ADVISORY SERVICES IN THE WIND INDUSTRY:

DUE DILIGENCE AND OPERATIONAL ASSESSMENTS

Wind Energy Science, Engineering and Policy (WESEP)

Iowa State University, 01 March 2018

AGENDA

1. Introduction
2. Brief History of UL & AWSTruepower
3. Overview of UL Renewable Energy Services
    - Evaluating Operational Wind Plant Performance
    - Using Wind Plant Data to Forecast OPEX Costs
    - Due Diligence: Turbine Suitability

BRIEF HISTORY OF AWS TRUEPOWER & UL

- AWS Truepower was founded as “Associated Weather Services” in 1985, providing energy forecasting and consulting services to the nascent US wind energy industry.
- Underwriters Laboratory acquired AWS Truepower in Q4 of 2016 and combined with other UL acquisitions under the UL Renewable Energy Services group.
- AWS Truepower provides ~50% of the energy forecasts for utility-scale wind projects in the U.S.
- Energy Forecasts for 60+ GW of installed renewable energy projects globally
- Independent Engineer on 450+ wind & solar projects
    - 200,000+ MW renewable energy assessed
    - Has advised 90% of the industry’s top Project Developers and Plant Owners
- Work with 90% of the top wind OEM’s
- UL 500+ employees in renewables and offices located in 143 countries around the world

RENEWABLE ENERGY SERVICES

Project Development Support:

- Site screening & Feasibility,
- Resource Assessment & Measurement,
- Plant Design & Technology Selection,
- Balance of Plant Review
- Permit Support & Environment Assessment

Asset Management

- Plant Performance Analysis & Optimization
- **Operational Energy Assessments,**
- Power Performance Testing,
- Turbine Inspections,
- Root Cause Analysis,
- Extreme Loads, LiDAR

Due Diligence & Bankability

- Independent Engineering
- **Technical Advisory for Operational Projects**
- Pre-construction Projects
- Operational & Repowering Projects,
- Turbine Technology Review,
- **Turbine Suitability**
- Electrical & Civil Design Review,
- Review of Contracts, Environmental Permitting, Financial Model,
- Construction Monitoring,
- Project Lifetime Assessment

RENEWABLE ENERGY SERVICES

Software, Data / Analytics

- Wind Developer Suite,
- Windographer, Openwind,
- Windnavigator,
- Resource Maps,
- Time Series Datasets

Standards

- Modules
- Inverters
- Converters
- Balance of Plant Systems

Grid Solutions

- Real-time energy forecasting
- Grid Management & Planning
- Atmospheric Modeling & Applied Research

Certification

- Certification of Turbines & components
- Project Certification
- Grid Code Compliance
- Foundation Assessments

Testing & Inspection

- Validation & Type Testing
- Mechanical Loads
- Power Performance Measurement
- Electrical Characteristics
- Low Voltage Ride Through Testing

OPERATIONAL WIND PROJECT ASSESSMENT

A typical operational advisory project is initiated due to Mergers & Acquisition activity and usually includes the evaluation of 1 or more operating Wind (and/or Solar) projects supporting investment Due Diligence activities for:

- Banks
- Finance Companies
- Investment Funds
- Tax Equity Investors (related to the PTC in the US)

Project scope typically includes:

- Historical Operations Review
    - Energy Production Analysis
    - Project Availability
    - Component Usage Analysis
    - Turbine Reliability Issues
    - OEM Warranty Review
- Electrical Design Review
- Contracts Review
- Environmental Permitting and Compliance
- Financial Model
    - Operational expenditure (OPEX) review and forecast
- Site Visit

OPERATIONAL ENERGY ASSESSMENT

1. Comparison with Pre-construction assessment
2. Methodology
    - Historical Net Energy Losses
    - Historical Gross Energy
    - Future Gross Energy
    - Future Net Energy and Probability Model

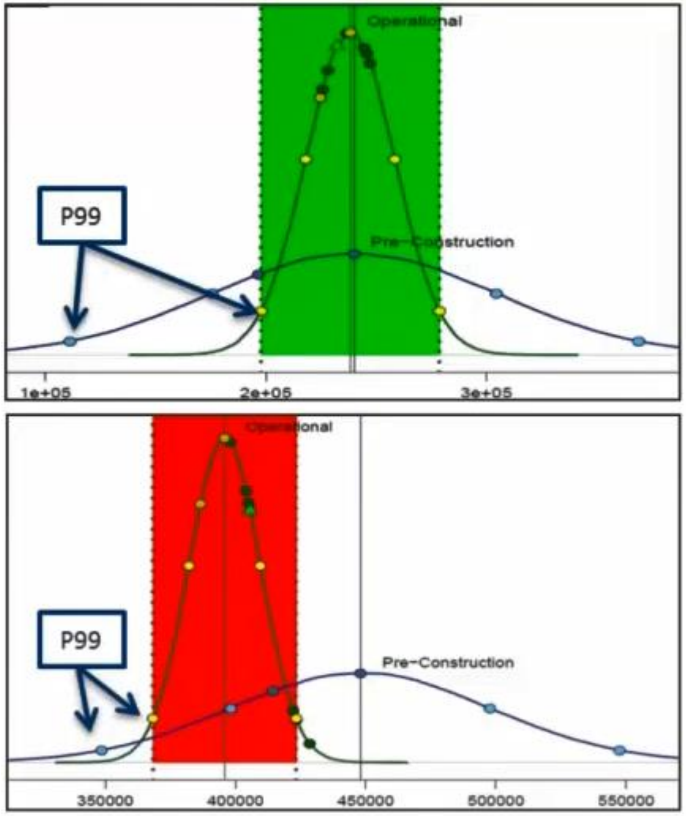
OPERATIONAL ENERGY ASSESSMENT

Preconstruction Energy Estimates:

- Use monitoring systems to collect wind speed
- Extrapolate to hub height or plane of array
- Extrapolate to all turbine locations
- Energy production is modeled - accounting for comingled effects of multiple generation sources
- Losses are **<u>assumed:</u>** availability, electrical losses etc.

Operational Assessments:

- All of the above are accounted for in the actual MEASURED energy reflected at the revenue energy meter of the project.
- Operational assessments have higher accuracy and lower uncertainty



OPERATIONAL ENERGY ASSESSMENT

Several activities may trigger an updated Energy Analysis

- Refinancing, M&A, Budget changes, Portfolio analysis

Uncertainty goes down with the # of months of available data

- Typically requires 12 months of consistent operational data

Project performance is rarely static:

- Performance changes
- Availability issues
- Turbine component reliability
- Blade leading edge erosion
- Grid congestion/curtailment
- Additional surrounding development

OPERATIONAL ENERGY ASSESSMENT

Inputs to the Analysis

Project Data:

Revenue Meter Data (by project)

Availability data parameters (SCADA)

Energy Loss Sources

Curtailment

BOP Issues

Environmental Issues

- Bird, Bat, Noise, Icing, Flicker

Operational reports (monthly)

On-site meteorological instrumentation

Plant Design

OEM specifications

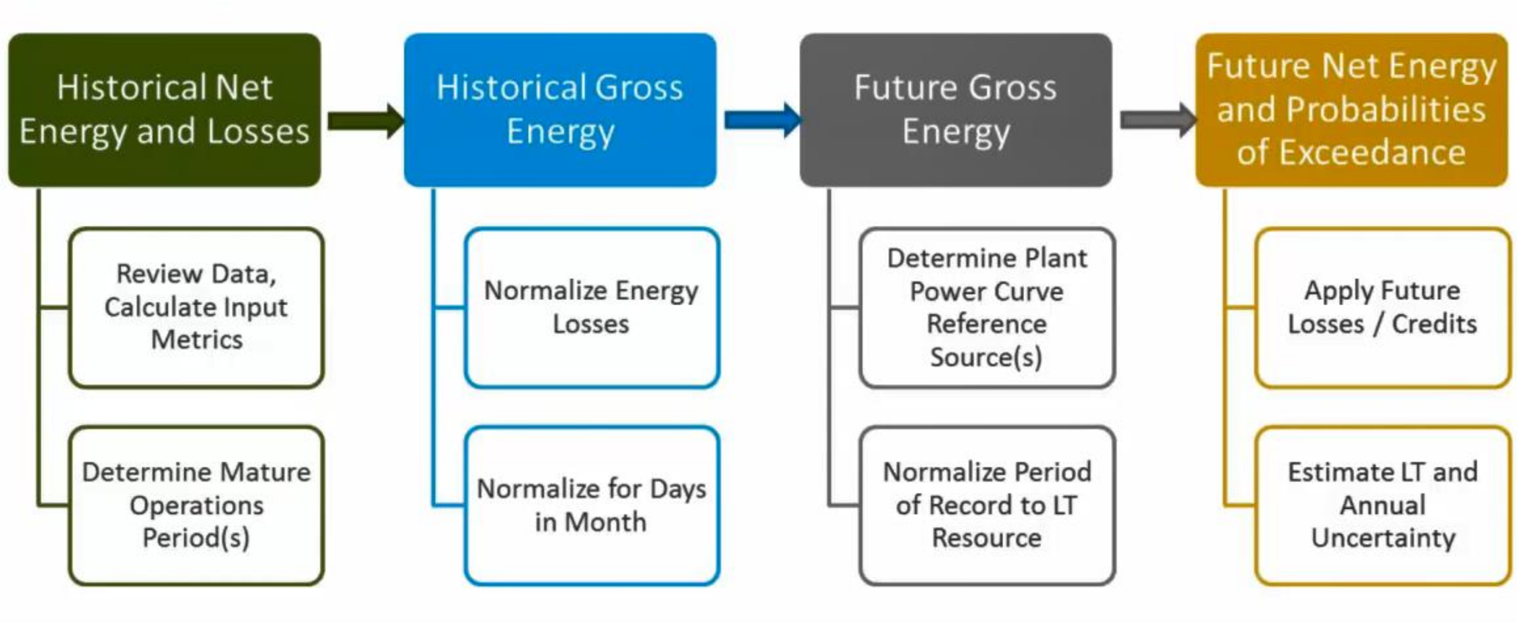
GPS coordinates of each turbine

Reference Data:

- Wind Speed,
- Wind Direction
- Temperature
- Pressure
- %RH
- Precipitation
- Data Sources:
- MERRA, MERRA2, ERA-Interim, Surface Station Networks, WRF

OPERATIONAL ENERGY ASSESSMENT

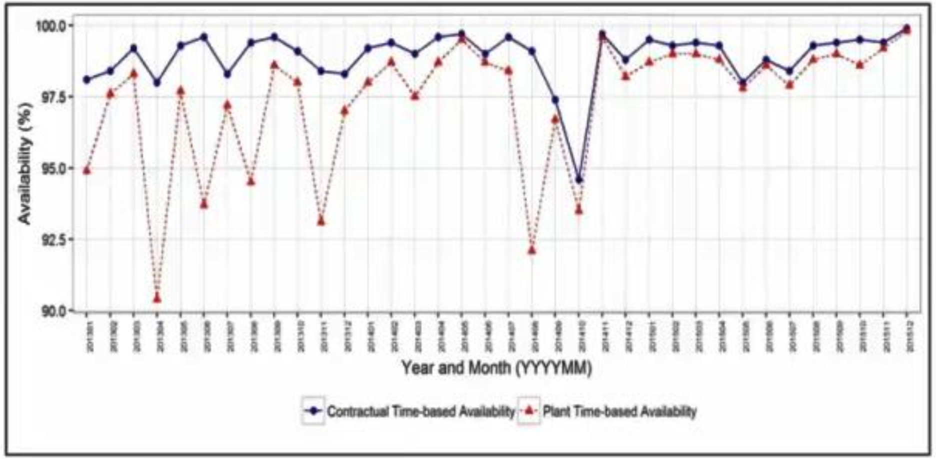
High Level Process Steps



OPERATIONAL ENERGY ASSESSMENT

Historical Net Energy & Losses

- Data screened for quality
- Remove plant start-up bias and one-time events where appropriate
- Availability and Energy Loss Data are assessed for consistency
- Plant Energy-based availability is preferred vs. time based or contractual
- Red-flags, questions etc. forwarded to client for comment
- Analysis is tailored to each project



OPERATIONAL ENERGY ASSESSMENT

Historical Gross Energy

- Adjust for availability, curtailment and other losses:
  - » $Gross_{POR} = \frac{Net_{POR}}{Avail_{plant}} + Curt + All\ Other$
    - $Gross_{POR}$ = Estimated monthly gross energy production
    - Net_{POR} = Reported monthly net energy production
    - $Avail_{plant}$ = Plant availability for the month, expressed as a fraction
    - $Curt$ = Plant curtailment, expressed as an energy loss
    - $All\ Other$ = All other plant energy losses
- Adjust for Days in the Month:
  - » $Gross_{POR,norm} = Gross_{POR}\left(\frac{30}{Days_{Month}}\right)$

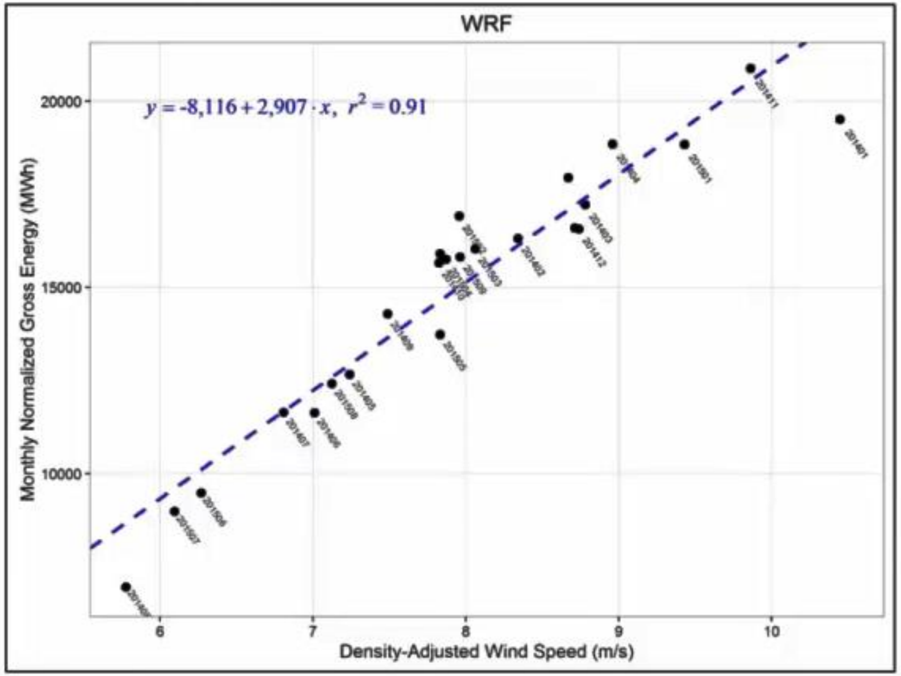
Future Gross Energy

- Adjust Resource for Seasonality:
  - » EX: Density-adjust reference wind speeds (Wind Only)
    - $Resource_{ref} = V_{obs}\left(\frac{\rho_{obs}}{\rho_0}\right)^{1/3}$
- Plant Power Curve: fit a linear model between normalized Gross and the reference resource
  - » $Gross_{\ norm} = m * Resource_{ref} + b$
- Use plant power curve to calculate LT normalized Gross Energy on a monthly basis
- Convert normalized values back to day-weighted months
  - » $Gross_{LT,monthly} = Gross_{LT,monthly,norm}\left(\frac{Days_{Month}}{30}\right)$

OPERATIONAL ENERGY ASSESSMENT

- Future Net Energy:
  - » $Net_{LT} = Gross_{LT} \times (avail_f) \times (1 - curt_f) \times (1 - deg_f) \times (1 - other_f)$
  - » Future loss assumptions are typically based on the historical annualized values.
  - » Assess one-off events, credits and penalties to loss assumptions
- Probabilities of Exceedance:
  - » Typical uncertainties include: measurement, analysis methods, adjustments, natural resource variations and future projections.
  - » Aggregated as Square Root Sum of Squares
  - » Assuming a normal distribution of errors, future annual and evaluation period projections are presented at the P50, P75, P90, P95 and P99 levels.

Example Plant Power Curve



OPERATIONAL ENERGY ASSESSMENT

Historical Performance per Project→

(aggregated annual and evaluation uncertainties and associated net energy probabilities of exceedance at the P50, P75, P90, P95, and P99)

Project	Uncertainty %	P50	P75	P90	P95	P99
	8.0%	383.6	362.9	344.4	333.3	312.5
	8.2%	329.8	311.7	295.3	285.6	267.2
	7.8%	352.8	334.3	317.7	307.7	289.0
	9.1%	165.3	155.2	146.1	140.7	130.5
	7.7%	268.2	254.4	241.9	234.4	220.4
	7.5%	349.3	331.6	315.6	306.0	288.0
	7.5%	255.7	242.7	231.1	224.1	211.0
	5.0%	297.4	287.3	278.2	272.7	262.5
	7.5%	513.8	487.8	464.3	450.3	424.0
	5.3%	166.3	160.5	155.2	152.0	146.0
	11.0%	158.6	146.8	136.2	129.8	117.9

Project	Future Evaluation Period (Years)	Uncertainty (%)	P50	P75	P90	P95	P99
	17	3.7%	383.6	373.9	365.2	360.0	350.2
	17	3.5%	329.8	322.0	315.0	310.9	303.0
	17	3.3%	352.8	344.8	337.7	333.4	325.4
	17	4.2%	165.3	160.6	156.4	153.9	149.1
	17	3.4%	268.2	262.0	256.5	253.2	247.0
	20	3.6%	349.3	340.9	333.2	328.7	320.1
	20	3.4%	255.7	249.9	244.6	241.5	235.6
	18	2.6%	297.4	292.1	287.4	284.6	279.3
	16	3.2%	513.8	502.6	492.4	486.4	475.0
	18	2.6%	166.3	163.4	160.8	159.2	156.2
	14	4.5%	158.6	153.7	149.4	146.8	142.0

→ Future Performance

EXAMPLE: OPERATING COST MODEL

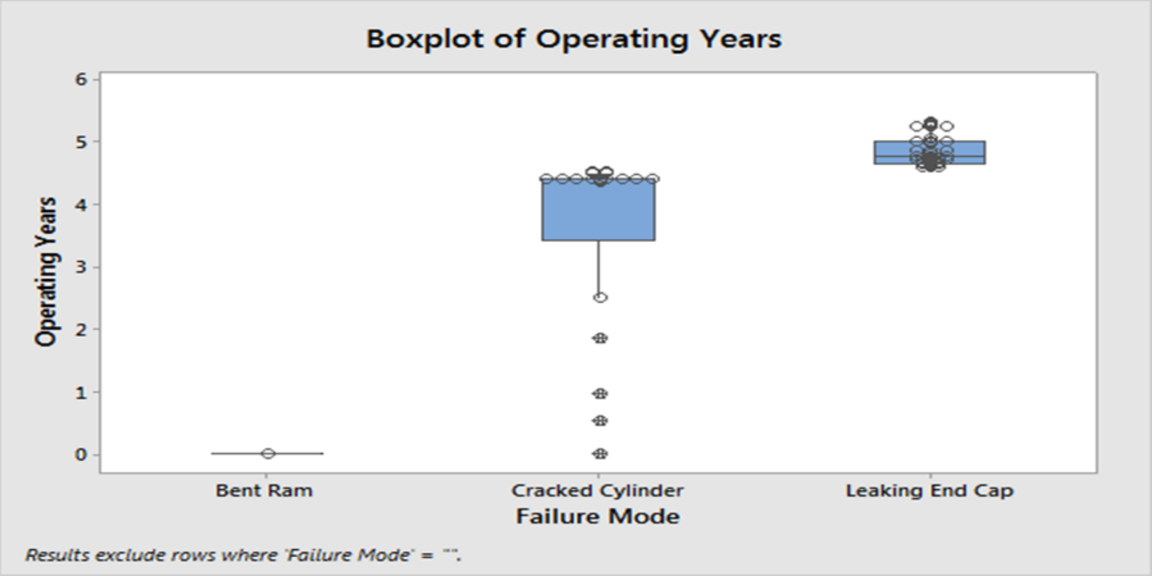
Hydraulic Pitch Actuator Failure Data

<u>Scenario:</u> Warranty dispute between plant owner and turbine OEM

<u>Failure Data:</u>

- Pitch actuators – 3 per turbine
- Cost of replacement: crane/labor costs exceed the cost of new actuator ~ 2X
- Inspection and replacement dates provided
- Multiple failure modes observed

<u>Objective:</u> develop a cost model that projects the operating costs out to year 20 and 25.



COD: 7/11/2011

1. **Bent Ram: N=1**
2. **Cracked Cylinder N = 21**
3. **Leaking End Cap N = 41**

Total: 63 Replacements

WEIBULL CURVE "FIT" FOR ALL 63 FAILURES

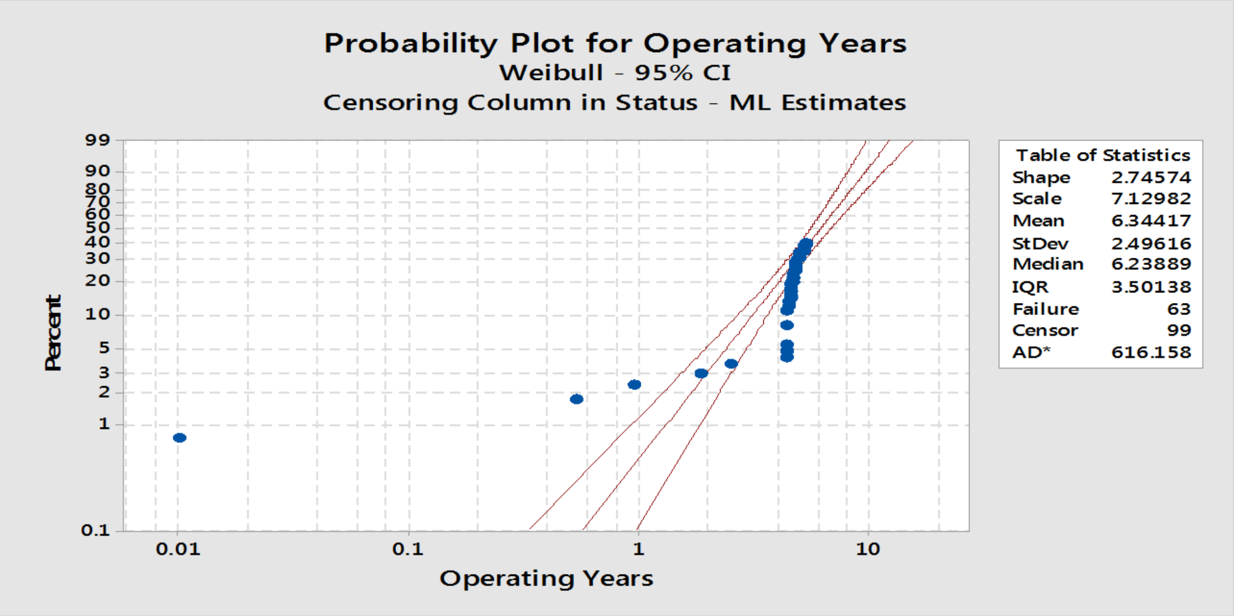
Observations:

Raw data has large "dog leg"

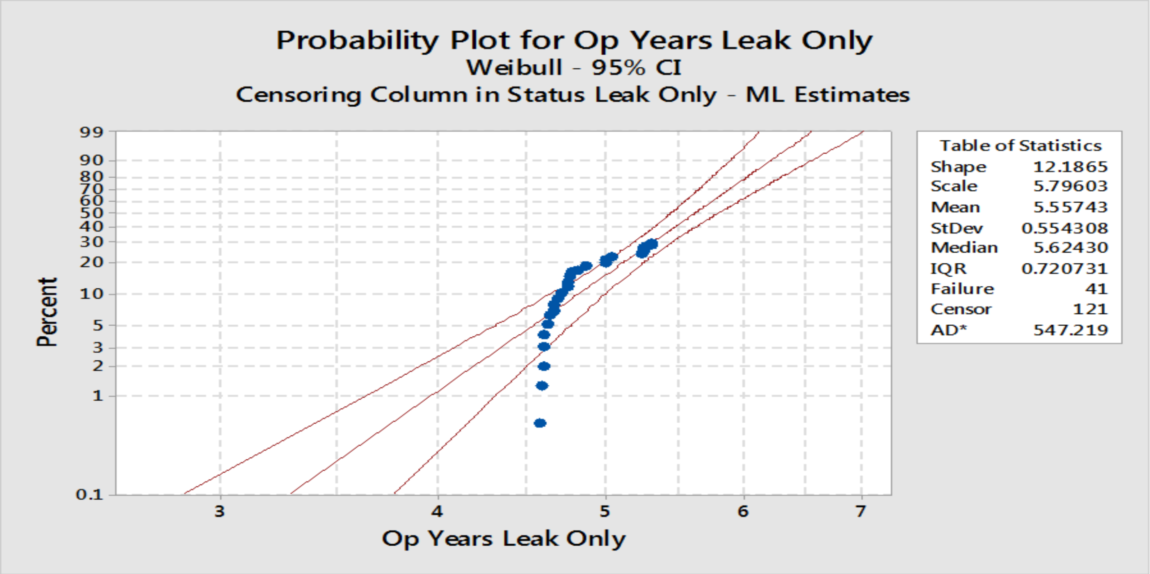
Typical for wind industry:

- Bathtub infant mortality
- Remote Equipment
- Failures declared based on inspection date
- Definitions of failure

  "Failing" vs. "Failed"



WEIBULL “FIT” FOR LEAK ONLY FAILURES



COST MODEL INPUTS

#	Cost Inputs:	Value	Comments
1	Project COD		
2	Number of WTG		
3	MW Rating:		
4	Net Capacity Factor		
5	PPA: ($/MW)		
6	PTC: ($/MW)		
7			
15	Actuator Cost		
16	Inflation rate		
17	Actuator Cost w/ inflation		
18	Pitch Actuator Delivery Cost @ 2.5%		
19	Avg. Crane & Labor Cost per actuator		
20	Total Cost (parts and labor) - per actuator		
21		Capacity Factor Multiplier	Lost production days per event
22	Best Case:	1	1
23	Base Case:	1	3
24	Worst Case:	1	5

Crane Fee
Pitch cylinders per day
Crew
Site Labor Rate ($/hr)
Hrs per day
Total labor per day
Avg. Cost per Pitch Cylinder (Crane and Labor)

Variables		
Time Horizon:	25 Years	25 years - fixed
Rounding Assumption: whole or fractional	Whole	Whole - fixed
Replacement Strategy	No Crane	Crane, No Crane
Life Improvements over time	Yes	Yes, No
Failure Mode:	Leak Only	All Modes, Leak Only

	Initial Weibull parameters @ 95% CI		Subsequent Life Values	
	Shape	Scale	Shape	Scale
Best Case:	9.13	5.58	4.00	9.40
Base Case:	12.19	5.80	12.00	8.00
Worst Case:	16.27	6.02	4.00	7.70

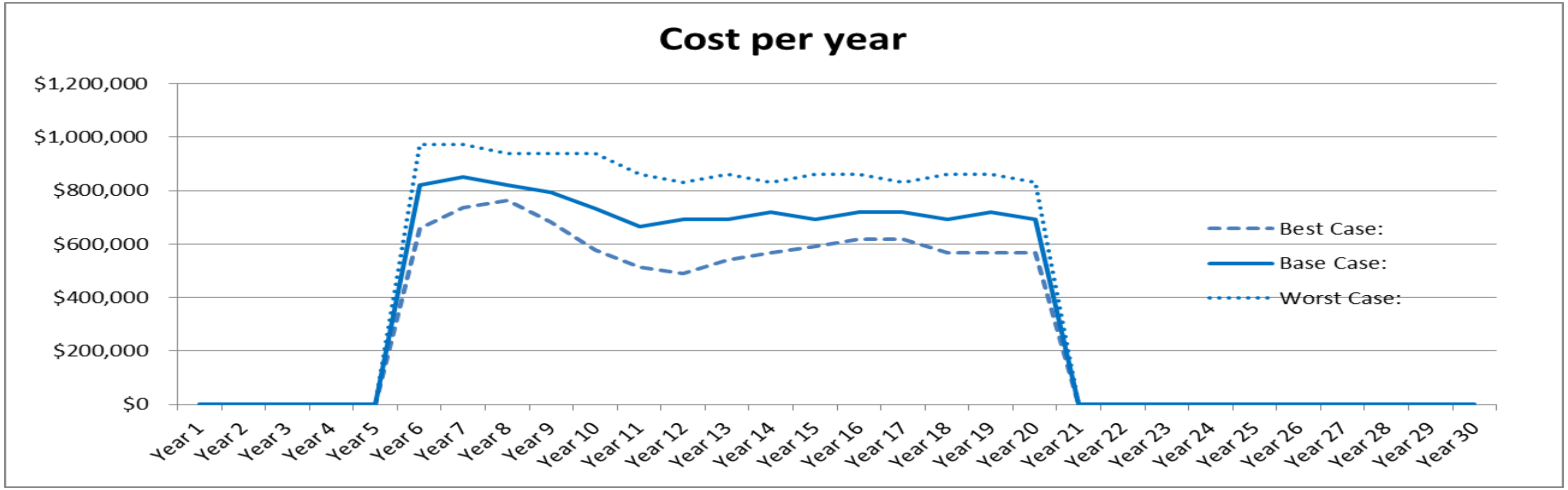
Outputs					
	Total Replacements	Yr 5 - Yr 25 Total Cost	1st Mean Life (yrs)	Weighted Avg. Life (yrs)	# of times each actuator replaced
Best Case:	400	$ 7,720,553	5.3	7.7	2.5
Base Case:	451	$ 9,732,477	5.6	7.1	2.8
Worst Case:	535	$ 12,826,380	5.8	6.6	3.3

MODEL SCENARIOS

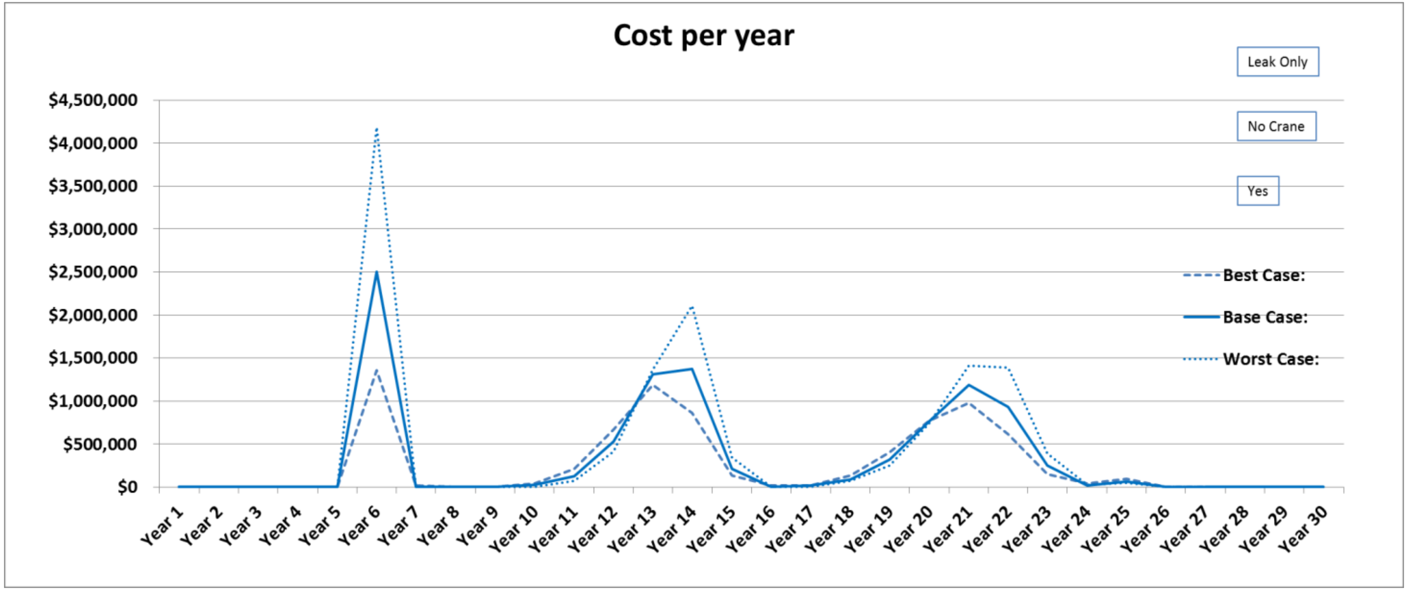
3 factors x 2 levels = 8 runs with 3 outputs each = 24 scenarios

No.	Failure mode	Crane	Improved Replacement	Variation Scenai	Total Replacements	1st Mean Life (yrs)	Weighted Avg. Life (yrs)	# of times each actuator replaced
1	All	Crane	Yes	Best Case:	432	7.2	7.7	2.7
2	All	Crane	Yes	Base Case:	421	6.3	7.1	2.6
3	All	Crane	Yes	Worst Case:	411	5.6	6.6	2.5
4	All	Crane	No	Best Case:	461	7.2	N/A	2.8
5	All	Crane	No	Base Case:	518	6.3	N/A	3.2
6	All	Crane	No	Worst Case:	576	5.6	N/A	3.6
7	All	No Crane	Yes	Best Case:	432	7.2	7.7	2.7
8	All	No Crane	Yes	Base Case:	421	6.3	7.1	2.6
9	All	No Crane	Yes	Worst Case:	411	5.6	6.6	2.5
10	All	No Crane	No	Best Case:	461	7.2	N/A	2.8
11	All	No Crane	No	Base Case:	518	6.3	N/A	3.2
12	All	No Crane	No	Worst Case:	576	5.6	N/A	3.6
13	Leaks Only	Crane	Yes	Best Case:	400	5.3	7.7	2.5
14	Leaks Only	Crane	Yes	Base Case:	451	5.6	7.1	2.8
15	Leaks Only	Crane	Yes	Worst Case:	535	5.8	6.6	3.3
16	Leaks Only	Crane	No	Best Case:	608	5.3	N/A	3.8
17	Leaks Only	Crane	No	Base Case:	680	5.6	N/A	4.2
18	Leaks Only	Crane	No	Worst Case:	915	5.8	N/A	5.6
19	Leaks Only	No Crane	Yes	Best Case:	400	5.3	7.7	2.5
20	Leaks Only	No Crane	Yes	Base Case:	451	5.6	7.1	2.8
21	Leaks Only	No Crane	Yes	Worst Case:	535	5.8	6.6	3.3
22	Leaks Only	No Crane	No	Best Case:	608	5.3	N/A	3.8
23	Leaks Only	No Crane	No	Base Case:	680	5.6	N/A	4.2
24	Leaks Only	No Crane	No	Worst Case:	915	5.8	N/A	5.6

COST MODEL OUTPUT



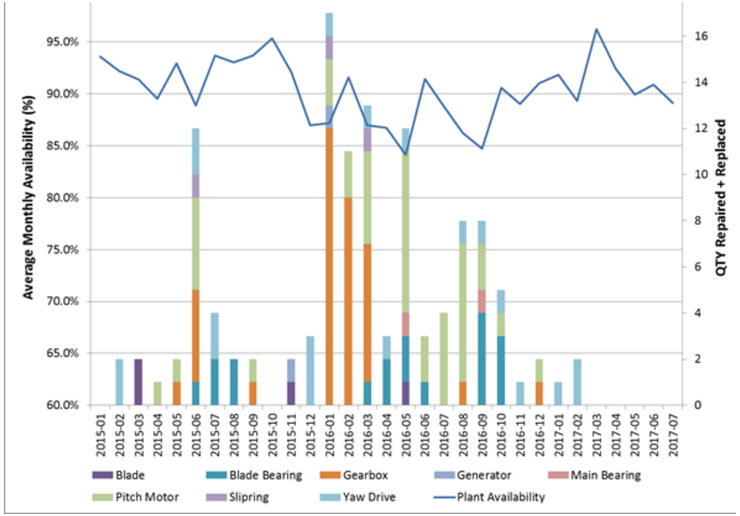
COST MODEL OUTPUT



OPERATIONAL ASSESSMENT FROM RECENT M&A PROJECT

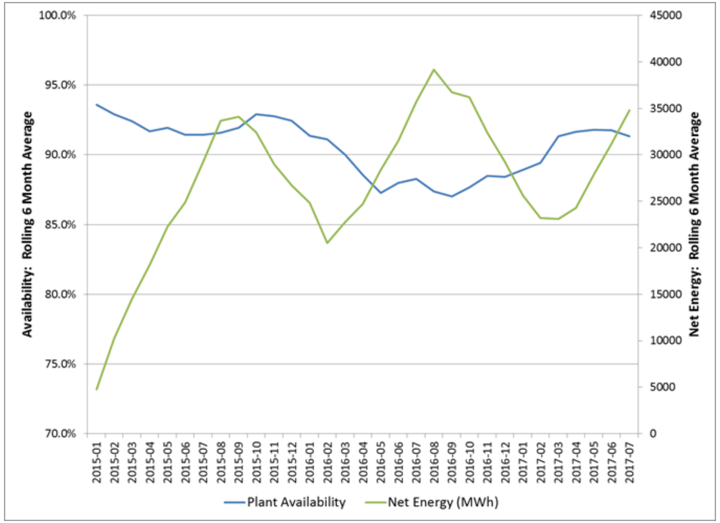
Availability along with component usage:

- Odd pattern, but no apparent correlation to component usage



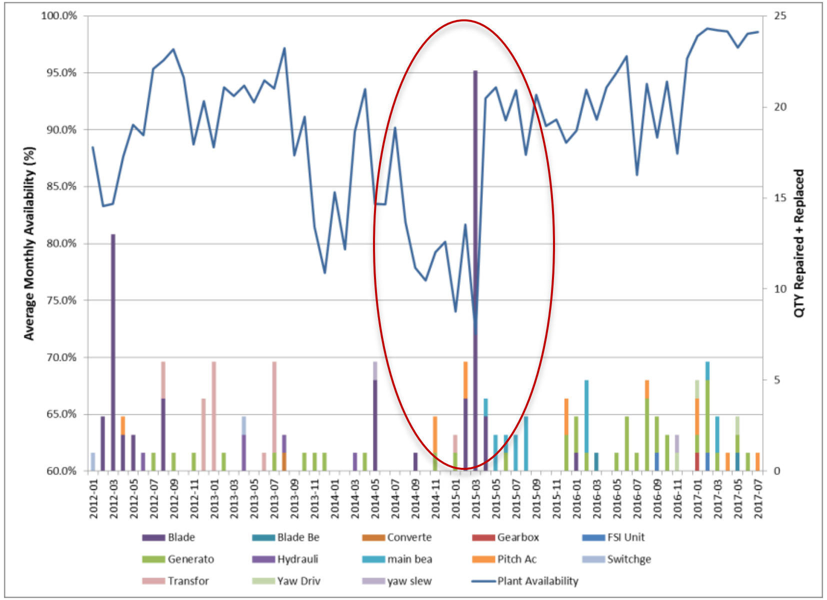
The same availability along with net energy plotted with 6 month rolling average:

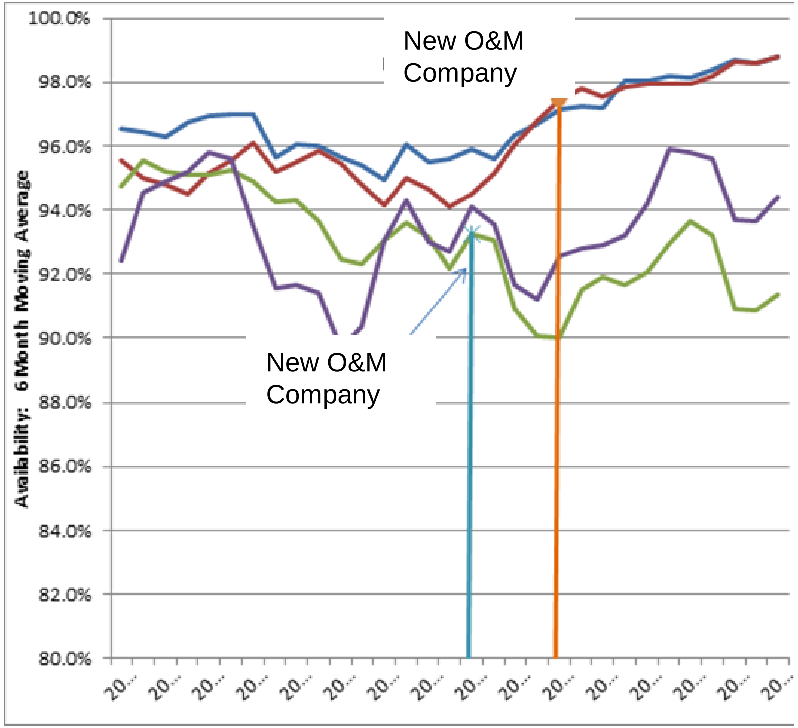
- Discovered that plant is curtailed seasonally due to presence of bats



OPERATIONAL ASSESSMENT

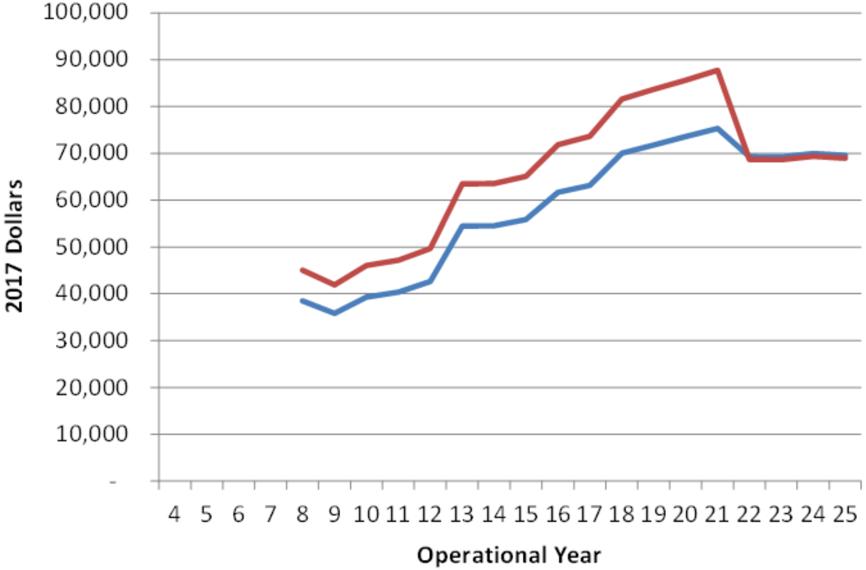
Availability and Component Usage Examples



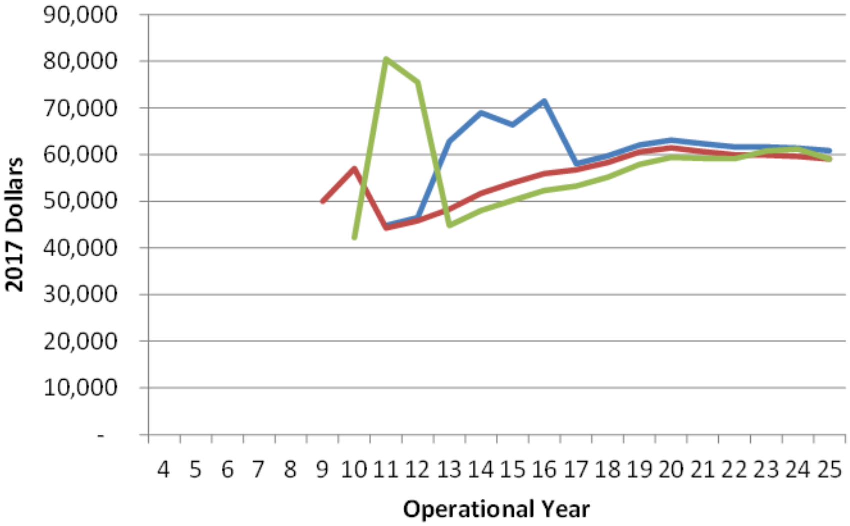


OPERATIONAL ASSESSMENT

Operating Expenditure (OPEX) Forecast Analysis by Turbine Type



2 Projects – Turbine Type “A”



3 Projects – Turbine Type “B”

ACKNOWLEDGEMENTS & CONTACT INFO

Stephen Lightfoote – Sr. Wind Energy Analyst

https://www.youtube.com/watch?v=oCunp8RX8yA

Emil Moroz – Sr. Wind Turbine Engineer

David Coffey – Sr. Wind Turbine Engineer

https://www.linkedin.com/in/david-coffey-40a5a74/

TURBINE SUITABILITY
IEC 61400-1 DESIGN REQUIREMENTS

“TO ENSURE THE STRUCTURAL INTEGRITY OF WIND TURBINES”

WIND TURBINE SUITABILITY PROCESS FOLLOWS TURBINE DESIGN PROCESS

Site Specific "Real World" environmental conditions simplified

If site conditions are not within design assumptions

(b) Demonstration of structural integrity "Design Load Cases"

per IEC 61400-1

"Wind Turbine Classes" and "Design Load Cases" per IEC 61400-1

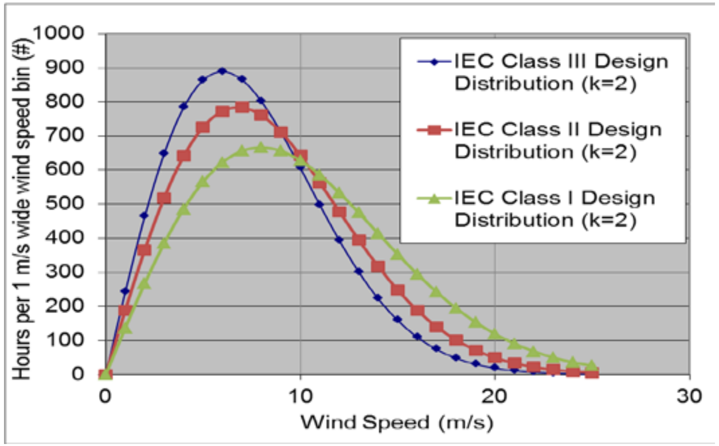
Site Specific Loads derived from scenarios mimicking Design Process

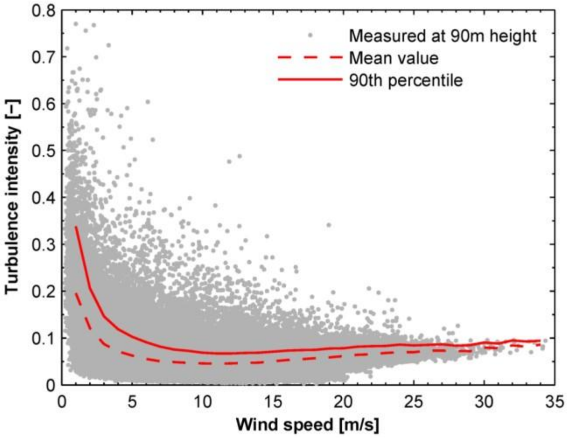
Compare to Design Loads

Draw Suitability Conclusions

IEC DESIGN CLASSES

Global "Real World" environmental conditions are simplified





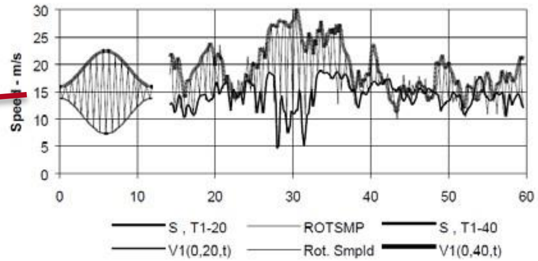
Wind turbine class		I	II	III	S
V_{ave}	(m/s)	10	8,5	7,5	Values specified by the designer
V_{ref}	* (m/s)	50	42,5	37,5	
	Tropical (m/s)	57	57	57	
$V_{ref,T}$	(m/s)	57			
A+	I_{ref} (-)	0,18			
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

COMPILATION OF CHALLENGING SCENARIOS FROM ALL AROUND THE WORLD

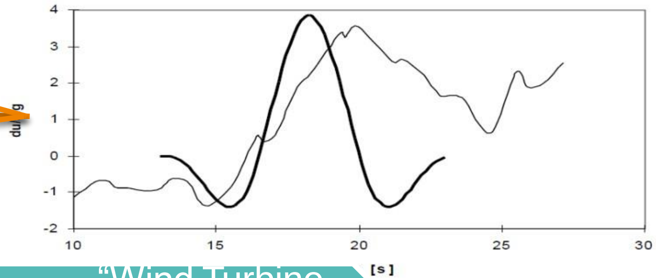
Table 2 – Design load cases

Design situation	DLC		Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r - 2$ m/s, V_r, V_r +2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and		U	N

Fig. 19 - EXTREME EVENTS FROM ONE YEAR OF DATA COLLECTION.
WIND SPEED TIME SERIES FROM MET. TOWER SENSORS
PLACED AT 20 METERS AND 40 METERS.
TCS Site 5 - 05/30/90 17:10 to 17:20



San Gorgonio Pass
Palm Springs, USA

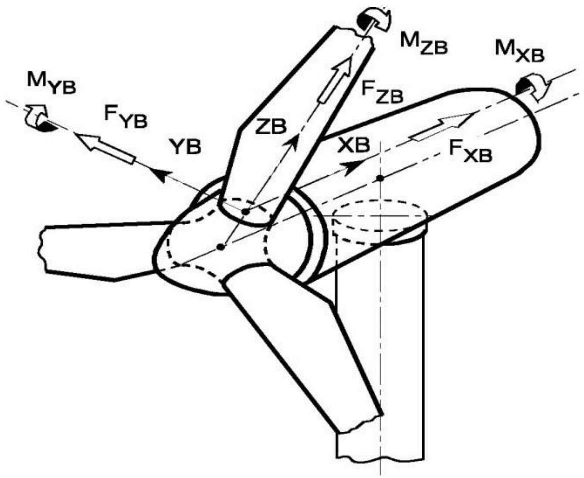


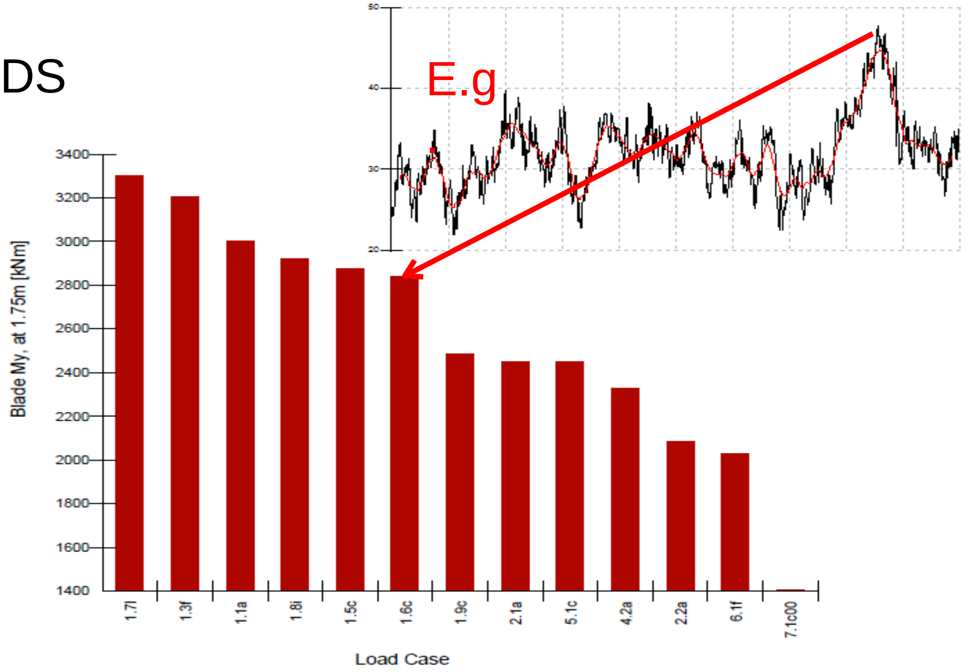
Extreme Operating Gust (EOG) – Ultimate Load Analysis (Growian site Germany)

Global “Real World” environmental conditions simplified

“Wind Turbine Classes” and “Design Load Cases” per IEC 61400-1

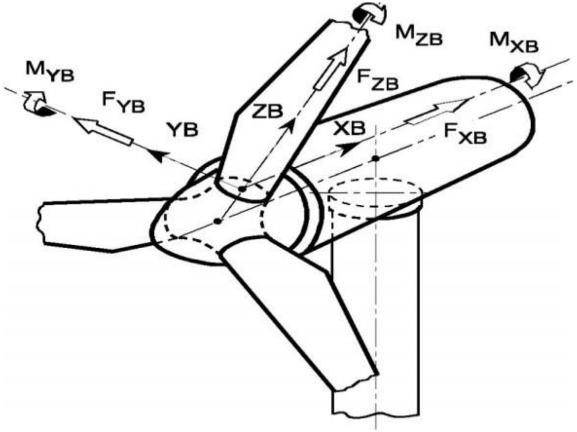
COMPONENT ULTIMATE LOADS

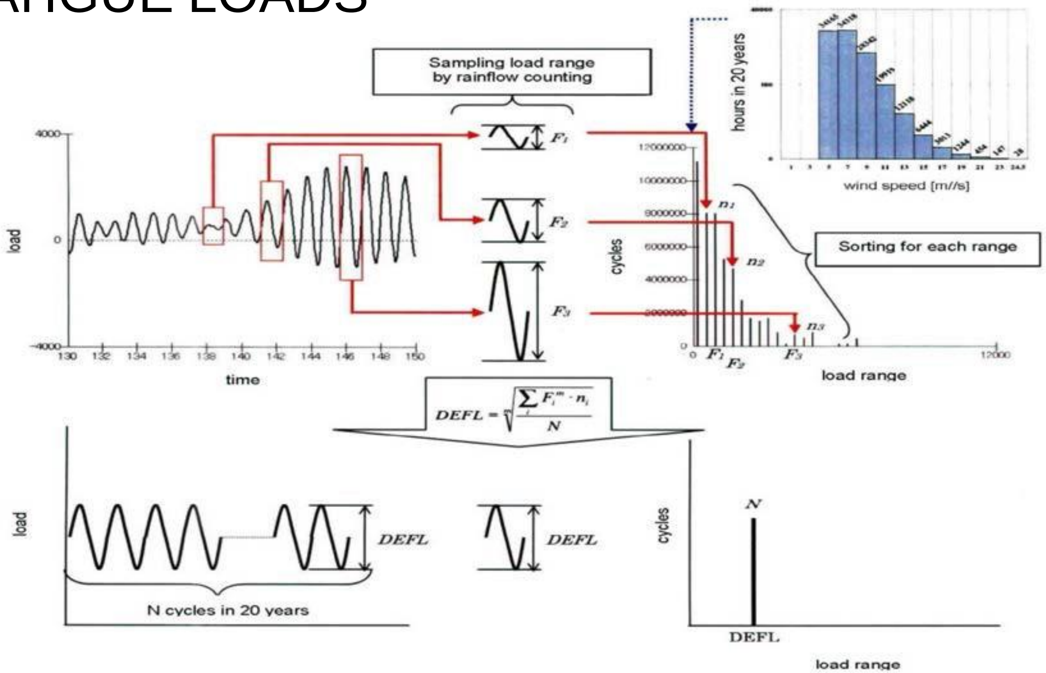




Global “Real World” environmental conditions simplified → “Wind Turbine Classes” and “Design Load Cases” per IEC 61400-1 → Design Loads (Ultimate)

COMPONENT FATIGUE LOADS





Global "Real World" environmental conditions simplified

"Wind Turbine Classes" and "Design Load Cases" per IEC 61400-1

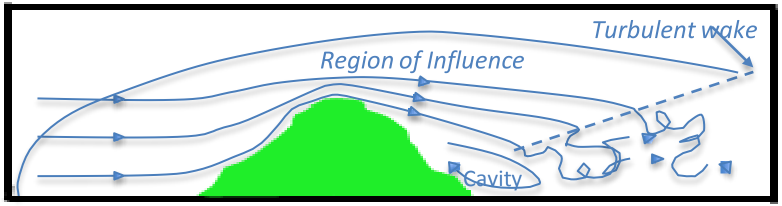
Design Loads (Fatigue)

TURBINE SUITABILITY

REAL WORLD CONDITIONS ARE IMPORTANT AND INFORMATION MAY BE LOST THROUGH SIMPLIFICATION

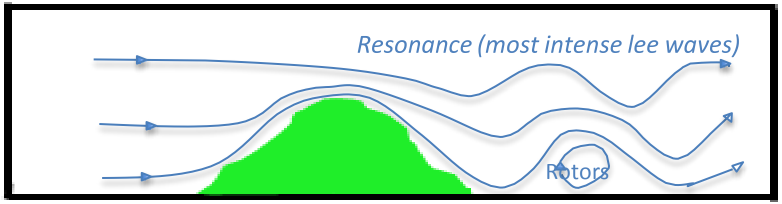
IDEALIZED FLOW OVER HILL

Neutral



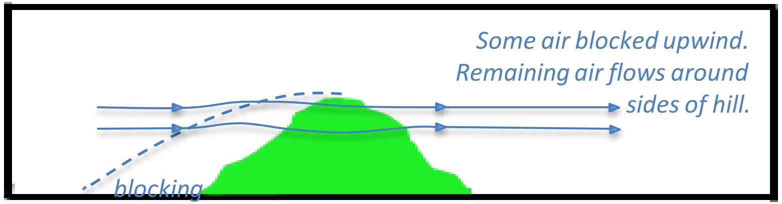
- Flow over and around hill
- Wakes and recirculation on lee side

Stable



- Capped flow over hill top
- Gravity waves on lee side

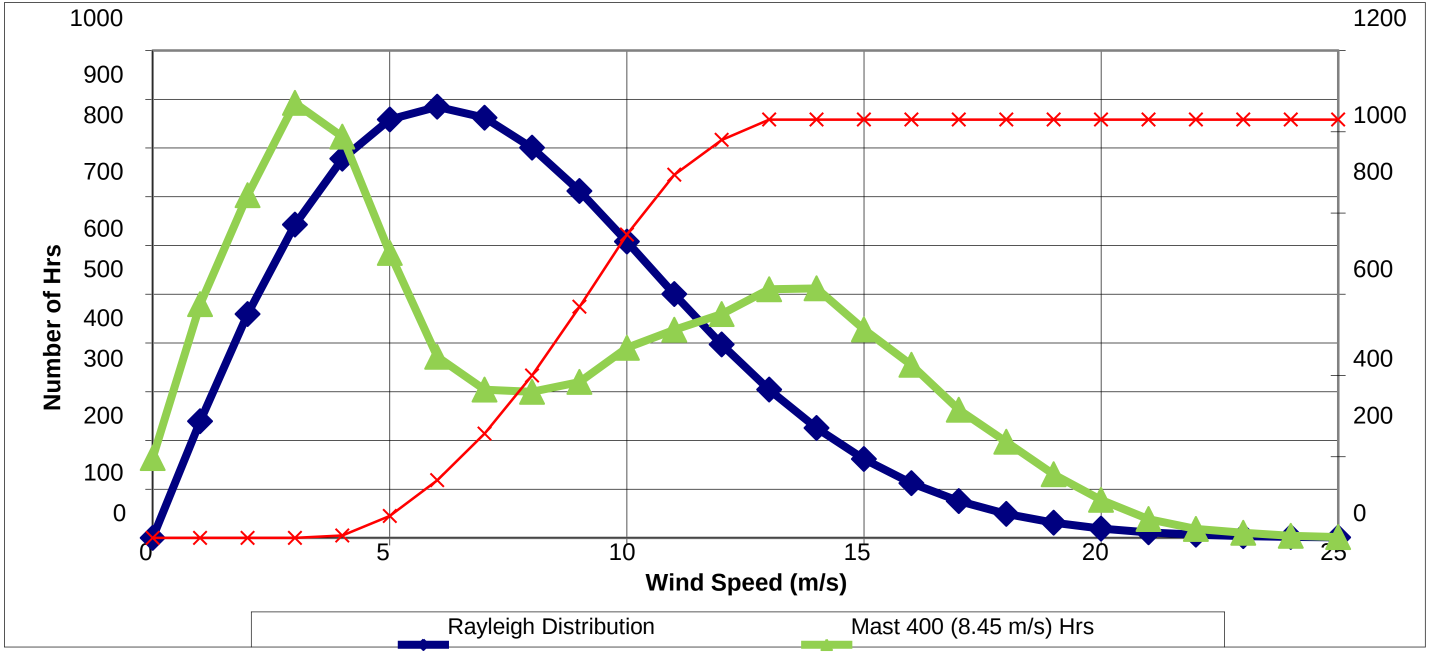
Very stable



- Air flow blocked at hill top
- Flow diverges around the side of the hill

Adapted from R.B. Stull (1988). "Introduction to Boundary Layer Meteorology"

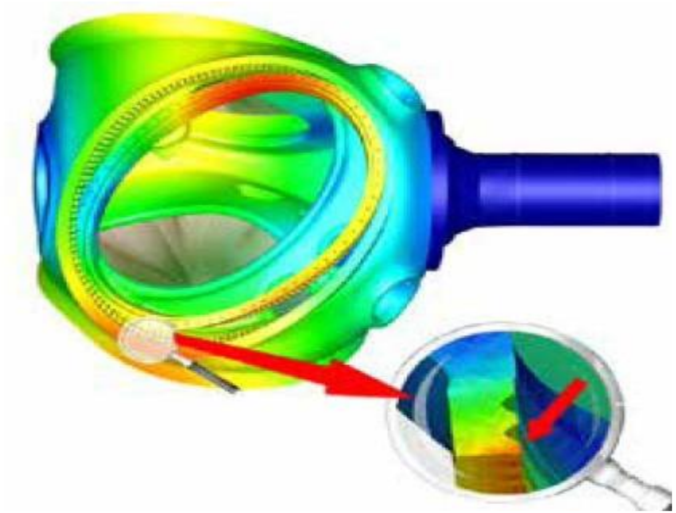
NON STANDARD WIND DISTRIBUTIONS



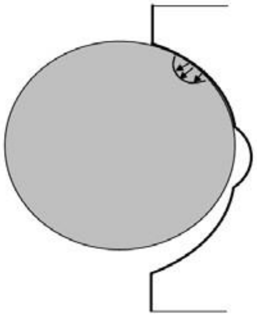
Both wind frequency distributions have an approx 8.5 m/s mean!

Double hump distribution means hours spent in above rated winds are closer to Class I than the Class II suggested by mean wind speed!

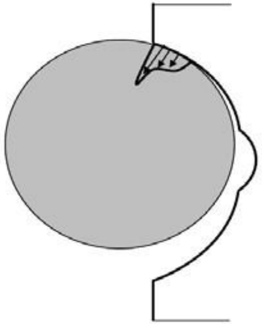
POSSIBLE RELIABILITY IMPACT OF UNEXPECTED LOADS



Better understanding could lead to lower COE



Normal Contact

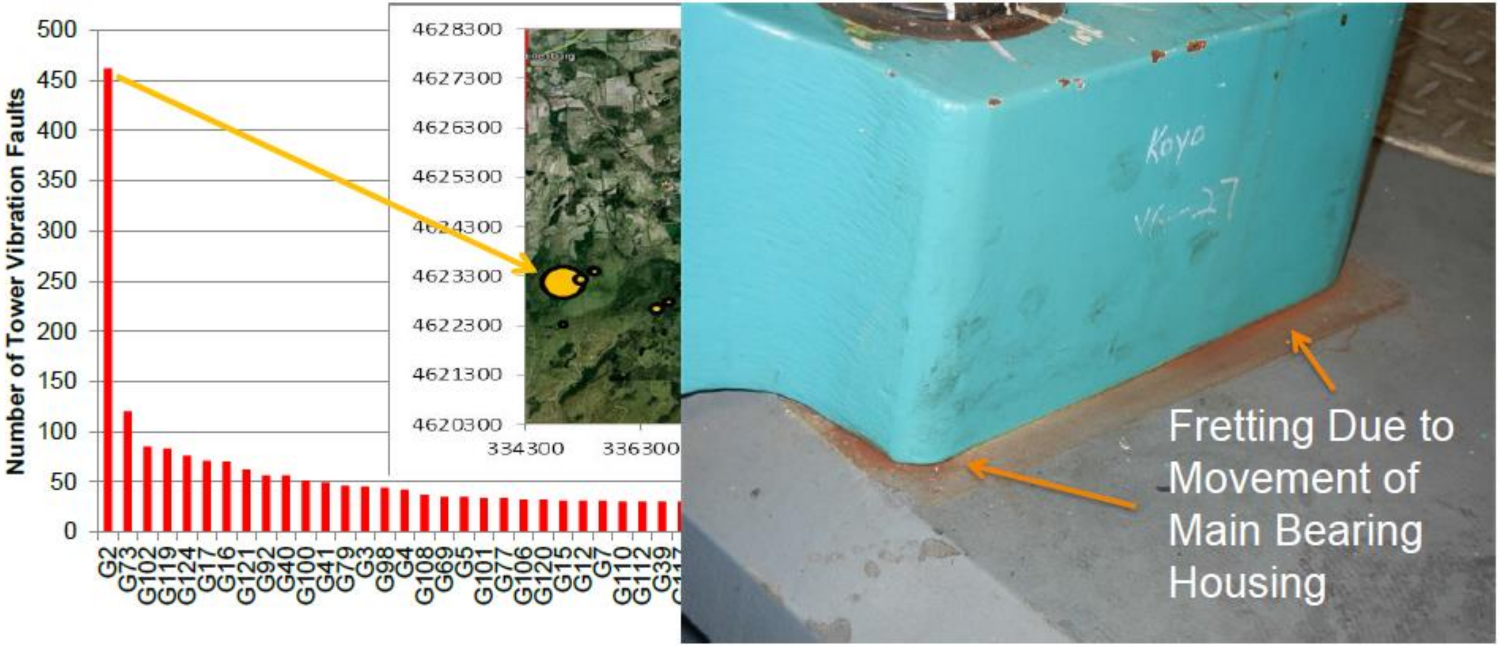


Contact with Ellipse Spill

- Design intent is for contact ellipse to be completely contained in raceway
- Under some load conditions, contact ellipse can spill over the end of the raceway
- Results in very high stresses on the end of the raceway

Bearing Damage from Ellipse Spill

CORRELATION OF (LESS COMPLEX) TERRAIN WITH TOWER VIBRATION FAULTS



Loads, Maintenance, or bit of both?

COMPARISON AGAINST DESIGN ENVIRONMENT

Site Characteristics	IEC Class IIA	Site*
50 Year Return 10-min Averaged V_{ref} (m/s)	42.5	40.7
Annual Average Wind Speed (m/s)	8.5	8.8
Wind Frequency Distribution – Shape Factor, k	2	2.5
Reference Turbulence Intensity (%)	16	16.5
Annual Average Air Density (kg/m^3)	1.225	1.19
Upflow (deg.)	8	6
Annual Average Vertical Shear	0.2	0.15
Minimum (Survival) Temperature (°C)	-20	-25

Design Basis Exceeded

Within Design Basis but is it ok?

* At most energetic / demanding location(s) within wind farm

Turbines may still be suitable if site specific loads are shown to be within Design Loads (IEC 61400-1 Section 11 option “b”)

Thank You!