Assessing the Impact of Lubrication on Efficiency and Life Cycle Economics of the US Wind Turbine Fleet

Cooperative Research and Development Final Report

CRADA Number: CRD-18-00765 (Project 20)

NREL Technical Contact: Shawn Sheng

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Technical Report
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Cooperative Research and Development Final Report

Report Date: May 14, 2025

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: ExxonMobil Technology and Engineering Company

CRADA Number: CRD-18-00765 (Project 20)

CRADA Title: Assessing the Impact of Lubrication on Efficiency and Life Cycle Economics of the US Wind Turbine Fleet

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Wind Energy Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

No NREL Shared Resources

Executive Summary of CRADA Work:

As with any mechanical system, lubrication plays a key role in the performance of wind turbines used to generate electricity. The lubricant design offers a way to optimize the competing requirements of efficiency, component reliability, and maintenance strategy. This project will estimate the impact of improved lubrication on the levelized cost of energy of the US wind turbine fleet as a means of identifying opportunities for disruptive innovation or system-level optimization. The models developed will provide a clear understanding of the benefits and potential for advanced lubrication of wind turbines. The project will enable identification of high value targets for wind turbine component suppliers and a roadmap that highlights where the greatest return on technology investment can be achieved. This will promote efficient resource allocation in areas of new technology development.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Uses the laboratory's core competencies

Summary of Research Results:

Task 1: Identify key information required to enable quantification of the impact of lubrication on wind turbine economics and life cycle.

Two reference turbine models (1.5 MW and 5 MW) and market scenarios in 2023 and estimated 2050 were chosen.

For each turbine model, selected input variables include the following:

- Power curve
- Cut-in/rated/cut-out speeds
- Turbine availability
- Icing loss
- Project lifetime
- Volume of oil
- Efficiency
- Oil costs
- Life of lubricant: replacement internals
- Reference wind plant

Task 2: Build quantitative model of the impact of lubrication on wind turbine economics and life cycle for the US wind turbine fleet.

The only wind turbine component considered in this study is gearboxes, as a result lubrication oil is assumed and there is no consideration of lubrication grease, which is also used in multiple turbine components. The results should be interpreted as conservative, and they should be magnified once the grease are also considered.

The overall modeling flow is shown in Figure 1.

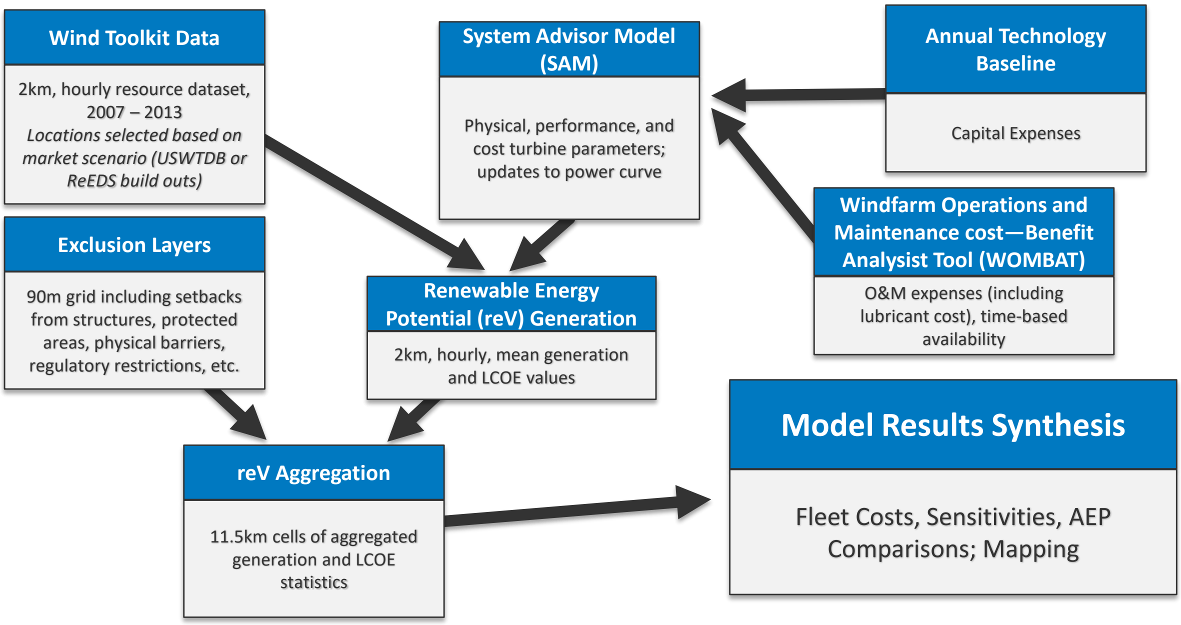

Figure 1. Overall Modeling Flow

- Modeling Tools Used:

  1. Wind tool kit[1]: hourly wind resource data
  2. Annual Technology Baseline (ATB)[2]: power curves, and capital expenses for reference turbines
  3. Exclusion layers[3]: reference siting scenario for turbine placement
  4. Windfarm O&M cost benefit analysis tool (WOMBAT)[4]: oil replacement intervals, component failure frequency including lubricant, and repair crew/costs, etc.
  5. System advisory model (SAM)[5]: performance & finance analysis, turbine power curve, annual energy production, efficiency, etc.
  6. Renewable Energy Potential Model (reV)[6]: national scale, spatial-temporal data, plant performance, Levelized Cost of Energy, etc.

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[1] https://developer.nrel.gov/docs/wind/wind-toolkit/
[2] https://atb.nrel.gov/electricity/2022/index
[3] https://www.sciencedirect.com/science/article/pii/S0360544221002930
[4] https://wisdem.github.io/WOMBAT/
[5] https://sam.nrel.gov/
[6] https://www.nrel.gov/gis/renewable-energy-potential.html

- Three lubrication technology advancement scenarios: baseline, realistic, and stretch, are modeled and the key parameters for each are provided in Table 1.

Table 1. Lubricant Technologies Modeled

	Unit	Baseline	Realistic	Stretch
Efficiency Improvements				
100% load	%		0.1	0.2
<50% load	%		0.2	0.4
<10% load	%		0.5	1.0
Cost of Oil	$/liter	15	10	5
Oil Replacement Intervals	years	5	7	10
Cold Starts	hours/event	7	5	3
IEA Ice Class 1 Region	#/year	0	0	0
IEA Ice Class 2 or Higher Regions	#/year	3	3	3

- Reference Turbines Used: General Electric (GE) 1.5 MW, ATB 5.5 MW and IEA/ATB 15 MW, detailed parameter can be found at[2].

- Modeling Assumptions:

  1. We utilized the US Wind Turbine Database (USWTDB; Hoen et al 2018) to determine the locations of the current US (January 2023) wind fleet. We utilized the provided turbine locations, but assumed turbines across the fleet were GE 1.5 MW machines. The installed capacity is approximately: 144 gigawatts (GW).

  2. For the 2050 market scenario, we used the Regional Energy Deployment Systems (ReEDS) modeled deployments from the 2022 Standard Scenarios report for both Land-based Wind (LBW) and Offshore Wind (OSW) (Gagnon et al. 2022). Estimated deployment scenarios include both wind farm locations and capacities. LBW farm assumptions included the use of the ATB 5.5 MW machine. Half of the 2050 OSW fleet is assumed to utilize direct drive technology, and these systems are not impacted by gearbox lubrication oil technology improvements. We modeled the remaining half of the 2050 OSW fleet with the ATB 15MW turbine. The installed LBW is projected to be ~333GW and for OSW to be ~61 GW.

Based on the WOMBAT modeling results shown in Figure 2, it is observed that:

- OpEx reduces as the lubricant technology advancement scenarios changed from baseline to realistic and stretch, while time-based availability increases accordingly.

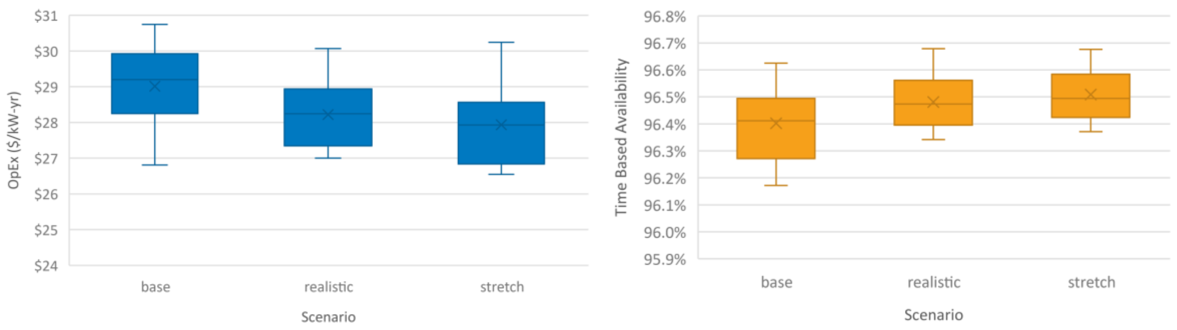

Figure 2. WOBMAT Modeling Results: OpEx (left) and Time-based Availability (right)

Based on the ReV modeling results shown in Table 2, it is observed that:

- Medial Levelized Cost of Energy (not including transmission) and fleet cost reduce as the lubricant technology advancement scenarios changed from baseline to realistic and stretch while annual energy production increases. For the stretch scenario, the increased energy production, 2,538 GWh, can serve ~209,500 more households.

Table 2. ReV Modeling Results

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

Task 3: Generate sensitivity analysis of lubricant-related factors that enables targeting of opportunities for the US wind turbine fleet.

NREL will leverage ExxonMobil input, publicly available sources and NREL historical expertice to model the lubrication impacts on the overall life cycle costs of the US wind turbine fleet. Where data is unavailable or unreliable, variables may be used as place holders in calculations. The goal of the work is to be as comprehensive as possible, such that small changes in lubrication capability and lubrication practices can be assessed for their impact when optimized and scaled to fleet level. Well-known lubrication impacts include: upfront cost, downtime (normal maintenance, lubrication failure), general efficiency benefits, maintenance costs (top-up, used oil analysis), hardware longevity benefits, peripheral systems (filter, filtration systems, breathers) and end of life costs such as disposal or recycling. Lubrication points on the turbine that are inscope include the main bearing, gearbox (where applicable), generator bearing, hydraulic system (where applicable), pitch bearing, yaw bearing, pitch gear and yaw gear systems. Mechanical failure statistics may be used to calculate the risk of downtime where the lubricant may provide wear protection. The analysis will be able to account for direct drive, medium speed geared and high speed geared turbine geometries using reasonable assumptions to generalize to a diverse turbine fleet.

Sensitivity studies were conducted in both WOMBAT and reV, the four cases are listed in Table 3. The corresponding results from ReV based on 2050 LBW fleet are provided in Table 4. It is observed that the cost reduction from case 1 to 4 has an impact of ~40% on fleet cost difference. Comparatively, the replacement interval extension from case 2 to 3 has an impact of ~133% on fleet cost difference and ~100% on fleet energy production difference. This indicates there is more incentive to advance new lubricant technologies that can extend life (or oil replacement intervals) and reduce the frequency of replacements throughout a turbine's lifecycle.

Table 3. Sensitivity Study Cases 1 to 4

Scenarios		Lubricant Cost		
		$15/liter	$10/liter	$5/liter
Replacement Frequency	5 years	Base	1	4
	7 years	2	Realistic	
	10 years	3		Stretch

Table 4. Sensitivity Study Results

	Fleet Annual Energy Production	Median Levelized Cost Of Energy (not including transmission)	Fleet Cost ($/yr)	Difference in Fleet Cost ($/yr)	Difference in Fleet AEP (GWh)	Difference in # Households
Baseline	905,960 GWh	$14.19 MWh	$12,660,031,084	-	-	-
1.) $10/L	905,960 GWh	$14.14 MWh	$12,610,254,527	$49,776,557	0	0
2.) 7yr replacement, $15/L	906,148 GWh	$14.16 MWh	$12,633,678,109	$26,352,975	188	~15,500
3.) 10yr replacement, $15/L	906,337 GWh	$14.12 MWh	$12,598,542,736	$61,488,348	377	~31,000
4.) $5/L	905,960 GWh	$14.11 MWh	$12,590,734,875	$69,296,209	0	0

Key Takeaways:

- Lubricant technology advancements impact both energy production and cost for wind power to various extents. The study has shown it may be more impactful to energy production.
- Technology innovations to extend lubricant life and reduce frequency of replacements throughout the life cycle of wind turbines have shown to be more impactful than cost of oil.

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ROI#: None.