contribution focuses on electricity, but future buildings and transportation sector electrification amplifying demands further underscore the importance of proofs-of-concept around community-focused hybrid renewables at this pivotal juncture for power system transformation. As rural regions weigh economic futures with declining legacy extractive industries, this hybrid model pioneers a way to channel disruption into opportunity-sustaining energy independence by harnessing the disruption of electrons. The methodology and measures of merit instituted aim to inform the solution space design, not prescribe optimality, during an epoch still rich in uncertainties and possibilities.

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FIGURES (Page 100 -120)

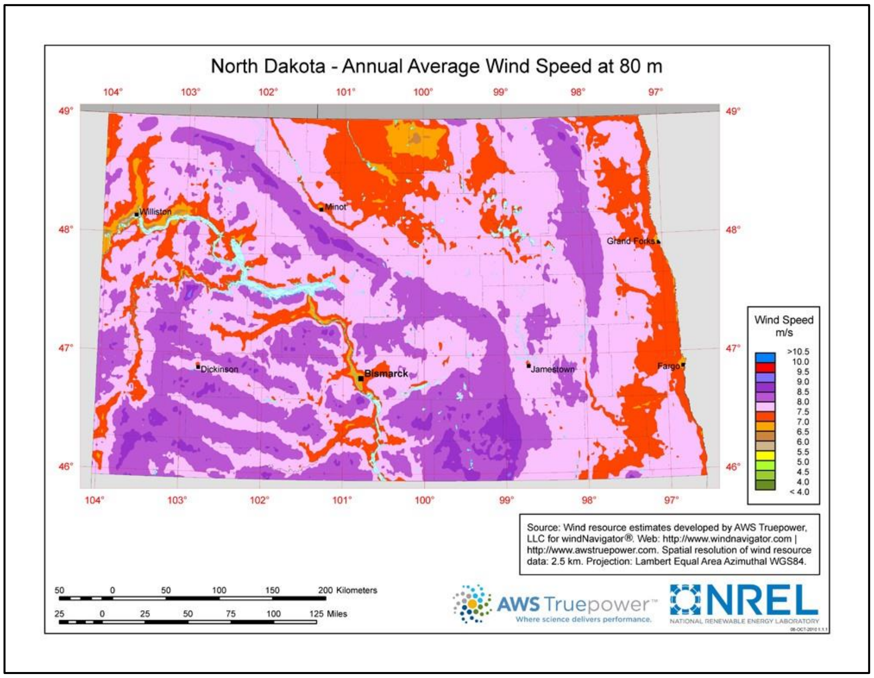

Figure 1. North Dakota's annual average wind speed at 80 m height (NREL)

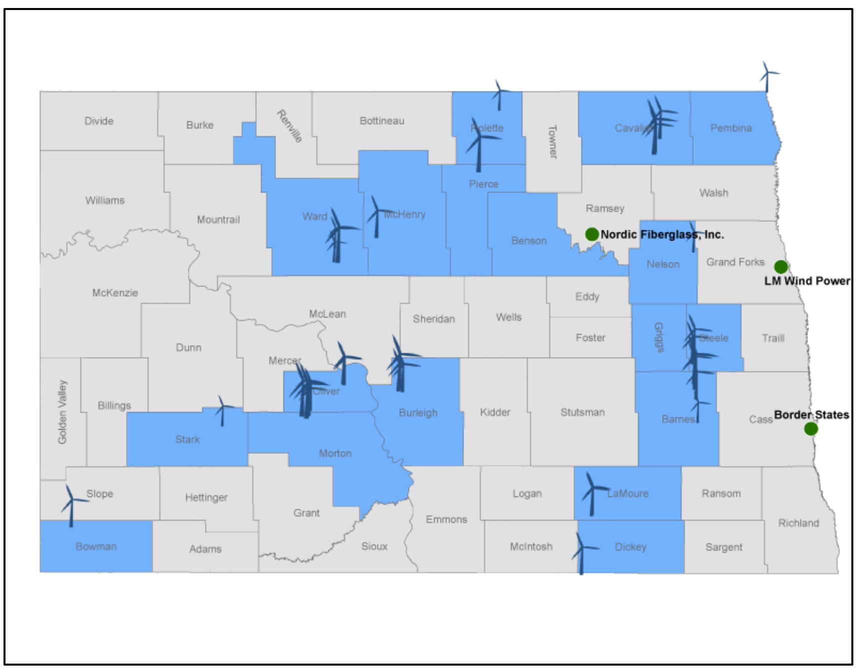

Figure 2.Map of North Dakota wind projects and manufacturing facilities (American Wind Energy Association)

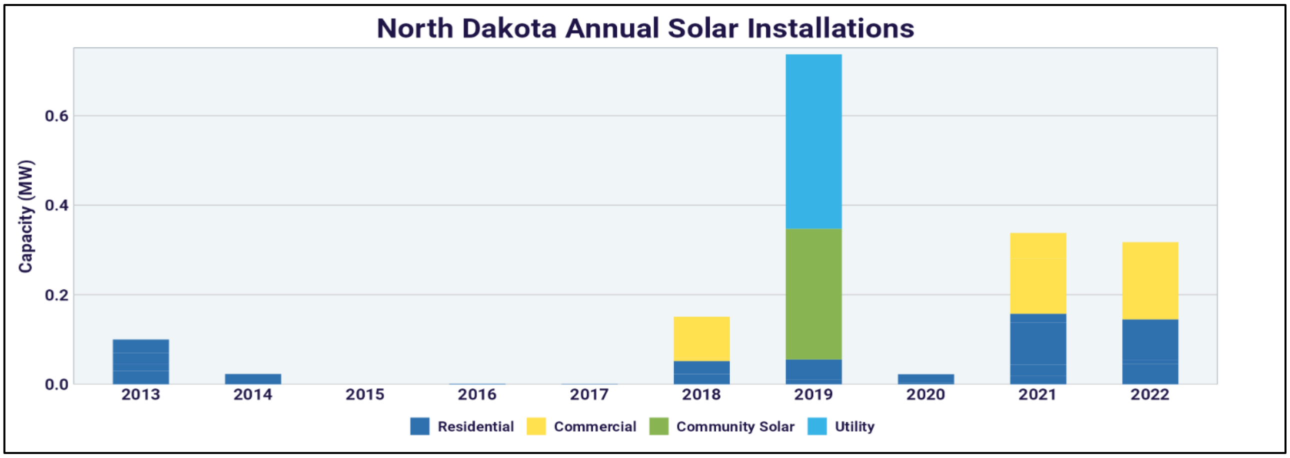

Figure 3. The annual solar installation in North Dakota (North Dakota Solar | SEIA, n.d.)

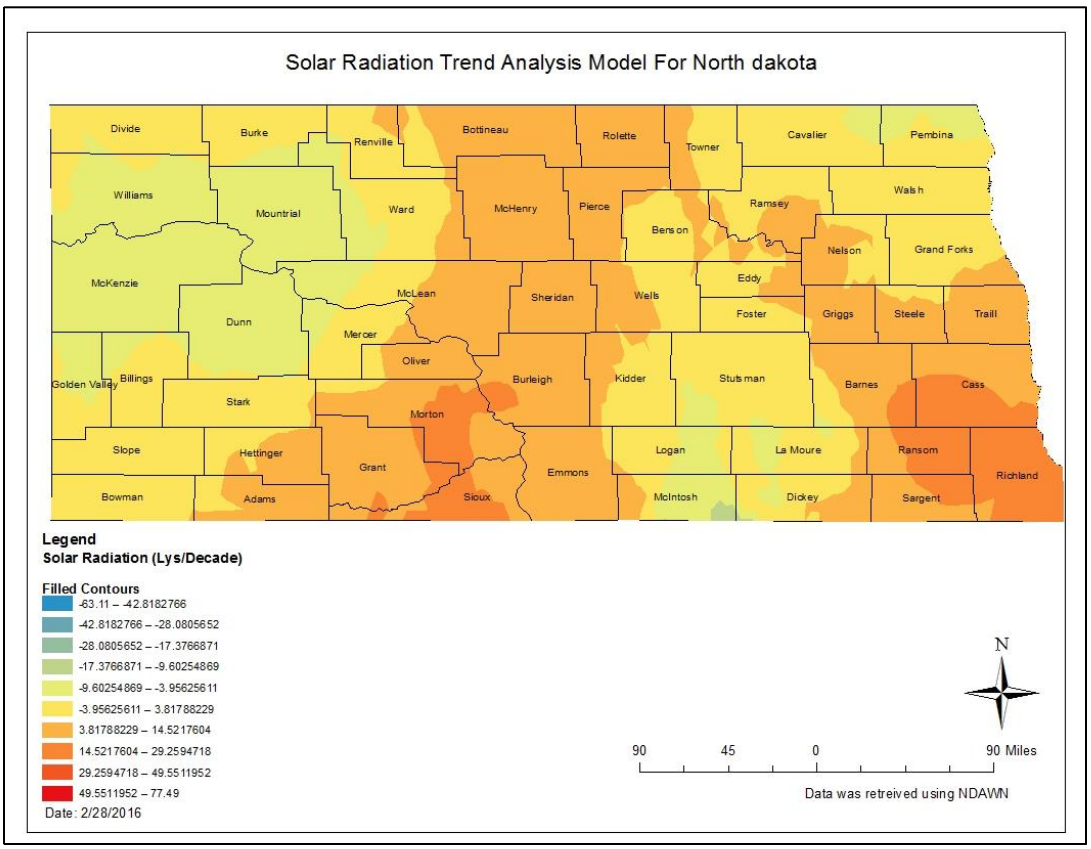

Figure 4. Solar Radiation Trend in North Dakota (Change in Solar Radiation North Dakota, n.d.)

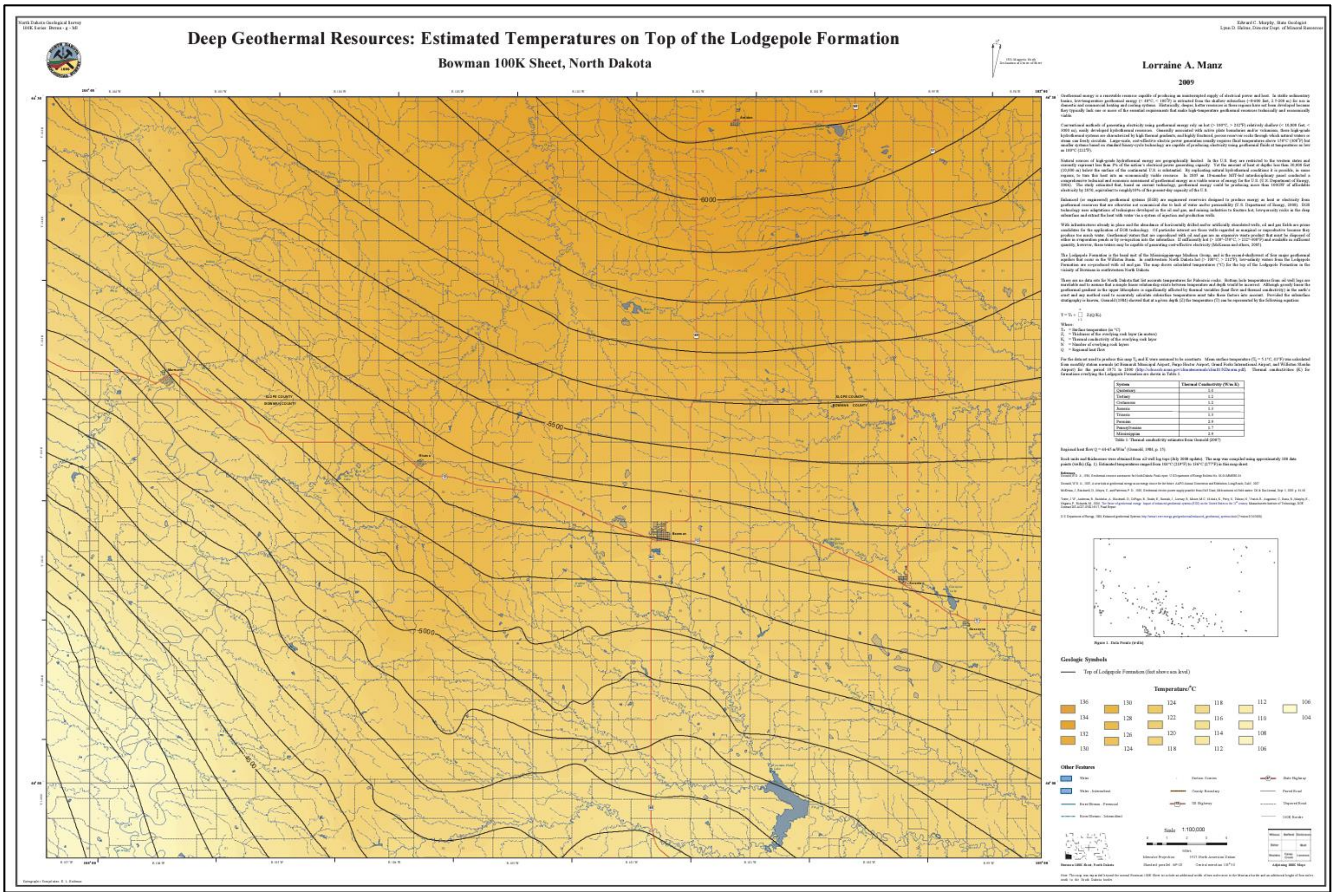

Figure 5. Estimated Temperature on Top of the Lodgepole Formation (Manz, 2008)

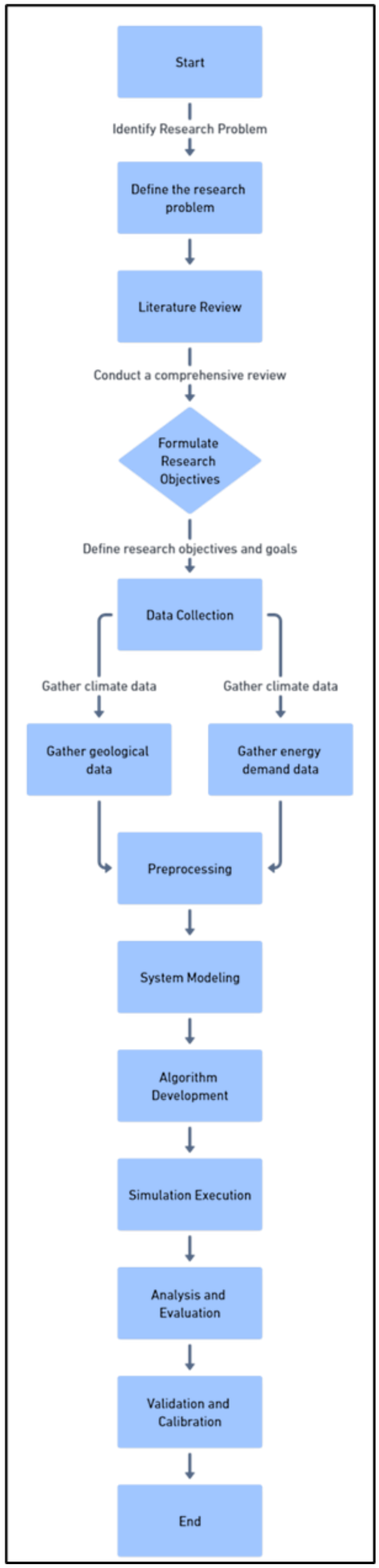

Figure 6. Proposed methodology for this research

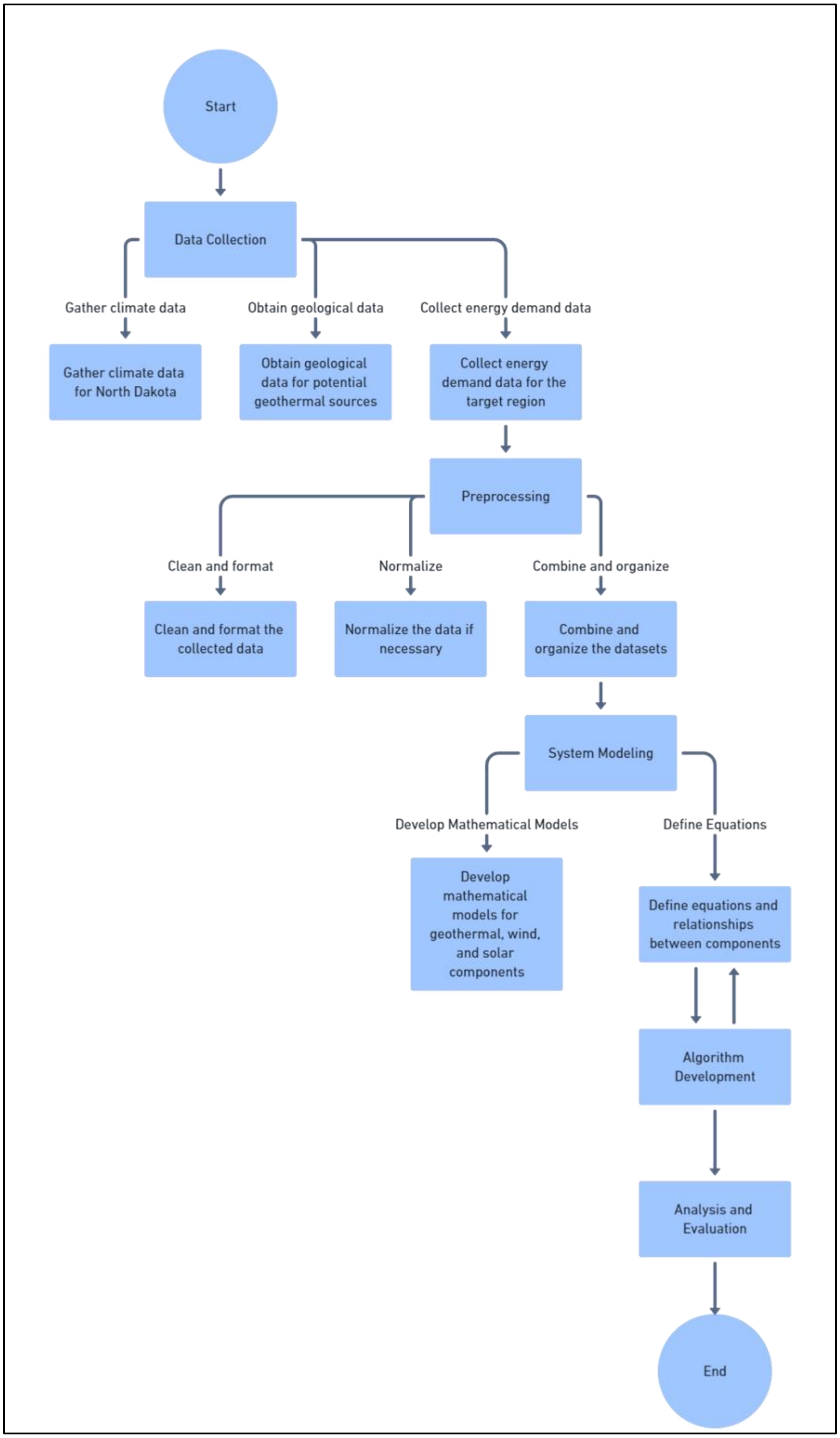

Figure 7. Flow chart for System Modeling and Simulation

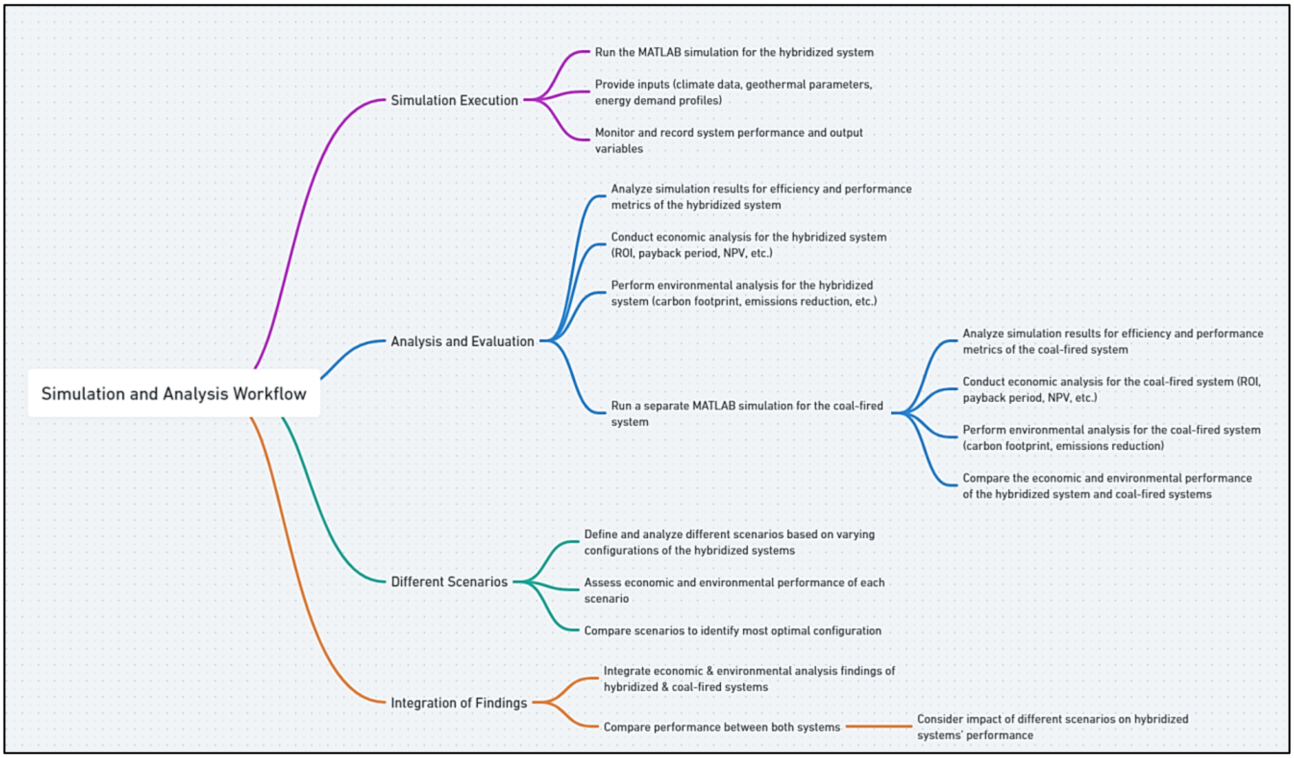

Figure 8. Modeling Philosophy and Approach

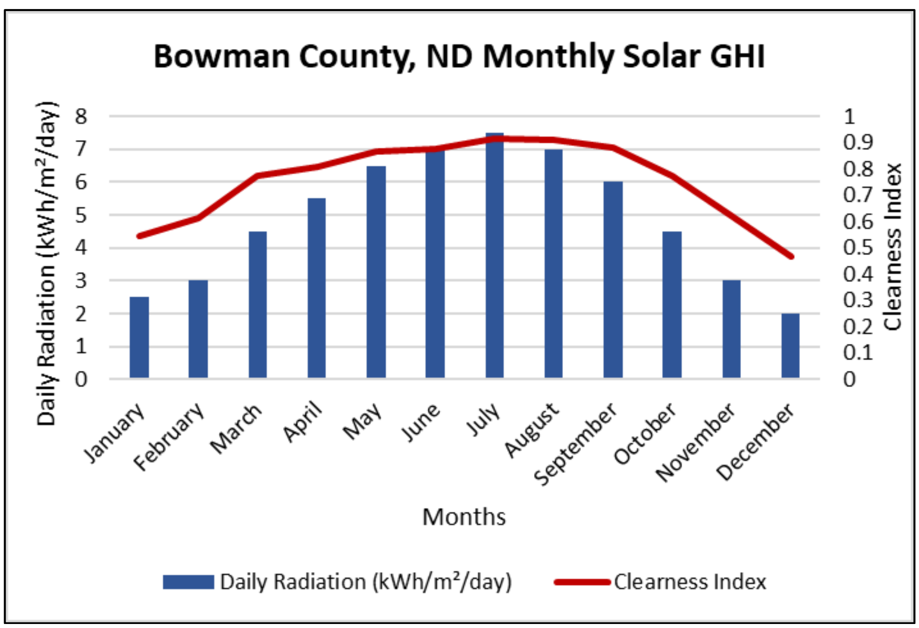

Figure 9. Monthly Solar Global Horizontal Irradiance (GHI), Bowman County, North Dakota

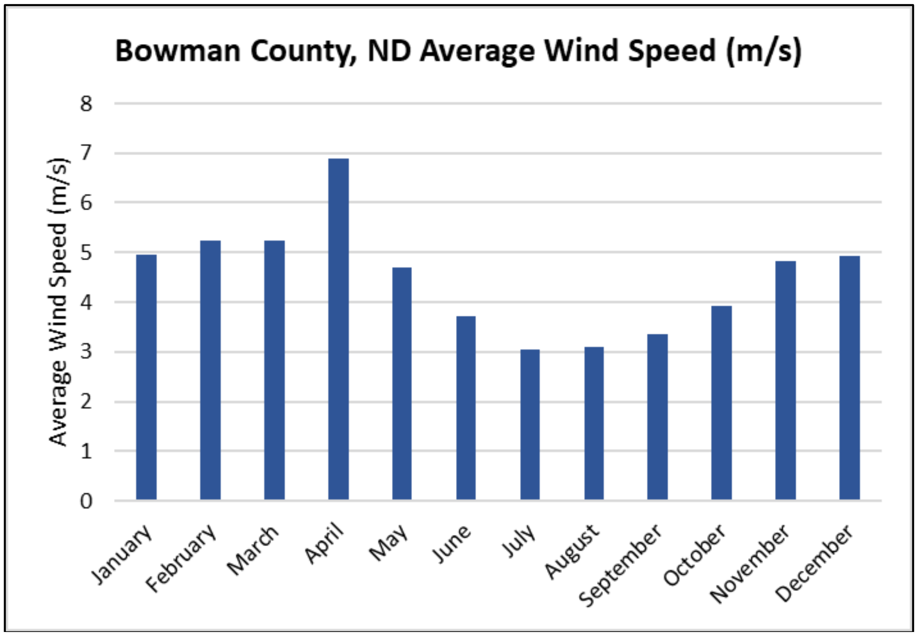

Figure 10. Average Wind Speed (m/s) of Bowman County, North Dakota

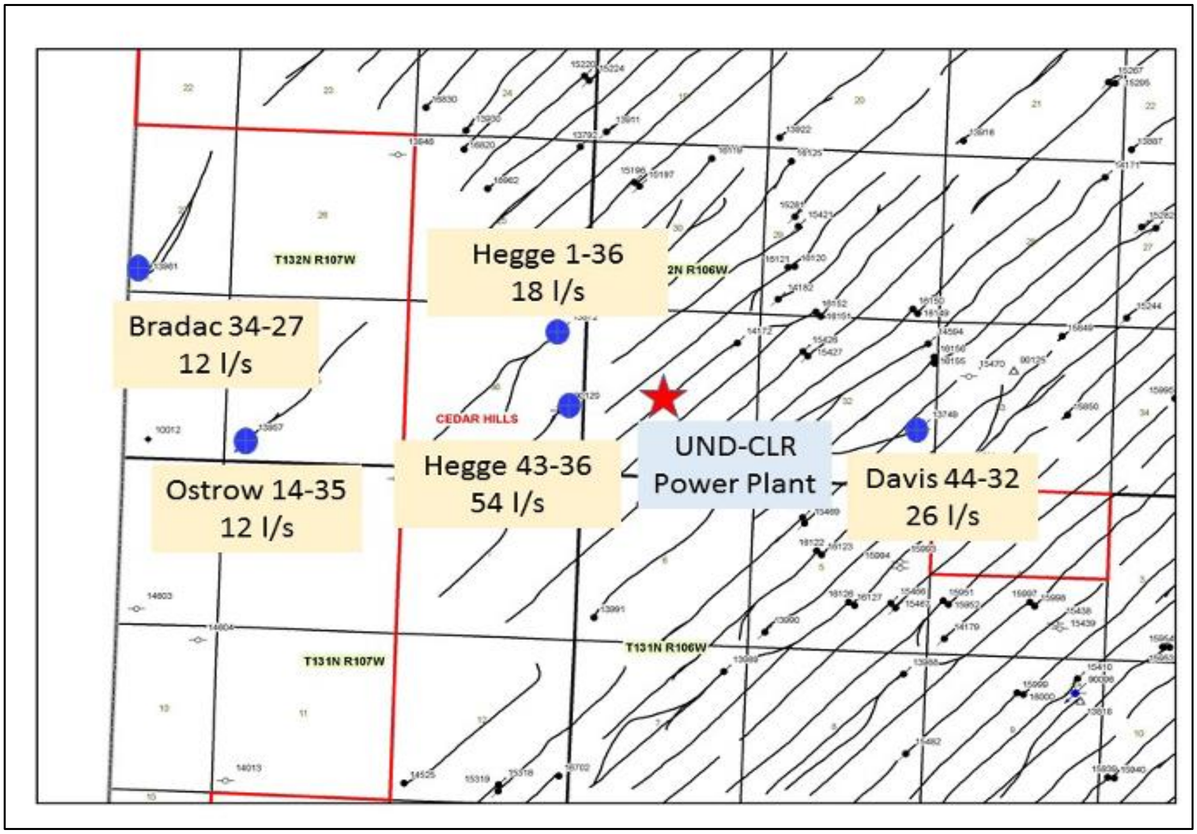

Figure 11. The UND-CLR power plant in Williston Basin(Gosnold, Mann, & Salehfar, 2017)

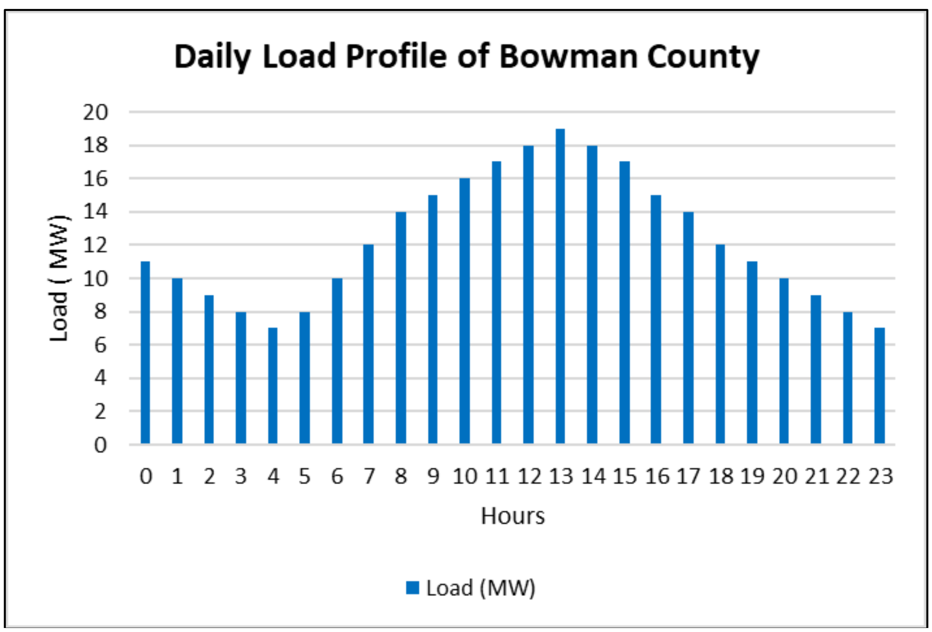

Figure 12. Daily Load Profile of Bowman County, North Dakota

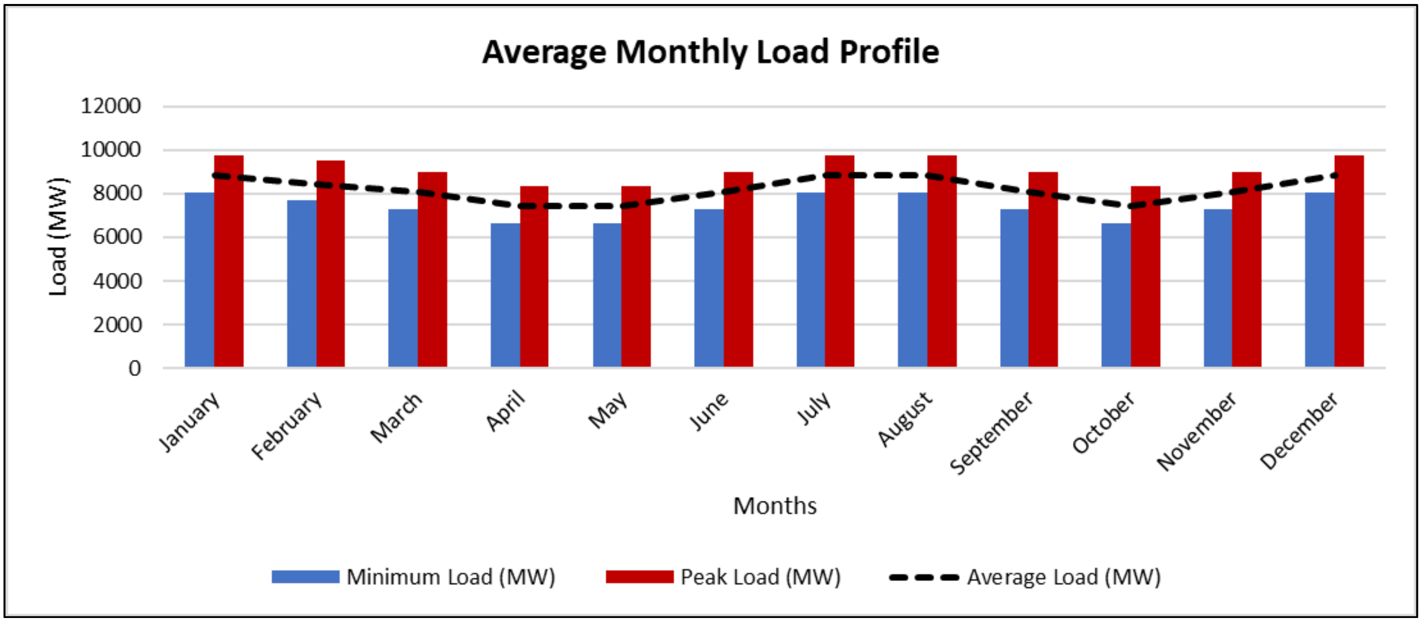

Figure 13. Monthly Load Profile of Bowman County, North Dakota

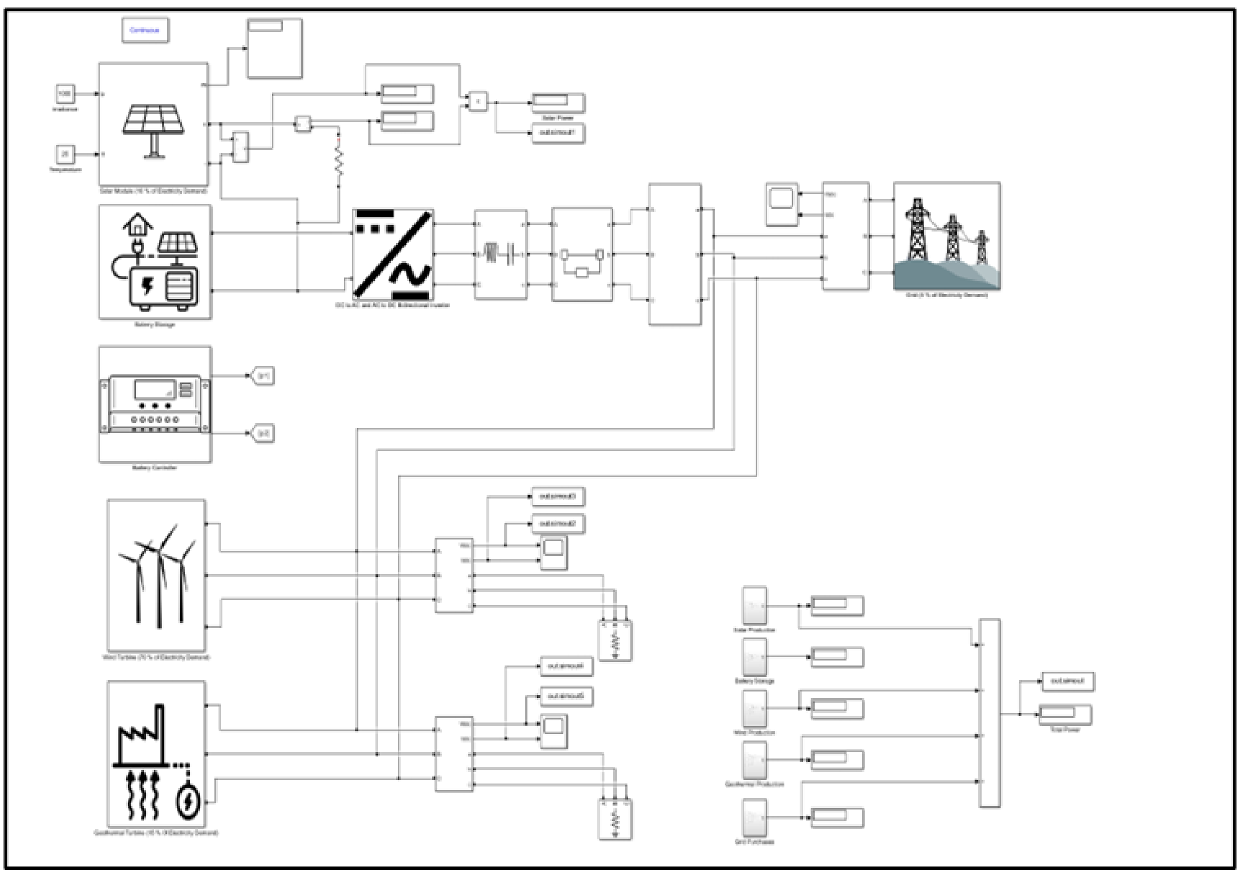

Figure 14. The hybrid system was designed for Bowman County, ND, using Simulink, MATLAB,2023

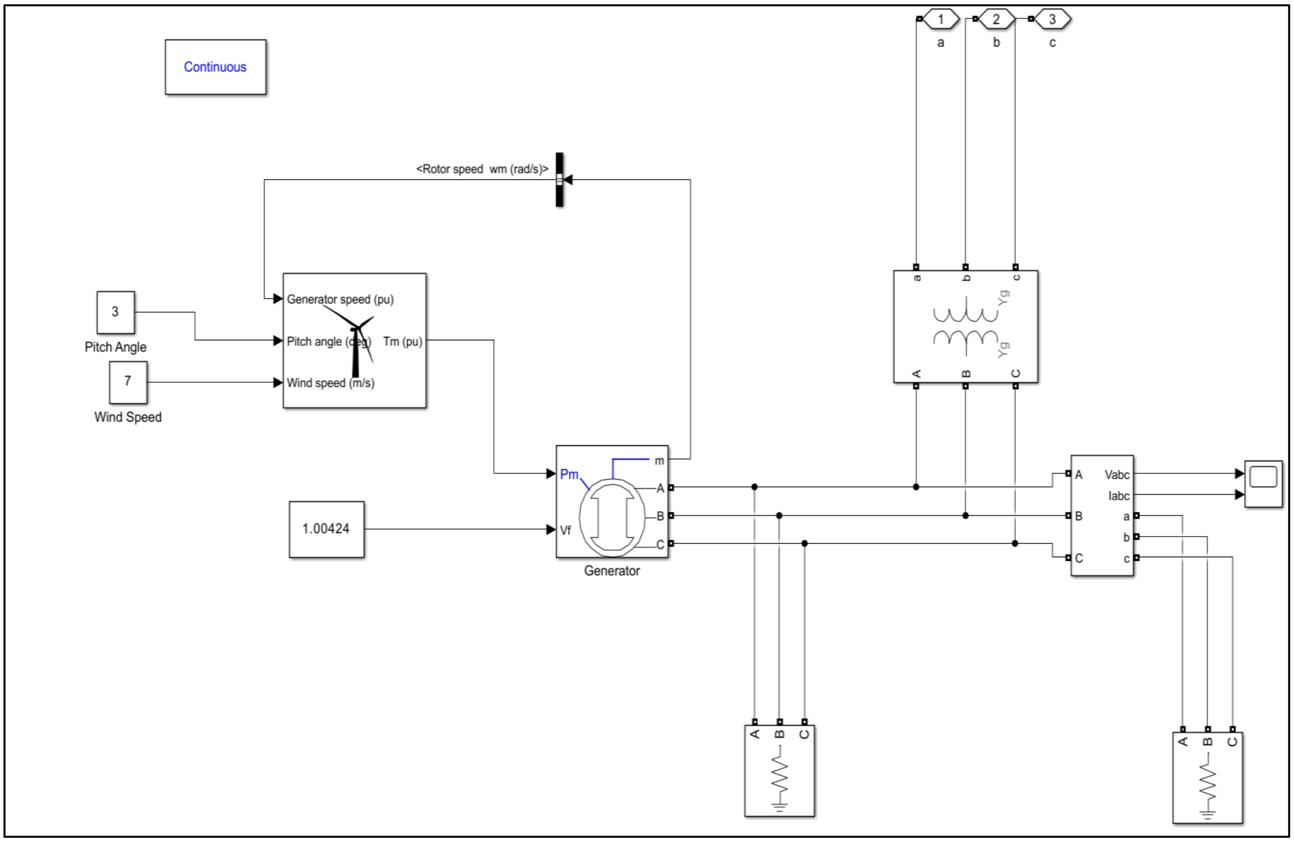

Figure 15. The wind turbine system was designed for Bowman County, ND, using Simulink MATLAB,2023

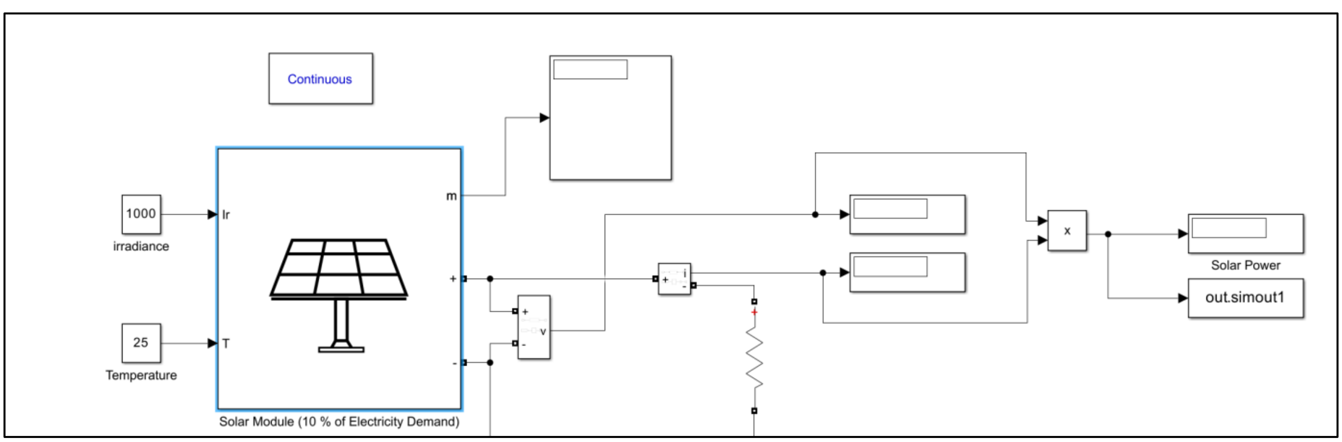

Figure 16. The solar panel system was designed for Bowman County, ND, using MATLAB,2023

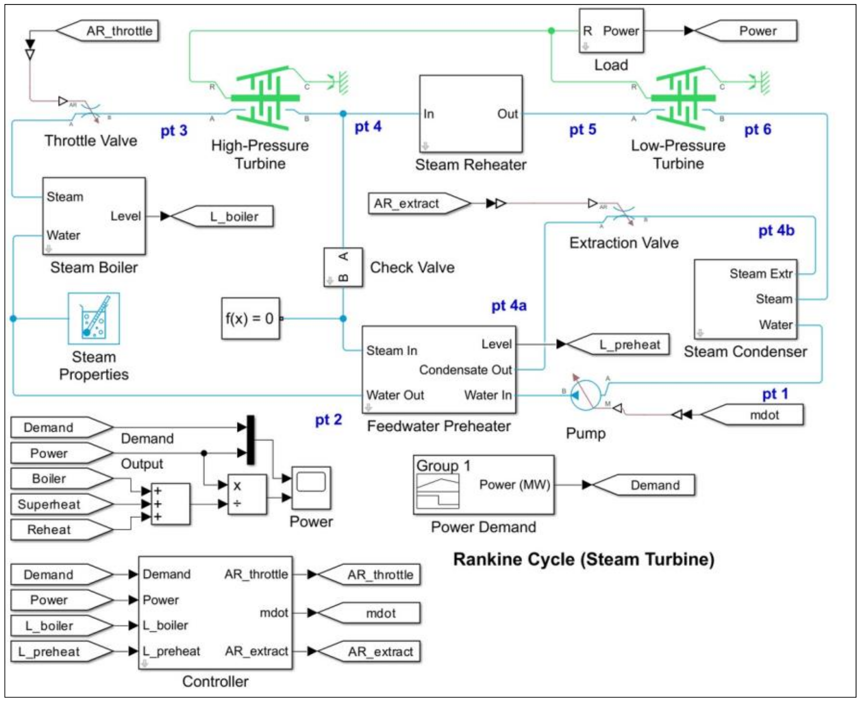

Figure 17. The geothermal system used for Bowman County, ND, using MATLAB,2023

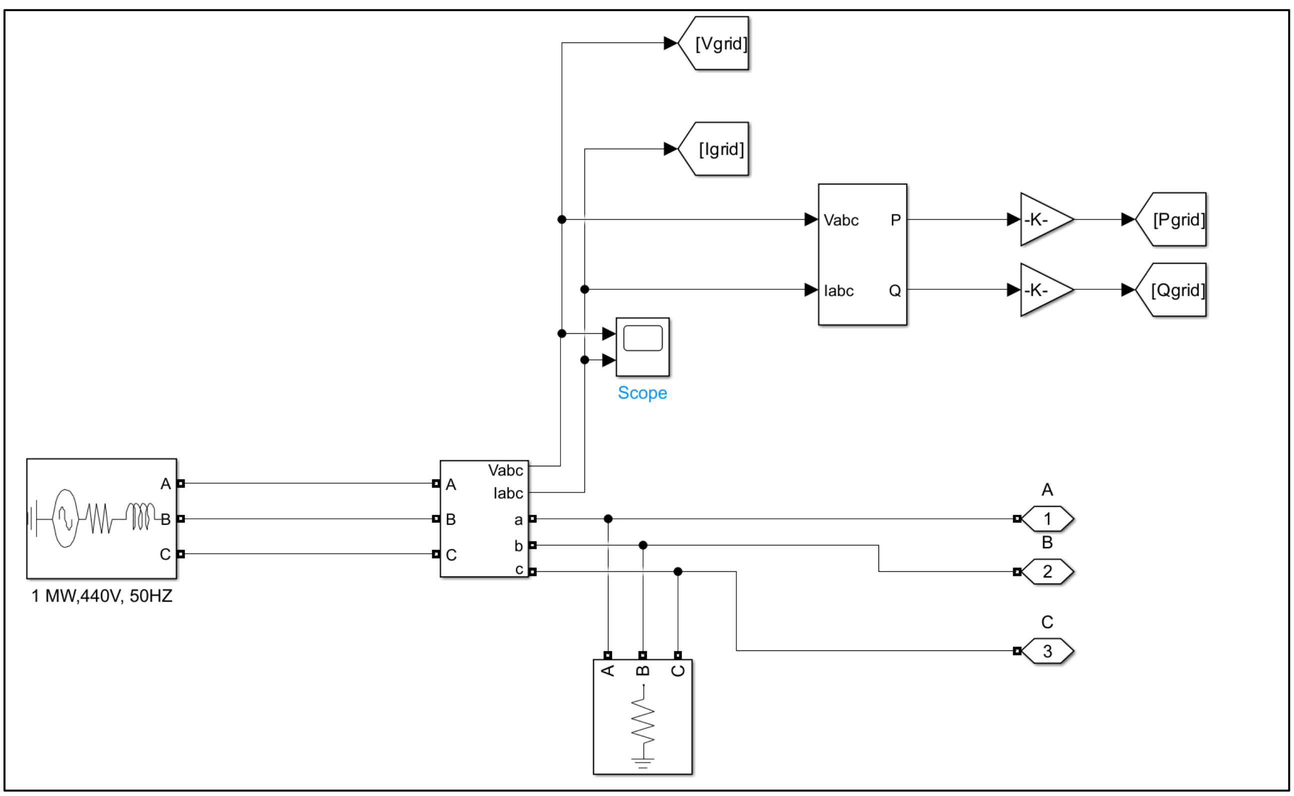

Figure 18. The grid system was designed for Bowman County, ND, using MATLAB,2023

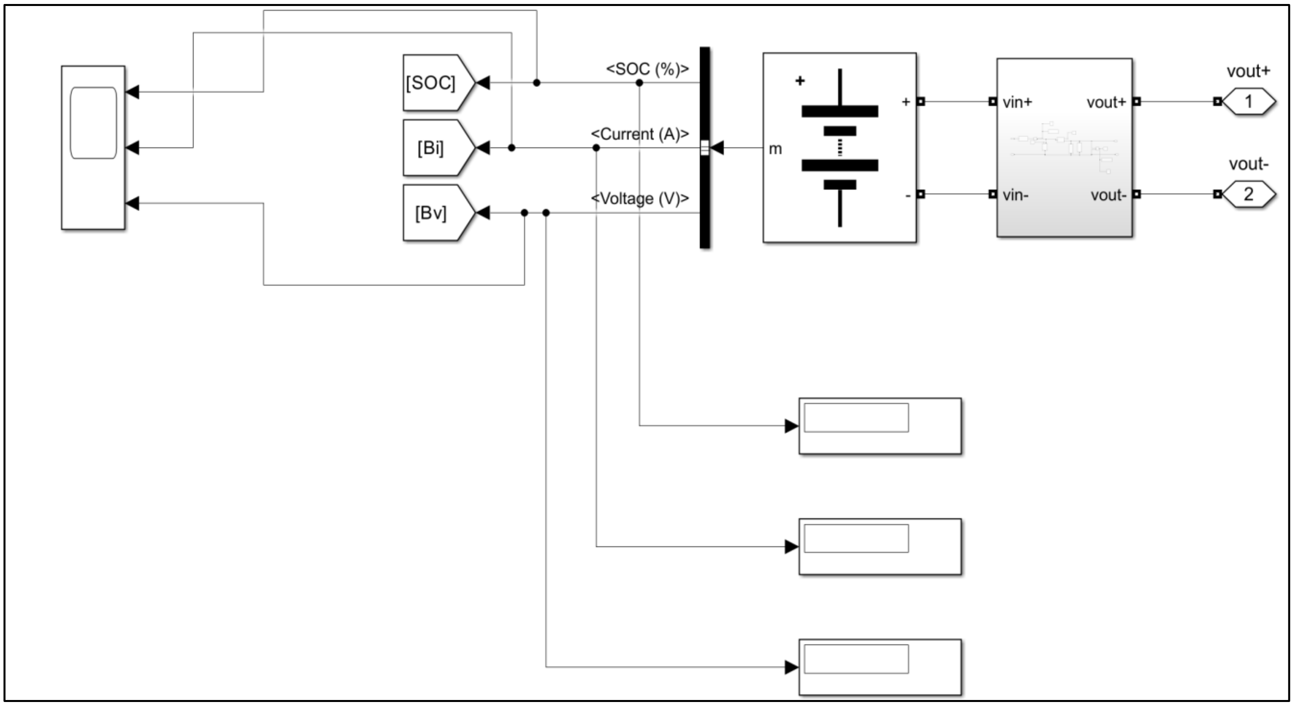

Figure 19. The solar storage system was designed for Bowman County, ND, using MATLAB,2023

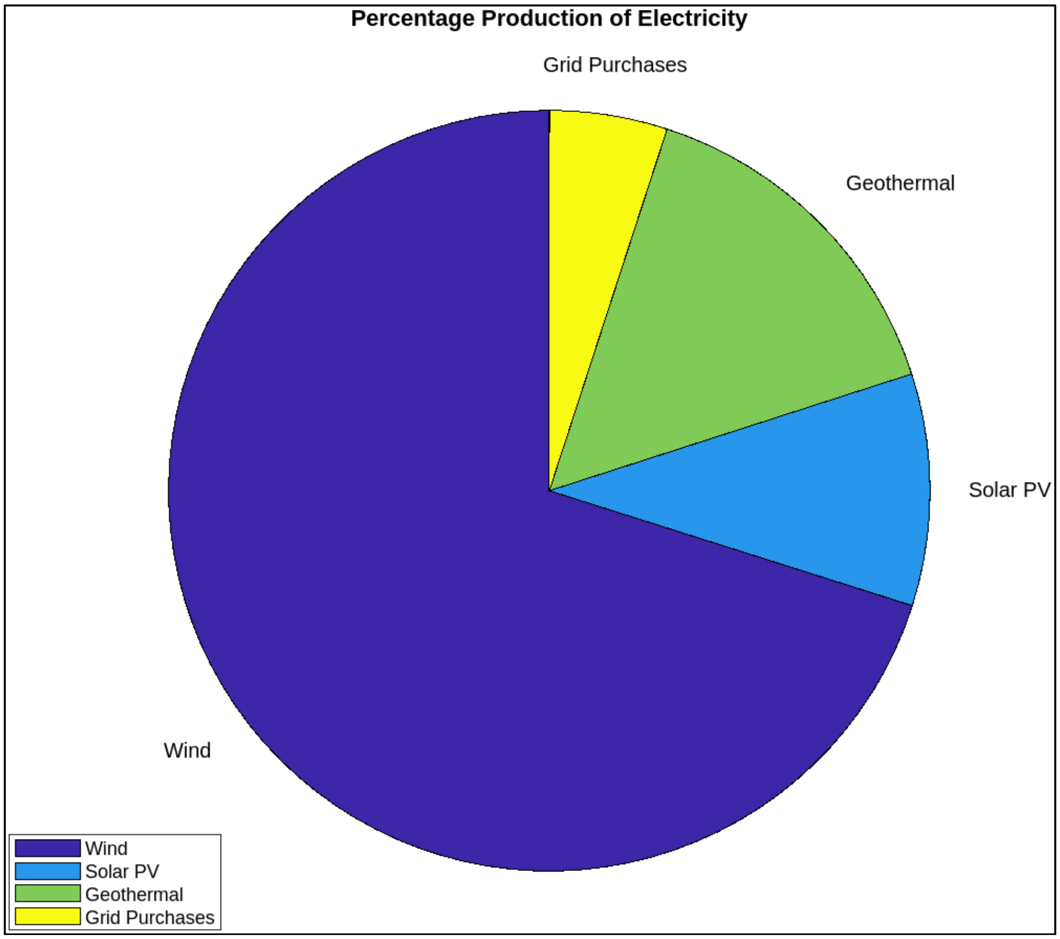

Figure 20. Percentage production of electricity

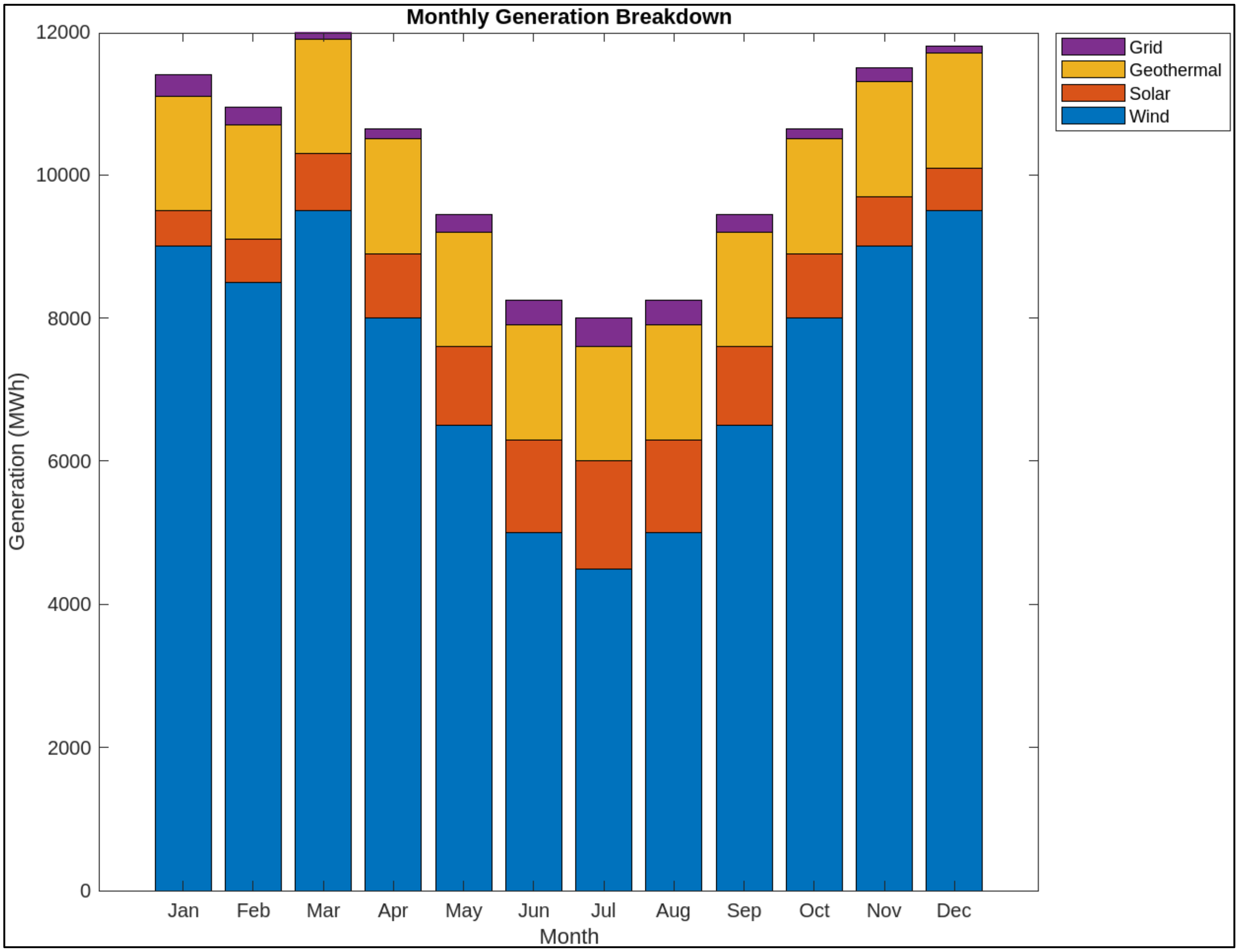

Figure 21. Monthly electricity generation from the hybrid system

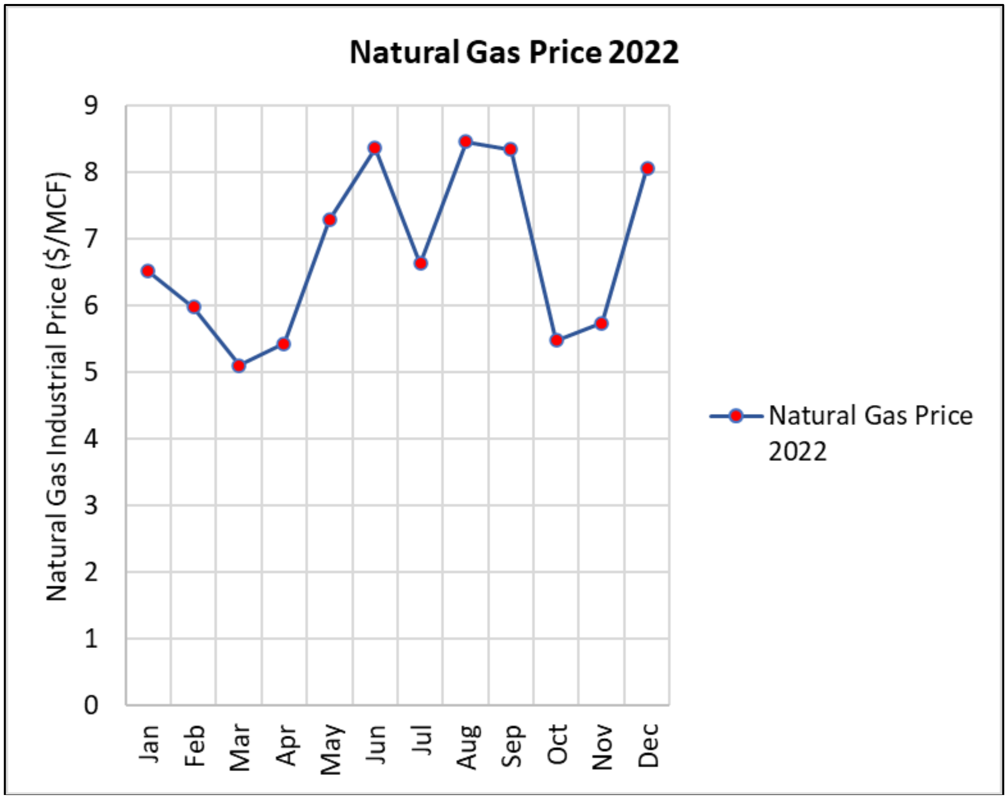

Figure 22. Natural Gas Price, North Dakota (EIA, 2022)

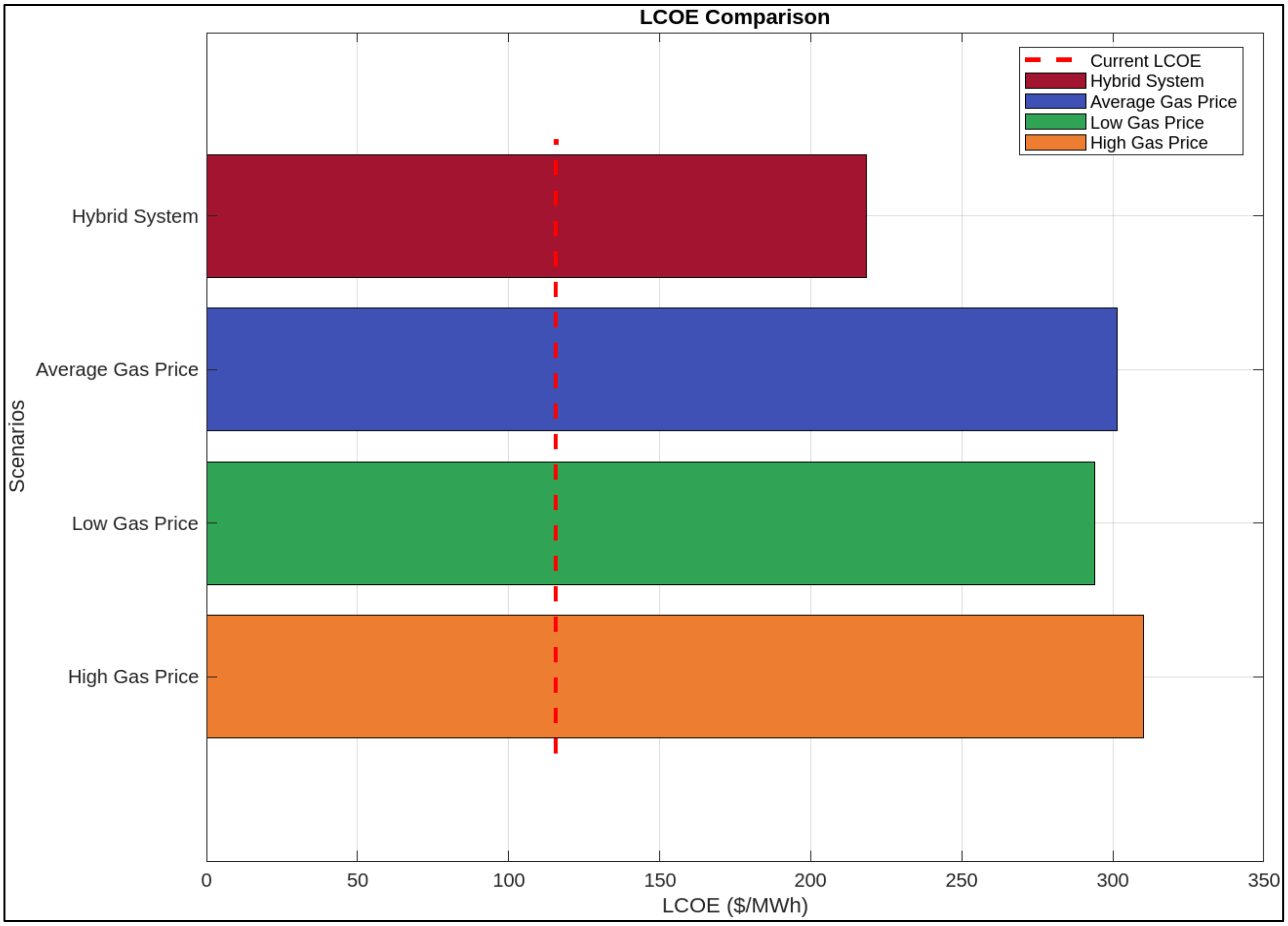

Figure 23. Levelized Cost of Electricity Comparison: Hybrid Wind-Solar-Geothermal-Storage System vs. Natural Gas

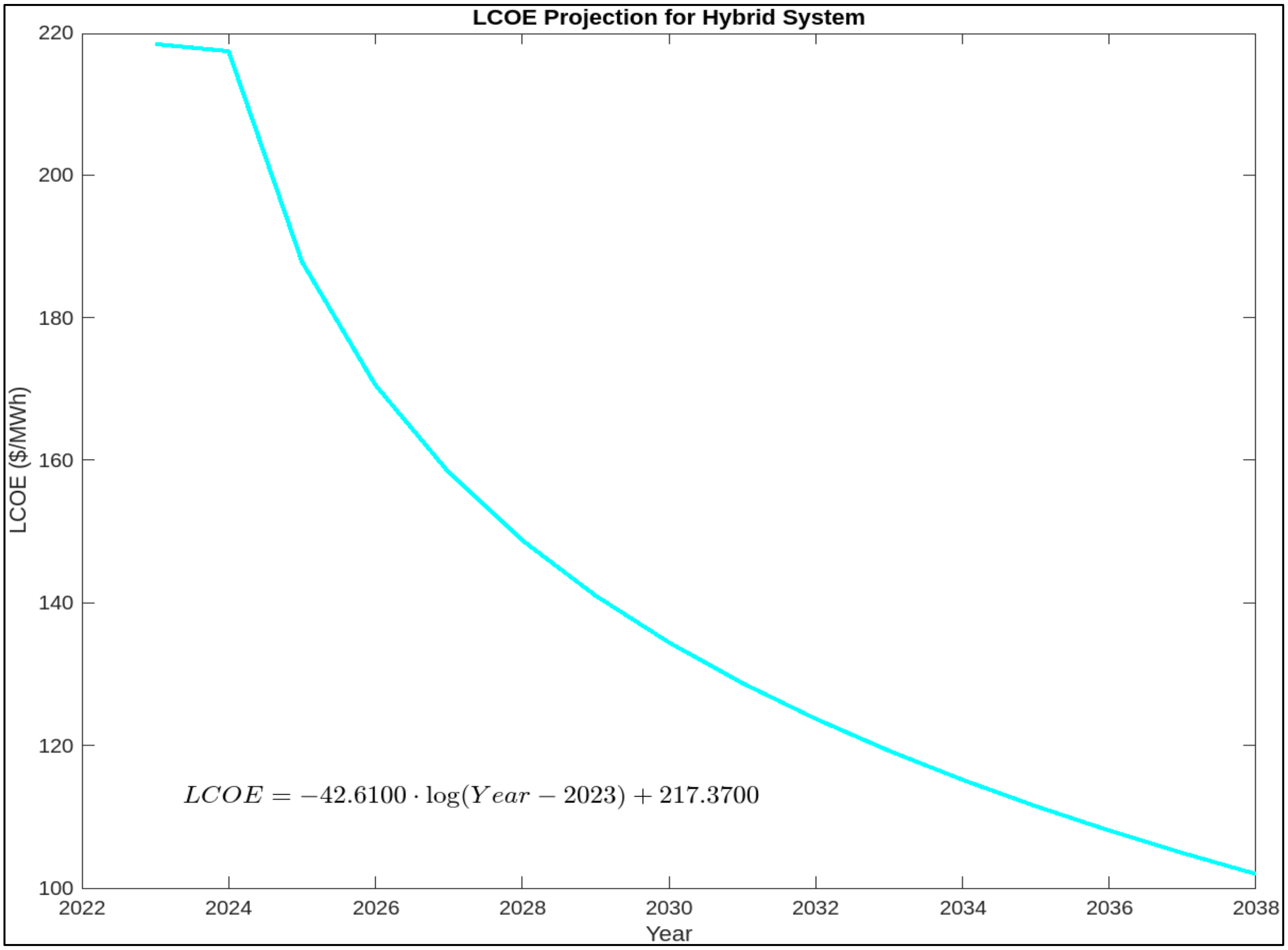

Figure 24. Levelized Cost of Electricity Projection for Hybrid System

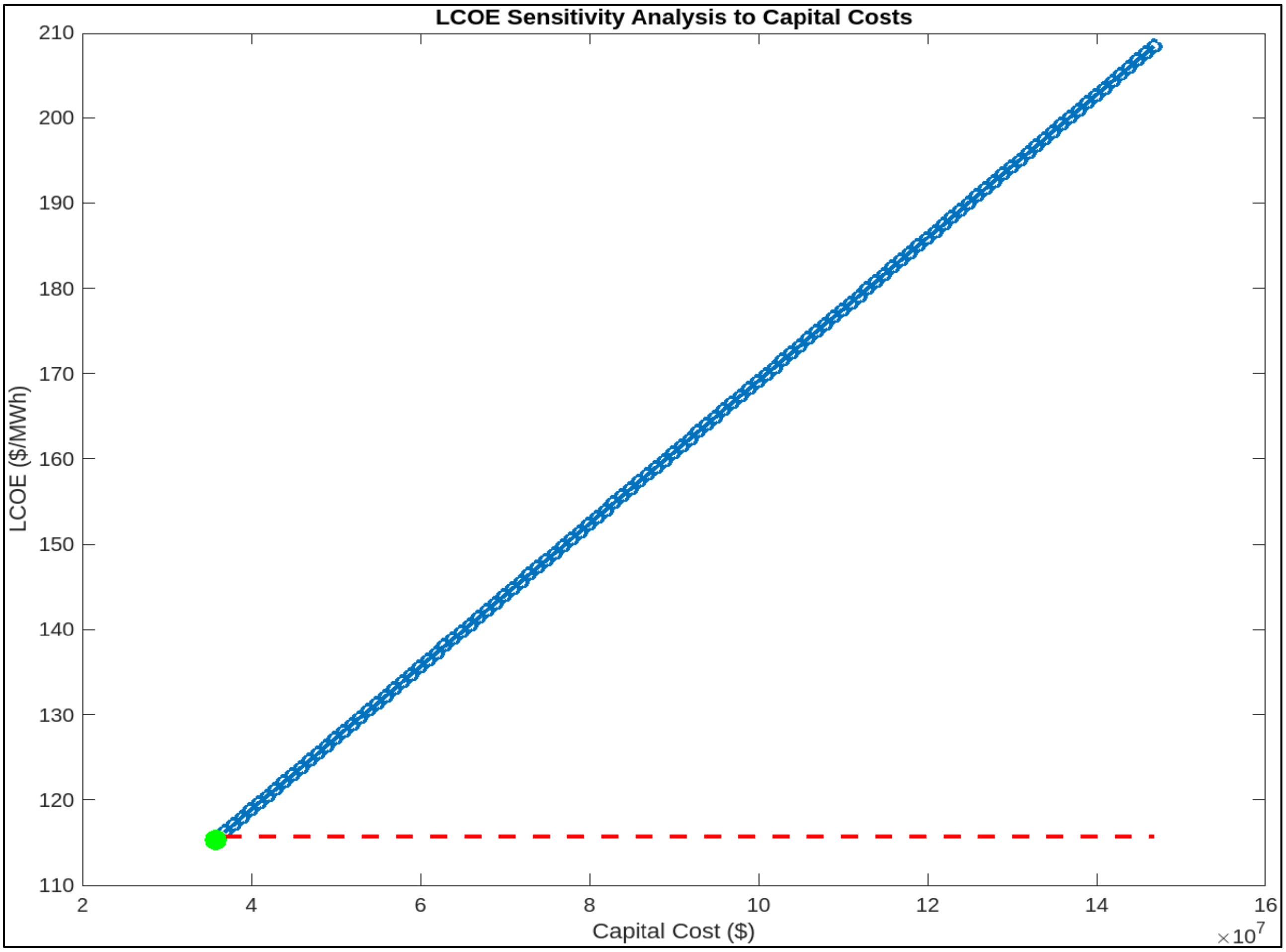

Figure 25. Levelized Cost of Electricity Sensitivity Analysis to Capital Costs

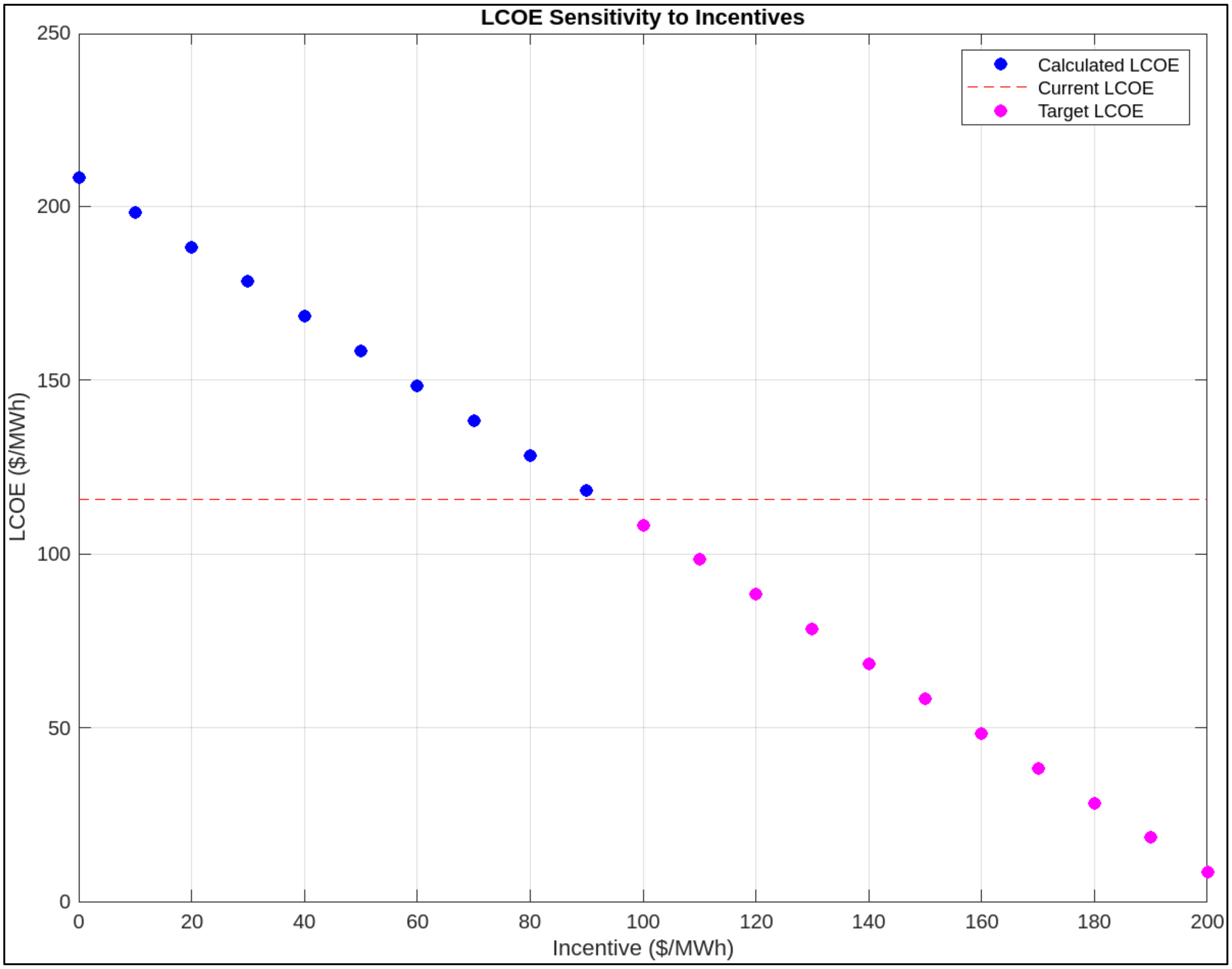

Figure 26. Levelized Cost of Electricity Sensitivity Analysis to Incentives

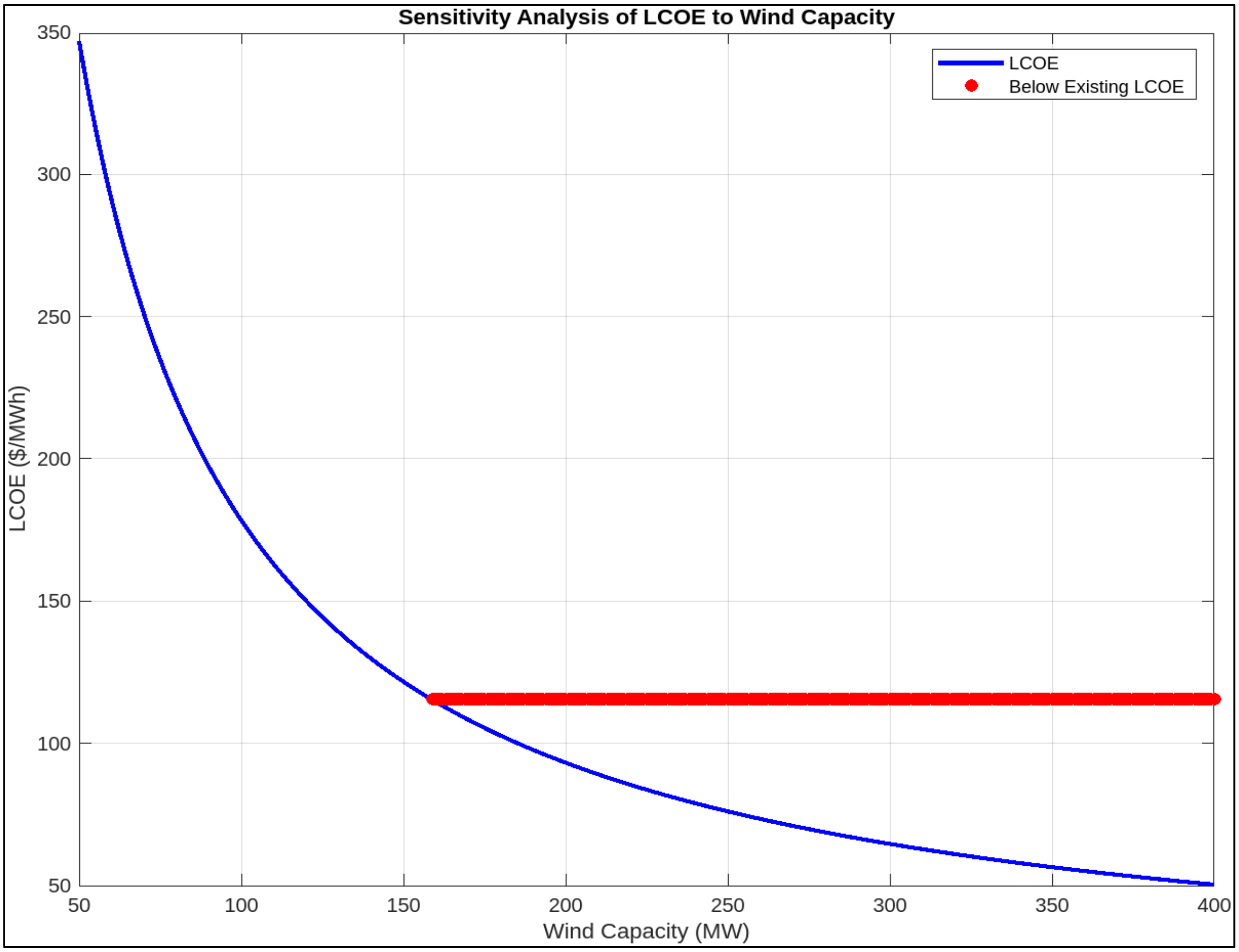

Figure 27. Levelized Cost of Electricity Sensitivity Analysis to Wind Capacity

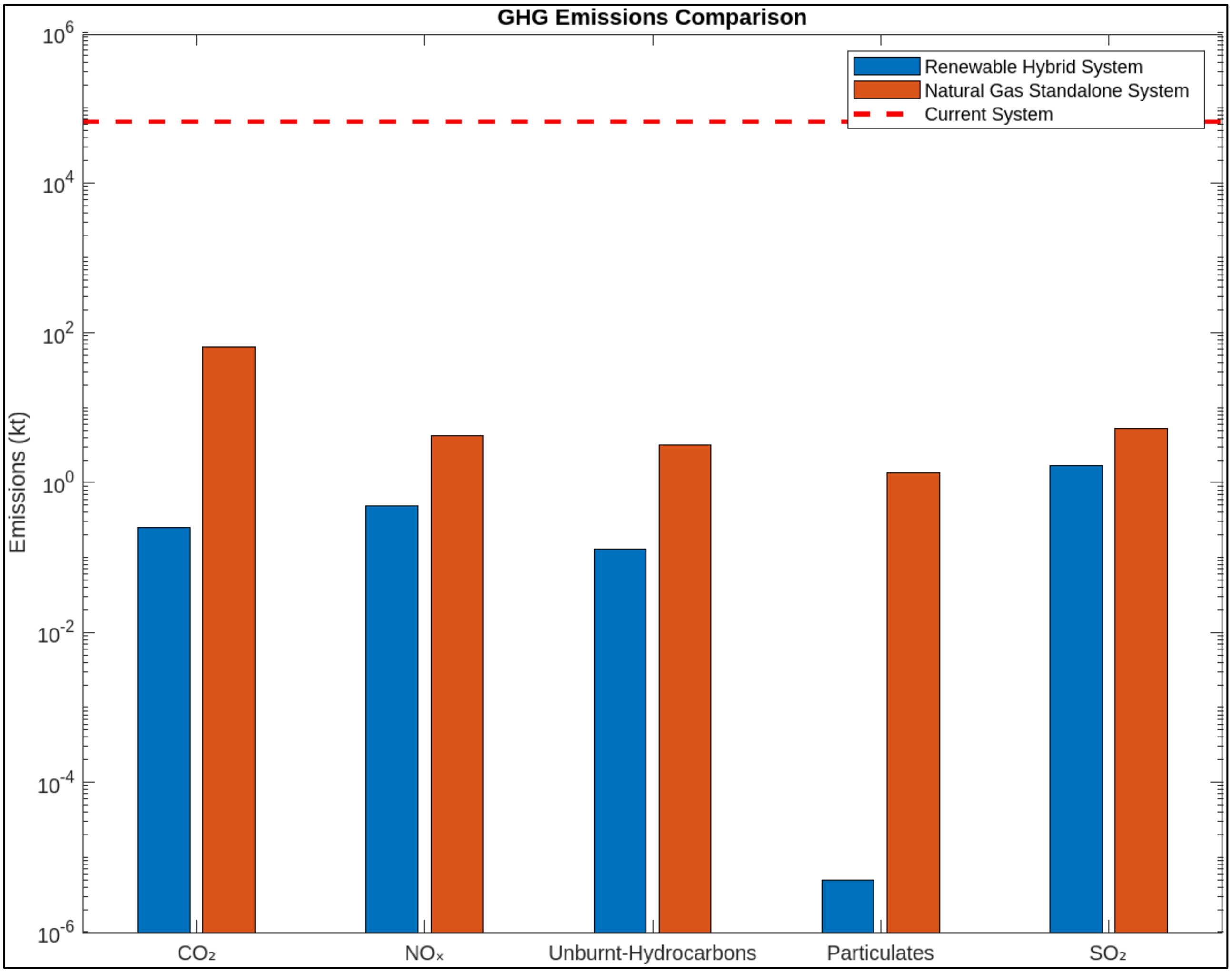

Figure 28. Greenhouse Gas Emission (GHG) Comparison: Hybrid Wind-Solar-Geothermal-Storage System vs. Natural Gas

TABLES

Table 1. Bowman County, North Dakota Monthly GHI

Month	Daily Radiation ($kWh/m^2/day$)	Clearness Index
January	2.5	0.545
February	3	0.612
March	4.5	0.776
April	5.5	0.809
May	6.5	0.867
June	7	0.875
July	7.5	0.916
August	7	0.909
September	6	0.882
October	4.5	0.776
November	3	0.625
December	2	0.465

Table 2.Bowman County, North Dakota Monthly Temperature

Year	Month	Average Daily Temperature (°F)
2022	January	19
2022	February	18
2022	March	30
2022	April	33
2022	May	50
2022	June	61
2022	July	70
2022	August	71
2022	September	62
2022	October	47
2022	November	23
2022	December	11
Averages:		41
Max:		71
Min:		11
Std. Dev.:		21.57492231

Table 3. Bowman County, North Dakota Monthly Average Speed of Wind

Month	**Average Wind Speed (m/s)**
January	4.962002682
February	5.230219043
March	5.230219043
April	6.884219937
May	4.693786321
June	3.71032633
July	3.039785427
August	3.084488154
September	3.352704515
October	3.933839964
November	4.827894502
December	4.917299955

Table 4. Summary of the UND-CLR Binary Geothermal Power Plant

Parameter	**Value**
Location	Cedar Hills Red River-B field, Williston Basin, North Dakota
Source Formation	Lodgepole (Mississippian Madison Group)
Supply Wells	Davis 44-29 and Homestead 43-33
Well Depths	2,300 m and 2,400 m
Lateral Lengths	1,290 m and 860 m
Total Flow Rate	51 liters per second
Temperature at Wellheads	103°C
Temperature at Plant Inlet	98°C
Injection Formation	Red River (Ordovician)

Table 5.Key Infrastructure and Services in Bowman County, North Dakota (Bowman County Development Corporation, 2021)

Category	**Description**	**Electric Utility**
Population	3,024	Montana Dakota Utilities
Schools	Bowman Campus: 1- Scranton: 1 - Rhame Campus: 1	
Apartments	17	
Motels	6	
Churches	11 total (8 Protestant, 3 Catholic)	
Grocery Stores	1	
Libraries	1	
Pharmacies	1	
Gas Stations	5	
Recreation	Outdoor Basketball Courts: 2 - Indoor Basketball Courts: 4 - Bowling Alley: 1 - Golf Courses: 2 - Parks: 5 - Outdoor Pool: 1 - Tennis Court: 1	
Medical	Hospital: 1 - Medical Clinics: 2 - Nursing Home: 1 - Optometrist: 1 - Dental Offices: 2	
Communications	Radio Station: 1 - Cable/Internet/Phone Provider: 2	
Government	Police Department: 1 - Sheriff Department: 1 - Fire Department: 1 - Court: 1	
Banks	5	

Table 6. Average daily load profile, Bowman County, North Dakota

Hour	Load (MW)	Peak / Off-peak
0	11	Off-peak
1	10	Off-peak
2	9	Off-peak
3	8	Off-peak
4	7	Off-peak
5	8	Off-peak
6	10	Morning ramp-up
7	12	Morning peak
8	14	Morning peak
9	15	Morning peak
10	16	Mid-day moderate
11	17	Mid-day moderate
12	18	Afternoon peak
13	19	Afternoon peak
14	18	Afternoon peak
15	17	Evening ramp-down
16	15	Early evening
17	14	Early evening
18	12	Early evening
19	11	Off-peak
20	10	Off-peak
21	9	Off-peak
22	8	Off-peak
23	7	Off-peak

Table 7. Monthly electricity generation, Bowman County, North Dakota

Month	Average Load (MW)	Peak Load (MW)	Minimum Load (MW)
January	8840	9750	8060
February	8450	9490	7670
March	8060	8970	7280
April	7410	8320	6630
May	7410	8320	6630
June	8060	8970	7280
July	8840	9750	8060
August	8840	9750	8060
September	8060	8970	7280
October	7410	8320	6630
November	8060	8970	7280
December	8840	9750	8060

Table 8. Percentage production of electricity

Energy Resource	Percentage	Annual Generation (MW)	Daily Generation (MW)
Wind	70%	74805.5	204.9465753
Solar	10%	10686.5	29.27808219
Geothermal	15%	16029.75	43.91712329
Grid	5%	5343.25	14.6390411
Total Generation	100%	106865	292.7808219

Table 9. Monthly production of the hybrid system, Bowman County, North Dakota

Month	Wind (MWh)	Solar (MWh)	Geothermal (MWh)	Grid (MWh)	Total (MWh)
Jan	9,000	500	1,600	300	11,400
Feb	8,500	600	1,600	250	10,950
Mar	9,500	800	1,600	100	12,000
Apr	8,000	900	1,600	150	10,650
May	6,500	1,100	1,600	250	9,450
Jun	5,000	1,300	1,600	350	8,250
Jul	4,500	1,500	1,600	400	8,000
Aug	5,000	1,300	1,600	350	8,250
Sep	6,500	1,100	1,600	250	9,450
Oct	8,000	900	1,600	150	10,650
Nov	9,000	700	1,600	200	11,500
Dec	9,500	600	1,600	100	11,800

Table 10. The strategy of load dispatch for 5 hours

Time	PV Output (MW)	Wind Output (MW)	Geo Output (MW)	Load (MW)	Grid Buy (MW)	Grid Sale (MW)	Total Served(MW)	Storage (MW)
12:00 PM	18.3	80	2	100	0	0.97	100.97	110
1:00 PM	24.4	75	2	101	0	1.4	102.4	146
2:00 PM	21.2	90	2	112	0	1.2	113.2	194.4
3:00 PM	19.8	95	2	116	0	1.03	117.03	194.4
4:00 PM	12.2	85	2	99	0	1.1	100.1	194.4

Table 11. Natural gas price in North Dakota, 2022 (EIA, 2022)

2022														
	Price ($/MCF)	6.51	5.98	5.1	5.43	7.28	8.36	6.63	8.45	8.34	5.48	5.74	8.1	**Highest**	8.45
	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Lowest**	5.1
														Average	6.78

Appendix A

Assuming the capacity factors are as follows

Wind: 30%

Solar: 20%

Geothermal: 90%

Grid: 100% (since it's not a specific type of generation but represents the overall consumption, we assume it's fully available when needed)

Assuming average operational hours per day:

Wind: 8 hours per day

Solar: 6 hours per day

Geothermal: 24 hours per day

Grid: 24 hours per day

Wind

$$Wind\ Capacity = \frac{204.9465753}{0.30\ \times 8} \approx 85.40\ MW$$

Solar

$$Solar\ Capacity = \frac{29.27808219}{0.20\ \times 6} \approx 24.40\ MW$$

Geothermal

$$Geothermal\ Capacity = \frac{43.91712329}{0.9\ \times 24} \approx 2.03\ MW$$

Grid

$$Grid\ Capacity = \frac{14.6390411}{1.0\ \times 24} \approx 0.61\ MW$$

Solar Storage

Given the daily solar capacity of approximately 24.30 MW and assuming that the solar system operates for 6 hours per day, the total daily energy produced is

$$24.40\ MW \times 6\ h = 145.8\ MWh$$

Now, let's calculate the surplus energy per day:

$$Surplus\ Energy\ per\ Day = \ Total\ Daily\ Energy - \ Demand\ During\ Solar\ Operation$$

$$Surplus\ Energy\ per\ Day = 145.8\ MWh - (\ 24.3\ MW \times 4\ h) = 145.8\ MWh - 97.2\ MWh = 48.6\ MW$$

Now, to calculate the required storage capacity for 4 hours:

$$Required\ Storage\ Capacity = \ Surplus\ Energy\ per\ Day \times Storage\ Duration$$

$$Required\ Storage\ Capacity = \ 48.6\ MWh * 4 = 194.4\ MWh$$

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Appendix B

The potential wind generation can be estimated as:

Wind generation (MWh) = Capacity (MW) × Hours in a year

With 85.4 MW of capacity allocated for Bowman County, the potential annual wind generation is

85.4 MW × 8,760 hours/year = 748,104 MWh

This far exceeds the county's current electricity consumption of 106,865 MWh per year. However, due to the intermittent nature of wind, the capacity factor must be considered. A capacity factor of 30% would be typical for a wind farm in this region (Lopez et al., 2012).

Assuming a 30% capacity factor, the estimated actual annual generation for Bowman County would be:

85.4 MW × 8,760 hours/year × 0.30 = 224,431 MWh

This value could supply over 210% of the county's current electricity needs. For a more conservative estimate, we can assume the wind farm supplies 70% of Bowman County's projected 2025 electricity demand of 115,000 MWh.

At 70%, the wind farm would supply:

115,000 MWh × 0.70 = 80,500 MWh

A spacing of 3 rotor diameters between turbines is recommended based on typical wind turbine specifications to minimize wake losses from turbulence. Modern 2.5-3 MW turbines with 120-meter rotors result in a spacing of 360 meters between turbines in the prevailing wind direction.

Arranging the 85.4 MW of turbines in a 10×10 grid with 360-meter spacing requires a 0.9 km x 0.9 km area. Allowing for roads and infrastructure, the total land required would be 1.2 km^2, or 296 acres. Previous studies have estimated 30-150 acres per MW of wind capacity depending on site configuration, so 85.4 MW could require anywhere from 2,562 to 12,810 acres (Denholm et al., 2009).

In summary, generating 74,805.5 MWh/year from the proposed 85.4 MW wind farm would require approximately 1,000-5,000 acres of land in Bowman County. This would supply 70% of the county's projected electricity needs 2025 through local renewable generation. Further analysis of optimal turbine siting and transmission infrastructure would refine the project development plans.

Appendix C

The solar PV system is sized to generate approximately 10% of Bowman County's projected 2025 electricity demand. With the demand forecast at 109,011 MWh, 10% equates to 10,901 MWh. A system sized to produce 10,901 MWh annually is selected to align with the 10% target.

- Key assumptions made in sizing the system:
- Average solar insolation: 4.75 kWh/m^2/day
- DC to AC conversion efficiency: 77%
- System losses (wiring, soiling, etc.): 14%
- Annual degradation rate: 0.5%

Based on these parameters, a PVWatts simulation (NREL 2022) shows that a 1 MWDC solar system in Bowman County would produce around 1,335 MWh per year. To generate the 10,512 MWh annual target, an 8 MWDC solar array is recommended.

$$System\ Efficiency\ Losses : E_{Delivered} = E_{avail} \times (1 - Losses) = E_{avail} \times (1 - 0.14)$$

$$Degradation\ Factor : E_{Degraded} = E_{Delivered} \times (1 - Degradation\ Rate) = E_{Delivered} \times (1 - 0.005)$$

Equating degraded energy to target:

$$E_{Target} = E_{Delivered} \rightarrow 10901 Mwh = 0.86 \times E_{avail} \times 0.995$$

Solve to find the required collection area :

$$Area = \frac{E_{target}}{Insolation \times Eficiency\ Factors} = \frac{10901.16\ MWh}{\frac{4.75 \frac{kWh}{m^2}}{day} \times 365 \frac{days}{year} \times 0.86 \times 0.995} \approx 54{,}196\ m^2$$

For a PV system with a panel efficiency of 0.4, this requires:

$$PV\ Capacity = Area \times Panel\ Efficiency = 54{,}196\ m^2 \times 0.4 \frac{kW}{m^2} = 21{,}678\ kW = 21.6\ MW$$

One challenge with solar PV generation is its variability throughout the day and seasonal fluctuations. Energy storage would be helpful to balance out the solar generation profile. Pairing battery storage with solar photovoltaic (PV) systems provides benefits including shifting solar generation to match evening demand peaks, improving grid resilience, and allowing higher penetration of renewables. This analysis examines solar energy storage options for a planned 8 MW solar PV array in Bowman County, North Dakota. A lithium-ion battery system is sized based on a storage capacity of 2 megawatt-hours (MWh).

Storage capacity=194.4MWh

The planned 8 MWDC solar array for Bowman County has a peak output of around 6 MWAC. The storage system power capacity should match the solar array's peak discharge capability for grid failure backup.

Energy capacity (MWh rating) determines the backup duration available.

With the 6 MW solar peak, the 194.4 MWh capacity could provide backup power in case of grid outage and time-shifting capabilities as previously described.

While additional capacity would benefit the system, through advanced software controls and battery engineering, can be optimized to maximize value from the available 194.4 MWh storage. This solar+storage system will help Bowman County incrementally move towards its renewable energy and grid modernization goals.

Appendix D

- Resource Assessment
- Wellhead temperature: 103°C
- ORC inlet temperature: 98°C (specified)
- Flow rate: 51 l/s

Available Thermal Power :

$$Q = m.c_P .\Delta T$$

$$m = 51\ kg/s$$

$$cp = 4.2\ kJ/kg°C$$

$$\Delta T = 103°C - 98°C = 5°C$$

$$Q = 51\ kg/s \times 4.2\ kJ/kg°C \times 5°C = 1070\ kJ/s = 1.07\ MW$$

Geothermal Plant Sizing:

$$Target\ Generation = 16{,}029\ MWh/year$$

$$Efficiency = 12\%$$

$$Capacity\ factor = 90\%$$

$$P = E_{annual}/\ (Hours/year * Capacity\ factor)$$

$$P = 16{,}029\ MWh\ /\ (8760\ hrs * 0.9) = 2.03\ MW$$

With the lower wellhead and inlet temperatures specified, the available geothermal power decreases to 1.07 MW. To still meet the target generation of 16,029 MWh/year, the required plant capacity remains 2.03 MW.

Additional wells or reservoir stimulation may be needed to increase the temperature differential and available thermal power. Optimized plant design and operation can maximize performance within the expected resource constraints.

Plant Equipment Sizing:

- Production wells: 6 wells to access resource
- Injection wells: 6 wells for fluid reinjection
- Piping: 6-8 inch diameter pipes, ~5 km total length
- Pumps: 400 kW (2 × 200 kW) pumps
- Power system: 2.3 MW steam rankine cycle binary turbine
- Heat exchangers: 2 ×1.2 MW capacity
- Condenser, cooling tower appropriately sized for 2.03 MW thermal input

- Switchyard and interconnection for 2.03 MW output

With optimized well configurations and plant equipment designed for the available resource temperatures, the 2.03 MW geothermal plant can meet the renewable energy generation targets.