Understanding financial risk from operating failures in wind turbines: A riskmetric approach.

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WIND VALUE

IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

Contents

Introduction

- There is a global movement to decarbonize power generation in response to climate change. Wind energy is an increasingly popular source of clean energy, with wind turbines being a common sight across many countries.

- However, like any other mechanical equipment, wind turbines are prone to failures that lead to costly repairs and downtime. This leaves the wind farm business open to significant risks which have implications for wind farm operators and investors.

- We introduce a novel way to quantify risks from wind turbines failures based on financial risk metrics. We model and use the underlying random processes to estimate the costs and risks associated with operating a windfarm. The results have practical implications for the appraisal, planning and financing wind projects.

- We make a methodological contribution by linking time-limited failure data to financial risk measures. Although applied to a wind farm here, the method is generic and can be applied to any business which relies on complex equipment.

- There are many studies on the operation and maintenance issues due to equipment failure, however the general applicability of their methods is limited due to problems of data availability and quality (Leahy et al., 2019; Li et al., 2016). While many studies focus on reliability alone and some incorporate costs, we extend the analysis to include financial risk.

Introduction cont..

- We use value-at-risk (VaR) and conditional VaR (CVaR) metrics to understand the scale and potential impact of risks and express these relative to the initial capital cost to aid interpretation

Key Terms

- Failure rates- refers to the frequency at which components or systems within a turbine experience malfunctions or breakdowns, leading to the turbine's inability to operate as intended.
- Expected cost (EC)- the discounted cost of failures in wind turbines
- Value at risk (VaR)- used to estimate the maximum amount of potential loss that a portfolio of investments may incur over a given time period, at a certain level of confidence
- Conditioned value at risk (CVaR)- also known as Estimated Tail Loss (ETL), is used to estimate the potential loss of a portfolio beyond the VaR

Literature review

First, we looked at the key issues in running the wind energy projects.

- large initial investment (Pookpunt et al., 2020)
- Long production cycles up to 25 years (Zaoui et al., 2022)
- Uncertainties in operation and maintenance(Dao et al., 2020)
- Political pressure to provide energy security while reducing carbon emissions (Rashid Khan et al., 2021)

Second, we investigate what are the risks facing wind energy industry

- Political risks- Sonnberger and Ruddat,2017; Rashid Khan et al., 2021; Broughel and Wüstenhagen, 2022;
- Environmental risk- Kucukali, 2016; Nazir et al., 2019
- Investment risk- Erfani and Tavakolan, 2020; Lei et al., 2020; Qiu et al., 2020; Zhou and Yang, 2020.
- Operational risk- Collier, 2005; Nielsen and Sørensen,2011; Weaver, 2012; Li et al., 2014
  Chemweno et al., 2015 Li et al.,2016; Bezrukovs and Sauhats,2017; Froger et al. 2018; Giglio et al., 2018;
  Jaderi et al., 2019; Lau, 2020; Zhou and Yang, 2020; Wagner, 2020; Costa et al., 2021; Kim et al., 2011; Ren et al., 2021)

Literature review cont..

Why risks from operations

- After project commissioning, most of the costs come from operation and maintenance (O&M) (Lau, 2020; Wagner, 2020)

- Operation and maintenance costs account for 20%-25% of the total levelized cost of electricity (LCOE) of the current wind power systems (Costa et al., 2021)

- Unscheduled maintenance due to random or unexpected failures is one of the biggest drivers of these costs (Kim et al., 2011).

- The effects of maintenance costs on the life cycle of wind farms are complex and uncertain (Costa et al., 2021; Ren et al., 2021).

Literature review cont..

What others did close to our aim of the study

- Li et al., (2016) conducted an operation risk assessment on wind turbines by focusing on convertors only and condition monitoring. Wind turbine outage probability was used as a measure of risk and varied with wind speed.

- Bezrukovs and Sauhats, (2017) assessed the economic and operational risk of wind projects by considering both wind speed, electricity market prices and technical issues. Their study was limited to Latvia and only generators were considered in the technical part.

- Lin et all, (2016) showed that the increase in capacity and turbine size is linked to increase in failures in turbine components. The findings showed that most wind turbine failures are due to failures of generators, gearboxes, or blades.

- Giglio et al., (2018) showed that management of assets including proper maintenance of infrastructure is essential for long-term economic viability of assets. Poorly maintained infrastructure causes risks of delays and damage in short run, while in long run there is a possible increase in cost of disposal and reconstruction.

Data and Methodology

Data

- The data used is extracted from two sources, (Lantz, 2013) and (Tazi et al., 2017). They provide failure rates from turbine components, downtime hours when failure occurs, and their associated cost of repair per failure.

Methodology

- We start by studying three components, generators, gearboxes, and blades as they represent most of the failures on a wind turbine (Shaun Campbell, 2015). Afterwards, the study includes the aggregation of turbines in wind farms.
- We use Weibull distributions to model failures profile, like engineering failures in (Hribar and Duka, 2010) power systems in (dos Santos and de Barros,2015) and spacecraft (Imken et al., 2018)

$$cdf = f(x;k,\lambda) = \sum_{0,}^{1} 1 - e^{-(\frac{x}{\lambda})^{k}} \quad , x \geq 0, x < 0$$

$$pdf = f(x;k,\lambda) = \sum_{0,}^{\frac{k}{\lambda}} \frac{k}{\lambda} (\frac{x}{\lambda})^{k-1} e^{-(\frac{x}{\lambda})^{k}} \quad , x \geq 0, x < 0$$

Components	Shape (k)	Scale (λ)
Blades	0.75	86.80
Gearbox	1.38	15.02
Generator	1.52	18.72

Data and Methodology cont..

Methodology cont..

- We use Monte Carlo simulation and NPV techniques to estimate failures costs of wind turbines over their operation life

$$EC = \sum_{t=1}^{t=20} \frac{TC * Ft}{(1+d)^t}$$

$$\mathrm{VaR} = \mathrm{EC} - \mathrm{z} * \sigma$$

$$\sigma = \sqrt{}(EC * Var(Ft)/1 + \mathrm{d}^{2t}))$$

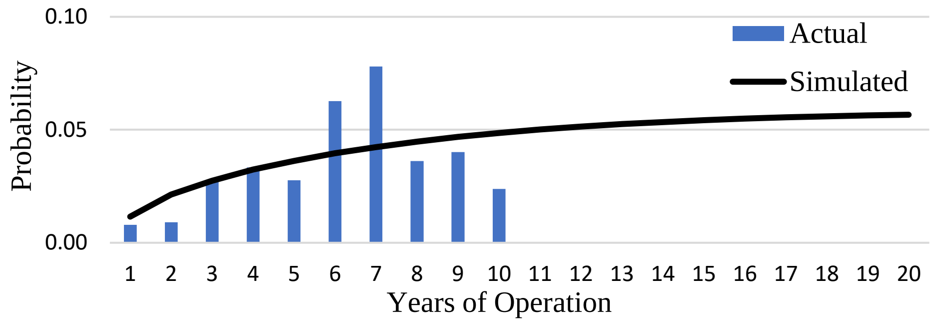
$$CVaR = (\,1/(1-\alpha)) * \sum EC * Ft * \Pr(l > VaR)/(1+d)^t$$

Where TC is the total cost, DC is the direct repair cost, OC is the opportunity cost, d is the annual discount rate, and t is the time in years. z is the z-score, or the standard score associated with the desired confidence level α in our analysis α = 0.05 (95% confidence level). Pr(L > VaR) represents the probability that the loss (L) exceeds the VaR

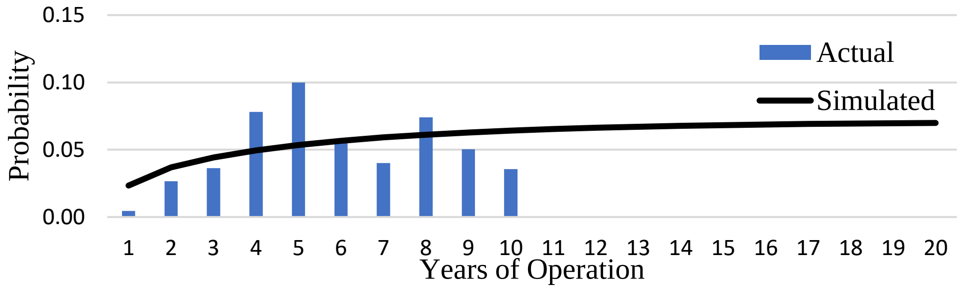
Results

Goodness of fit

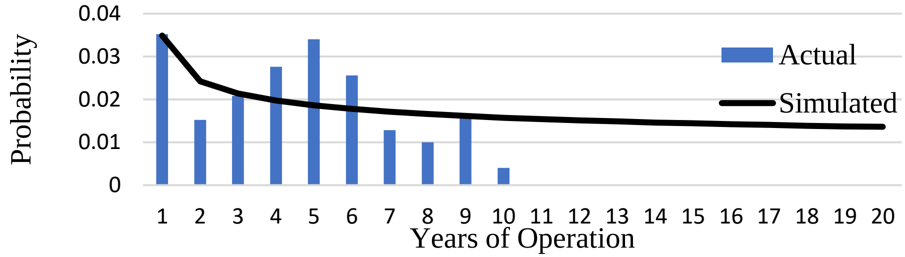
Generator



Gearbox



Blades

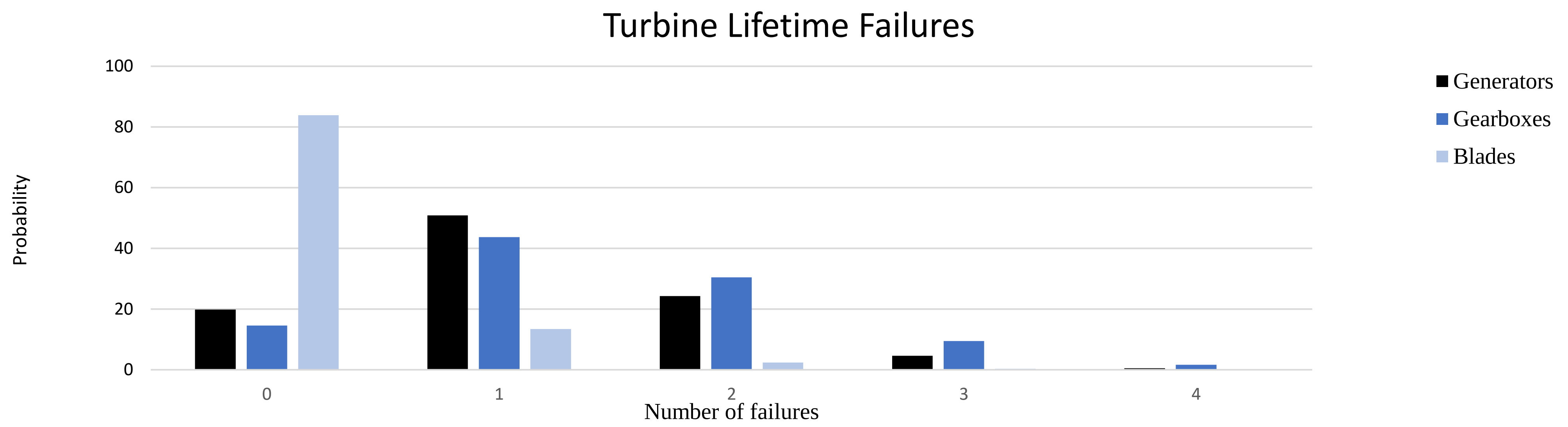


The opportunity cost (OC) uses €166.2 as an electricity price(Statista, 2023), 0.24 as a utility factor (IEA, 2020), the installed capacity of a single turbine is 2.5 MW, and we use European 1.89 inflation rate (Ian Webster, 2023) . ADC is the adjusted direct cost.

	Dt(hrs)	OC(€)	ADC(€)	TC(€)	Total (%)	OC (%)	ADC (%)
Blades	147	14,649	368,702	383,351	30	3.8	96.2
Gearboxes	261	26,043	636,761	662,804	51	3.9	96.1
Generators	126	12,609	228,917	241,526	19	5.2	94.8

Results

1.Failure Rates



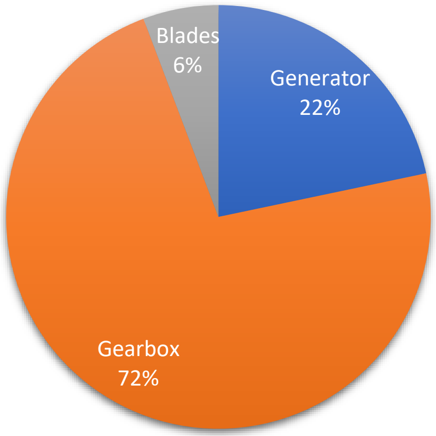
year	1 turbine	5 turbines	10 turbines	20 turbines
Mean failure rate	0.13763	0.68814	1.37628	2.75300
std	0.00058	0.00292	0.00584	0.01200

- Gearboxes display higher failure rates than other components. Blades are more reliable which explains the pilling up of blades after the end of operational life.
- The mean failure rate and deviation in failures is a result of the size of the farm.

Results cont..

2.Cost Analysis

Components cost distribution



Turbine cost analysis

	Generator	Gearbox	Blades	Total	**CAPEX (%)**
EC	152,285	510,563	40,440	703,289	**23**

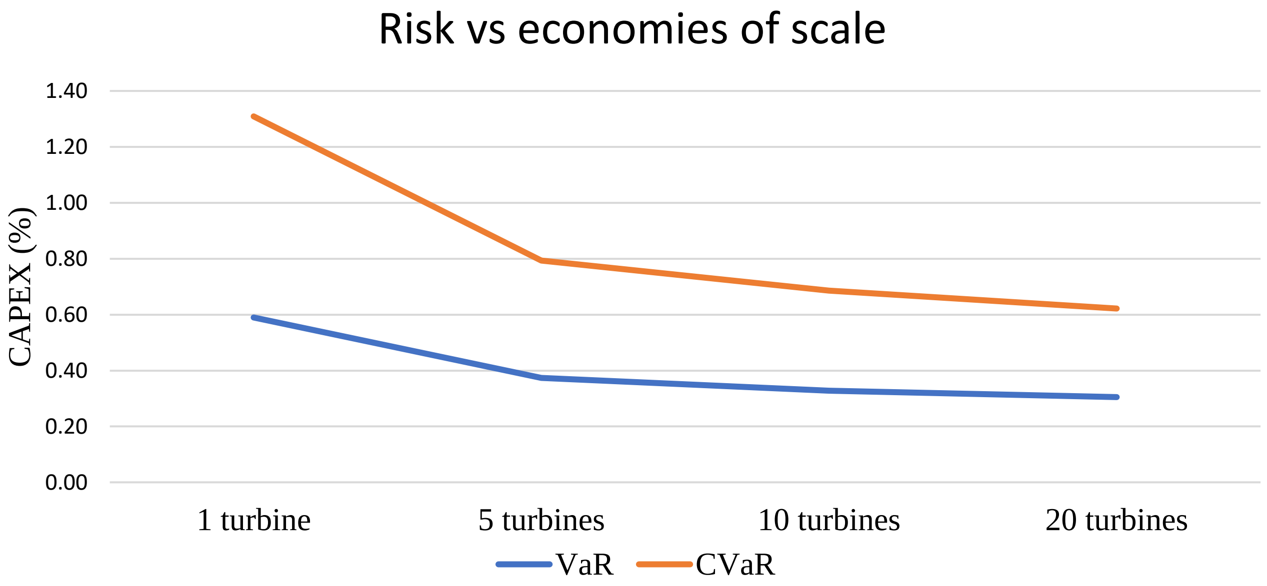
- Gearboxes have high cost of failures than other components, the effect comes from the high direct repair cost and long downtime hours from fail state to operating state.
- The expected failure cost over the lifetime of a wind turbine is 23% of the initial capital cost.
- Since the mean failure rates and deviation follows the size of the farm, the expected failure cost as a percentage of CAPEX does not change with size of the farm.

Results cont..

3. Risk Analysis

Wind farms Risk in €

No of Turbines	1	5	10	20
VaR	1,844,016	5,834,469	10,242,562	19,057,475
CVaR	2,247,828	6,561,884	11,190,809	19,784,938
CAPEX	3,125,000	15,625,000	31,250,000	62,500,000



- The VaR and CVaR for a single turbine is 59% and 72% of the CAPEX.
- There is a decreasing trend in the percentage of capital expenditure required to cover potential losses (% CAPEX) from 59% to 37% to 32% and 30% as we move from a single turbine wind farm to a 20 turbines farm.
- Diminishing return effect

Conclusion

Highlights

- The results section shows that operation and maintenance in wind turbines have significant contribution to the CAPEX in wind projects
- For generators spend more on quality, gearboxes spend more on maintenance and a good guarantee from operation and maintenance companies and for blades ensure they are installed correctly.
- Owning one turbine has more risk profiles than having several turbines in a farm, a large loss can deplete the capital reserves of a business, leaving it with insufficient funds to cover future expenses or investments.
- If the viable end of life option will be life extension or repowering, an increase in the size of the farm should be given a priority.
- To mitigate these financial risks, wind farm operators/ investors should assess and monitor their VaR and take steps to reduce their exposure to potential losses. This may involve diversifying their investments, such as increasing the number of turbines in a wind farm, implementing risk management strategies like scheduled maintenance, or investing in insurance or warranties.

Thank You

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