HARNESSING RENEWABLE RESOURCES IN SOUTHERN ALBERTA: A HOMER PRO AND GIS APPROACH TO ENERGY AND AGRICULTURE

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DEDICATION

To my late Father Aftab Alam, Mother Arjumand Amin, Amaan Aftab , Dr. Arfa Aftab and Neda Ali for their prayers, support, love, care, and patience that gave me confidence during this journey.

ABSTRACT

With robust and innovative federal policies and initiatives, Canada has rapidly shifted its focus from conventional fuels to renewable energy resources, aiming to reduce greenhouse gas emissions and achieve a sustainable energy future. The Pan-Canadian policy 2030 on Clean Growth and Climate Change laid out by the Canadian Government presented a comprehensive framework to reduce carbon emissions by 30%. This policy comprises detailed measures to promote clean energy projects and build resilience to the impact of climate change by adopting renewable energy resources across the country. Alberta, the country's largest energy producer, plays a vital role in policy adoption to promote clean and environmentally friendly renewable technologies. Alberta’s Electric System Operation statistics show that the province boasted over 6 GW of Wind and 1.5 GW of Solar photovoltaic capacity in 2023. Alberta’s 2016 initiative, “Renewable Energy Program 2030,” aimed at achieving 30% of the province’s energy from renewable energy resources. These goals are driven by Alberta’s abundant renewable energy resources and a decreasing trend in PV and WT technology costs.

This research redefines the integration of hybrid renewable energy systems by introducing an innovative tri-brid photovoltaic-wind turbine-battery energy storage system (PV-WT-BESS) model, strategically designed for remote communities in Alberta. Unlike Conventional approaches, this research pioneers a techno- economical, geospatial and agricultural synergy by leveraging HOMER Pro for energy optimization, Geographic Information System (GIS) based strategic land use assessment and FAO’s

CROPWAT for precision irrigation planning. The first objective of the research was to conduct a detailed techno-economic analysis by considering hybrid renewable energy resources in the country, especially in remote communities that mainly rely on conventional resources such as fossil fuels, etc. Furthermore, the research was extended towards finding out the strategic land use and resource assessment process to efficiently optimize the integration of renewables such as solar and wind energy into the major sectors contributing to the economy. Agriculture is considered one of the main pillars of Canada's economy, generating 7% of the GDP and creating substantial employment opportunities. Hence, efficient utilization of the land for renewable installation is crucial to keep the land used for agricultural purposes at its maximum. Agriculture output efficiency mainly relies on the irrigation of land. Different rivers, such as the Bow, Oldman, South Saskatchewan Rivers, etc. supply the irrigation water to fulfil the crop water requirements. However, extensive water use reduces water reservoirs, which could significantly affect the hydel energy generation in coming years, i.e., 60% of the total energy generated throughout the country.

Keeping in view the sustainable development goal (SDG 7), i.e., Affordable and Clean Energy, the presented research work leverages Homer Pro energy modelling, Geographic Information System (GIS) techniques, and FAO's CROPWAT software to optimize renewable energy resources for energy generation and irrigation purposes tailored for Alberta, mainly focusing on communities such as Gleichen and irrigation districts of Lethbridge and St. Mary River. This study has been conducted to achieve the most optimized hybrid renewables combination with the lowest cost of energy

(LCOE) and reduced greenhouse gas emission (GHG) compared to conventional fuel-based electricity.

In the first part of the study, a tri-brid system was modelled for the Siksika Nation in Gleichen, Alberta, due to its proximity to high renewables availability. The proposed hybrid system comprises grid-tied PV-WT-BESS to compensate for the community load demand. The techno-economic analysis revealed that LCOE for the proposed system is $0.075 CAD/kWh compared to conventional energy costing $0.127 CAD/kWh. These results authenticate the cost-effectiveness and environment-friendly nature of hybrid renewables. In the second part of the research work, the scope was extended to Lethbridge Northern Irrigation District (LNID) and St. Mary River Irrigation District (SMRID) for strategic land use and resource assessment processes to integrate renewables such as PV and WT systems into these areas. GIS techniques were used to determine the impact of various factors, such as land use, elevation, soil morphology, water bodies, road and electric networks, etc., on the suitability of different sites. Principal Component Analysis (PCA) and Fuzzy Overlay Analysis were used to identify the most suitable sites. The study outcomes can prove valuable for policymakers, planners, and stakeholders in driving the region toward sustainability.

In the concluding part of the research study, the importance of cost-effective and efficient irrigation has been emphasized, considering that agriculture contributes 2.8% to Alberta's economy. Due to the closure of the issuance of new water licenses for Oldman River in the area mainly used for irrigation, groundwater pumping has become the complementary source for irrigation purposes to fulfill the crop water requirements. The study explored the utilization of PV and WT systems to supply the required energy for the groundwater pumping mechanism. CROPWAT was used for the calculation of crop water requirements of an agricultural farm for one complete season. This requirement was further converted into energy needs. Homer Pro was used to design the most optimized hybrid renewable system to fulfill the energy needs of agriculture farms and compensate for the water requirement for a complete season.

The valuable findings from the above studies signify the importance and practicality of integrating renewables into the regional economy. This research highlights renewable energy's role in boosting economic growth and mitigating environmental impacts in the region by providing the roadmap for energy independence and ensuring sustainability.

Contribution of Authors

This thesis is a manuscript-based thesis. All the authors have contributed equally for all the manuscripts, which is in this thesis as Chapter 2, Chapter 3 and Chapter 4. Mohammad Adnan Aftab , A PhD Candidate has drafted the manuscript which is published now in Implementing Tri-brid Energy Systems for Renewable Integration in Southern Alberta, Canada(Aftab, M.A et.al 2024).The manuscript is published in 'Clean Technologies'. Dr. Dan Johnson, Dr. Paul Hazendonk, and Dr. Locke Spencer have supervised and reviewed the manuscript. Dr James Byrne assisted in acquiring the grants for this valuable research.

Chapter 3 titled: *Developing A Strategic Land Use and Resource Assessment Process to Optimize Renewable Energy Integration into the Regional Economy of two irrigation districts LNID and St. Mary River, Alberta, Canada'* will be submitted shortly for publication.

Chapter 4 titled: *Sustainable Crop Irrigation with Renewable Energy: A Case Study of Lethbridge County, Alberta, Canada* has been submitted and currently under review.

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List of Abbreviations

PV	Photovoltaic
WT	Wind Turbine
BESS	Battery Energy Storage System
GIS	Geographic Information System
SDG	Sustainable Development Goals
FAO	Food and Agriculture Organization
LCOE	Lowest Cost of Energy
GHG	Greenhouse Gas
HRES	Hybrid Renewable Energy Sources
NRCan	Natural Resources Canada
AUC	Alberta Utilities Commission
ACT	Agricultural Clean Technologies
CAP	Canadian Agricultural Partnership
GF2	Growing Forward 2
MILP	Mixed Integer Linear Programing
BAU	Business as Usual
LCON	Low Conflict
MCDM	Multi-Criteria Decision Making
PCA	Principal Component Analysis
LNID	Lethbridge Northern Irrigation District
IEA	International Energy Agency
CHP	Combined Heat and Power
EPM	Energy Production Mix
TCE	Total Carbon Emission
REP	Renewable Energy Program
AESO	Alberta Electric System Operator
CanWEA	Canadian Wind Energy Association
NPC	Net Present Cost
NPV	Net Present Value
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
ROI	Return on Investment
IRR	Internal Rate of Return
DSS	Decision Support System
FAHP	Fuzzy Analytical Hierarchy Process
SMRID	St. Mary River Irrigation District

Chapter 1: Introduction

The exponentially increasing population, urbanization, dietary change, and climatic variation impact on agriculture, and other aspects of economic development, have raised questions about how to eradicate global hunger in the future (Van Dijk et al., 2021). Studies revealed that energy and food demand will be increased by 30-56% by 2050 (Esmaeli & Roshandel, 2020) . Consequently, rapid shifting from conventional fossils to renewable energy systems marks a significant stride in facing global challenges to combat climate changes for sustainable development, leading to energy and food security as well as mitigating environmental impact associated with GHG emissions by conventional fuels (Maliat et al., 2024). Hybrid renewable energy resources (HRES) have emerged by integrating various energy resources as the most efficient and most feasible solution to ensure a stable and continuous energy supply (Jiang et al., 2022). Researchers suggest that integrating renewable and conventional resources is a more reliable and cleaner source than series integration. Furthermore, advanced energy storage technologies ensure the stability of such HRES by storing excess renewable energy and providing services such as peak saving and frequency stabilization (Mufutau Opeyemi, 2021). Canada has shown its serious commitment to renewable utilization to rectify the issues related to climatic changes. Almost 80% of Canada's GHG emissions are directly related to energy generation and utilization. Provincial GHG emissions breakdown can be analyzed in Table 1 (*Greenhouse Gas Sources and Sinks in Canada*, 2023). According to the International Energy Agency, Canada is a signatory of the Paris Agreement to reduce greenhouse gas emissions (GHG) to 45% by 2030 and further legislated to zero carbon emissions by 2050. Even though almost 68% of the country's electricity comes from renewable energy resources, nearly all the microgrids supplying electricity to remote communities are disconnected from the primary utility grid and rely on conventional fossil fuels for generation. The "Decarbonizing Canada's Remote Microgrids" report highlights the significance of transitioning from traditional fuels to renewable resources to ensure energy reliability and environmentally friendly energy. The report further highlights the critical demand for efficient and innovative energy solutions to facilitate sustainability in remote communities (Stringer & Joanis, 2023). Canada's energy future can be seen in Table 1 as well as Figure 1. Table 1 (Hastings-Simon et al., 2022) depicts the provincial breakdown of Canada's GHG emissions from electricity generation revealing significant regional disparities, highlighting both progress and challenges in the country's energy transition. Provinces such as Manitoba, Quebec, and Prince Edward Island report virtually zero emissions from electricity, indicating a strong reliance on clean energy sources like hydropower and wind. In contrast, Alberta and Saskatchewan contribute the highest emissions from electricity generation, largely due to continued dependence on fossil fuels such as coal and natural gas. Nova Scotia also stands out with the highest proportion of electricity-related emissions relative to its total GHG output, emphasizing the critical need for renewable energy integration. While electricity generation accounts for only 9% of Canada's total emissions, targeted decarbonization in high-emission provinces and investment in clean energy infrastructure for remote and northern communities will be essential to achieving national climate goals. This data underscores the need for region-specific strategies to ensure an equitable and effective energy transition across the country. Alberta legislated policy in 2016 , in which the government committed to shifting 30% of the state's energy from conventional fuels to renewable energy resources by 2030. Prior to the commitment of the Alberta government to the Renewable Electricity Program, only 10% of electricity in Alberta came from renewable resources. The success of these policies shows the importance of economical and environmentally friendly hybrid renewable energy systems.

Table 1 Provincial Breakdown of Canada's GHG Emissions

Jurisdiction	**Electricity Total Greenhouse Gases (Mega tonnes)**	**Total Generation (terawatt-hours)**	**Electricity Sector Emissions as a % of Total Emissions**
British Columbia	0.4	58.4	1%
Alberta	**32.7**	**55.8**	**13%**
Saskatchewan	13.9	24.0	21%
Manitoba	0.0	37.2	0%
Ontario	3.7	149.0	2%
Quebec	0.3	188.0	0%
New Brunswick	3.5	12.0	28%
Nova Scotia	6.3	9.4	43%
Prince Edward Island	0.0	0.7	0%
Newfoundland and Labrador	1.0	39.8	10%
Yukon	0.1	0.5	9%
Northwest Territories	0.1	0.4	4%
Nunavut	0.2	0.2	25%
Canada	62.1	575.4	9%

Figures 2 (Natural Resources Canada, 2023) and 3 (Powering the Clean Energy Transition, n.d.) show renewable energy's impact on job creation and expenditure savings associated with shifting to renewables in the coming years. Alberta is considered the wealthiest state in Canada, with abundant conventional fossil reservoirs.

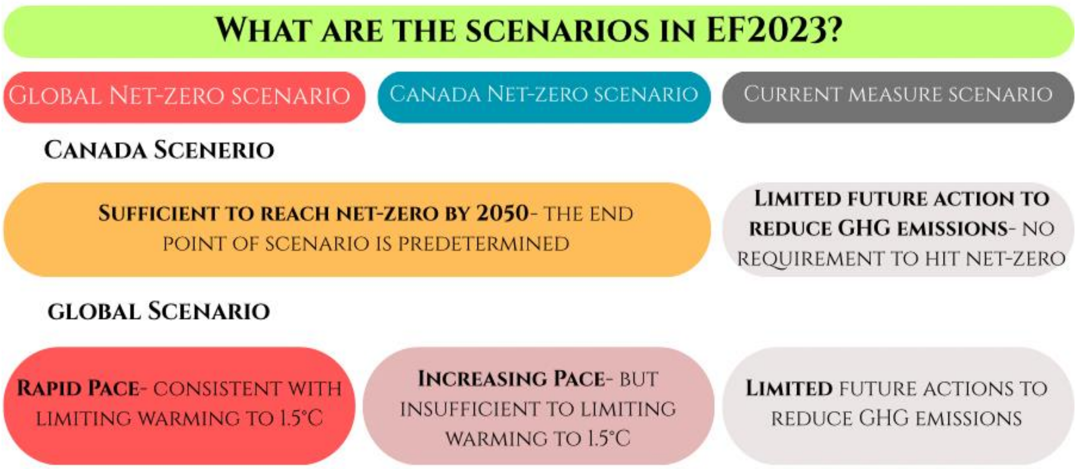

Figure 1: Illustration of Canada Energy Future *(Regulator, n.d.)*

Figure 2: Jobs Creation by Electricity Sector 2020-2050 (Rys., 2018)

However, land utilization based on resource assessment in the specific area holds significant value in capturing the full potential of renewables and making them economically viable. In this regard, various policies have been implemented by governments on all levels, i.e., federal, provincial, and municipal (*Impact Assessment Act*, n.d.) The Federal Government outlines a process of assessing the impact of designated projects, including large-scale renewable projects carried out on federal land. This Act assesses the environmental, health, social, and economic effects of the selected project, along with the positive and negative impacts.

Furthermore, this Act further highlights the impact of these projects on Indigenous people and their rights. In relevance to renewable projects, this Act considers the impact by evaluating land use and potential conflicts with existing land use.

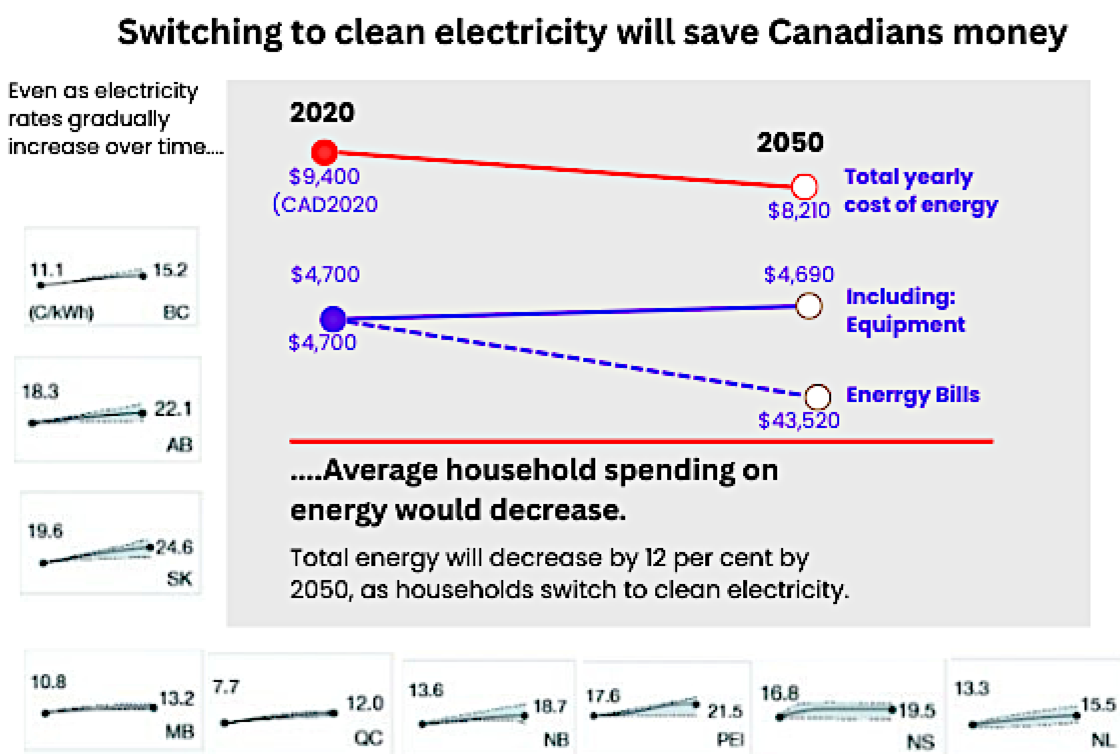

Figure 3: Canada's Household Expenditures and Savings 2025-2050 *(*Powering the Clean Energy Transition*, n.d.)*

Figure 3 illustrates how switching to clean electricity can lead to reduced household energy spending in Canada by 2050, despite a gradual increase in electricity rates. On the left, a series of small line graphs display projected residential electricity costs for each province, showing a moderate rise in cents per kilowatt-hour from 2025 to 2050. For instance, British Columbia is expected to see an increase from 11.1 to 15.2 ¢/kWh, Alberta from 18.3 to 22.1 ¢/kWh, and Saskatchewan from 19.6 to 24.6 ¢/kWh. Provinces like Manitoba and Quebec continue to project some of the lowest electricity rates, as a result of their reliance on clean energy sources. The central portion of the infographic compares average household energy spending in 2020 and 2050. While the total cost of energy per household in 2020 was $9,400, it is projected to decrease to $8,210 by 2050. This overall reduction includes a notable drop in energy bills, from $4,700 to $3,520, while equipment-related costs, such as those for electric vehicles and heat pumps, remain relatively stable at around $4,690. The graphic explains that in a net-zero transition, households will spend less on energy as they replace fossil fuel-based systems with electric alternatives, leading to lower ongoing energy costs even with higher electricity rates.

Moreover, Natural Resources Canada (NRCan) provides guidelines and support regarding land use planning for renewables. For this purpose, various guides, such as the “Best Practices Guide for Wind Power Projects and The Solar Photovoltaic Energy Guide”, have sections on site selection and land-use considerations and guide the regulations for such projects.

Following the federal government, provincial governments have also adopted various regulations regarding land utilization and resource assessments for renewable energy resources. Alberta has significant renewable potential and has implemented several policies to deploy renewable technologies.

Alberta Utilities Commission (AUC) (*Alberta Utilities Commission Act (SA 2007, c. A-37.2). | FAOLEX*, n. d.) administers the review and approval of renewable energy projects in Alberta. It ensures that the projects comply with environmental and land- use regulations. Similarly, the (*Renewable Electricity Act (SA 2016, c R-16.5). | FAOLEX*, n.d.) supports the development of renewable energy projects by establishing targets for renewable generation and integration into the primary grid. This act encourages suitable land use for renewables by avoiding conflict with other land uses.

In conclusion, Canada's federal, provincial, and municipal policies related to land utilization for renewable resource deployment focus on promoting sustainable development while minimizing conflict with other land uses. Federal policies provide a framework for assessing and mitigating renewable resources' relevant environmental and social impacts. Alberta's policies facilitate renewable energy integration into land use planning. Canada aims to achieve renewable goals in 2030 by considering several factors such as site selection, social and environmental impact, land-use planning, and stakeholders' engagement.

Moreover, Canada is the world's fourth-largest electricity producer by hydel sources, i.e., almost 62% of Canada's electricity is generated through moving water; Canada's agriculture sector's share of the GDP is approximately 8% ; 11% of jobs are associated with this sector (Agriculture and Agri-Food Canada, 2021a); and farms cover almost 6.2% of Canada's land area. Due to the high-water consumption by a growing population, limited water reservoirs, and semi-arid land in Southern Alberta, ensuring water availability to fulfil crop water requirements is important. Irrigation districts in Alberta get their water from the Bow, Oldman, and South Saskatchewan River sub-basins. However, the government banned new water licenses in 2006 due to limited reservoirs. The electricity grid's dependence on conventional fuels for electrical production contributes disproportionately to the province's GHG emissions, compared to other provinces with both less demand and more renewable sources.

In this connection, Agriculture and Agri-Food Canada's Sustainable Agriculture Strategy (SAS) ensures long-term direction for collective actions required to improve environmental behaviour in agriculture (Sustainable Agriculture Strategy, 2025). Similarly, the government's initiative, the Agricultural Clean Technology (ACT) program, aims to support R&D and deployment of clean technologies in machinery for precision agriculture (Agriculture and Agri-Food Canada, 2020). This step will ultimately support reducing GHG emissions and generate positive environmental aspects by achieving sustainable growth.

The Canadian Agricultural Partnership (CAP) is a federal and provincial government-funded five-year program to strengthen the agriculture sector by promoting environmental sustainability through adopting renewables in agricultural operations. Provincial governments are also making efforts to promote sustainable energy in agriculture. Growing Forward 2 (GF2) is the initiative by the Government of Alberta to support the adoption of renewable energy technologies and sustainable farming practices. The government's focus on integrating renewable energy and agriculture shows the commitment to enhancing the sustainability and resilience of the energy and agriculture sector to achieve the broader goals of a clean environment and economic stability (Housdorff, 2007).

Considering the effects discussed in the above section, a relevant literature review has been cited below:

The authors (Hassan et al., 2023) presented a comprehensive report on hybrid energy systems and their allied challenges, opportunities, and policy implications. Despite the intermittent nature and geographic limitations of renewables such as PV and WTs, hybrid renewable systems have stimulated the interest of stakeholders to maximize efficiency and energy system stability. A critical analysis of the literature revealed that hybrid systems can ensure system efficiency and stability and overcome renewables' intermittent nature. Similarly, Sanongboon and Pettigrew (2022 worked on the electrification of residential space in remote Ontario to mitigate climate change by reducing carbon emissions. Cogeneration from various sources can be used for electricity supply and other purposes such as space heating, irrigation, and industrial use. A mixed integer linear programming (MILP)-based management algorithm has been proposed in this study to find the best energy mix from different sources based on various parameters such as cost, lower emissions, etc. The outcome revealed that the utilization of hybrid systems for both purposes could ensure a clean environment and cost-effectiveness.

In their study, Longo et al., (2019) explored the potential of a hybrid renewable system for underserved and remote communities highly influenced by the climatic changes caused by the dependency on conventional fuels in northern Canada. Remote communities in Red Lake have been considered as case studies. Focus has been given to the well-being, care, and improvement of green ecological factors to reduce the effects of global warming in Ontario. Homer Pro was used to find the most optimal combination of hybrid resources to fulfil the community's electricity needs. Comparison with the conventional setups showed that hybrid systems could play a vital role in the transformation towards a clean environment and economically viable energy solutions.

The authors conducted a detailed review of renewable energy systems to electrify remote communities by 2050 (Agu et al., 2023). Efficient technology deployment, along with long-term policy implementation, is required to meet the low carbon emission goal of the Canadian government in 2050. Previously installed renewable energy projects deployed for electricity purposes were reviewed in this work. The outcome revealed that by balancing the demand-supply gap in remote communities of Canada by shifting towards renewables, the net-zero GHG emission target of 2050 can be achieved. The research work (Arriaga et al., 2013) investigated reducing dependency on diesel generators in remote Northern Ontario communities by shifting to renewables. The diesel generators are highly pollutant and have high operating costs. Moreover, limitations on electricity consumption, due to the diesel generator being a sole generation setup, severely affected economic growth in these communities. Six different scenarios of renewable resources with varying penetration were analyzed to support the supply-demand of these communities. The results showed that these hybrid systems ensure system stability and reduce fuel consumption and CO2 emissions, thus promoting environmental sustainability in the region.

Guo et al., (2020), presented a technical mapping layout to the government regarding land use for renewable resource deployment to achieve the zero-carbon emission goal. Efforts were made by local governments to facilitate the stakeholders in renewable installations. Locating suitable land for the renewable energy systems installation is one of the key parameters to sustain land based economies and ecosystem services. This work laid out a detailed framework for RE installations in land constrained areas for the local government of Canmore, Alberta, as this city has a limited usable land area with complex land use by laws and an environmentally sensitive ecosystem. Various land use scenarios were considered with various factors such as theoretical resources, recoverable land, and capital costs of integrating these REs with the current electricity system. The main objective of this study was to calculate the total available land with the least conflicts for renewable deployment. The study revealed that the city has enough land available to achieve renewable energy deployment and reduced emissions targets, even with strict bylaws.

Van De Ven et al. (2021) developed an innovative method based on an assessment model that considered socioeconomic, energy, land, and climate systems. Potential land-use requirements for solar photovoltaic deployments in the EU, India, Japan, and South Korea have been calculated in this study (Van De Ven et al., 2021). The study revealed that keeping in view the 20-80% solar potential capacity installation by 2050, a maximum of 0.5-5% of the land in these countries will be used. This change in land cover will have a net release of carbon from 0-50 g CO_2/kWh. This shows that a significant policy is required to halt the increase in carbon emissions in these territorial regions.

Cogato et al. (2023) proposed a novel method to assess the land use of on-land and rooftop photovoltaic systems and wind turbines. This study considered a case study of 186 different plants installed in Italy to assess the total land area covered, the land area required to install the new projects, and the land use change. The results showed that almost 98% of new wind power plants required new road infrastructure, whereas 35% of PV plant installations needed new building constructions. Furthermore, it was suggested that this methodology can be extended to calculate the global footprints of new renewables deployment on environmental sustainability.

Identification and assessment of low conflict areas for wind and solar installations have been carried out for Europe's renewable energy installation and integrated land use. Areas in Europe that can adopt the new renewable installation swiftly by ensuring minimal harm to areas valuable for rural communities were identified in this study (Kiesecker et al., 2024). Business-as-usual (BAU) and low-conflict (LCON) development scenarios were kept into consideration while identifying sites for new renewable energy installations. The study showed a network of land-based WTs and PV systems encompassing upwards of 164,789 km^2 by 2030 to achieve renewable energy penetration targets. The study concluded that low-conflict lands can generate up to 10.1 million GWh by solar and wind systems despite the large footprints. The policy design implementations should be carried out to carefully decide the land use for renewables installation, either due to large land required or areas with limited land availability.

Sultan et al. (2022) presented the applications of energy systems in the agriculture sector. High reliance on conventional fuel-based energy by agriculture resulted in increased carbon emissions, directly impacting the global climate. Even though per capita emissions in Pakistan are quite low, in comparison to other parts of the world, it is still ranked 17th among the most affected countries by climate change. As an agricultural country, achieving sustainable development goals is difficult due to the country's reliance on conventional fuels and due to the natural calamities that occur because of climatic variation. Hence, the deployment of renewable energy- based technologies in preharvest and postharvest applications would both reduce the reliance on conventional fuels and reduce the climatic variations, which have led to devastating natural disasters. Post harvest storage is crucial for the minimization of postharvest losses, and fulfilling the storage conditions through solar-assisted cooling pads can help in the reduction of carbon emissions, as well as the maintenance of quality. Similarly, shifting irrigation pumping systems from conventional energy sources to wind-solar-based energy can help increase system reliability, provide shorter payback, and reduce GHG emissions.

A report presented the Canadian farmers' rapid adoption of renewable energy (*Why More Farmers Are Choosing Renewable Energy | FCC*, n.d.). As per the report, Statistics Canada's 2021 Census Agriculture reported that one out of every eight farms in Canada have shifted to renewable energy for agricultural applications, i.e., 12% (22,576) of total farms in Canada reported at least one form of renewable energy utilization. Nazim Cicek, a biosystems engineering professor at the University of Manitoba, stated that lower energy costs and higher incentives, such as carbon tax, etc., played a vital role in this high rate of renewable adoption. Furthermore, reduced dependency on utility grid energy is another benefit of this shift.

A study on Canada's farms integrating renewable energy production and technologies towards a future of sustainable and efficient agriculture (Government of Canada, 2023). The 2021 Census showed that renewable energy not only makes farmers resilient but also diversifies the farm's output by selling energy to the grid. The report explored the adoption of technology and its benefits for farmers between 2015 and 2020, as can be seen in Figure 4.

Keeping in view the above-mentioned issues, benefits, shortcomings, and relevant policies, the main motive of this research is to highlight the importance of renewable energy systems in various fields of life to promote resilience, cost-effectiveness, and sustainable climate. The feasible and the fastest way to achieve this goal was to design and analyze the hybrid renewable energy using Homer Pro for the remote communities of Alberta, Canada.

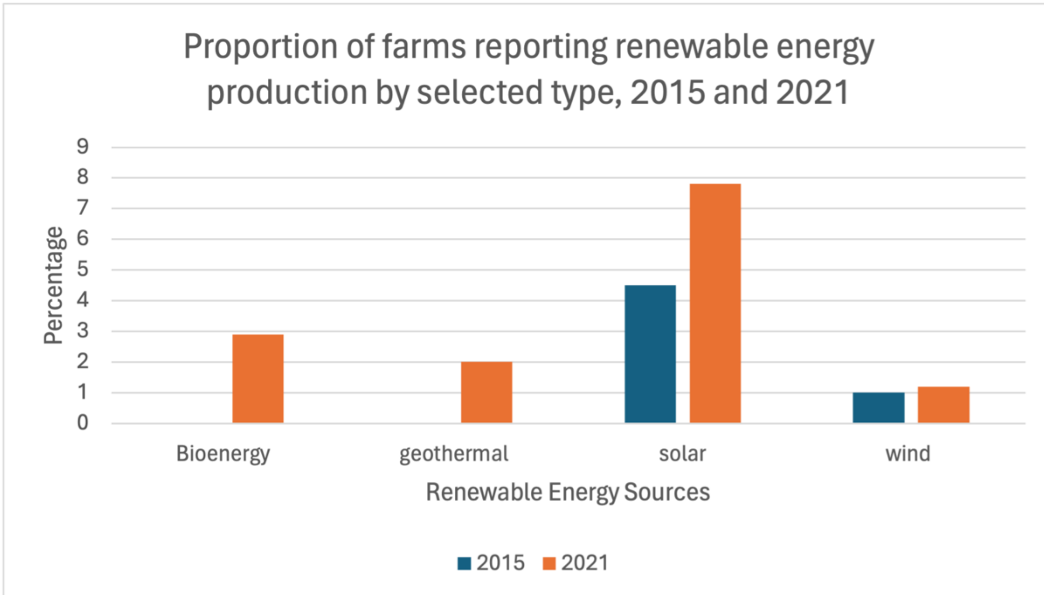

Figure 4: Selection of Renewable Energy Sources by Farmers (Census of Agriculture, 2016, 2021)

Then the study was extended towards land use and resources assessment using GIS techniques to ensure the suitable and economically viable use of available land. In the end, the feasibility of renewable energy applications in agriculture for irrigation purposes was carried out for the whole of Canada. Moreover, the novelty of the work conducted in the thesis is as follows;

1. Pioneering a cost-effective hybrid renewable energy model for remote communities:
    - This research introduces a tri-brid PV-WT-BESS system specifically designed for Siksika Nation in Gleichen, Alberta, addressing the high cost and environmental impact of conventional energy sources.

- The techno-economic analysis proves the feasibility of this system, achieving a remarkably low LCOE of 0.075 CAD/kWh compared to 0.127 CAD/kWh for conventional power, demonstrating significant cost savings and sustainability benefits.

2. Strategic land use optimization for large-scale renewable integration in agriculture:
   - Unlike previous studies, this work goes beyond mere feasibility assessments by leveraging GIS-based multi-criteria decision-making (MCDM), PCA, and Fuzzy Overlay Analysis to pinpoint the most suitable locations for renewable energy deployment in Lethbridge Northern Irrigation District (LNID) and St. Mary River irrigation district.
   - By systematically evaluating factors such as land use, soil morphology, water resources, and infrastructure proximity, the study offers a scientifically-backed roadmap for large-scale renewable integration in Alberta's agricultural economy.
3. Innovative renewable-powered groundwater pumping system for sustainable irrigation:
   - With Alberta facing water licensing restrictions and an increasing reliance on groundwater for irrigation, this study pioneers a PV-WT hybrid system designed to power groundwater pumping, ensuring agricultural sustainability.
   - CROPWAT and HOMER Pro are integrated in a novel way to precisely determine crop water requirements and optimize the energy system for an

entire farming season, bridging the gap between energy management and water resource sustainability.

4. Policy-driven framework for energy independence and economic growth:

   - The research extends beyond technical analysis by providing actionable insights for policymakers, planners, and stakeholders, emphasizing renewable energy's role in economic growth, carbon footprint reduction, and energy security.
   - The findings align with Canada's Pan-Canadian 2030 Clean Growth Policy and SDG 7 (Affordable and Clean Energy), serving as a blueprint for scaling hybrid renewable systems across Alberta and beyond.

By integrating advanced energy modeling, geospatial intelligence, and sustainable agriculture practices, this research lays the groundwork for a holistic, data-driven transition toward a clean energy future. It not only demonstrates the economic and environmental feasibility of hybrid renewable systems but also provides a scalable and replicable model for sustainable energy adoption in rural and agricultural regions worldwide.

1.1 Thesis objectives

This research has three main objectives to investigate the feasibility of designing hybrid renewable energy systems in Southern Alberta to sustain their ecosystem and economic growth in Southern Alberta. The overall aim of this study is also to support Alberta's initiative to achieve net-zero emissions by 2050. The objectives of the study are as follows:

- Carry out a detailed techno-economic analysis to evaluate the feasibility, cost-effectiveness, and climatic benefits of hybrid renewable systems in the remote community of Gleichen, in Southern Alberta.
- Develop and implement efficient strategies for beneficial land use and resource assessment to optimize the integration of renewable energy resources into Alberta's economic infrastructure by utilizing tool

  such as GIS and methods like Principal Component Analysis (PCA), and Fuzzy Overlay Analysis.
- Investigation and design of hybrid renewable energy systems tailored to support the agricultural sector's energy needs, specifically for groundwater pumping and irrigation by using FAO's CROPWAT software and HOMER Pro energy modelling tool.

1.2 Thesis structure

This thesis is in journal article format. The first chapter comprised a detailed thesis introduction along with the objective subsection. The objectives stated above are presented in the three following chapters. The second chapter modelled a tri-brid system for the Siksika Nation in Gleichen, Alberta, due to its proximity to high renewable availability. The proposed hybrid system comprises a grid-tied PV-WT-BESS to compensate for the community load demand and fully utilize the cost-effectiveness and environmentally friendly nature of hybrid renewables.

HOMER Pro software was used to carry out the techno-economic analysis of the proposed system. In the third chapter, the scope of the work was extended to irrigation districts of LNID and St. Mary River for strategic land use and resource assessment processes for the integration of renewables such as PV and WT systems into these areas. GIS techniques were used to determine the impact of various factors, such as land use, elevation, soil morphology, water bodies, road and electric networks, etc., on the suitability of different sites. Principal Component Analysis (PCA) and Fuzzy Overlay Analysis were used to identify the most suitable sites. The study outcomes can prove valuable for policymakers, planners, and different stakeholders in driving the region towards sustainability.

In the fourth chapter, the critical role of economical and efficient irrigation has been discussed. The study explored the utilization of PV and WT systems to supply the required energy for the groundwater pumping mechanism. CROPWAT was used for the calculation of crop water requirements of an agricultural farm for one complete season. This requirement was further converted into energy needs. Homer Pro was used to design the most optimized hybrid renewable system to fulfil the energy needs of agriculture farms to compensate for the water requirement for a complete season. The fifth chapter is the summary and conclusion of the thesis and outlines the main findings of the research.

Chapter 2: Literature Review

2.1 Introduction

HRES have become essential research territory because of rising climate change urgency and energy security needs along with agricultural sustainability demands. HRES operate through the integration of PV energy with WT technology and BESS units and prove beneficial when serving remote areas and agricultural locations. The existing knowledge pertaining to HRES techno-economic viability and GIS-based evaluation and agricultural renewable usage through HOMER Pro and CROPWAT along with socio-technical implementation frameworks receives an integrated analysis in this chapter. The review focuses mainly on studies from Southern Alberta, Canada and uses worldwide case studies for reference purposes.

2.2 Techno-Economic Viability of HRES

The main driving factor for adopting HRES rests in their capability to supply affordable power along with sustainable energy systems that minimize greenhouse gas (GHG) emissions. The connection problems between centralized grids and rural Indigenous communities in Canada find proper resolution through HRES systems. The Siksika Nation received power from a PV WT BESS hybrid system which HOMER Pro calculated could deliver energy at 0.0705 CAD/kWh and reduce the 0.127 CAD/kWh rate from the current grid. Such systems demonstrate techno-economic viability because they simultaneously cut expenses and improve system robustness and protect the environment.

The comparison between standalone and grid-connected hybrid systems in Canadian territories undertaken by Abdin and Merida (2019) showcased cost reductions together with GHG emissions decreases. The research by Arabzadeh Saheli et al. (2019) established how PV-Diesel-Battery systems demonstrate both financial and operational advantages for remote areas of Manitoba. Research findings from Kapoor and Sharma (2021) and Longo et al. (2019) validated that hybrid systems provide economic benefits coupled with environmental advantages both in India and Northern Ontario.

The system needs to demonstrate resistance against economic and environmental changes. The HOMER Pro software contains features for sensitivity analysis which enable users to test scenarios through combinations of solar irradiance and wind speed along with diesel price variations and battery pricing elements. HOMER Pro serves as an essential tool for hybrid system design because it models complex systems under dynamic environmental settings.

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2.3 Renewable Energy in Agricultural Irrigation

Agricultural operations representing 8% of Canada's GDP consume energy heavily throughout irrigation systems. Both diesel-powered irrigation systems and electric grid-powered irrigation systems prove to be simultaneously expensive and carbon-intensive. Renewable-based irrigation technology delivers decreased operational expenses together with SAS compliance in Canada.

CROPWAT which the FAO created serves as one of the key systems for determining irrigation requirements. Aftab's study (2025) applied CROPWAT software in combination with HOMER Pro for hybrid system design at wheat and barley farms in Lethbridge County. The software transformed crop water needs into daily power requirements before HOMER Pro analyzes energy setups to fulfill these energy needs.

The approach of renewable interventions was validated by Solangi et al. (2022) and Singh et al. (2022) in their respective studies of Pakistan and India. The authors determined that solar-powered pumping systems both reduced irrigation costs together with cutting down greenhouse gas emissions. Sultan et al. (2022) explained that renewable systems function effectively throughout pre- and post-harvest agricultural operations. The study confirmed hybrid agricultural systems function to lengthen food storage periods while minimizing product waste and achieving greater financial returns.

Researchers He & Rosa (2023) stressed that irrigation systems need modification to accommodate the changing climate pattern. The combination of green water management together with renewable-powered systems functions as crucial tools for food security reduction especially within areas such as Southern Alberta which experience semi-arid climate conditions.

The research by Ali et al. (2023) demonstrated that sub-Saharan agricultural systems gained a 47% improvement in water utilization from solar-powered drip irrigation when compared to surface irrigation driven by diesel. This irrigation method also produced double the crop yield. The experimental data reveals new possibilities for using similar irrigation approaches in the semi-arid belts of Alberta.

2.4 GIS and Strategic Land Use for Renewable Deployment

Renewable energy projects need suitable sites for their installations to succeed. GIS allows analysts to evaluate geographical feasibility through assessments of solar irradiance combined with wind potential measurements and measurements of slope and land cover and soil morphology and infrastructure proximity. Through implementation of GIS combined with Principal Component Analysis (PCA) and Fuzzy Overlay Analysis in LNID and SMRID irrigation districts this study provides an essential foundation for uniting land and energy planning systems.

Nadizadeh Shorabeh et al. (2021) conducted research which confirmed the validity of combining Fuzzy AHP and PCA approaches to identify suitable sites for solar installation areas in Iran. Noorollahi et al. (2016) and Aydin et al. (2013) utilized GIS-based MCDM to locate suitable renewable energy zones with reduced conflicts in Turkey and Spain. The systems create precise technical outcomes which help prevent social and environmental controversies.

Guo et al. (2020) developed a watered-down planning approach for Canmore , Alberta that allows repeated usage by policy-makers. The authors demonstrated through their research that site selection needs to factor in financial expenses and land management guidelines together with environmental consequences. GIS-based data analyses offer sustainable development direction when they examine theoretical renewable potential against actual spatial limitations.

The research of Van De Ven et al. (2021) evaluated solar land requirements through a study that compared the EU with Indian, Japanese, and South Korean national policies. When land suitability models direct installation decisions their assessments demonstrate that energy requirements can be fulfilled with 0.5% land usage even when analyzing all available territory.

2.5 Policy and Institutional Frameworks

Hybrid renewable systems implementation follows closely with national and provincial government policies. The Pan-Canadian Framework on Clean Growth and Climate Change, alongside Alberta’s Renewable Electricity Program 2030, seek to reduce carbon emissions from the energy sector by promoting renewable integration throughout residential, commercial and agricultural applications.

Natural Resources Canada publishes guides for wind power project development in their "Best Practices Guide for Wind Power Projects" document and provides solar photovoltaic energy instructions through "Solar Photovoltaic Energy Guide." These guides outline protocols for site selection, environmental assessment, and community engagement.

Nadizadeh Shorabeh et al. (2021) demonstrated the effectiveness of Fuzzy AHP and PCA methods for locating solar installation sites throughout Iran. The identification of renewable energy sites with minimal social conflicts served as a purpose for Noorollahi et al. (2016) and Aydin et al. (2013) during their GIS-based MCDM studies in Spain and Turkey. These data evaluation methods deliver precise technical results alongside lower social and environmental confrontation points.

Guo et al. (2020) developed a policy-relevant framework to handle land limitations in Canmore, Alberta through their investigation. These authors showed how capital costs and land use policies and ecological factors should be included when selecting sites for development. The use of GIS-based approaches allows researchers to compare theoretical renewable possibilities against real-life limitations to create sustainable development plans through data-driven methods.

2.6 Comparative Global Insights

The comparison of Alberta's renewable strategy with global sustainability models produces beneficial understanding. Van De Ven et al. (2021) conducted research on land requirements needed for solar PV systems in EU countries together with India, Japan, and South Korea. The model determined between 0.5% and 5% land requirement impacts when analyzing renewable capacity targets between 20% and 80%

for 2050. The presented data strengthens this study's arguments about optimal land utilization.

The study by Cogato et al. (2023) focused on evaluating infrastructure specifications and environmental effects of 186 renewable projects operating in Italy. Wind power projects demanded 98% of new road expansion compared to solar PV projects which needed new buildings in 35% of the cases. The established method for analyzing land use modification from Cogato et al. (2023) enables application within Alberta’s irrigation districts.

The study by Kiesecker et al. (2024) introduced a Europe-wide land-use strategy that would achieve renewable targets by using 164,789 square kilometers of space by 2030. The application of the Business-As-Usual (BAU) vs Low-Conflict (LCON) analytical scheme delivers important information regarding feasible ways to preserve nature while integrating energy strategies.

Research about decentralized energy solutions emerges from Kenya and Ethiopia alongside other African nations. Juma et al. (2020) established that distributing PV-battery systems at individual locations improved both rural medical facilities' independence from the main grid and their resistance to power outages. The planning methods used by these irrigation operations closely match the organizational requirements Alberta needs.

2.7 Summary and Research Gap

Evidence derived from the literature emphasizes that hybrid renewable power systems must be implemented in rural and agricultural zones. The integrated tools HOMER Pro, CROPWAT and GIS-based MCDM develop effective methods for creating optimized systems while evaluating land qualities. National and provincial support through regulatory and financial policies exists parallel to the documentation of scalable global best practices. However, several research gaps remain:

- Lack of integration with smart grid technologies and real-time monitoring.
- Limited studies on community engagement and social acceptance.
- Inadequate focus on AI-driven optimization and predictive analytics.
- Absence of life-cycle environmental impact assessments for hybrid systems.
- Limited exploration of hydrogen-based storage in hybrid agricultural models.

The analysis of HRES planning in Southern Alberta through diverse methodologies forms the main objective of this thesis.

2.8 Conclusion

The combination of renewable energy systems presents an effective sustainable solution that solves both power blackouts and inefficient agriculture. An extensive review of the literature related to techno-economic modeling and GIS site analysis, irrigation energy planning and policy frameworks enables the creation of a detailed research foundation. The combination of HOMER Pro and CROPWAT with GIS applications proved both academically sound and practical for real installations in this research. The literature review presented here supports the analysis in later chapters that focus on developing customized hybrid systems for Alberta’s rural territory.

Chapter 3: HOMER

3.1 Introduction

HRES adoption represents an essential tool for climate emergency solutions especially in areas that combine rural electricity development with sustainable farming needs (Priyanka et al., 2023). The Indigenous communities of Southern Alberta, together with their agricultural districts located in remote regions, face energy accessibility problems and high fuel expenses while dealing with environmental impacts from emissions and water resource restrictions. The effective integration of renewable energy sources—such as solar photovoltaics (PV), wind turbines (WT), and battery energy storage systems (BESS)—offers a promising solution. Designing such systems requires access to a highly advanced simulation platform which effectively models the dynamic energy systems involving various inputs along with varying loads and dispatch tactics alongside changing environmental conditions.

The National Renewable Energy Laboratory (NREL) in the United States developed HOMER Pro (Hybrid Optimization of Multiple Energy Resources) (HOMER Software, 2014) which served as the main modelling tool in this research because of its effectiveness in simulation. Engineers, researchers, and policymakers use HOMER – Hybrid Optimization of Multiple Energy Resources – for microgrid and distributed energy system simulation. This allows them to achieve optimal system designs that consider technical aspects and economic and environmental factors. This chapter explains in detail the reasons behind choosing HOMER Pro as the main modelling tool while discussing its essential attributes and comparing it against competing tools alongside analyzing its strategic benefits for achieving clean energy objectives in Alberta.

3.2 Purpose and Benefits of Using HOMER

3.2.1 Hybrid System Simulation

The unique features of HOMER distinguish it from generic electrical simulation tools because the software exclusively supports modelling renewable energy units with conventional energy components (HOMER Software, 2014). This thesis needed an assessment platform which simulated solar PV, wind turbines and battery storage systems under grid-connected and self-generating operation throughout extensive time periods.

The HOMER platform performs time-series modelling which includes simulating hourly and daily changes and season-based adjustments affecting energy system inputs and outputs. The software system tracks battery charging and discharging patterns in addition to power component transfers to provide exact assessments of system autonomy levels and operating reliability. This technical feature proved vital to assess renewable power solutions for Siksika Nation isolation and water pumping systems for LNID and SMRID irrigation regions (Priyanka et al., 2023).

3.2.2 Techno-Economic Optimization

The platform of HOMER Pro contains advanced optimization features which assist researchers in performing techno-economic assessments through (Priyanka et al., 2023; Pujari Harish Kumar et al., 2024):

- Levelized Cost of Energy (LCOE)
- Net Present Cost (NPC)
- Capital and Operational Expenditures (CAPEX/OPEX)
- Internal Rate of Return (IRR)
- Payback Period and ROI

HOMER Pro allowed researchers to analyze four system setups which included Grid-only and PV-Grid and WT-Grid and PV-WT-Grid. The PV-WT-Grid system optimized to achieve economical operation at 0.0705 CAD/kWh presented lower costs when compared to conventional grid electricity at 0.127 CAD/kWh. HOMER demonstrated to financial stakeholders that hybrid power systems would prove stable both technically and economically in Alberta through its economic assessment evaluations.

3.2.3 Sensitivity and Scenario Testing

The sensitivity analysis engine in HOMER allows users to predict changes in system performance resulting from variations in key components like solar irradiance as well as wind speed and diesel fuel prices, battery costs and load demand and discount rates (HOMER Software, 2014):

- Solar irradiance
- Wind speed
- Diesel fuel prices
- Battery costs
- Load demand
- Discount rates

The weather fluctuations, together with market price fluctuations, throughout the year in Alberta required this analysis tool to select dependable yet economical energy systems across multiple future projections. The scenario testing capabilities of HOMER provided systems with immunity to unpredictable conditions.

3.2.4 Resource Data Integration

System design depends heavily on precise resource information and data. The HOMER Pro software uses NASA POWER (Prediction of Worldwide Energy Resources) database functions that enables users to automatically import global horizontal irradiance (GHI) along with wind speed and temperature measurements through precise geographical coordinates (HOMER Software, 2014).

The modeling ofrenewable potential throughout Southern Alberta relied heavily on this feature during the study because it processed historic climate data from Gleichen, Lethbridge, and Stavely locations. The software functionality of HOMER enables users to upload specific load usage patterns as well as business and residential sector energy consumption forecasts into the system.

3.2.5 Battery Dispatch and Storage Strategy

The essential part of hybrid renewable power systems consists of battery energy storage which enables load balancing and backup operations in off-grid or peak-demand applications (Shezan, Ali & Rahman, 2021). HOMER supports:

- Through the Load Following Strategy renewable generators receive priority status as customers draw power with batteries providing backup support.
- Utilize Cycle Charging Strategy to charge batteries when energy costs are low and there is surplus supply.

Multiple dispatch methods underwent assessment for achieving best system configurations between reducing diesel usage and optimizing battery lifetime and operational efficiency.

3.3 Comparison with Other Software Tools

The selection of the optimal simulation platform became possible through an extensive review process of alternative simulation systems. The following table presents an overview of the examined simulation platforms' comparison:

Software	**Strengths**	**Limitations**
RETScreen Expert	Feasibility studies, GHG tracking, policy support	No real-time dispatch modeling or detailed hybrid energy optimization
PVsyst	Detailed PV performance modeling	The platform operates solely with PV but does not allow simulation of multi-source hybrid systems nor dispatch strategies.
SAM (NREL)	Advanced solar economics, financial modeling	Complex for hybrid systems; lacks intuitive dispatch control and battery modeling
Hybrid2 (NREL)	Early hybrid simulation tool	The user interface of this platform has been discontinued because it fails to support current technological data while keeping up with modern data standards.

No other software tool surpassed the capabilities that HOMER Pro delivers through its integrated hybrid simulation approach along with detailed economic analyses capability and dispatch modelling features together with its intuitive user interface. The capacity of HOMER to balance between technical accuracy and economic forecasting and scenario testing capabilities made it stand out because of its usefulness for research with complex needs.

3.4 Strategic Fit for Alberta's Renewable Goals

The state of Alberta experienced an extensive energy transformation period when the Renewable Electricity Act and 2030 Renewable Energy Program established policies for achieving 30% renewable power generation in the province. Agricultural activities hold essential importance in economic activities of the province because they produce 2.8% of the GDP while using significant quantities of both water and energy resources.

HOMER Pro provides an ideal framework for Alberta's terrains because it creates models for tri-bird systems and customizes power use profiles for homes and farms while the CROPWAT tool operated by the FAO determines irrigation needs (Shezan, Ali & Rahman, 2021). The results from HOMER Pro analysis served as the basis to develop this thesis research through various outputs:

- Techno-economic evaluation of energy systems for the Siksika Nation
- Hybrid-powered irrigation systems for groundwater pumping in LNID and SMRID
- GHG emission reductions of up to 63% compared to grid-only solutions
- Payback periods as short as 6.18 years for optimized WT-Grid configurations
- Techno-economic evaluation of energy systems for the Siksika Nation
- The combination of hybrid power systems suits groundwater pumping for irrigation purposes in LNID and SMRID water districts.

- The hybrid energy systems reduce GHG emissions by 63% below grid-sole operation
- The optimized WT-Grid systems enable rapid financial recovery within 6.18 years.

SDG 7 (Affordable and Clean Energy) as defined by Canada finds direct support through these outcomes while the province enhances both carbon reduction and energy resilience efforts.

3.5 Conclusion

The research found HOMER Pro the best solution for creating, optimizing, and validating hybrid renewable energy systems. The tool enables thorough analysis of complex energy interactions together with extensive economic assessments and sensitivity testing which creates an all-round decision-making platform for community electrification as well as sustainable agricultural development (Shezan, Ali & Rahman, 2021).

HOMER offers a completely integrated and flexible user-friendly platform that deals with multiple energy transition challenges currently active in Alberta. The features of HOMER Pro support academic research along with practical implementation which drives the creation of affordable sustainable energy systems that protect the environment in Canada, as well as worldwide.

Chapter 4: Implementing Tri-brid Energy Systems for Renewable Integration in Southern Alberta, Canada

4.1 Introduction and background

Chapter 2 is a published paper in ‘Clean Technologies’. Dr. Dan Johnson, Dr. Paul Hazendonk, and Dr. Locke Spencer supervised and reviewed the manuscript. Dr James Byrne assisted in acquiring the grants for this valuable research.

There is increasing global concern over the establishment of a more secure and sustainable energy sector that mitigates the effects of fossil fuel power plants on global warming. The International Energy Agency (IEA) has recommended addressing this issue by increasing the implementation of renewable technologies and systematically eliminating carbon-emitting fuels, including coal, lignite, and diesel oil, from the energy sector. Each signatory of the 2015 Paris Climate Agreement committed to addressing the consequences of global warming and formulating strategies to mitigate global greenhouse gas emissions. In pursuit of its objective in the Paris Agreement, Canada has committed to reducing its carbon dioxide emissions by 40-45 percent from 2005 levels by 2030. The oil sector is the principal cause of pollution in Canada (Nikzad & Sedigh, 2017). In Alberta, conventional and combined heat and power (CHP) facilities predominantly depend on coal and natural gas to fulfil almost 90% of the region's energy needs. Despite the increase in the share of renewable energy technologies (RETs) in the Energy Production Mix (EPM), Alberta’s conventional power based facilities still represent the predominant source of Canada's total carbon emissions (TCE) from electricity generation (Hosseini et al., 2022).

In 2015, Alberta committed to the progressive elimination of coal-fired power plants and to producing 30% of its electricity from renewable sources by 2030. At the time of the Renewable Electricity Program (REP) authorization, renewable energy constituted approximately 10% of Alberta's electricity supply. The Alberta Electric System Operator (AESO) reported that coal-fired power plants accounted for almost 60% of total energy generation in 2016 (Hastings-Simon et al., 2022).

The expense of using solar power, a renewable energy source, has consistently diminished as the price of solar photovoltaic (PV) systems has fallen. Consequently, solar energy is presently among the most economical energy sources globally. Grid-integrated photovoltaic systems are becoming popular and should be evaluated when addressing the energy requirements of households and enterprises in colder areas (Jamil & Pearce, 2022).

The Canadian Wind Energy Association (CanWEA) asserts that wind energy is fundamental to Canada's renewable energy portfolio. From 2004 until 2023, Canada boosted its wind generating capacity by 444 MW, reaching a cumulative total of 21,900 MW. Wind power is presently one of the most economical methods for generating energy without government subsidies, making investment in it more attractive than in conventional power plants. The National Energy Board forecasts that wind power will provide 27% of new energy generation from 2017 to 2040. Investment in wind energy generation has surged in Western Canada, encompassing Alberta, British Columbia, Manitoba, and Saskatchewan, which possess the region's most substantial wind resources. Wind energy constitutes Alberta's second most significant emerging power source, attracting $1.2 billion in private investment across five new projects in the past three years (Martins Godinho et al., 2023).

Table 2 : Economic Viability of Solar and Wind Energy (Bilicic, 2023)

Technology	**Average LCOE ($/MWh)**	**LCOE Range ($/MWh)**	**Competitive With Fossil Fuels?**
Utility-scale Solar PV	40	20 – 60	Yes
Onshore Wind	33	25 – 50	Yes
Offshore Wind	78	60 – 110	In some markets
Natural Gas (CCGT)	60 – 120	-	Yes (but varies by region)
Coal	70 – 150	-	Rarely
Nuclear	90 – 200	-	No (in most cases)

Table 2 summarizes the economic viability of solar and wind energy globally based on the LCOE, a common metric that accounts for the total cost to build and operate a power-generating asset over its lifetime, per unit of electricity generated (USD per megawatt-hour, or $/MWh). Diesel generators supply electricity to the residences of the three Indigenous communities of the Siksika Nation. This practice is very detrimental to the environment as it exacerbates the risks of climate change, elevates greenhouse gas emissions, contributes to air pollution, and leads to water contamination. Climate change will significantly impact the energy management techniques of an Indigenous Canadian community (Priyanka et al., 2023), and this study presents a renewable energy hybrid system for the inhabitants of Trout Lake, a remote locality in Northern Alberta, to alleviate the adverse environmental impacts of diesel generators in off-grid Canadian settlements. The system aims to fulfil the community's thermal, electrical, and hydrogen requirements through the utilization of solar photovoltaics (PV), wind turbines, electrolyzers, hydrogen storage tanks, batteries, fuel cells, and a hydrogen boiler. Upon assessing five scenarios with HOMER Pro software, the fifth option was determined to be optimal, with an energy cost of $0.675/kWh, significantly lower than diesel-based systems, and achieving a 99.99% decrease in carbon emissions. The research identifies fuel cells, batteries, and thermal load controllers as technologies capable of diminishing environmental impact while enhancing system reliability. Battery energy storage is highlighted as the most economical approach, whereas fuel cells are seen as too expensive for remote populations. Furthermore, we conducted sensitivity analyses to examine the impact of different parameters on cost, excess energy, and the proportion of renewables.

Recent studies have examined the outcomes of hybrid renewable energy systems utilizing HOMER Pro, an economic feasibility and viability analysis tool, to identify the optimal approach for a certain technological endeavor. A study examined the feasibility of supplying power to remote regions with a grid- connected hybrid renewable energy system (Ur Rashid et al., 2022). The results indicate that the proposed HRES will promote investments in renewable energy and reduce dependence on conventional energy sources. Moreover, another study (Li et al., 2018), investigated grid-connected systems across five diverse sites in China, analyzing three specific configurations: grid alone, grid/PV system, and grid/PV/battery. A grid/PV system was demonstrated to be the most economical and durable alternative.

Similarly, the integration of photovoltaic systems with wind turbines might decrease power prices from 0.060 to 0.0446 Canadian dollars per kWh. The proposed hybrid system may fulfil 82% of electricity demands. In another study, (Kapoor & Sharma, 2021) examined the feasibility of a grid-connected photovoltaic system in a remote region of India in which the technology reduced greenhouse gas emissions (GHG) and energy expenses of CAD 0.027 per kWh as compared to CAD 0.095/kWh. Likewise, (Das et al., 2021) demonstrated that on-grid systems had the lowest levelized cost of energy (LCOE) in comparison to two hybrid energy systems.

(Abdin & Mérida, 2019) examined the economic and environmental impacts of photovoltaic, wind, diesel, and battery-powered hybrid energy systems (HES), both standalone and grid-connected, across five distinct climatic zones. The HOMER model for hybrid optimization of electric renewables was employed toexamine various configurations and the benefits of grid integration. The research examined the ecological advantages of HESs and the impact of the national grid on resale values. The Rajshahi region exhibited a comparatively lower cost of electricity (COE) and net present cost (NPC) for standalone PV/Diesel/Battery systems than other locations, as per the statistics. The Chattogram region was abundant in economic and environmental resources. Grid expenses were offset by the cost savings generated by grid-connected HESs with sell-back functionalities. In comparison to grid-only systems and independent hybrid PV/Diesel/Battery systems, researchers estimated that this system might decrease carbon dioxide emissions by 45,582 kg annually. The research examined the benefits and drawbacks of implementing such initiatives in off-grid regions. The authors aimed to enhance the accessibility of modern energy and reduce dependence on petroleum for power generation in far northern areas, including Red Lake, Ontario, Canada (Longo et al., 2019). To mitigate global warming and enhance environmental sustainability, Ontario's energy sector decided to implement a microgrid.

Electricity is essential for enabling the nation and rural regions to swiftly achieve sustainable development objectives. This study concluded that a microgrid integrating several renewable energy sources yields the most favorable results, following extensive simulations with various configurations utilizing the HOMER tool.

In another study, Arabzadeh Saheli et al., (2019) examined the design and modeling of a hybrid power generating system using photovoltaic (PV), wind, and diesel energy sources for a load site at Winnipeg, Manitoba, Canada. The system optimization and feasibility examined and contrasted many setups utilizing the simulation software Homer to identify the most efficient and realistic option for the system. The peak load observed was 1.9 kW, with an average load of 16 kWh per day. The optimal design had five batteries, a 2-kW diesel generator, a 2- kW converter, and one-kilowatt photovoltaic arrays, resulting in a total net present cost of $33,110 and an energy cost of $0.444 per kWh. This hybrid system was the most cost-effective and efficient option among those assessed, and it also contributed to the reduction of greenhouse gas and pollutant emissions.

The reliance on diesel fuel in Northern Canada's off-grid power systems has led to many operating challenges. The authors of the study utilized the HOMER tool to improve the remote off-grid electrical infrastructure in Northern Canada. Various topologies, such as Battery-Diesel, PV-Diesel, and PV-Diesel-Battery, were evaluated to identify the optimal retrofit for a generating plant predominantly utilizing diesel. The results indicated that at elevated levels of renewable integration, the PV-Diesel-Battery configuration surpassed the conventional diesel system, achieving up to 22% savings on fuel expenses while somewhat reducing the Levelized Cost of Electricity (LCOE). This design mitigates environmental impact while ensuring the reliability, security, and availability of the power supply.

This planned project is distinguished by its comprehensive approach to utilizing locally available renewable energy sources. This hybrid system is the first in the nation to supply Indigenous villages with renewable energy. The HOMER Pro energy modelling tool is employed in the study to assess diverse configurations of wind turbines, solar photovoltaics, and BESS to minimize the levelized cost of energy

(LCOE) and greenhouse gas emissions relative to traditional fossil fuel-generated electricity. This "tri-brid" system integrates many renewable energy sources and ensures a consistent electricity supply by strategically linking to the grid, selling excess energy, and procuring power when renewable generation is insufficient. Additionally, the design incorporates a "load-following strategy" for energy management to ensure that charging the battery backup system or deferring the load to renewable energy sources occurs just when economically viable. The study is more pertinent and simpler to duplicate in other similar regions globally, as it centers on an actual town abundant in renewable resources and near wind and solar facilities. It can also assist in formulating policies and solutions to fulfill Canada's commitment to reduce carbon dioxide emissions by 45% by 2030, in accordance with the Paris Agreement.

4.1.1 Objective

The objectives of the study are as follows:

i. To meet the electricity and heat demand, a techno-economic analysis of a grid-connected tri-brid energy system consisting of PV, wind turbines, and a battery energy storage system was simulated for the Siksika Nation community near Gleichen, Alberta, Canada.

ii. Four different scenarios, grid-only, PV-grid, Wind turbine-grid, and WT-PV-grid, were developed in HOMER and compared to determine the best combination of hybrid energy systems, in accordance with Net Present Values (NPV), LCOE, Capital Expenditures (CAPEX), and Operation Expenses (OPEX).

iii. To reduce the current electricity prices and GHG emissions by increasing the use of renewable electricity.

4.2 Methodology

HOMER is an abbreviation for a program that assists in identifying the optimal combination of energy systems. The National Renewable Energy Laboratory (NREL) in the United States developed it, and it is presently owned by UL Solutions. The objective is to utilize NPC and LCOE metrics to develop and evaluate the sensitivity of each proposed hybrid model system for a designated region (*How HOMER Calculates Wind Turbine Power Output*, n.d.). The technical and economic characteristics of both grid-integrated and freestanding systems may be assessed.

HOMER evaluates the ideal system configuration by analyzing NPC, LCOE, OPEX, and module dimensions, utilizing a load model and various component sizes provided to the program. HOMER is constructed on reliable and cost-effective microgrids that utilize both traditional and renewable energy sources (Ur Rashid et al., 2022).

4.2.1 Site Selection

Gleichen is a hamlet located in Wheatland County, southeastern Alberta, Canada. It is situated around 40 kilometers (25 miles) southeast of Strathmore, adjacent to the Siksika Nation, at the junction of Highways 1 and 547, with an elevation of 903 meters above sea level. Details are present in Table 3.

Table 3: Data of the Proposed Location

Particulars	**Description**
Project Location	Gleichen, Alberta (Reserve Land)
Geographical Coordinates	50° 52’0’’ N, 113°3’0’’ W
Population	7800 +
Daily Average Solar Irradiance Average Solar Irradiance (Summer) Average Solar Irradiance (Winter	3.57 kWh/m^2 5.88 kWh/m^2 0.950 kWh/m^2
Annual Average Wind Speed	5.90 m/s at 50m
Annual Wind Speed	21.5 m/s at 80m

A minimum of 15 acres of land is required for this capability. "Helioscope" is used to determine the dimensions of the PV plant size. Legend 'A' represents the potential PV plant, 'B' signifies the wind turbine site, 'C' refers to Gleichen town, and 'D' indicates Highway 547. Locations C and A are around 10 kilometers distant, whereas locations D and A are roughly 5 kilometers apart. Additionally, Figure 6 illustrates the operational flowchart of the Homer Pro software.

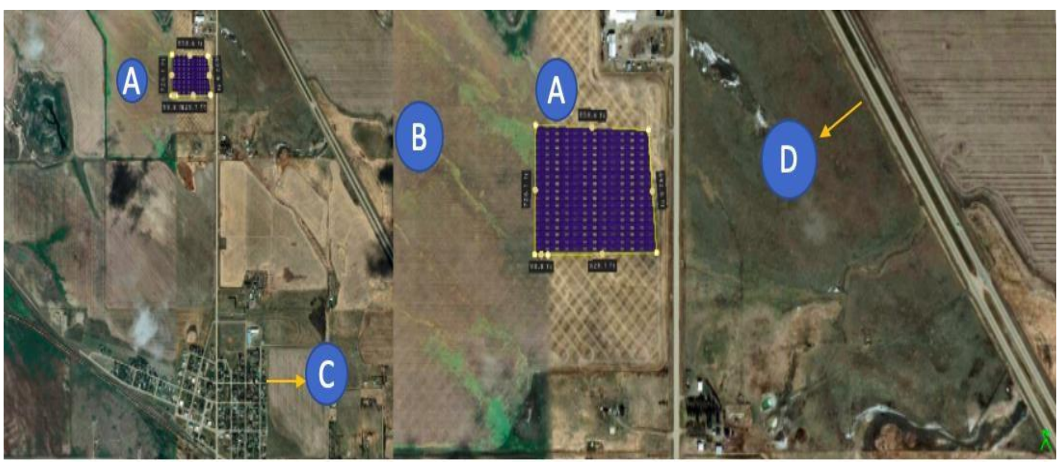


Figure 5: Potential Site of PV and Wind Installation

Alberta possesses the second-greatest solar energy potential of all Canadian provinces. Alberta's annual solar PV (fixed axis) output is anticipated to be 1,276 kWh per kilowatt (Urban, 2021). Figures 7 and 8 provide maps of the region under examination for wind potential and solar irradiation.

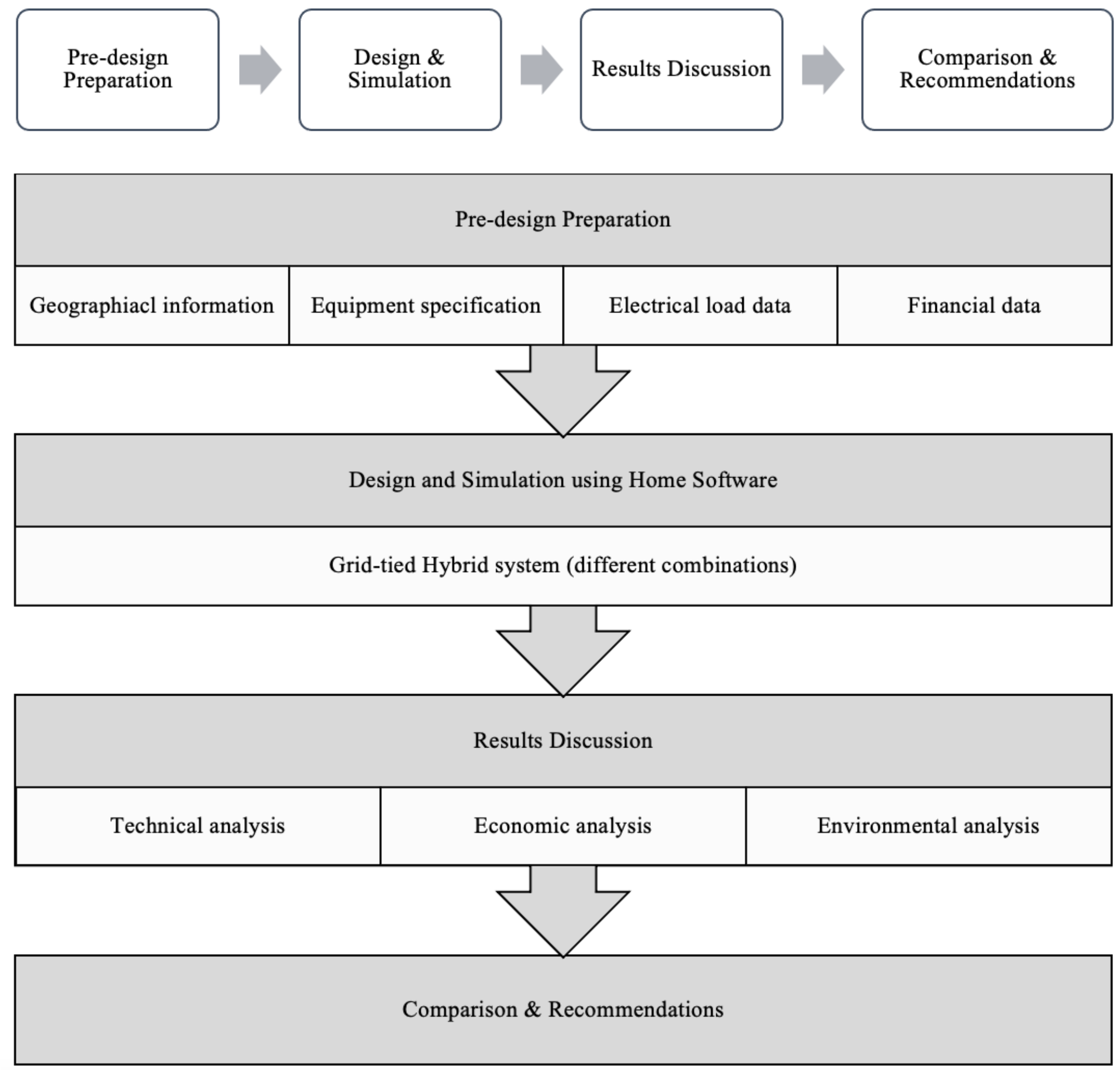


Figure 6: Homer Pro Simulation Flowchart

4.2.2 Load Profile

To design the hybrid renewable system, it is essential to ascertain the energy consumption of residential properties. The Siksika Nation comprises of about 1,000 residences with a population of 7,800 individuals (Government of Canada, 2022). A typical house in Canada consumes 37.5 kWh per day (*How Many kWh Does the Average Home Use?*, n.d.). The profile seen here illustrates the energy use of more than 1,000 residences and small enterprises within the Siksika Nation and the adjacent town of Gleichen, Alberta. The anticipated peak demand is around 5.4 MW, based on an average daily energy consumption of 44.8 MWh. The system's load factor is 0.35. The load factor, 0-1, is determined by dividing the average load by the peak load for a certain time. Table 4 indicates that an optimally built system exhibits a superior load factor.

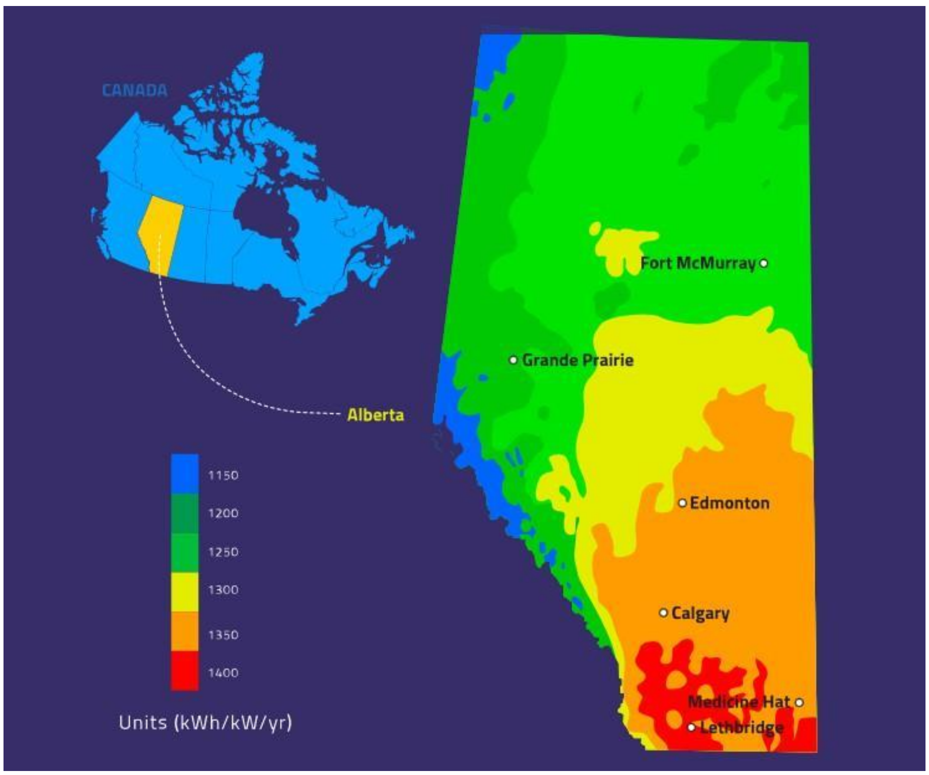


Figure 7: Solar Potential Map of Southern Alberta (Urban, 2018)

4.2.3 Wind Speed Data

The grasslands in southern Alberta are perpetually subjected to strong winds year- round. Gleichen utilized data from NASA's Prediction of Global Energy Sources project to compute wind velocities (*NASA POWER | Prediction Of Worldwide Energy Resources*, n.d.). The annual average wind speed at 50 meters above ground level was 5.90 meters per second. Site coordinates (longitude, latitude) were used to extract the requisite data from the NASA database.

Figure 8: Wind Potential Map of Southern Alberta (Iuele, n.d.)

Table 4: AC Load Parameters of Gleichen, Alberta

Metric	**Baseline**	**Scaled**
Average (kWh/day)	44899	44899
Average kW	1870.83	1870.7
Peak (kW/day)	5412.12	5412
Load Factor	0.35	0.35

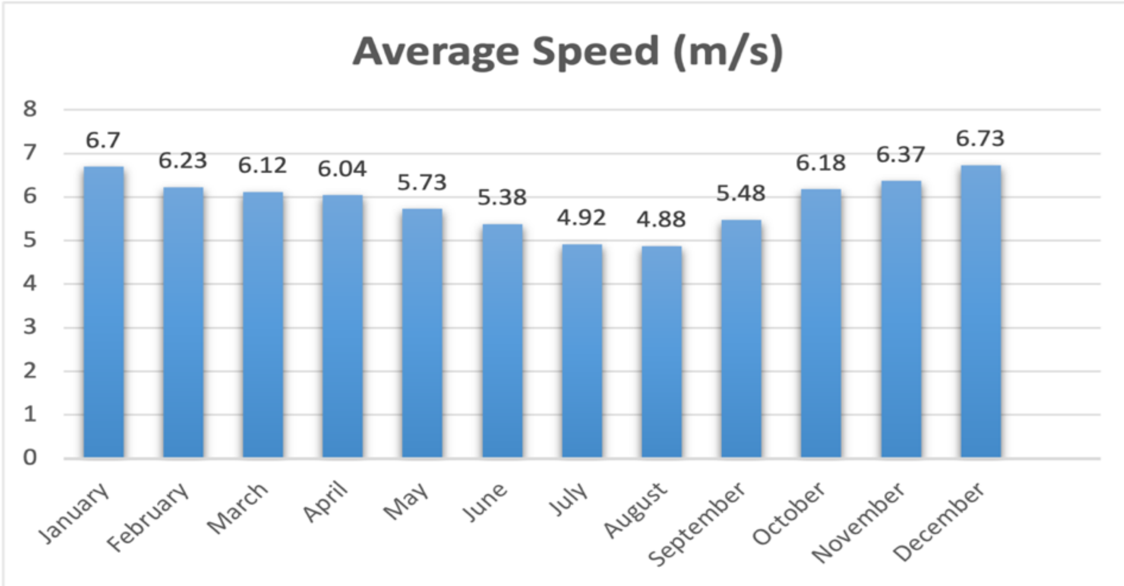


Figure 9: Monthly Average Wind Speed in Gleichen, Alberta

4.2.4 Solar GHI Data

Alberta experiences greater solar exposure than the remainder of Canada, averaging over 2500 hours a year. The Prediction of Worldwide Energy Source in the United States offers daily data on radiation and clarity indices (*NASA POWER | Prediction Of Worldwide Energy Resources*, n.d.). The annual radiation levels measure 3.57 kWh/m²/day. The clarity index attains its peak in July and its lowest in January. Figure 10 illustrates the monthly average solar generation heat index in Gleichen, Alberta.

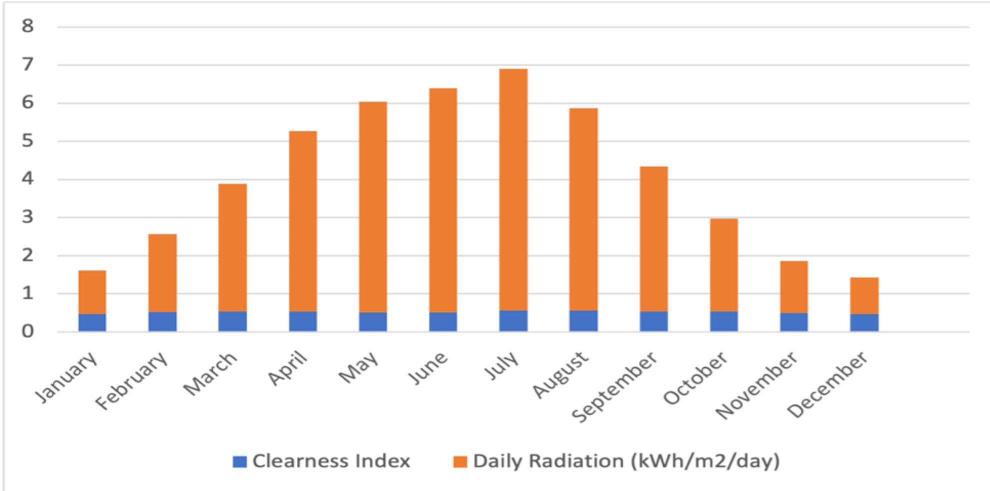


Figure 10: Monthly Average Solar Global Horizontal Irradiance (GHI) in Gleichen, Alberta

4.3 Mathematical Modeling

4.3.1 Solar Photovoltaic System

Using the Osterwald method for calculating the PV output power is one of the most commonly used method and the equation for this purpose can be seen below (Osterwald, 1986):

$$Ppv = N \times Am \times \eta g \times G_t \tag{4-1}$$

In this context, Ppv, N, and A_m denote the power generated by photovoltaic systems, the quantity of solar photovoltaic modules, and the area of the modules, respectively. G_t represents the global radiation on the inclined surface in W/m², whereas η indicates generator efficiency.

4.3.2 Wind Turbine System

Wind turbine output power can be calculated as follows:

$$Power\ (P) = 0.5 * \rho * A * V^3 \qquad (4\text{-}2)$$

In this equation, P represents power generated from WT in kilowatts,

wind speed is donated by V, whereas ρ represents the air density, and the cross-sectional area A is in m^2.

4.3.3 Performance Factors for Techno-economic Analysis

Key performance indicators, including economic metrics such as LCOE and NPC, together with greenhouse gas emission concerns, are employed to ascertain an optimal design when assessing the techno-economic feasibility of a system aimed at maximizing renewable resource utilization.

4.3.3.1 Net Present Cost (NPC)

To calculate the NPC, aggregate all costs associated with the hybrid system to date and subtract any salvage value accrued during that timeframe. Estimating the NPC requires the inclusion of capital, replacement, operating, and maintenance costs. The provided system's components NPCs are calculated using Equation 2-3 through the HOMER Pro software, where $C_{capital}$ denotes the initial investment, $C_{replaces}$ the cost of replacement, $C_{maintain}$ costs of upkeep, $C_{salvage}$ denotes the cost of salvage, T represent time in years.

$$NPC = \sum_{t=1}^{T} \left(C_{capital} + C_{Replace} + C_{maint} - C_{salvage} \right) \qquad (4\text{-}3)$$

4.3.3.2 Levelized Cost of Electricity

The LCOE for a system is determined by averaging its costs per kilowatt-hour of electrical production. To determine the LCOE, we use the HOMER equation and divide the total annualized cost by the aggregate of $L_{primeAC}$ and $L_{primeDC.}$ The primary load for alternating current is denoted as $L_{primeAC}$ in this equation, whereas the main load for direct current is represented by $L_{primeDC}$.

$$COE = \frac{Total\ annualized\ cost}{(L_{primeAC} + L_{primeDC})} \qquad (4\text{-}4)$$

4.3.3.3 Total Annualized Cost

The project's total value is actualized within the anticipated timeframe. This expense also computes the net present value for the component cash flow sequence. Upon determining the cost with NPC, the capital recovery factor is multiplied by the total annualized cost utilizing HOMER Pro software.

4.3.4 System Strategy

The system strategy integrates renewable energy generation, grid interaction, and battery storage to optimize cost-efficiency, reliability, and sustainability. By leveraging a hybrid approach, combining grid-tied and off-grid capabilities—the design ensures uninterrupted power supply while minimizing operational expenses.

4.3.4.1 National Grid Configuration

When idle, electricity can be sold or utilized as a supplementary power source in grid-connected systems. It allocates electricity and utilizes renewable energy sources during periods of surplus, such as when inadequate midnight sunlight fails to meet load requirements. The system depends on battery energy storage when operating off-grid.

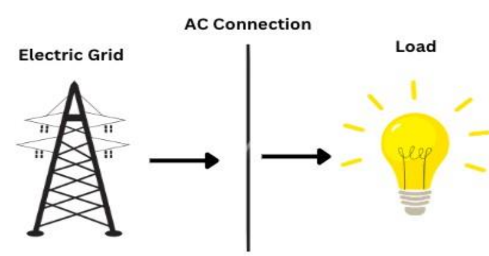


Figure 11: Schematic Presentation of Grid and AC Load (Base Case)

The energy price was determined by averaging the rates provided by many electrical suppliers in Gleichen, Alberta. As shown in Table 5, the rate encompasses transmission and distribution expenses of 0.127 CAD/kWh, in addition to the grid acquisition cost (base cost of electricity excluding transmission and distribution expenses) of 0.065 CAD/kWh. The grid accommodates peak loads of up to 2.5 MW, guaranteeing optimal output from the BESS.

4.3.4.2 Grid-tied PV System

In this configuration, seen in Figure 12, a significant portion of the demand is supplied by the PV system. HOMER optimized the requirement for a 9500-kWh system with a BESS capacity of 2500 kWh. Renewable sources constituted 24.1% of the system's composition.

Table 5: Energy Providers and their Rates in Gleichen

Serial Number	Energy Providers	Energy Rates ($/kWh)
1	Spot power	0.127
2	ATCO Energy	0.123
3	ENCOR	0.127
4	Easy Max	0.127
5	Just Energy	0.144

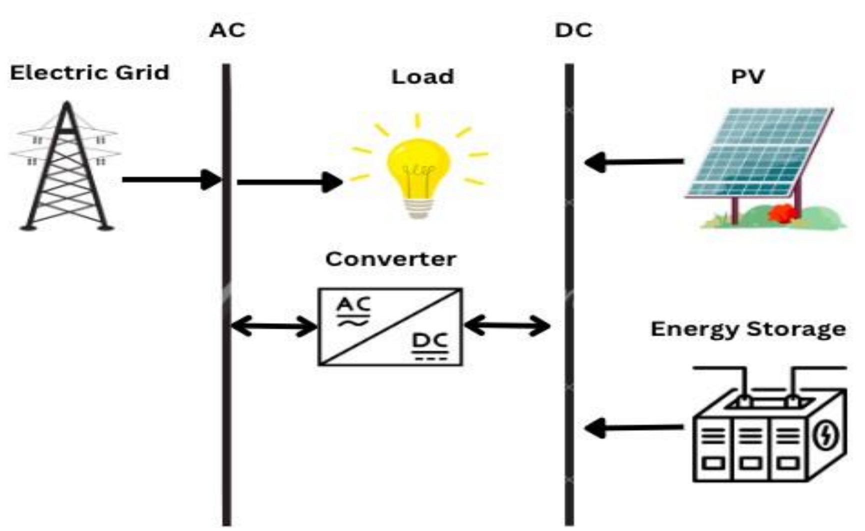


Figure 12: Schematic Presentation of Grid-connected PV System

4.3.4.3 Grid-tied WT System

Figure 13 illustrates that the Wind Turbine (WT) system serves as the principal clean energy source for the power generation system in this design. The HOMER algorithm was employed to optimize a 6000-kW wind turbine system with a 2500 kWh battery capacity. In this context, renewable sources accounted for 79.6% of the overall energy supply.

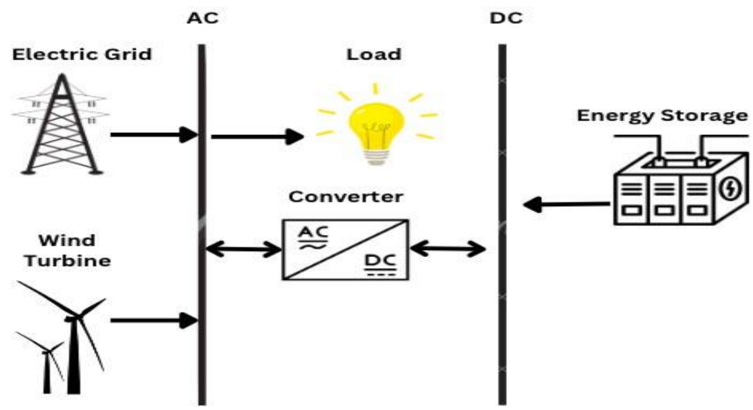


Figure 13: Schematic Presentation of Grid-tied WT System

4.3.4.4 Grid-tied PV-WT System

Figure 14 illustrates the ideal power generation system that integrates wind turbines and photovoltaics to deliver clean energy. In this configuration, the HOMER software modeled the use of a 2500 kWh Battery Energy Storage System (BESS) as a key component. The integration of the BESS allowed for a significant reduction in the required capacities of the PV and wind systems, which were initially sized at 6264 kW and 4500 kW, respectively. As a result, the system became more balanced and cost-effective while maintaining high efficiency. Overall, renewable energy sources accounted for 80% of the total system design, highlighting a strong shift towards sustainable energy generation.

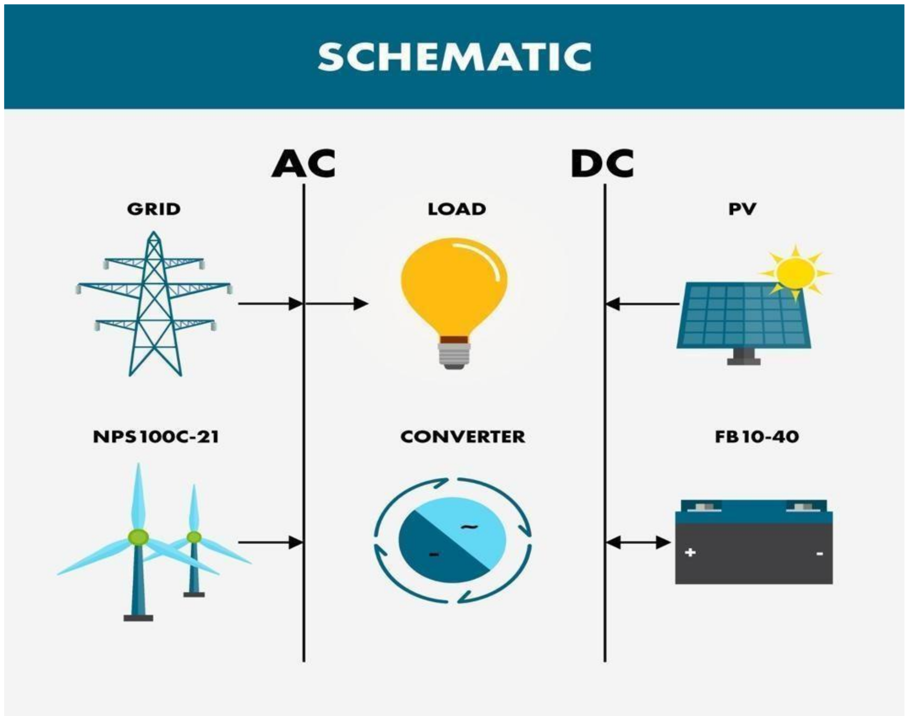


Figure 14: Schematic Presentation of PV-WT System *(Aftab et al., 2024)*

4.4 Results and Discussion

4.4.1 Techno-economic Analysis and Comparison of System Configuration

To ascertain the most cost-effective, environmentally sustainable, and practically viable option while maintaining low initial costs and other system attributes, we evaluate various hybrid configurations utilizing renewable energy sources, incorporating a utility grid and battery backup (baseline scenario). Table 6 enumerates all viable system configurations, together with their respective economic evaluations and greenhouse gas emissions.

Table 6: Simulation Results of Considered Configurations of Power System

Parameters	**Unit**	**National Grid**	**Hybrid (PV-Grid)**	**Hybrid (WT- Grid)**	**Hybrid (PV-WT-Grid)**
LCOE	CAD/kWh	0.127	0.172	0.0412	0.0705
Net Present Value (NPV)	CAD (Million)	22.4	36.4	14.4	22.3
Capital Cost	CAD (Million)	0.430	11.4	13.4	20.1
Replacement Cost	CAD (Million)	0.182	1.7	4.4	3.7
Maintenance Cost	CAD (Million)	21.816	23.45	1.1	0.12
Salvage Value	CAD (Million)	0.034	0.11	2.2	1.7
IRR	%	-	9.4	15	8.3
ROI	%	-	-2.8	11	5.6
Payback Period	Yrs	-	9.21	6.18	9.72
ESS Qty.	Battery	18	2500	2500	2500
System Autonomy	Hr.	0.922	1.07	1.07	1.07
Renewable Fraction	%	-	24.1	79.6	80
Energy Purchased	kWh	-	13,860,187	5,520,959	5,030,628
Energy Sold	kWh	-	19,156	10,660,754	8,023,980
Total Emissions	kg/yr.	8,719,564	8,816,188	3,511,711	3,199,882

The shift to renewable energy sources is increasingly motivated by economic realities rather than environmental concerns. The findings presented in Table 6 indicate that hybrid systems have a reduced levelized cost of energy (LCOE) compared to conventional National Grid systems. The LCOE is higher in this configuration because of the PV-Grid design's lower renewable penetration rate of 24.1%, compared to 79.6% and 80% in the WT-Grid and PV-WT-Grid configurations, respectively. The installation of large-scale solar panels would incur significantly greater initial capital costs. Capital expenditures (CAPEX) and operational expenditures (OPEX) are distributed variably among systems. CAPEX pertains to capital and replacement expenditure, while operating expenses encompass elements such as maintenance and fuel costs. Figure 15 represents capital, replacement, and maintenance expenditures across diverse system topologies.

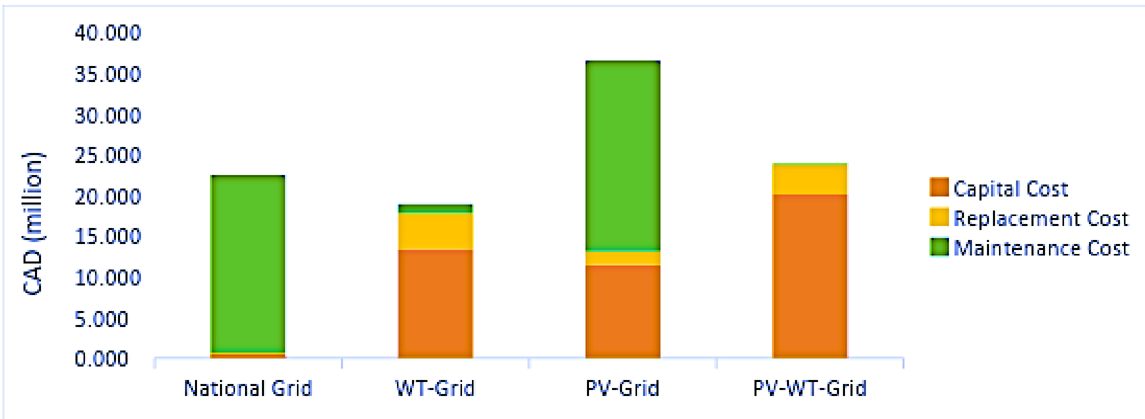


Figure 15: Cost Analysis of Different Power Systems Configuration

PV panels, wind turbines, converters, and ESS collectively diminish the initial capital expenditure of a project, sometimes financed directly at the outset. Solutions based on renewable energy are more cost-effective to deploy than conventional grid designs, as they do not necessitate solar photovoltaic panels or wind turbines. The capacity of the renewable energy system is the primary determinant of the capital cost of hybrid systems utilizing it.

The utilization of the national grid may seem more economically advantageous than hybrid solutions. Nonetheless, its cost is considerably greater than OPEX, diminishing its efficacy as a power source. Although exhibiting a favorable OPEX, systems utilizing solar panels and wind turbines incur substantial CAPEX owing to the significant initial costs associated with renewable energy.

A hybrid system, utilized independently or alongside the grid, seems to be the most economically viable option for commercial and industrial demands.

Renewable energy solutions are frequently more cost-effective due to their prolonged operating lifespan and, in several instances, shorter payback periods. In contrast to the grid-tied WT system, which has a payback period of 6.18 years, the optimal grid-tied PV-WT hybrid system has a payback period of around 9.7 years owing to higher capital expenditures. Figures 16–19 present further financial statistics for each configuration.

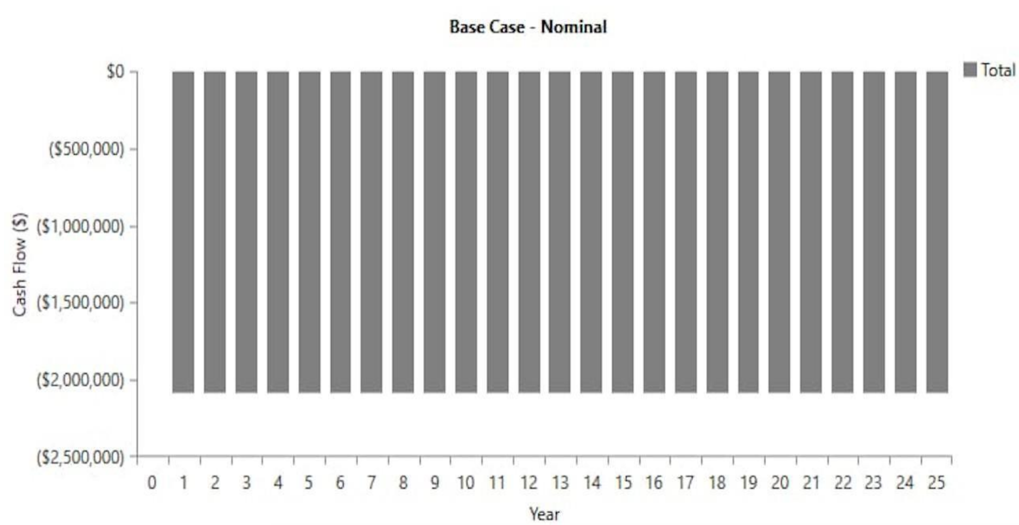


Figure 16: Cash Flow of National Grid Only System Configuration

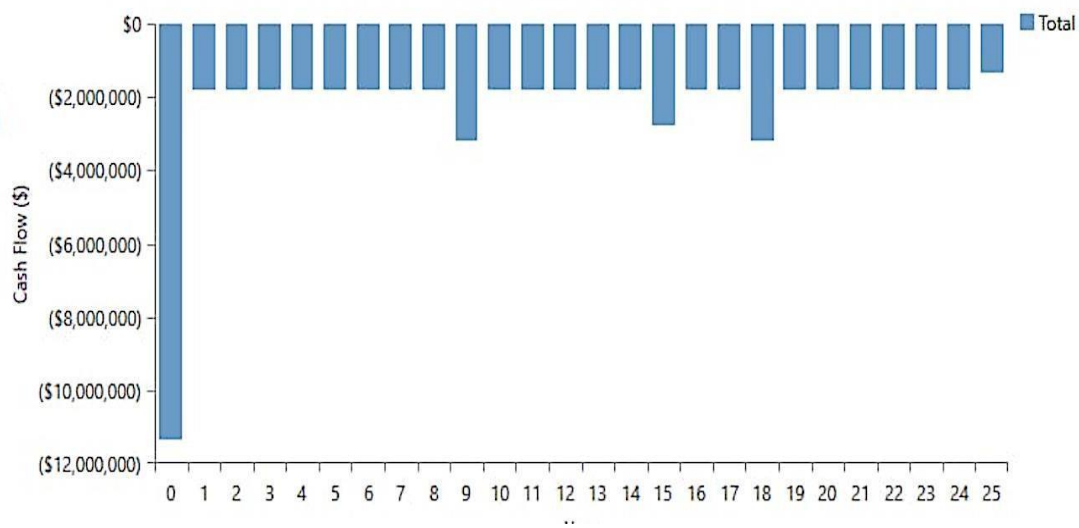


Figure 17: Cash Flow of PV-Grid System

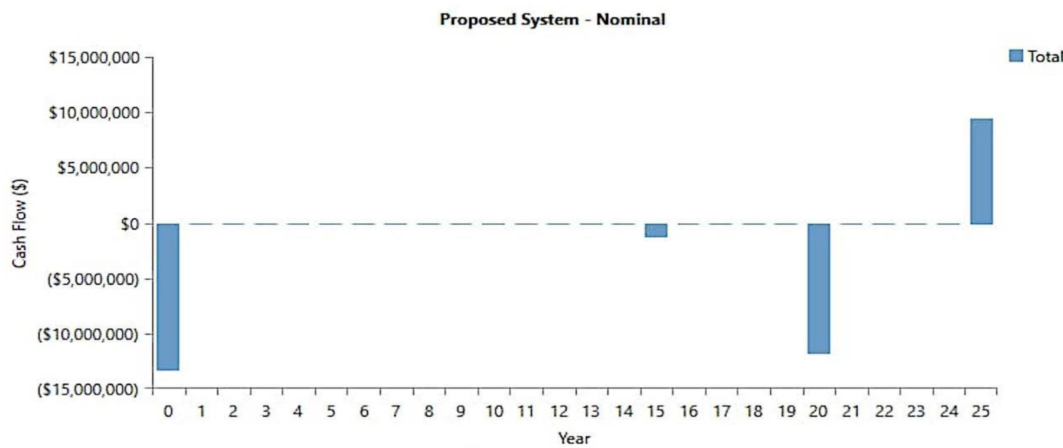


Figure 18: Cash Flow of Grid-WT System Configuration

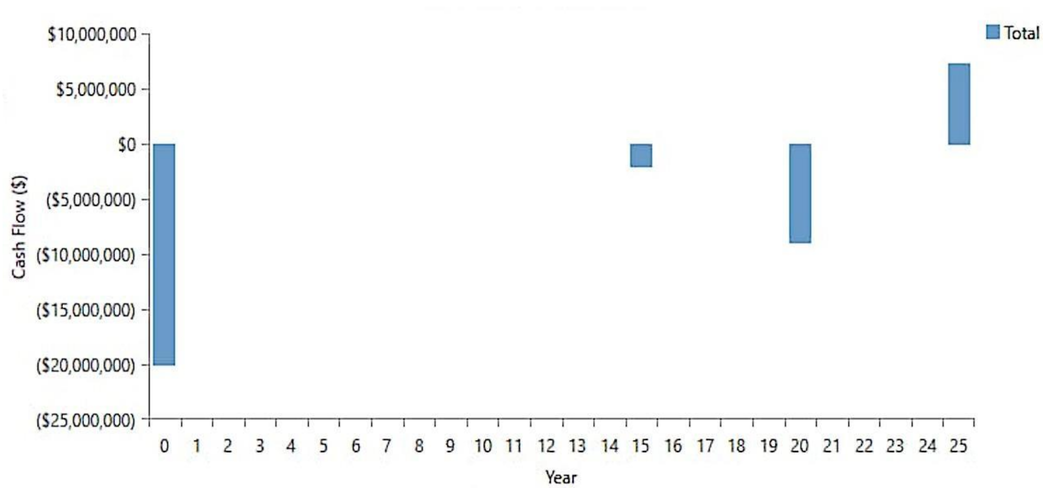


Figure 19: Cash Flow of Grid-tied PV-WT System Configuration

The figure 16 shows the projected cash flow for a National Grid-only system over 25 years, starting with an initial investment of 500,000 and increasing to 2.5 million, indicating increasing costs or negative net flow over time. The trend suggests higher expenses or lower revenues as the system ages. As can be seen in the above figures, cash flow represents the costs associated with the power system considered in terms of expenses or income. Regarding storage and modulation, Figure 20 shows the number of batteries utilized for backup systems.

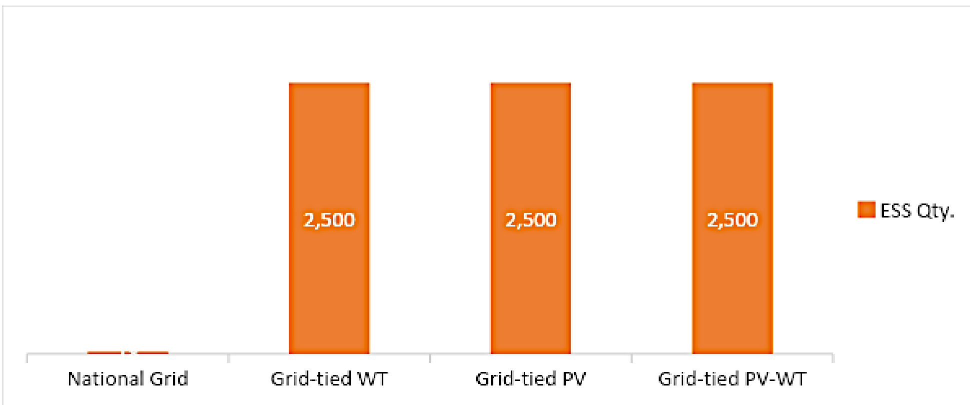


Figure 20: ESS Quantity for Different Power System Configuration

In choosing the battery backup size, the storage autonomy, defined as the ratio of storage bank capacity to electrical load, was considered. By configuring the BESS autonomy to 1.07 hours (keeping in view the backup required for the critical load), we can uniformly evaluate each hybrid configuration and determine the most optimal option. The payback period for grid- connected wind turbine-battery energy storage system hybrid power systems was the shortest, at 6.18 years. Grid-tied PV-WT hybrid systems had a payback period of 9.7 years, longer than the 9.21 years associated with grid-tied PV installations. The rationale for this is that solar and wind turbine systems are inherently more costly, leading to an increase in both total expenditure and payback duration.

To enable a techno-economic study under uniform conditions, the battery backup of the hybrid renewables architecture was maintained at a constant level, as seen in Figure 20. This has been executed to ensure consistency. Figure 21 illustrates that the enhanced system reduces annual greenhouse gas emissions to 3,199,882 kg, a significant decrease from the 8,719,564 kg generated by the National Grid-only configuration at the equivalent load capacity. The revised approach resulted in substantial decreases in environmental contamination.

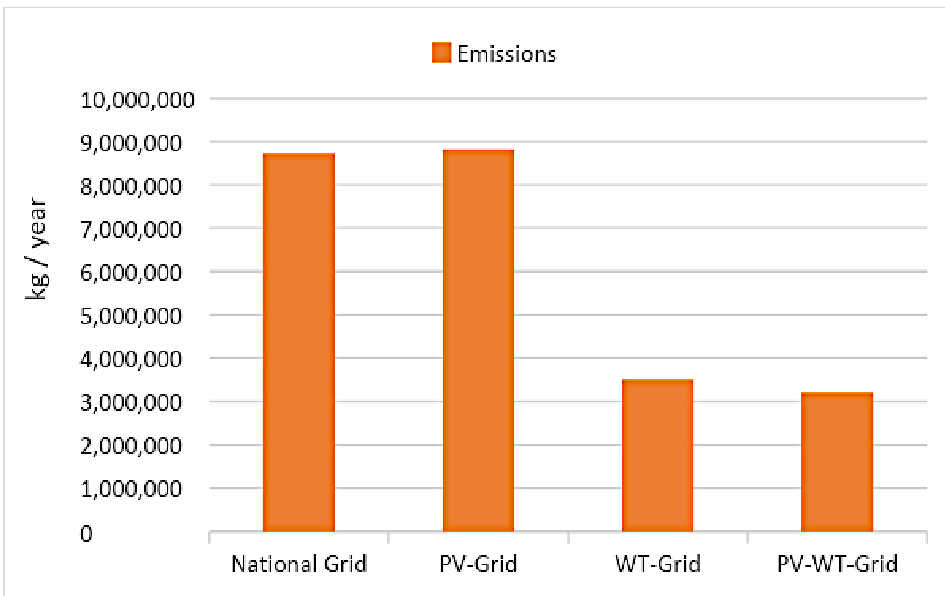


Figure 21: GHG Emissions for Different System Configurations

As shown in Table 7, the LCOE ranges from 0.0412 CAD/kWh to 0.127 CAD/kWh, and the proposed optimized hybrid system comprising a grid-tied PV- WT configuration exhibits an LCOE of 0.0705 CAD/kWh. The proposed hybrid configuration reduces the environmental impact because the renewable fraction has improved.

Although the investment needed exceeds that of previous hybrid systems lacking renewable energy sources, the proposed grid-tied PV-WT hybrid system demonstrates a lower levelized cost of energy (LCOE) of 0.0705 CAD/kWh, as indicated by simulation findings. The optimal hybrid system (PV-WT-Grid) comprises 80% renewable energy. The simulation results indicate that, based on current economic and emission metrics, the suggested load-side hybrid system design is the optimal choice.

Table 7: Simulation Results of Considered Configurations of Power Systems

Parameter	**Unit**	**Hybrid (PV-Grid)**		**Hybrid (WT- Grid)**		**Hybrid (PV-WT-Grid)**	
		Lead Acid	Li-Ion	Lead Acid	Li-Ion	Lead Acid	Li-Ion
LCOE	CAD/kWh	0.172	0.165	0.0412	0.0351	0.0705	0.0621
Net Present Value (NPV)	CAD (Million)	36.4	25.3	14.4	8.1	22.3	14.4
Capital Cost	CAD (Million)	11.4	12.6	13.4	14.7	20.1	21.5
Replacement Cost	CAD (Million)	1.7	0	4.4	0	3.7	0
Maintenance Cost	CAD (Million)	23.45	20.13	1.1	0.89	0.12	0.05
ESS Qty.	Battery	2500	1875	2500	1875	2500	1875
System Autonomy	Hr.	1.07	2.32	1.07	2.32	1.07	2.32
Renewable Fraction	%	24.1	26.2	79.6	80.8	80	81.5
Total Emissions	kg/yr.	8,816,188	6,632,158	3,511,711	2,712,544	3,199,882	2,332,673

4.4.2 Sensitivity Analysis

The performance of a system is affected by numerous factors. The study used sensitivity analysis to specifically examine the performance of the proposed system under varying situations, including variations in grid unit cost and battery type. A comparative analysis of lead-acid and lithium-ion batteries was conducted to evaluate the technological and economic performance of the system. Lithium-ion energy storage systems evidently rival lead-acid options concerning levelized cost of energy, replacement, and maintenance expenses (Table 7).

The technology enhances the renewable component by minimizing the quantity of lithium-ion batteries required to meet criteria. The integration of lithium-ion battery technology significantly strengthens the renewable energy component of the system by reducing the number of battery units required to meet energy storage demands. Compared to traditional lead-acid batteries, lithium-ion batteries offer a much higher energy density, longer lifespan, and better efficiency. This means that fewer batteries are needed to store the same amount of energy, which not only reduces system size and weight but also lowers long-term operational and maintenance costs.

Moreover, lithium-ion batteries play a pivotal role in improving the overall performance and reliability of the energy storage system. Their ability to charge and discharge more efficiently allows for better alignment with variable renewable energy inputs like solar and wind, thereby enhancing system responsiveness and stability. This improved performance translates into a greater share of renewable energy utilization, as the system can store and deliver clean energy effectively.

From an environmental standpoint, lithium-ion batteries are also a more sustainable option. They produce approximately 20–25% fewer greenhouse gas (GHG) emissions over their lifecycle compared to lead-acid batteries. This reduction in emissions contributes to the broader goal of decarbonizing the energy sector, making lithium-ion batteries an essential technology in the transition toward cleaner, more efficient, and environmentally responsible energy systems. The capital expenditure of the system increases when lead-acid batteries are substituted with lithium-ion batteries due to the higher cost of each battery (Yousef et al., 2022), but its longer life decreases the overall system costs.

As demonstrated in Table 8, fluctuations in fuel prices significantly affect the overall system performance. Utility networks have significantly elevated unit prices; however, the integration of renewables has diminished overall unit costs and greenhouse gas emissions. Moreover, a significant portion of the generation has been accomplished using renewable resources. The results of the sensitivity analysis underscore the necessity of validating the long-term viability of the proposed renewable-based hybrid design.

Table 8: Simulation Results of System Configurations with Current Electricity Unit Prices and Future Forecast Prices

Parameter	**Unit**	**Grid Only Configuration**	**Hybrid (PV-WT-Grid) With Current Unit Price**	**Hybrid (PV-WT-Grid) With Forecasted Unit Price**
LCOE	CAD/kW	0.302	0.0705	0.072
Net Present Value (NPV)	CAD (Million)	64	22.3	22.7
Operating Cost	CAD (Million)	4.95	0.210	0.210
Payback Period	Yrs	-	9.72	4.10
Renewable Fraction	%	-	80	78.7
ROI	%	-	5.6	19.7
IRR	%	-	8.3	24.1

4.4.3 Comparative Studies

The study considered the real-time demand profile of the Siksika Nation community in Gleichen to develop and optimize a hybrid power generation system that is economically feasible and environmentally sustainable. Table 9 presents the results of a comparison between the suggested configuration and the existing system documented in the literature. No case studies in literature are equivalent to the specified one regarding daily load consumption. The comparison aimed to illustrate the significance of renewable components in balancing load demand. The comparative research underscores the significance of the tri-brid system in generating energy with little CO_2 and GHG emissions. Nonetheless, diesel generators were utilized as an additional backup source in most of the preceding experiments, hence augmenting overall greenhouse gas emissions.

Table 9: Comparative Studies

Parameter	**Unit**	**Hybrid (PV-WT-DG-Grid)** (Akindeji & Ewim, 2023)	**Hybrid (PV-WT-Grid)** (AL Hammadi et al., 2022)	**Hybrid (PV-WT-Grid)**
LCOE	CAD/kW	0.075	0.092	0.070
Net Present Value (NPV)	CAD (Million)	27.03	2.06	22.3
Capital Cost	CAD	-	1.76	20.1
Renewable Fraction	%	-	68.2	80
Payback Period	Yrs	4.1	-	9.72

4.5 Conclusions

The study highlighted the importance of switching to renewable energy sources to meet the rising energy demands from industrial and technical breakthroughs, ensuring clean and reliable power for residences, enterprises, and manufacturing facilities. This research paper presents a hybrid grid-connected system that blends photovoltaic (PV) technology, wind energy, and batteries to meet actual load demands while reducing overall system costs by around 56%. The suggested alternative is more ecologically sustainable, with an exceptionally low LCOE of 0.0705 CAD/kWh and about 80% renewable content in the hybrid system. The study's findings indicate that the use of intelligent energy management systems is essential for advancing the green energy sector and enabling the transition to renewable energy.

Aligned with the worldwide objectives of the Green Initiative, the study's recommended design for an efficient tri-brid energy system would surpass traditional fuel-based power systems. The tri-brid system's connection to the grid allows for the sale of surplus energy when not utilized, enhancing its reliability and cost-efficiency.

Investigating alternative renewable sources is the subsequent stage in enhancing renewable energy adoption while reducing costs. Integrating the latest technological advancements into battery backup systems can enhance overall efficiency.

Chapter 5: Developing A Strategic Land Use and Resource Assessment Process to Optimize Renewable Energy Integration into the Regional Economy of two irrigation districts LNID and St. Mary River, Alberta, Canada

5.1 Introduction and background

Mohammad Adnan Aftab, a PhD Candidate has drafted the manuscript. Dr. Dan Johnson, Dr. Paul Hazendonk, and Dr. Locke Spencer have supervised and reviewed the manuscript. Dr James Byrne assisted in acquiring the grants for this valuable research. This manuscript will be sent shortly to the journal for review and publication.

The integration of renewable energy sources into regional economies has become imperative for sustainable development (Noorollahi et al., 2016). Optimizing the utilization of renewable energy requires a strategic land use and resource assessment process (Kumar et al., 2022). Consequently, GIS technology serves as an effective decision-making instrument across several domains, including renewable energy management. Solar and wind energy have the most potential as the optimal renewable energy sources for the generation of clean power. Identifying suitable sites for wind and solar energy projects is difficult without doing thorough analyses of many socioeconomic, environmental, and geographical issues.

Several studies have utilized GIS-based approaches to assess the suitability of different regions for renewable energy projects (Ali et al., 2019; Sánchez-Lozano et al., 2015). These studies have demonstrated the effectiveness of GIS in providing valuable insights into the spatial distribution of renewable energy resources and the identification of suitable sites for energy projects (Nadizadeh Shorabeh et al., 2021).

In this study, we proposed a strategic land use and resource assessment process to optimize solar and wind energy integration into the irrigation districts of LNID and St. Mary, Canada. We employ GIS techniques to analyze various factors influencing the suitability of different sites for solar and wind energy projects. These factors include land use, elevation, slope, aspect, soil morphology, population density, solar radiation, wind speed, road network, and proximity to water bodies and transmission lines. By applying Principal Component Analysis (PCA) and Fuzzy Overlay analysis, we aim to identify the most suitable sites for solar and wind energy projects in the study area.

This work contributes to the expanding knowledge on renewable energy utilization and may significantly help policymakers, energy planners, and stakeholders engaged in the sustainable development of regional economies.

Solar and wind energy are two renewable energy sources being examined as viable alternatives to fossil fuels due to the potential environmental advantages that these sources provide. Conversely, power systems predominantly dependent on renewable energy sources such as wind and solar power are not consistently reliable, and this is due to the unpredictability of various energy sources (Shaner et al., 2018). This study used 36 years of hourly worldwide meteorological data to evaluate the geophysical resource attributes of solar and wind energy in the United States. The researchers determined that to provide over 80% of demand using solar and wind energy, either twelve hours of energy storage or comprehensive transmission infrastructure throughout the United States is necessary. The requisite energy storage or surplus solar and wind generation capacity needed to mitigate the erratic nature of weather patterns and seasonal variations is escalating by over 80%. Moreover, the study indicated that, although wind-dominant wind/solar combinations may benefit from regional wind variability, solar-dominant combinations need energy storage to offset the daily solar cycle.

Similar concerns have been addressed by various studies focusing on the suitability of locations for renewable energy systems (Arefiev et al., 2015; Sindhu et al., 2017; Van Haaren & Fthenakis, 2011). In one study, (Aydin et al., 2013), the researchers proposed a methodology for identifying locations for hybrid renewable energy systems in western Turkey utilizing geographic information systems. They employed a fuzzy decision-making methodology utilizing geographic information systems to determine optimal locations for renewable energy systems, including solar photovoltaics and wind energy.

Nadizadeh Shorabeh et al. (2021) assessed the viability of establishing geothermal, biomass, wind, and solar power facilities in eastern Iran by employing several environmental and economic criteria. The data indicates that 13% of the research area was appropriate for geothermal energy, 23% for solar energy, 19% for wind energy, and 5% for biomass energy facilities.

Watson & Hudson (2015) assessed the potential for solar and wind energy in the central region of Southern England. Expert stakeholders participated in the decision-making process using a multi-criteria decision-making framework employing an analytical hierarchy method. The study's findings indicate that solar power projects are a superior possibility for building in the region compared to wind farms.

Villacreses et al.(2017) employed GIS and MCDM methodologies to assess potential solar farm sites in southern Morocco. They identified regions that might possibly benefit from renewable energy initiatives following their investigation.

Finally, Janke (2010) executed a study that replicated wind and solar farms in Colorado utilizing a multicriteria geographic information system (GIS). They evaluated several geographical and environmental criteria to identify the optimal locations for wind and solar farms. This research elucidates the advantages and disadvantages of using renewable energy sources such as wind and solar to power an electrical system. Nonetheless, they underscore the need to evaluate both geographical and environmental aspects when determining sites for renewable energy initiatives.

5.1.1 Objective

The objectives of this study are as follows:

i. To identify and map the most suitable locations for renewable energy-based power systems deployment within LNID and St. Mary River Districts. For this purpose, GIS techniques have been utilized for efficient and economical assessment to consider the various spatial and non-spatial factors such as land use, elevation, slope, soil morphology, population density, renewable resources availability, road network, and transmission lines setup for integration.

ii. Applicability of various advanced analytical techniques such as Principal Component Analysis (PCA) and Fuzzy Overlay Analysis to assess the most feasible and least conflicted sites in the area for renewables deployment. Findings from this work can offer valuable insights and recommendations to policymakers, energy planners, and stakeholders, facilitating decision-making for the sustainable development and integration of renewable resources into the regional economy.

5.2 Materials and Methodology

5.2.1 Methodology Overview

As shown in Figure 22, this research employed a mixed methods approach that integrated spatial data acquisition and analysis techniques. To begin, relevant environmental variables were identified, including demographic data, soil morphology, slope, elevation, and climatic data such as solar radiation and wind speed. Spatial data were then collected through rasterization of maps and resampling to a common resolution. Once collected, the data was preprocessed through reclassification. Principal Component Analysis (PCA) and fuzzy overlay techniques were used to classify land suitability for solar and wind energy production.

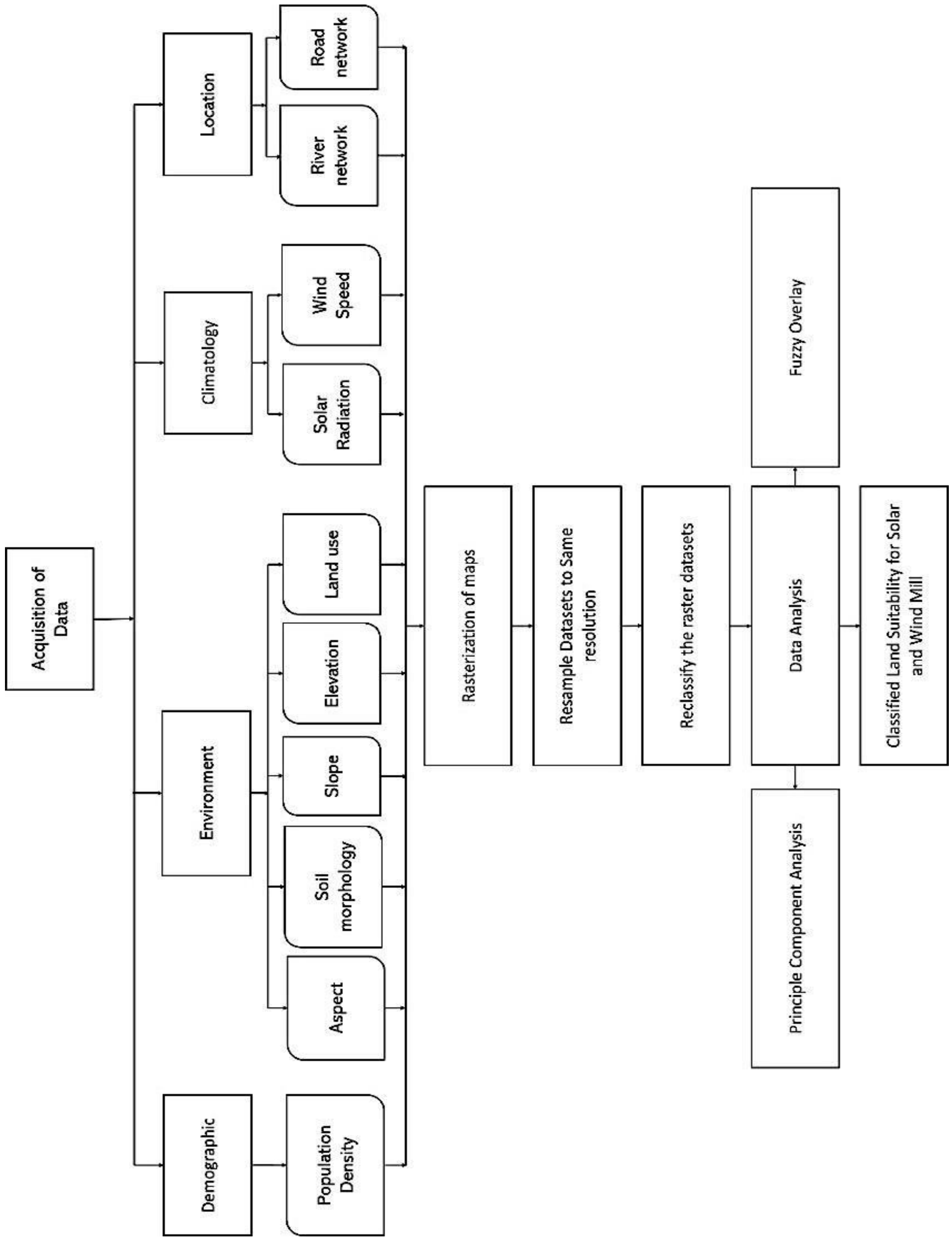


Figure 22: Flowchart of the Proposed Methodology

5.2.2 Study Area

The St. Mary River Irrigation District (SMRID) covers over 500,000 acres of land, providing extensive potential for solar energy development (Alberta Irrigation

Districts Association) as shown in Figure 23. Similarly, the Lethbridge Northern Irrigation District (LNID) offers significant land resources suitable for renewable energy projects. Both districts are primarily focused on irrigated agriculture, making them vital areas for understanding water usage patterns and potential impacts on irrigation needs. The existing infrastructure within SMRID and LNID, including canals and pipelines, presents opportunities for integrating solar energy systems.

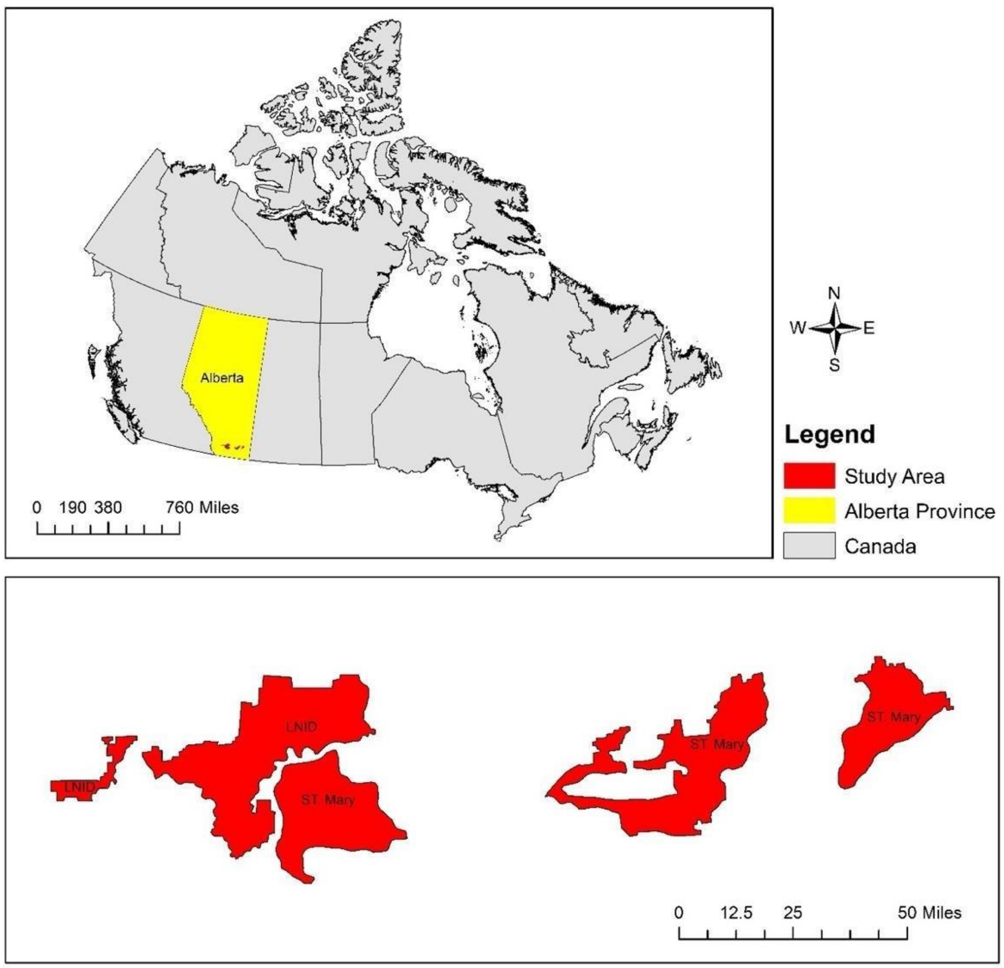


Figure 23 Geographical Location of the Study Area in Alberta, Canada

5.2.3 Data and Their Resources

Various spatial and non-spatial factors considered for this study are mentioned below (Noorollahi et al., 2016):

i. **Slope (%):** When evaluating a site's viability for solar and wind energy projects, slope is a crucial factor. Slope percentage was used to carefully classify the areas, giving special attention to areas with lower slopes. These areas are very conducive to the development of renewable energy because of their ideal topography, which makes solar panels and wind turbines easier to install and operate.

ii. **Elevation (m):** Elevation plays a crucial role in determining wind speed and solar radiation potential, two variables crucial to producing renewable energy. After a thorough classification process, areas with elevations between 680 and 930 meters above sea level were given precedence. Because of their elevated locations, renewable energy projects are more productive and efficient overall since they can better utilize the sun's and wind's energy resources.

iii. **Aspect: Focus was given** to areas gifted with favorable aspects that were beneficial to solar exposure and optimal wind patterns. By placing renewable energy projects in areas that optimize energy yield and operational efficiency, this strategic consideration improves the projects' overall viability and sustainability.

iv. **Proximity to Road (km):** Building, maintaining, and running infrastructure for renewable energy all depend heavily on accessibility. Given its critical importance, priority was given to areas situated near major road networks, with distances ranging from 0 to 30 kms. This strategic approach ensures seamless logistical support and facilitates efficient transportation of equipment and personnel, thereby streamlining project implementation and reducing operational costs.

v. **Proximity to Waterbody (km):** Water bodies have a major impact on microclimate conditions and wind patterns, which affect how well solar panels and wind turbines operate. As a result, locations close to bodies of water—within a range of less than one to five kms—were given precedence. These sites optimize energy generation and operational stability due to improved wind flow dynamics and climatic moderation.

vi. **Proximity to Transmission Line (km):** To ensure the successful integration of renewable energy projects into the electrical grid, they must be in proximity to transmission lines. Consequently, regions situated between 5 and 16 kilometers from transmission lines were prioritized. This crucial component facilitates effective energy transfer and grid integration, enhancing the overall dependability and longevity of renewable energy systems.

vii. **Land Use:** Assessing land use suitability is fundamental in identifying areas conducive to renewable energy development. Priority was accorded to areas characterized by grass and barren land, agricultural land, and flooded vegetation and shrubs. These land uses offer favorable conditions for installing and operating solar panels and wind turbines, thereby enhancing the viability and effectiveness of renewable energy projects.

viii. **Soil Morphology:** Soil morphology assessment provides valuable insights into the suitability of land for renewable energy development, particularly about irrigation requirements. Priority was accorded to areas characterized by soil types conducive to irrigation, such as coulee and valley. These soil types facilitate efficient water management practices, thereby enhancing the overall sustainability and productivity of renewable energy projects.

ix. **Population Density:** Population density serves as a crucial indicator of potential conflicts and compatibility issues with residential areas. Priority was given to areas characterized by lower population density, thus minimizing potential conflicts and to improve harmonious coexistence with local communities. This strategic approach enhances social acceptance and support for renewable energy projects, thereby fostering sustainable development and regional prosperity.

x. **Solar Radiation and Wind Speed:** Solar panels and wind turbines are the most effective in regions with abundant sunshine and robust winds. Specific locations were chosen because of their superior environmental attributes and enhanced energy generation capabilities. This strategic emphasis prioritizes the effective use of renewable energy resources, hence fostering regional economic growth and advancing sustainable development.

The study utilized data from various sources to assess the suitability of renewable energy development in the study area. All datasets were processed to a 10-meter resolution for accurate analysis. Table 10 shows the sources of the data used.

Table 10: List of Data and Their Sources

Data Used	**Sources**
Slope, Aspect, Elevation	opentopography.org
Land use	livingatlas.arcgis.com
Soil Morphology	Food and Agriculture Organization (FAO)
Population Density	Worldpop.org
Solar Radiation and Wind Speed	power.larc.nasa.gov
Road and River Network	extract.bbbike.org

5.2.4 Methods and Techniques

In this study, a strategic land use and resource assessment process was developed using ArcGIS software to optimize the integration of renewable energy into the regional economy of LNID and St. Mary regions in Canada. The methodology involved the utilization of various GIS-based techniques, including Principal Component Analysis (PCA) and Fuzzy Overlay Analysis, to assess the suitability of different areas for solar and wind energy development. The PCA was employed to identify and prioritize suitable areas based on these factors.

Additionally, Fuzzy Overlay Analysis was used to refine further the suitability assessment (Kumar et al., 2022). The creation of final suitability maps for wind and solar power projects entailed formulating a conceptual model and utilizing several criterion layers. Legislators and stakeholders in the LNID and St. Mary areas may leverage the results to make informed decisions on renewable energy policy and development (Noorollahi et al., 2016).

The analytical hierarchy process (AHP), first developed by (Saaty, 1996), has been extensively utilized by scholars across many disciplines to address the intricacies of various challenges. A group of scholars established a framework that may be employed with the AHP method to prioritize options based on their importance. The AHP methodology disregards the inherent unpredictability of the process. Several scholars have employed fuzzy set theory to address this challenge. Zadeh invented fuzzy set theory, which addresses the inherent ambiguity, vagueness, and imprecision of the process (Saaty, 2004).

5.2.4.1 Principal Component Analysis

PCA is a multivariable computing technique that maintains data dependability while lowering data set complexity. Trimming is the process of dividing the original data into two or more important, unrelated, orthogonal, and relatively significant components. The revised orthogonal elements perform a vital function in preserving the variables' absolute maximum variance. Subsequent components exhibit minimal or marginal variation that does not belong to either component, whereas the first PC has one or more parameters that account for most of the data set's volatility. Using the same scale for all factor calculations is the most effective way. Almost all morphometric properties in the PC may be determined using PCA. These are the four key steps to put PCA into effect. To boost PCA performance, the data set was standardized first. To standardize, each data point was removed from the general average. Also, the standard deviation was applied to the data set. This technique reduces the mean and standard deviation of all data to zero (Kumar et al., 2022). The procedure is as follows:

$$Z = \frac{C_{ij} - C_j}{S_j} \qquad (5\text{-}1)$$

where Z denotes the standardized matrix of parameters, C_{ij} stands for ith observation on the jth parameter, i ranges from 1, 2...n (number of observations), j ranges from 1, 2...p (number of parameters), C_j is the mean of the jth parameters and S_j is the standard deviation of the jth parameter.

The second step involved the computation of the covariance matrix to identify any possible correlation between the data set variables. The study assumed Z matrix of n observations and p number of PCs may be represented in the matrix notation as:

$$Z = X * P \qquad (5\text{-}2)$$

Where Z and X are the n*p matrices and P indicates coefficient matrix with p * p dimension; j^{th} PC Z_j is generally expressed as:

$$Z_j = X_{aj} \quad for\ j = 1, 2 \ldots p \qquad (5\text{-}3)$$

Where Z_j is n*1 column vector, and aj is p*1 column vector of coefficients.

In general, the covariance matrix is presented as:

$$C = \frac{XX}{n-1} = \begin{pmatrix} C_{11} & \cdots & C_{1p} \\ \vdots & \ddots & \vdots \\ C & \cdots & C \end{pmatrix} \qquad (5\text{-}4)$$

Where X' denotes the transpose of the standardized matrix of X predictor variables. Every covariance matrix element is evaluated as:

$$C = \frac{1}{n-1} \sum_{k-1}^{n} X_{kj} X_{ki} \qquad (5\text{-}5)$$

The PCs of the data were determined in step three by computing the eigenvalues and eigenvectors for the covariance matrix. The solution can be described by the characteristic equation as follows if λ^' is an eigenvalue for the covariance matrix C:

$$|(C - \lambda' I)| = 0 \qquad (5\text{-}6)$$

As the necessary condition for matrix subtraction, I is the identity matrix of the same dimension as C. It is possible to solve each eigenvalue λ^' by using the appropriate eigenvector v.

$$|(C - \lambda' I) * v| = 0 \qquad (5\text{-}7)$$

The eigenvector corresponding to the first PC is v1, and the one relating to the second PC is v2, if the eigenvalues are ranked in decreasing order, as ʎ'1 > ʎ'2. The development of PCs and the function vector was the fourth and last step. A matrix of eigenvectors representing the biggest eigenvalue and, in the case of two PCs, PC1 and PC2 makes up the function vector. Correlation between the X variables and the Z PCs is represented by the final loading matrix PC, which was created by multiplying the transpose of the feature vector by the transpose of the scaled version of the original data set. Therefore, the square roots of the eigenvalues of the C matrix were pre-multiplied with the characteristic's values of the correlation matrix to generate the PC loading matrix. A possible method to write the PC loading matrix is as follows:

$$R = PD^{\frac{1}{2}} \qquad (5\text{-}8)$$

The diagonal matrix with nonzero elements is represented by $PD^{\frac{1}{2}}$

which is the reciprocal of the square roots of the eigenvalues of the C matrix as given. Equations 3-6 and 3-7 were used in this work to get the eigenvalues and eigenvectors.

5.2.4.2 Principal Component Analysis

The methodological basis of the multiple assessments of the landscape parcels is the section of the fuzzy set theory devoted to multicriteria assessment and choice of alternatives. A is a set of m land parcels under consideration.

$$A = \{a_1, a_2, \dots\dots a_m\} \qquad (5\text{-}9)$$

A is the set of alternatives for decision making. Then for some particular criterion r can be considered fuzzy set:

$$R = \left\{\mu_r\left({}^{a_1}/_{a_1}\right), \mu_r\left({}^{a_2}/_{a_2}\right), \dots\dots, \mu_r\left({}^{a_j}/_{a_j}\right)\right\}, \qquad \mu_r\left({}^{a_j}/_{a_j}\right) \in [0,1] \qquad (5\text{-}10)$$

Where membership function $\mu_r(a_i)$ is evaluation of the a_i must meet criterion r. Thus, we can determine how the alternative a_i meets the criterion r. If we consider n criteria $r_1, r_2, \dots, r_n$, the best alternative a_i must meet criteria r_1, and criterion r_2, and so on to criterion r_n. Therefore, a rule for choosing the best a_i, should be written as the intersection of the corresponding fuzzy set:

$$X = R_1 \cap R_2 \cap \ldots \cap R_n \quad (5\text{-}11)$$

As the best alternative, we must select element a* from (3-9), which has the highest value of the membership function in the set X:

$$\mu_X(a^*) = max_{j=1,m}\, \mu_X(a_j) \quad (5\text{-}12)$$

If criteria r_{1i} have different importance, each of them is attributed with the coefficients of relative significance of these criteria $a_1, a_2, \ldots, a_n$. In this case, the rule should take the form:

$$X = R^{a_1} \cap R^{a_2} \cap \ldots \ldots \ldots \cap R^{a_n}; a_i > 0, i = 1, n; \frac{1}{n}\sum_{i=1}^{n} a_i = 1 \quad (5\text{-}13)$$

5.2.5 Land Suitability Analysis Modelling

In this section, the results of our suitability analysis for solar and wind energy development in Alberta, Canada, will be presented. Utilizing a Geographic Information System (GIS) as a decision-support system (DSS), we investigated various criteria to determine the most suitable locations for renewable energy projects. Information gathered from elevation models, population density data, land use classifications, soil morphology, solar radiation, wind speed, and proximity to infrastructure such as roads, transmission lines, and water bodies was processed and prepared for analysis, as can be seen in Figure 24. Each criterion was transformed into a spatial layer using GIS techniques.

The criteria layers were integrated using Principal Component Analysis (PCA) and Fuzzy Analytical Hierarchy Process (FAHP) techniques to generate final suitability maps for solar and wind energy development. Based on calculated suitability indexes for each district, these maps highlight priority areas for renewable energy projects.

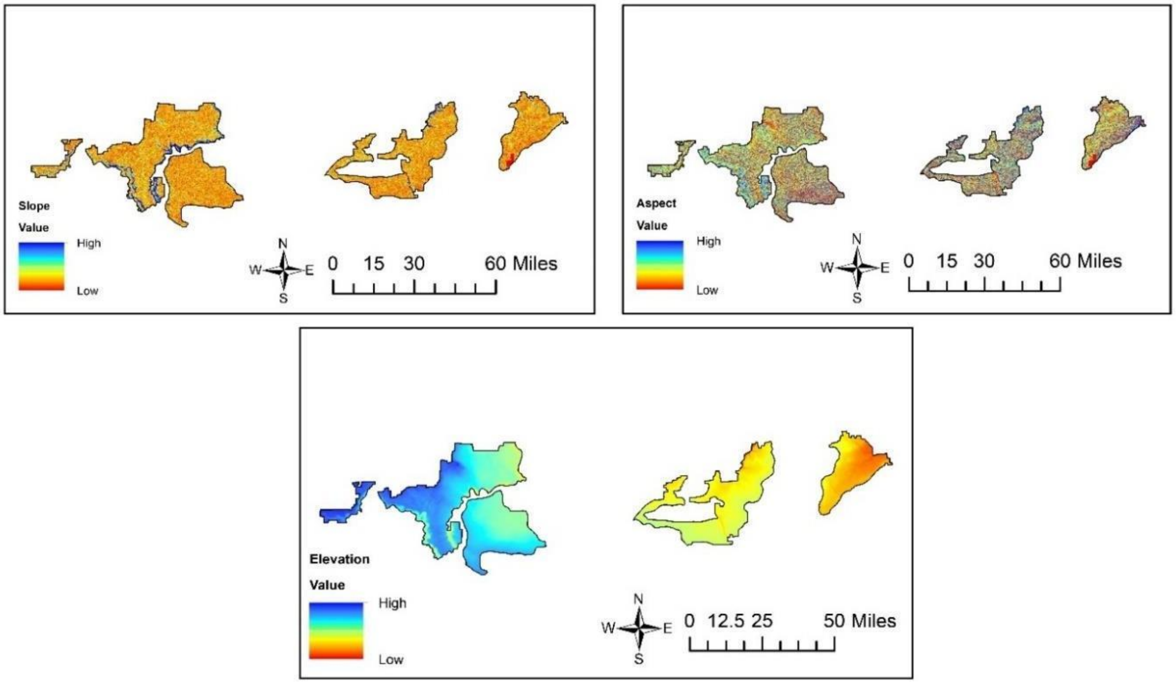
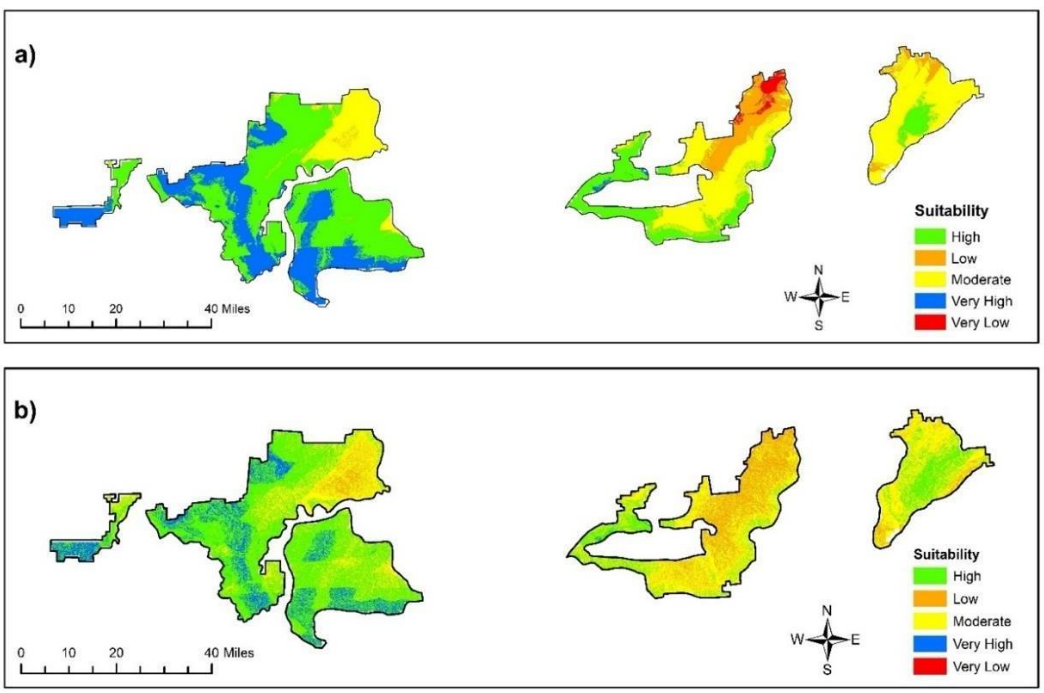


Figure 24 Evaluation criteria layers for land Suitability analysis: **(a)** Soil morphology; **(b)** Distance from waterbody; **(c)** so Distance from transmission line; **(d)** Distance from road; **(e)** wind speed; **(f)** Solar Radiation; **(g)** Population density; **(h)** Land Cover;**(i)** Slope**; (j)** Aspect; and **(k)** Elevation.



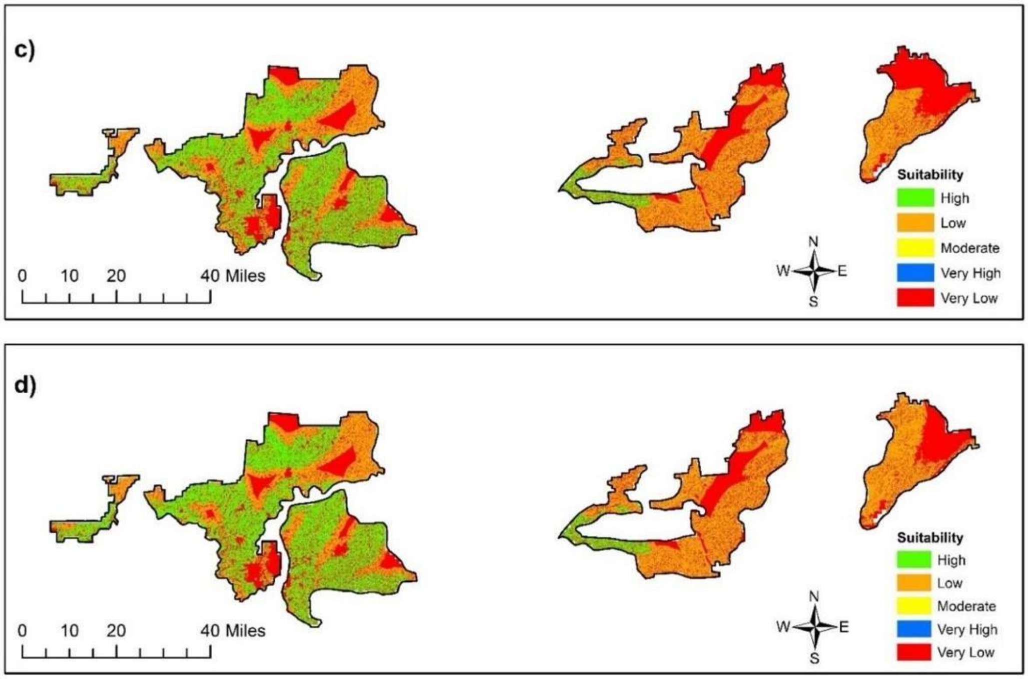


Figure 25: Classified land suitability map for exploiting solar and wind turbines: **(a)** Suitable site for Solar Plant using PCA technique; **(b)** Suitable site for wind turbines using PCA technique; **(c)** Suitable site for Solar Plant using Fuzzy Overlay technique; **(d)** Suitable site for wind turbines using Fuzzy Overlay technique

5.3 Results and Discussion

5.3.1 The Percentage of the Area Related to Various Classes

5.3.1.1 Using PCA Techniques

Table 11 revealed a significant difference in the suitability of land for solar energy development between LNID and St. Mary. LNID has a higher percentage of land categorized as "Very High" and "High" suitability for solar plants (73.24%) compared to St. Mary (72.72%). Conversely, St. Mary has a substantially larger portion of land classified as "Moderate" (34.29%) and "Low" (9.55%) suitability compared to LNID (10.99%). These findings suggest that LNID might offer more favorable conditions for large-scale solar power installations.

Table 11: Percentage Distribution of the Area for two regions, LNID and St. Mary for Solar Plant

Suitability Level of Solar Plant (PCA)	**LNID (%)**	**St. Mary (%)**
Very High	28.13	19.47
High	45.11	53.25
Moderate	10.79	34.29
Low	0.20	9.55
Very Low	0.00	1.52

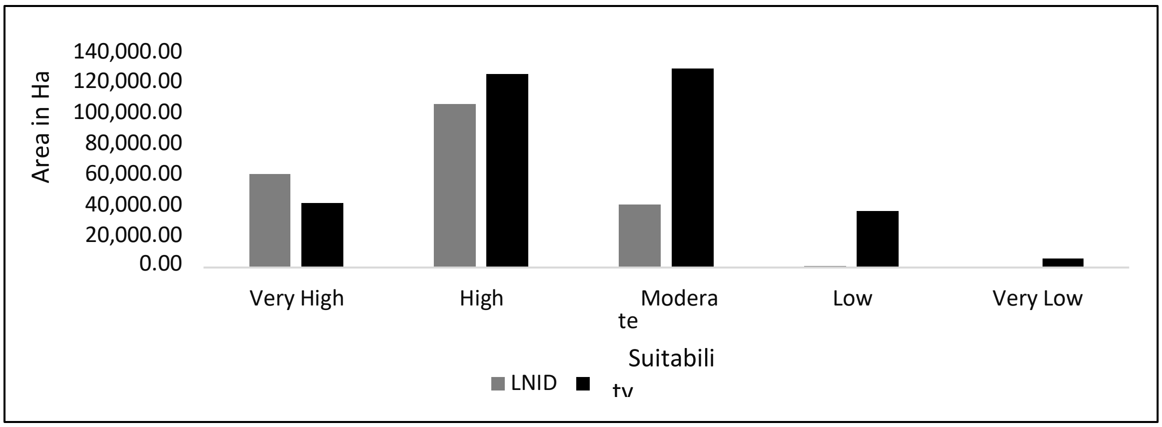


Figure 26: Location wise Suitable Area for Solar Plant using PCA Technique

It can be analyzed from the above figure that the St. Mary is better for solar plants in terms of high and moderate suitable area.

Table 12: Percentage Distribution of Area of Two regions LNID and St. Mary for Wind Turbines

Suitability Level of Wind Turbines (PCA)	**LNID (%)**	**St. Mary (%)**
Very High	10.22	4.87
High	39.82	40.66
Moderate	20.83	55.61
Low	3.14	18.76
Very Low	0.00	1.07

St. Mary has a larger percentage of land classified as 'Moderate' and 'Low' suitability for wind turbines compared to LNID, suggesting it might be less favorable for large-scale wind energy development.

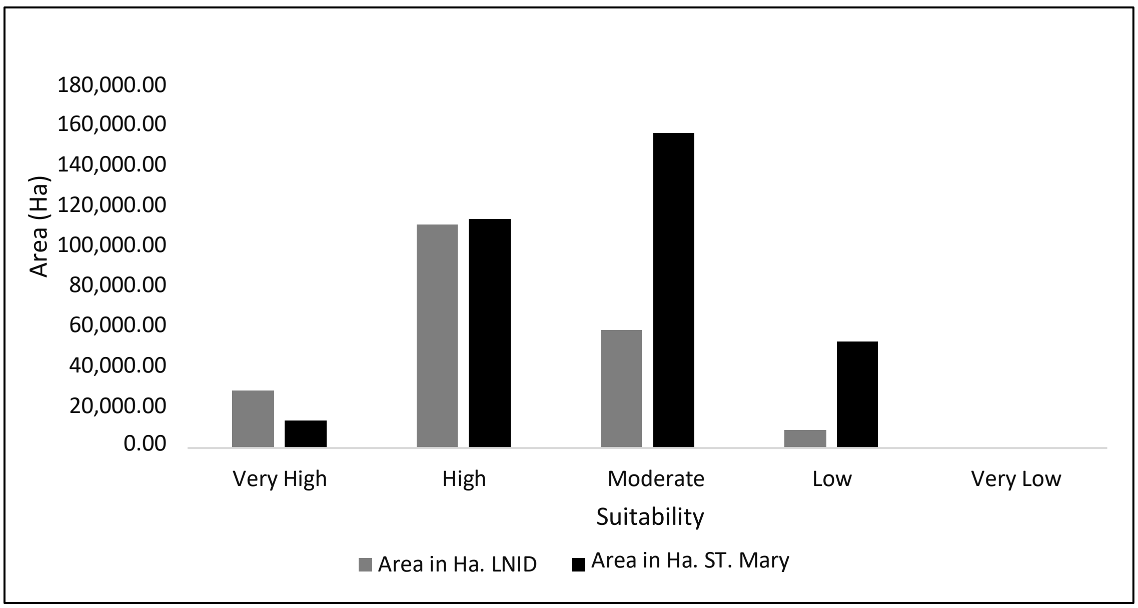


Figure 27: Location wise Suitable Area for Wind Turbines using PCA

5.3.1.2 Using FAHP Techniques

Table 13 presents the percentage distribution of area for two regions, LNID and St. Mary, based on their suitability levels for solar and wind energy development.

Compared to LNID, St. Mary has a significantly larger percentage of land classified as 'Low' and 'Very Low' suitability for solar plants. Conversely, LNID has a considerably higher proportion of land categorized as 'High' suitability.

Table 13: Percentage Area of Distribution for Two Regions LNID and St. Mary for Solar Plant.

Suitability Level of Solar Plant (FAHP)	**LNID (%)**	**St. Mary (%)**
Very High	0.16	0.00
High	23.23	21.59
Moderate	0.01	0.04
Low	50.80	95.58
Very Low	39.79	78.79

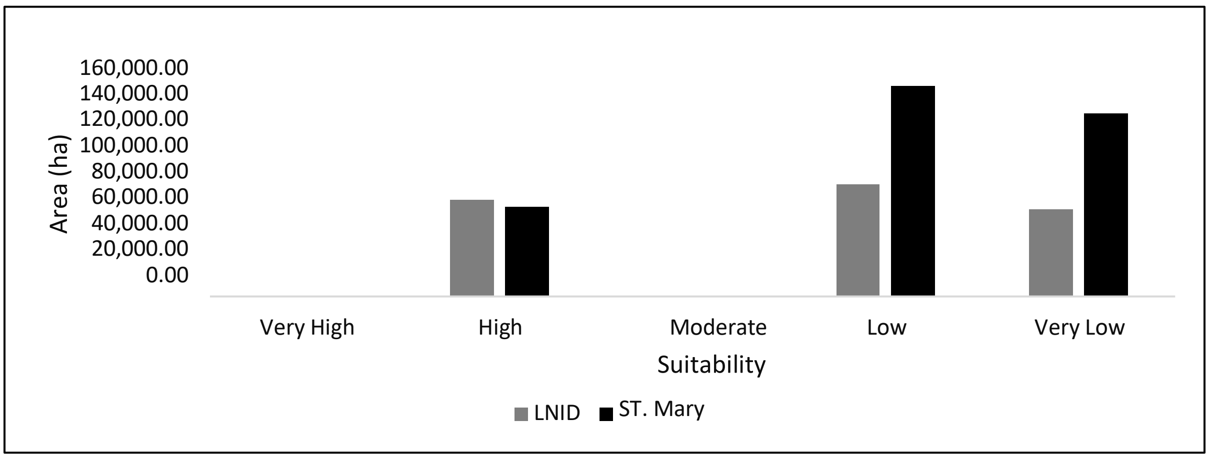


Figure 28: Location wise Suitable Area for Solar Plant using FAHP Technique

Table 14: Percentage Area of Distribution for Two Regions LNID and St. Mary for Wind Plant

Suitability Level of Wind Turbines (FAHP)	**LNID (%)**	**St. Mary (%)**
Very High	0.04	0.00
High	21.94	40.72
Moderate	0.02	0.01
Low	16.82	32.59
Very Low	16.82	32.59

.

St. Mary has a larger percentage of land classified as 'Low' and 'Very Low' suitability for wind turbines compared to LNID. However, LNID also has a significant portion of land in these categories. Both locations might have limited suitability for large- scale wind energy development based on FAHP.

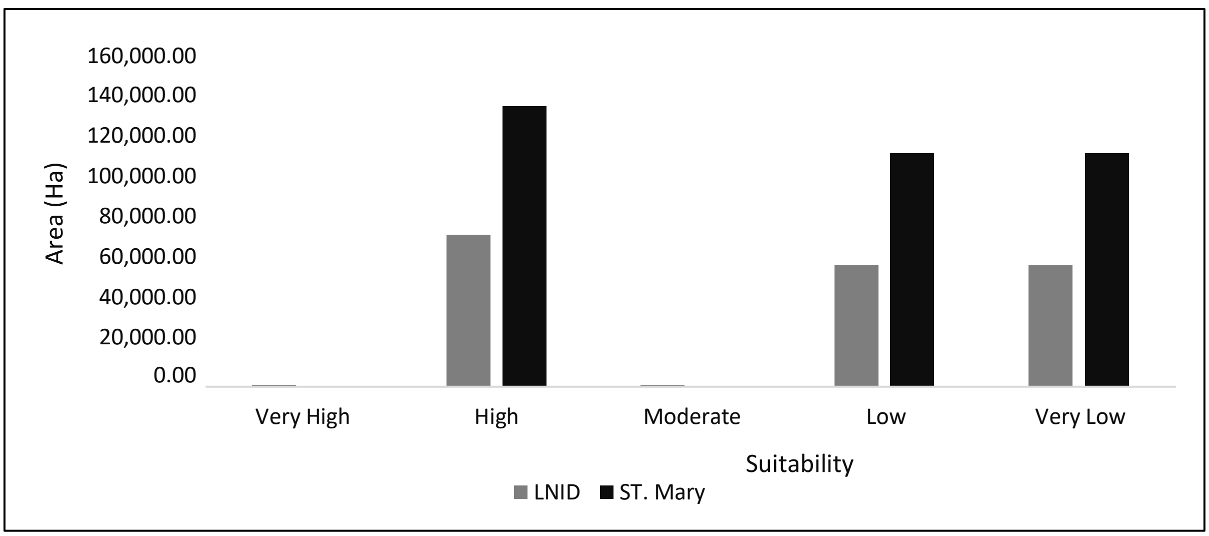


Figure 29: Location wise Suitable Area for Wind Turbines using FAHP Techniques

5.3.2 Common Suitable Region

Based on the results of our analysis, both the LNID and St. Mary's irrigation district in Alberta, Canada, exhibit considerable potential for solar and wind energy development. However, our findings indicate that LNID offers a greater proportion of suitable areas for renewable energy projects than St. Mary. The suitability analysis revealed that LNID has higher percentages of suitable areas for both solar and wind energy development, as shown in Table 11.

The map representations further illustrate the distribution of suitable areas for solar and wind turbines in both regions. These findings underscore the importance of strategic land use and resource assessment processes in identifying optimal sites for renewable energy integration into regional economies, contributing to sustainable development and environmental conservation efforts.

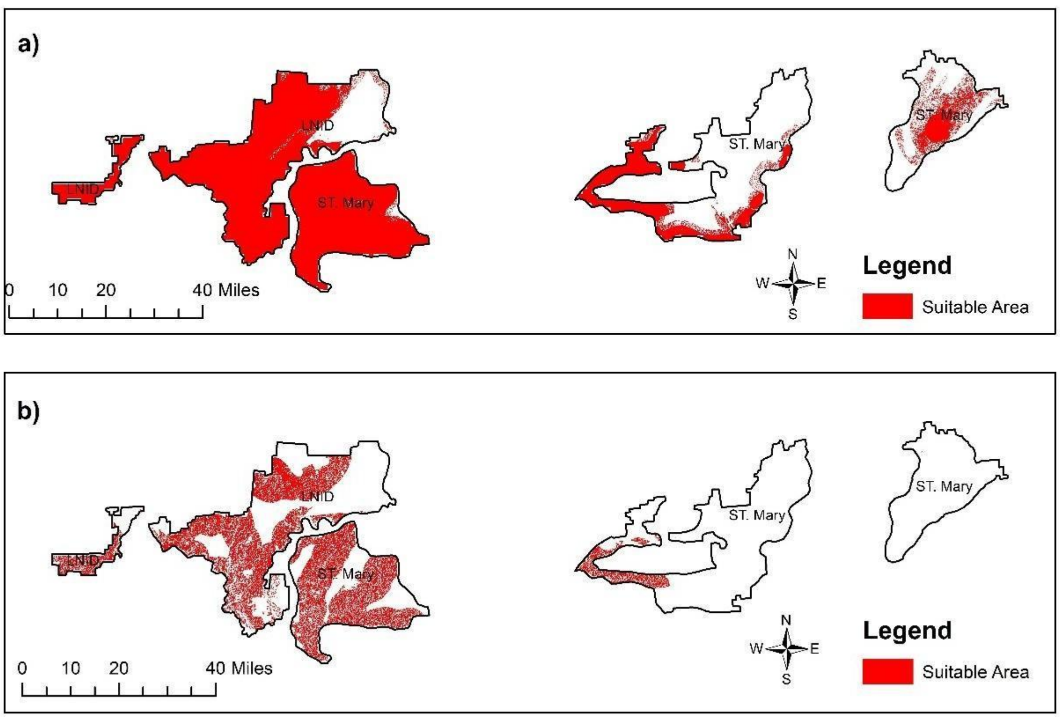


Figure 30 Common suitable region for both solar and wind turbines: **a)** Common suitable region by PCA technique; **b)** Common suitable region by Fuzzy overlay technique

5.4 Findings and Conclusion

Research findings indicate that, in comparison to the St. Mary River Irrigation District (SMRID), the Lethbridge Northern Irrigation District (LNID) possesses a greater amount of land suitable for wind and solar energy development. Tables 10 and 11 depict the percentage distribution of optimal sites for wind turbines in St. Mary and solar plants in LNID. The major component research indicates that LNID surpasses St. Mary for the proportion of land deemed very or highly suitable for solar and wind power. St. Mary underperformed in comparison to LNID. Furthermore, FAHP determined that LNID had a greater area conducive to solar and wind energy compared to St. Mary. This research offered insights into potential methods for integrating renewable energy into the economies of the LNID and St. Mary regions in Canada using strategic land use and resource assessment techniques. The research findings can assist stakeholders, lawmakers, and energy planners in determining optimal sites within the study region for the implementation of renewable energy projects. This study identifies optimal locations for the development of solar and wind energy, therefore facilitating the integration of renewable energy sources and the sustainable growth of the area economy.

Chapter 6: Sustainable Crop Irrigation with Renewable Energy: A Case Study of Lethbridge County, Alberta, Canada

6.1 Introduction and background

Mohammad Adnan Aftab, a PhD Candidate has drafted the manuscript. Dr. Dan Johnson, Dr. Paul Hazendonk, and Dr. Locke Spencer have supervised and reviewed the manuscript. Dr James Byrne assisted in acquiring the grants for this valuable research. This manuscript has been sent to the journal and is currently under review.

Rapid climate changes, exponential population growth, and urbanization are some of the major challenges nations face in the efficient management of water resources for crop irrigation. Scientists in this century consider water scarcity the second biggest issue after climate change (Shah et al., 2021). An increase in the gap between water supply and demand on a global scale is highly imminent in the upcoming years (Abdo et al., 2009; Panhwar et al., 2022). Almost 87% of water consumed directly helps in fulfilling approximately 40-45% of the world's food requirements (Taye et al., 2021). Similarly, crops play a vital role in the economy of Canada, i.e., 7% of Canada's GDP and 11% of jobs are related to the agriculture sector (Agriculture and Agri-Food Canada, 2021b; Windfeld & Lhermie, 2022). Of the 7% of Canada's GDP, Alberta's agriculture sector represents a significant share of 2.8% (*Government of Alberta*, 2024). Wheat and barley are the two major crops of the Alberta region, accounting for 28.4% and 52.2% of Canada's harvested crops, respectively (*Agriculture and Irrigation Annual Report - Open Government*, n.d.). In 2022, wheat and barley produced in Alberta were estimated at around 416 million bushels and 247.13 million bushels, respectively (*Government of Alberta*, 2024). Water usage for irrigation purposes in southern Alberta mainly relies on Bow, Oldman, and South Saskatchewan

River sub-basins (SSRB). Population and economic growth have significantly increased the pressure on these basins, which resulted in the closure of further water license allocations in 2006. This water scarcity has been further increased in recent years due to increases in temperature, greater evapotranspiration, and changes in the timing and amounts of precipitation due to sudden climate changes (Bennett & Harms, 2011).

Crop evapotranspiration, or Eto, is a crucial indicator of the hydrological cycle that must be considered when managing water resources in both rainfed and irrigated agriculture (Djaman et al., 2018). With the increase in Eto, the crop water requirement also increases in a linear trend to keep the quality of crops. The water requirement of a significant crop (ET_C) can be estimated by multiplying Et_O with the crop coefficient (kc). The Penman-Monteith equation is considered one of the most reliable sources for estimating crop water requirements. The United Nations Food and Agriculture Organization designed software, named CROPWAT, based on this method to calculate potential Eto using various parameters such as temperature, wind, and irradiance.

Lethbridge County is one of the major stakeholders in the agriculture sector of Alberta, and being a semi-arid area, it relies on the Oldman River for crop irrigation. Due to water reduction from the river basins, groundwater can play a supplementary role in fulfilling the remaining water demand of Lethbridge County. However, groundwater pumping on a large scale is an energy-intensive task.

Conventional energy resources are costlier and considered one of the major reasons for abrupt climate changes. Renewable energy resources such as PV, wind, biomass, etc. are needed to shift from conventional power sources to clean and environment- friendly sources for groundwater pumping (Michelsen & Madlener, 2016). Solar photovoltaic systems are considered one of the most economical energy sources due to the decreasing cost over time. Dependency on solar photovoltaic systems has significantly increased all over the globe to shift the reliance from conventional to renewable energy resources (Jamil & Pearce, 2022). Another source of renewable energy, wind power, has surpassed all other forms of renewable energy to become Canada's primary source of clean energy, according to the Canadian Wind Energy Association. The National Energy Board forecasts that wind power may represent 27% of the country's new energy production from 2017 to 2040. Wind power has lately become the second largest new energy source, behind solar power, having garnered $1.2 billion in private investment for five new wind generation facilities in Alberta (Martins Godinho et al., 2023). These renewable and clean energy sources are vital in providing cost-effective and environment-friendly energy for groundwater pumping.

M. J. Khan et al.(n.d.) presented the water requirement of various crops in Peshawar, Pakistan, using CROPWAT. Wheat, sorghum, and millet crops were considered for the study which revealed that irrigation water is required from quality crops, as rainwater is not enough per the area's calculated crop water requirement.

Similarly, Z. A. Khan et al. 2021) presenteda comprehensive analysis of the potential of wind and solar energy resources-based hybrid systems for water pumping required for irrigation of the agriculture sector in Sudan. Different combinations of renewables were considered when designing a hybrid system at 1 different locations in Sudan using soil and weather data. The outcome revealed that optimal hybrid system selection mainly relies on the cost and availability of renewable resources on specific sites.

Alghassab et al. (2022) stated that the reduction of rainfall due to climate change severely affects crop production globally. To compensate for these changes and ensure food security, the motorization of irrigation decreases droughts' impact. Renewable hybrid systems have been considered for providing energy requirements for irrigation in Shaqra, Saudi Arabia. Crop water requirements for three crops have been calculated using CROPWAT and Homer Pro to design the hybrid system and perform its techno-economic analysis to understand system behavior. The result showed that the hybridization of PV systems and wind turbine setup could help in ensuring the required energy for irrigation purposes in the vicinity.

The authors discussed renewable energy and irrigation nexus concerning various parameters in northwestern India (Singh et al., 2022). The study found that 72% of the tube wells are electrically powered and consume almost 40% of the total electric power in the area. This has significantly increased the irrigated area by 36% due to low losses and economic energy factors. Due to the dependency on renewable energies, the area's yield is more economical compared to the yield of the Uttar Pradesh, Bihar, and Gujarat states. Solangi et al. (2022) determined that agriculture consumes almost 70% of the water available globally, and its half share is being wasted in processes that require efficient water management to ensure food security. The study was carried out to analyze the irrigation water requirement for specific crops in the Shaheed Benazirabad district of Sindh. CROPWAT software designed by FAO has been used to meet the water requirement of the area crops. Outcomes revealed that using efficient tools, such as CROPWAT, CLIMWAT, etc., improves inefficient irrigation, thus increasing the crops' productivity.

Likewise, in Jangre et al. (2022), the authors presented a study on the assessment of crop water requirements for maize to manage the irrigation setup effectively. CROPWAT was used in the study to analyze the water requirement for the specific crop using 16 years of available data for various parameters associated with water requirement calculations. The output of the research revealed the daily, monthly, and annual requirements of water at different stages of growth to avail high-quality crops. The authors worked on the evaluation of suitable solutions to reduce agricultural green water scarcity due to rapid climatic changes (He & Rosa, 2023). The study mentioned that rain-fed agriculture incorporates almost 60% of food production on a global scale, which is being greatly affected by current environmental pollution and its adverse effects in the form of low ratios of rain and even droughts. In the case of poor availability of rainwater, green water has been accessed. The study revealed that green water adaptation strategies have the potential to reduce food production loss for up to 100 million people.

The current study aims to tackle the issue of surface water shortage in Lethbridge County, Alberta, due to the little published literature on using renewable energy sources for agricultural water needs. The CROPWAT project, developed by the Food and Agriculture Organization of the United Nations, was initially employed to assess the water needs of barley and wheat, two principal crops cultivated in the study area. The energy required to extract groundwater has been determined by empirical estimates derived from agricultural water demand. A hybrid energy system utilizing renewable resources was developed using Homer Pro software. The system was evaluated from both a technical and financial perspective to satisfy the energy demands for agricultural irrigation utilizing groundwater pumps. Results revealed that hybrid systems are efficient and viable solutions in fulfilling the energy requirements for irrigation.

6.2 System Design and Working Methodology

The area selected for the proposed study is an agricultural farm in Lethbridge County of Alberta, Canada having coordinates of 49.6956° N, 112.8451° W. The county is approximately 120 square kilometers and is situated at an elevation of 910 metres above sea level. Figure 31 illustrates the county's geographical location on the Alberta map, including its adjacent regions.

The primary objective of energy system design is to ascertain the load requirements of the system. A hybrid renewable energy system will underpin the groundwater-pumped irrigation mechanism to be built in a research project in Lethbridge County, Alberta. Figure 32 depicts the schematic of the proposed system. Initially, the study determined the water requirements for the primary crops cultivated in the region, including wheat and barley. The energy needed for crop irrigation is directly proportional to the water they need. Subsequently, the power required to operate the pumps that draw groundwater may be assessed by considering the extent of irrigated land in the area and the depth of the water table.

Figure 33 shows that being a semi-arid area, Lethbridge County has had the driest to below-normal precipitation accumulation in the last ten years on average. This fact has increased the requirement for reliance on groundwater pumping to preserve surface water. Considering the area's abundant renewable resources, high solar and wind potential can be analyzed from the Alberta map, as shown in Figure 34.

Figure 31: Alberta Map Overview Highlighting Lethbridge Location *(GISGeography, 2021)*

The outcome of the proposed work is to find the most economical solution for fulfilling the energy demand of groundwater pumping for the irrigation of crops as calculated by the crop water requirement. For this purpose, net present cost has been considered as the objective function to optimize the designed renewable resources-based energy system efficiently. Figure 35 explains the working methodology in the flowchart adopted to achieve the goal of the study.

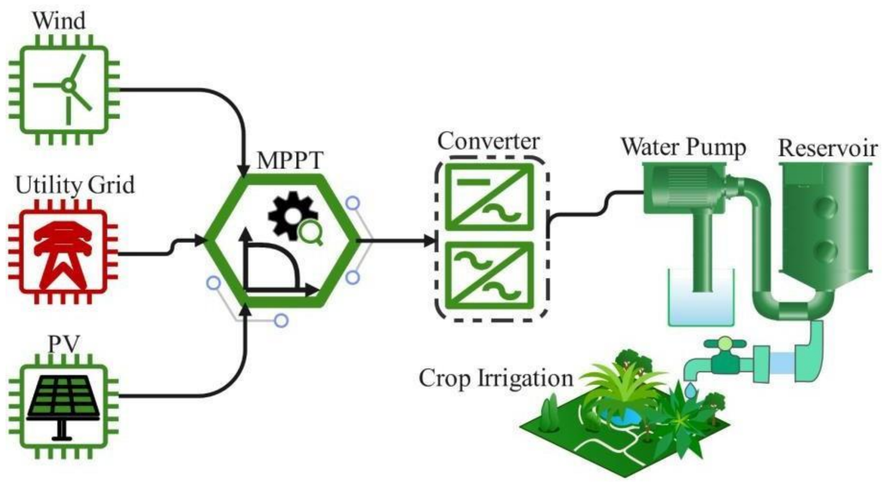


Figure 32: Block Diagram of the Proposed System

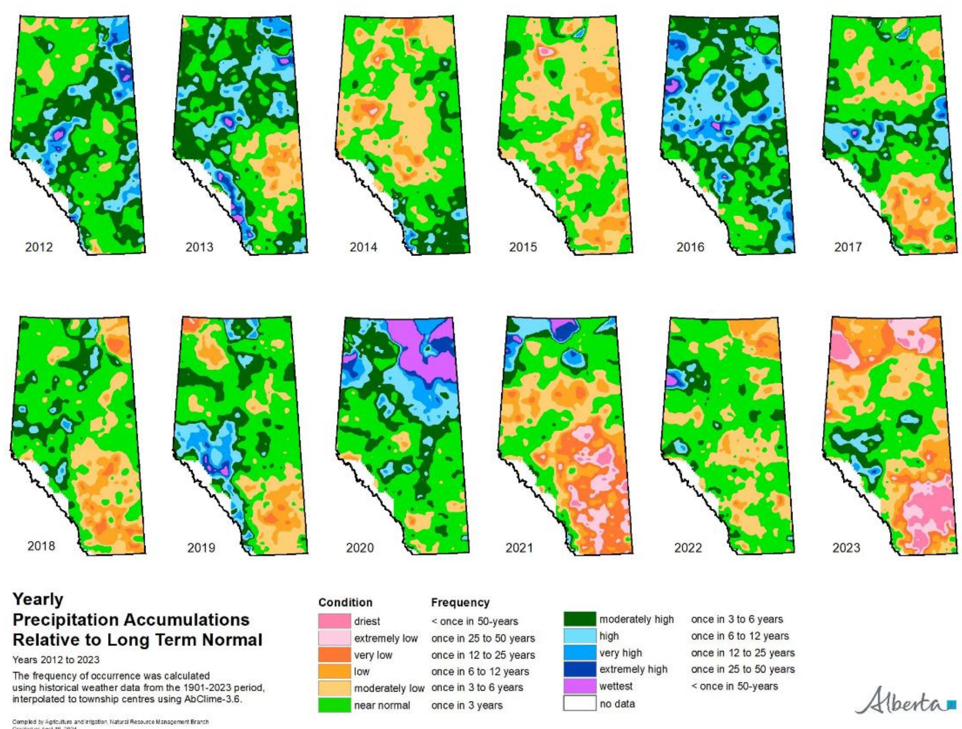
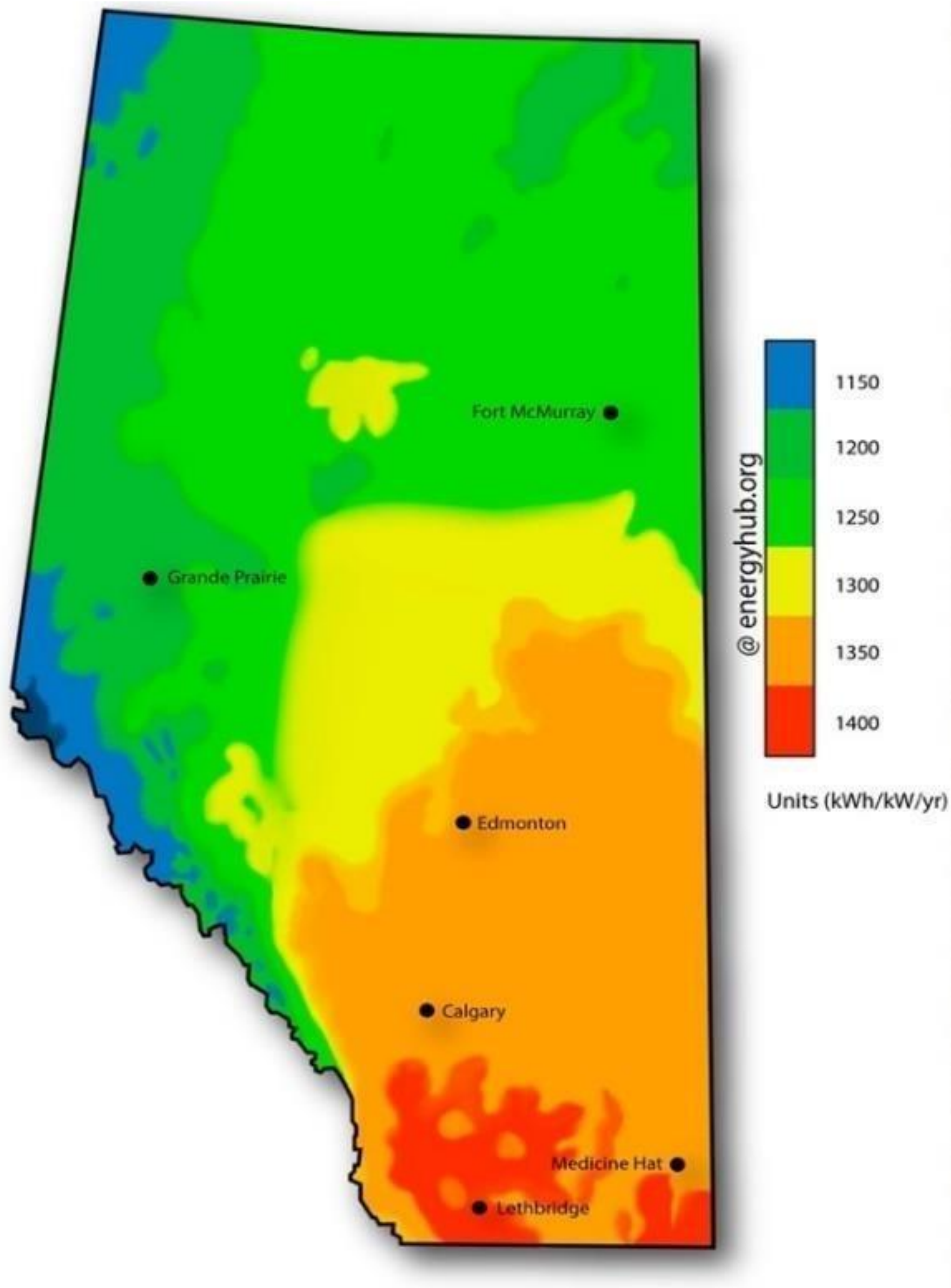
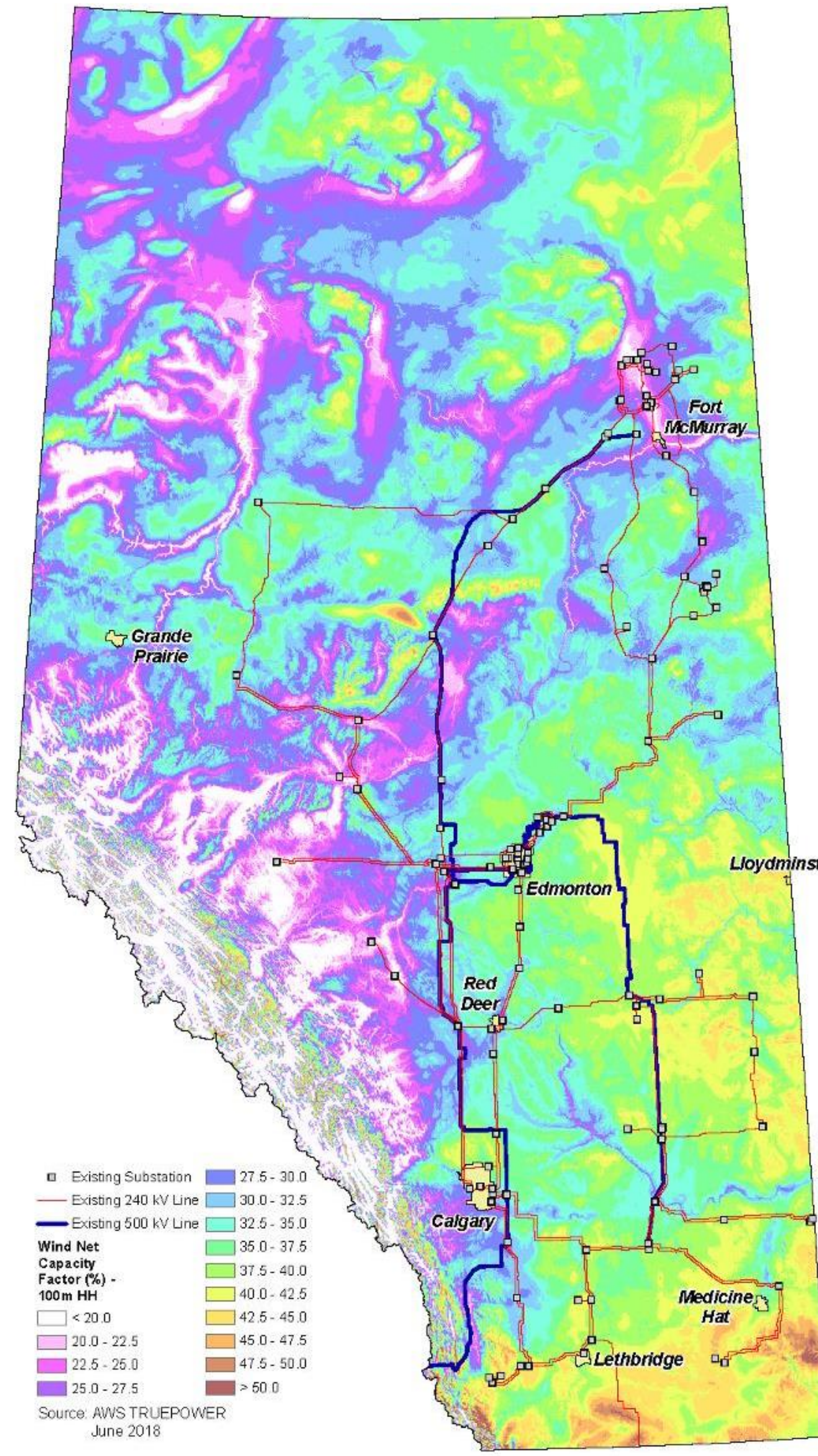


Figure 33: Precipitation Accumulation in Alberta (County, 2024)

As Figure 34 shows, Lethbridge ranked among the areas with the highest solar irradiance and wind speed potential in the region.



(a)



(b)

Figure 34: Alberta Map highlighting (a) Solar Irradiance and (b) Wind Intensity in Region *(Wilson, 2020)*

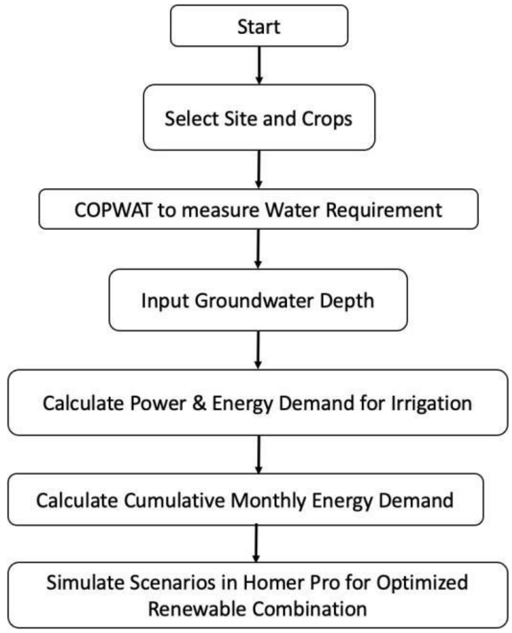


Figure 35: Working Flowchart of the Proposed Study

6.2.1 Crop Water Requirement Calculation Using CROPWAT

The United Nations Food and Agriculture Organization designed the CROPWAT software to calculate the crop water requirement. It works on the principle of calculating ET_O using the Penman-Monteith model (FAO Chapter 4 1998) with the help of several parameters such as type of crops, soil data, rain and temperature data, etc. Based on these several factors, crop water requirement from planting till harvest time can be calculated for specific crops using Equation 6-1.

$$ET_C = k_c * ET_O \qquad (6\text{-}1)$$

Where ET_O and k_c represent reference evapotranspiration and crop coefficient respectively. ET_O can be calculated using the Penman-Monteith equation, as shown in Equation 6-2.

$$ET_O = \frac{0.408\Delta(Rn-G)+\frac{900}{T+273}u2(es-ea)}{\Delta+\gamma(1+0.3442)} \qquad (6\text{-}2)$$

In the above equation, R_n and G represent net radiation, and soil heat flux density in MJ/m^2/day, T, $e_s - e_a$ represents daily air temperature and vapor pressure deficit of air in kPa, respectively. Whereas Δ & γ represents the slope of vapor pressure and psychometric constant.

Crop water requirement refers to the water required to maintain the moisture in the soil lost to evapotranspiration. However, while calculating the crop water requirement, all water sources, such as rainfall or deep seepage, need to be considered (Z. A. Khan et al., 2021). Considering the different sources, the net irrigation water requirement can be calculated using the equation below.

$$NIWR = ET_O - R_{eff} \qquad (6\text{-}3)$$

As stated above, wheat (spring and winter wheat) and barley crops have been selected for the proposed study in Lethbridge County of Alberta, Canada. The area selected for crop water requirement calculations is 1000 acres (405 hectares).

Lethbridge Airport weather station has been used to acquire the required weather data. Considered data from the weather station can be seen in Table 15.

Table 15: Climate Data from Lethbridge Airport Weather Station for the Proposed Study *(*Historical Climate Data - Climate - Environment and Climate Change Canada, *n.d.)*

Month	**Min Temp**	**Max Temp**	**Humidity**	**Wind**	**Sun**	**Rad**	**ETo**
Units	oC	oC	%	Km/day	Hours	MJ/m^2/day	Mm/day
January	-10.5	0.5	0	11	8.7	7.2	0.12
February	-8.3	2.8	0	11	10.1	11.2	0.17
March	-4.4	7.2	0	10	12.0	17.4	0.74
April	0.5	13.9	0	10	13.8	24.1	1.86
May	5.5	18.9	0	10	15.4	29.2	2.95
June	10.0	22.8	0	9	16.2	31.4	3.53
July	12.2	26.1	0	8	15.8	30.2	4.04
August	11.1	26.1	10	8	14.3	25.7	2.56
September	7.2	21.1	0	9	12.5	19.4	1.37
October	1.6	13.8	0	10	10.7	12.9	0.39
November	-4.4	5.6	0	11	9.1	8.0	0.15
December	-9.4	0.6	0	12	8.2	6.0	0.13
Average	0.9	13.3	1	10	12.2	18.6	1.50

The above table shows that the temperature stays between -10.5ºC and 26.1ºC. Furthermore, precipitation is another important factor in calculating the crop water requirement. Monthly precipitation data can be seen in Table 16.

Table 16: Precipitation Data for the Proposed Study

Month	**Max Rain**	**Min Rain**
Units	mm/month	mm/month
January	2.5	2.5
February	0.0	0.0
March	5.1	5.1
April	17.8	17.3
May	45.7	42.4
June	61.0	55.0
July	30.5	29.0
August	30.5	29.0
September	27.9	26.7
October	12.7	12.4
November	2.5	2.5
December	2.5	2.5
Average	238.7	224.3

As can be seen, the total rainfall in the area is calculated as 238.7 mm, which is quite low, being a semi-arid area requiring aridity. Irrigation, as a secondary source of water, has been considered. However, the closure of water license issuing for Oldman River, due to limited supply reservoirs since 2006, meant groundwater pumping has been recommended in the proposed study. Crop water requirement for wheat and barley has been made using CROPWAT, as shown in Tables 17 and 18. This data was acquired by incorporating the climatic and rain data and other parameters, such as soil data from study area, into the CROPWAT software.

Table 17: Crop Water Requirement for Wheat

Month	**Decade**	**Stage**	**Kc**	**ETc**	**ETc**	**Eff Rain**	**Irr. Req.**
Units			coeff	mm/day	mm	mm	mm/crop season
November	2	Init	0.40	0.06	0.6	0.4	0.2
November	3	Init	0.40	0.06	0.6	0.5	0.1
April	2	Deve	0.93	1.73	17.3	5.2	12.1
April	3	Deve	1.02	2.27	22.7	8.2	14.5
June	2	Mid	1.10	3.89	38.9	20.1	18.8
June	3	Mid	1.10	4.08	40.8	16.7	24.1
July	2	Late	1.09	4.63	46.3	8.5	37.8
July	3	Late	0.83	3.05	33.6	8.9	24.7
Total					447.1	196.9	268.3

Table 18: Crop Water Requirement for Barley

Month	**Decade**	**Stage**	**Kc**	**ETc**	**ETc**	**Eff Rain**	**Irr. Req.**
Units			coeff	mm/day	mm	mm	Mm/crop season
May	2	Init	0.30	0.88	0.8	13.2	0.0
June	1	Deve	0.64	2.13	21.3	18.1	3.1
June	2	Deve	0.96	3.39	33.9	20.1	13.7
July	2	Mid	1.10	4.68	46.8	8.5	38.3
July	3	Mid	1.10	4.06	44.7	8.9	35.8
August	2	Late	0.92	2.35	23.5	9.7	13.8
August	3	Late	0.62	1.34	14.7	9.4	5.3
Total					**328.2**	**149.6**	**190.5**

The crop water requirement for both crops has been found to be 268.3 mm/dec and 190.5 mm/dec, respectively. It can be assessed from Tables 17 and 18 that the crop water requirement for both crops is significantly higher than the available rainwater.

The obtained data from the software depicts that crops with longer period of growth need a high amount of irrigation, and the elevated water requirement during the summer shows the need for a supplemental water source beyond rainfall due to the arid conditions .[1.1] Furthermore, water evapotranspiration and a decrease in soil moisture are some of the major reasons behind the increased water requirement during these dry months. A better understanding of irrigation schedules and proper planning ensures efficient irrigation management by controlling the timing and volume of irrigation. For this purpose, the total irrigation requirement and irrigation schedule for both crops can be seen in Tables 19, 20, 21, and 22.

Table 19: Total Irrigation Requirement for Wheat

Parameters	**Value**
Total Gross Irrigation (mm)	465.1
Total Net Irrigation (mm)	325.6
Actual Water Use by Crop (mm)	446.4
Efficiency of Irrigation Schedule	100%
Total Rainfall (mm)	208.8
Effective Rainfall (mm)	208.8
Efficiency Rain	100%
Moist Deficit at Harvest (mm)	62
Actual Irrigation Requirement (mm)	237.6

Table 20: Irrigation Schedule for Wheat

Date	**19 April**	**11 July**	**08 September**
Day	220	303	End
Stage	Dev	Mid	End
Rainfall (mm)	0.0	0.0	0.0
Ks (fraction)	1.00	1.00	1.00
ETa (%)	100	100	0.0
Depletion (%)	55	56	21
Net Irrigation (mm)	157.6	168.0	-
Deficit (mm)	0.0	0.0	-
Loss (mm)	0.0	0.0	-
Gross Irrigation (mm)	225.1	240.0	-
Flow (litre/sec/ha)	0.12	0.33	-

Table 21: Total Irrigation Requirement for Wheat

Parameters	**Value**
Total Gross Irrigation (mm)	351.4
Total Net Irrigation (mm)	246.0
Actual Water Use by Crop (mm)	327.6
Efficiency of Irrigation Schedule	100%
Total Rainfall (mm)	165.0
Effective Rainfall (mm)	155.8
Efficiency Rain	94.4%
Moist Deficit at Harvest (mm)	35.7
Actual Irrigation Requirement (mm)	171.7

Table 22: Irrigation Schedule for Barley

Date	**26 June**	**31 July**	**08 September**
Day	46	81	End
Stage	Mid	Mid	End
Rainfall (mm)	0.0	0.0	0.0
Ks (fraction)	1.00	1.00	1.00
ETa (%)	100	100	100
Depletion (%)	57	55	16
Net Irrigation (mm)	124.6	121.4	-
Deficit (mm)	0.0	0.0	0.0
Loss (mm)	0.0	0.0	0.0
Gross Irrigation (mm)	178.1	173.4	-
Flow (litre/sec/ha)	0.45	0.57	-

The above tables show a detailed analysis of the total gross and total net irrigation requirement of crops before and after the consideration of effective rainfall, i.e., 237.6 mm and 171.7 mm for wheat and barley, respectively. The irrigation supply scheme for the annual crop season comprising these two crops can be seen in Table 23.

Table 23: Irrigation Supply Scheme for Complete Season

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Precipitation Deficit												
1. Wheat	0.0	2.5	11.6	35.0	56.6	61.5	94.9	6.0	0.0	0.0	0.3	0.0
2. Barley	0.0	0.0	0.0	0.0	0.0	39.9	104.8	42.1	0.0	0.0	0.0	0.0
Net Scheme Irr. Req.												
in mm/day	0.0	0.0	0.2	0.5	0.8	1.7	3.2	0.8	0.0	0.0	0.0	0.0
in mm/month	0.0	1.1	5.2	15.7	25.5	49.6	100.3	25.9	0.0	0.0	0.1	0.0
in l/s/h	0.00	0.00	0.02	0.06	0.10	0.19	0.37	0.10	0.00	0.00	0.00	0.00
Irrigated Area (% of total area)	0.0	45.0	45.0	45.0	45.0	100.0	100.0	100.0	0.0	0.0	45.0	0.0
Irrigation Required for Actual Area (l/s/h)	0.00	0.01	0.04	0.13	0.21	0.19	0.37	0.10	0.00	0.00	0.00	0.00

Irrigation water requirements for both crops were observed for the entire season. The finding reveals that crops having crop cycles across the year need high irrigation capacity. Furthermore, crops having a hot summer season in their cycle require more irrigation to fulfil their water demand as well as maintain the moisture of the soil.

6.1.2 Energy Calculations to Meet Crop Water Requirement

Based on the calculations of crop water requirements for the selected crops using CROPWAT software in the above section, energy calculations have been made to design the renewable energy hybrid power system for groundwater pumping and fulfilling the crop requirements. Considering the irrigation requirement and the depth of the water table at the site, waterpower has been calculated using the equation below.

$$W_P = \frac{Net\ Irr.Required\ (mm) * groundwater\ depth\ (m)}{76} \tag{6-4}$$

Here, W_P represents waterpower in hp. Groundwater depth has been considered 31m to calculate waterpower on site, i.e., 168 hp for selected land area of 1000 acres . From this waterpower and pump efficiency (60%), we can calculate the break horsepower using Equation 6-5.

$$\eta_P = \frac{Wp}{BP} \tag{6-5}$$

Here, η_P represents pump efficiency and B_P represents brake horsepower. Using this formulation, brake horsepower (280 hp) has been calculated as necessary to evaluate the motor input power to extract groundwater. Using Equation 6-6, motor input power has been calculated as follows:

$$\eta_m = \frac{Bp}{IP} \tag{6-6}$$

In this equation, η_m represents motor efficiency, and I_P represents motor input power, respectively. By considering the motor efficiency of 65%, motor input power has been calculated, i.e., 431 hp. It has been evaluated from the above calculations that at least 325 kW input power is required by the motors to extract the same capacity of groundwater as required by the crops on 1000 acres for a complete season. With the limitations of motor power capacity, the land area can be further subdivided into different sections to irrigate the land efficiently.

6.3 Renewable Energy-Based Hybrid System Design using Homer Pro

Homer Pro software developed by the US National Renewable Energy Laboratory (NREL) has been utilized to design and analyze the techno-economic analysis of the renewable energy-based hybrid power system at the site to provide the required energy for the extraction of groundwater. The levelized cost of electricity and net present value are two of the major parameters, among many, to assess the most optimized and feasible hybrid scenario using Homer Pro (*HOMER's Calculations*, n.d.). Based on the calculations in the above section, and approximations of the fluctuating nature of the renewables, a modeled load along with different capacity components have been incorporated in the software and it provides best-optimized design based on various parameters such as LCOE, NPV, OPEX, CAPEX, and GHG emissions, etc. The main objective of this software is to evaluate the most efficient and optimized system design by combining the conventional and renewable energy resources available on-site (Ur Rashid et al., 2022). The potential site for the proposed hybrid energy system is a farm at Lethbridge County in Alberta, Canada, as can be seen in Figure 36.

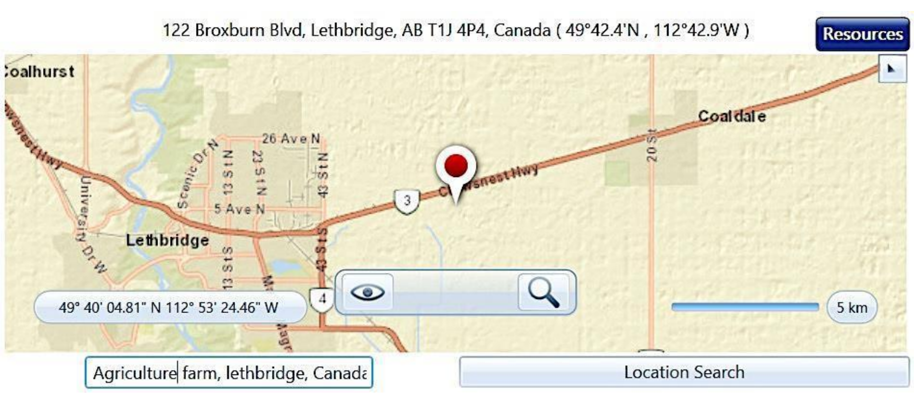


Figure 36: Site Selected for the Proposed Study

The proposed grid-tied hybrid system comprises a PV system with a capacity of 250kW and 100kW wind turbine systems, respectively. Similarly, as calculated in the above section, an AC load with a capacity of 325kW has been considered for the proposed system. The average monthly load profile can be seen in Figure 37.

Furthermore, the working flowchart of Homer Pro software can be seen in Figure 38.

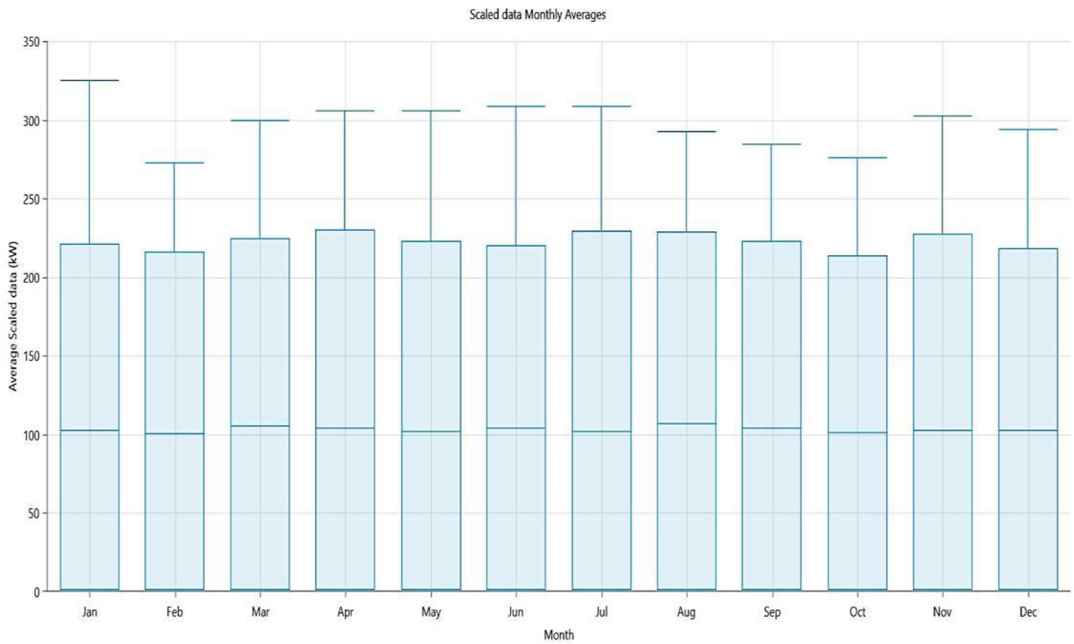


Figure 37: Average Monthly Load Profile

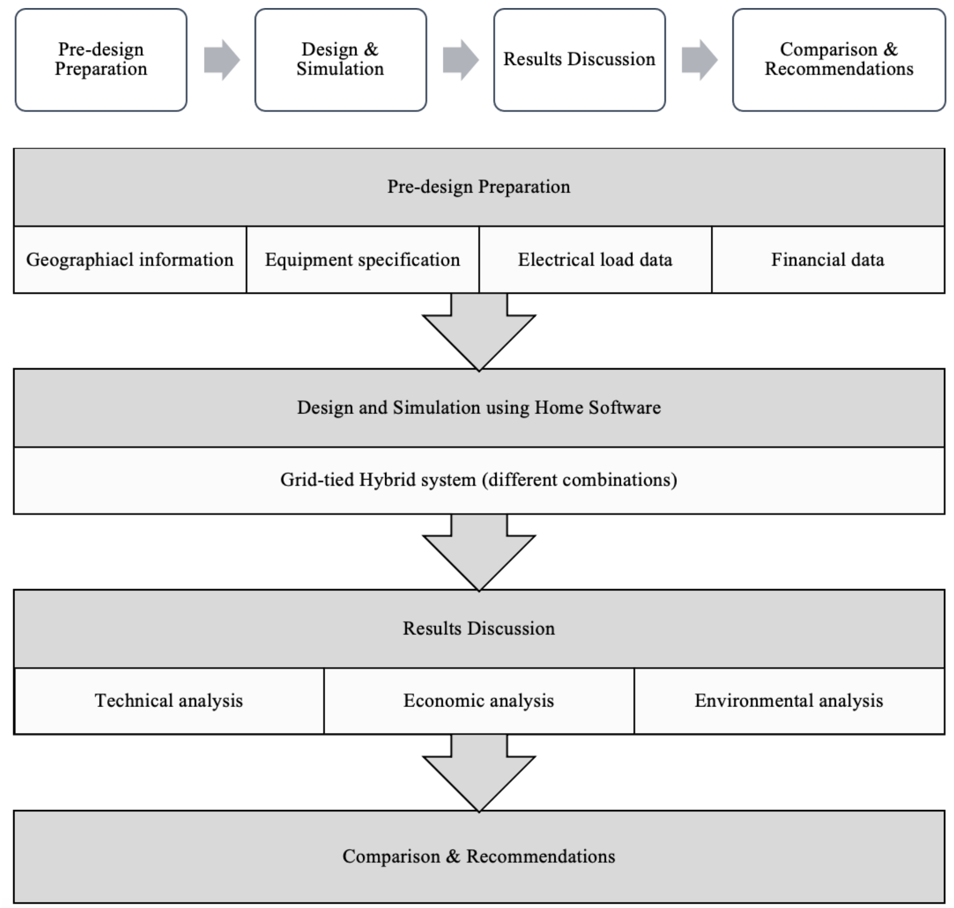


Figure 38: Homer Pro Simulation Flowchart

6.3.1 Wind Speed Data

Lethbridge County, Alberta, Canada, experiences strong winds throughout the year. The county's wind speed data was collected from the NASA Prediction of Worldwide Energy Sources (*NASA POWER | Prediction Of Worldwide Energy Resources*, n.d.). The average wind speed in the area was 6.63 m/s at a 32 m wind turbine hub height.

Figure 39: Monthly Average Wind Speed in Lethbridge, Alberta

6.3.2 Solar GHI Data

Like wind speed data, typical locations in Alberta have more than 2500 hours of sun yearly, exceeding most other regions in Canada. The annual average radiation was estimated to be 3.65 kWh/m^2/day. The clearness index was found to be highest in July and lowest in December, and it can be analyzed in Figure 40.

Figure 40: Monthly Average Solar Irradiance at Selected Site of the Proposed Study

6.3.3 Mathematical Modelling

6.3.3.1 Solar Photovoltaic System

Using the Osterwald method for calculating the PV output power is the most authentic method, and the equation for this purpose can be seen below (Osterwald, 1986):

$$Ppv = N \times Am \times \eta g \times Gt \tag{6-7}$$

Here, Ppv, N, A_m, represents PV's generated power, number of solar PV modules, and area of the module, respectively. Similarly, η is the generator's efficiency, and G_t is the global radiation on the tilted plane (W/m^2).

6.3.3.2 Wind Turbine System

Wind turbine output power can be calculated using equation 8 as follows:

$$Power\ (P) = \frac{1}{2} \times \rho \times A \times V^3 \qquad (6\text{-}8)$$

In this equation, P represents power generated from WT in kW, v denotes the wind speed (m/s), whereas ρ represents the density of the air (kg/m^3), and A is the cross-sectional area of the wind in m^2.

6.3.3.3 Performance Factors for Techno-economic Analysis

Various parameters, such as LCOE, NPV, CAPEX, OPEX, and GHG emissions, play a fundamental role in techno-economic analysis to determine the most optimized and feasible hybrid renewable systems.

6.3.3.3.1 Levelized Cost of Electricity

The LCOE is the average cost per kilowatt-hour of electrical energy a specific system produces. LCOE is determined by the division of total annualized cost by the sum of $L_{primeAC}$ and $L_{primeDC}$ from the equation below in HOMER

$$LCOE = \frac{Total\ Annualized\ Cost}{L_{PrimeAC} + L_{PrimeDC}} \qquad (6\text{-}9)$$

In this equation, $L_{primeAC}$ represents the alternating current primary load, whereas $L_{primeDC}$ represents the direct current main load.

6.3.3.3.2 Net Present Value

The current total of all the expenditures incurred by the hybrid system during its specified useful life, minus the salvage value over that useful life, is its net present value. Costs to be considered in NPV are capital, replacement, operating, and maintenance costs as shown in Equation 6-10.

$$NPC = \sum C_{Capital} + C_{Replace} + C_{Maintenance} - C_{Salvage} \qquad (6\text{-}10)$$

In the above equation, Ccapital denotes the initial investment, Creplace is the cost of replacement, $C_{Maintenance}$ Costs upkeep, and $C_{salvage}$ denotes the cost of salvage.

6.3.3.3.3 Total Annualized Cost

The total value occurs throughout the project's expected timeframe. This cost also provides the net present value that was connected to the component cash flow order. Using HOMER Pro software, the capital recovery factor is multiplied after the entire annualized cost has been determined using NPC.

6.3.4 Grid-tied PV-Wind Hybrid Power System

As discussed, grid-tied PV-WT systems were considered while proposing the optimal solution for the site. In this configuration, the power generation system's optimization was carried out using a combination of PV and wind turbine systems to provide renewable and environment-friendly energy, as shown in Figure 41.

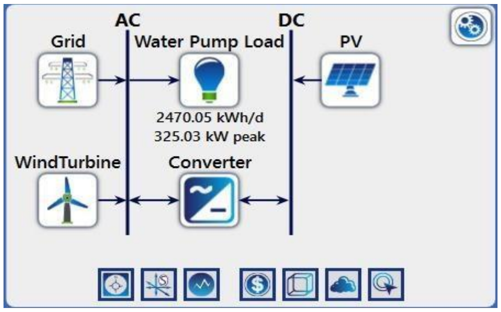


Figure 41: Schematic Overview of Grid-connected

6.4 Results and Discussion

6.4.1 Techno-economic Analysis and Comparison of System Configurations

The performance of the proposed concept has been assessed for various configurations of hybrid systems utilizing renewable energy. We evaluated the outcomes of these possible combinations against energy production from a utility grid-only system, considering many critical factors to determine techno-economic viability and environmental sustainability. Table 24 indicates that techno-economic analysis and greenhouse gas emissions consider all potential system configurations.

Table 24: Techno-economic Comparison of Various Hybrid Combinations of Proposed System

Parameter	**Unit**	**National Utility Grid**	**Hybrid (PV-Grid)**	**Hybrid (WT-Grid)**	**Hybrid (PV-WT-Grid)**
LCOE	CAD/kWh	0.320	0.231	0.204	0.128
Net Present Value (NPV)	CAD (Million)	3.73	2.82	2.55	1.82
Capital Cost	CAD (Million)	-	0.205	0.216	0.422
Replacement Cost	CAD	-	9,843	34,542	44,385
Maintenance Cost	CAD (Million)	3.73	2.61	2.31	1.38
Salvage Value	CAD	-	-1,852	-19,467	-21,319
IRR	%	-	42.2	50.5	43
ROI	%	-	37.9	46	39
Payback Period	Yrs	-	2.63	2.17	2.3
Renewable Fraction	%	0.00	35.2	40	65.4
Energy Purchased	kWh	901,568	631,072	579,092	398,176
Energy Sold	kWh	-	44,400	64,378	198,358
Total Emissions	kg/yr.	573,469	401,413	368,349	253,272

As can be seen in the above table, shifting to renewable resources from conventional pollutant resources has become critical from technical, economic, and environmental perspectives. Table 24 shows that the LCOE of hybrid systems is less than the rates/kWh provided by the conventional utility grid. The most optimized and efficient hybrid combination of conventional and renewable resources has been observed as the Grid-tied PV-WT system as it has a comparatively lower LCOE than the WT-Grid, PV-Grid, and Grid-only system i.e., 0.128 CAD/kWh in comparison to 0.204 CAD/kWh, 0.231 CAD/kWh and 0.320 CAD/kWh, respectively. Furthermore, renewable penetration in the hybrid combination of PV-WT is higher than in the remaining scenarios as well. Variability in the CAPEX and OPEX costs has been observed in between different combinations of hybrid systems. The CAPEX includes capital and replacement costs, while the OPEX includes maintenance and fuel costs.

In Table 24, the comparison of capital costs shows that the most optimized configuration (PV-WT-Grid) has the highest capital cost. This is due to the inclusion of the cost of equipment such as solar PV panels, wind turbines, and converters at the beginning of the project lifecycle. The capital cost in other configurations is comparatively less, as they are using one renewable source or none.

The above comparative study highlights the importance of the utility grid configuration from a CAPEX perspective; however, the high OPEX costs exponentially reduce its importance in the sense of energy generation in comparison to renewables for compensation of energy demand. Renewable solutions include a longer operational lifespan and payback period, thus rendering them more cost- effective. In contrast to the grid-tied wind turbine system, which has a payback length of 2.17 years, the optimal grid-tied photovoltaic-wind turbine hybrid system has a payback period of around 2.3

years, due to the former's greater initial costs. From the above simulation results, it can be concluded that hybrid renewable energy systems are more efficient, cost-effective, and environmentally friendly in compensating the load demand required by the groundwater pumping system for efficient crop irrigation throughout the season. The proposed hybrid configuration reduces the environmental impact because the renewable fraction has improved.

6.5 Conclusion

The proposed research study presented a techno-economically viable solution to fulfill the irrigation requirements of crops throughout the season. An agricultural farm in Lethbridge County of Alberta, Canada, has been considered as the case study. Initially, the crop water requirement was calculated using the CROPWAT software.

Results revealed that 410 mm/acre of water was required for both crops throughout the season. Then, the calculated irrigation water requirement was converted into energy required to pump groundwater for the said purpose. Later, a hybrid grid-tied renewable energy system was designed using Homer Pro to assess the feasibility of reliance on renewables to fulfill the energy demand.

The main objective of the study was to assess the techno-economic feasibility of the proposed system. The results revealed that the integration of wind energy with solar resources can very well reduce the dependency on the utility grid electricity.

The proposed study demonstrated that shifting from conventional resources to renewable energy technologies is necessary to gain reliable, clean electricity for residential, commercial, agricultural, or industrial loads. The proposed design of the hybrid system resulted in approximately a 52% cost reduction of the overall system

Similarly, the renewable energy penetration of the hybrid system is almost 65.4%, highlighting the environmentally friendly nature of the proposed design while having a quite low LCOE of 0.128 CAD/kWh. The outcomes revealed that an optimized and efficient energy management system and irrigation scheduling are required to utilize the benefits of renewables throughout the day fully.

Considering the application of renewables in the agriculture sector, a multidimensional approach with higher agricultural loads (farm machinery) and other renewable resources, such as bioenergy, must be explored to capitalize on the higher benefits from this Agro-Energy integration.

Chapter 7: Summary and Conclusion

The techno-economic feasibility of the hybrid renewable power systems for the electrification purposes of remote communities in Alberta, Canada, as well as their potential applications in the agriculture sector, have been examined in this study. The most optimized, economical, and environment-friendly power system has been assessed by comparing different combinations of hybrid renewable resources. Additionally, the research highlights the importance of renewables in remote communities, which depend on expensive and polluting diesel generators.

Integrating renewables in these areas can significantly lower energy costs, reduce carbon emissions, and improve energy security. Moreover, efficient land utilization and resource assessment have been carried out using various GIS techniques to gain the full potential of energy resources and land, especially in smaller territories and cities with conflicted land utilization, to uplift the economy. The outcomes of the study revealed that when efficiently deployed, renewable energy resources can prove highly reliable in relevance to technicality, economic viability, and environmentally friendly nature. Furthermore, it highlights the importance of renewables integration into different sectors, such as residential, commercial, industrial, and agricultural applications, while emphasizing the benefits of efficient energy management and strategic planning for maximizing sustainability.

HOMER Pro, GIS Techniques, and CROPWAT software were used for this study. The results of the study can be summarized as follows:

- Hybrid renewable systems play a fundamental role in the cost reduction of power generation for any sector and application, either residential or commercial. A hybrid system comprising PV (Photovoltaic), wind, and battery storage has been proposed, achieving approximately a 56% cost reduction and an 80% renewable fraction. The system has a very low Levelized Cost of Energy (LCOE) of 0.0705 CAD/kWh in comparison to other scenarios.

Moreover, sensitivity analysis showed that even after consideration of increasing fuel prices every year for the project lifetime, proposed renewable resources-based configuration generates electricity units at the rate of 0.072 CAD/kWh in comparison to 0.302 CAD/kWh by the Grid-only scenario.

- Renewable's higher penetrations can significantly help in the reduction of GHG emissions, ultimately providing a sustainable environment globally. Results depicted that the proposed hybrid configuration (PV-WT-Grid) emits a significantly lower quantity (3,199,882 kg) of different gases per year in comparison to 3,511,7118 kg, 816,188 kg and 8,719,564 kg by WT-Grid, PV-Grid and Grid-Only scenarios respectively.

  Efficient land utilization and resource assessment while deploying renewables can help in identifying optimal sites for renewable energy integration into regional economies, contributing to sustainable development and environmental conservation efforts.
- Our Studies revealed that LNID has a higher potential and proportion of suitable areas for wind and PV deployment in comparison to the Saint Mary district. The percentage distribution of suitable areas for solar in LNID and St. Mary are 28.13% and 19.47%, respectively. Whereas the distribution of suitable lands for wind turbines was found to be 10.22% and 4.87%, respectively.

- The study's findings provide valuable insights for policymakers, energy planners, and stakeholders to identify suitable sites for renewable energy projects.
- Keeping in view the continuous and timely requirement of irrigation for the high yield and energy-intensive nature of groundwater pumping, renewables play a vital role in efficient and clean energy generation.
- A case study revealed that 410 mm/acre of water is required for both crops considered for the study throughout the season. This water requirement was converted into energy required to extract this capacity, i.e., 325kWp. Results analysis showed that integrating PV and WT-based renewable systems can reduce dependency on utility grid electricity, achieving a cost reduction of approximately 52%, i.e., 0.128 CAG/kWh in comparison to 0.320 CAD/kWh from the National Grid scenario. Similarly, significant reductions in carbon emissions were observed, which highlighted the significance of renewables utilization in comparison to conventional fuels for groundwater pumping.

7.1 Recommendation for future research

- Exploration of various other renewable resources, such as geothermal and tidal energy, as well as bioenergy from agricultural waste, to further decrease the reliance on conventional fuels.
- Development of advanced storage technologies, such as solid-state batteries, having increased capacity and operational life, to increase the system stability and autonomy.

- Efficient energy management, predictive maintenance, and demand response optimization using AI and ML techniques to ensure the system's sustainability.
- Extension of renewables integration in other agricultural applications such as farm mechanization as well as preharvest and postharvest applications.
- Design and implementation of stakeholder-friendly policies can increase investments in the renewable sector.
- Integration of EV infrastructure with renewables and exploration of V2G technologies can enhance grid stability.

Lastly, expanding research to include international case studies in different climatic and socio-economic contexts and comparing results across various regions can identify global trends and region-specific strategies for renewable energy integration, ultimately enhancing the efficiency, sustainability, and applicability of renewable energy systems worldwide.

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