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Design of a Renewable Energy-Driven System for Supplying Electricity in a Remote Area of Canada

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Abstract - This project aimed to design a hybrid renewable energy system with photovoltaic panels, wind turbines, and batteries to meet the annual hourly electricity demand of Sanikiluaq, an Arctic region in Canada. Two turbine types were analyzed in different layouts, with the number of turbines fixed for each array to determine the required solar panels and battery capacity. The goal was to identify the most cost-efficient layout with the lowest levelized cost of electricity (LCOE). Results showed that combining three high-rated power turbines with 1,033 photovoltaic panels achieved the lowest LCOE of $1.25/kWh. With 100% annual reliability, batteries represented nearly 90% of the system's total cost.

Keywords: *PV panel; Wind turbine; Batteries; LCOE*

1.Introduction

Nowadays the increasing demand for accessing energy has highlighted the key role of sustainable energy solutions, particularly renewable energy (RE) sources. These sources are not only necessary for supplying the energy needs but also for decreasing the environmental impact of fossil fuel-based systems[1]. In many remote areas, access to conventional grid access is really challenging. Also, on the other hand, in many of these regions, the energy required is supplied using diesel generator since they are more cost efficient compared to providing grid access, but their environmental pollution is the main issue which must be addressed. This emphasizes the importance of harnessing renewable energies, such as solar and wind, in such isolated regions, fostering a resilient and sustainable energy future[2-4]. There have been conducted several studies in the field of designing a renewable energy-driven system integrated with energy storage, like batteries or H_2 based system, for remote areas. Yang et al.[5] explored the use of solar-wind hybrid energy systems in China, assessing their impact on power supply reliability and cost-effectiveness. Key findings included identifying optimal locations for these systems, analyzing how wind speed and solar irradiation affect reliability and costs. Temiz and Dincer [6] conducted a detailed investigation on the application of solar and wind energy, integrated with energy storage components such as electrolyzer and fuel cell, for power generation. The system was assessed in terms of energy and exergy efficiency, using a time-dependent analysis and the results showed that these parameters were the highest in December with values at 23.41% and 22.96%, respectively. Babatubde et al.[7] studied the performance of an off-grid renewable energy system incorporating photovoltaic (PV) panels, wind turbines as well as a storage system which included both batteries and hydrogen in different sun tracking configurations. Authors investigated technical and economic feasibility of these systems in various tracking modes for Nigeria and South Africa. Zia et al.[8] studied a DC microgrid system which consists of PV panels, wind and tidal turbine integrated with batteries for energy management. Furthermore, an optimization algorithm was employed for the purpose of reducing communication bandwidth and ensuring efficient energy utilization. Nasser et al.[9] conducted a comprehensive evaluation of a hybrid renewable energy system, consisting of photovoltaic panels, wind turbines, and a water electrolyzer, for green hydrogen production. The performance of the system was evaluated in terms of energy and exergy efficiencies, economic viability, and environmental aspects. Obtained results showed that the system could produce a yearly amount of 1926 kg of Hydrogen with energy and exergy efficiencies equal to 16.42% and 12.76%, respectively. Allouhi et al.[10] presented a detailed study on a hybrid renewable energy system (HRES), which integrated Solar Dish

Stirling (SDS) technology with wind turbines and hydrogen production, for multi-family residential buildings. Authors conducted an optimization for the system to find maximum efficiency and cost-effectiveness, analyzing various configurations in different climatic conditions in Morocco. Akram et al. [11] designed a hybrid system consisting of PV and wind turbine for a remote area in Pakistan. The system was simulated in HOMER and optimized in terms of configuration and sizing. In this regard, four different setups were considered to find the optimal solution that would give the best system in terms of cost, energy efficiency and CO_2 emission reduction.

The aim of this project is to design a hybrid renewable energy system with batteries as energy storage system to meet the annual electricity demand of an arctic region in Canada called Sanikiluaq. The outline of the current project consists of two main phases:

1. In the first phase, the entire system is mathematically modeled in MATLAB. The wind farm is modeled with a specified number of turbines, accounting for wake interactions, unlike previous studies, marking the novelty of this project. For PV panels, the optimal surface angle is determined, followed by hourly output modeling for a year. Batteries are modeled based on their energy storage capacity.
2. After modeling, various wind farm arrays with specific numbers of turbines and PV panels are analyzed to meet Sanikiluaq's electricity demand. Each configuration is assessed based on the economic indicator of LCOE to identify the most cost-efficient option.

Also, since the aim of the project is to supply the electricity completely with renewable energy (RE) system it must be designed in a way that has 100% reliability throughout the year.

2.Methodology and Modeling

Case of study for this project is Sanikiluaq; a local government and Inuit community situated along the northern shoreline of Flaherty Island in Hudson Bay, within the Belcher Islands[12]. According to the TMY file, latitude and longitude of this island are 56.54°N and-79.23°W, respectively[13]. The electricity demand profile for this region is shown in Fig.1 . According to [14], the annual demand for this region is 3.15 $GWh.year^{-1}$.

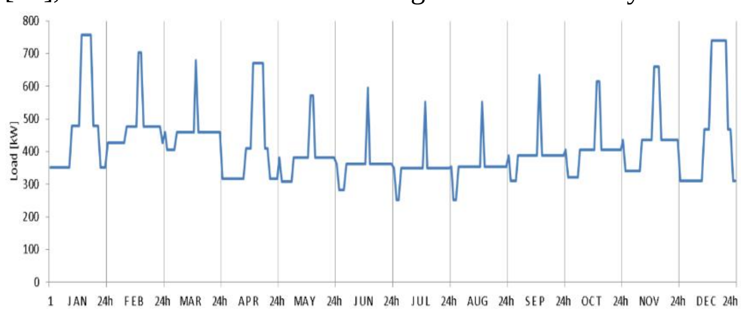

Fig.1: Monthly average electricity demand for Sanikiluaq[14].

The key aspect of WT modeling is calculating wind speed at hub height for each turbine. When modeling multiple wind turbines, the "wake effect", caused by turbines disrupting wind flow, must be considered. This effect creates zones of slower, turbulent air downstream, reducing performance for subsequent turbines. In wind farms with limited land, wake effects emphasize the need for optimal turbine placement, often determined using optimization methods to maximize total power output [15]. A visual representation of a WT wake is shown in Fig. 2. [16].

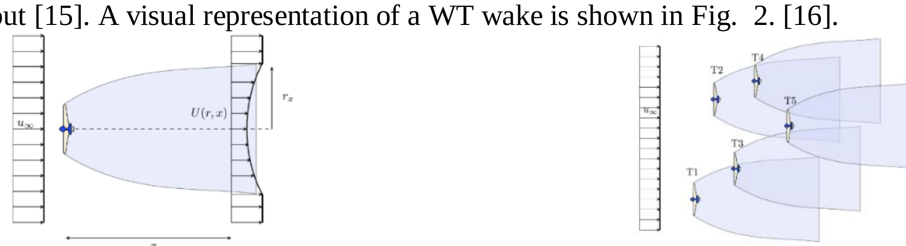

Fig. 2: Wake effect; left: single turbine wake effect, right: multi wake effect.

The Jensen-Gaussian approach is used to model turbine wake effects in this study. It improves upon the basic Jensen model by using a Gaussian velocity profile to accurately estimate wind speed reduction and wake expansion behind a turbine. This method provides greater precision by accounting for wind speed variations across different wake sections. The model is shown in Fig. 3.

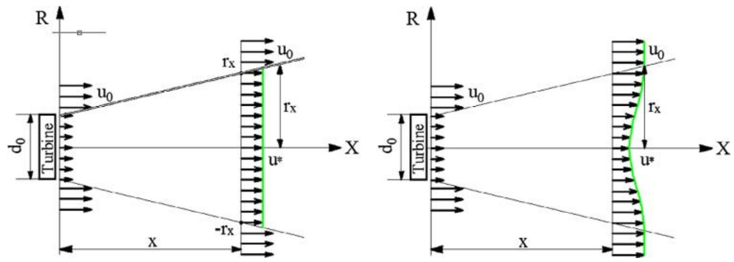

Fig. 3: comparison of the proposed wake models; left one is Jensen model and the right one is Jensen-Gaussian model[17] .

Modeling of PV panel means calculating its hourly power output which can be calculated using the following equation [18]:

$$P_{ele} = P_{mpp}\left(\frac{I_{TP}}{1000\ W/m^2}\right)\left(1+\mu_{mpp}\left(T_{PV}-T_{ref}\right)\right) \tag{1}$$

In this equation, P_{mpp} is maximum power point (MPP) power at standard test condition (STC), μ_{mpp} is temperature coefficient at MPP and T_{ref} is reference panel temperature at STC. These three parameters depend on the type of panel implemented.

Table 1: specifications of TOPBiHiKu7 PV panel [19].

Parameter	Value	Unit
μ_{mpp}	-0.29	%/℃
T_{ref}	25	℃
P_{mpp}	715	W
T_{NOCT}	41	℃

The energy that batteries store hourly, $E_{Bat(t)}$, can be represented concerning the energy that is stored in the previous moment, $E_{Bat(t-1)}$, the amount of energy entering the battery, $E_{el,in}$, the amount of energy leaving the battery, $E_{el,out}$, written as Eq.(2) [20]:

$$E_{Bat(t)} = E_{Bat(t-1)}(1-\mathrm{Dis}) + \left(E_{el,in} - \frac{E_{el,out}}{\eta_{inv}}\right)\eta_{bat} \tag{2}$$

where η_{bat} is the battery's charging efficiency, Dis is the battery's self-discharge and η_{inv} inverter efficiency. For this project, the considered battery is a Lithium-Ion one proposed in the article published by Sanye and Sarrafi [21] and the values of the parameters used for modeling it is available in Table 2.

Table 2: parameters used for modeling battery tank [21].

Parameter	Value	Unit
Efficiency	95	%
Discharge	0.001	-

For the economic model, the whole system is analyzed in terms of levelized cost of electricity (LCOE). Levelized cost of electricity is a term used to measure how much has been spent for supplying each unit of electricity. In order to calculate the LCOE of a renewable energy system, Eq.(3) can be used [22]:

$$LCOE = \frac{PW_{IPC,lifespan} + PW_{O\&M,lifespan}}{AEP_{lifespan}} \quad (3)$$

In this equation, $PW_{IPC,lifespan}$ and $PW_{O\&M,lifespan}$ means the present worth associated with initial purchase cost of system components and present worth of operation and maintenance of the system throughout its lifespan. $AEP_{lifespan}$ is the annual energy produced during the lifespan of the RE system.

In order to find the number of batteries for this RE system, the following equation can be used:

$$\sum_{i=1}^{8760} N_{WT} P_{WT,direct} + \sum_{i=1}^{8760} N_{PV} P_{PV,direct} + \sum_{i=1}^{8760} N_{bat} P_{bat} \geq P_{load} \quad (4)$$

In this equation, $P_{PV,direct}$ and $P_{WT,direct}$ means the power that will be used directly from the PV panels and WTs on an hourly basis.

3.Results and Discussion

The wind farm model was validated by comparing it with the study by Mirsane and Torabi[16]. A plot from their study was selected, illustrating the output power of a wind farm with 16 Mapna MWT2.5-103 wind turbines at a wind direction of 0° for five different distance ratios. The distance ratio is calculated using the following equation:

$$x_D = \frac{2r_d}{y_d} \quad (5)$$

The result of validation is shown in Fig. 4. The maximum error in comparison with the reference is about 16%.

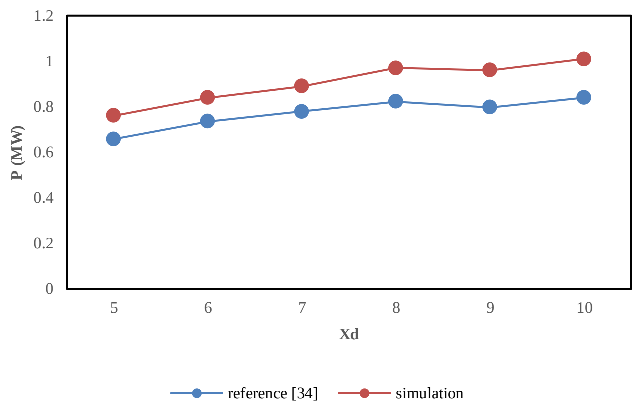

Fig. 4: Comparison of simulation results with a reference article.

In this project, various wind farm arrays with two different WTs were tested to determine the most cost-effective layout integrated with PV panels. The number of turbines is fixed, determining the corresponding number of PV panels and the maximum battery capacity. Before obtaining results, the optimal surface angle for PV panels must be identified. **Error! Reference source not found.** illustrates how a single PV panel's output power varies with this angle.

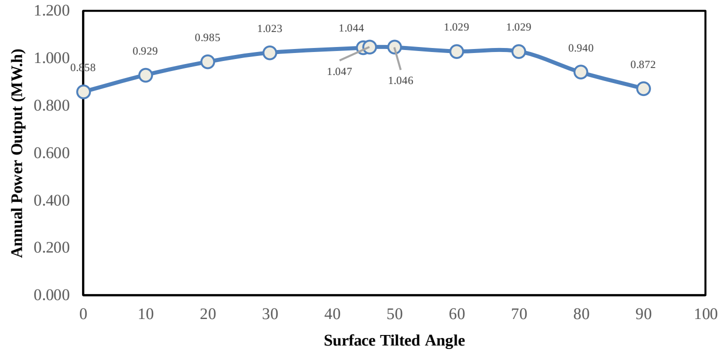

Fig. 5: Annual power output change of a PV panel according to different surface angles.

The monthly power produced by a single turbine of Enercon E-30 is shown in Fig. 6.

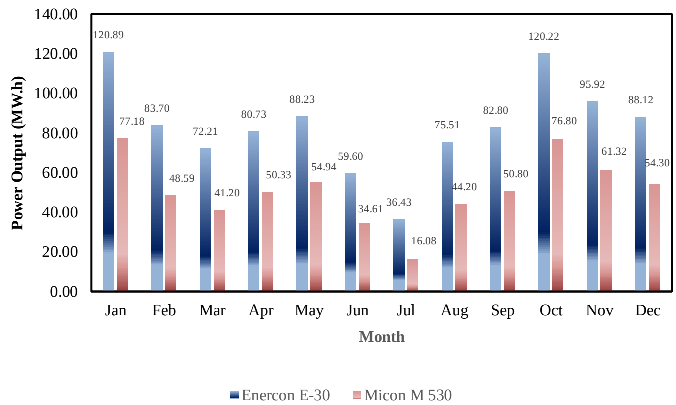

Fig. 6: Monthly power output for the considered wind turbines.

The power generated by the Enercon E-30 in some months is nearly double that of the Micon M 530. This means fewer Enercon E-30 turbines are needed, making it a more cost-efficient choice.

Table 3: Comparison of the cost-effective arrays for each considered WTs.

WT type	Array Num.	WT Num.	PV Panel Num.	AEP (GW.h/year)	Total IPC(M$)	LCOE ($.kW^{-1})
Micon M 530	8	5	1111	4.14	111.9683	1.3729
Enercon E-30	3	3	1033	4.06	99.9012	1.2511

Table 3 shows that for the Micon M 530, using five turbines is the most cost-effective option based on LCOE. For the Enercon E-30, three turbines are optimal. Overall, Enercon E-30 is preferred due to its lower LCOE and total IPC. Fig. 7and Fig. 8 illustrate monthly energy demand fulfillment. As seen in Fig. 7, the renewable energy system supplies over half of Sanikiluaq's demand year-round. Fig. 8 reveals that wind turbines generate more than twice the power of PV panels each month, attributed to high wind speeds at 50 m and low solar radiation, especially in March, November, and December. During these months, battery reliance increases due to reduced wind turbine output.

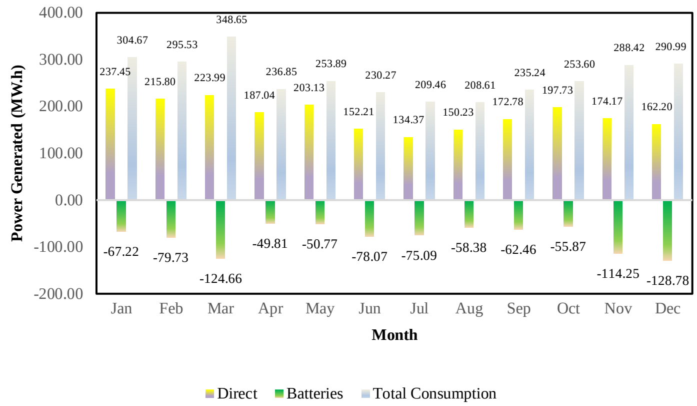

Fig. 7: Monthly power supplying directly and indirectly (Batteries).

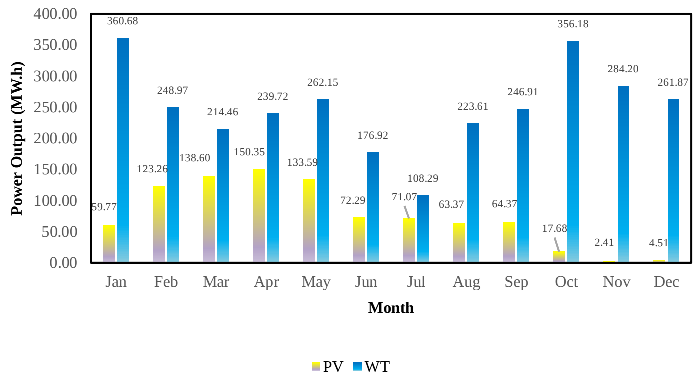

Fig. 8: Monthly Power generation by PV panels and WTs.

In terms of economic indicator of LCOE, **Error! Reference source not found.** represent the contribution of each RE system component in IPC and O&M costs. According to this figure, IPC account for nearly 98% of the total costs that should be taken into account for running this system throughout 20 years. Furthermore, in terms of IPC, about 90% of the expenditure goes for batteries. The main reason for this is that the purpose of this project was to design a 100% reliable system on an annual basis. Also, since the lifetime of the batteries is 10 years, its total cost is calculated twice.

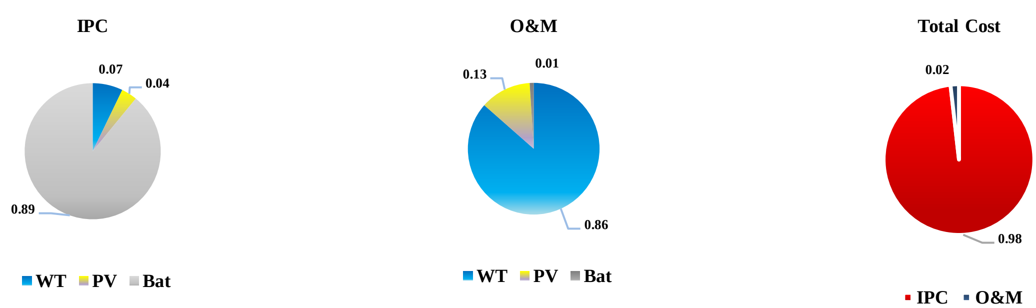

Fig. 9: IPC, O&M and total cost final analysis of the cost-efficient system.

4. Conclusion

This project evaluated the economic performance of a renewable energy system designed to supply electricity to Sanikiluaq, a remote area. The system combined two types of wind turbines with PV panels and batteries in various layouts, aiming for 100% reliability to meet the area's annual hourly electricity demand. The system's lifespan was set at 20 years. LCOE calculations considered the initial purchase cost and the present worth of operation and maintenance over the lifespan. The following conclusions were drawn from the modeling:

- Standalone wind turbines or PV panels are not as cost effective as a hybrid system with both wind and PV generation for an Arctic region like Sanikiluaq.
- Wind turbines supply twice as much electricity as PV panels in such regions.
- The optimal surface angle for PV panels in this area is 46°, yielding a power output of 1.047 MWh/year.
- Wind turbines with higher rated power and hub height are more cost-effective than those with lower ratings.
- A combination of three Enercon E-30 turbines and 1,033 PV panels results in an LCOE of $1.25/kWh.
- Batteries account for the highest total cost of $89M due to their shorter lifespan (10 years) compared to PV panels and wind turbines (20 years).
- Batteries dominate the initial purchase cost, while wind turbines incur the highest operation and maintenance costs.

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