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AEP Improvement from Swarm Confirmed at Longroad's Milford, Utah Wind Plant

Early results from Phase 1 of the 165-turbine implementation confirm collective control for wake steering and validate expectations for plant-wide AEP improvement.

About the Site: Milford I &II

Located in central Utah, USA

- Site commissioned in two phases in 2009 and 2011
- 165 Turbines (306 MW) consisting of a mix of GE 1.5-MW and Clipper 2.5-MW

The team at Longroad has operated the Milford wind sites since commissioning.

A long-standing PPA with a California utility and successful track record of the site made it an ideal candidate for repowering.

About Longroad Energy

Longroad Energy is a Boston, MA-headquartered renewable energy developer focused on the development, ownership, and operation/asset management of wind and solar energy projects in North America.

It was founded in 2016 by the former executive team of First Wind Energy, which originally developed the Milford I & II plant.

Challenges at Milford I & II

1. The site was aging and provided the opportunity to increase annual energy production.

2. Wakes at the site were creating turbulence, curtailment and reducing output for many turbines.

3. Longroad decided to repower the site, extending the useful life of the turbines and increasing energy output.

The Solution: WindESCo Swarm

- As a trusted partner of Longroad, WindEsco was selected to participate in the repowering effort by increasing energy production through Swarm.
- Repowering at Milford will increase the generation and extend the remaining useful life of the 165-turbine site.
- WindESCo Swarm is being applied on all 165 turbines in two phases.

This case study reviews the results from Swarm Phase 1 implementation, which was commissioned in August of 2022 and leverages high frequency SCADA collected since 2021.

- Swarm (Phase 1 and 2) was fully commissioned across the site in late December 2022.

Sign up up to see the results from the fully commissioned Swarm project.

What is Swarm?

WindESCo Swarm is the industry's first commercial solution for collective control of wind turbines. Combining advanced analytics, model-in-the-loop control and Industrial Internet of Things (IIOT), Swarm accomplishes what the industry has failed to achieve to date, +3% increase in AEP via wake steering and other collective contral strategies without adversely impacting loads.

Inspired by nature, Swarm allows turbines to adapt and learn from each other.

Working cooperatively, Swarm increases plant output and turbine lifetime while improving wind plant resilience.

Utilizes multiple applications including wake steering, yaw by consensus, predictive and dynamic yaw, and online static yaw misalignment correction.

Unique SaaS and hardware model ensures continued optimization through a growing list of applications and benefits.

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The Swarm System

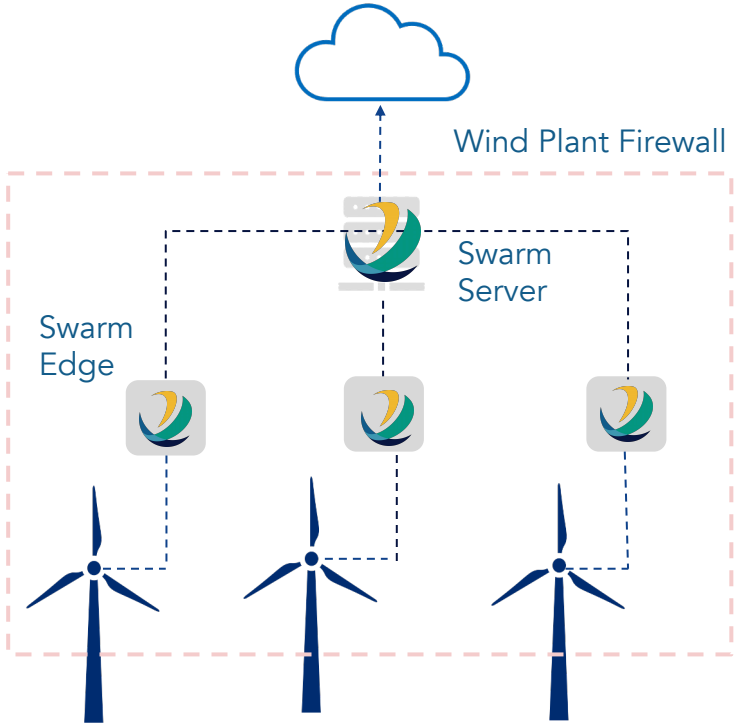
The Swarm system is cybersecurity compliant and is comprised of an Edge computing device installed on each turbine and an onsite Swarm server.

Swarm Server

- On-premise optimization within wind plant firewall
- Secure system keeps critical infrastructure safe
- Multiple applications run in parallel to increase plant output

Swarm Edge

- Patented IIoT device implemented as a retrofit solution
- Seamless integration with any turbine OEM
- Enables absolute nacelle position control



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The Swarm Assessment Process

For each project, a Swarm Assessment is used to create site-calibrated wind and wake models to determine the potential AEP benefit of Swarm. WindESCo considers improvements from several Swarm Applications including wake steering, yaw by consensus, predictive and dynamic yaw, and online static yaw misalignment correction.

1

1-year of high-speed SCADA data are used to calibrate the WindESCo wind and wake models to match the plant's historical behavior.

2

Swarm optimization algorithms are applied to the SCADA data to compute wind plant response and to quantify the energy improvement from the Swarm applications

3

Wind plant response to the Swarm applications is evaluated to determine the plant-level control strategy for maximizing energy production, which is used to estimate the improvement in AEP from Swarm

Milford I & II Swarm Assessment Results

According to the Swarm assessment for the Milford plants based on model simulation, the investment in Swarm would deliver a desirable ROI with predicted IAEP. The majority of these IAEP will be from wake steering. However, additional Swarm apps adds critical benefits to the business case.

Model simulations predicted IAEP of up to 3.7% at Milford. Field data presented later in this case study suggests the potential to reach or exceed this goal and achieve desirable project ROI.

Modeling Results for Milford

- Wake Steering + Yaw by Consensus: 1-2% IAEP
- Predictive + Dynamic Yaw: 0.2-0.7% IAEP
- Online Static Yaw Misalignment Correction: 0.2-1% IAEP

*IAEP indicates the Improvement in Annual Energy Production (AEP)

1.4-3.7%

Predicted Improvement in AEP from Swarm

“We selected Swarm because we are comfortable that WindESCo will deliver the expected AEP gain.”

Jeremy Law,
Head of Asset Management
Longroad Energy

Phase 1 of Swarm at Milford

Once Longroad and WindESCo determined financial feasibility for Swarm at Milford in late 2021, WindESCo installed Swarm Edge devices on 10 turbines and began collecting data for the 10 turbines as part of Phase 1 implementation and analysis.

There were three key goals set for Phase 1 Swarm deployment at Milford.

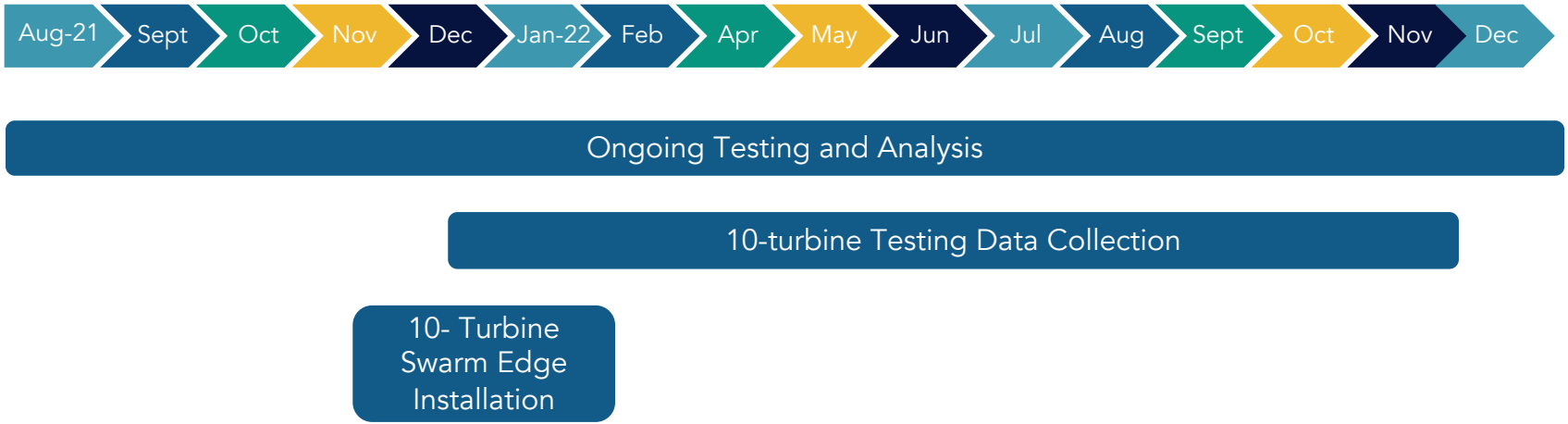
1. Install Swarm Edge devices and test functionality for absolute nacelle position control
2. Swarm the ten turbines included in Phase 1 to demonstrate improvements in AEP from wake steering using a model-in-loop approach
3. Measure and examine the relative change in loads for a downstream Swarm turbine

Goal 1:

Implement Swarm on Phase 1 Turbines and Demonstrate Nacelle Position Control

Implementation Timeline: Phase 1

Data covered in this case was collected between August 2021 and November 2022.



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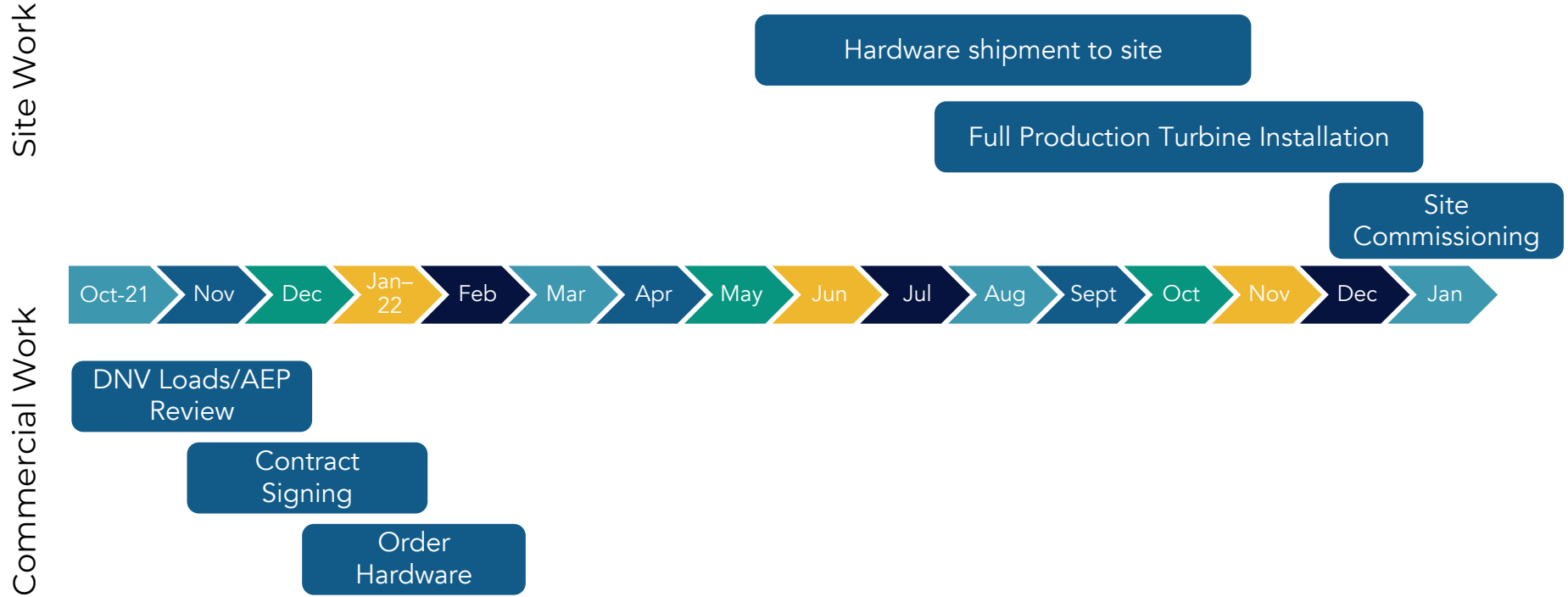
Implementation Timeline: Phase 2



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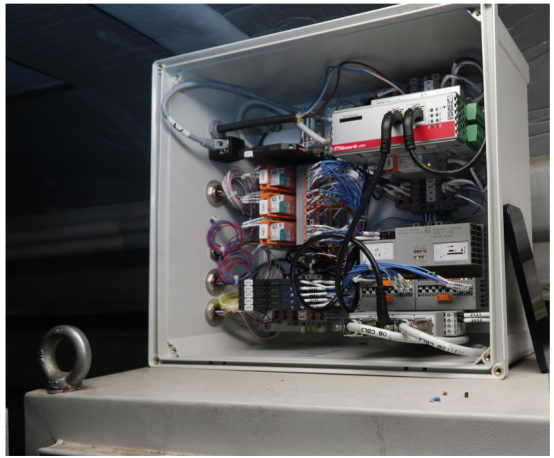
Phase 1 Installation

For phase 1 of the Milford swarming project, WindESCo installed Swarm Edge devices on 10 of the 165 turbines at the plant.

Site layout at Milford. Red dots indicate Phase 1 of Swarm deployment



Swarm Edge devices (shown) connect to Swarm Server at site to take collective control nacelle setpoints and drive turbines into optimized position.

Swarm Edge installed in each of 10 turbines, both GE and Clipper models.

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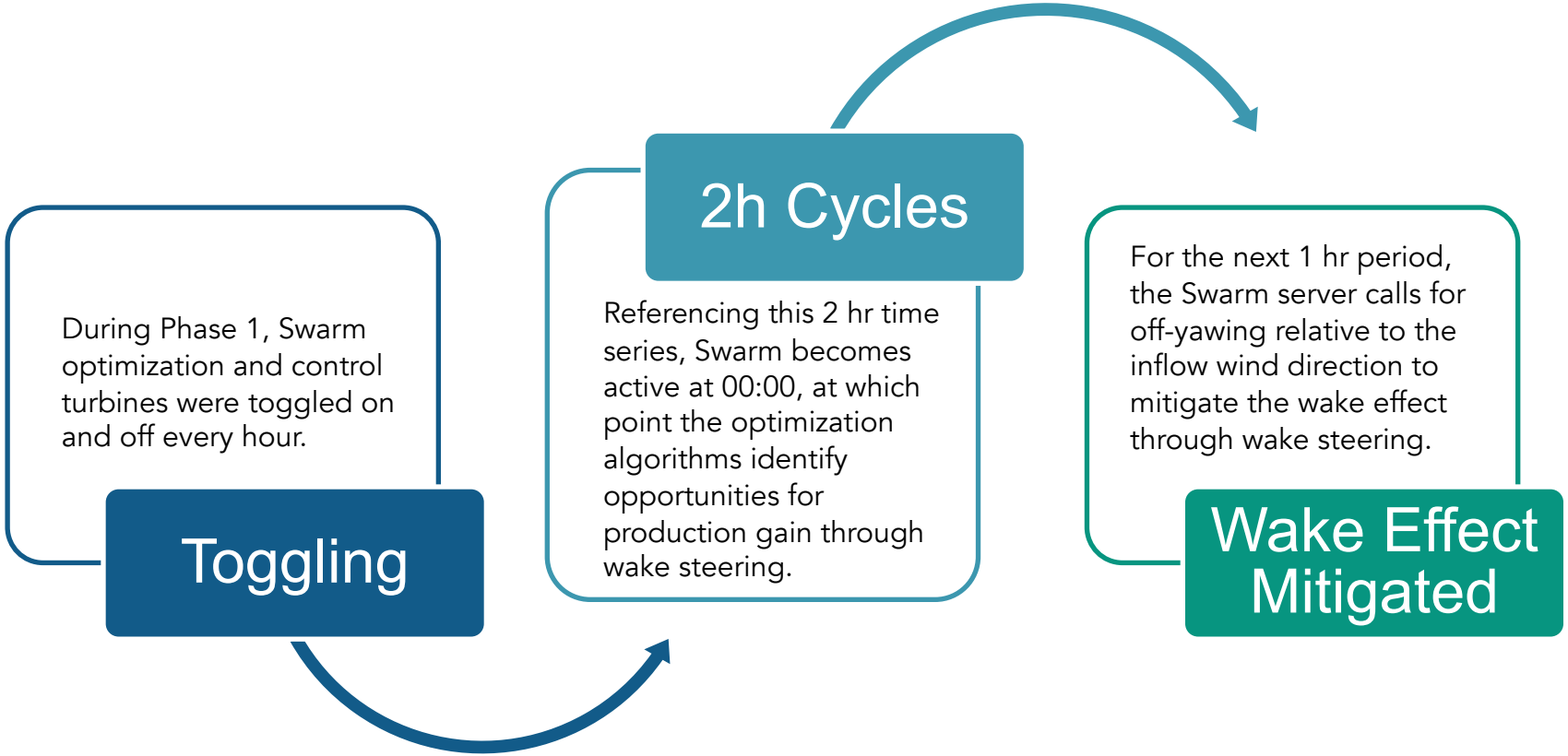
Testing Swarm Hardware Installation



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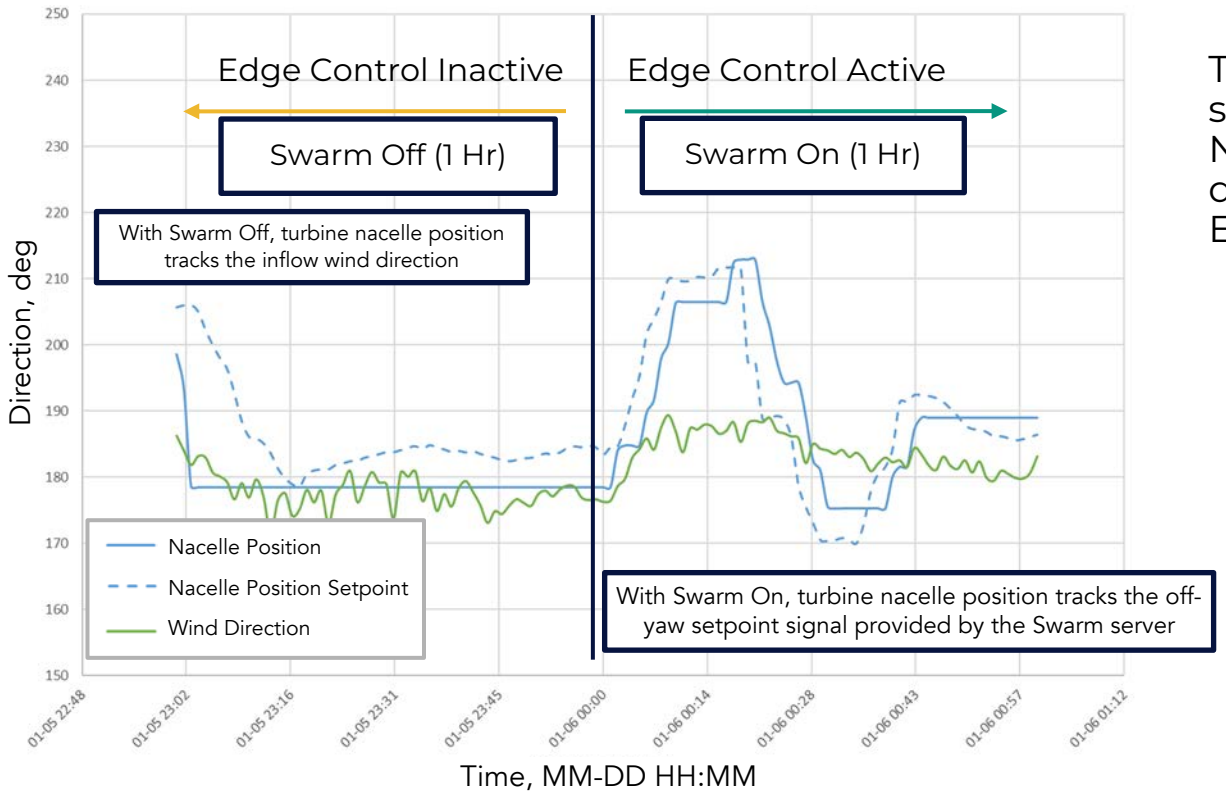
Swarm Edge Testing in Action



The graph to the right shows a demonstration of Nacelle Position Control during a Wake Steering Event.

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Goal 1 Summary

1. The WindESCo team mapped out and successfully installed the Swarm on 10 turbines

2. Turbine nacelle position control was achieved and demonstrated during periods apt for wake steering

3. Phase 1 success allows the team to continue installation with the goal of site completion by the end of 2022

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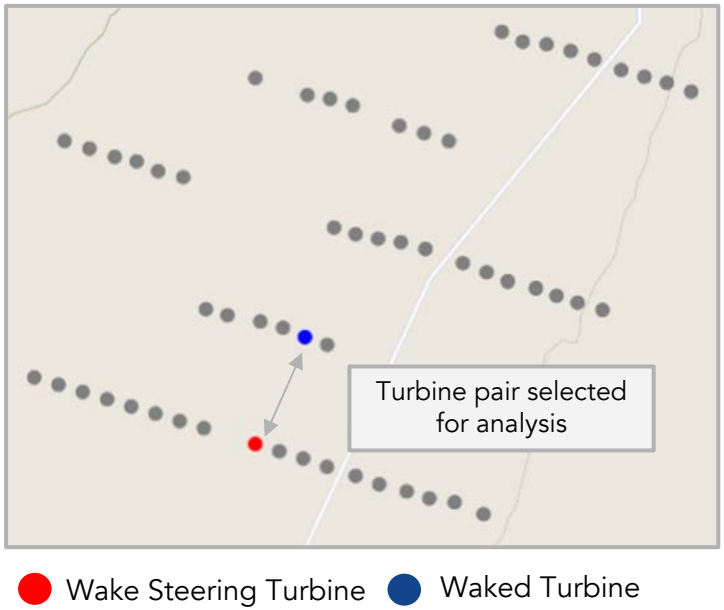
Goal 2:
Demonstrate energy production improvement from Swarm wake steering

Phase 1 Energy Improvement

1. An objective of Phase 1 was to examine the interaction between select turbine pairs and to discern the relative change in energy production from wake steering

2. A single upstream-downstream (i.e., steering-waked) turbine pair was analyzed for wake steering effectiveness over 3 months beginning in December 2021

3. WindESCo verified improvements in energy production through wake steering for the downstream turbine as predicted by model-in-the-loop control



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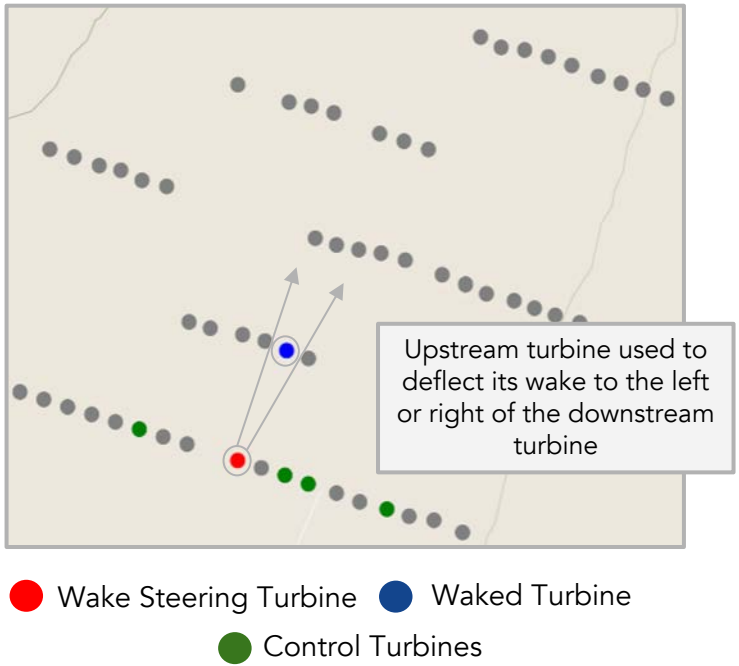
Experimental Setup

A turbine pair (defined by the red and blue dots in this figure) were selected to examine the effectiveness of wake steering for improvements in energy production

The selection of this turbine pair was guided by SCADA analysis in an attempt to identify a turbine pair subject to the frequency and significant waking prior to Swarm installation

To determine the relative change in energy production due to Swarm governed wake steering, the production of both the upstream and downstream turbine was compared to the average power of a set of control turbines (denoted by the green dots)



Control turbines were qualified to ensure they were online and operational, undisturbed from wakes, not employing wake steering, and pass a normal behavior check during the respective analysis periods

Energy Improvement Testing

By toggling of the Swarm system on and off every hour, comparison periods were created, enabling analysis of the production impacts of wake steering.

To further isolate the impact of wake steering, production data were limited to wind conditions consistent with waking, defined as periods with wind directions between 190 and 210 deg and wind speeds between 8 and 13 m/s.

This approach allowed WindESCo to isolate the impact of the wake steering, and eliminate other confounding variables.

Positive Production Benefits from Wake Steering

Based on the results from this sample pair, a production improvement will be recognized for this pair of turbines from wake steering. AEP benefits will be measured once the site is fully commissioned, and other Swarm applications come online.

Turbine	Relative Change in Energy Production due to Wake Steering
Steering Turbine	-1.2%
Waked Turbine	+3.4%

WindESCo and Longroad are encouraged that these early results will prove out expectations for AEP improvement site wide.

**Change in energy production defined relative to the set of control turbines*

Goal 2 Summary

1. WindESCo examined the interaction between a select turbine subject to significant waking in Phase 1.

2. Through toggling and focused analysis, WindESCo analyzed the relative change in energy production due to Swarm wake steering.

3. WindESCo confirmed an increase in energy production from Swarm wake steering for the turbine pair under analysis.

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Goal 3:

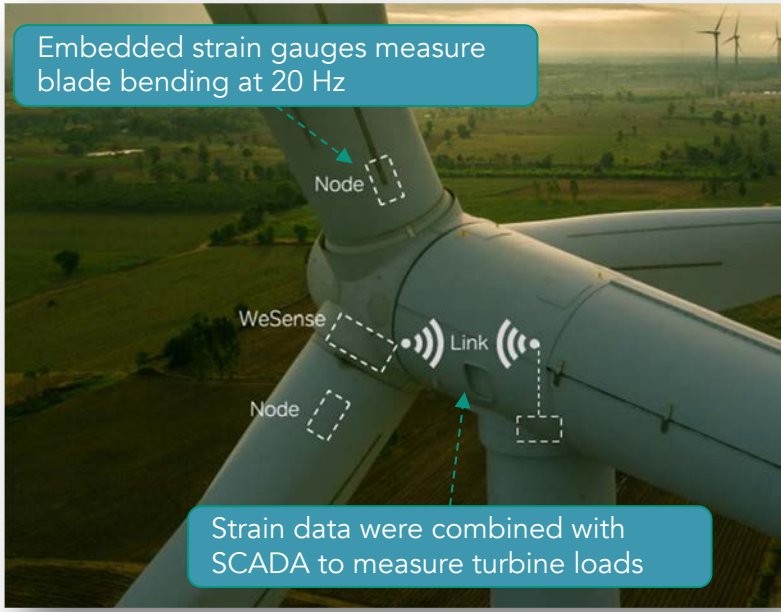
Measure the relative impact of Swarm wake steering on downstream turbine loads

Phase 1 Load Testing for Downstream Turbine

1. WindESCo installed its proprietary load measurement system to monitor load changes from Swarm wake steering

2. These load measurements were combined with SCADA to examine the relative change in blade root bending moments (RBM) and blade root damage equivalent loads (DEL)

3. WindESCo confirmed no meaningful increase in the examined blade loads (i.e., loads remain within the design envelope) due to Swarm wake steering



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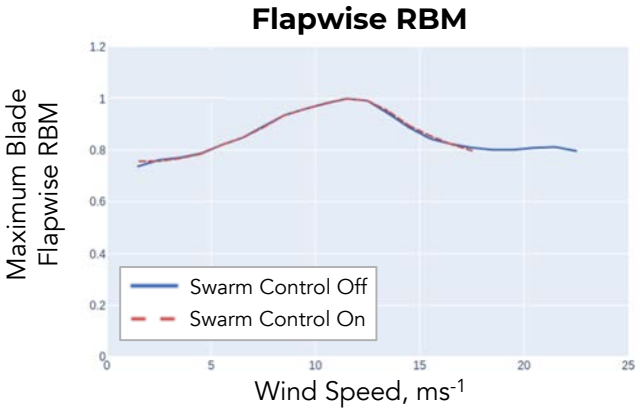
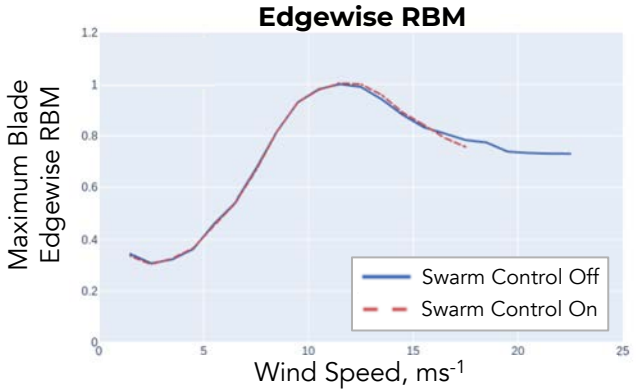
Testing Swarm Impact on Downstream Turbine Loads

Analysis of the load sensor data indicates no meaningful increase in the maximum RBMs in either the flapwise or edge direction, and an overall reduction in the blade root fatigue loads when Swarm is versus off due to reduced turbine inflow waking for the downstream turbine.





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Minimal Load Impact Measured

As part of the Milford Repowering project, DNV performed an IE review of these load data, analysis approach, and calculations, and confirmed the approach was reasonable

In general, very low impact to turbine loads and component life due to Swarm primarily operating in low-to-moderate wind speeds (i.e., below rated power) and yaw error for wake steering remaining within OEM yaw misalignment limits

Blade Root DELs

Blade Root DEL Moments	Percent Difference (Swarm On vs. Off)
Blade 2 DELs (Edgewise Moment)	-0.106
Blade 2 DELs (Flapwise Moment)	-1.244
Blade 3 DELs (Edgewise Moment)	-0.100
Blade 3 DELs (Flapwise Moment)	-2.664

Goal 3 Summary

1. Analysis indicate no meaningful increase in the maximum blade RBMs and blade root fatigue loads from Swarm wake steering.

2. DNV reviewed these calculations as part Milford IE review and confirmed the approach.

3. UL has approved a similar site-specific loads assessment process for application to other Swarm sites.

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Conclusions and Next Steps

- Initial results demonstrate positive production benefits to Swarm wake steering with no meaningful impact to turbine loads, which is promising for model-in-the-loop collective control.
- Installation on all 165 turbines was complete at the end of 2022, and full site commissioning and analysis is on track for the new year 2023.
- Once commissioned, WindESCo will begin running the full network of Swarm applications, and will further analyze the production data to quantify the AEP improvements from Swarm.

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Swarm coming soon to....

Swarm has the potential to provide billions of dollars in value to with wind industry. These projects are already underway.

Swarming Milford I & II marks the first full-scale, commercial collective control project at a wind plant. Results from Milford will provide critical lessons for implementing Swarm globally.

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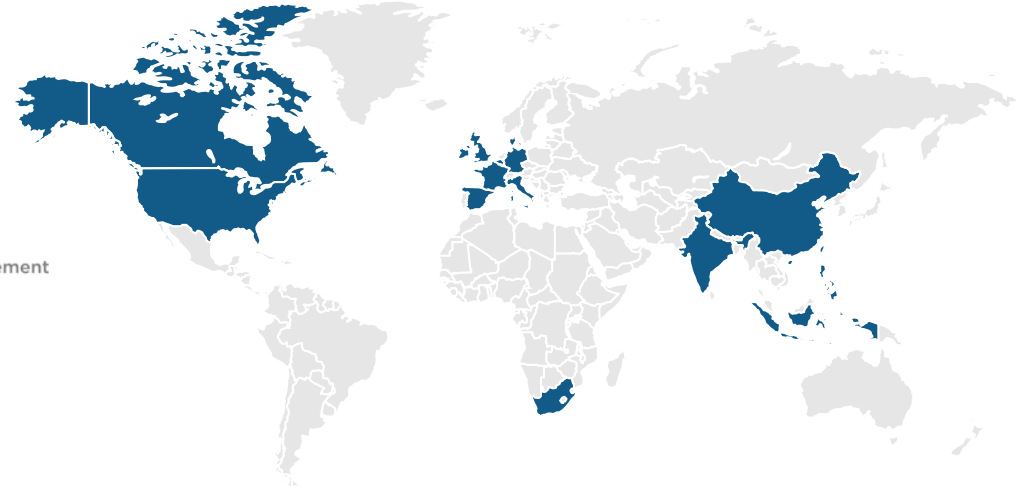

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