Quantifying the Benefits of Diversification: An Example Relating to the Size of Wind Farms

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Contents

Introduction

- A Wind Farm has a large sunk cost (75%).
- The cost of Operations and Maintenance is usually modelled as a stochastic variable using Weibull distributions for the many components of each wind turbine.
- We measure risk using four related measures: VaR, CVaR, VaR /CAPEX and CVaR /CAPEX.
- If we assume the failures of turbine components are independent, then the more turbines in a wind farm the lower the risk relative to the CAPEX.
- How many turbines would be required to achieve an “appropriate” reduction in our measures of risk?

Literature Review

Key Issues for 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)

Key Issues 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 Random Failures

Our Focus is Random Failure

- After project commissioning, most of the costs come from operations and maintenance (O&M) which account for 20% - 25% of the total levelized cost of electricity (LCOE) (Lau, 2020; Wagner, 2020; Costa et al., 2021)

- Random or unexpected failures drive these costs (Costa et al., 2021; Ren et al., 2021; Kim et al., 2011)

Closely Related Literature.

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, and that most failures are due to failures of generators, gearboxes, or blades.

- Giglio et al., (2018) showed that 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)

$$cdf, \mathrm{F}(x, k, \lambda) = 1 - e^{-(\frac{x}{\lambda})^k} \quad , x \geq 0$$

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

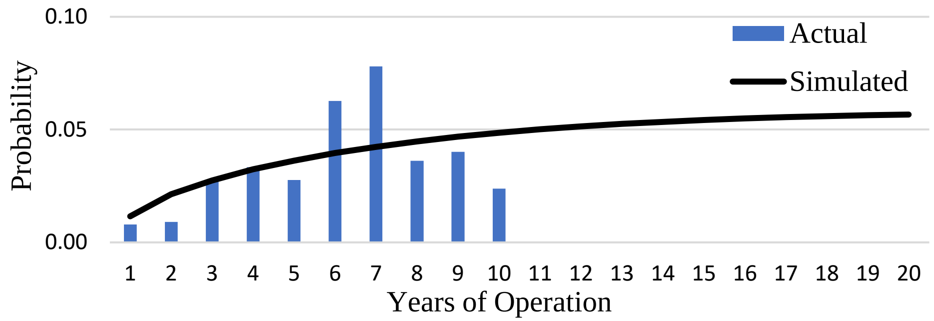
$$var, V(k, \lambda) = \lambda^2 \left[\Gamma\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^2 \right]$$

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

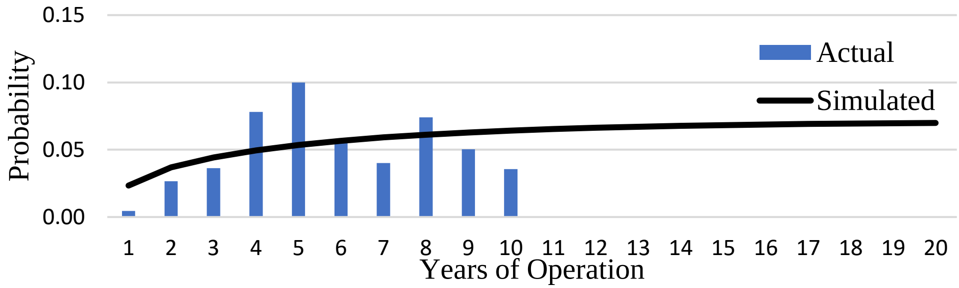
Results

Goodness of fit

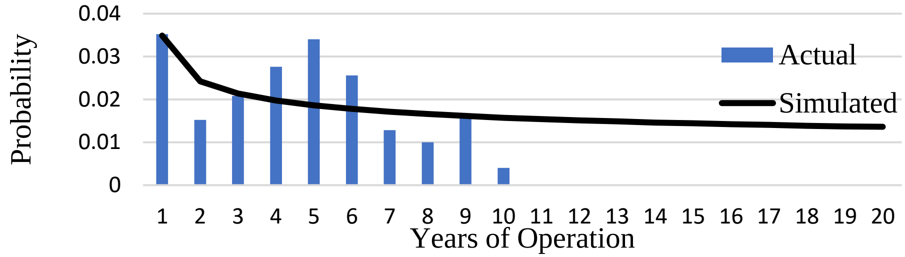
Generator



Gearbox



Blades

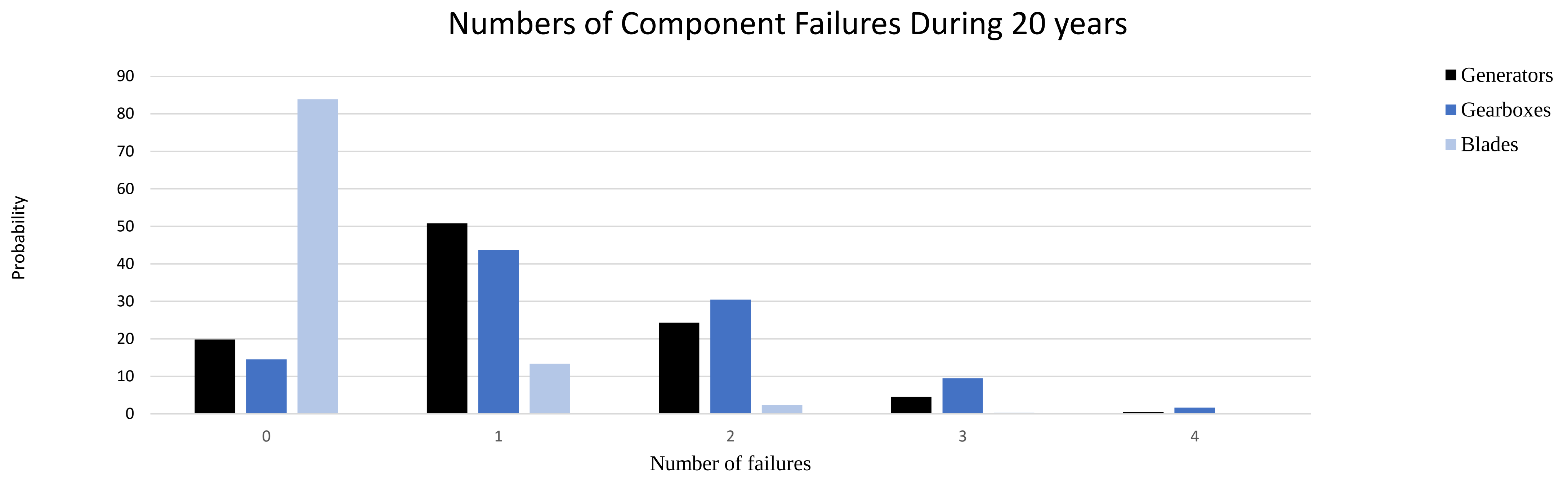


The opportunity cost (OC) uses:
€166.2/MWh as an electricity price(Statista, 2023),
0.24 as a utility factor (IEA, 2020),
2.5 MW the installed capacity of a turbine,
1.89% European inflation rate (Ian Webster, 2023) .
ADC is the adjusted direct cost after downtime.

	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

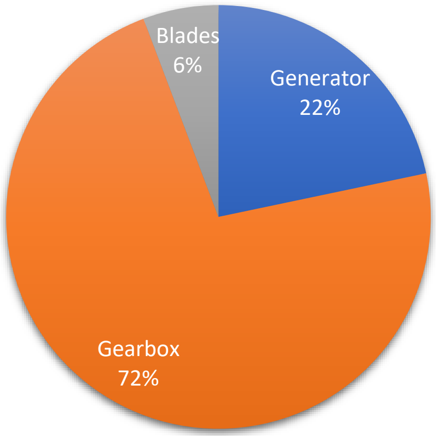


- Gearboxes fail the most frequently, followed by gearboxes and blades are the least likely to fail.

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, but the distribution of these costs does change considerably.

Data and Methodology for VaR and CVaR

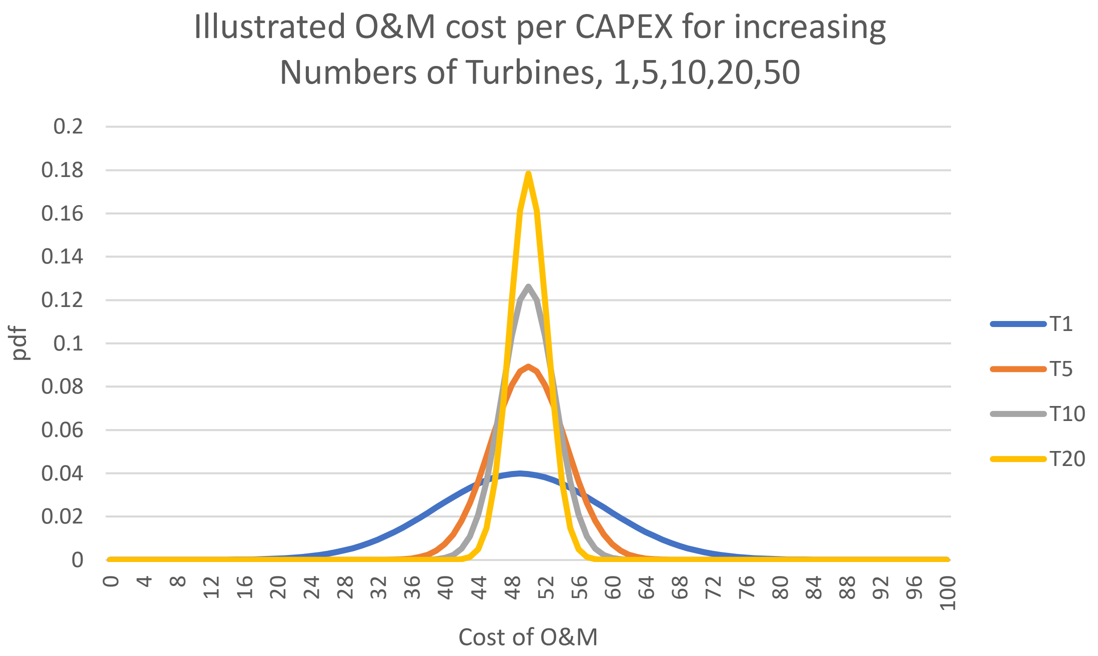
Calculating VaR and CVaR

- We calculate a series of cash flows due to repairs over a 20 years
- These cash flows are discounted to their value at the start of the wind turbine's life.
- These discounted costs of repairs are used to calculate the 95th percentile of the distribution of the repair costs from the 10,000 Monte Carlo simulations.
- This provides the VaR and CVaR

Central Limit Theorem and Normal Distribution

How the risk measures behave as the number of turbines increases

Since the variance of the Weibull distribution is finite, and we are effectively dealing with a mean of Weibull output, the results will tend towards a Normal Distribution. This is illustrated for a mean cost of 50 and a variable number of turbines, N, which reduce sigma by a factor of 1/sqrt(N).
Note that with increased N, the VaR and CVaR per CAPEX approach the expected value of 23%.



Main Result

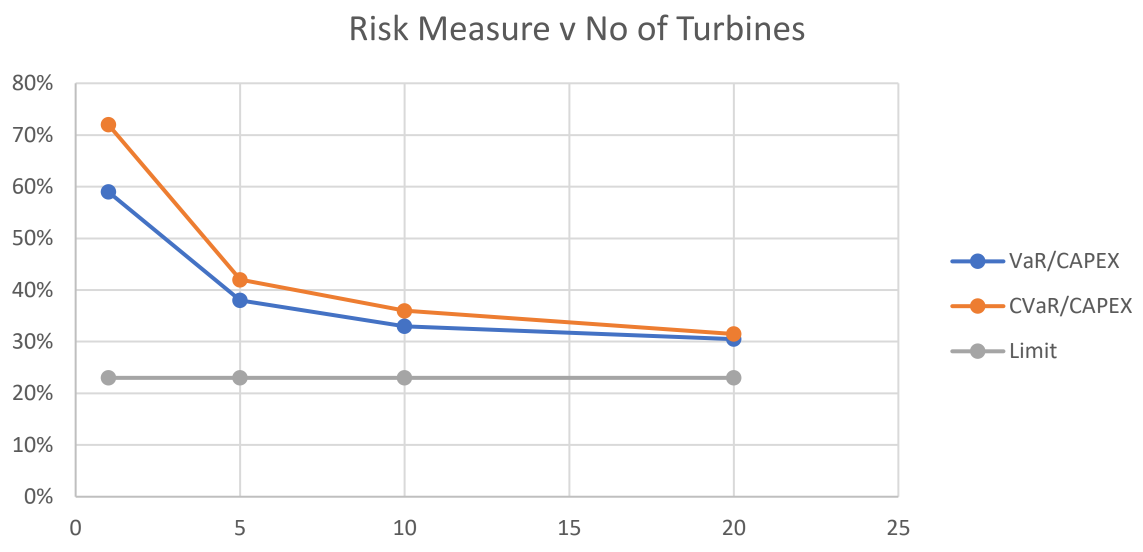
3. Risk Analysis

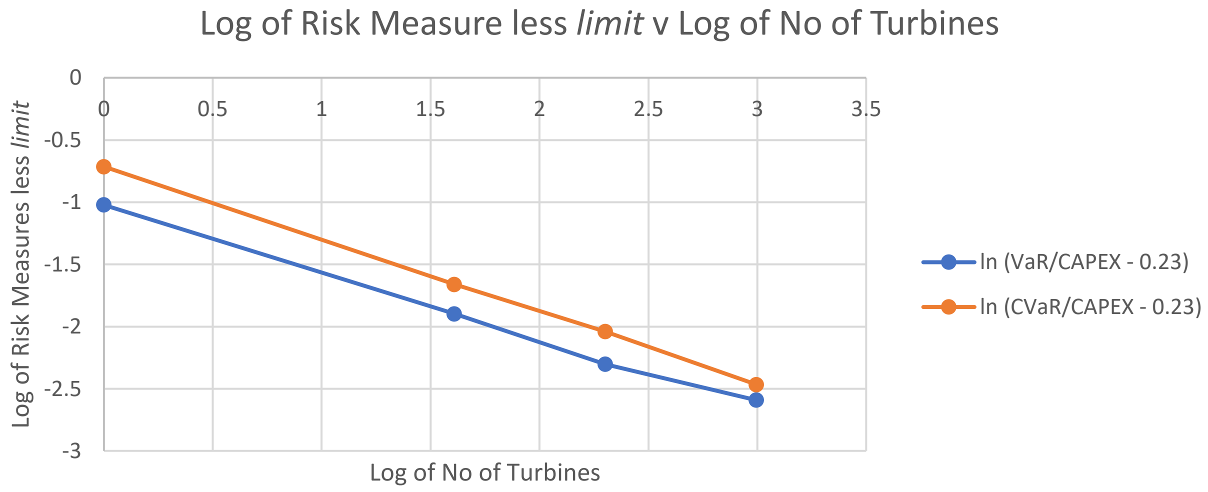
Wind farms Risk measured in € and as a proportion of CAPEX

No of Turbines	**1**	**5**	**10**	**20**
VaR	1,844,016	5,834,469	10,242,562	19,057,475
VaR/CAPEX	**59%**	**38%**	**33%**	**30.5%**
CVaR	2,247,828	6,561,884	11,190,809	19,784,938
CVaR/CAPEX	**72%**	**42%**	**36%**	**31.5%**
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.
- The reduction in risk decreases in size with each additional turbine.
- The limit is 23% the expected ratio of OPEX to CAPEX.

Main Result





50% and 90% Improvement in Risk Reduction compared with a single turbine.

Propose the following model:

$$R - limit = Cn^{a}$$

Where *R* is the risk measure (either); *limit* is the limit of R as n-> infinity; *C* and *a* are constants calculated using linear regression

Then

VaR/CAPEX = $0.36 * n^{-0.53} + 0.23$

CVaR/CAPEX $= 0.49 * n^{-0.58} + 0.23$

	VaR/CAPEX	CVaR/CAPEX
50% Reduction	4	4
90% Reduction	77*	52*

Sources of error:

*Both of these are far outside the data we have checked and so are very rough estimates. Also, the 23% limit looks to be too low.

Conclusion

Highlights

- The results show that operation and maintenance has a significant contribution to the cost of running a wind farm, relative to CAPEX
- Generators should spend more money on gearboxes and make sure blades are installed correctly.
- **Owning one turbine has more risk relative to CAPEX than having several turbines.**
- Most of the advantage from risk reduction of owning multiple turbines is achieved by owning **4** turbines, 90% of the risk reduction is achieved by owing more than 50.

Thank You

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