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Theoretical Cost Analysis of Electrical Energy for an Off-grid Island Community Using a Single 10MW Wind Turbine and Lithium-Ion Batteries

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Abstract- **In this paper theoretical cost analysis of a 10 MW wind turbine with lithium-ion batteries as storage for an Off-grid Island community is made. The Vestas V164-10.0 MW wind turbine is considered for calculations. Calculations are calculated using numerical computation, and figure data is collected using MATLAB software. The paper aims to give researchers and investors a rough idea about the economic outcomes of using Li-ion batteries as a storage system for wind turbines. The surplus energy needed to be stored is calculated, and then the cost of the system is calculated numerically, targeting the return on investment. If the return on investment of a system is lower than 8%, then investors do not invest in such a system. The return on investment in these calculations is about 17%.**

Index Terms-- **Energy storage, Li-ion batteries, Offshore wind turbine, Payback time, wind energy storage.**

I. INTRODUCTION

Researchers worldwide are looking forward to carbon dioxide-free energy sources, and at the end of 2050, the aim is to reach net zero emissions [1] to overcome climate change. Awareness about the impacts of global warming and consensus on the need to reduce greenhouse emissions has led to a situation where the energy production market must undergo a fundamental change. And as a direct result of this, several significant wind turbines will be integrated into the power network soon as wind power generation has shown itself to be one of the most promising fields of renewable energy production. However, this mass integration of new energy production brings with it its challenges.

If it is said that wind is indirectly driven by the sun, it would not be wrong. Sun's radiation causes uneven heating of the earth's surface, as the earth's terrain is not uniform and absorbs sun heat differently at various locations. This heat further warms the air above it, the air above the equator becomes hotter than air on the poles, and the same heat difference produces in the air on the ocean and desert. The warm air expands and becomes less dense than the air in cooler places. Thus, pressure produces, and the resulting moving air is known as wind [2].

The power produced by wind needs some specific wind speeds and consistency. For fulfilling the energy demand at lower wind speed times and storm conditions, a storage system is needed to store the energy from the wind turbine during normal operation and wind speed times.

The approach of this research was born out of the speculation of providing off-grid electricity solutions for remote communities. Rather than being realistic, we wanted to play around with a futuristic idea of a simple, easily manageable, and completely renewable energy source. In 2018, Vestas introduced a 10 MW wind turbine V164-10.0 MW [3]. What if it was possible to provide electrical energy for the whole town community with a single wind turbine? We may not be there yet, but the idea of this work is to see how such a system could be managed in terms of cost with the energy storage systems of today. Since the estimates are very rough, only the wind turbine and the energy storage system are considered without further infrastructure. Since we are using an offshore wind turbine, the community it provides energy for would be located on an island.

The power curve is estimated by combining the available information on the 10 MW wind turbine and the general shape of the power curve of an older V164 wind turbine [4]. The resulting approximation is achieved, and the need for energy storage is managed by using lithium-ion batteries at low wind speeds.

The amount of energy needed to be stored is calculated using numerical integration in MATLAB software. Then, cost analysis is made based on the data storage system chosen as lithium-ion batteries, and the system's life is calculated.

III. LITERATURE REVIEW

Energy production is moving towards renewable energy sources to reduce carbon dioxide emissions. Also, the recent crises in energy due to the Russia-Ukraine war have raised the power shortage problem even in developed countries, and they are planning to shift the energy production technology to renewable energies [5].

The wind is one of the main abundantly available renewable energy resources. A wind turbine is used to harvest the kinetic energy of wind to produce electricity. A specific capacity of wind energy could be converted into electrical energy; there are several technicalities to address for using the full capacity of wind energy.

Through decades of development in the wind industry for higher wind speeds, wind diameter has also increased from 15m for 50kw of power capacity to 164m for 8000kw power capacity. For the effective operation of wind energy, the design of wind turbines plays an important role in utilizing wind speed adequately. The wind energy market is competitively developing faster than any other renewable energy market, with larger wind turbine diameters and large energy productions.

Though wind is a vast available resource, we still need a maintained specific wind speed to run wind turbines and generate electricity. Above all benefits from the wind, there is still a challenge in wind source utilization. The uncertainty can affect the Grid and can be overcome using storage systems. Some of the storage systems for wind power consumption have been reviewed [6]. However, they settled the fixed Offshore transmission channel's capacity without combined planning of the offshore energy storage and the offshore transmission channel.

Different kind of energy storage for wind turbine has been studied before [7]. Others say that Li-ion batteries have higher energy and power density, higher round-trip efficiency, and lower environmental impact. Therefore, they are a good option for grid-scale stationary application areas, especially grid integration with renewable energies [8]. However, a cost analysis has not been made for combining the storage for large-scale wind turbines.

III. APPROXIMATE POWER OF VESTAS WIND TURBINE

Since the 10 MW version of the Vestas V164 wind turbine is new and some practical information is still unavailable, the power curve is estimated by combining the available information of the 10 MW wind turbine and the general shape of the power curve of an older V164 wind turbine [4] [9]. The resulting approximation is an S-curve that reaches its plateau at the nominal power of 10 MW at the wind speed of 10 m/s.

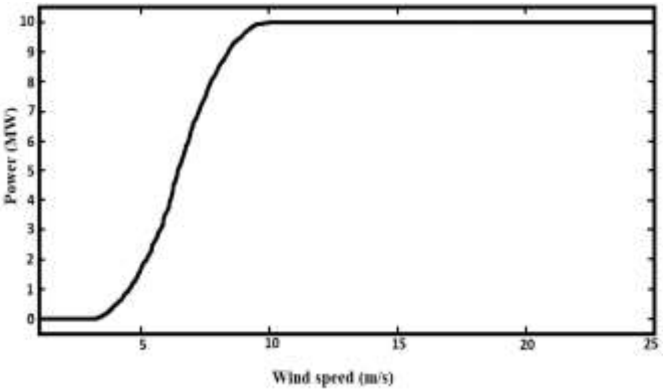

FIGURE 1. Approximated Power Curve of Vestas V164-10.0 MW Wind Turbine

An energy storage system is needed for times of lower wind speeds.

III. CALCULATING THE AMOUNT OF ENERGY TO BE STORED

The size of the storage is dependent on the variability of power generation. The wind turbine will be situated on or nearby an island where the average wind speed is 10 m/s. With the widely used Weibull distribution method, the cumulative wind distribution in an offshore location would be as in Fig 2.

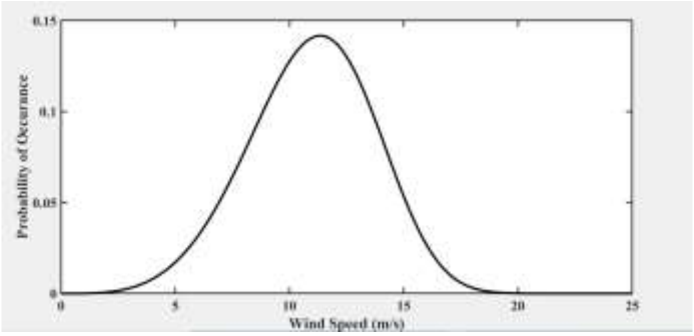

FIGURE 2. Estimated Wind Distribution on an Offshore Location with the Average Wind Speed of 10 m/s

By numerically integrating the curve in Figure 2 between wind speeds 0 and 10 m/s in MATLAB, the occurrence of wind speed being less than 10 m/s, and therefore power generation being less than 10 MW, is found to be 49.1 % of the time. The point where the turbine starts generating energy is estimated to be at 3 m/s: by integrating the wind distribution curve from 0 to 3 m/s, it is found that 0.5 % of the time, there is no power generated.

A cumulative figure of Megawatt hours is achieved by multiplying the corresponding power generated by the probability of occurrence and hours in a year. The integral of this figure is the total energy generated in a year by the wind turbine in the chosen location.

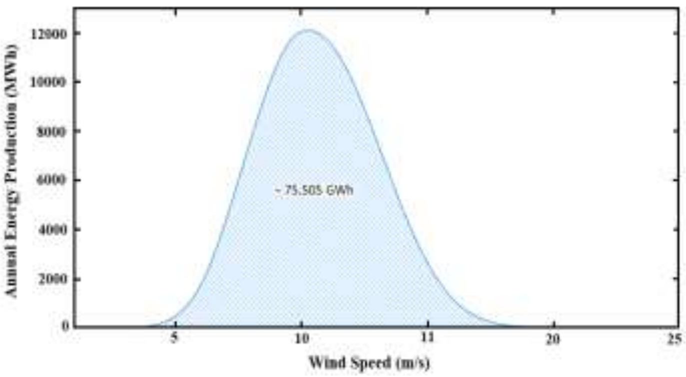

FIGURE 3. Annual energy production of Vestas V164-10.0 MW based on previously presented information

The energy generated in a year is the integral of Fig. 3, which is approximately 75.505 GWh. Residential electricity consumption is assumed to be a constant: the consumption rate is 75.505-gigawatt hours divided by 8760 hours, roughly 8.6193 Megawatts. Based on the roughness of the estimations of the wind turbine data, we shall round this to 8.6 MW.

Very large energy storage is needed to get a constant 8.6 MW by using a wind turbine that irregularly produces between 0 and 10 MW. The idea can be illustrated graphically by using the previously presented power curve of the wind turbine:

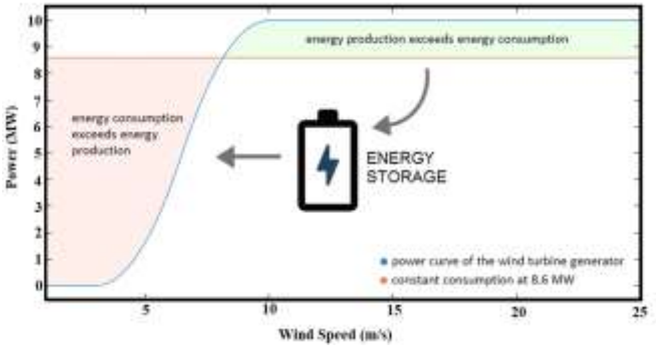

FIGURE 4. Graphical illustration of the operation of the energy storage

The wind turbine exceeds 8.6 MW production at the wind speed of 8.15 m/s, which is where surplus energy starts to get stored. Calculated from Fig. 2, this is 74.2 % of the time annually. Subtracting the constant 8.6 MW for 0.742*8760 hours from the total annual energy production of wind speeds over 8.15 m/s that can be calculated from Fig. 3, we get the total amount of energy that needs to be stored:

$$64.147\ \text{GWh} - 55.899\ \text{GWh} = 8.248\ \text{GWh}$$

Since wind speed occurrence frequency does not correlate to time, and wind fluctuations can happen very quickly, it would be possible 8.248 GWh of storage is the maximum amount needed to guarantee constant power supply based on average wind speed. This amount of storage would be economically unreasonable.

The trend is that maximum wind speeds occur during winter months. Consequently, higher frequencies of lower wind speeds can be observed during summer. Median wind speeds tend to occur at similar rates each month. [10]The trend is the same in both the Northern and Southern Hemispheres. The months of winter and summer are just the opposite. The topology of the location, together with wind and sea currents, could mean radically different distributions in wind speeds. More data specific to the location would be needed to determine the power supply required. However, the most predictable wind distributions are assumed to keep the work more universal.

The energy storage size will be modelled based on the assumed summer wind frequencies when the most storage is needed. For the worst-case scenario, let the assumption be that the average wind speed is the critical 8.15 m/s instead of the annual 10 m/s – which is still reasonable seasonal variation. That would mean that the energy storage would be modelled to level the power each month individually.

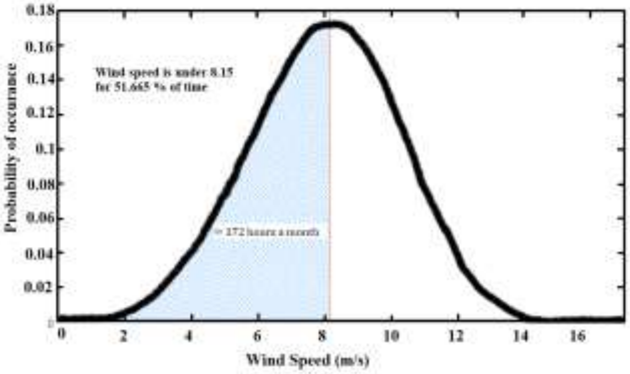

FIGURE 5: Estimated wind distribution of a summer month with an average wind speed of 8.15 m/s

Integrating the summer wind distribution curve between 0 and 8.15 m/s and multiplying by the hours of a 30-day month, it is found that energy supply is needed for 372 hours monthly. Using the worst-case scenario thinking again, it is now assumed that these low-wind-speed hours occur consecutively each month.

The curve for monthly energy production is produced using the same method of combining the probability function with the generator power curve as in Fig. 6. However, this time, the only area integrated is the ones below 8.15 m/s wind speed:

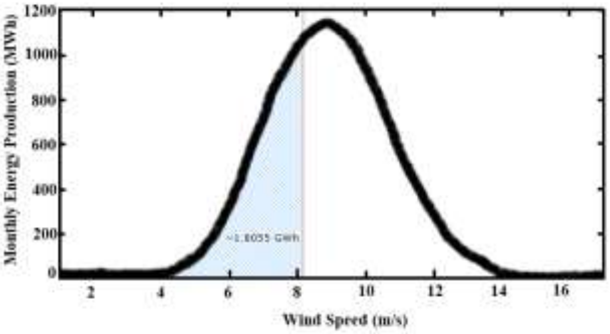

FIGURE 6. Monthly summer energy production of Vestas V164-10.0 MW, with an integrated and highlighted portion that is for wind speeds under 8.15 m/s

The total energy produced by monthly summer wind speeds under 8.15 m/s is 1.8055 GWh. The amount of storage needed is calculated by subtracting this from the desired constant of 8.6 MW for the same time, which is 372 hours, which is 3.1992 GWh:

3.1992 GWh – 1.8055 GWh = 1.3937 GWh

The desired size of the energy storage is 1.3937 GWh. It is still high and higher than a twelfth of the formerly calculated 8.248 GWh because of the seasonal differences.

A constant 8.6 MW supply can provide residential power to 5000 households with annual electrical energy consumption of approximately 15,000 kWh in the whole town. Since the project is quite ambitious, it is assumed that more frugal consumers and users of electrical energy will not be moving to this island. The residents who use the energy pay off the cost of maintaining the electrical energy system for 25 years.

IV. CHOOSING THE ENERGY STORAGE

Because energy is produced and consumed continuously in our system, the ideal storage solution could be flow batteries. Flow batteries have high charge and discharge capacity, are lightweight and would not make the system oversized. However, as stated in the Concept chapter, the idea of this research is to use battery systems that are available today – unlike flow batteries that are not yet widely commercially available. Therefore, the choice of storage shall be lithium-ion batteries, which are also recommended for a grid size of 10 MW or less [11].

The lifetime of the Vestas V164-10.0 MW is 25 years [9], and those of lithium-ion batteries are relatively high at 10-15 years [11], so the energy system should be replaced completely only once during the operation of the system. The cycle life of a cell of 2,000-3,000 recharges, about 200 per year, should also be plenty for the system's purposes: if wind variation cycles do not happen frequently, there will be fewer recharges, and if they do, cells in operation should be rotated to preserve efficiency.

Lithium-ion batteries have a fast enough response to meet grid instabilities within seconds. They are the best match for wind energy storage, as wind sources can vary. Lithium-ion batteries provide long-duration storage with fast charging and low self-discharge. [12]

Among the different types of lithium-ion batteries, Lithium manganese cobalt oxide-based (NMC) batteries are the most suitable for the given storage specifications. They have high energy density as compared to lead-acid batteries, a balanced component composition (NMC 111, NMC 333, and NMC 532,) and safety at low cost. They can store a large amount of energy with stability. The cathode material is LiNiMnCoO2, and the anode material is graphite.

The worldwide installed capacity of lithium-ion batteries in 2016 was 1 GWh. Several combinations with such capacity could be built up to fulfill the energy storage more reliably. Further, it is expected that the price of batteries could go lower to a rate of 120 $/MWh by 2025 [13]. And currently, in 2022, the worldwide installed capacity of lithium-ion batteries is 948 GWh globally [14].

V. PRICE INFORMATION

The following price information will be used in the economic analysis. The costs for Li-ion batteries are taken
from IRENA's report from 2012 [11]:
capital cost per discharge power = 400-1000 $/kW and 372 €/kWh
capital cost per capacity = 500-1500$ $/kWh cap
levelized cost of storage = 0,30-0,45 $/kW $_{\text{life}}$
the initial cost of battery = 372€/kWh
annual operating costs = 20 $/kW-year.

Vestas does not have set commercial prices for their products, so for the wind turbine, we went with the general estimate of 1 million euros for 1 MW of turbine power.

There would be additional costs for shipping the materials, building the infrastructure, etc. Since the foundational parts of our system are already so expensive, we shall ignore the smaller costs for this work**.** "Principal

VI. ECONOMIC ANALYSIS: TOTAL COST OF LIFETIME

The cost to generate power [15] with offshore wind turbines with lithium-ion storage is given by:

$Cost\ to\ generate\ power\ (CGP) = [((FCR * IC) + (LRC + OM + LLC))/\ AEP]$ (1)

Where:

Fixed charge rate at which we sell electricity: $(FCR) = 0.062\ cents/kwh$

The initial cost of the entire installation of 10 MW turbine:
$IC_{turbine} = 10\ million$ €

Initial the cost of the battery for 1.3937 GWh: $IC_{battery} = 5208\ million$ €

Annual energy production: $AEP = 75.505\ GWh$

Levelized replacement cost of turbine:
$LRC_{turbine} = 10\ million$ €$/25\ years = 40000$ €

Levelized replacement cost of the lithium-ion battery:
$LRC_{battery} = 4730400$ €

Overall $LRC = LRC_{turbine} + LRC_{battery} = 4770400$ €

Operation and Maintenance cost of Wind turbine:
$OM_{turbine} = AEP * FCR * 0.08 = 374504$ €

Operation and Maintenance cost for storage system:
$OM_{battery} = 6909$ €

Overall Operation and Maintenance cost:
$OM = OM_{turbine} + OM_{battery} = 381414$ €

Land lease cost $LLC = 75.505 GWh * 0.062 * 0.05 = 234065$ € .

After substituting all the values to Equation (1), the cost to generate power(CGP) is:
$CGP = 0.04998$ €$/kWh = 4.9\ cents/kWh.$

Total annual expense is given by:
$TAE = CGP * AEP = 3773739900$ € (2)

Annual profit (PAN) from the turbine using:
$PAN = (PFCR - PCGP) * AEP = (0.062 - 0.0499) * 7505000000$€ $= 90210100$€ (3) Now return on investment can be calculated as:

$$ROI = PAN/\ Total\ investment = 0.172 = 17.2\ \% \tag{4}$$

The overall results of the economic analysis for the system are given in Table I.

TABLE I
COST ANALYSIS OF LITHIUM-ION NMC BATTERY WITH A 10 MW

Wind turbine and NMC storage battery	
Overall Initial cost	5218 $million$ €
Levelized replacement cost	48 $million$ €
Annual energy production	75.505 GWh
Operation and maintenance cost	4 $million$ €
The total cost of Power Generation	0.04998 €/kWh
Total annual expense	37738 $million$ €
Annual profit	903 $million$ €
Return on investment	17 %

If the return on investment is lower than 8%, investors do not invest capital. We can check the break-even point **[15]**:

$$BEP = Initial\ cost/annual\ profit = 6\ years.$$

VII. CONCLUSION

The cost of the 10 MW offshore wind turbine with lithium-ion batteries as storage is calculated in the previous chapter. It is found that the payback time for the system is six years, which is less than the system's lifetime. Although the battery storage system must be replaced after the first 10-15 years, the profit generated can not only replace the storage system, but the whole turbine replacement cost could be achievable within 25 years of its lifetime.

Due to the large scale of the analyses and little source information, several inaccuracies must be addressed. Primarily, any commercial wind turbine project would not be initiated without proper weather information on the exact location. Since there is no real location, in this case, there is also no real information on daily or weekly weather fluctuations: the assumptions were that every month, the wind blows strongly in the first days and gradually slows down until the beginning of the next month. This is unrealistic, but at least the direction of the error can be determined with certainty. The size of energy storage is too large, and by that, the investment costs must be at least partially too high. The cost analysis is carried out with estimations that would be near the actual values, but in practice, there might be differences depending on environmental and aesthetic aspects.

Given how the whole concept was initially approached, the results are pleasantly surprising. We aimed to come an environmentally sustainable yet most likely economically unviable system from a place of curiosity. A major problem of renewable energy is discussed to be the technological shortcomings of modern electrical energy storage systems. From the results of this research work, it can be concluded that we are already in a place to take a step towards the future with new, more sustainable energy.

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CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest to report regarding the present study.

REFERENCES

[1] Bouckaert, Stéphanie, Araceli Fernandez Pales, Christophe McGlade, Uwe Remme, Brent Wanner, Laszlo Varro, Davide D'Ambrosio, and Thomas Spencer. "Net Zero by 2050: A Roadmap for the Global Energy Sector." 2021

[2] Ghosh, Tushar K., and Mark A. Prelas, eds. Energy resources and systems: volume 1: fundamentals and non-renewable resources. Dordrecht: Springer Netherlands, 2009.

[3] Vestas, "Media," 25 09 2018. [Online]. Available: https://www.vestas.com/en/media/mwow-press-releases/2018/mhi-vestas-launches-the-first-10-mw-wind-turbine-in-history. [Accessed 26 12 2022].

[4] Vestas, "Vestas V164-8.0," Vestas, 2022. [Online]. Available: https://en.wind-turbine-models.com/turbines/318-vestas-v164-8.0. [Accessed 26 12 2022].

[5] S. S. Kulkarni, L. Wang and D. Venetsanos , "Managing Technology Transfer Challenges in the Renewable Energy Sector within the European Union," *Wind,* vol. 2, no. 1, pp. 150-174, 2022.

[6] Yu, Hao, Xiaojuan Yang, Honglin Chen, Suhua Lou, and Yong Lin. "Energy Storage Capacity Planning Method for Improving Offshore Wind Power Consumption." Sustainability vol. 14, no. 21, p. 15, 2022.

[7] R. Pourebrahim, S. Tohidi and H. Khounjahan, "Overview of energy storage systems for wind power integration," *In Energy Storage in Energy Markets. Academic Press,* pp. 41-64, 2021.

[8] A. A. Kebede, T. Kalogiannis and J. V. Mierlo, "A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration," *Elsevier,* vol. 159, p. 112213, 2022.

[9] Vestas, "V164-10.0 MW," Vestas, 2022. [Online]. Available: https://www.vestas.com/en/products/offshore/V164-10-0-MW. [Accessed 27 12 2022].

[10] meteoblue, "Weather Reykjavik," metablue, 10 05 2022. [Online]. Available: https://www.meteoblue.com/en/weather/week/reykjavik_iceland_3413829. [Accessed 27 12 2022].

[11] P. Komor and J. Glaamire, "Electricity Storage and Renewables for Island Power, A Guide for Decision Makers," IRENA, Colorado, 2012.

[12] Research Interfaces, "Lithium-ion batteries for large-scale grid energy storage," RESEARCHINTERFACES, 14 04 2018. [Online]. Available: https://researchinterfaces.com/lithium-ion-batteries-grid-energy-storage/. [Accessed 27 12 2022].

[13] D. Vaughan and N. West, "Batteries vs pumped storage hydropower – a place for both?," Renew economy, 21 06 2017. [Online]. Available: https://reneweconomy.com.au/batteries-vs-pumped-storage-hydropower-place-87554/. [Accessed 27 12 2022].

[14] S&P global mobility, "Growth of Li-ion battery manufacturing capacity in key EV markets," 20 05 2022. [Online]. Available: https://www.spglobal.com/mobility/en/research-analysis/growth-of-liion-battery-manufacturing-capacity.html. [Accessed 27 12 2022].

[15] a. Johnson , "How much does a wind turbine earn? When will it pay for itself? Let's calculate profit and break-even points," Wind Power Engineering and developmement, 2018. [Online]. Available: https://www.windpowerengineering.com/windpower-profitability-and-break-even-point-calculations/. [Accessed 26 12 2022].