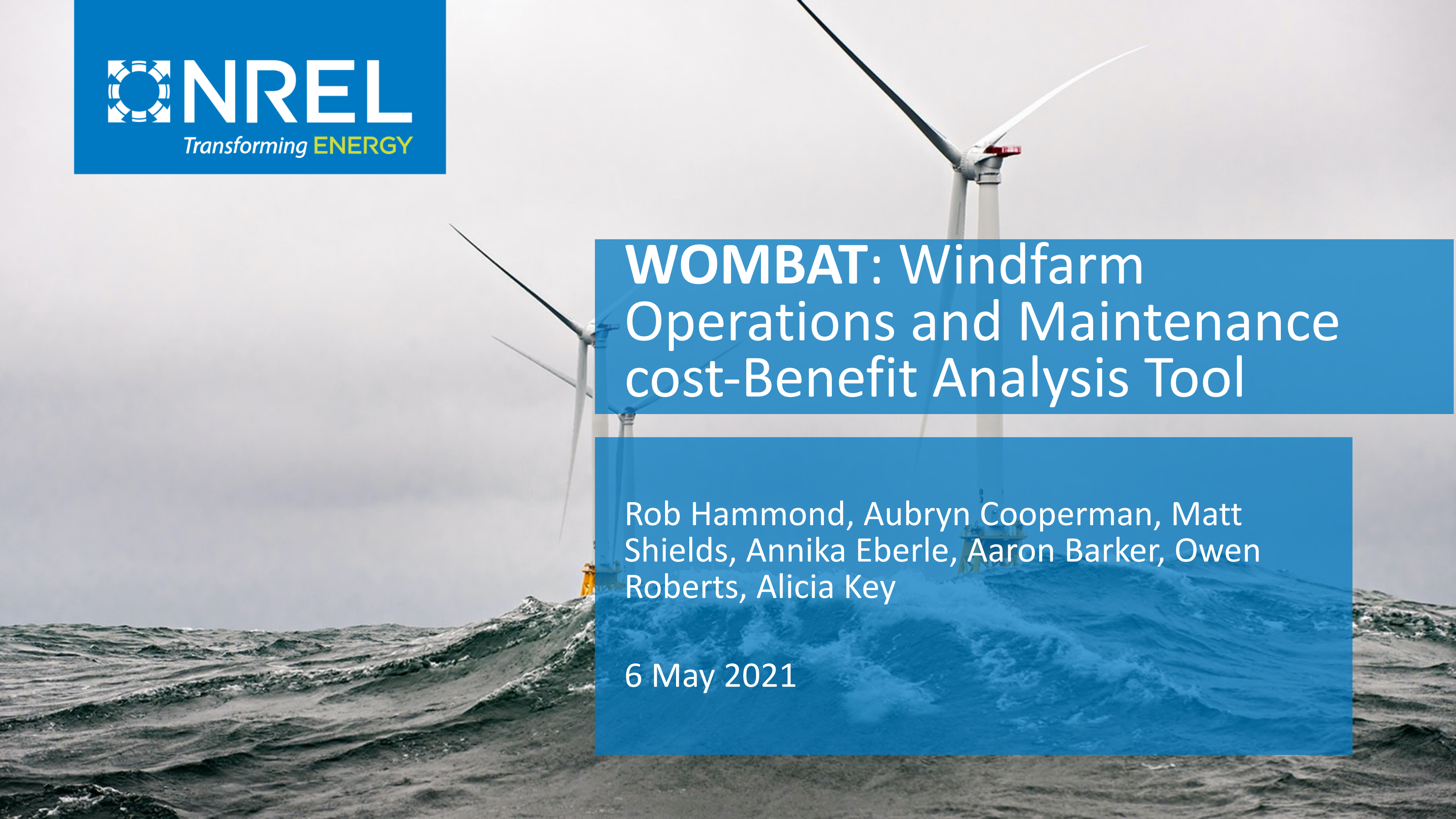


WOMBAT: Windfarm Operations and Maintenance cost-Benefit Analysis Tool

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

6 May 2021

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.

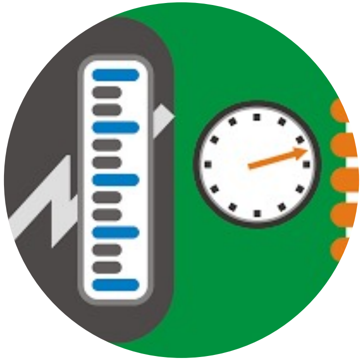
Prior Work

- 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

Model Overview

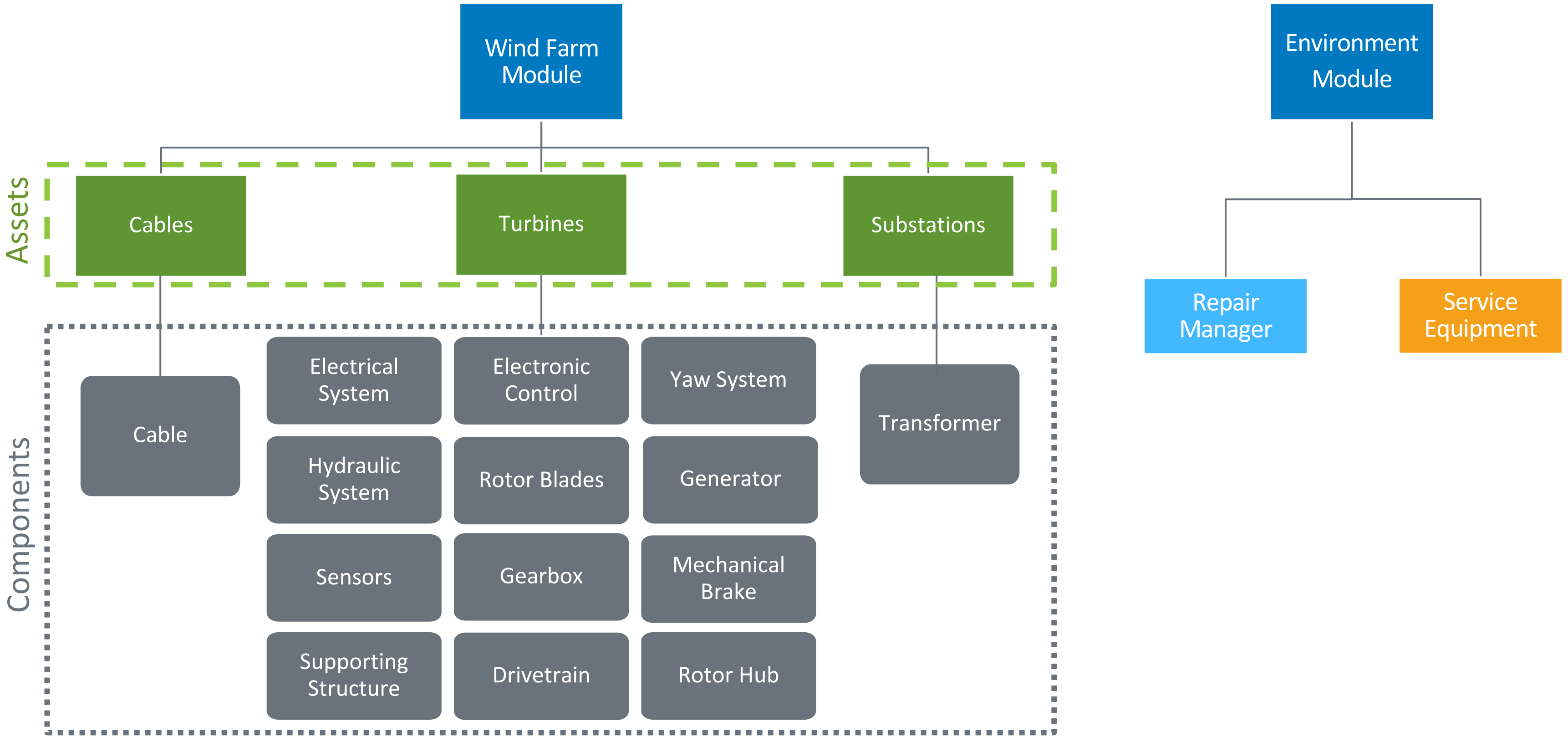
Approach

- 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

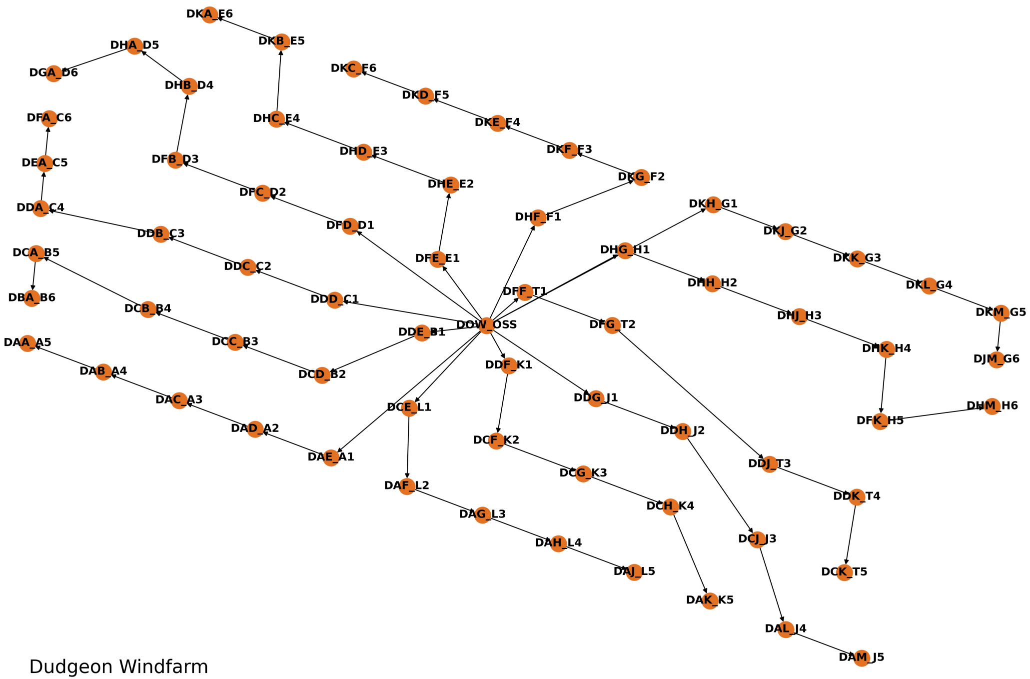
- Modular and flexible code base:
  - Allows for new methodologies to be tested with ease
  - Provides a tool to analyze both offshore and land-based windfarm O&M costs

- 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.

High-Level Software Architecture



The Windfarm Model

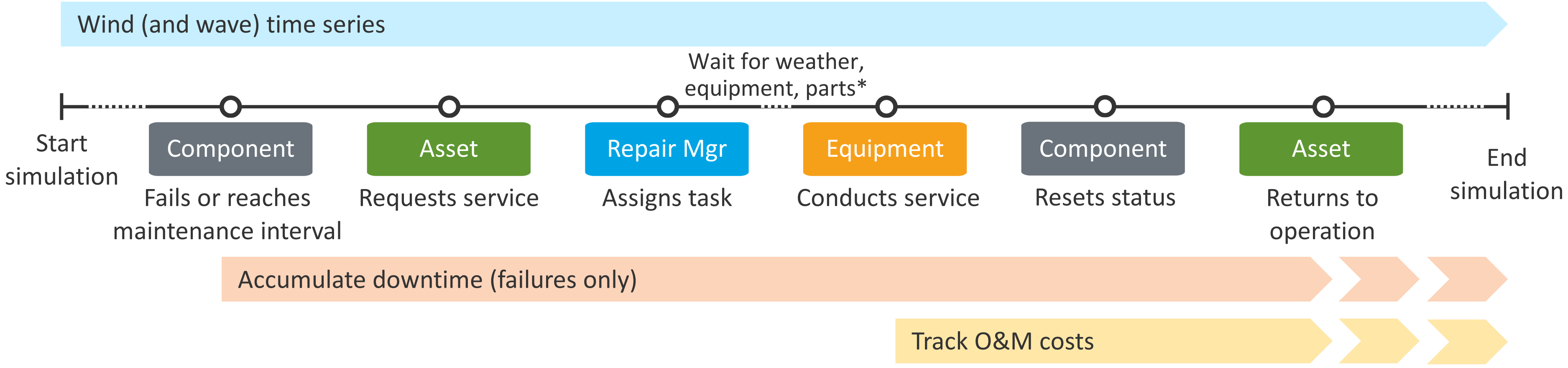


Dudgeon Windfarm

- **The model relies on a set of spatial locations and modeling definitions to create the interdependency between substations, cables, and turbines**

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, Outputs, and Model Capabilities

Baseline Inputs

Components

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

Service 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

- Time-based availability
- Production-based availability
- Power production
- Fixed costs
- Capacity factor
- Task completion rate
- Service equipment costs
- Service equipment utilization
- Labor costs
- Combined service equipment and labor costs by productivity
- Component costs
- Servicing time breakdown
- NPV, real and nominal LCOE, and IRR
- More on the way

High fidelity log files to compute further metrics

- Event logs
- Operating level logs
- Power production logs
- Power potential logs

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

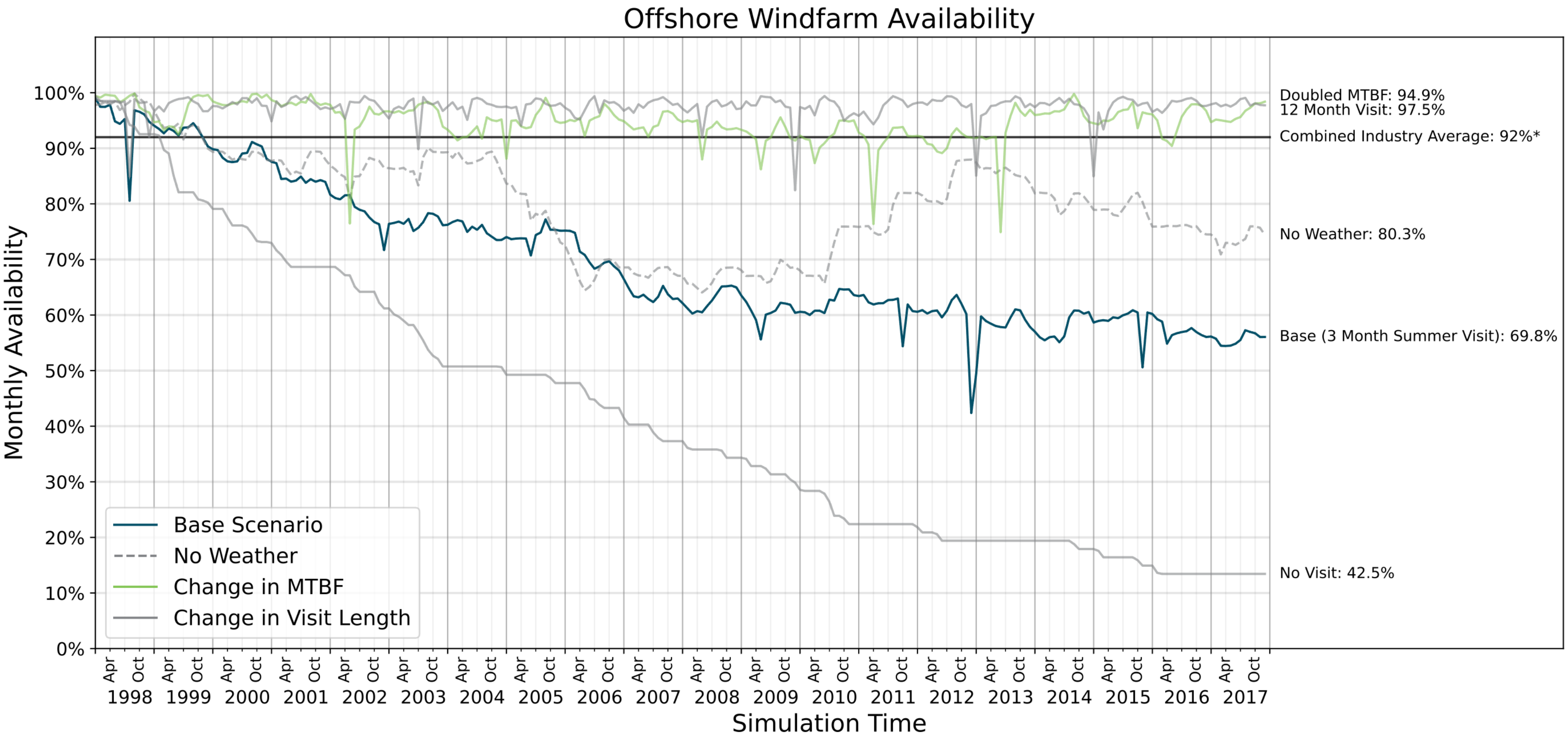
- Standard across all scenarios:
  - Full-time crew year-round for minor repairs
  - Major repairs conducted during a pre-determined window
  - Working hours are 8am – 6pm
  - Results only include material, equipment, and labor costs
  - Failure data is intended as placeholder with current rates based 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**

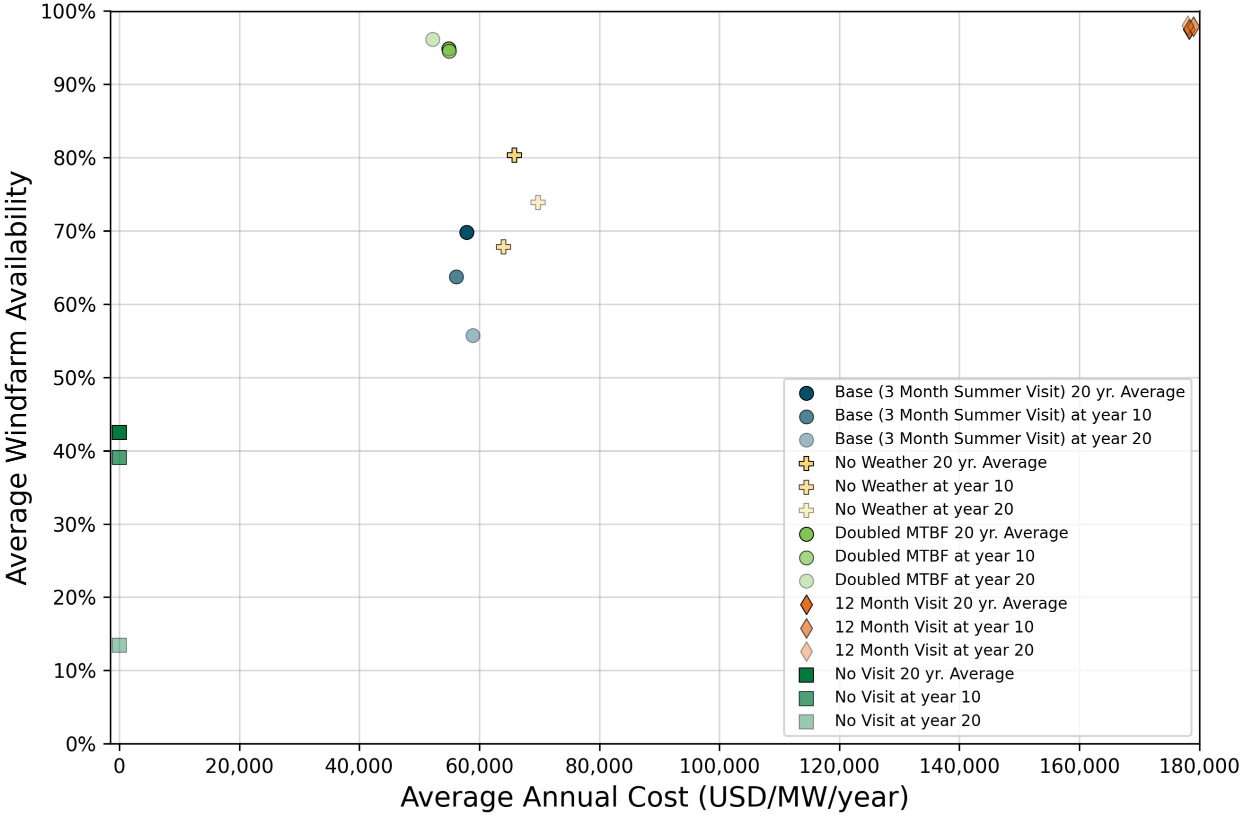
Note: Bolded scenarios have results in main section of slides with all other scenario results in the appendix.

Offshore: Availability



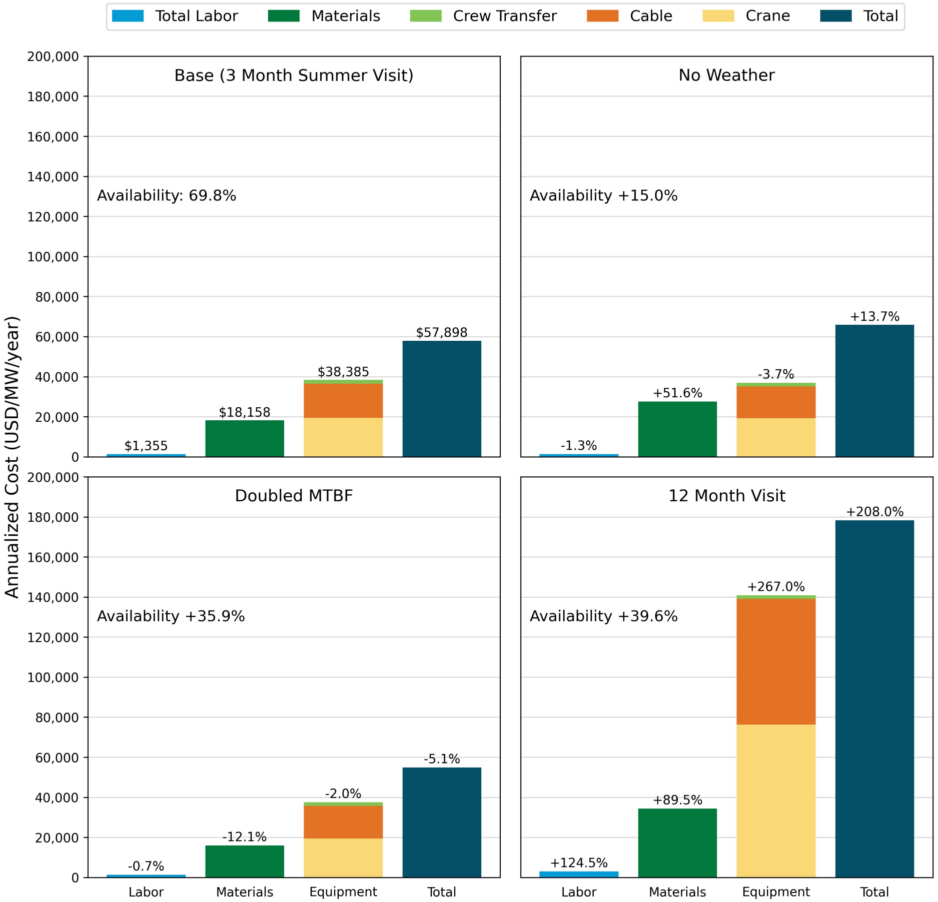
*Source: Pfaffel et al. (2017)

Offshore: Cost vs. Availability



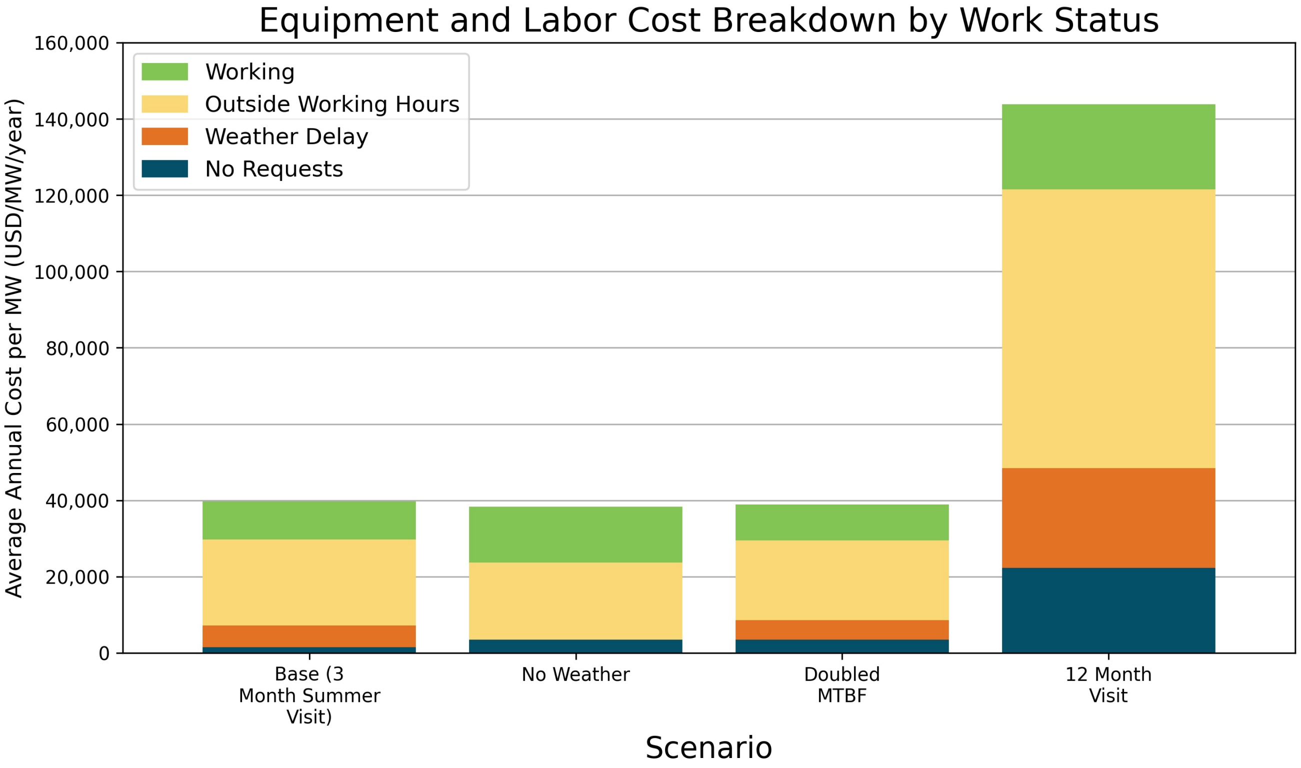
- Weather delays save on direct costs, but with a direct impact on availability.
- Lower failure rates and increased equipment availability can lead to more stable asset availability.

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.

Code-to-Code Comparison

IEA Task 26, 2016 Results Comparison

	NOWIcob	ECN	WOMBAT – 1 visit	WOMBAT – 2 visits	WOMBAT – 3 visits
Availability (%)					
Time-Based	93.3%	94.9%	64.2%	89.5%	94.3%
Energy-Based	92.6%	94.8%	64.4%	90.0%	94.9%
Costs (million €/yr)					
Total annual costs	25.4	28.4	15.2	20.9	25.2
Technicians	3.0	2.3	3.0	3.0	3.0
Spare parts	7.8	7.9	4.0	6.1	7.2
Vessels	14.5	18.2	8.2	11.8	15.0
- CTV	3.8	1.8	2.6	2.6	2.6
- Jack-up	9.5	15.5	3.6	7.2	10.4
- Diving Support	1.1	0.9	0.5	0.5	0.5
- Cable Laying	0.1	0.1	1.6	1.6	1.6

	NOWIcob	ECN	WOMBAT – 1 visit	WOMBAT – 2 visits	WOMBAT – 3 visits
Downtime (days/turbine/year)					
Total downtime	26	19	89.6	34.6	17.0
Manual resets	7	4	0.4	0.6	0.7
Minor repair	7	4	0.9	1.3	1.5
Major repair	2	1	0.5	0.7	0.8
Major replacement	5	6	85.8	29.7	12.0
Remote reset	1	1	0.0	0.1	0.1
Annual service	3	2	0.7	1.9	1.8
BoS	1	1	0.0	0.0	0.0

Dinwoodie, et al., 2015 Results Comparison

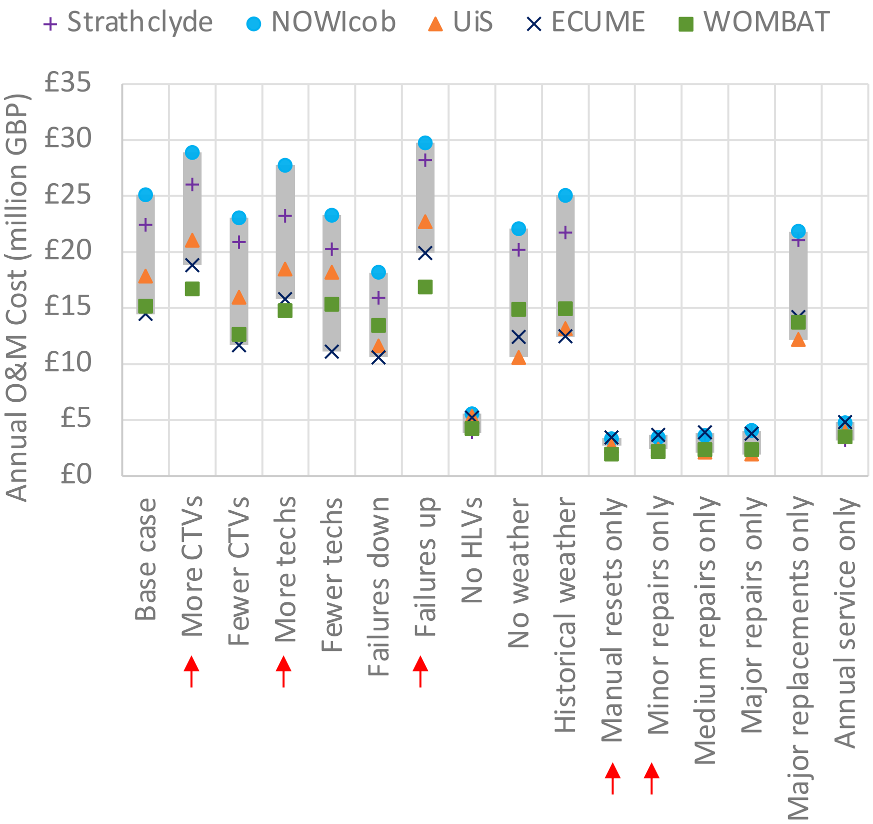
	Strathclyde	NOWIcob	UiS Sim	ECUME	**Average**	WOMBAT – 3 visits*
Availability - time based	83.70%	83.74%	84.40%	80.82%	**83.16%**	94.08%
Availability - energy based	82.11%	82.86%	84.00%	81.70%	**82.67%**	93.98%
Production loss (million £/yr)	£17.28	£16.63	£15.48	£18.64	**£17.01**	n/a
Direct O&M cost (million £/yr)	£22.44	£25.17	£17.93	£14.48	**£20.00**	£17.42
Vessel cost (million £/yr)	£17.84	£19.18	£12.24	£9.30	**£14.64**	£11.90
Repair cost (million £/yr)	£3.00	£4.39	£4.08	£3.58	**£3.76**	£3.92
Technician cost (million £/yr)	£1.60	£1.60	£1.60	£1.60	**£1.60**	£1.60
Standard error: availability	0.22%	0.14%	0.12%	n/a	**0.16%**	n/a
Standard error: cost	n/a	£1.34	£2.05	n/a	**£1.70**	n/a

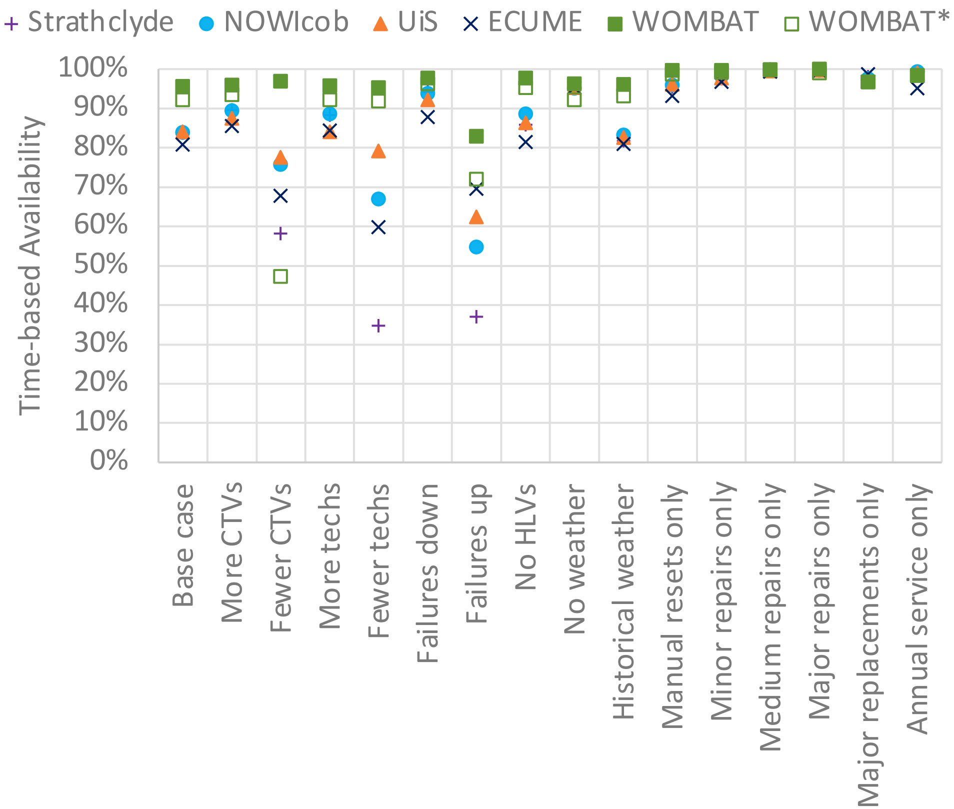
*HLV visit schedules:

1 visit: June 1-30, 24-hour work shift

3 visits: May, July, and September (2 weeks each), 7am-7pm work shift

Dinwoodie, et al., 2015 Results Comparison





Note: Dinwoodie results digitally extracted from plots

*Availability assuming 100% operations reduction for all failures

Future Work

By Late Summer

- Simple Unscheduled Maintenance Model
- Multi-run API for sensitivity analyses
- More metrics
- Crew transfer and potentially multi-crew handoffs
- Public release: https://github.com/WISDEM/WOMBAT/
- Documentation site for how to work with the code

Next Year and Beyond

Model Development

- Testing!
- Robust unscheduled maintenance model
- Continue to gather input data on relevant costs, fatigue and reliability, and O&M logistics.
- Creation of a GUI
- Code optimization for shorter runtimes as projects grow.

Validation and Review

- Engagement through industry review and validation of modeling strategy and inputs.
- Cross-validation with results from literature and commercial O&M models.
- Technical report describing the model

Thank you

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Dinwoodie, Iain, et al. "Reference cases for verification of operation and maintenance simulation models for offshore wind farms." *Wind Engineering* 39.1 (2015): 1-14.

Appendix

Additional Details

Supplementary Slides

Full DOE Results

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

Scenario Definitions

Scenario Name	Description
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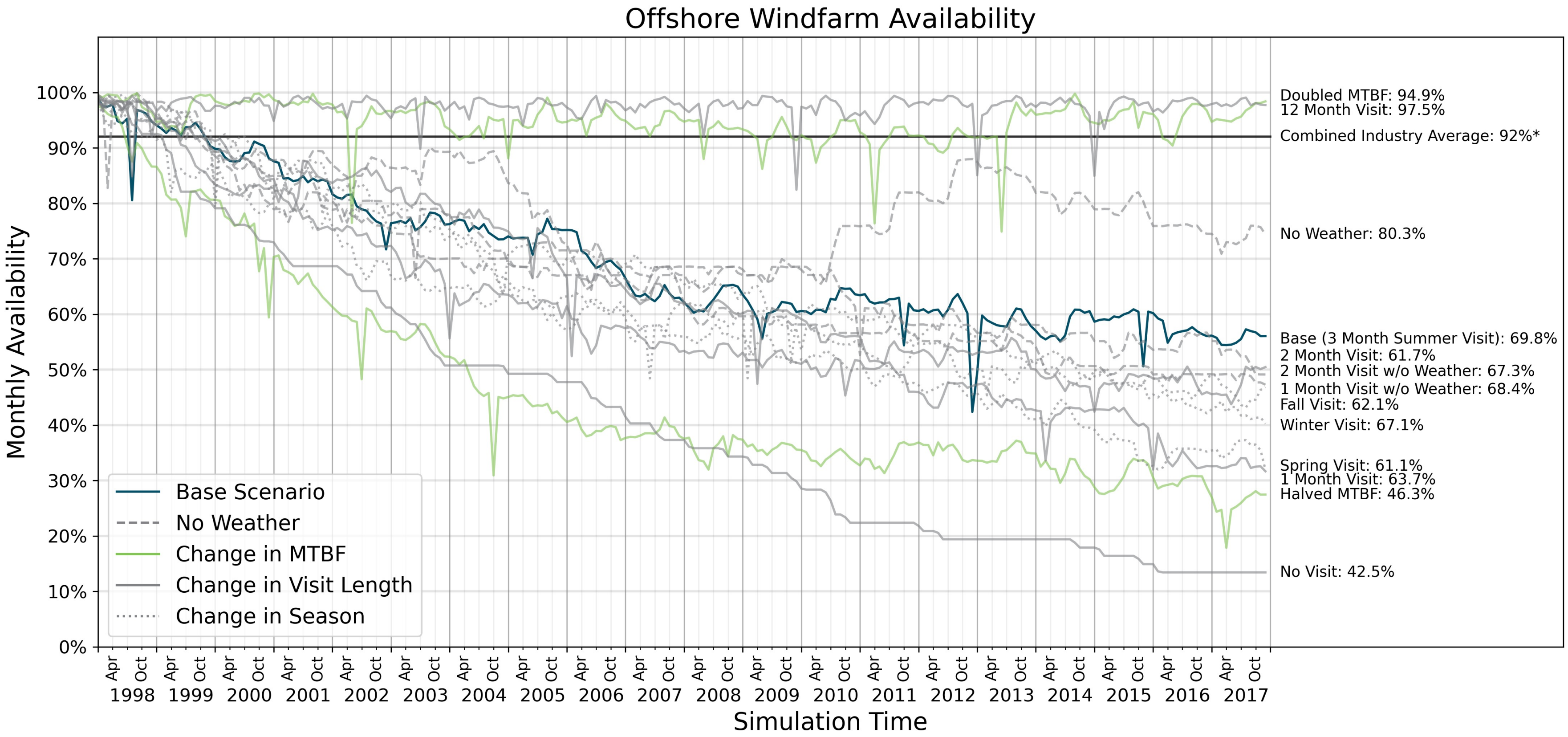
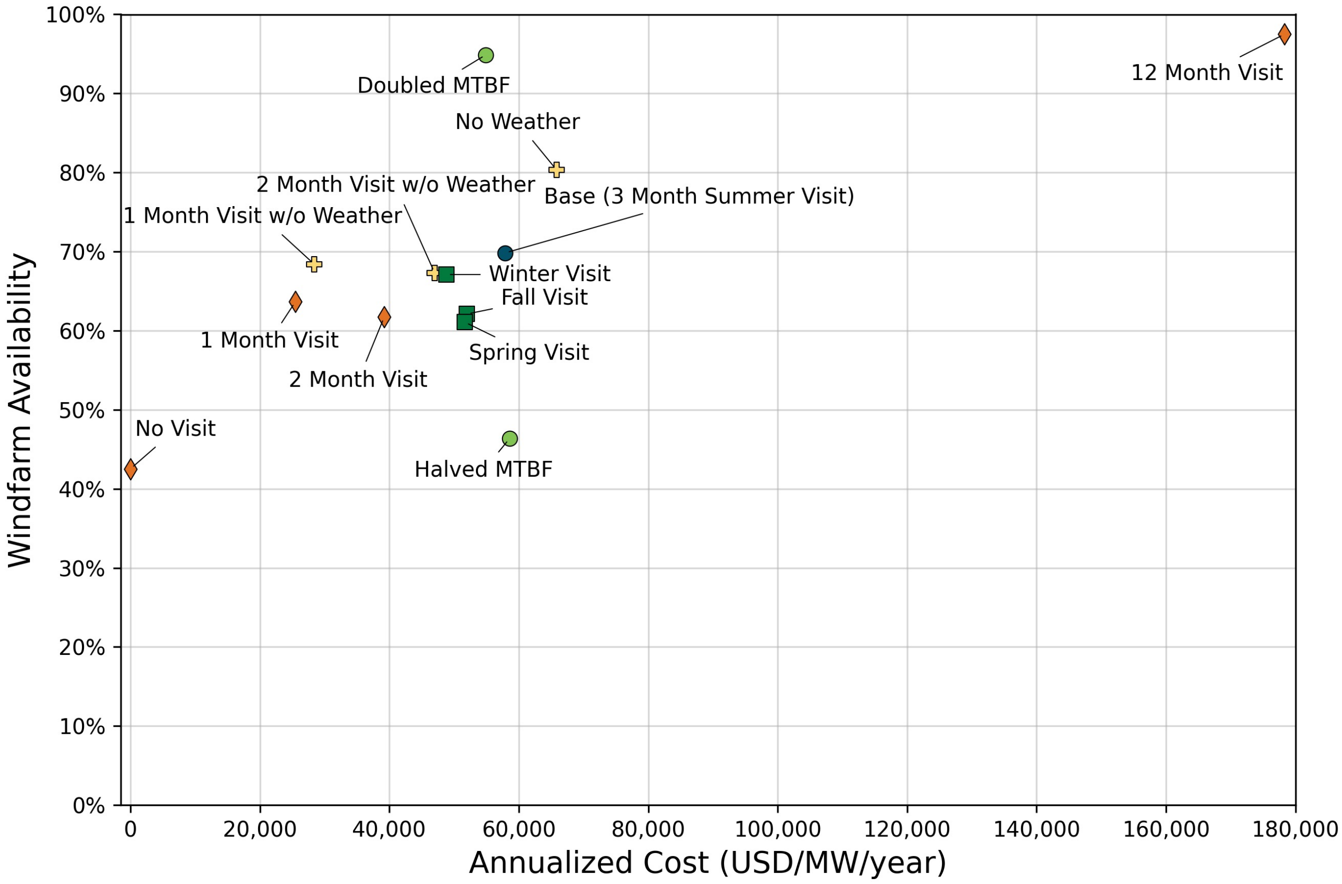
Offshore: Availability

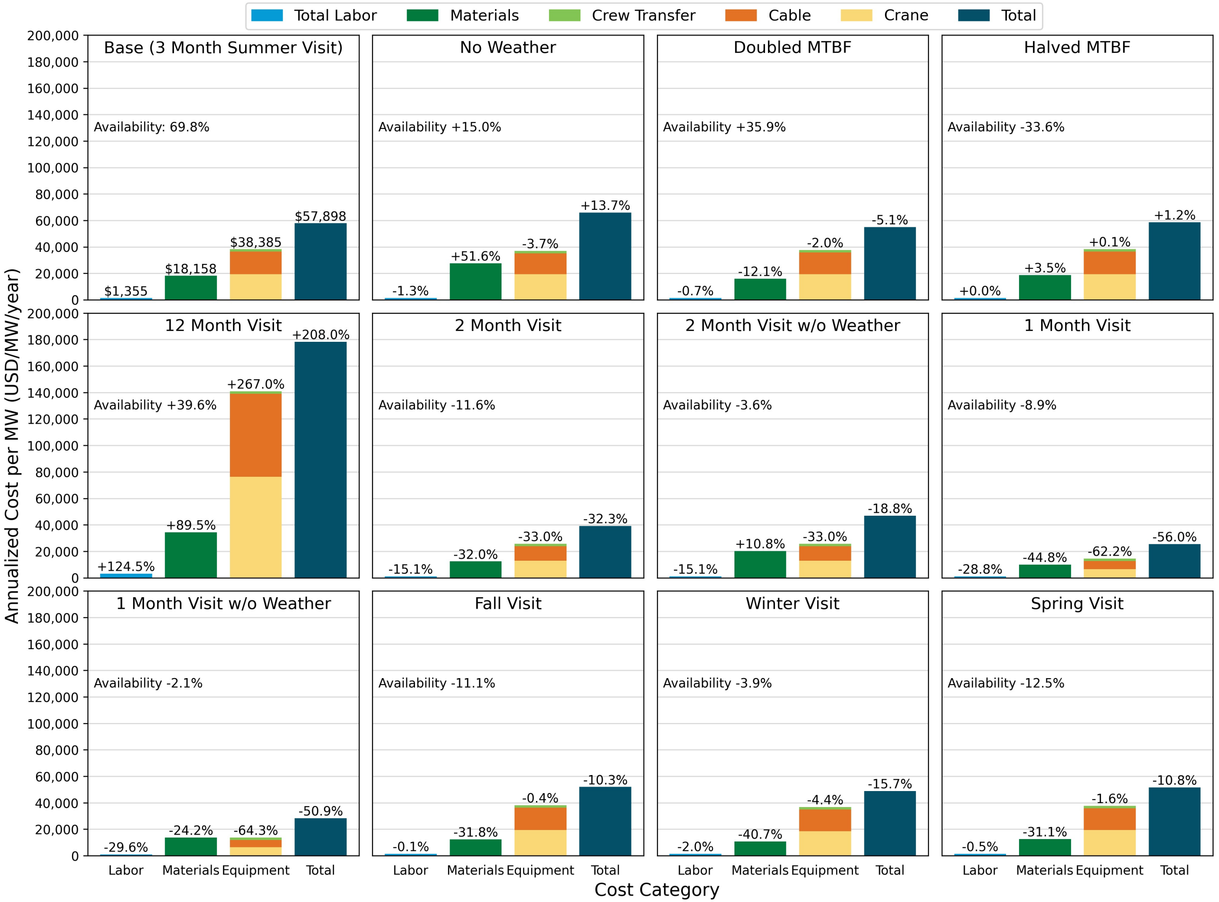


*Source: Pfaffel et al. (2017)

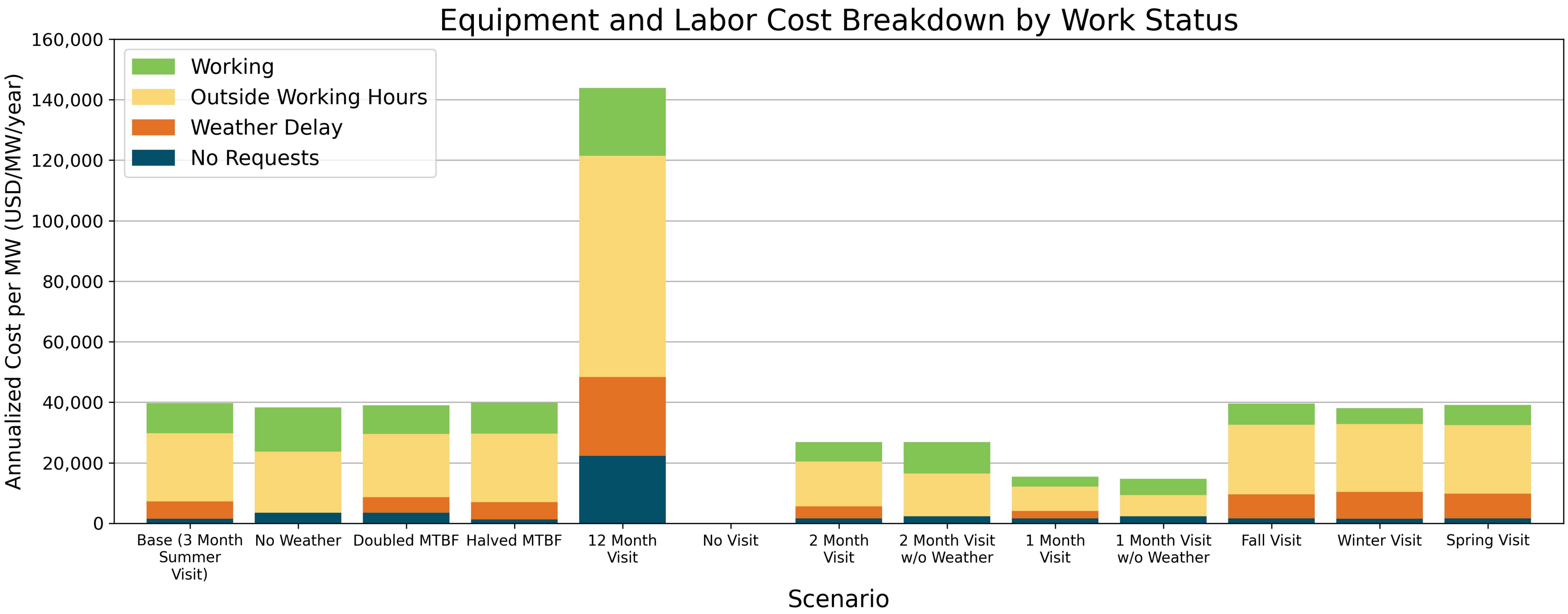
Offshore: Cost vs. Availability



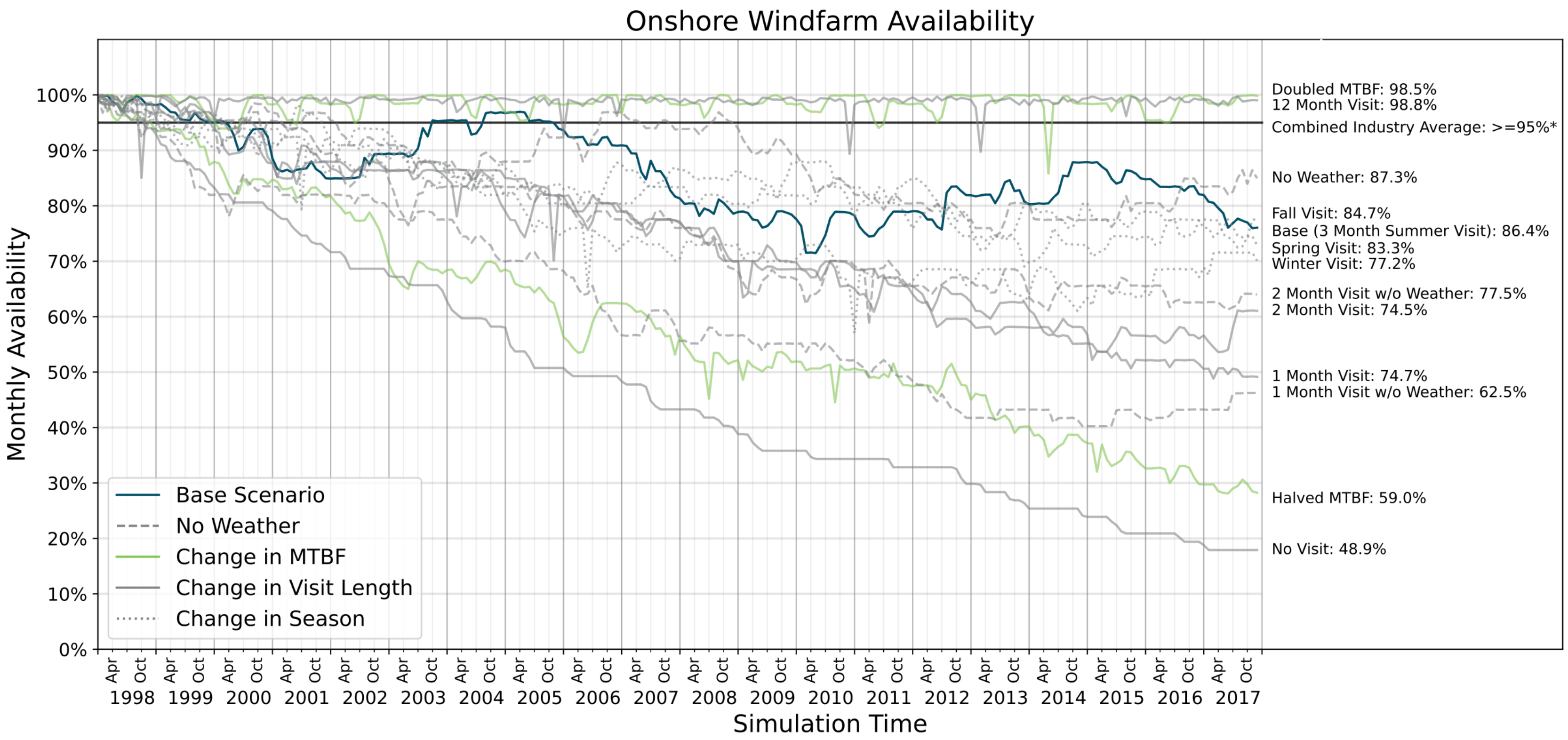
Offshore: Cost Breakdown



Offshore: Equipment Cost Breakdown

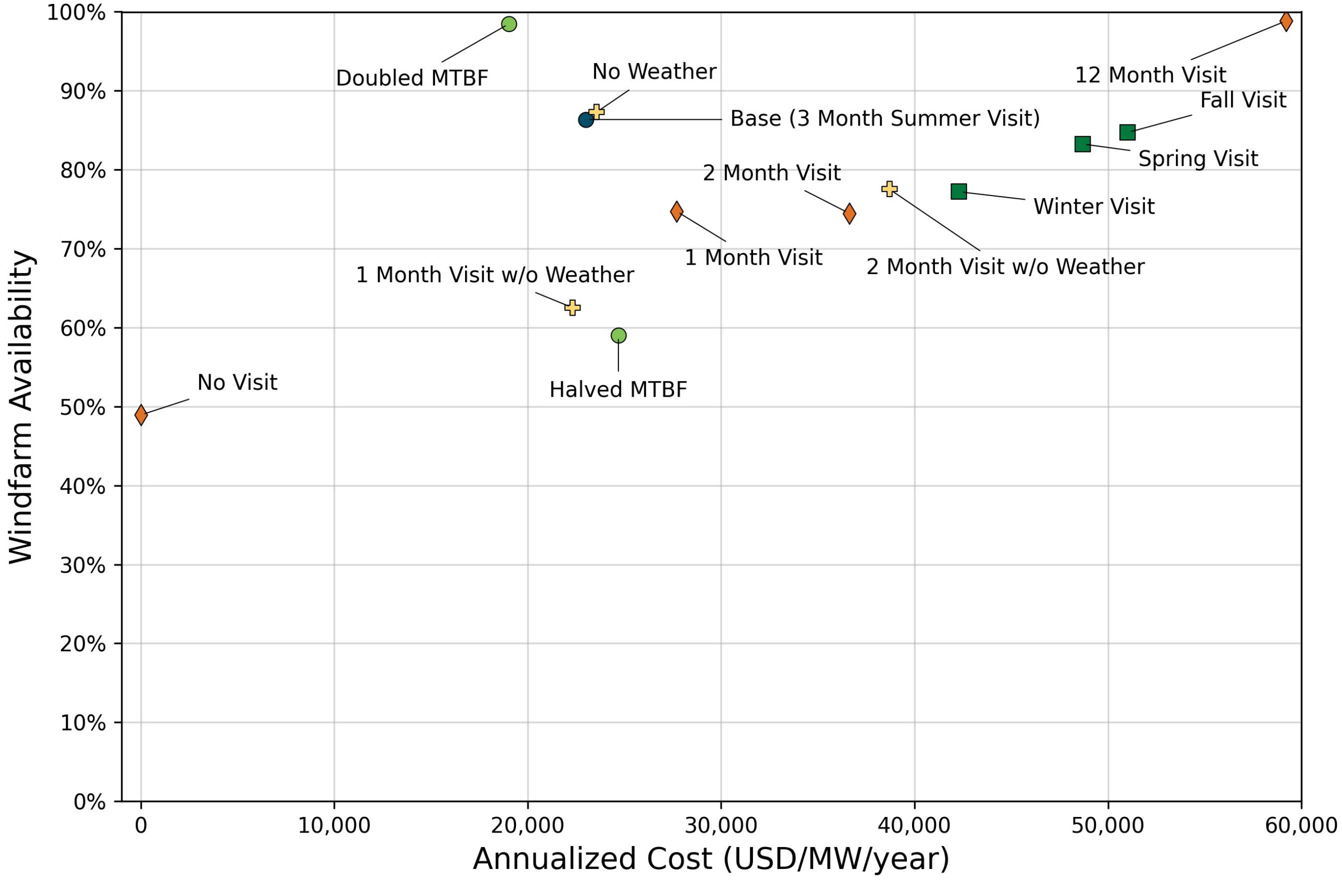


Onshore: Availability



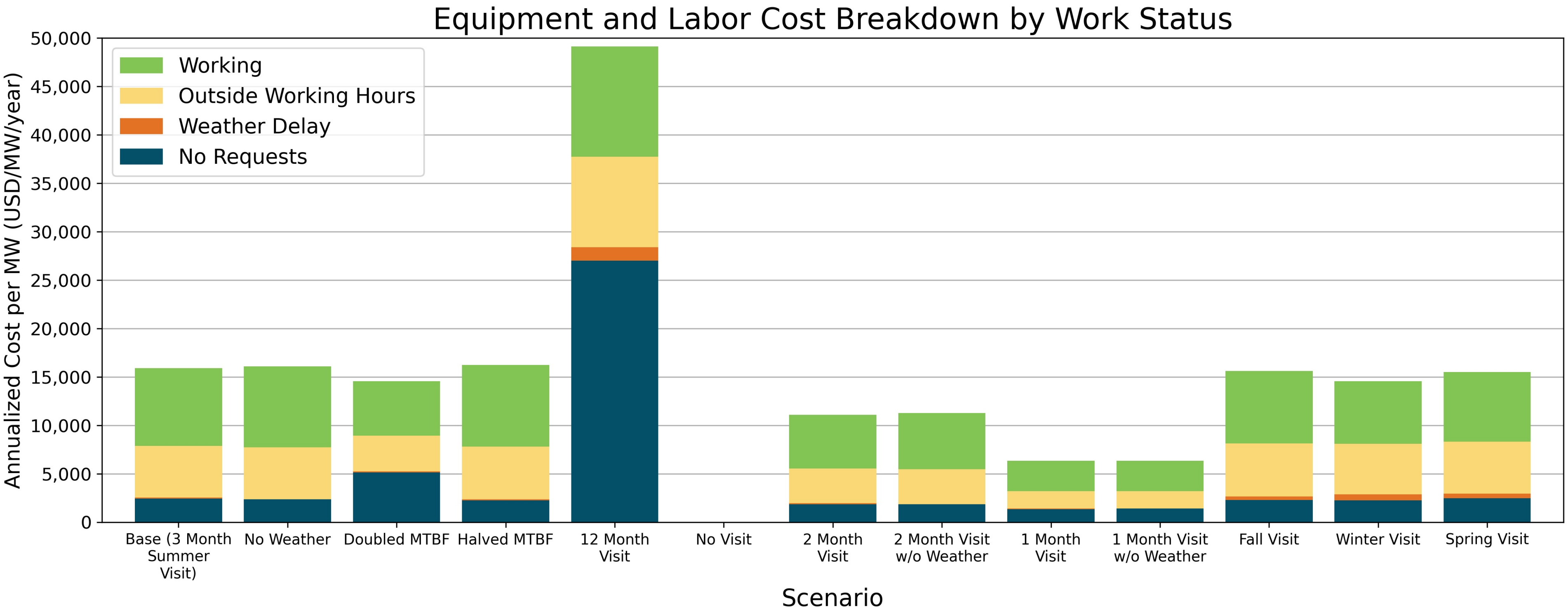
*Source: Pfaffel et al. (2017)

Onshore: Cost vs. Availability



Onshore: Cost Breakdown

Onshore: Equipment Cost Breakdown



Supplementary Slides

Dinwoodie, et al., 2015 Definitions

Case Description

- Plant capacity: 240 MW
  80 x 3-MW Vestas V90 turbines
- Location: North Sea, 50 km from port
- Simulation period: 10 years
- Weather: FINO 1, 2004-2012 Dinwoodie et al.
  Alpha Ventus, 2002-2014 WOMBAT
- Labor costs: 20 technicians at £80,000/yr
- BOS: not modeled (no cables, substation, etc.)
- O&M models: NOWIcob, Univ. of Stavanger (UiS), ECUME, Strathclyde University

Vessels, Maintenance and Repairs

Vessel type	#	Mobilization time	Mobilization cost	Charter period	Day rate	Max. wave
Crew transfer vessel	3	N/A	N/A	N/A	£1,750	1.5 m
Field support vessel	1	3 weeks	£0	4 weeks	£9,500	1.5 m
Heavy lift vessel	1	2 months	£500,000	4 weeks	£150,000	2 m

Repair type	Time	# Techs	Vessel type	#/turb/yr	Cost
Manual reset	3 h	2	CTV	7.5	£0
Minor repair	7.5 h	2	CTV	3	£1,000
Medium repair	22 h	3	CTV	0.275	£18,500
Major repair	26 h	4	FSV	0.04	£73,500
Major replacement	52 h	5	HLV	0.08	£334,500
Annual service	60 h	3	CTV	1	£18,500

Supplementary Slides

IEA Task 26, 2016 Definitions

Case Description

- Plant capacity: 400 MW
  100 x 4-MW generic turbines (NREL CSM)
- Location: North Sea, 40 km from port
- Simulation period: 20 years
- Weather: Horns Rev 3, 1996-2015
- Labor costs: 30* technicians at €100,000/yr
- BOS: array layout with 6 turbines per string, single export cable, offshore substation with 2 transformers
- O&M models: NOWIcob, ECN O&M Tool

*NOWIcob takes # techs as input, ECN calculates required # techs (between 15-30 throughout year, average ~22)

Vessels, Maintenance and Repairs

Turbine Repairs	Time	Techs	Vessel	#/turb/yr	Cost
Remote reset	2 h	N/A	N/A	7	€0
Manual reset	3 h	2	CTV	5	€238
Minor repair	7.5 h	3	CTV	3	€5,279
Major repair	30 h	4	CTV	0.3	€29,230
Major replacement	42 h	N/A	HLV	0.11	€441,373
Annual service	50 h	3	CTV	1	€4,385

BOS Repairs	Time	Techs	Vessel	#/yr	Cost
Substation inspection	30 h	3	CTV	4	€0
Structure inspection	4 h	2	CTV	100	€0
Small scour repair	8 h	N/A	DSV	2.3	€5,000
Small transformer repair	8 h	3	CTV	0.9	€5,000
Large transformer repair	48 h	4	CTV	0.1	€250,000
Cable replacement	32 h	N/A	CLV	0.04	€350,000

Vessel types
- CTV: crew transfer vessel
- DSV: diving support vessel
- HLV: heavy lift vessel
- CLV: cable laying vessel

Vessel	CTV	DSV	HLV	CLV
#	3	1	1	1
Mob. time	N/A	15 d	60 d	30 d
Mob. cost	N/A	€225k	€500k	€550k
Charter	N/A	4 d	20 d	10 d
Day rate	€3.5k	€75k	€140k	€100k
Max. wave	2 m	2 m	2 m	1 m