Wind Turbine Maintenance Costs

Assessing the Potential of Gear Oil Improvements

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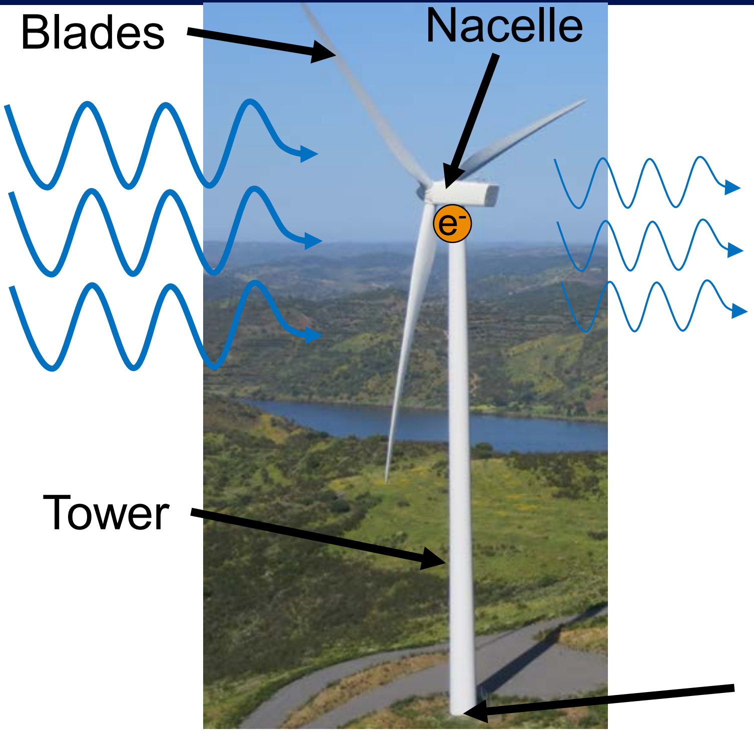
Anatomy of a Wind Turbine



Base

Energy Output $\propto W\alpha\beta D^2$ **<60%**

W = wind quality

α = mechanical transfer function

Β = electrical transfer function

D = swept diameter

Ranjbar, Mohammad Hassan, et al. 2019. “Reaching the Betz limit experimentally and numerically.” *Energy Equipment and Systems* 7(3): 271–278.

Most wind turbines look unremarkable from the outside

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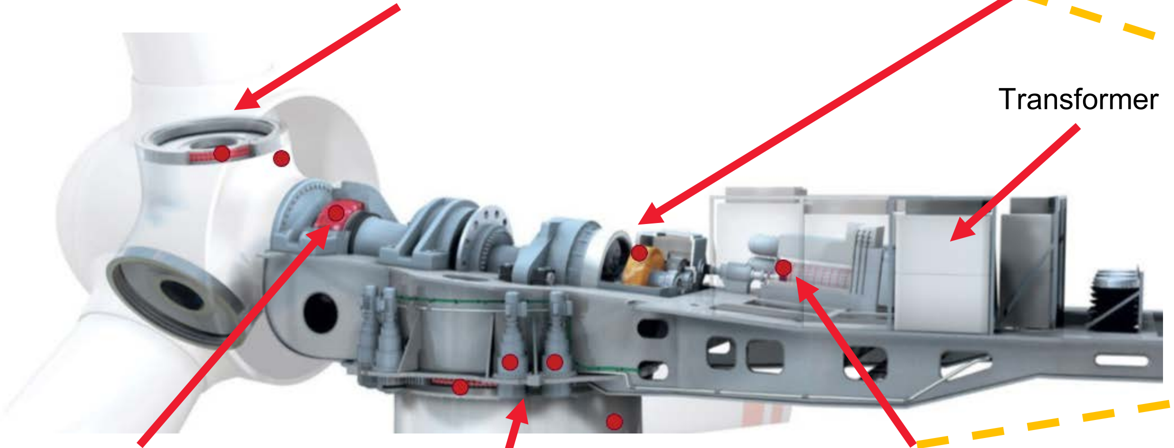
Torque to Electricity



2.2 Megawatt Turbine

rpm = rotations/minute

“It’s a Tribology Lab on a Tower”

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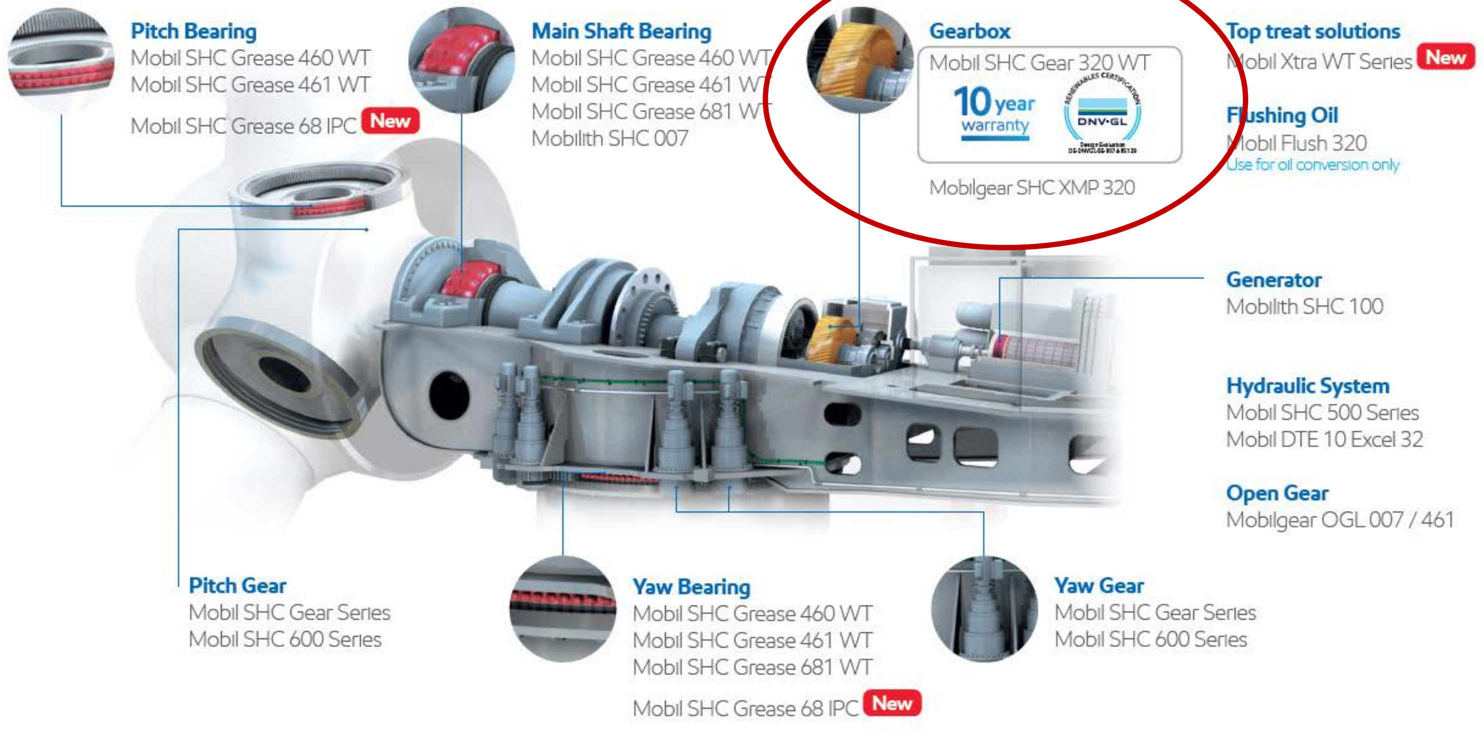
High-Performance Lubricants for Wind Turbines



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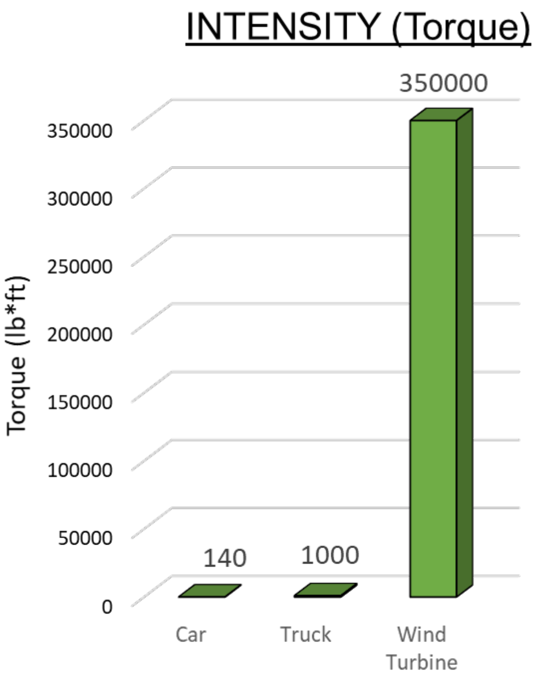
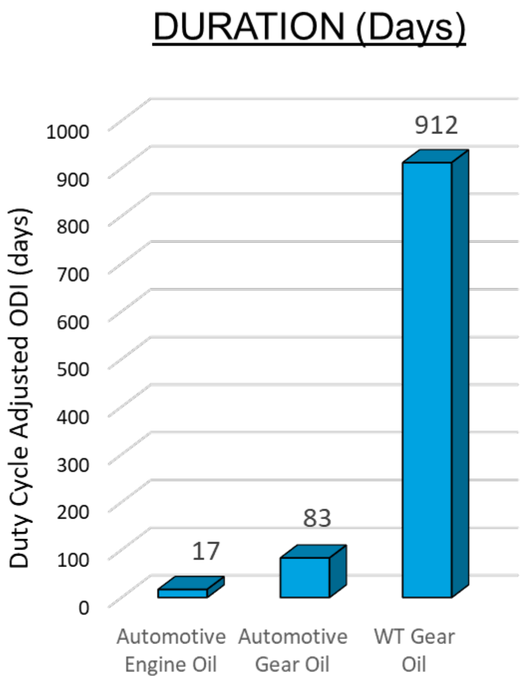
A Challenging Application

car = typical 2 liter inline 4 engine

truck = typical 14 L inline 6 engine on a class 8 truck

wind turbine = 1 MW with a rotor speed of 20 rpm





Wind turbine gear oils (WTGO) require advanced technology

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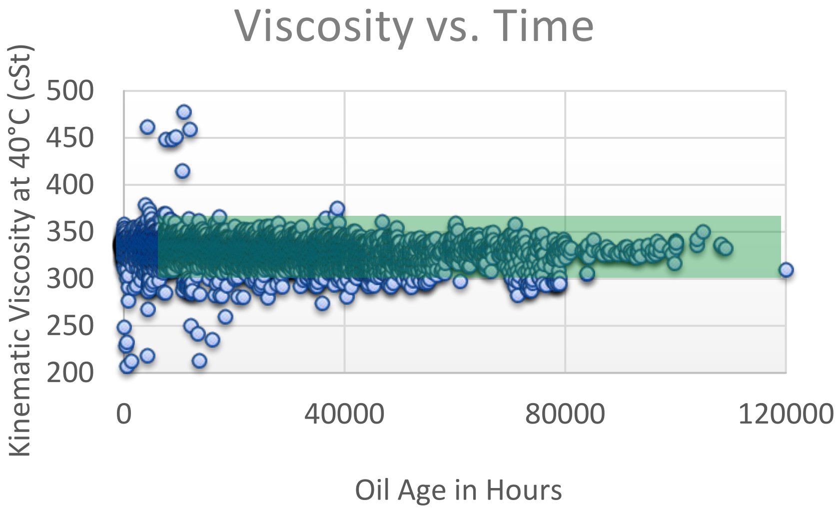
How long can a WTGO last?

Wind turbines are typically a well-controlled environment

- Low Sump Temperature (<70°C)
- Highly Filtered
- Remote Locations
- Actively Monitored

- *data from lubricant analysis database*
- *37,000 data points*
- *1 product*
- *“wind turbine main gearbox” in the meta data.*



A well-maintained gear oil can last more than a decade

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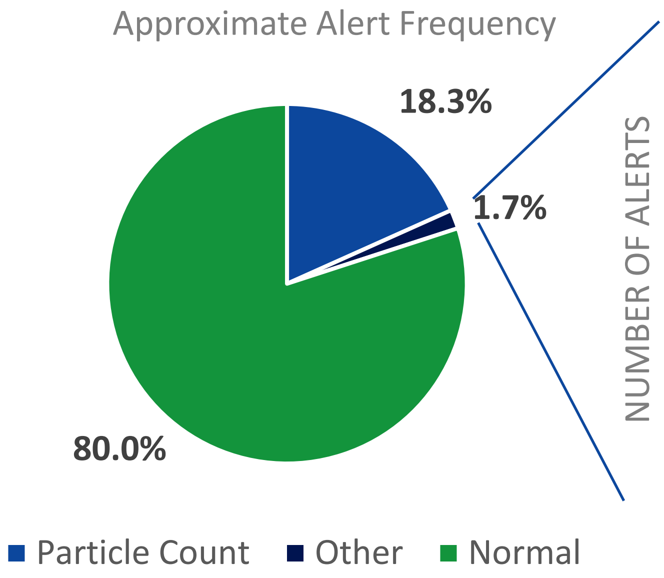
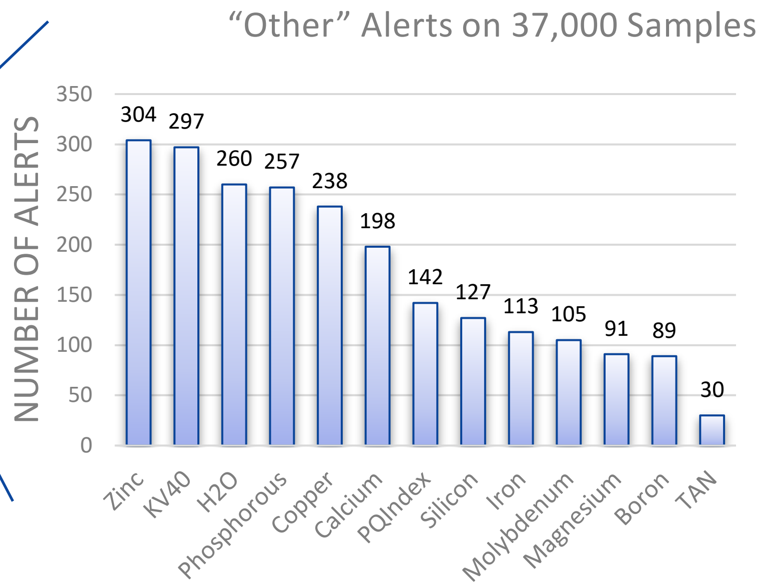
How are WTGO condemned?

Failure modes from previous slide





Lubricants are an asset

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Background on Wind Operations & Maintenance (O&M)

- Operations and maintenance (O&M) costs make up 17%–34% of the lifetime cost of wind energy
- Gearbox maintenance is a significant cost driver
  - High repair cost
  - Relatively high failure rate
- Is there an opportunity for new gear oils to reduce costs associated with gearbox maintenance?

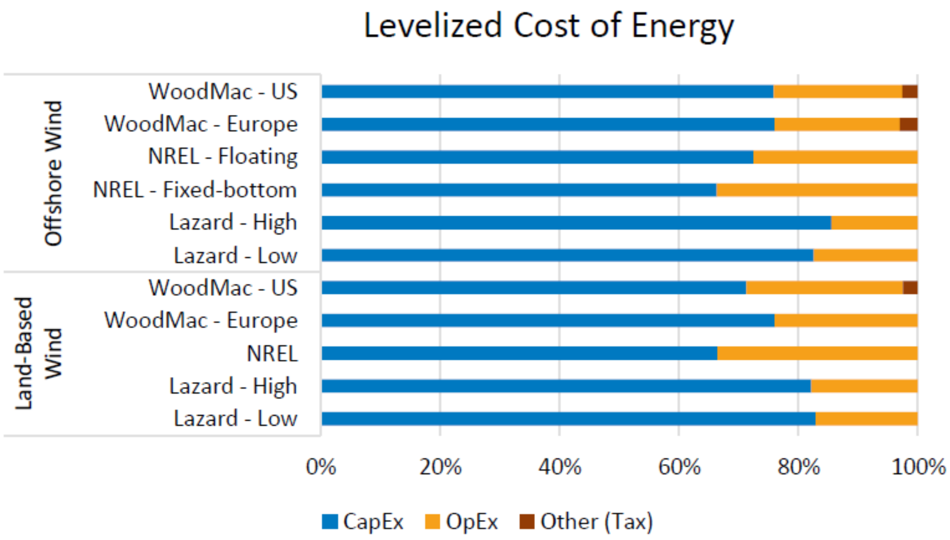

Figure Data Sources:

- Wood Mackenzie. 2023. “Europe Levelized Cost of Energy 2022 (LCOE) – Sensitivity Analysis Report.” Accessed via subscription.
- Wood Mackenzie. 2022. “United States Levelized Cost of Energy (LCOE) Report.” Accessed via subscription.
- Stehly, T., and P. Duffy. 2022. *2022 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-81209.
- Lazard. 2023. “Lazard LCOE+.” https://www.lazard.com/media/nltb551p/lazards-lcoeplus-april-2023.pdf.

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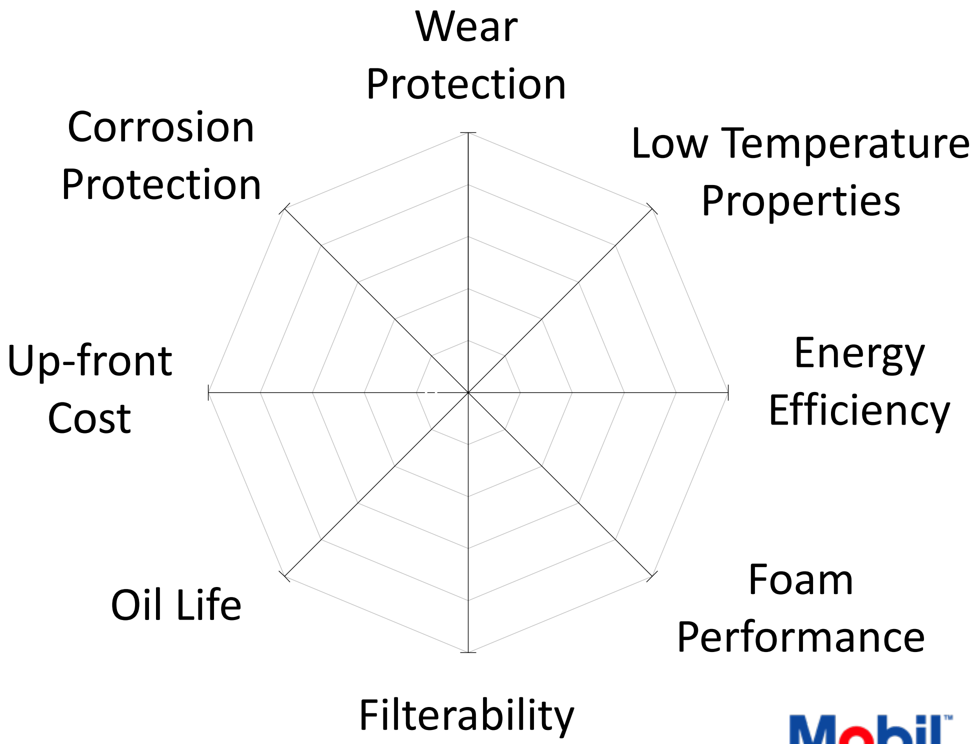
Lubricant Development Philosophy

- Listen to the *Voice of the Customer*
- Stay ahead of *Equipment Trends*
- Keep a large *Chemical Toolbox*
- Develop a *Balanced Formulation*
- Reduce the *Total Cost of Ownership*



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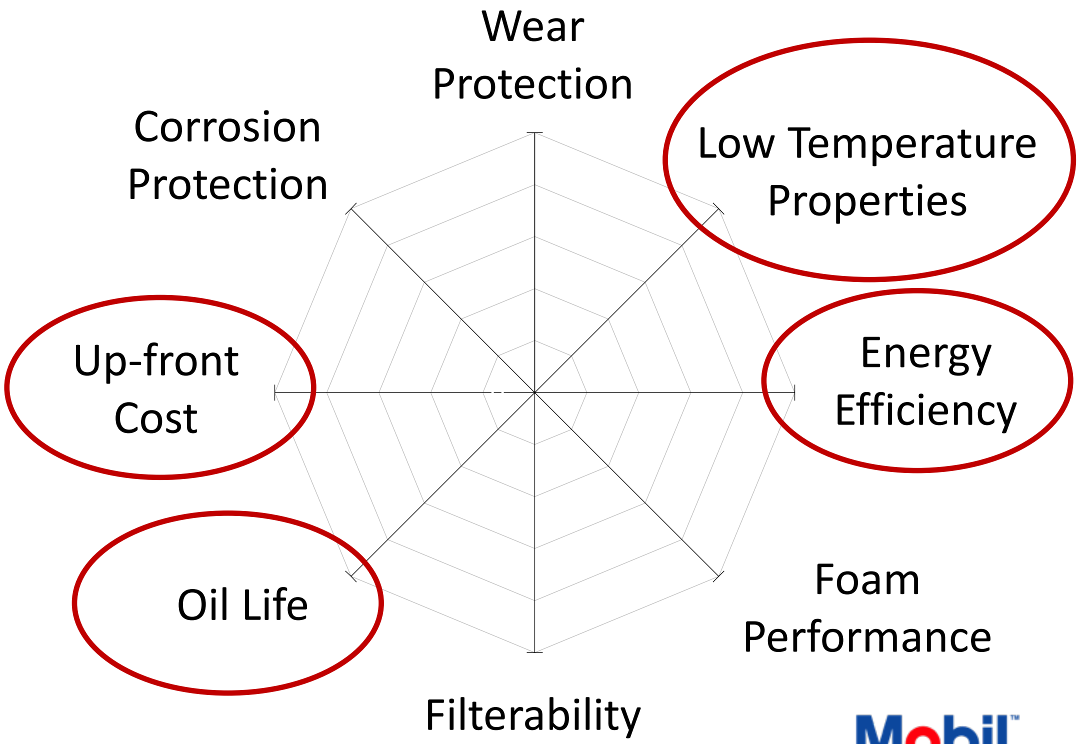
How do wind turbine gear oils contribute to overall wind levelized cost of energy in the U.S. fleet?



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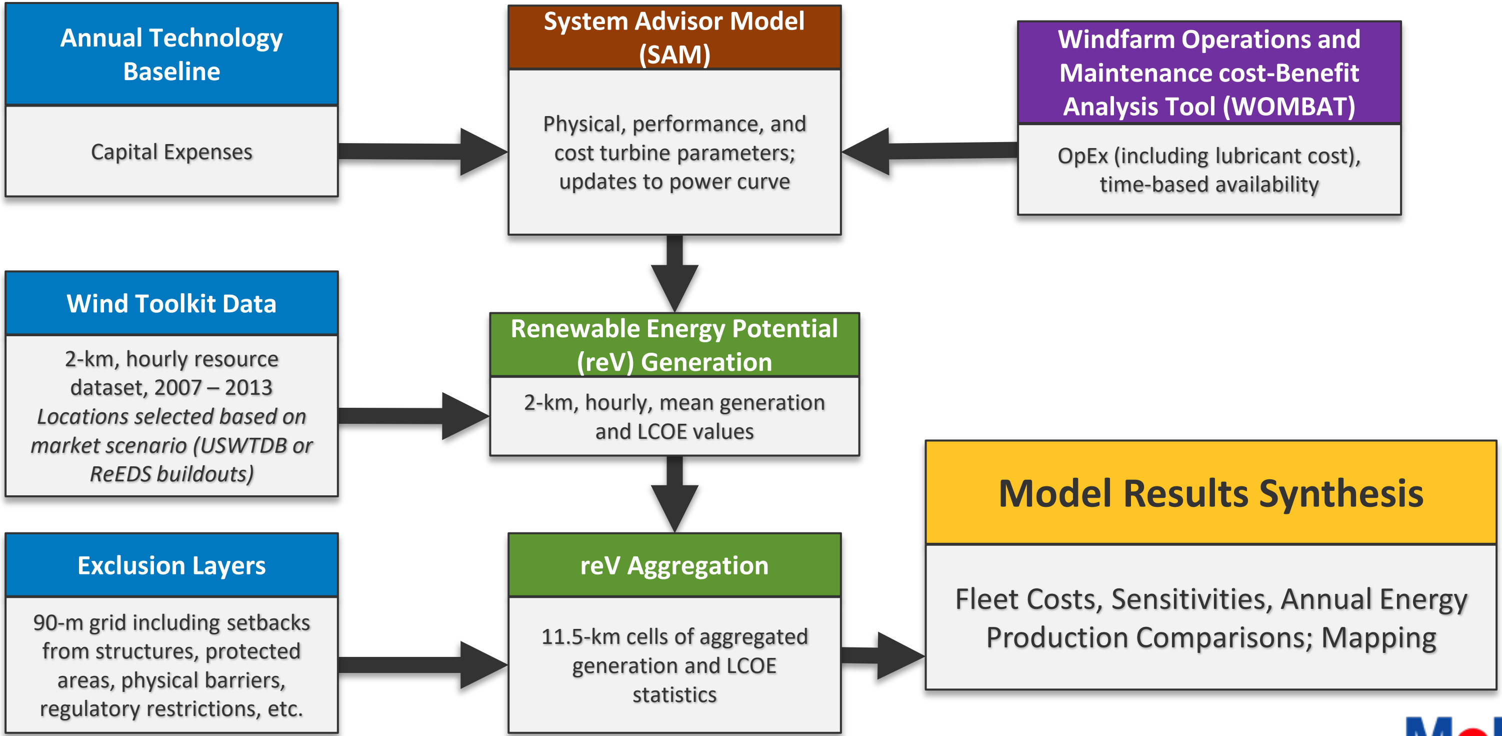
Project Vision

1. Develop Realistic / Lubricant Scenarios
2. Simulate Lubricant Impact on Individual Turbine
3. Scale Simulation to Wind Farm Impacts
4. Extrapolate Simulation to Provide Fleet Levelized Cost of Energy
5. Perform Sensitivity Analysis to Inform Lubricant Design

Overall Modeling Flow



Lubricant Scenario Development

Improvement Mechanism	Scenario		
	Baseline	Realistic	Stretch
Oil change frequency	Every 5 years	Every 7 years (-29%)	Every 10 years (-50%)
Oil cost	$15/liter	$10/liter (-33%)	$5/liter (-67%)
Cold weather operation	21 hours of cold weather stoppage per year in Ice Class 2+	15 hours / year (-29%)	9 hours / year (-57%)
Gearbox efficiency	Unmodified reference power curve	+0.5% at <10% load +0.2% at 10-50% load +0.1% at >50% load	+1.0% at <10% load +0.4% at 10-50% load +0.2% at >50% load

Value? →

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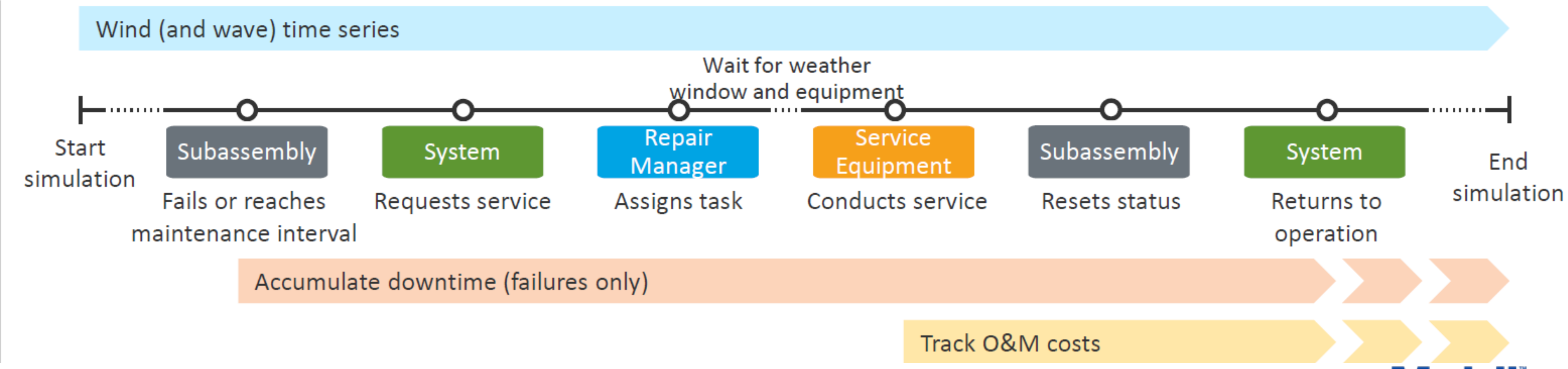
WOMBAT: Windfarm Operations and Maintenance cost-Benefit Analysis Tool

- WOMBAT evaluates O&M costs using discrete event simulation
- Each subassembly has user-defined repair and maintenance tasks with their own timing



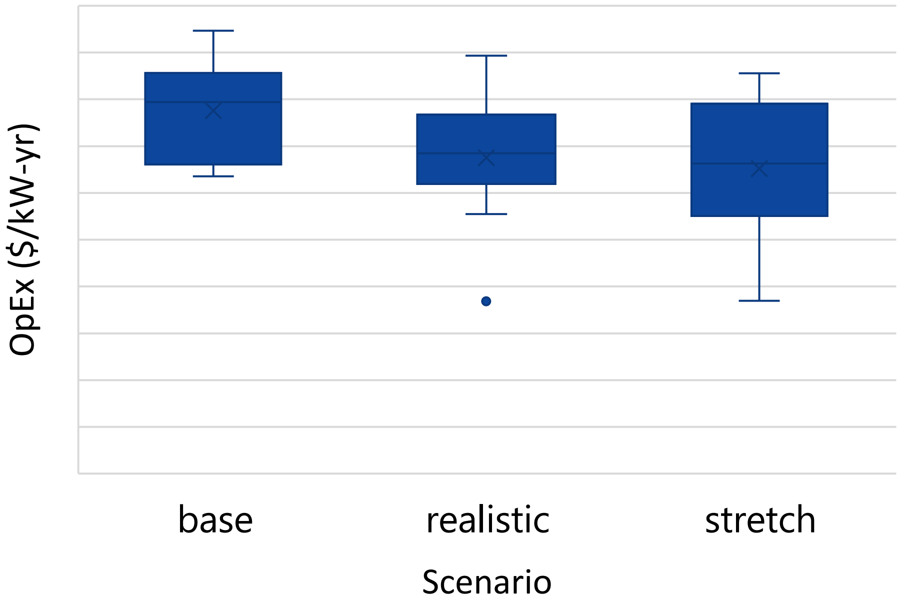
Lubricant O&M Tasks in WOMBAT

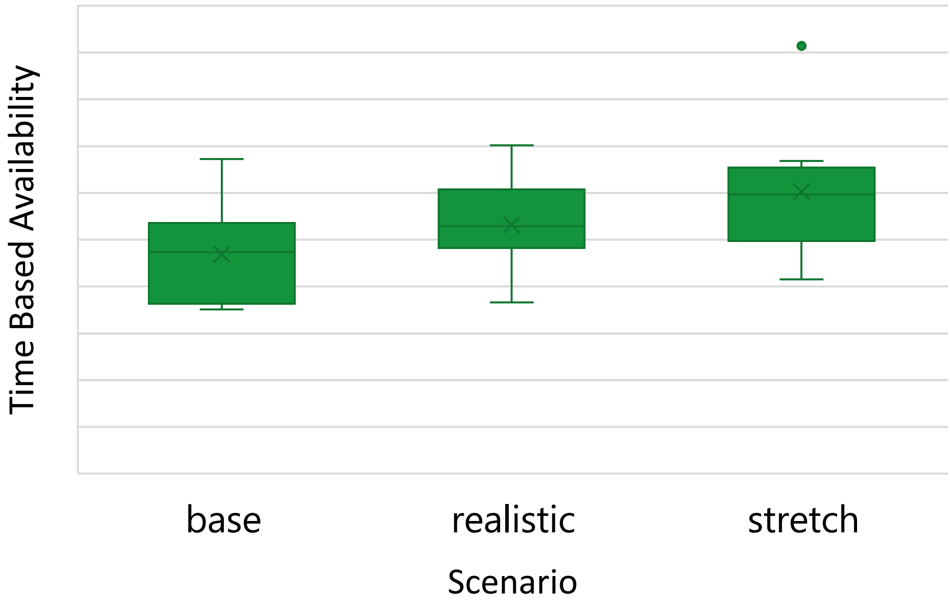
Current Land-Based Wind: 40 GE 1.5-MW turbines

Task	Frequency	Hours	Material Cost	Metrics Affected
Oil change	Every 5 / 7 /10 years	12	$3,600 / $2,400 / $1,200	OpEx, Availability
Minor repair	0.4 per turbine per year	8	$288 / $192 / $96	OpEx
Major repair	0.006 per turbine per year	22	$3,600 / $2,400 / $1,200	OpEx
Cold start	3 per year in Ice Class 2+	7 / 5 / 3*	None	Availability

**Each number represents a cold start time needed for the turbine to connect with the grid*

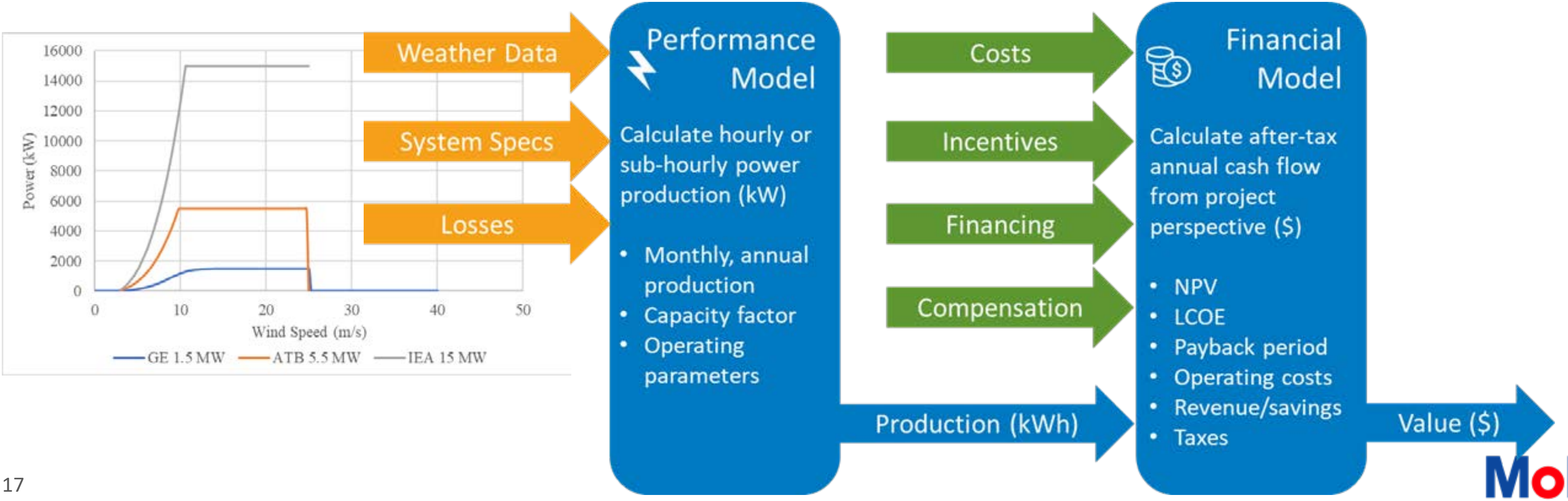
Example WOMBAT Results: 1.5 MW Turbine





SAM: System Advisor Model

- Combines robust wind energy performance models with detailed project cash flow modeling
- Calculates metrics such as annual energy production (AEP)



SAM Modeling Parameters

Turbine	Market Scenario	Hub Height (m)	Rotor Diameter (m)	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut-out Wind Speed (m/s)	CapEx ($/kW [from ATB])	Annual Performance Degradation (%)	Project Lifetime (years)
GE 1.5 MW	Current LBW	80	77	3.5	14.5	25	$1,233	0.87%	30
ATB 5.5 MW	2050 LBW	120	175	3.25	10	25	$525	0.53%	30
IEA 15 MW	2050 OSW	150	240	3	10.6	25	Fixed: $1,850 Floating: $2,703	1%	30

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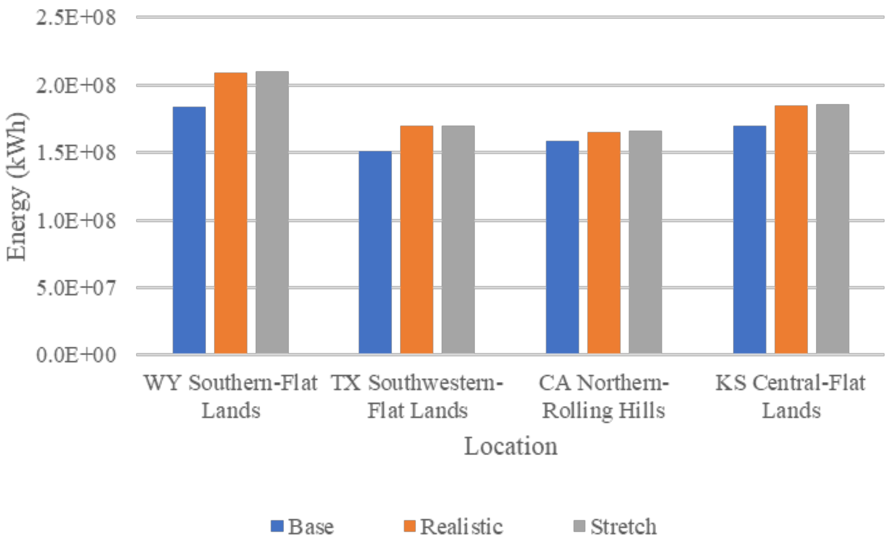
Example SAM Results

1.5 MW Turbine Assumption Set			
Hub Height (m)	80	**Cut-out Wind Speed (m/s)**	25
Rotor Diameter (m)	77	**CapEx ($/kW [from ATB])**	$1,233
Cut-in Wind Speed (m/s)	3.5	**Annual Performance Degradation (%)**	0.87%
Rated Wind Speed (m/s)	14.5	**Project Lifetime (years)**	30



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Levelized Cost of Energy

reV efficiently calls SAM simultaneously across thousands of locations to calculate LCOE (levelized cost of energy [$/MWh]), where:

$$LCOE = \frac{1000 * ((FCR * CapEx) + OpEx)}{AEP_{net}}$$

FCR = fixed charge rate (%/year)
CapEx = capital expenditures ($/kW), from ATB
OpEx = average annual operational expenditures ($/kW/year), from WOMBAT
AEP_{net} = net average annual energy production (MWh/year), from WTK

LCOE is helpful to compare projects/technologies with <u>different cash flow profiles and over time.</u>
LCOE does <u>not</u> capture the locational and time <u>value</u> of the generated energy and other services.

Impact on Levelized Cost of Energy

$$LCOE = \frac{1000 * ((FCR * CapEx) + OpEx)}{AEP_{net}}$$

where:

LCOE = levelized cost of energy ($/MWh)

FCR = fixed charge rate (%/year) NO CHANGE

CapEx = capital expenditures ($/kW) NO CHANGE

OpEx = average annual operational expenditures ($/kW/year) Changes with WOMBAT (cost)

AEP_{net} = net average annual energy production (MWh/year)

Changes with WOMBAT (time-based availability) & updates to power curves; cold-location dependent

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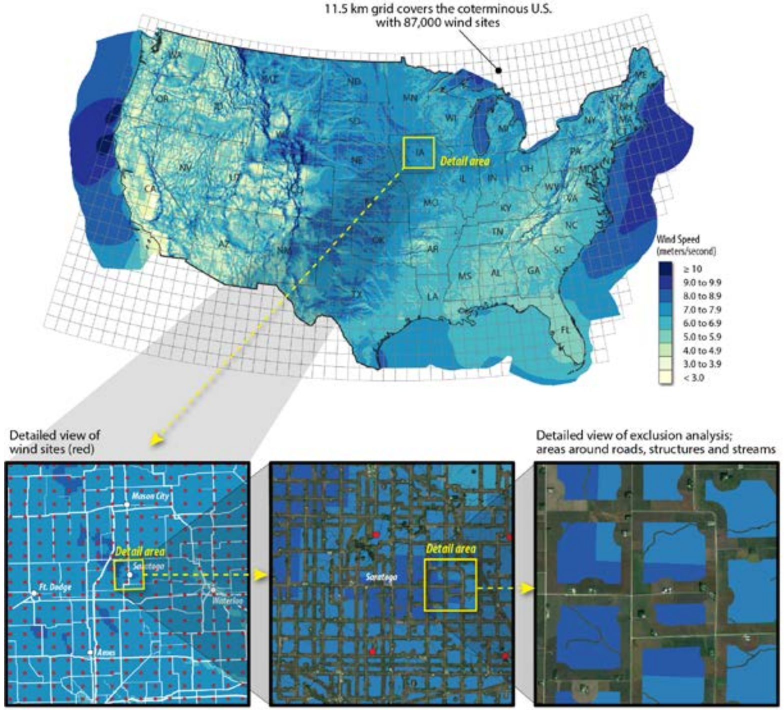
reV – Renewable Energy Potential Model

- High-performance computing model for massive spatial-temporal data
- Hourly multi-year generation profiles
- Installable capacity based on land characteristics
- Pulls results from SAM and WOMBAT together
- Extrapolates to fleet scale



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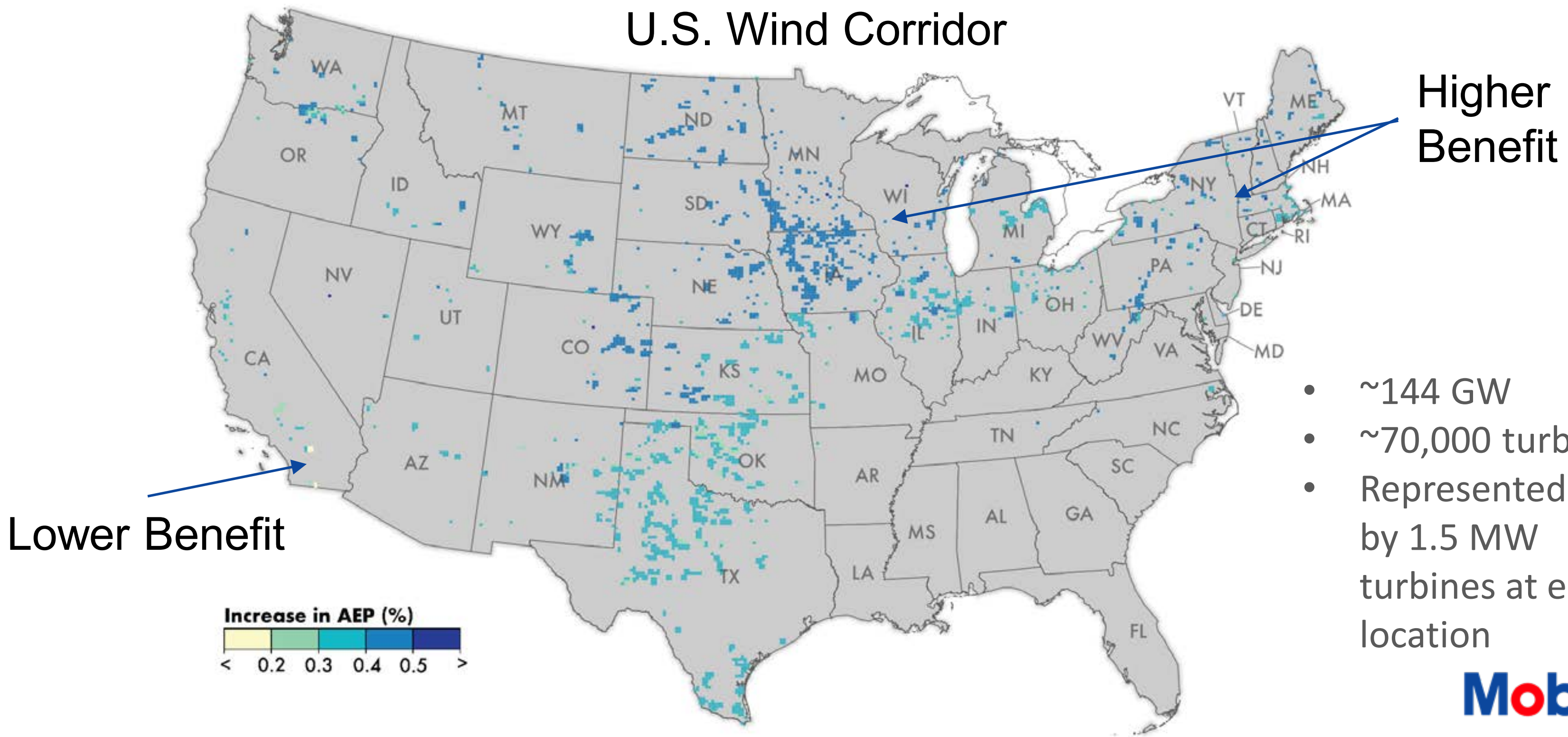
reV – Current Fleet Results



- ~144 GW
- ~70,000 turbines
- Represented in reV by 1.5 MW turbines at each location

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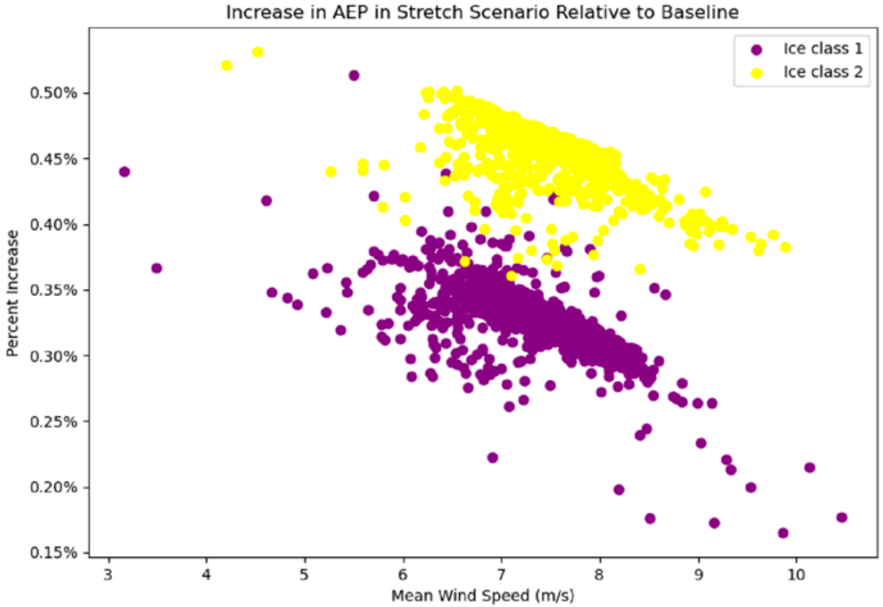
reV – Current Fleet Results

- Site-based AEP improved by 0.39% on average in stretch relative to baseline
- Approx. 45% of plants in “Ice Class 2”
- *Relative* improvement is better in low wind speed areas



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Results: Current Land-Based Fleet (~144 GW)

	Fleet Annual Energy Production	Median LCOE (not including transmission)	Fleet Cost ($/yr)	Difference in Fleet Cost ($/yr)	Difference in Fleet AEP	Difference in # Households
Baseline	492,191 GWh	$40.41 MWh	$18,030,199,848	–	–	–
Realistic	493,100 GWh	$40.01 MWh	$17,885,340,128	$144,859,720	909 GWh	~85,500
Stretch	493,998 GWh	$39.87 MWh	$17,851,535,361	$178,664,487	1,807 GWh	~170,000

Replaces all existing turbines with the GE 1.5 SLE; difference relative to baseline scenario; 2022 U.S. energy demand was 4,050,000 GWh (EIA); Household electricity consumption in 2021 was on average 10,632 kWh (EIA)

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Results: 2050 Projected Land-Based Fleet (~333 GW)

	Fleet Annual Energy Production	Median LCOE (not including transmission)	Fleet Cost ($/yr)	Difference in Fleet Cost ($/yr)	Difference in Fleet AEP	Difference in # Households
Baseline	905,960 GWh	$14.19/MWh	$12,660,031,084	–	–	–
Realistic	907,464 GWh	$13.99/MWh	$12,504,754,447	$155,276,637	1,504 GWh	~124,000
Stretch	908,498 GWh	$13.91/MWh	$12,448,848,518	$211,182,566	2,538 GWh	~209,500

2050 ReEDS mid-case scenario deployment using 5.5 MW turbines; difference relative to baseline scenario; 2050 U.S. energy demand estimated at about 6,000,000 GWh (Gagnon et al. 2023); household electricity consumption assumed 14% higher than 2021 numbers (EIA) resulting in 12,120 kWh

Results: 2050 Projected Offshore Fleet (~30.5 GW)

	Fleet Annual Energy Production	Median LCOE (not including transmission)	Fleet Cost ($/yr)	Difference in Fleet Cost ($/yr)	Difference in Fleet AEP	Difference in # Households
Baseline	141,480 GWh	$48.32/MWh	$6,820,974,376	–	–	–
Realistic	141,650 GWh	$47.97/MWh	$6,778,872,891	$42,101,485	170 GWh	~14,000
Stretch	141,761 GWh	$47.92/MWh	$6,778,062,343	$42,912,033	281 GWh	~23,200

2050 ReEDS mid-case scenario deployment using 15-MW turbines for half of the deployment of 61 GW; difference relative to baseline scenario; 2050 U.S. energy demand estimated at about 6,000,000 GWh (Gagnon et al. 2023); household electricity consumption assumed 14% higher than 2021 numbers (EIA) resulting in 12,120 kWh

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Lubricant Technologies Modeled

	Unit	Baseline	Realistic	Stretch	Inputs to Modeling Tools	Metrics Affected
Efficiency Improvements					SAM	AEP
<99.99% load	%	–	0.1	0.2		
<50% load	%	–	0.2	0.4		
<10% load	%	–	0.5	1.0		
Cost of Oil	$/liter	15	10	5	WOMBAT	OpEx
Oil Replacement Interval	years	5	7	10	WOMBAT	AEP (Availability), OpEx
Cold Start for IEA Ice Class 2+ Regions	hours/year	21	15	9	WOMBAT, reV	AEP (Availability)

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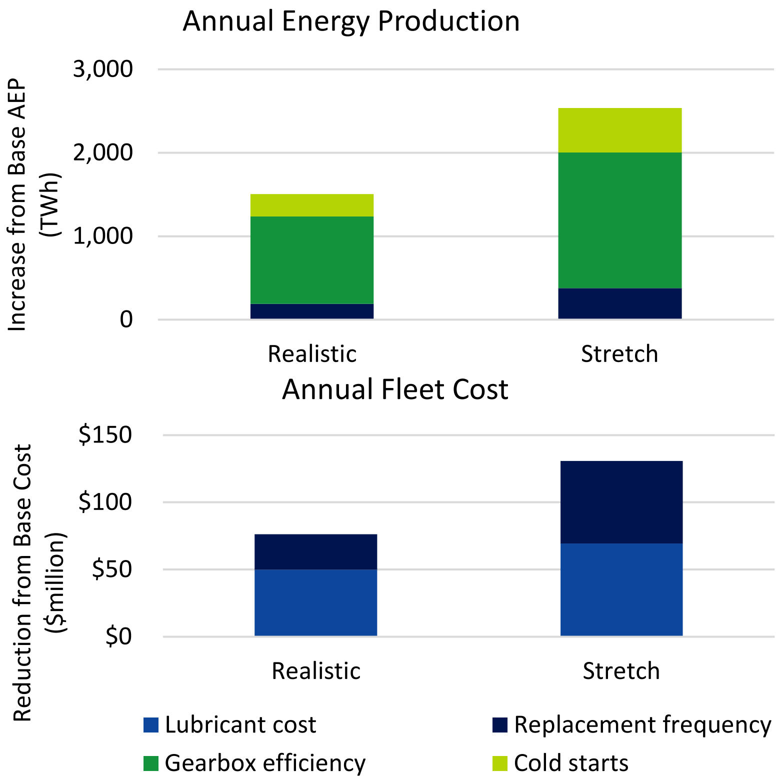
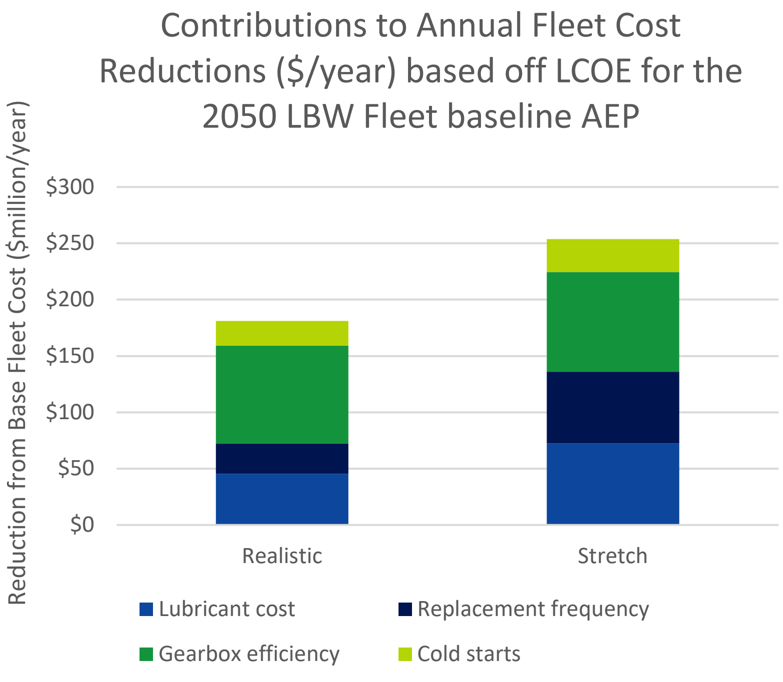
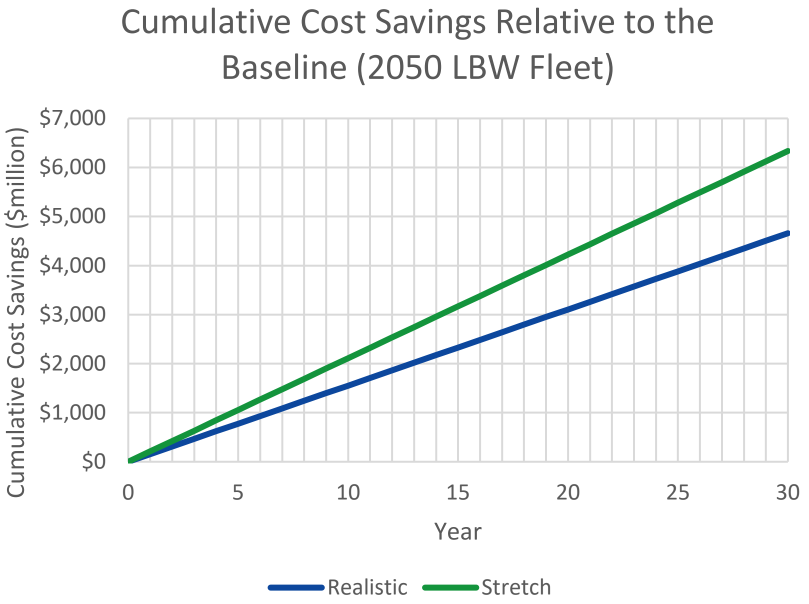
Sensitivity Analysis – 2050 Land-Based Wind Fleet



- Annual energy production is affected by changes to oil replacement interval, gearbox efficiency and cold start performance
- Variations in annual fleet costs are only affected by lubricant cost and oil replacement frequency

Cumulative LCOE Impact Assessment





Conclusions

- Lubricant technology has the potential to greatly improve mechanical system affordability
- NREL-developed tools have been combined to estimate potential impact of improved gear lubricants on U.S. wind economics
- All modeled lubricant improvements reduce OpEx and increase annual energy production
- Lubricant improvements in stretch scenario reduce median levelized cost of energy by 0.8%–2.0%
- Modeled gear oils estimated to save ~ $6 billion over 30 years

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Lubricant O&M Tasks in WOMBAT

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Minor repair	0.4 per turbine per year	8	$288 / $192 / $96	OpEx
Major repair	0.006 per turbine per year	22	$3,600 / $2,400 / $1,200	OpEx
Cold start	3 per year in Ice Class 2+	7 / 5 / 3*	None	Availability

2050 Land-Based Wind: 26 ATB 5.5-MW turbines

Task	Frequency	Hours	Material Cost	Metrics Affected
Oil change	Every 5 / 7 /10 years	12	$11,250 / $7,500 / $3,750	OpEx, Availability
Minor repair	0.4 per turbine per year	8	$900 / $600 / $300	OpEx
Major repair	0.006 per turbine per year	22	$11,250 / $7,500 / $3,750	OpEx
Cold start	3 per year in Ice Class 2+	7 / 5 / 3*	None	Availability

2050 Offshore Wind: 30 IEA 15-MW turbines

Task	Frequency	Hours	Material Cost	Metrics Affected
Oil change	Every 5 / 7 /10 years	12	$24,750 / $16,500 / $8,250	OpEx, Availability
Minor repair	0.4 per turbine per year	10	$1,980 / $1,320 / $660	OpEx
Major repair	0.006 per turbine per year	36	$24,750 / $16,500 / $8,250	OpEx
Cold start	3 per year in Ice Class 2+	7 / 5 / 3*	None	Availability

**Each number represents a cold start time needed for the turbine to connect with the grid*