*Nathan C. Oliver*1

*05/18/2018*

1Department of Electrical and Electronic Engineering, Xi’an Jiaotong Liverpool University, Suzhou, China 215123

*Corresponding email: Nathan.oliver17@Student.xjtlu.edu.cn*

Abstract

Wind-diesel hybrid systems is a power generation scheme that can reduce electricity prices for remote communities that are not connected to a large regional or national grid. The island of Masirah is a community off the coast of Oman that relies on diesel generators to produce electricity. Electricity on Masriah is expensive due to the high price of diesel on the island. The island has a high load in the summer due to air-conditioning, yet also receives high winds during the summer months. A simulation using Matlab and Homer Energy software was performed for Masirah to determine if wind turbines could be installed to reduce fuel costs. It was determined that 3 wind turbines could be installed without energy storage, and 8 turbines could be installed with energy storage.

Introduction

Remote communities around the world are facing economic and financial challenges due to the high energy prices. This is typically due to communities not being connected to a large national or regional grid where they would otherwise benefit from cheap and dependable electricity. This leaves communities facing a difficult situation where they need to overcome geographical, logistical, and economic barriers in order to obtain the required electricity at a reasonable price. The centralized nature of electricity generation, where large coal, natural gas, and nuclear power plants have typically been the foundation of electrical grids, have left remote communities at a disadvantage due to remote communities. Centralized power plants are typically located in densely populated areas, which has left remote communities to support themselves. A typical solution to this dilemma is to install diesel generators that are properly sized to the local electricity demand. Using diesel generators can mean high fuel costs for operating the generators.

With the advent of renewable energy technologies, wind and solar energy have become viable options for communities struggling with high electricity prices. Wind energy can be combined with diesel generators to provide steady power generation while reducing electricity prices [1]. The hybrid system can take advantage of the variable wind speed while maintaining high quality energy, as well as reduce diesel generator operating time and the environmental impact. Communities with a steady source on wind can implement this hybrid system to lessen their financial burden.

One particular community with the potential to utilize the wind-diesel hybrid system is the is Masirah Island. Masirah is the largest island of Oman, located about 15 km from the coast of the Arabian Peninsula [2]. The island is about 15 km long and 5 km wide, with a population of 10,000 people. Transportation between the mainland and the island consists of ferries and air travel. The electrical demand is supplied entirely by ten diesel generators ranging in size from 265 to 3136 kW [2]. Fuel costs for the generators are high due to the costly transportation required to ship the fuel to the island. The price of diesel on Masirah is $0.468/L [3]. The electrical demand is highest in the summer due to higher air-conditioning load, while it decreases during the winter months. The wind speed relatively matches the electrical demand for the island, with wind speeds highest in the summer. A wind-diesel hybrid system might be an option for this community, and will be evaluated in this simulation.

For this simulation, one wind turbine will be selected from six candidate turbines to be integrated into a wind-hybrid diesel system on Masirah Island. Simulations will be performed in Matlab and Homer Energy to select the optimum wind turbine, number of turbines, and if energy storage is a viable option. Matlab will be used to determine the ideal wind turbine based on which turbine has the highest average coefficient of performance for the wind speed profile of Masirah. The annualized cost and generated electricity for eight 1000 MW diesel generators and one wind turbine will be calculated using Homer Energy. The cost of electricity (COE) for each generator can then be calculated, and the price of fuel will be used as a variable to determine the break-even point for diesel generators and wind turbines. If the price of diesel is above the break-even point, then installing wind turbines will be a worthwhile investment. Matlab will then be used to determine the maximum number of wind turbines that can be installed with and without energy storage.

Theory

In order to evaluate the economic feasibility of installing a wind-diesel hybrid for a particular site, many factors need to be determined, including wind speed and load distribution, diesel fuel price, operation and maintenance cost, and capital cost. The wind speed and load profiles are shown below.



*Figure 1: Masirah (a) average load profile and (b) average wind speed profile*

The data for the load and wind speed are the average values for each day. Typical wind speed and load profiles are generally created from taking the wind speed and load at regular intervals, such as every minute or every hour, but the available data for Masirah are the average values. This should be sufficient to evaluate the economic viability of the system for Masirah.

The efficiency of a wind turbine is an important factor in determining which wind turbine will be installed for a wind farm project. For this simulation, six different Enercon wind turbines will be evaluated and selected based on which turbine has the highest average coefficient of performance (cp). Each wind turbine has a cp vs. wind speed curve. By comparing this curve and the wind speed for a particular location, the efficiency can be calculated and compared for various wind turbines. The wind speed profile for Masirah will be compared to the cp vs. wind speed curve to determine which turbine is the most efficient.

Once the most efficient turbine has been selected, the cost of energy (COE) of diesel generators and wind turbines will be compared to determine the viability. The COE of a generator is defined as annualized cost divided by the energy generated. Listed below are the factors that determine the cost of generation [4]:

Annualized Cost Parameters

1. Annualized Capital Cost
2. Annualized Replacement
3. Operation Cost
4. Maintenance Cost
5. Salvage Cost
6. Fuel Cost

It is expected that the price of diesel will be a major factor in determining whether or not it is economically feasible to install wind turbines on Masirah Island. Diesel fuel prices have been a driving factor to install wind turbines in rural Alaska communities. In rural communities of Alaska, price of diesel can be as high as $2.50/L, resulting in electricity prices of about $0.40/kWh [5]. Various rural Alaskan communities have installed wind turbines to lessen the burden of operating costly diesel generators, primarily driven by the high cost of diesel.

If wind turbines are an economical option, then the number of wind turbines needs to be evaluated. For an isolated grid network with wind turbines and no energy storage, then the power generation at any moment can never be larger than the load. The minimum load and the maximum wind turbine power output will need to be compared to determine the maximum number of turbines. This situation assumes there is no energy storage, dump load, or control system to store, divert or limit power. This will be a limiting factor in designing a wind-diesel hybrid system. If a community wants to install more wind turbines, then the previously mentioned options will need to be considered.

Energy storage can be installed to increase the installed capacity for an isolated community. This is assuming that it is impossible for the wind power generation at any given time is higher than the load. This means that wind turbines can never be shut down to decrease power generation, and that there is no dump load installed to divert excess power generation.

Method

In order to determine the wind turbine that will be selected for Masirah, the wind data and the coefficient of performance will be compared. The coefficient of performance data is available in a Enercon brochure with detailed information for each turbine. Using Matlab, the coefficient of performance for each wind turbine will be calculated for each wind speed, and the average coefficient of performance can then be determined. The wind turbine with the highest efficiency will be the turbine selected for Masirah.

The cost of diesel is not constant, therefore in this simulation the break-even point for investing in wind turbines on Masirah Island will be investigated. If the price of diesel is above the break-even point, then it will be beneficial to invest in wind turbines, but if it is below the break-even point, then it will be economically preferable to continue using diesel generators. To determine the break-even point, the annualized cost and annual energy generation of wind turbines and diesel generators will be calculated to determine the cost of energy (COE) for each method. Below is a summary of the calculation for the COE. The annualized cost and energy generation will be determined using the Homer Energy software.

(1)

(2)

Table 1 summarizes the generators to be used in the Homer Energy simulation. Since fuel cost will be the main component of the annualized cost, eight 1000 kW generators were selected to simplify the simulation. More generators and generators of different sizes will complicate the simulation. The generators in table 1 will be used to calculate the break-even point of diesel on Masirah Island.

*Table 1: Summary of the generators to be used in the Homer Energy simulation*

|  |  |  |  |
| --- | --- | --- | --- |
| Generator | Quantity | Unit Power Generation | Total Power Generation |
| Wind Turbine | 1 | 810 kW | 810 kW |
| Diesel Generator | 8 | 1000 kW | 8000 kW |

Assuming that the price of diesel is above the break-even point, the maximum number of wind turbines will be determined with and without energy storage. For a situation without energy storage, the determining factor will be that power generation can never exceed power load at any given time. The maximum power output for the ideal wind turbine will be added together and compared to the minimum load for Masirah to determine the maximum number of turbines without energy storage.

For the situation with energy storage, the annual energy generated from the total number of wind turbines cannot exceed the annual energy consumed by Masirah. The energy capacity of the energy storage can never be exceeded at any given time. The charge and discharge rates will also be reasonably rated. The batteries will be added to the cost of the wind turbines to determine a new COE for the wind turbines.

Results

Table 2 summarizes the average coefficient of performance for each Enercon wind turbine. The E48 wind turbine has the highest efficiency on Masirah.

*Table 2: Average coefficient of performance for each wind turbine based on Masirah wind data*

|  |  |
| --- | --- |
| **Enercon Wind Turbine** | **Average Coefficient of Performance** |
| E33 | 0.344 |
| E44 | 0.356 |
| **E48** | **0.377** |
| E53 | 0.364 |
| E70 | 0.330 |
| E82 | 0.338 |

Table 3 summarizes the annualized costs for the E48 wind turbine and eight 1 MW diesel generators. The price of diesel is used as a variable that was used to compare the break-even point for wind turbines and diesel generators on Masirah, shown in figure 3.

*Table 3: Annualized cost comparison with price of diesel (p) as a variable*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Generator Type | Quantity | Annualized Capital ($/yr) | Annualized Replacement ($/yr) | O&M ($/yr) | Salvage  ($/yr) | Fuel Cost ($/yr) | Total  ($/yr) |
| E48 Turbine | 1 | 355,830 | 113,441 | 4,000 | -63,931 | 0 | 409,340 |
| 1 MW Diesel Generator | 8 | 185,651 | 797,319 | 433,680 | -15,122 | 9,029,839\*p | 1,401,528 + 9,029,839\*p |

Table 4 shows the annual energy generation for one turbine and 8 diesel generators. The annualized costs and annual energy generation were used to calculate the COE for each form of power.

*Table 4: Annual energy generation for each generator*

|  |  |  |
| --- | --- | --- |
| Generator Type | Quantity | Energy Generation (kWh/yr) |
| E48 Turbine | 1 | 1,899,594 |
| 1 MW Diesel Generator | 8 | 34,519,204 |

Table 5 shows the COE for an E48 turbine and eight 1 MW generators. It is assumed that the COE will be constant for wind turbines when adding additional wind turbines. This was assumed because the annualized cost and annual energy generation for each wind turbine will be the same when an additional wind turbine is added. The annualized cost of diesel generators is also assumed to be constant for a given price of diesel. As more wind turbines are added, the annualized costs of the diesel generators will be reduced due to an extended service lifetime, since the generators operate for a shorter amount of time. The major component of operating the diesel generators is the cost of fuel. As the generators operate for a shorter time, the amount of fuel used will be reduced, and it is assumed the generators fuel consumption rate remains constant. These assumptions provide a constant COE for diesel generators and wind turbines. The only variable considered for the diesel generators is the price of fuel, as shown in figure 3.

*Table 5: COE of each generator with price of diesel (p) as a variable*

|  |  |  |
| --- | --- | --- |
| Generator Type | Quantity | COE ($/yr) |
| E48 Turbine | 1 | 0.215 |
| 1 MW Diesel Generator | 8 | 0.041 + 0.262\*p |

Figure 2 shows the Masirah load and diesel generator and wind turbine power generation profiles. It is assumed that the wind turbine and diesel generators generated power always equals the load.



*Figure 2: Masirah power load and generation comparison*

Figure 3 shows the break-even point for one wind turbine and eight 1 MW generators. The COE of wind turbines was determined from Homer Energy and US EIA. The COE of onshore wind turbines for the US is $0.073/kWh [6]. The break-even point based on the USEIA COE for wind turbines is $0.124/L, which means that at a fuel price higher than $12.4/L it is profitable to install wind turbines. For the COE calculated from Homer Energy, the break-even point of diesel is equal to $0.67/L. This shows that the price of diesel needs to be above $0.67/L for the COE of wind turbines to be below the COE of diesel generators.

*Figure 3: COE vs. price of diesel for wind turbines and diesel generators on Masirah*

Table 6 summarizes the maximum and minimum Masirah load and the power generated from one wind turbine on Masirah and the theoretical maximum power from one wind turbine. The E48 wind turbine never reached maximum power because the wind on Masirah never exceeded 14 m/s, which would produce the maximum power of 810 kW. These values were used to determine the maximum number of wind turbines suitable for Masriah without using energy storage or dump loads.

*Table 6: Comparison of maximum and minimum Masirah load and turbine power generation.*

|  |  |  |
| --- | --- | --- |
|  | Maximum | Minimum |
| Masirah Load | 7000 kW | **1700 kW** |
| One E48 Turbine (On Masirah) | **771 kW** | 0 kW |
| One E48 Turbine (Maximum) | **810 kW** | 0 kW |

Table 7 shows the excess energy produced depending on the number of wind turbines, and shows that three wind turbines is the maximum number of turbines that does not produce excess energy. Figure 4 shows the power profiles of wind turbines, generators, and the load when using three E48 wind turbines.

*Table 7: Excess energy generated based on number of turbines without energy storage*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Number of Wind Turbines | 1 | 2 | 3 | 4 | 5 |
| Excess Energy (kWh) | 0 | 0 | 0 | 9,049 | 110,170 |



*Figure 4: Maximum number of wind turbines’ power generation profile with load profile and diesel power generation profile*

Table 7 shows the maximum energy capacity, and maximum charge and discharge rates required for a certain number of wind turbines. These values were determined using Matlab in order to simulate a battery. If the wind turbine power exceeded the load, then energy would be added to the battery, and the battery would discharge if the load was higher than the wind turbine power.

*Table 7: Energy storage requirements based on number of wind turbines*

|  |  |  |  |
| --- | --- | --- | --- |
| Number of Turbines | Maximum Energy Capacity (kWh) | Maximum Charge Rate (kW) | Maximum Discharge Rate (kW) |
| 5 | 1,878 | 765 | -6,762 |
| 10 | 27,337 | 4,531 | -6,525 |
| 15 | 66,533 | 8,296 | -6,500 |
| 20 | 107,850 | 12,121 | -6,500 |

Table 8 shows the COE for batteries only and the COE for batteries and turbines for a certain number of wind turbines. The annualized costs for the batteries were assumed to be proportional to the size of the battery. The size of the battery equals the maximum energy capacity calculated in table 7. The cost of batteries was given as $300/kWh [7]. The COE for batteries and wind turbines were added to give the COE for a given number of turbines. 19 turbines were selected as the maximum number of wind turbines evaluated because the annual energy generated by 20 turbines exceeds the annual energy consumed by Masirah, while 19 wind turbines energy production is below the island’s annual consumption. Figure 5 shows the COE of wind turbines for a given number of wind turbines. The energy capacity for 20 turbines, shown in table 7, does not exceed the annual energy consumption of Masirah because the maximum energy capacity is for a certain period of time. It is not equal to the annual energy production of 20 turbines.

*Table 8: COE for batteries and turbines*

|  |  |  |  |
| --- | --- | --- | --- |
| Number of Turbines | COE – Batteries ($) | COE (Homer) – Batteries & Turbines ($) | COE (USEIA) – Batteries & Turbines ($) |
| 5 | 0.02 | 0.24 | 0.09 |
| 6 | 0.04 | 0.26 | 0.12 |
| 7 | 0.06 | 0.28 | 0.13 |
| 8 | 0.07 | 0.29 | 0.15 |
| 9 | 0.11 | 0.32 | 0.18 |
| 10 | 0.15 | 0.37 | 0.22 |
| 11 | 0.18 | 0.39 | 0.25 |
| 12 | 0.20 | 0.41 | 0.27 |
| 13 | 0.21 | 0.43 | 0.29 |
| 14 | 0.23 | 0.45 | 0.30 |
| 15 | 0.24 | 0.46 | 0.32 |
| 16 | 0.26 | 0.47 | 0.33 |
| 17 | 0.27 | 0.48 | 0.34 |
| 18 | 0.28 | 0.49 | 0.35 |
| 19 | 0.29 | 0.50 | 0.36 |

*Figure 5: COE of turbines vs. the number of wind turbines*

Discussion

Based on the price of fuel of Masirah, which is $0.468/L and the COE of wind turbines provided by the USEIA shows that it is economically feasible to install wind turbines of Masirah. At a diesel price above $0.124/L, it may be economically viable for remote communities to install wind turbines to reduce dependency on diesel generators. The Homer Energy simulation concluded that the COE of wind turbines is $0.215/kWh, which is similar to offshore wind turbines. According to the USEIA, the average COE of offshore wind turbines in the US is $0.197/kWh. The break-even point of the price of diesel is $0.67/L, and this conclusion is similar to [2], which concluded that installation of wind turbines is only viable if the price of diesel is above $0.60/L. The maximum number of wind turbines that can be added without energy storage is 3 wind turbines. 3 wind turbines are the maximum number of wind turbines that would not generate excess electricity.

The COE of diesel generators at a price of $0.468/L for diesel is $0.164/kWh. For wind turbines with energy storage, the maximum number of wind turbines without exceeding the COE of diesel generators is 8 wind turbines. Using the COE of wind turbines and combining the COE of batteries for 8 wind turbines results in a COE of $0.15/kWh. With batteries it is recommended to install 8 turbines, and without energy storage it is advisable to install 3.

Improvements could be made in the analysis of the battery. The Homer Energy software was unable to run a simulation for generators, wind turbines and energy storage. In order to calculate the annualized costs of the batteries, the average cost of batteries was used, which is $300/kWh, and the lifetime of the batteries was assumed to be 10 years. These two values were used to calculate the annualized cost. The annualized cost for each battery was proportional to the size of the battery, and did not consider the number of cycles each battery encountered. If a proper simulation was performed, then a more accurate calculation of the annualized cost of batteries could be included in the COE of wind turbines.

Another improvement that could be made is to include a dump load in the simulation. The power generation when 8 turbines are used exceeds the load for only a few days. It might be a better and cheaper option to install more than 8 turbines and include a dump load. The dump load would only need to be used for a few days out of the year to divert excess electricity away from the load. Another option would be to include a simple and cheap control device to shut down the wind turbines when the wind speed is high and the load is low.

Conclusion

In order for isolated communities like Masirah to reduce energy costs, it would be recommended to install wind turbines to reduce the expensive fuel cost needed to operate diesel generators. It was determined that without energy storage, 3 turbines could be installed to reduce the fuel costs. This was determined because 3 wind turbines do not produce excess electricity on Masirah. For the simulation with energy storage, it was determined that 8 turbines could be used. This number was determined from comparing the COE of wind turbines with batteries and the COE of diesel generators at the price of diesel on Masirah. More turbine may be able to be installed on Masirah without energy storage if a dump load is used to divert excess electricity generated during high winds and a low load. This simulation shows that isolated communities that are not connected to a regional or national grid could utilize wind turbines to reduce electricity costs. The addition of wind turbines for remote communities not only reduces electricity prices, but also emits fewer greenhouse gases and gives these communities a sense of energy independence.

References

[1] Drouilhet, S. (n/a). National Renewable Energy Laboratory. Wind-Diesel Hybrid System Options for Alaska. https://www.nrel.gov/docs/fy16osti/64987.pdf

[2] Al-Ismaily, H.A., Al-Alawi A.S. and Al-Rawahi, N. (2006). Viability of Hybrid Wind-Diesel Power Generation in Fossil Fuel Rich Countries: A Case Study of Masirah Island, Sultanate of Oman. ISESCO Science and Technology Vision, 2(1).

[3] Ahmed Said, A.B., Hussein, A.K., Abdullah, A.B., Mohammad F.K., (2016). A review of optimum sizing of hybrid PV-wind renewable energy systems in Oman, Renewable and Sustainable Energy Reviews. Renewable and Sustainable Energy Reviews, 53(1), 185-193.

[4] DOE Office of Indian Energy. (2013). Levelized Cost of Energy (LCOE). https://www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf

[5] Mooney, C. (2016). *Alaska Dispatch News*. How new ways to power remote Alaska villages could spread clean energy worldwide. Retrieved 24 May, 2018, from https://www.adn.com/rural-alaska/article/how-new-ways-power-remote-alaska-villages-could-spread-clean-energy-worldwide/2015/08/16/

[6] US Energy and Information Administration. (2018). Annual Energy Outlook 2018. https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf

[7] National Renewable Energy Laboratory. (2015). Economic Analysis Case Studies of Battery Energy Storage with SAM. https://www.nrel.gov/docs/fy16osti/64987.pdf