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Modeling a Hybrid Renewable Energy System for Bowman County, North Dakota: Assessing the Feasibility of Transitioning from Coal to Wind, Solar, and Geothermal Power

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ABSTRACT

Bowman County, North Dakota, currently relies heavily on coal power, accounting for over half of its electricity generation and leading to substantial greenhouse gas emissions. This study utilizes advanced MATLAB modeling to evaluate the potential of transitioning the county to a renewable energy system comprising wind, solar photovoltaics (PV), geothermal, and energy storage. The proposed hybrid system is tailored to Bowman County's growing electricity demand, with nameplate capacities of 85.7 MW for wind, 24.4 MW for solar PV, 2.03 MW for geothermal, and 195 MWh for storage. Simulations verify that by 2040, this custom-designed system could supply over 90% of the county's projected daily loads, with an estimated levelized cost of $105.226/MWh over 15 years that is cost-competitive with conventional power. Implementing this plan would reduce Bowman County's daily carbon dioxide output by approximately 97% relative to continued coal usage. More broadly, this hybrid model serves as a versatile template for other communities striving toward clean, locally focused energy self-sufficiency. It provides a sustainable and adaptable roadmap to support the renewable transition while meeting regional electricity needs, demonstrating one pathway toward a greener future.

1. Introduction

1.1 Background on the Global Energy System

The global energy landscape has been predominantly shaped by the utilization of fossil fuels, which, despite their abundance and historical ease of extraction, have led to significant environmental and climatic challenges. According to the BP Statistical Review of World Energy (2021), fossil fuels account for over 80% of the world's primary energy consumption. This heavy reliance has resulted in elevated levels of greenhouse gases (GHGs) in the atmosphere, contributing to global warming and climate change (Intergovernmental Panel on Climate Change [IPCC], 2021).

The International Energy Agency (IEA) (2021) reports that global energy demand has been increasing at an annual rate of approximately 1.3%, driven by population growth and industrialization. This surge in demand exacerbates the environmental impact, highlighting the urgent need to transition to more sustainable energy sources. Renewable energy, including solar photovoltaics (PV), wind turbines, hydropower plants, and geothermal heat, presents a promising solution to these challenges. These sources of energy are abundant, sustainable, and have a significantly lower environmental footprint compared to fossil fuels (Chen, Wu, & Wang, 2022).

1.2 Inefficiency of Traditional Energy Systems

Traditional energy systems, particularly those based on coal and natural gas, are inherently inefficient. The energy conversion processes in these systems result in substantial losses. For instance, the average efficiency of coal-fired power plants is around 33%, meaning that two-thirds of the energy content of the coal is lost as waste heat (Patil, Kulkarni, & Kshirsagar, 2018; US Energy Information Administration [EIA], 2020). This inefficiency is compounded by transmission and distribution losses, which further reduce the net energy delivered to end-users.

On the other hand, tri-generation systems offer a more efficient alternative by simultaneously producing electricity, heating, and cooling from the same energy source. These systems can achieve overall efficiencies exceeding 80%, making them significantly more effective in utilizing fuel (Wu & Wang, 2006). By capturing and using waste heat, tri-generation systems improve energy efficiency and reduce greenhouse gas emissions, contributing to environmental sustainability.

1.3 Addressing the Need for Sustainable Energy Solutions in North Dakota

With its vast renewable energy resources, North Dakota is well-positioned to lead the transition to a more sustainable energy system. The state is endowed with significant wind and geothermal resources, which, if harnessed effectively, can provide a substantial portion of its energy needs. Despite this potential, over 70% of North Dakota's electricity generation currently comes from coal-fired power plants characterized by high carbon dioxide emissions and other environmental pollutants (US EIA, 2020b; Zygarlicke et al., 2006).

The heavy reliance on coal has significant environmental and public health implications. Coal combustion releases carbon dioxide, sulfur dioxide, nitrogen oxides, and particulate matter, which contribute to air pollution and associated health problems (Parker, 1979). Transitioning to a hybrid renewable energy system in Bowman County can mitigate these issues by leveraging the region's renewable resources, including wind, solar, and geothermal. This study explores the feasibility of such a transition, providing a comprehensive analysis of the technical, economic, and environmental benefits of a hybrid renewable energy system.

This research evaluates the feasibility of implementing a hybridized tri-generation energy system that combines geothermal, wind, and solar resources to meet the electricity needs of Bowman County, North Dakota. While studies have explored integrating complementary technologies like wind and solar photovoltaics, few have comprehensively analyzed the combination of these three renewable sources into a unified system. This study contributes an original feasibility assessment tailored to North Dakota's specific renewable energy potential.

The significance lies in exploring a sustainable energy pathway that could reduce greenhouse gas emissions and air pollution by displacing fossil fuels, creating environmental and public health benefits. The proposed tri-generation system presents an opportunity to enhance energy security, drive economic development, and contribute to climate change mitigation efforts. This research offers valuable insights to policymakers and industry stakeholders regarding the viability of investing in innovative renewable energy infrastructure.

Through an interdisciplinary approach, the study synthesizes data and modeling techniques from engineering, geosciences, economics, and environmental science to deliver a robust analysis. The methodology encompasses simulations of energy output, economic cost-benefit evaluations, and quantification of environmental impacts associated with the proposed system. By holistically assessing the technical, economic, and environmental dimensions, this research aims to provide a comprehensive feasibility evaluation.

The integrated tri-generation system leveraging North Dakota's abundant renewable resources could serve as a model for other regions pursuing sustainable energy initiatives. This study's findings may guide policymakers and industry in implementing hybridized renewable solutions that provide consistent and reliable energy.

2. Energy Portfolio of North Dakota

2.1 North Dakota's Wind Energy Potential

North Dakota possesses immense wind energy resources, ranking among the top US states. The state's high wind speeds, flat and expansive lands, low population density, and abundant rural areas provide ideal conditions for large-scale wind projects (Zhang et al., 2014). North Dakota's installed wind capacity has grown exponentially from just 25 megawatts (MW) in 2000 to over 3,000 MW today, currently supplying approximately 26% of the state's total electricity (American Clean Power Association, 2021).

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). The strongest winds are most abundant in the central and north-central regions. The National Renewable Energy Lab has confirmed that North Dakota has some of the best wind resources in the US, with capacity factors exceeding 50% (Figure 1). Higher capacity factors result in greater energy production per turbine.

The state's topography and low surface roughness due to sparse human development allow unobstructed wind flow. Cold winters and warm summers create seasonal wind patterns that are conducive to wind generation. Wind output is typically highest in winter when heating demand is most significant (Raupach & Finnigan, 1997). North Dakota's wind resources can support a significant expansion of wind power.

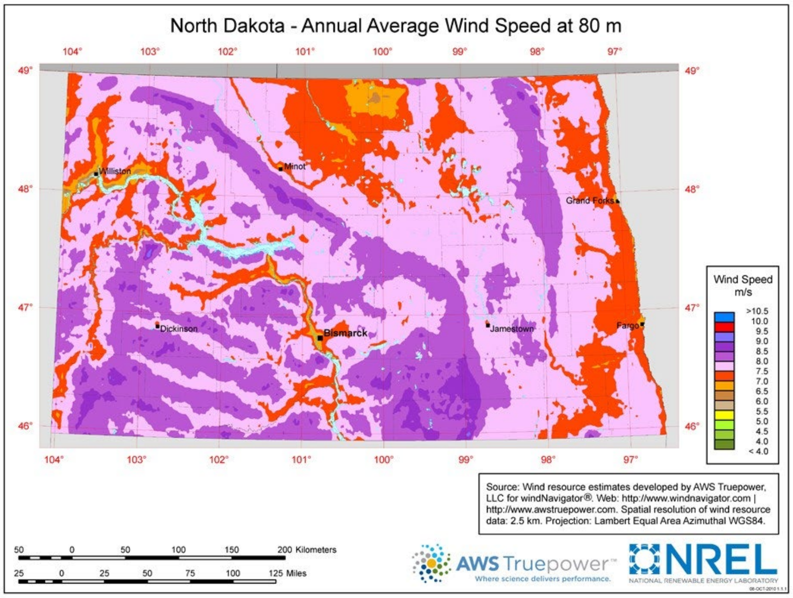

Figure 1. North Dakota's annual average wind speed at 80 m height (NREL, 2021).

North Dakota's first utility-scale wind farm, the 25 MW Lyonsdale project, was built in 1998. 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, 2021). 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 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.

Further wind energy development can bring additional economic activity to North Dakota communities. 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.

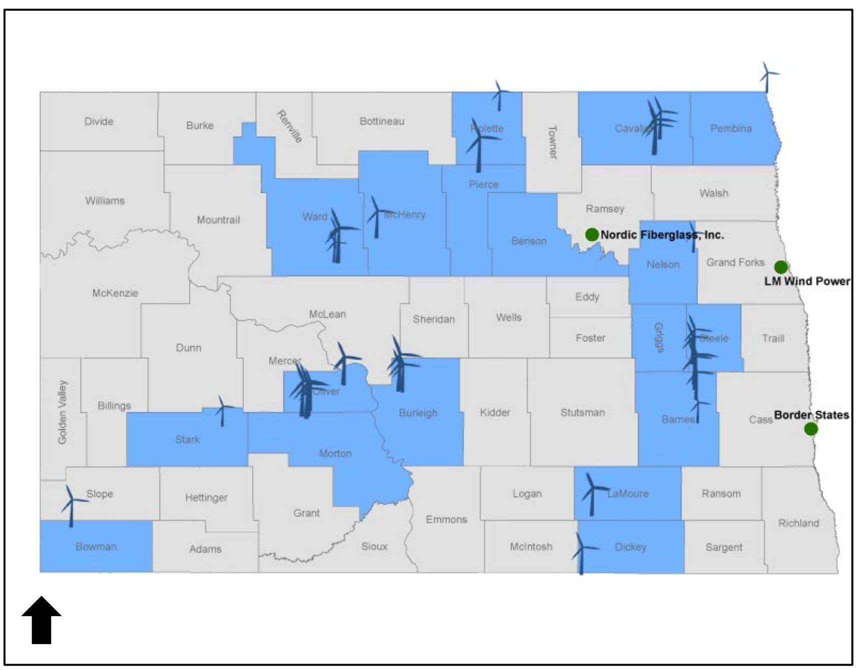

Figure 2. Map of North Dakota wind projects and manufacturing facilities (American Wind Energy Association).

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 further harness North Dakota's bountiful wind resources. North Dakota can realize its tremendous wind power potential with supportive policies and infrastructure.

2.2 North Dakota's Solar Energy Potential

Despite solar energy's immense potential as a sustainable power source, North Dakota has been slow to adopt it compared to leading states. With only about 12 megawatts (MW) of installed solar photovoltaic capacity, North Dakota ranks 36th nationally for solar development (SEIA, 2023). The state's current solar power capacity can power approximately 1,600 typical homes (Figure 3). In contrast, neighboring Minnesota boasts over 800 MW of solar capacity, more than 60 times that of North Dakota. Germany, a global solar energy leader, has an impressive 45,000 MW of total installed solar capacity (Vaidyanathan, 2013). Most of North Dakota's existing solar arrays are relatively small, with capacities under 2 MW. However, as solar costs continue to decline, some electric utilities are starting to develop larger, utility-scale solar farms in the state. The North Dakota Public Service Commission has implemented policies such as net metering to encourage solar growth, which provides credits to homeowners and businesses for the excess solar power they generate. Despite these efforts, North Dakota has significant potential for further development in its solar energy market.

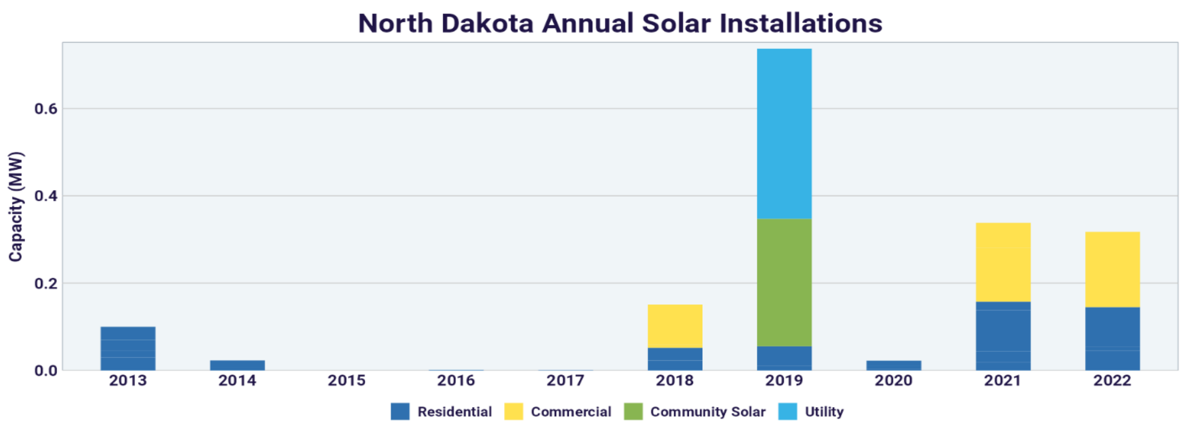

Figure 3. The annual solar installation in North Dakota (North Dakota Solar | SEIA, 2022).

Several factors suggest North Dakota has strong potential for substantially expanding its solar energy capacity. Firstly, the state has reasonably good solar resources, receiving an average of 4 to 5 kWh/m^2/day of solar radiation (Figure 4), which is comparable to Germany's solar resources (NREL, 2020). Even the colder northern regions of North Dakota receive usable levels of sunlight. Secondly, as solar panel manufacturing has scaled up and technology has advanced, costs have decreased significantly, making solar power more economically viable and competitive. Thirdly, federal tax credits and state incentives in North Dakota help reduce the cost of new solar installations, stimulating market growth.

Furthermore, North Dakota has vast rural land areas that could accommodate large, utility-scale solar farms. The declining cost of battery storage technology also complements solar growth by helping to address the intermittent nature of solar power. While solar energy peaks during the day, batteries can store excess power for use at night or on cloudy days. More robust policy mechanisms from state governments, such as renewable portfolio standards, could further incentivize solar adoption. Given its solar resource potential and available space, North Dakota has the opportunity to significantly increase its solar power generation with the help of continued cost declines.

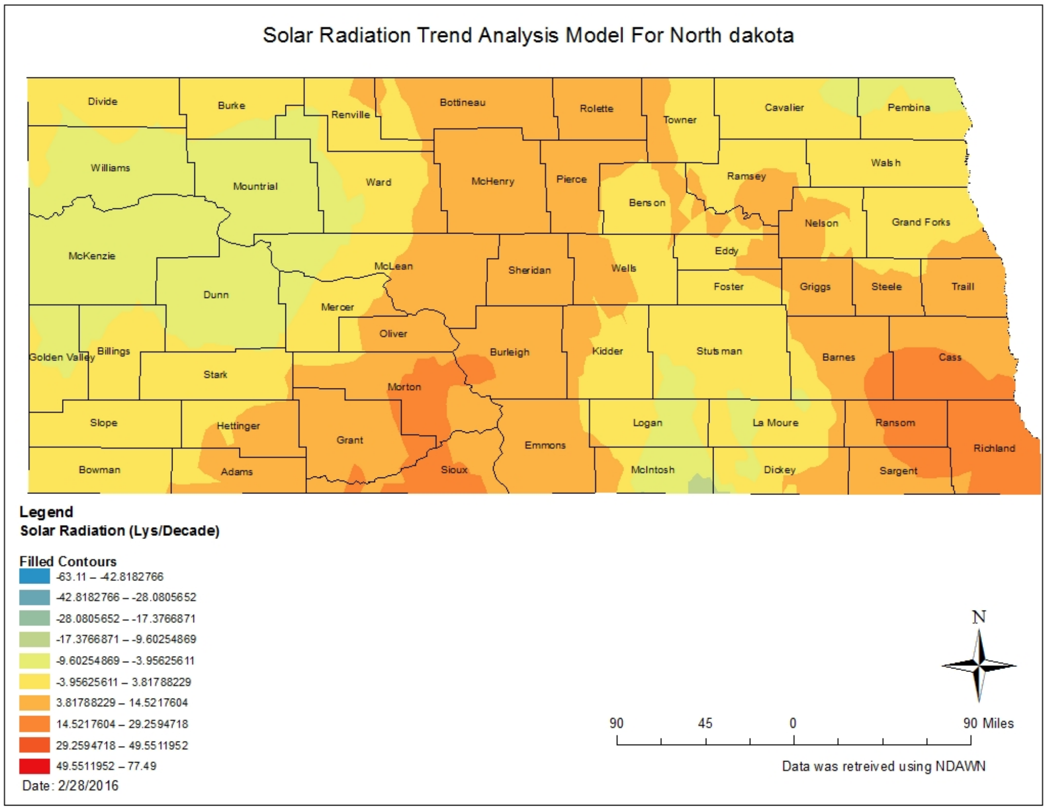

Figure 4. Solar Radiation Trend in North Dakota (Change in Solar Radiation North Dakota, 2016).

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

2.3 North Dakota's Geothermal Energy Potential

Geothermal energy utilizes heat from the Earth's interior to generate electricity and provide direct-use applications such as district heating and heating and cooling of buildings via geothermal networks. North Dakota's geothermal resources, particularly in the Williston Basin, offer significant potential for integration into a hybrid renewable energy system (Matek, 2015). Geothermal energy provides a reliable baseload power source, which is essential for balancing the intermittent nature of wind and solar energy.

Studies have demonstrated the economic and environmental benefits of geothermal energy. Blanco and Faaij (2018) highlight the low greenhouse gas emissions associated with geothermal power, which are typically less than 5% of those from coal-fired power plants. The high capacity factors of geothermal plants, which can exceed 90%, make them a dependable source of continuous power, complementing wind and solar energy variability.

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).

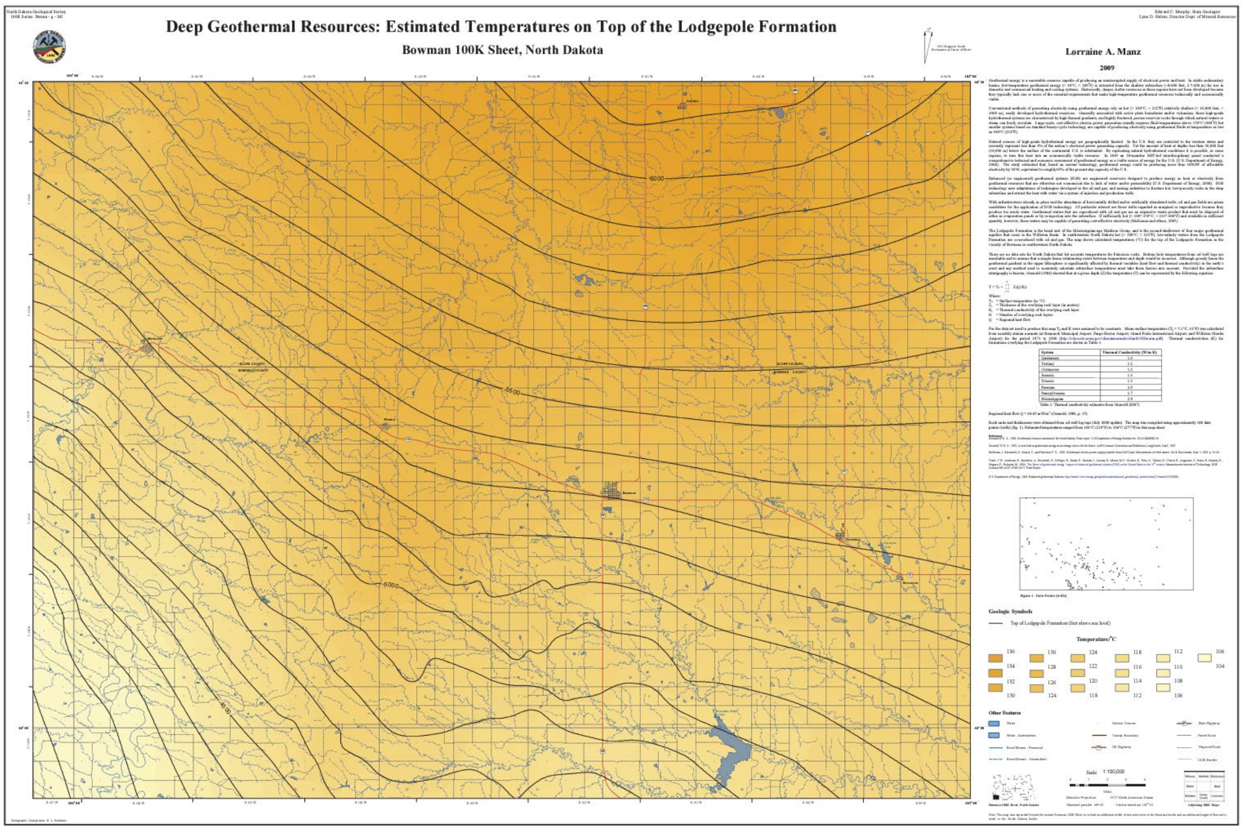

Figure 5. Estimated Temperature on Top of the Lodgepole Formation (Manz, 2008).

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 Systems

Hybrid energy systems combine multiple renewable energy technologies to improve overall system reliability and efficiency. Hybrid systems can provide a stable and continuous energy supply by integrating wind, solar, and geothermal energy with storage solutions. Previous research demonstrates the advantages of hybrid systems in achieving sustainable energy solutions, reducing greenhouse gas emissions, and enhancing energy security (Chen et al., 2022).

Hybrid systems offer the flexibility to optimize energy generation and consumption, ensuring that energy supply matches demand more effectively. This study builds on existing literature to develop a MATLAB-based simulation model for a hybrid renewable energy system tailored to the specific conditions of Bowman County. The hybrid approach also allows for integrating advanced storage technologies, which are crucial for managing the intermittency of renewable energy sources.

3. Methodology

This study employs a comprehensive MATLAB-based simulation to model the proposed hybrid energy system. The research methodology (Figure 6) involves a systematic data collection, system design, simulation, and analysis approach. The key steps in the research methodology include:

3.1 Data Collection

Gathering historical weather data, energy consumption patterns, and renewable resource assessments for Bowman County. This involves obtaining detailed wind speed, solar irradiance, geothermal gradient data, and electricity consumption profiles from various sources, including the National Renewable Energy Laboratory (NREL) and the US Geological Survey (USGS).

3.2 System Design

Defining the capacities of wind turbines, solar PV panels, geothermal energy sources, and storage systems based on the collected data. This step includes selecting appropriate technologies and determining optimal configurations to maximize efficiency and reliability. The design process considers factors such as resource availability, system efficiency, and energy demand patterns.

The system (Figure 7) includes wind turbines, solar PV panels, geothermal energy sources, and storage capacities. The MATLAB model simulates energy production, storage, and consumption based on real-time data and predictive algorithms. The hybrid system is designed to optimize energy production from each renewable source while ensuring a continuous and reliable energy supply.

- *Wind Energy Modeling*: The wind energy component of the model uses historical wind speed data and turbine performance curves to simulate energy production. The model accounts for factors such as wind speed variability, turbine efficiency, and capacity factors.

The performance of different turbine models is evaluated to select the most suitable option for the site.

- *Solar Energy Modeling:* The solar energy component utilizes solar irradiance data and PV module characteristics to estimate energy production. The model includes factors such as panel orientation, tilt angle, shading effects, and temperature coefficients. Different PV technologies are compared to determine the optimal choice for the hybrid system.
- *Geothermal Energy Modeling:* The geothermal energy component simulates heat extraction from the Earth's subsurface and its conversion into electricity. The model incorporates geothermal gradient data, well characteristics, and conversion efficiencies. The potential for direct use applications, such as district heating, is also evaluated.
- *Storage System Modeling:* The storage system is designed to balance supply and demand, ensuring a continuous energy supply. The model simulates the charging and discharging cycles of the storage system based on energy production and consumption patterns. Different storage technologies, including batteries and thermal storage, are analyzed to determine the most effective solution.

3.3 Simulation

In this study, we use MATLAB to model and simulate the hybrid system's energy production, storage, and grid integration. The simulation incorporates various scenarios to assess system performance under different conditions. Key parameters, including capacity factors, energy conversion efficiencies, and storage capacities, are integrated into the model to ensure accurate simulations.

3.4 Analysis

This research evaluates the proposed system's technical feasibility, economic viability, and environmental impact. This analysis includes calculating the levelized cost of electricity (LCOE), assessing greenhouse gas emissions reductions, and conducting sensitivity analyses to determine the impact of different variables on system performance. The analysis comprehensively assesses the hybrid system's potential benefits and challenges.

The economic analysis involves calculating the levelized cost of electricity (LCOE) for the hybrid system. This analysis includes capital, operation, maintenance, and financing costs. The LCOE is compared to traditional coal-based energy systems to assess the economic viability of the hybrid system. The analysis also considers potential cost savings from policy incentives and technological advancements.

The environmental analysis assesses the reductions in greenhouse gas emissions achieved by the hybrid system, which involves comparing the lifecycle emissions of each hybrid system component to a baseline scenario of coal-based energy production. The analysis includes the emissions associated with the system's manufacturing, installation, operation, and decommissioning.

The sensitivity analysis models various scenarios to assess the impact of different variables on the system's economic and environmental performance, which includes changes in capital costs, energy prices, policy incentives, and technological advancements. The sensitivity analysis helps to identify the most critical factors influencing the viability of the hybrid system and provides insights into potential risks and opportunities.

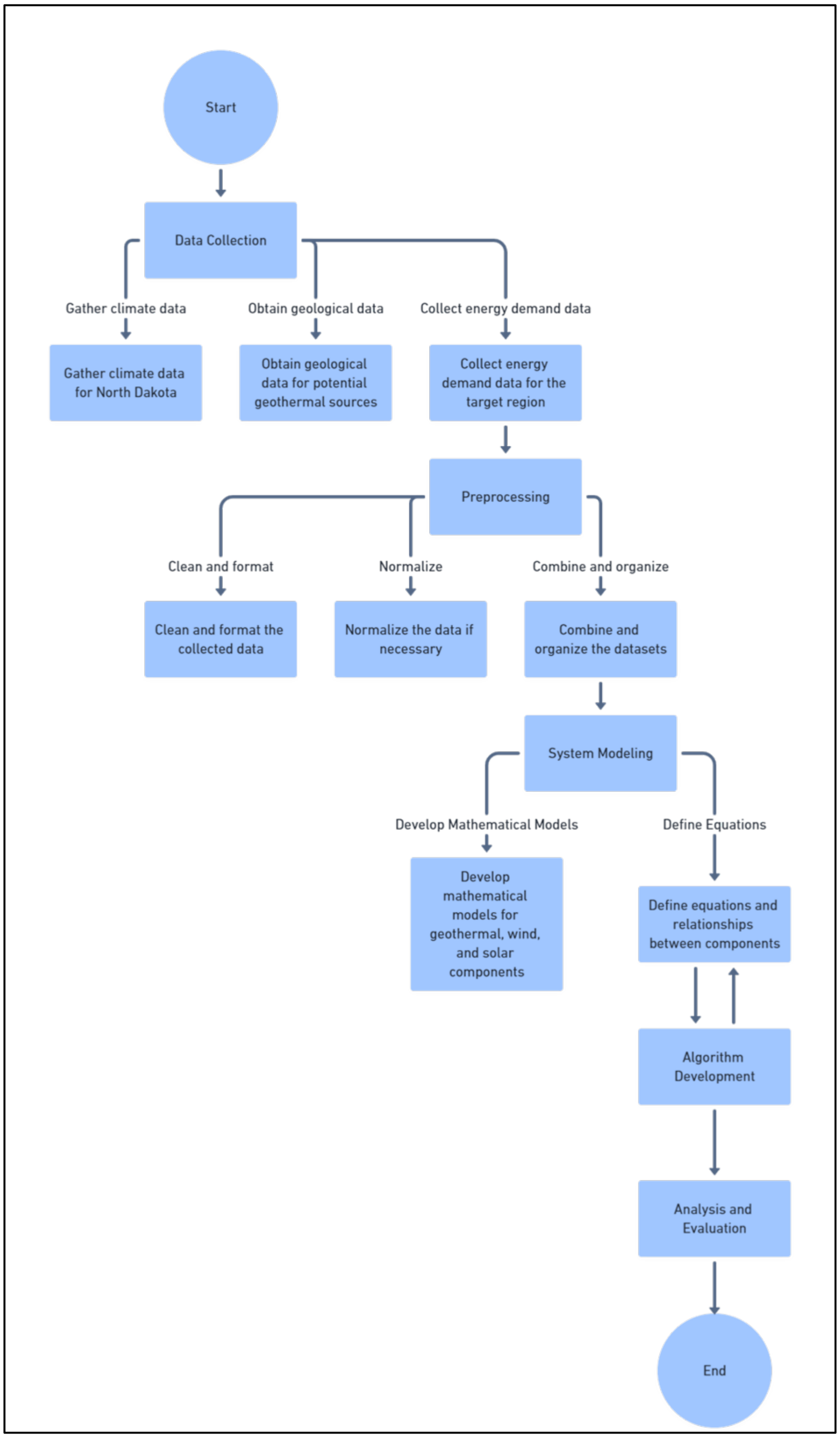

Figure 6. Flow chart for System Modeling and Simulation.

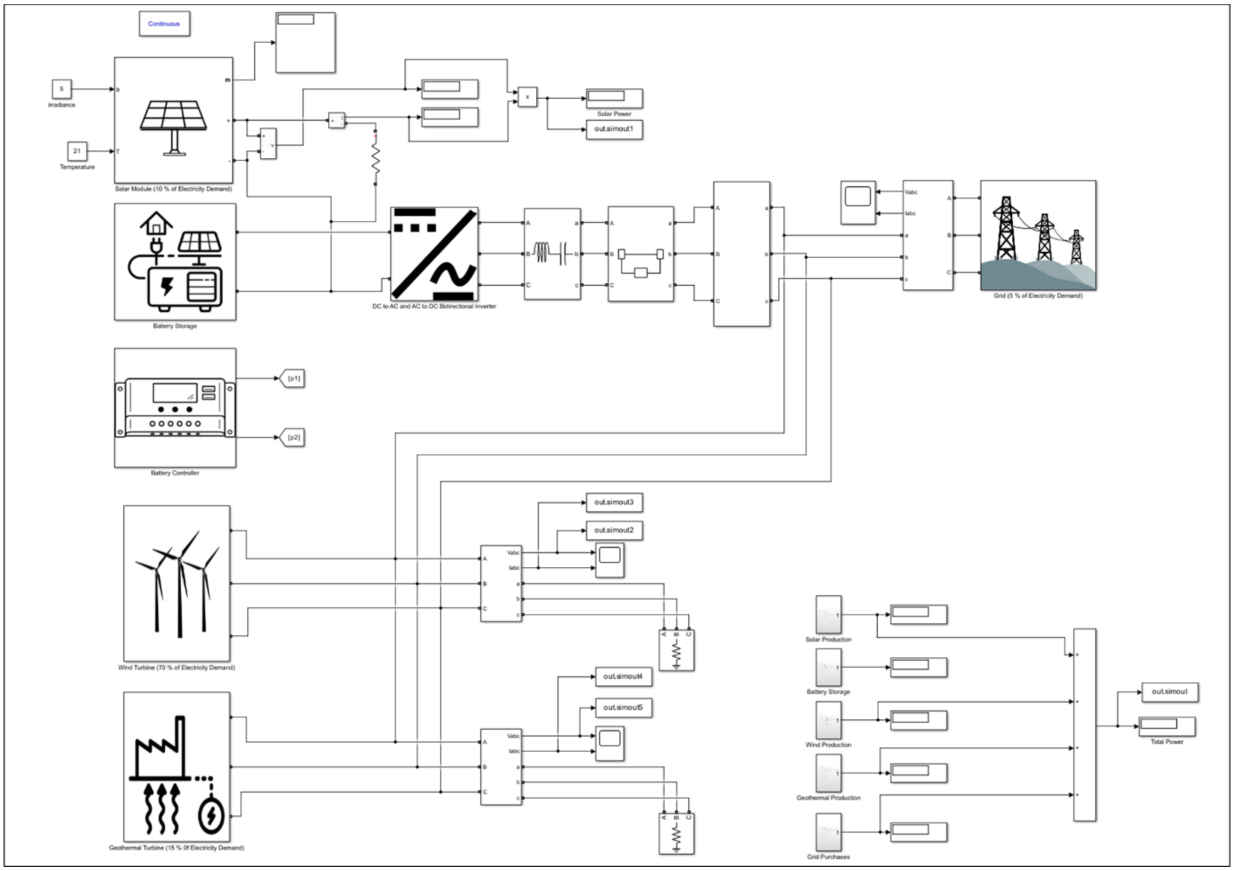

Figure 7. The hybrid system was designed for Bowman County, ND, using Simulink, MATLAB, 2023.

4. Results and Discussions

4.1 Feasibility of the Hybrid System

A proposed hybrid renewable energy system for North Dakota combines wind, solar, geothermal, storage, and grid purchases to meet an assumed local annual electricity demand of 106,865 MWh (Table 1). The system is designed to supply 70% of the total demand from wind, 10% from solar, and 15% from geothermal, with the surplus coming from storage and 5% from grid purchases.

- The wind component of the hybrid system has a capacity of 85.4 MW, with an estimated capital cost of $107,347,800 and an annual operation and maintenance (O&M) cost of $3,561,180. The wind turbines are expected to generate 74,805 MWh of electricity annually.
- The solar PV component has a capacity of 24.4 MW, with an estimated capital cost of $26,181,200 and an annual O&M cost of $458,720. The solar panels are expected to generate 10,688 MWh of electricity annually.
- The geothermal component has a capacity of 2.03 MW, with an estimated capital cost of $13,010,270 and an annual O&M cost of $212,338. The geothermal plant is expected to generate 16,029 MWh of electricity annually.

- The solar storage component has a capacity of 194 MWh, with an estimated capital cost of $243,605.8 and an annual O&M cost of $6,072.2. The storage system will store surplus energy generated by the solar panels for use during periods of low solar output.
- To supplement the renewable energy sources, the system will also purchase 5,343.25 MWh of electricity annually from the grid at an O&M cost of $5,343,250.

Table 1. Monthly production of the hybrid system, Bowman County, North Dakota, by 2040.

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

The total annual electricity generation from these combined sources is estimated to be 112,210 MWh, which exceeds the assumed local demand of 106,865 MWh. This hybrid renewable energy portfolio is designed to provide a reliable and sustainable source of electricity for North Dakota while minimizing reliance on fossil fuels and reducing greenhouse gas emissions. Simulations indicate that the proposed hybrid system can meet over 90% of Bowman County's daily energy demands by 2040 (Figure 8). The wind and solar components produce the bulk of energy, while the geothermal component offers a stable baseload power source. The storage system effectively balances supply and demand, ensuring a continuous energy supply. The results demonstrate the technical feasibility of integrating multiple renewable energy sources to create a reliable and efficient hybrid system.

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 technically enable the vast majority of local load from Indigenous variable generation to be fulfilled 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.

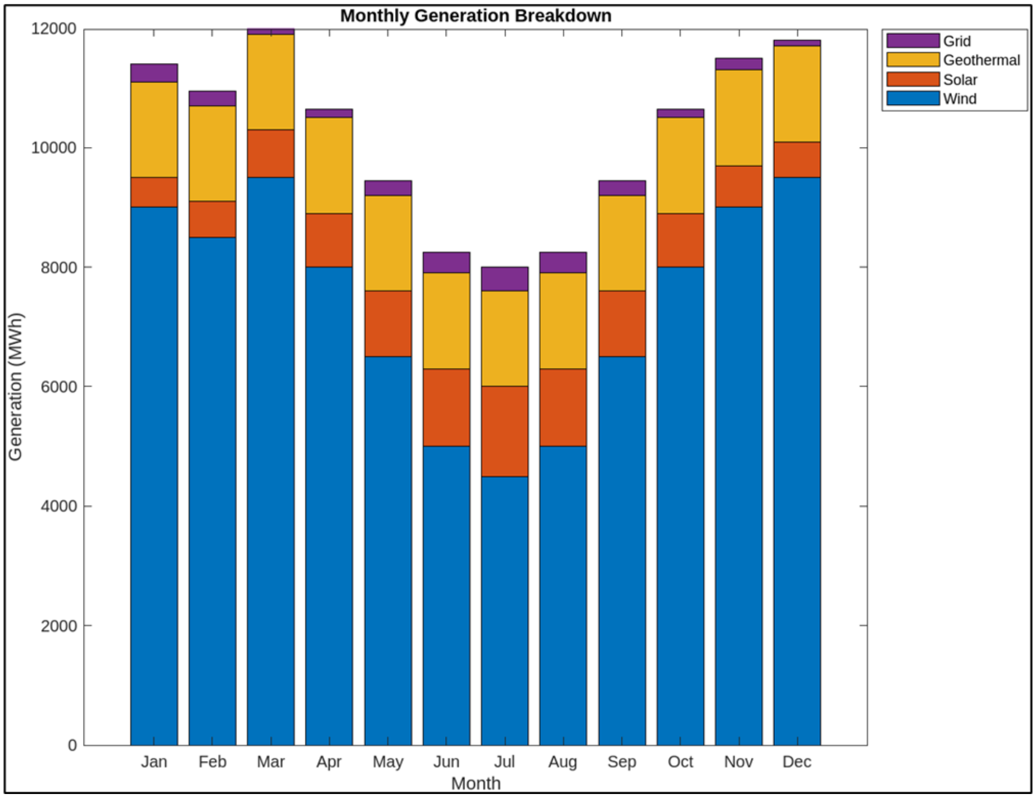

Figure 8 . Monthly electricity generation from the hybrid system by 2040.

4.2 Economic Assessment

The proposed hybrid renewable energy system for Bowman County, North Dakota, demonstrates economic solid viability, with a projected Levelized Cost of Electricity (LCOE) of $105.226/MWh over a 15-year period (Figure 9). This cost is comparable to or lower than traditional coal-based energy systems, making the hybrid system an attractive alternative from a financial perspective. Sensitivity analyses conducted as part of the economic assessment reveal that the hybrid system remains economically viable under various scenarios, including fluctuations in capital costs, energy prices, and policy incentives. Integrating multiple renewable energy sources enhances the system's resilience and reduces dependency on a single energy source, further improving economic stability. The study also highlights the potential for cost savings through policy incentives and technological advancements, which can further improve the hybrid system's economic performance. These findings provide valuable insights for policymakers and investors considering the transition to renewable energy systems. Overall, the economic assessment emphasizes the financial benefits of adopting a hybrid renewable energy system in Bowman County, demonstrating the potential for cost-effective, stable, and environmentally friendly energy production.

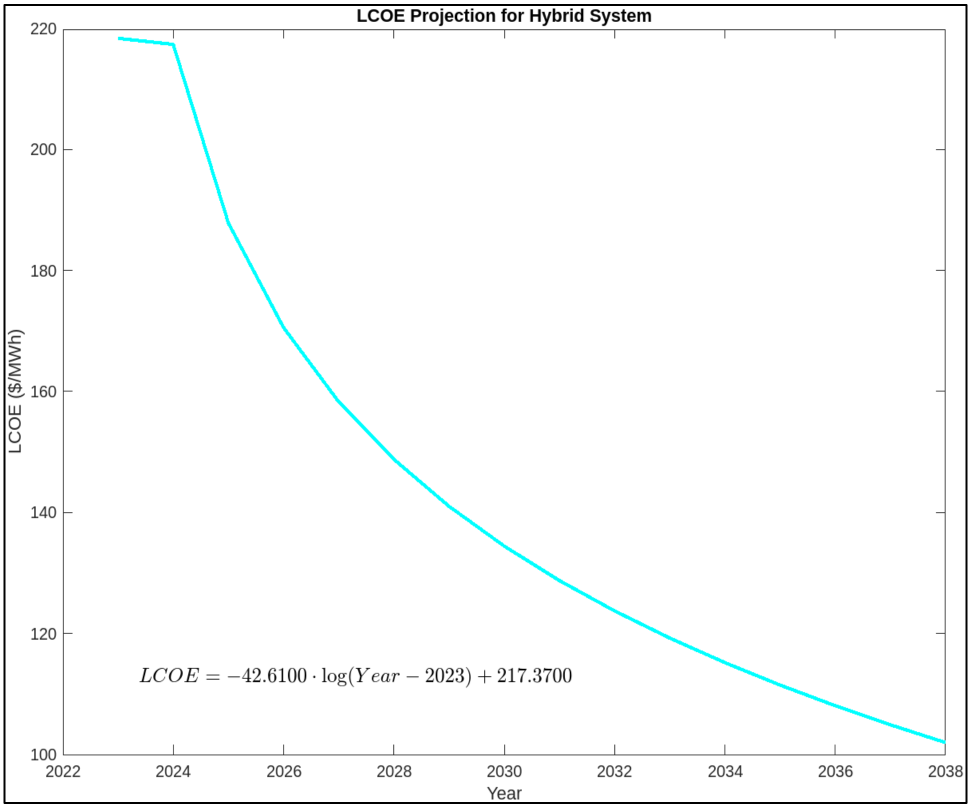

Figure 9. Levelized Cost of Electricity Projection for Hybrid System.

4.3 Environmental Impact

The proposed hybrid renewable energy system for Bowman County, North Dakota, offers significant environmental benefits by reducing daily CO_2 emissions by 97% compared to coal-based energy systems (Figure 10). This substantial reduction in greenhouse gas emissions aligns with global sustainability goals and contributes to the mitigation of climate change (Blanco & Faaij, 2018). The displacement of coal-based energy with clean, renewable energy sources is the primary driver behind the reduction in emissions. By harnessing wind, solar, and geothermal resources, the hybrid system minimizes the environmental impact of energy production and helps improve air quality in the local community. The environmental impact assessment underscores the wide-ranging benefits of reducing greenhouse gas emissions and other pollutants. In addition to combating climate change, the hybrid system can enhance public health by reducing the incidence of respiratory illnesses and other health problems associated with air pollution. Furthermore, the study highlights the potential for renewable energy systems to provide long-term environmental sustainability. Bowman County can contribute to global efforts to create a more sustainable and resilient energy future by transitioning to a hybrid renewable energy system.

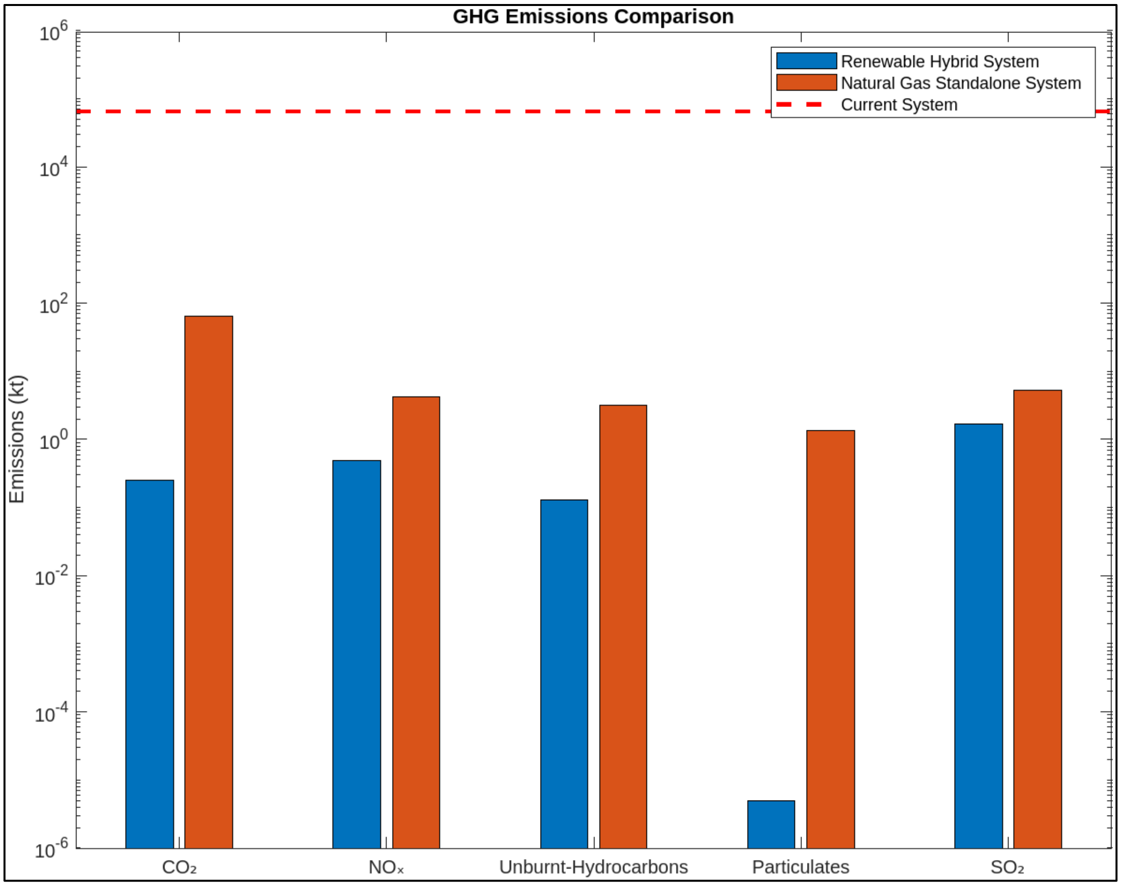

Figure 10. Greenhouse Gas Emission (GHG) Comparison: Hybrid Wind-Solar-Geothermal-Storage System vs. Natural Gas.

5. Conclusions

5.1 Overview of the Study

This study provides a comprehensive analysis of a hybrid renewable energy system tailored to the specific needs of Bowman County, North Dakota. By integrating wind, solar, geothermal energy, and storage technologies, the proposed system aims to meet the growing energy demands while significantly reducing greenhouse gas emissions. The study employs advanced MATLAB-based simulations to model and evaluate the system's performance under various scenarios, ensuring a robust and reliable analysis.

5.2 Key Findings

The simulations and analyses conducted in this study yield several key findings:

- *Technical Feasibility:* With its diverse mix of renewable energy sources, the hybrid system is technically feasible for Bowman County. The integration of wind, solar, and geothermal energy ensures a stable and reliable energy supply that meets over 90% of the county's projected daily energy demands by 2040. Including a storage system effectively balances supply and demand, addressing the intermittency issues associated with wind and solar energy.

- *Economic Viability:* The levelized cost of electricity (LCOE) for the hybrid system is projected to be $105.226/MWh over 15 years, making it competitive with traditional coal-based energy systems. The economic analysis demonstrates that the hybrid system is financially viable, with the potential for cost savings through policy incentives and technological advancements. Sensitivity analyses confirm the system's economic robustness under various scenarios, highlighting its resilience to changes in capital costs, energy prices, and policy environments.
- *Environmental Benefits:* The hybrid system significantly reduces greenhouse gas emissions, with a projected 97% reduction in daily CO_2 emissions compared to coal. This substantial decrease in emissions aligns with global sustainability goals and contributes to mitigating climate change. The environmental analysis also highlights the additional benefits of improved air quality and public health, underscoring the importance of transitioning to renewable energy.

5.3 Implications for Bowman County

The successful implementation of the proposed hybrid renewable energy system has profound implications for Bowman County. It offers a pathway to achieving energy independence and sustainability, reducing reliance on fossil fuels and enhancing energy security. The system's economic viability and environmental benefits make it an attractive option for local policymakers, investors, and the community.

- *Energy Independence:* Bowman County can reduce its dependency on imported fossil fuels by leveraging local renewable resources, which enhances energy security and resilience and protects the community from the volatility of global energy markets and potential supply disruptions.
- *Economic Development:* Developing and deploying renewable energy technologies can stimulate local economic growth. It creates job opportunities in constructing, operating, and maintaining renewable energy facilities, contributing to the local economy. The potential for cost savings and revenue generation from excess energy production further enhances economic benefits.
- *Environmental Stewardship:* Transitioning to a hybrid renewable energy system positions Bowman County as a leader in environmental stewardship. It demonstrates a commitment to sustainability and climate action, serving as a model for other communities. The environmental benefits, including reduced emissions and improved air quality, contribute to the overall well-being of the local population.

5.4 Broader Implications and Future Research

The findings of this study have broader implications beyond Bowman County, providing valuable insights for other communities and regions seeking to transition to renewable energy. The hybrid model serves as a versatile template that can be adapted to different geographic and climatic conditions, offering a scalable solution for sustainable energy development.

- *Scalability and Adaptability:* The hybrid system model can be adapted to various scales, from small communities to larger urban areas. It is flexible enough to incorporate additional renewable energy sources and advanced storage technologies, enhancing its applicability across different contexts. The model's adaptability makes it a valuable tool for planning and designing renewable energy systems worldwide.

- *Policy and Investment:* The study underscores the importance of supportive policy frameworks and investment in renewable energy. Policy incentives, such as subsidies, tax credits, and feed-in tariffs, play a crucial role in enhancing the economic viability of renewable energy projects. Investment in research and development is also essential to drive technological advancements and cost reductions in renewable energy technologies.
- *Further Research:* While this study provides a comprehensive analysis, further research is needed to explore additional aspects of renewable energy integration. Future research should focus on optimizing system configurations, incorporating emerging technologies, and assessing the long-term sustainability of hybrid systems. Studies on renewable energy transitions' social and cultural impacts are also critical to ensure community acceptance and engagement.

In conclusion, the proposed hybrid renewable energy system offers a viable and sustainable solution for Bowman County, North Dakota. It effectively meets the growing energy demands while significantly reducing greenhouse gas emissions, contributing to environmental sustainability and climate action. The study demonstrates the hybrid system's technical, economic, and environmental feasibility, providing a comprehensive roadmap for its implementation. The findings underscore the potential for renewable energy systems to drive the transition to a sustainable and resilient energy future, offering valuable insights and a model for other communities seeking to achieve clean, locally focused energy independence.

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