# Deliverable Description

## Wind Plant Technology Characterization (4.1.0.401)

- Subtask 1.4 - Land-based O&M Cost Model Development
  - Produce a beta version of one module for a new land-based O&M model
- Subtask 2.3 - Offshore O&M cost model development
  - Create a beta version of the simulation module for a new offshore O&M model
- Joint (Subtask 1.4 + Subtask 2.3) Deliverable
  - Internal presentation that summarizes the capabilities and initial results by September 30, 2020

# Executive Summary

- Motivation

  Future innovations are expected to bring costs down significantly, with potentially large impacts on LCOE, but current commercial tools don’t allow flexible testing of hypotheses.

- Approach

  Modular and flexible code base, powered by a discrete even simulation model, with separate failure and maintenance models for each component.

- Key Takeaways

  Possible to model numerous sensitivities at this early stage, given the model’s flexibility with results that scale in the correct direction.

- Outcomes

  The model design and outputs enable deep dives into the results to dissect every step of the simulation, and allow for robust metric computation.

- Next Steps

  Further model development to prepare for a public release

  Industry and IEA Task 43 review and validation

  Publications

# Operations and Maintenance Modeling for Offshore and Land-based Wind Plants

FY20 Q4 Deliverable

Rob Hammond, Aubryn Cooperman, Matt Shields, Annika Eberle, Aaron Barker, Alicia Key

30 September 2020

# Motivation

# Relevance of O&M Costs

- O&M activities are estimated to comprise between 29% and 34% of total wind plant lifecycle costs (Stehly & Beiter, 2018).
  - $33 – $59/kW/year for land-based wind
  - $65 – $194/kw/year for offshore wind

- Innovations in the O&M sector have the potential to drive down the overall cost of wind energy.

- However, quantifying the impact of these innovations on cost is challenging because:
  - Data on wind plant O&M costs are not often publicly available or broken down into detailed categories.
  - Understanding cost impacts and tradeoffs for O&M strategies requires a model with appropriate resolution to capture relatively small changes at the level of individual tasks.

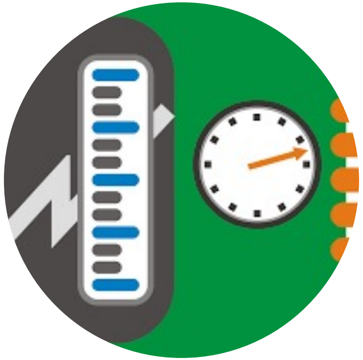
# Prior Work

- NREL's O&M cost modeling for wind energy has traditionally relied on commercial tools or empirical relationships based on market research.
  - None of the available tools are flexible or modular enough to evaluate the cost implications of novel technologies.
  - Equations and methodologies used by commercial tools can neither be adequately inspected nor modified to assess cost implications of new technologies and approaches.
- This project enables more comprehensive O&M cost modeling that will allow for integration with other NREL wind cost models.
  - WISDEM: assessing design costs for wind plants
  - ORBIT/LandBOSSE: assessing balance-of-system costs
- Overarching goal is to develop a suite of cost models that allow for more robust estimates of LCOE under different wind energy innovation scenarios.

# Primary Research Question

How might maintenance strategies, technological innovations, and site conditions influence wind plant OpEx and ultimately LCOE?

Methodology Innovations



Technology Innovations

Site Conditions

# Approach

# What

- Intent of this project is to develop beta versions of two modules for a new wind plant O&M model that can:
  - Allow users to define maintenance strategies and simple failure probabilities for major components and calculate the resulting impact on O&M costs.
  - Enable exploration of tradeoffs between innovative maintenance scenarios.
  - Account for constraints such as weather limits using a process-based approach.

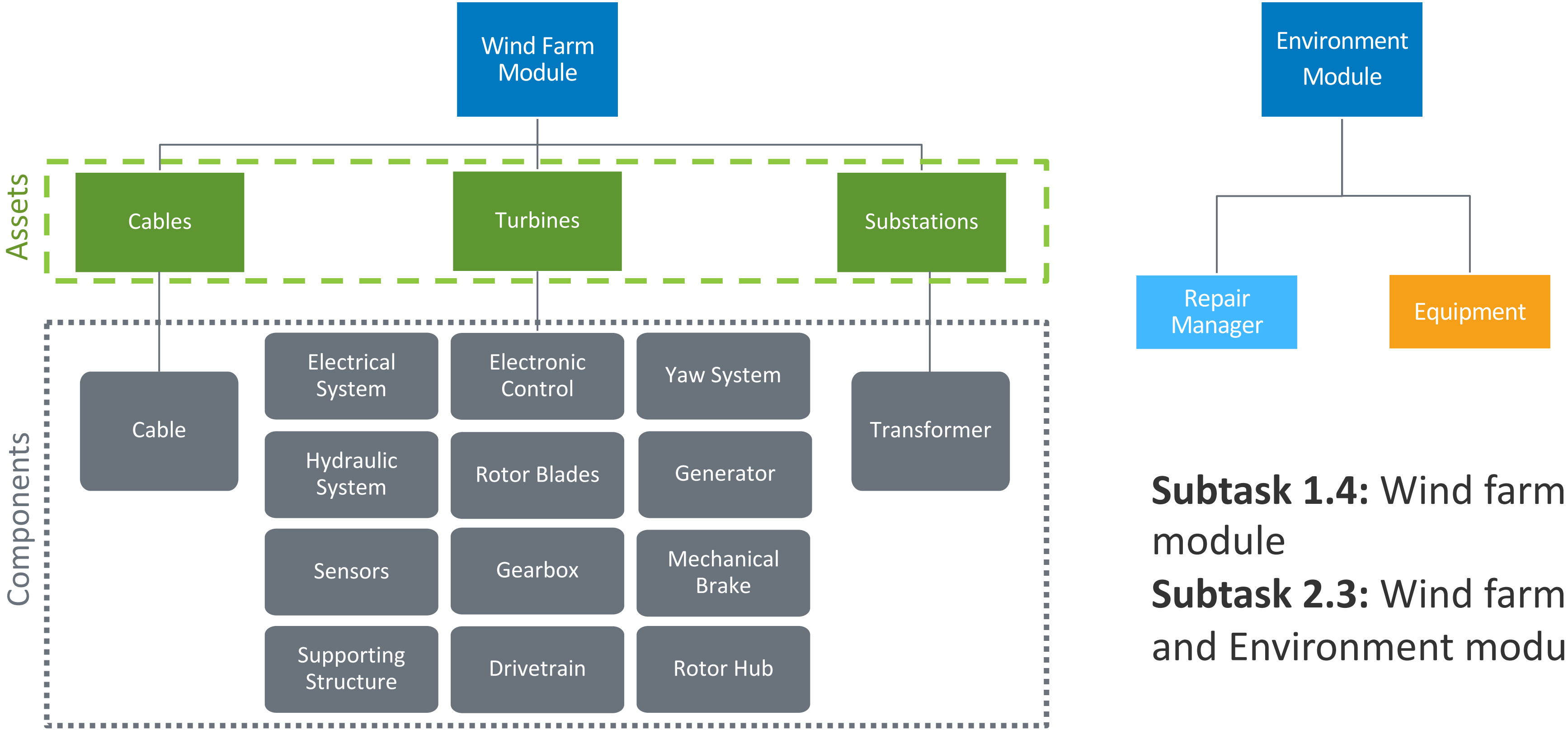
- Model development leverages prior work and current O&M models:
  - Component-specific failure rates
  - Equipment costs and operational limits
  - Simulation framework based on ORBIT

# How

- Prescriptive modeling via discrete event simulation:
  - Enables weather and site-specific variability
  - Allows a user to define O&M strategies and understand impacts
  - Focuses on what-if scenario modeling instead of optimizing for costs
- Modular and flexible code base:
  - Allows for new methodologies to be tested with ease
  - Provides a tool to analyze both offshore and land-based windfarm O&M costs
- Well-documented code base:
  - Enables other NREL researchers to understand the code in its preproduction stage to continuously assess the cost implications of new technologies and strategies.

# Model Overview

# High-Level Software Architecture

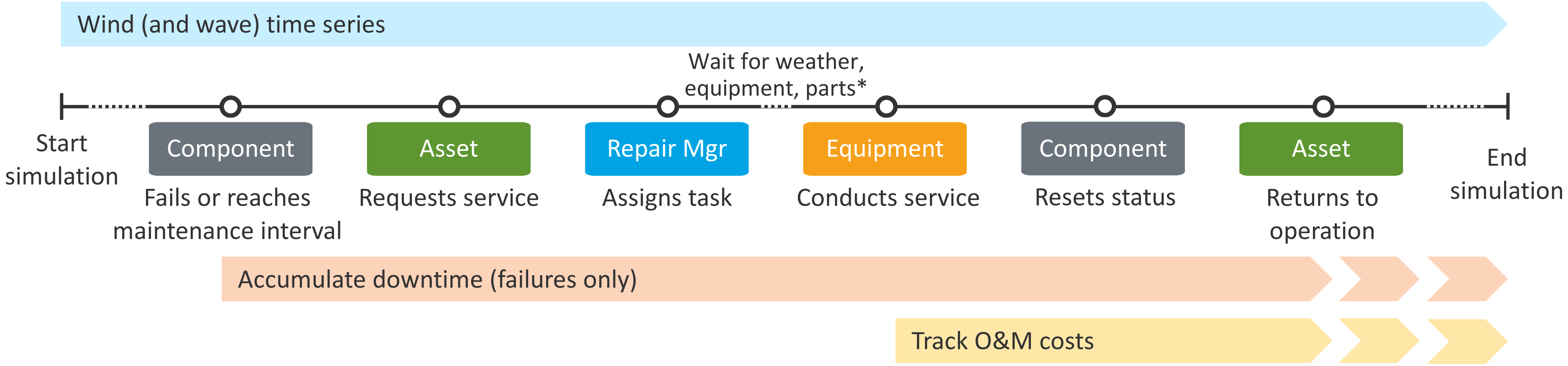



**Subtask 1.4:** Wind farm module

**Subtask 2.3:** Wind farm and Environment modules

# High-Level Simulation Architecture

- Model evaluates O&M costs using discrete event simulation (series of events in sequential order where no changes occur between events):
  - Allows for detailed documentation of a system and its processes.
  - Allows for a prescriptive approach for exploring specific impacts compared to an optimization with a "best choice."




*Parts availability not yet implemented

# Inputs and Outputs

# Baseline Inputs

**Components**

- Failure rate(s)
- Maintenance tasks
- Equipment requirements
- Cost and time to complete repairs

**Equipment**

- Visit schedule
- Capabilities
- Labor rates
- Equipment rates
- Operational limits

**Miscellaneous**

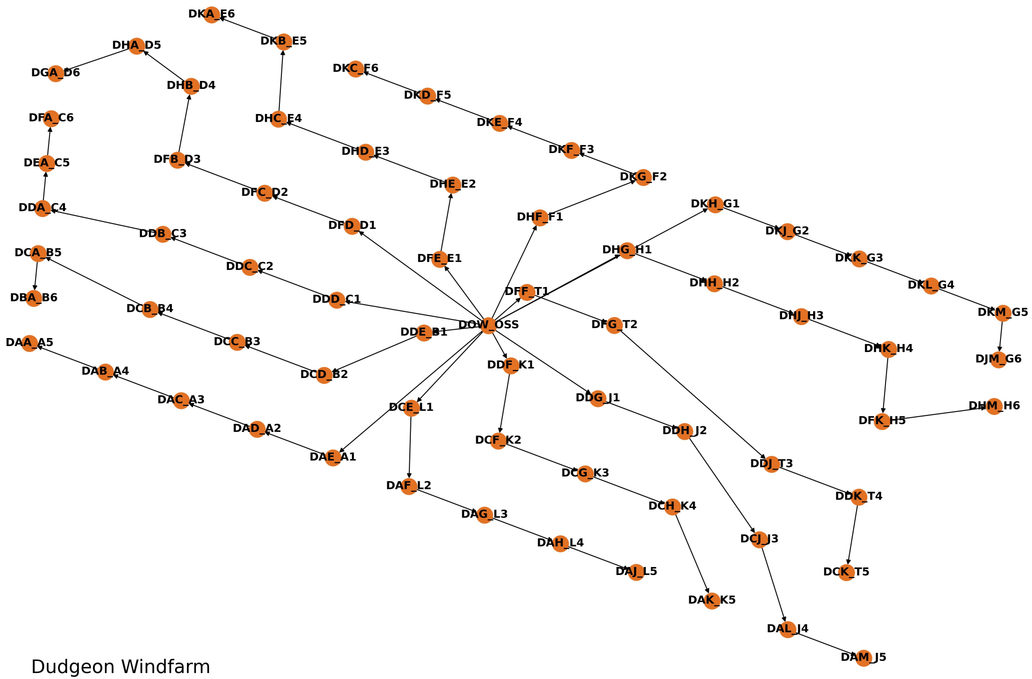
- Weather profile
  - Hourly windspeed and/or wave height
- Windfarm layout
- Site working hours

# Outputs

- For wind farm and assets (turbine/substation/cable), the model outputs:
  - Hourly (simulation time) operational rates for all turbines and substation(s).
    - Enables external computation of availability metrics
    - Allows for future metrics such as revenue production to be computed as model matures
  - Event logs:
    - Time of failure or maintenance request and descriptions
    - Equipment tasks
      - Timing (and associated costs) by weather delay, working, waiting for request
      - Cost by parts, equipment, and labor (salary and contract)

# Capabilities

# The Windfarm Model




Dudgeon Windfarm

- **The model can create the windfarm layout from a given set of spatial positions.**
- **The layout is primarily used for modeling downstream impacts of cable and substation failures.**
- **A basic layout is required to define the turbine and cable parameters as well as their placement for analysis, though locations can be arbitrary.**

# Failure and Maintenance Modeling

- For each of the turbines, cables, and substations (each with a set number of components) the following are modeled:
  - An arbitrary number of maintenance tasks
  - An arbitrary number of failure event classifications
  - Maintenance and failure materials costs (compiled via absolute or proportional amounts)

# Equipment Modeling

- An arbitrary number of pieces of equipment can be used on site.
  - Labor costs can be broken down into salaried and hourly labor with an arbitrary number of workers.
- Equipment can have annual visits, one-time visits, or be designated as on-site equipment.
- Three equipment categories align with failure and maintenance equipment requirements:
  - Cranes
  - Cabling
  - Crew Transfer/On-site

# Current Capabilities

- What are the knobs we can turn?

**Repairs**

Cost

Time

Labor

Failure rate

**Equipment**

Cost

Operating limits

**Site Conditions**

Layout

Weather

**Strategy**

Maintenance schedule

Required equipment

# Initial Results

# Scenario Basics and Assumptions

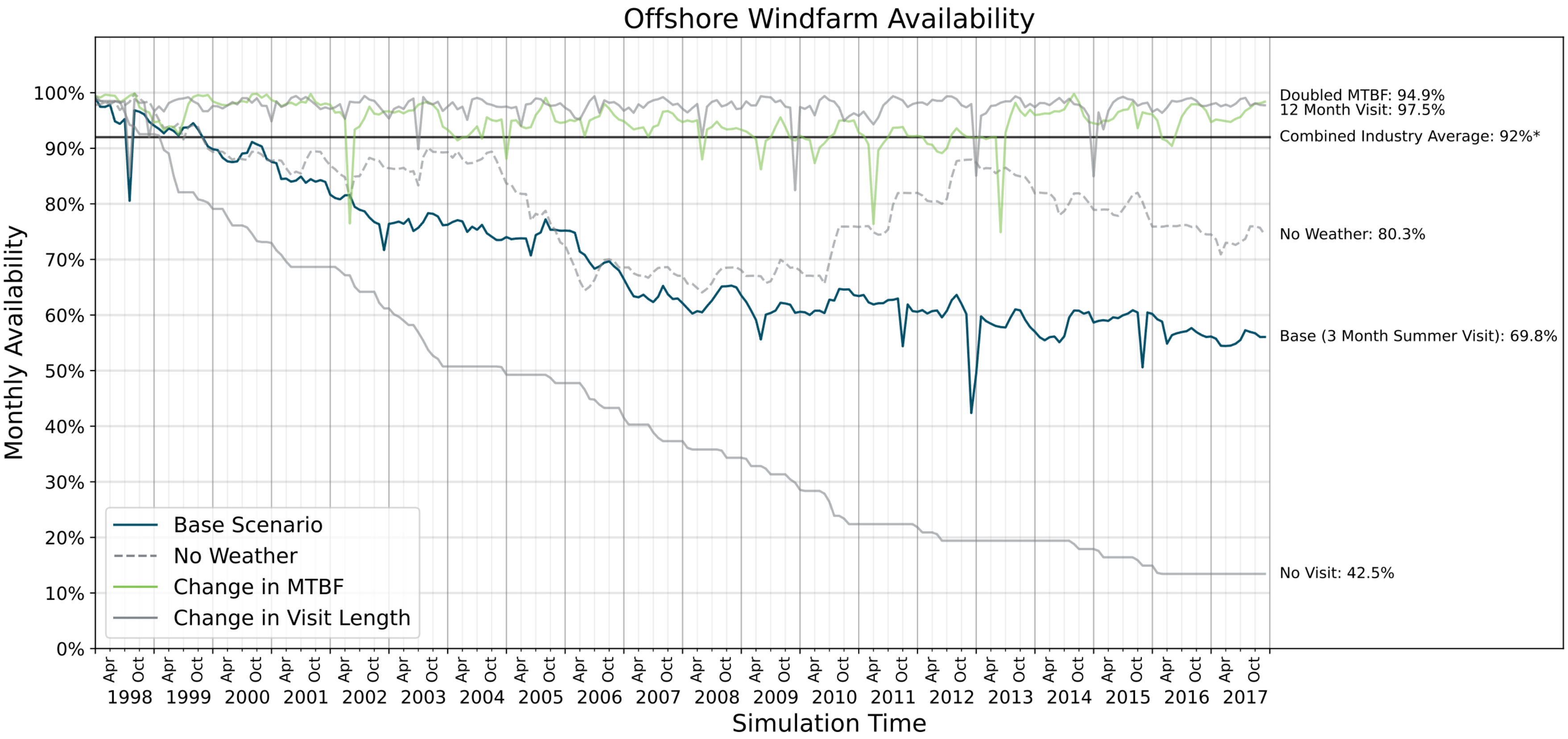
- Standard across all scenarios:
  - Full-time crew year-round for minor repairs
  - Major repairs conducted during a pre-determined window
  - Working hours are 8am – 6pm
  - Results only include material, equipment, and labor costs
  - Failure data is intended as placeholder with current rates based on the ECN Data (reference) and onshore rates scaled at 1.25x
  - Offshore weather: Vineyard Wind (MA)
  - Onshore weather: Sweetwater, TX
- Availability is time-based availability in all instances

# Scenario Definitions

| Scenario Name | Description |
|---|---|
| **Base** | **3-month summer-time visit (June – August)** |
| **No Weather** | **3-month summer-time visit (June – August) with wind and/or wave set to 0** |
| **Doubled MTBF** | **Mean time between failure (MTBF) is doubled: fewer failures** |
| Halved MTBF | Mean time between failure is halved |
| 2 Month Visit | 2-month summer-time visit (June – July) |
| 2 Month Visit w/o Weather | same as above without wind/wave |
| 1 Month Visit | 1-month summer-time visit (June) |
| 1 Month Visit w/o Weather | same as above without wind/wave |
| Fall Visit | 3-month fall-time (September – November) |
| Winter Visit | 3-month winter-time (December – February) |
| Spring Visit | 3-month spring-time (March – May) |
| **12 Month Visit** | **All Equipment Scheduled year-round** |
| **No Visit** | **No Equipment Scheduled** |

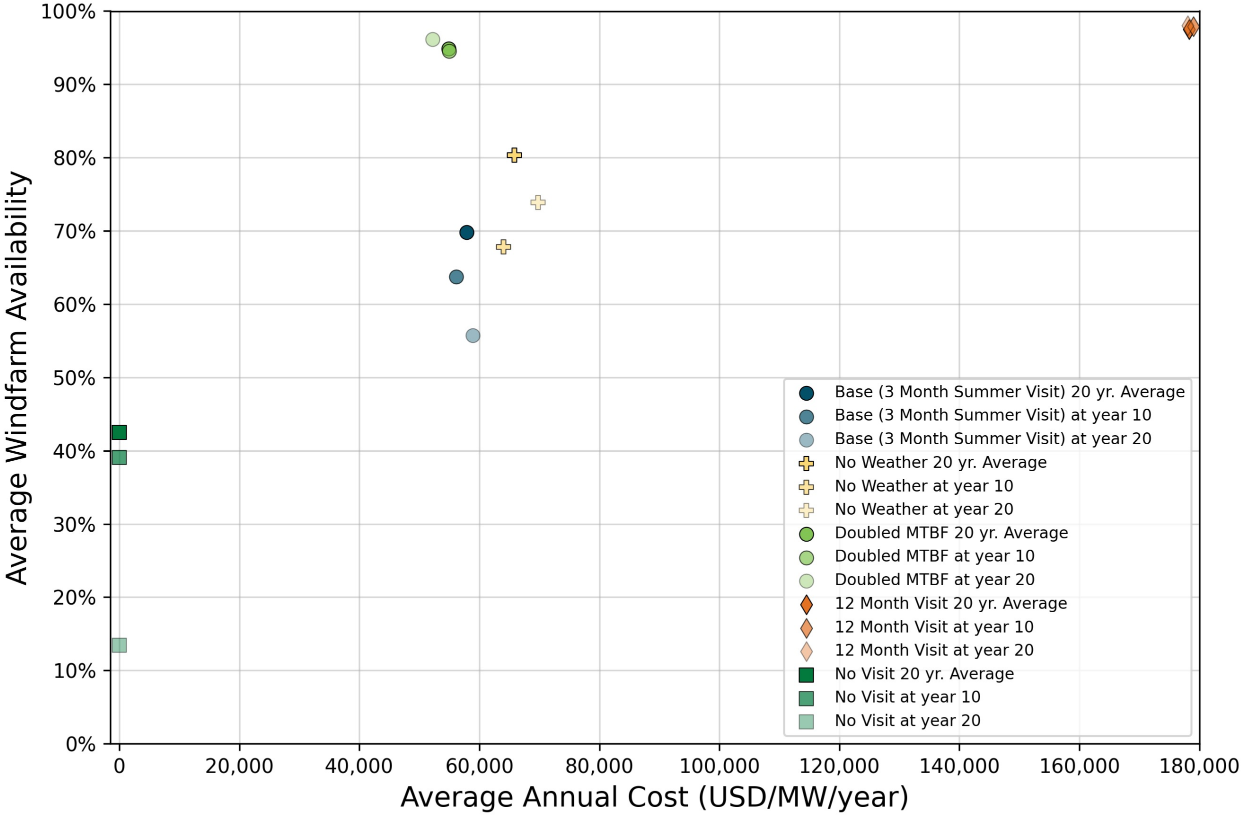
**Note:** Bolded scenarios have results in main section of slides with all other scenario results in the appendix.

# Offshore: Availability



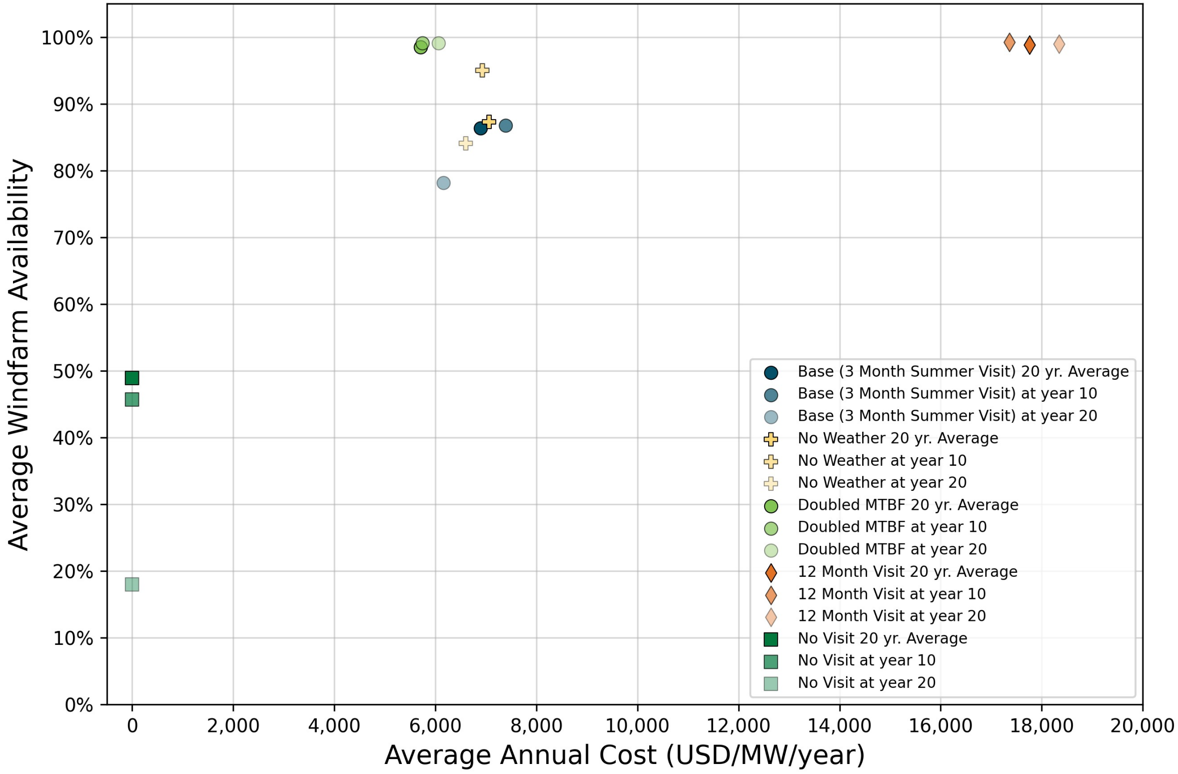

*Source: Pfaffel et al. (2017)

# Offshore: Cost vs. Availability



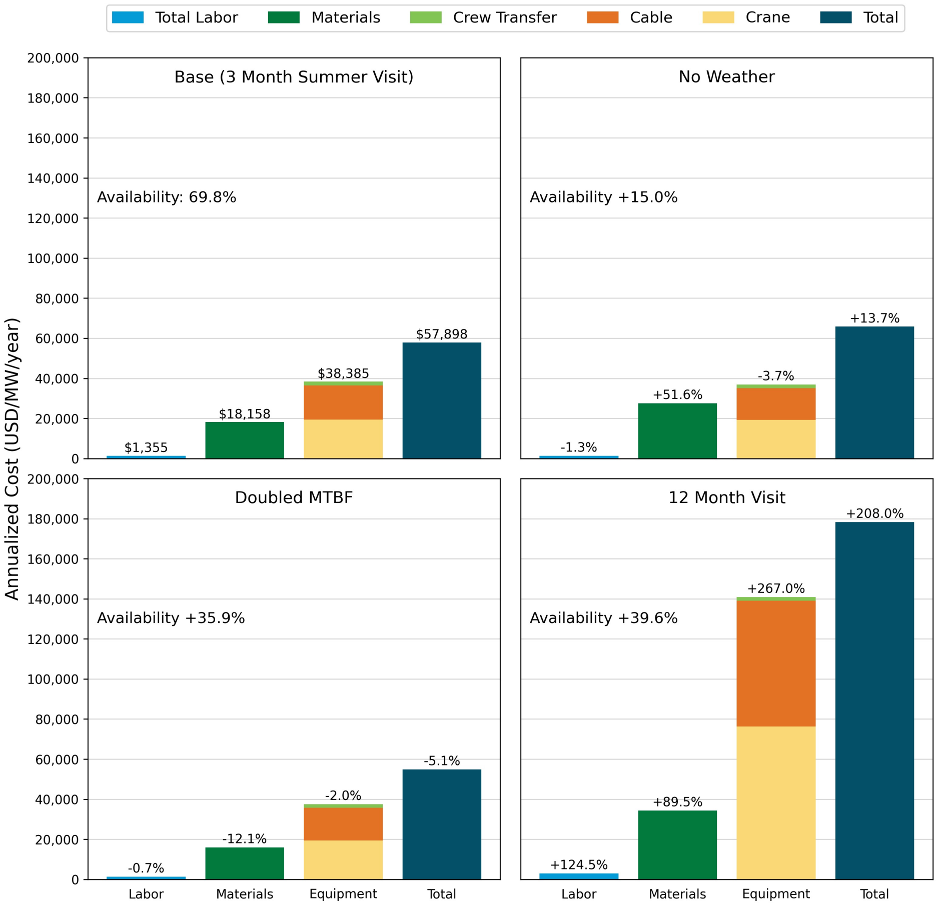

- Weather delays save on direct costs, but with a direct impact on availability.
- Lower failure rates and increased equipment availability can lead to more stable asset availability.

# Onshore: Cost vs. Availability



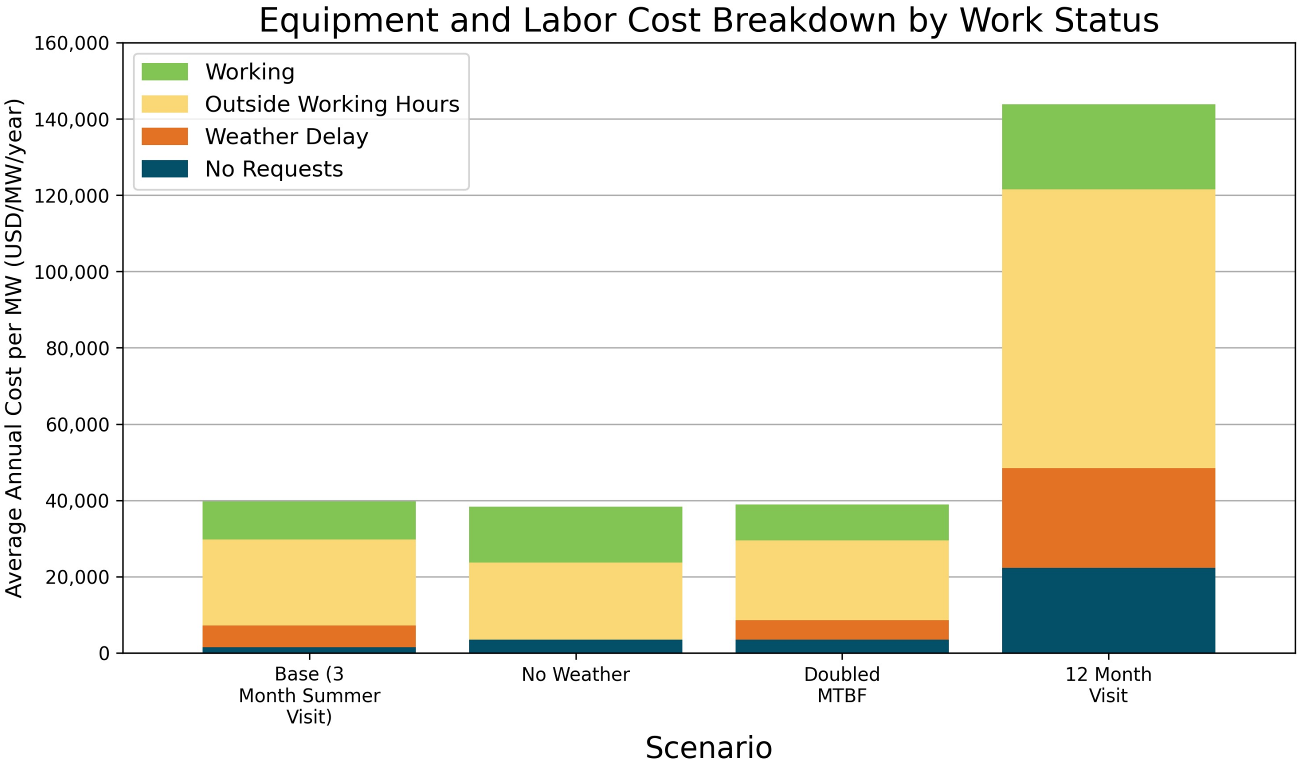

- Increased MTBF and milder weather (compared to offshore) causes weather to be a lesser factor.
- 12-month equipment schedules maintains little annual variability in cost or availability.

# Offshore: Cost Breakdown




- Equipment costs are the primary driver of project costs.
- Materials costs balloon as the weather considerations are removed from the simulation.
- Results suggest that decreasing failure rates (technological innovations) will have the best tradeoff between long-term availability and direct costs.

# Offshore: Equipment Cost Breakdown




- Weather delays become a significant consideration as visit lengths increase.
- As weather becomes more favorable, unproductive hours are a smaller cost consideration.

# Future Work

Types of research questions that could be addressed in the future

# FY2021 AOP

**Deliverables (September 15, 2021)**

- Revenue model
  - Inflation, energy production, annualized costs
- Documentation
  - Online documentation (started)
  - Rough draft of written documentation

# Potential Future Work

**Model Development**

- Further develop repair manager module to enable assessment of LCOE impacts of different maintenance strategies.
- Continue to gather input data on relevant costs, fatigue and reliability, and O&M logistics.
- Create unit tests.
- Creation of a GUI and/or user-friendly API.
- Code optimization for shorter runtimes as projects grow.

**Validation and Review**

- Engagement through PRUF/OpenOA/IEA Task 43 and industry review/validation of modeling strategy and inputs.
- Cross-validation with results from literature and commercial O&M models.
- Public release as standalone NREL software with API to allow integration with other modeling software.
- Describe model and validation results in publication.

# Thank you

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Musial, Walter, and Bonnie Ram. *Large-scale offshore wind power in the United States: Assessment of opportunities and barriers*. No. NREL/TP-500-40745. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2010.

Pfaffel, S., S. Faulstich, and K. Rohrig. “Performance and Reliability of Wind Turbines: A Review.” *Energies*, 10(11), 2017.

Stehly, T., and D. Heimiller. *Cost of Wind Energy Review.* NREL TP-6A20-70363, 2016.

Valpy, Bruce, et al. "Future renewable energy costs: offshore wind." *KIC InnoEnergy,* 2014.

# Supplementary slides

Data Snippet

# Sample failure rates (ECN)

| Component | Category | MTBF (years) | Materials Cost (% of Turbine CapEx) | Repair Time (hours) |
|---|---|---|---|---|
| Rotor Blades | Medium Part Replacement | 100 | 1% | 16 |
| Drive Train | Large Part Replacement | 1000 | 2% | 24 |
| Yaw System | Inspection/Small Repair | 3 | 0.01% | 4 |
| Transformer | Small Part Replacement | 29 | 0.1% | 16 |
| Electrical System | Inspection/Small Repair | 2 | 0.01% | 4 |

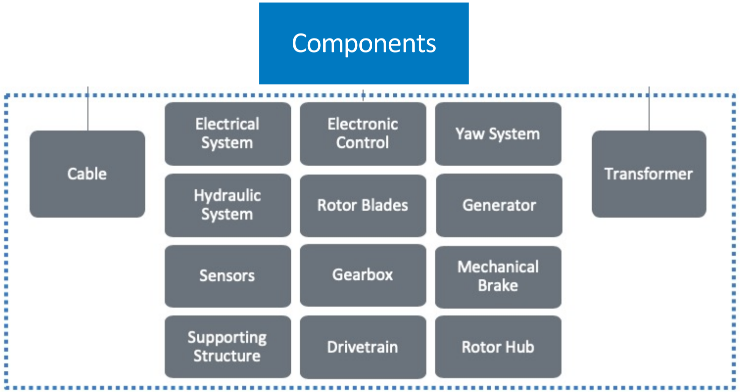
# Supplementary slides

Additional Details

# Wind Farm Module

Wind Farm Module

- Allows for the site-specific definition of a windfarm.
- Models assets (i.e., turbines, substation, and cables).
  - May contain multiple turbine types and different component definitions.
  - Uses a graph model to ensure cable failures translate to downtime for upstream turbines.




- Defines O&M requirements and costs for each component.
  - Routine maintenance.
  - Failure rates and severities.
  - Repair time and parts cost.
  - Equipment needs.

# Environment Module

## Environment Module

- Simulation module that tracks time and weather.
  - Land-based sites track wind speed for operational limits.
  - Offshore sites also monitor wave height.
- Logs all events.
- Shares information with other modules.

## Equipment

- Defines equipment for repair and maintenance (e.g., cranes, jack-up vessels, cable lay vessels, CTVs).
- Equipment parameters:
  - Cost (labor and equipment).
  - Operational limits/capabilities.
  - Crew size.
  - Charter period.
- Allows for site-specific modeling to assess cost implications of various equipment and crew strategies.

## Repair Manager

- Tracks maintenance and repair requests.
- Core model structure that will enable additional decision-making functionality in the future.
  - Current functionality only allows repairs during predetermined windows.

# Discrete Event Simulation

- Models a discrete series of events in sequential order where no changes occur between events.
- Allows for detailed documentation of a system and its processes enabling  advanced diagnostics.
- Running simulations enables a prescriptive approach to research to understand specific impacts compared to an optimization with a ”best choice”.

# Equipment

- Provides a flexible equipment definition of crew-based equipment with repair and maintenance logic.
- Enables easy definition of land-based and offshore vehicles such as cranes, jack-up vessels, cabling vehicles, and CTVs.
- Enables flexible cost definitions for different sized and specialized crews.
- Allows for site-specific modeling to fully assess cost implications of various equipment and crew strategies.

# Windfarm Module

- Central infrastructural element to collect and model turbines, substation(s), and cables (assets).
- Uses a graph data structure to ensure cable failures translate to downtime for upstream turbines
- Allows for the site-specific modeling of a windfarm that may contain one or multiple turbine types with various subassembly definitions to fully realize the impacts on cost.

# Subassembly Module

- Provides failure and maintenance modeling functionality for:
  - 12 subassemblies of turbine
  - The transformer in a plant substation
  - Cables.
- Enables site-specific modeling to capture the costs of failures of individual turbines at a plant.

# Repair Manager

- Tracks maintenance and repair requests submitted by the turbines, substation(s), and cables.
- Provides a centralized place to model decision-making functionality.

# Turbines and Substations

- The System module enforces that all subassemblies are created and modeled.
- By allowing the subassemblies to model themselves, the system can keep track of each process and its immediate downstream cable section.

# Cables

- A separate module that acts very similarly to the turbine and substation but can switch “off” upstream turbines in the event of a failure.
- Cable failures are a significant part of offshore O&M costs, but less so for land-based so they can selectively be excluded from the modeling.

# Supplementary slides

Additional Results

# Scenario Definitions

| Scenario Name | Description |
|---|---|
| Base | 3-month summer-time visit (June – August) |
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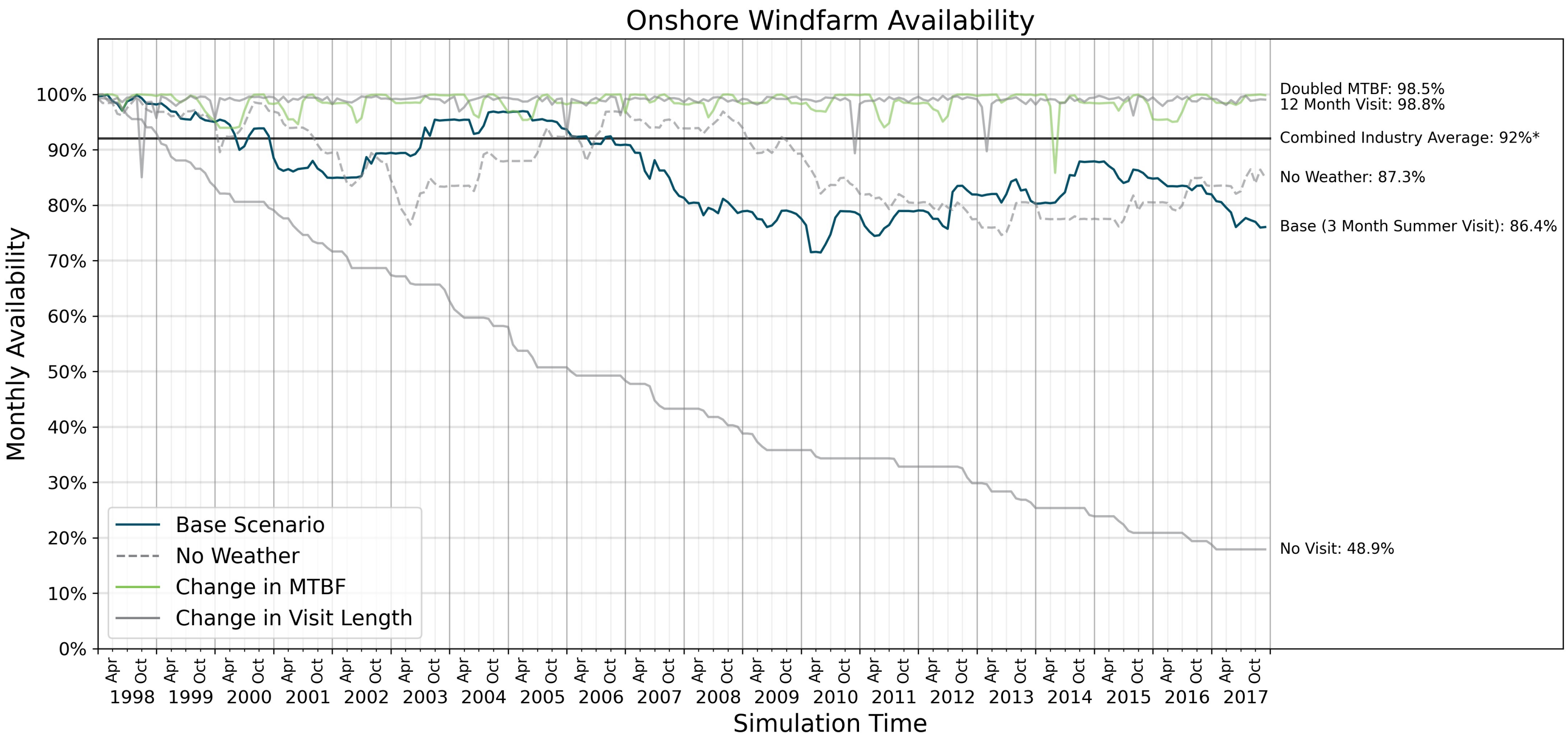
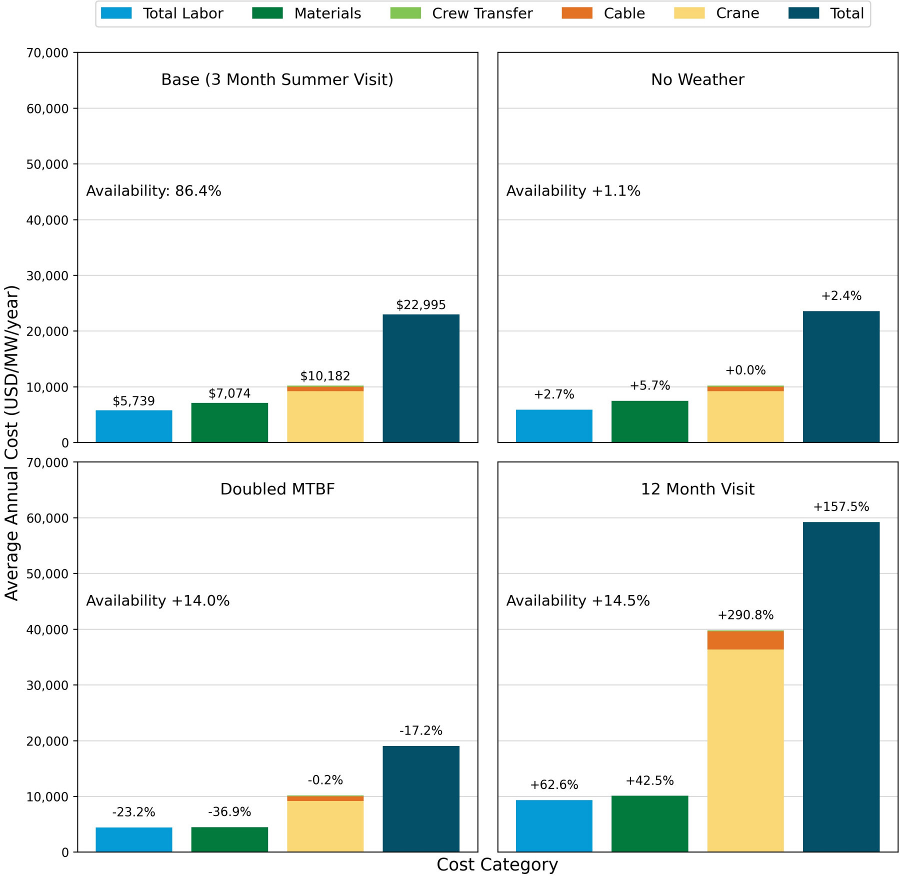


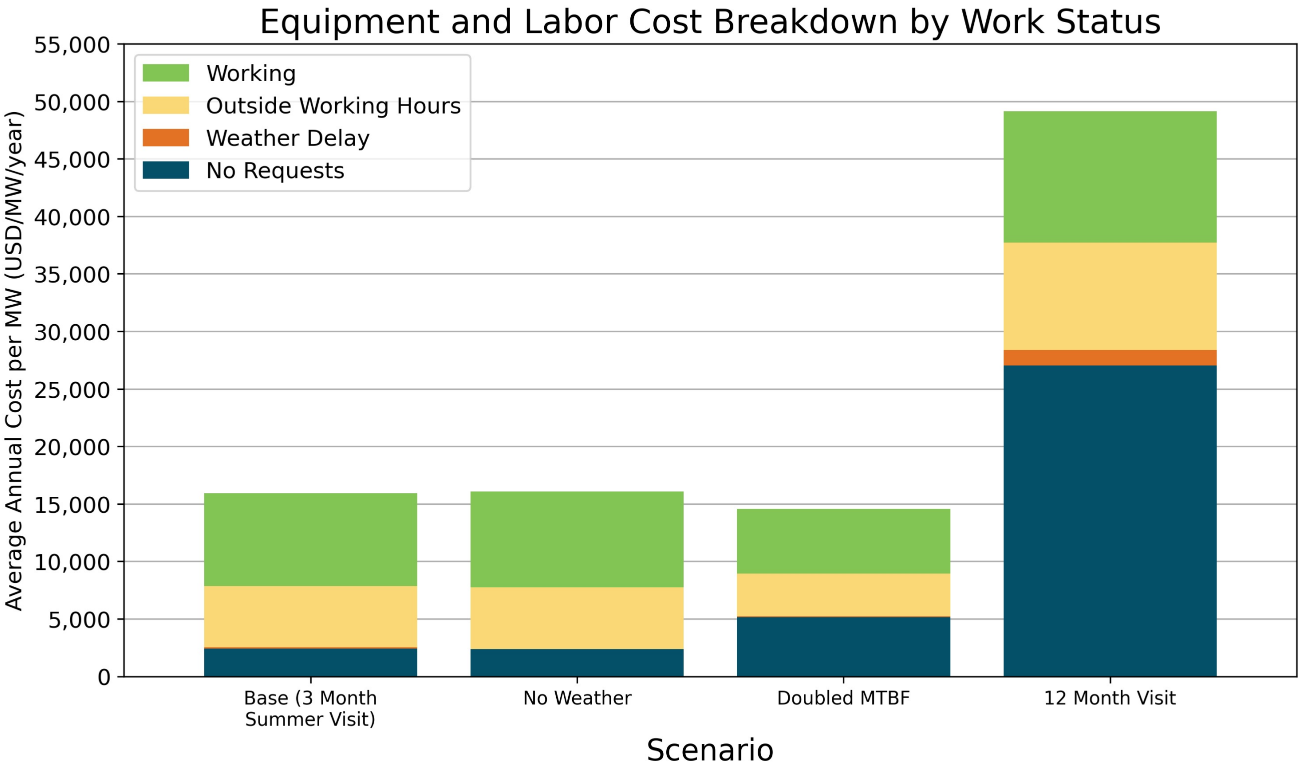

*Source: Pfaffel et al. (2017)

# Onshore: Cost Breakdown




- Cranes remain the leading cost driver compared to offshore.
- Failure rate reduction is still the most beneficial improvement to the overall cost-availability trade-off.
- Weather has little impact on overall costs.

# Onshore: Equipment Cost Breakdown

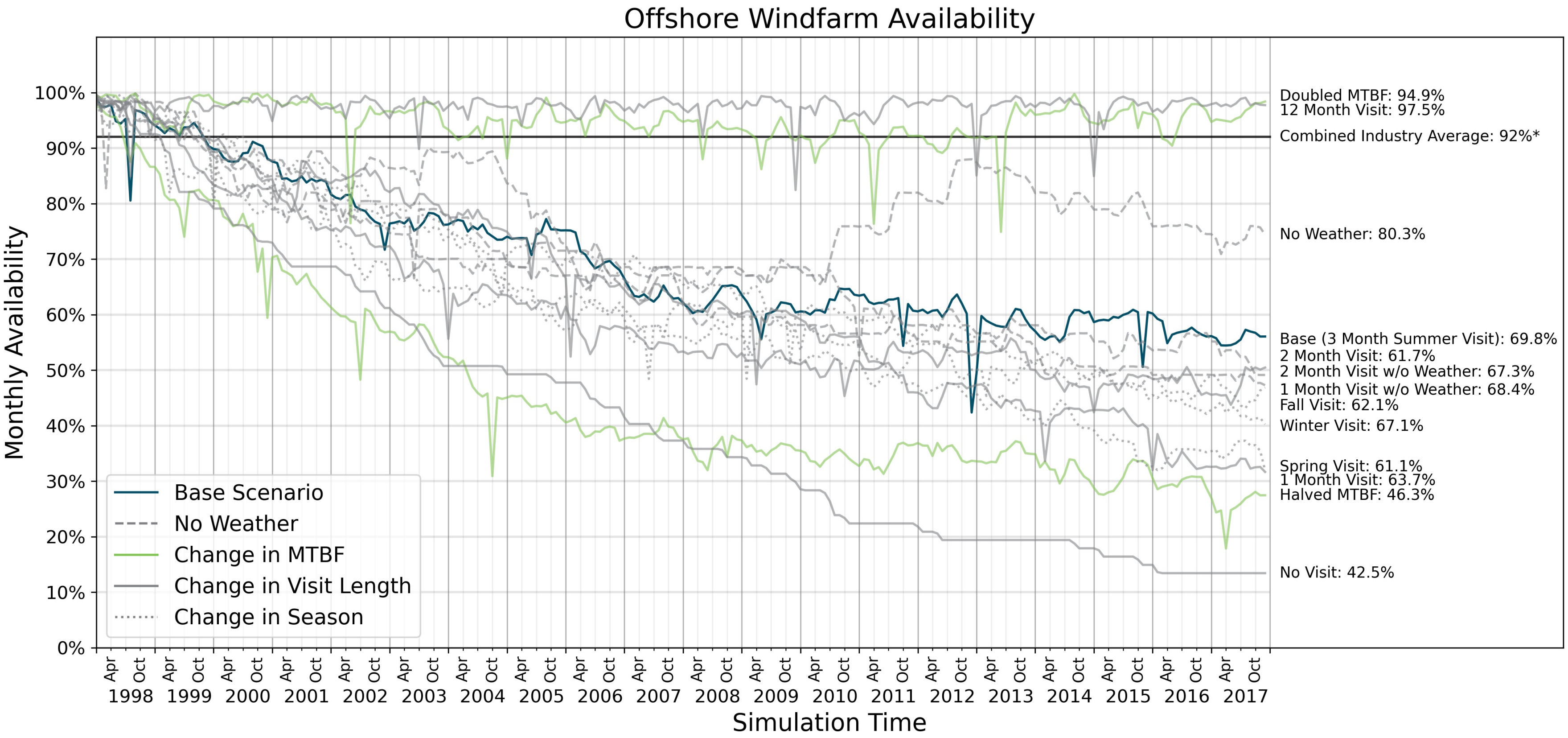



- Little change in productive hours when weather is a lesser factor due to equipment.
- Higher costs for unproductive hours when failure rates are decreased compared to baseline.

# Supplementary slides

Full Results

# Offshore: Availability

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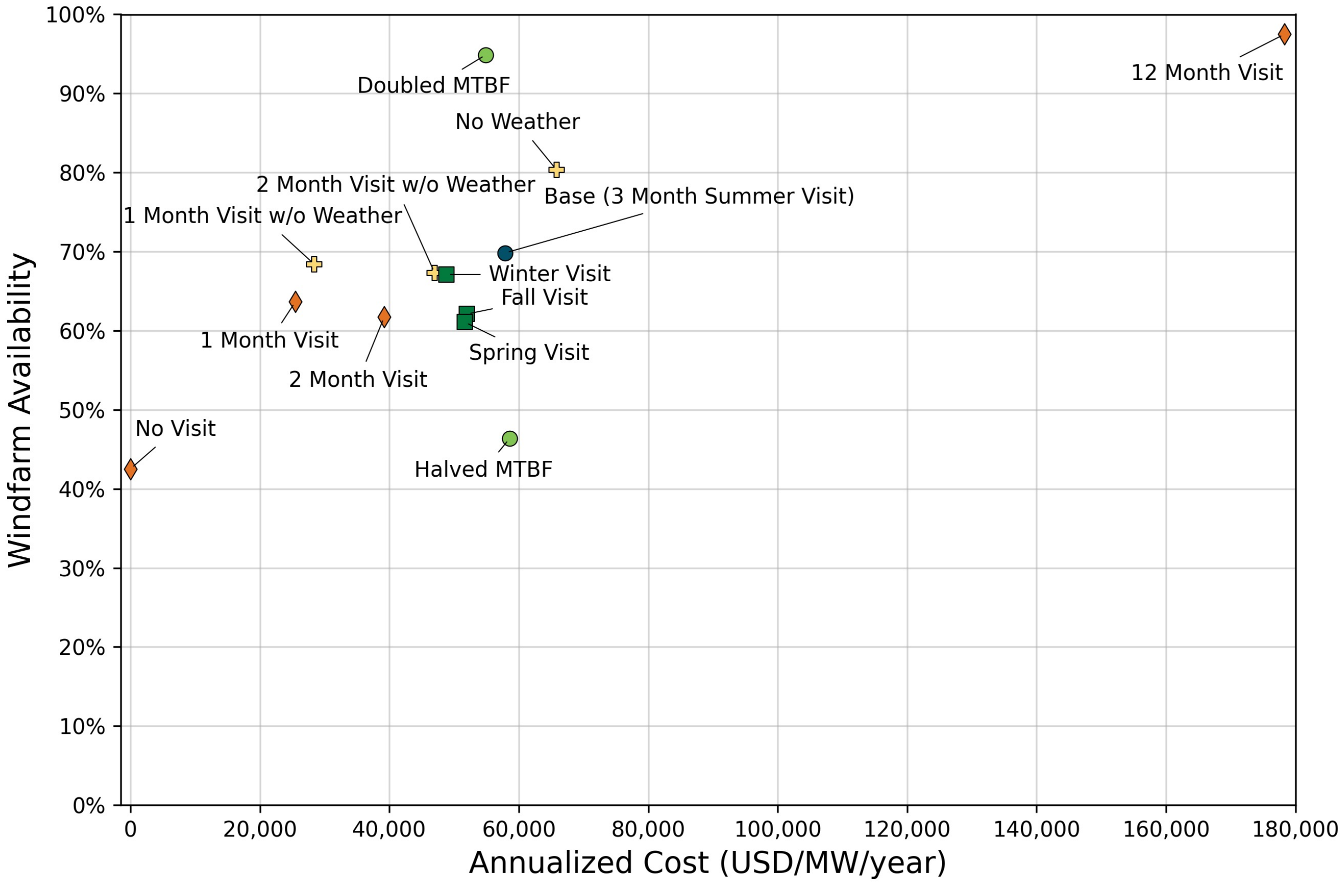

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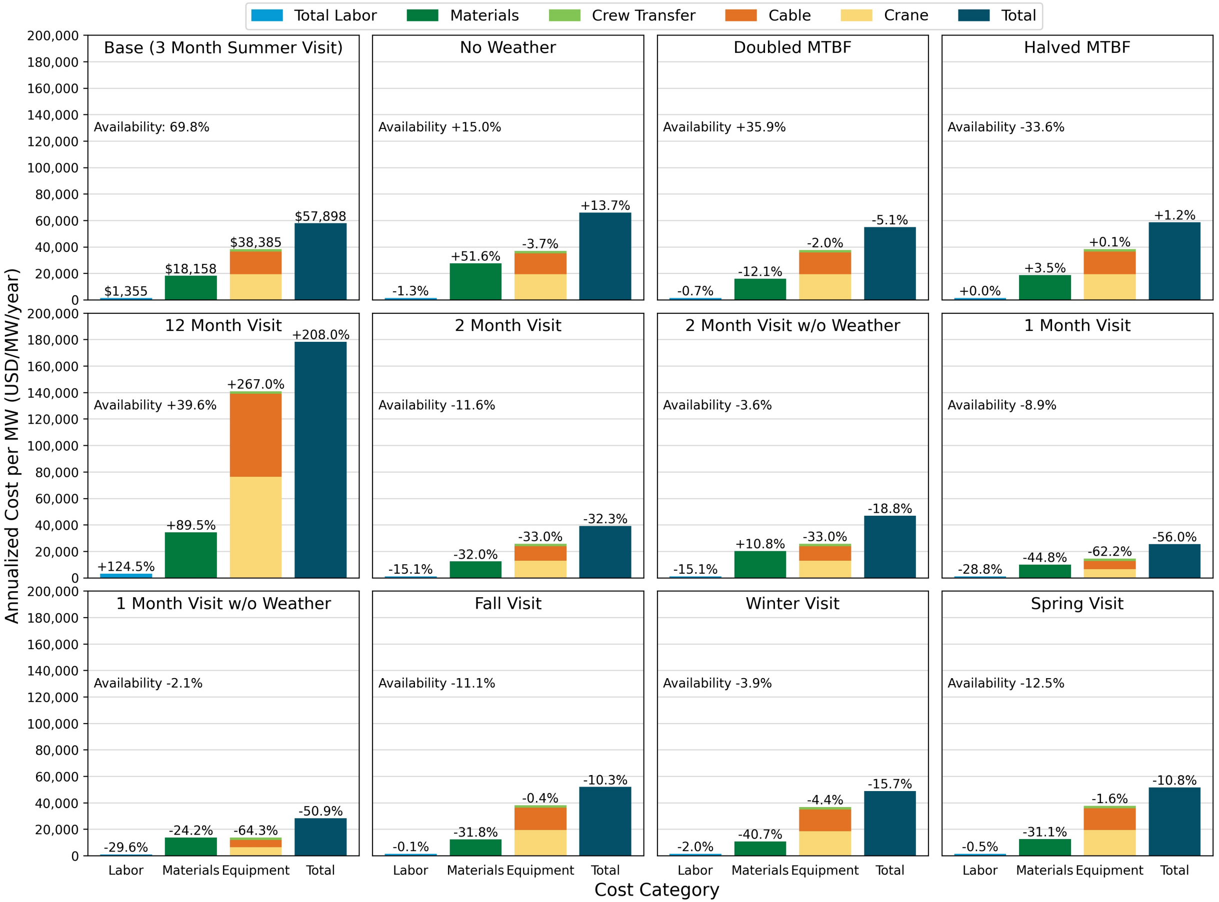

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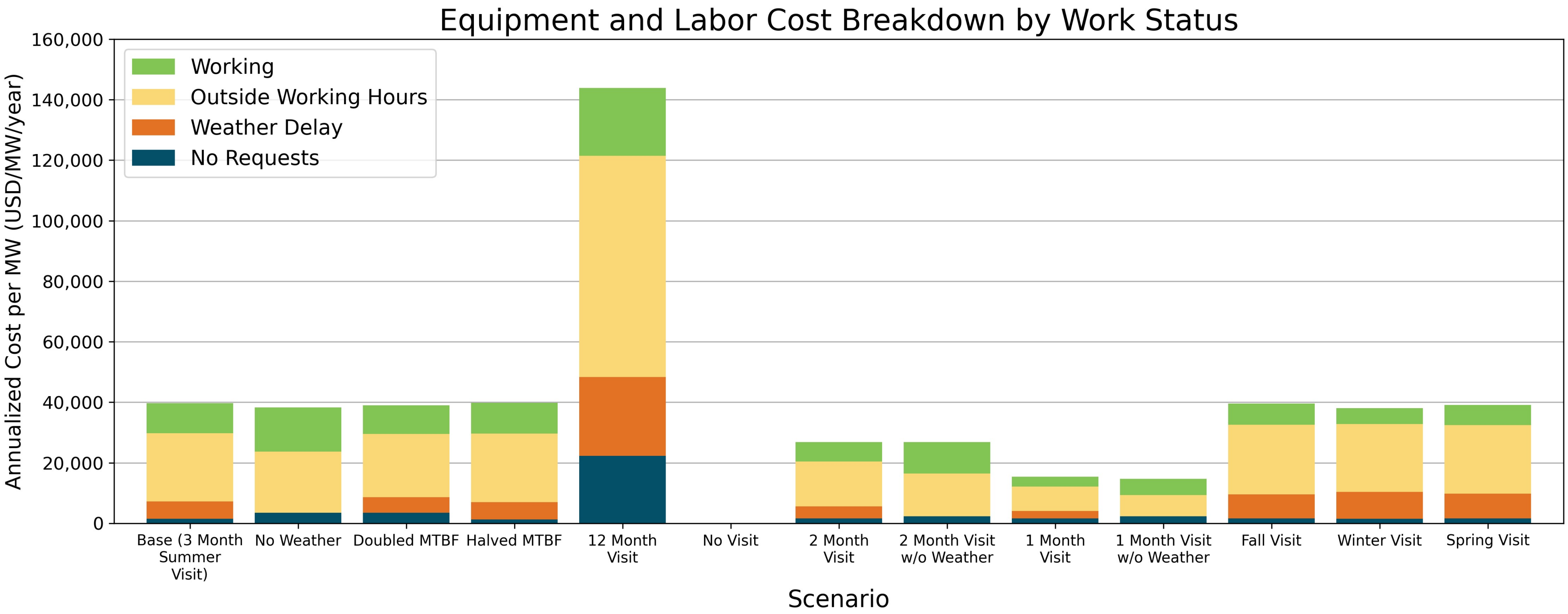

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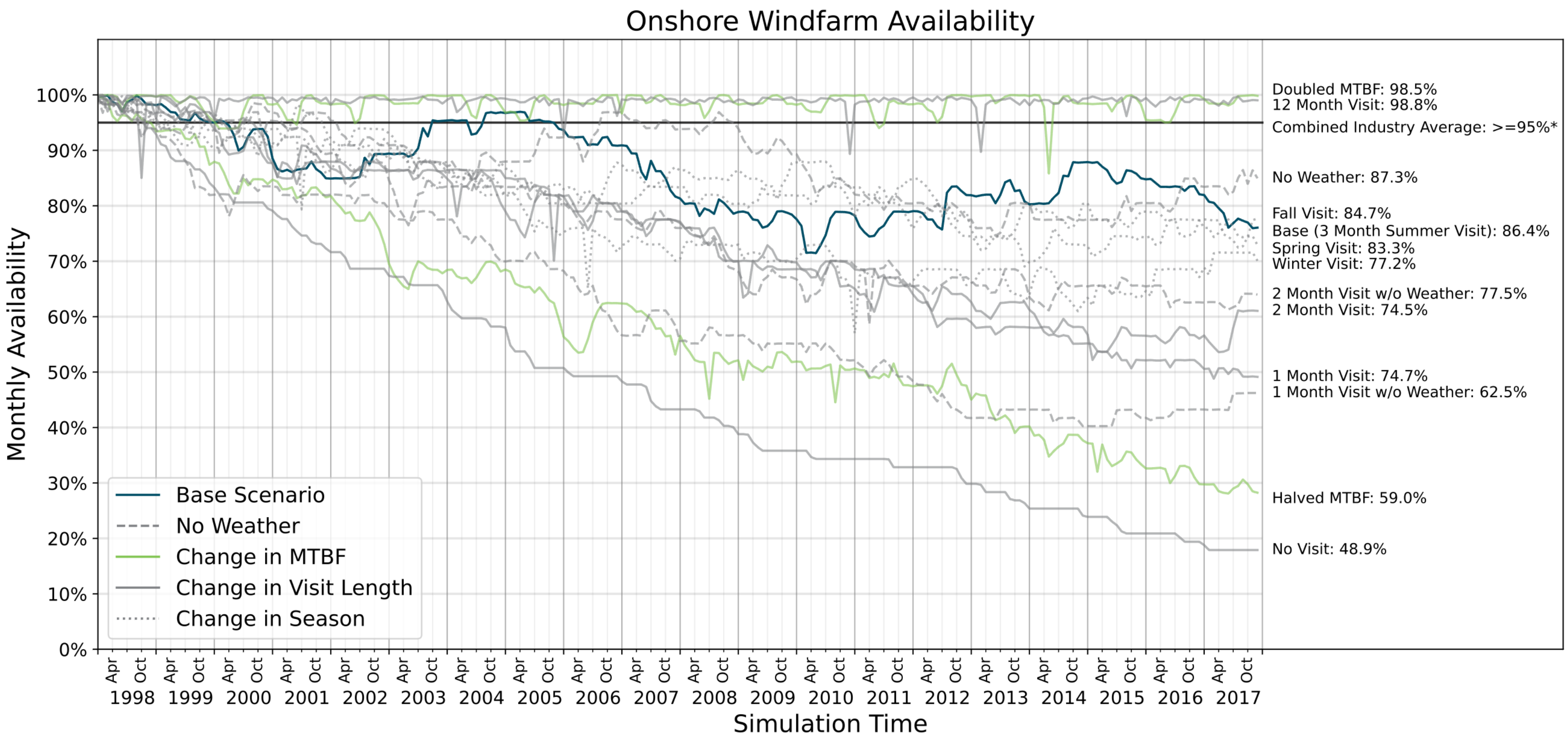


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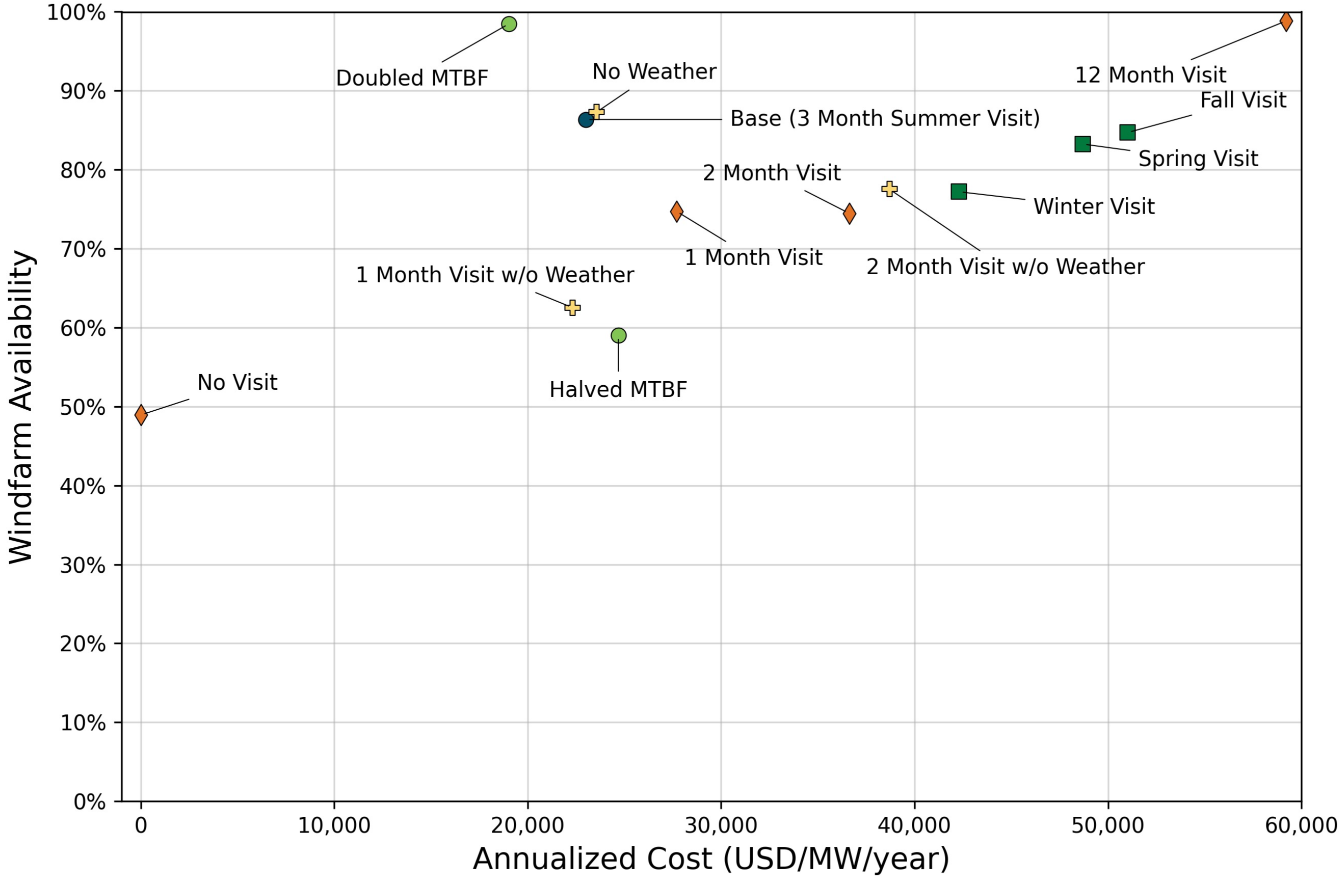
# Onshore: Cost vs. Availability



# Onshore: Cost Breakdown

# Onshore: Equipment Cost Breakdown