



# WOMBAT Tutorial

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November 2, 2023

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# WOMBAT at a Glance

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# Relevance of Operation and Maintenance (O&M) Costs

- O&M activities are estimated to comprise between 29% and 34% of total wind power plant life cycle costs\*.
  - \$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 power 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.

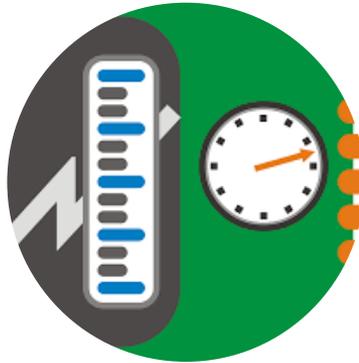
\*Stehly, T., P. Beiter, D. Heimiller, and G. Scott. *cost of wind energy review*, National Renewable Energy Laboratory. Technical Report NREL/TP-6A20–70363. Available at <https://www.nrel.gov/docs/fy18osti/70363>

# Primary Research Question

How might maintenance strategies, technological innovations, and site conditions influence wind power plant operational expenditures (OpEx) and, ultimately, levelized cost of energy (LCOE)?



Methodology  
Innovations



Technology  
Innovations

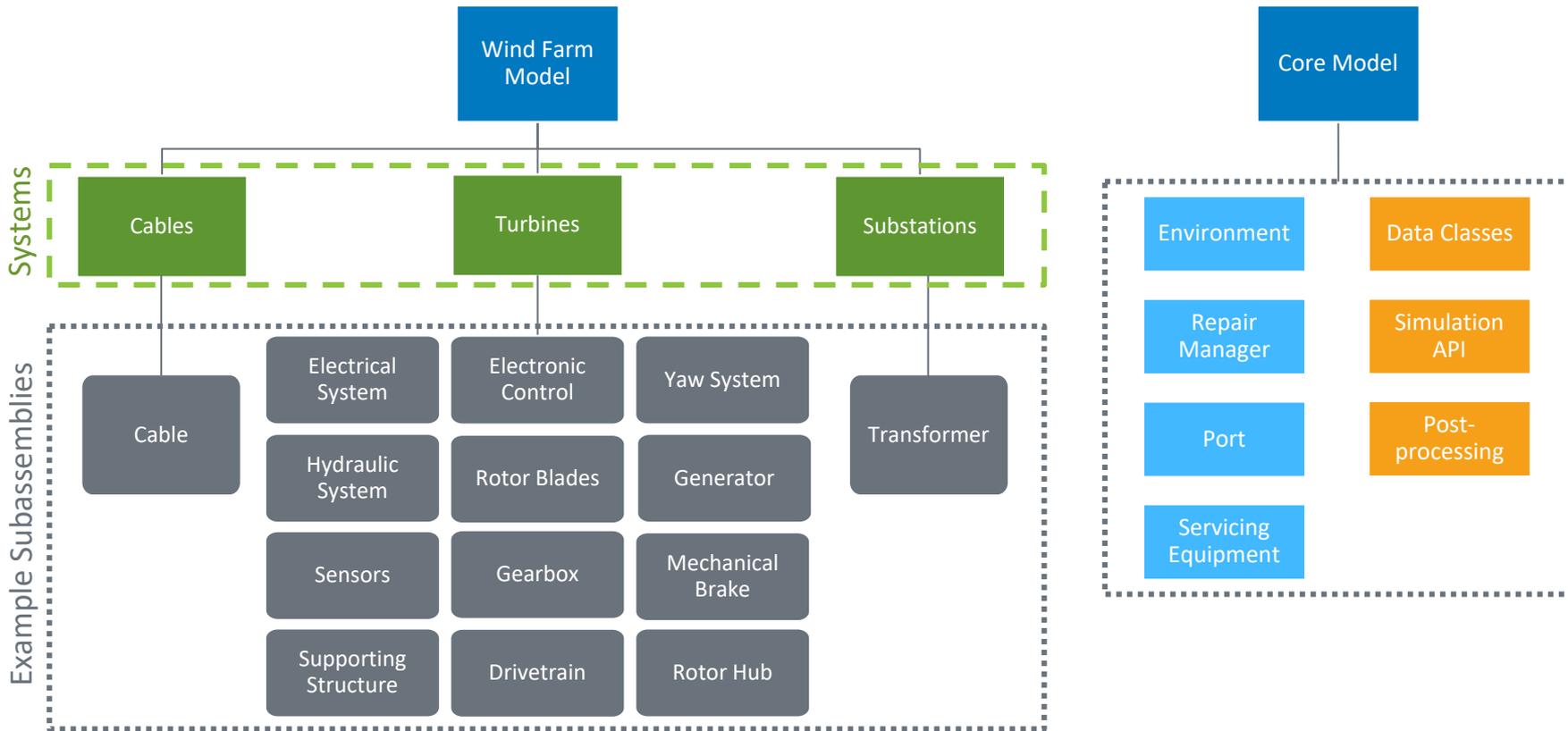


Site  
Conditions

# Approach

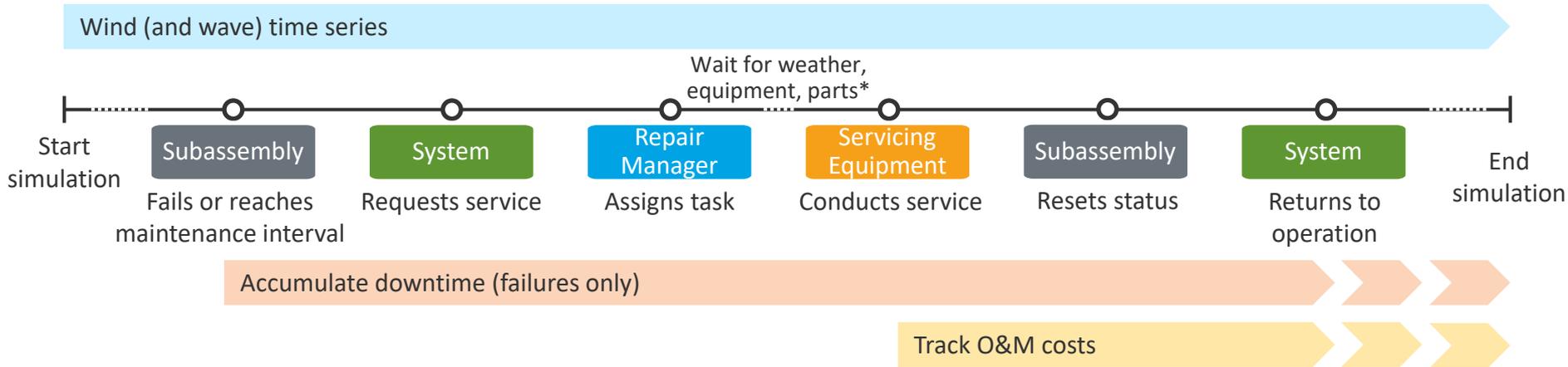
- Minimal code by the user to run the model
  - Empower a broad user base by requiring minimal Python skills
  - Configure models through YAML files, not complicated setup code
- Prescriptive modeling via discrete event simulation:
  - Enables weather- and site-specific variability
  - Allows a user to define O&M strategies to understand cost and energy impacts
  - Focuses on what-if scenario modeling instead of optimization
- Modular and flexible code base:
  - Allows for new methodologies to be tested with ease
  - Provides a tool to analyze both offshore and land-based wind farm O&M costs
  - Allows users to define their turbine failure models in as much or as little detail as desired
- Documentation-driven development:
  - Use of inline comments and docstrings explains what nearly all functionality is supposed to be doing
  - Enables easier modification or improvement for researchers and/or developers

# High-Level Software Architecture



# 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.”



# Configuring WOMBAT

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# Repairs and Maintenance

- Maintenance (scheduled)
  - Fixed frequency model (number of days) to align with regular servicing intervals
- Failures (unscheduled maintenance)
  - Weibull distribution (exponential if using 1 for the shape parameter)
    - Scale =  $1 / (\# \text{ Failures/system/year}) = \text{Mean Time Between Failures (MTBF, in years)}$
  - Random sampling for the next time a failure occurs
- Shared parameterizations
  - Materials cost (whole cost or proportional to system CapEx)
  - Repair time
  - Service equipment categories that can perform corrective maintenance
    - CTV, DRN, RMT, SCN, LCN, CAB, DSV, TOW, AHV (more details on the next slide)
  - Operating reduction
  - Severity level (helps prioritize repairs across the farm)

# Servicing Equipment

- Strategy
    - Scheduled
    - Unscheduled: downtime
    - Unscheduled: requests
    - Unscheduled: tow (offshore only)
  - Capabilities
  - Working hours
  - Mobilization
  - Port distance
  - Crew
  - Weather constraints
    - Wind speed
    - Wave height
    - Speed (including during inclement weather)
    - Nonoperational periods
    - Slowdown periods
- CTV:** crew transfer vessel (onsite truck for land-based)
- DRN:** drone
- RMT:** remotely operated vessel/vehicle
- SCN:** small crane (e.g., field support vessel)
- LCN:** large crane (e.g., WTIV, jackup vessel)
- CAB:** cable laying vessel (or similar for land-based)
- DSV:** diving support vessel
- TOW:** tugboat (requires a port)
- AHV:** anchor handling vessel (can be based out of a port, or operate like other vessels)



# Baseline Inputs

## Subassemblies

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

## Servicing Equipment

- Maintenance strategy and related definitions
- Port (if required)
- Capabilities
- Labor rates
- Equipment rates
- Operational limits

## Miscellaneous

- Weather profile
  - Hourly wind speed and/or wave height
- Wind farm layout
- Site working hours
- Port distance

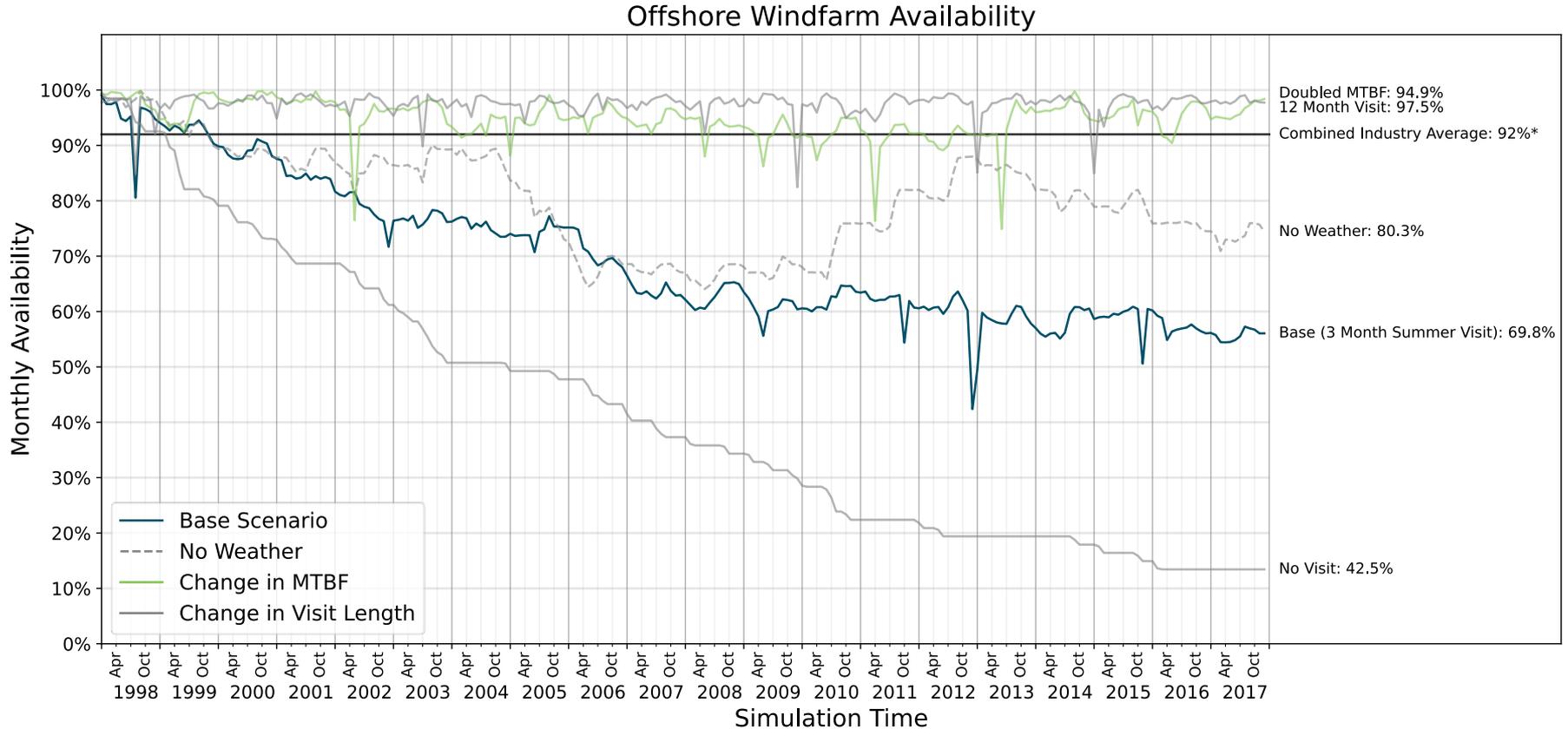
# Outputs

- Time- and production-based availability
- Power production
- Fixed costs
- Capacity factor
- Task completion rate
- Service equipment costs & utilization
- Labor costs
- Combined service equipment and labor costs by productivity
- Component costs
- Servicing time breakdown
- OpEx
- Emissions
- More on the way

## High-fidelity log files to compute further metrics

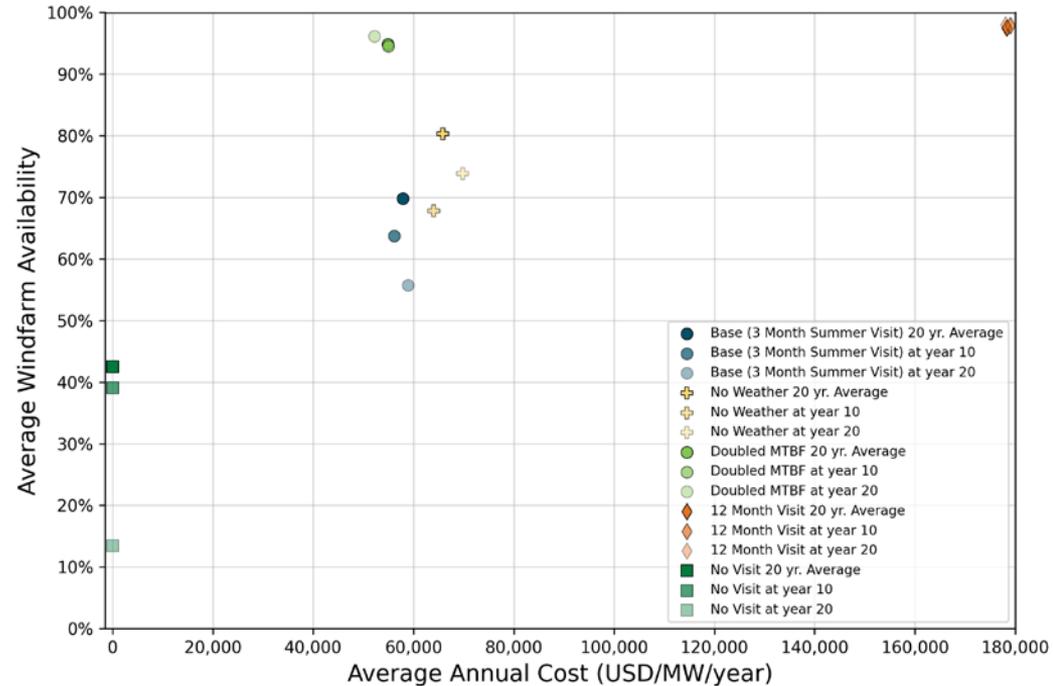
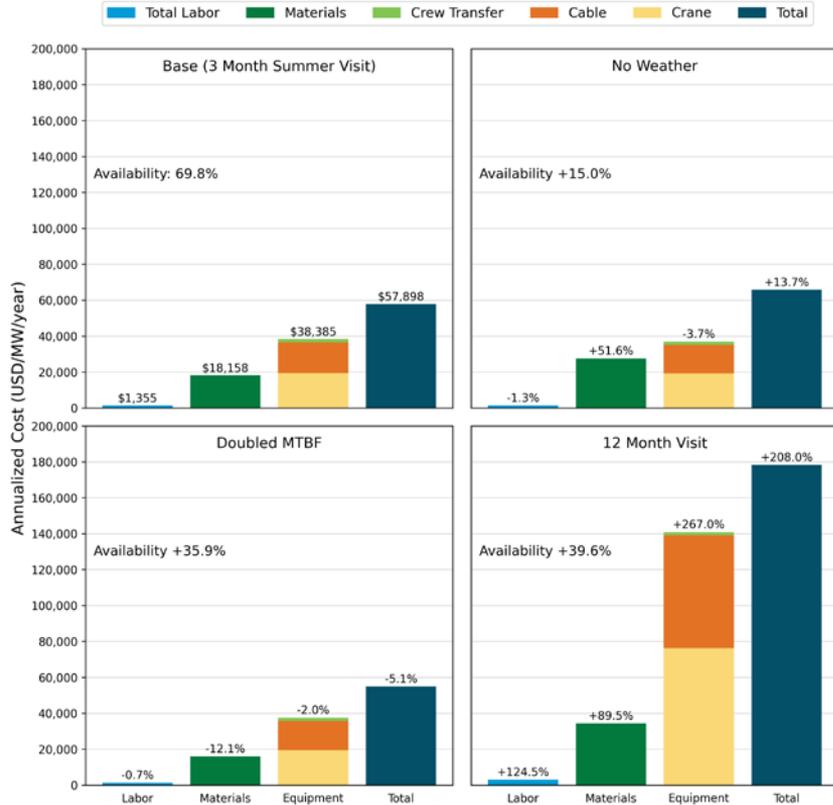
- Event logs
- Operating level logs (hourly)
- Power production logs (hourly)
- Power potential logs (hourly)

# Examples: Availability Comparison



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

# Examples: Cost Breakdowns



# COREWIND Assumptions

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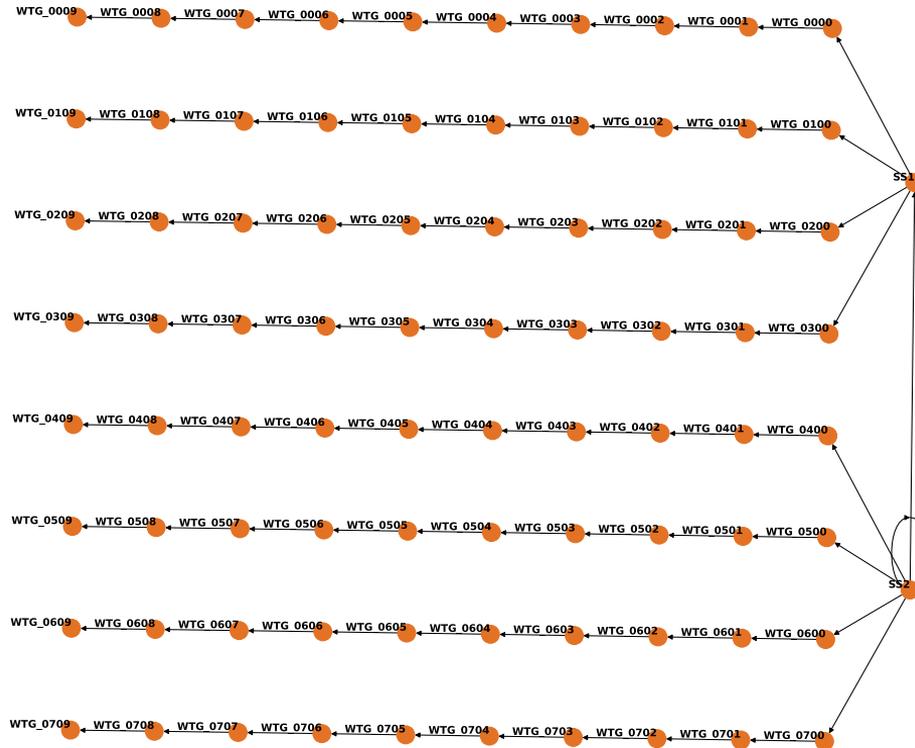
# High-Level Information

- Plant assumptions (D6.1)  
<https://corewind.eu/wp-content/uploads/files/publications/COREWIND-D6.1-General-frame-of-the-analysis-and-description-of-the-new-FOW-assessment-app.pdf>
- Assessment assumptions (D4.2)  
<https://corewind.eu/wp-content/uploads/files/publications/COREWIND-D4.2-Floating-Wind-O-and-M-Strategies-Assessment.pdf>

## Summary

- 1.2 GW in Morro Bay, California, with reference coordinate: (35.367222, -121.645163)
- 60 km distance to shore
- 80 x IEA 15 MW Reference Turbines on floating platforms, spaced 2,160 m (9 rotor diameters) apart
- 2 offshore substations
- 7 Crew Transfer Vessels, Anchor Handling Vessel, Diving Support Vessel, Cable Lay Vessel, Remotely Operated Vessel
- Technician salary: €80K

# Plant Layout



# Failure Data

Component or Maintenance Task	Frequency (scheduled)	Failure Rate (N/turbine/year)	Duration (hours)	Technicians (number)	Cost (Euros)	Vessel
Subsea Inspections of Cables, Mooring Lines, and Floater Hull	2 years		12	5	500	SOV with ROV
Direct Drive Generator: Minor Failure		0.546	13	2	1000	CTV
Main Shaft Replacement		0.009	144	5	232000	CTV

- Data doesn't quite match the expected format in WOMBAT
- Some assumptions don't quite align with expectations
- **So, how would this get translated to WOMBAT, given what we know?**

# Vessel Data

Vessel	Number	Purpose	Day Rate (Euros)	Mobilization Cost (Euros)	Wave Height Limit (m)
Crew Transfer Vessel (CTV)	7	Access to systems	3,500	0	2 (simplified from matrix)
Anchor Handling Vessel (AHV)	1	Mooring line and anchor repairs	55,000	500,000	2.5
SOV with ROV	2	Subsea inspection and repairs	75,000	225,000	2
Monohull Crane Vessel (HLV)	1	Major component exchange offshore	290,000	325,000	2
Tugboat	2	Tow-in and tow-out	30,000	200,000	2.5

- Data doesn't quite match the expected format in WOMBAT
- Some assumptions don't quite align with expectations
- **So, how would this get translated to WOMBAT given what we know?**

# Setting Up a Simulation

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# Working Through the Simulation Setup

1. We will work through creating a piece of every simulation aspect in this part of the workshop, from the layout to the servicing equipment. Keep the COREWIND reports open because I won't be able to put it on the screen and the information I'll be providing.
2. Focus on understanding how to get each of the aspects set up and how everything interconnects, not exhaustively recreating the paper's assumptions.
3. To run the model, ask new questions of the scenarios, generally tinker, and we'll then switch to an example that is already available on the GitHub repository and built to accompany this presentation.

# Create a New Project

- Note: Everything we need is already set up in the repository
- Open a VSCode (or preferred code editor/IDE) window
- In the terminal/Anaconda prompt
  1. “cd <your-path-the-workshop-data>”
  2. “python”
  3. “from wombat import create\_library\_structure”
  4. “create\_library\_structure(<your-library-name>)”

```
(wombat_workshop) [~] cd Documents/Projects/nawea_tutorial
(wombat_workshop) [~/Documents/Projects/nawea_tutorial] python
Python 3.10.13 (main, Sep 11 2023, 08:16:02) [Clang 14.0.6 ] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> from wombat import create_library_structure
>>> new_library = "library/"
>>> create_library_structure(new_library)
>>> █
```

# Overarching Configuration File

- Create a configuration file in `<library>/project/config` called “base.yaml”
- Now, we need to create most of the inputs on the right as direct inputs or pointers to other files:  
[https://wisdem.github.io/WOMBAT/API/simulation\\_api.html#configuration](https://wisdem.github.io/WOMBAT/API/simulation_api.html#configuration)
- To get started, I’ll directly guide this first part

- **name** (*str*) – Name of the simulation. Used for logging files.
- **layout** (*str*) – The windfarm layout file. See `wombat.Windfarm` for more details.
- **service\_equipment** (*str* / *list[str]*) – The equipment that will be used in the simulation. See `wombat.core.ServiceEquipment` for more details.
- **weather** (*str*) – The weather profile to be used. See `wombat.simulation.WombatEnvironment` for more details.
- **workday\_start** (*int*) – Starting hour for a typical work shift. Can be overridden by equipment-specific settings.
- **workday\_end** (*int*) – Ending hour for a typical work shift. Can be overridden by equipment-specific settings.
- **inflation\_rate** (*float*) – The annual inflation rate to be used for post-processing.
- **fixed\_costs** (*str*) – The file name for the fixed costs assumptions.
- **project\_capacity** (*int* / *float*) – The total capacity of the wind plant, in MW.
- **port** (*dict* / *str* / *Path*) – The port configuration file or dictionary that will be used to setup a tow-to-port repair strategy, default None.
- **port\_distance** (*int* / *float*) – The simulation-wide daily travel distance for servicing equipment. This should be used as a base setting when multiple or all servicing equipment will be operating out of the same base location, but can be individually modified.
- **start\_year** (*int*) – Start year of the simulation. The exact date will be determined by the first valid date of this year in `weather`.
- **end\_year** (*int*) – Final year of the simulation. The exact date will be determined by the last valid date of this year in `weather`.
- **non\_operational\_start** (*str* / *datetime.datetime* / *None*) – The starting month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of prohibited operations. When defined at the environment level, an undefined or later starting date will be overridden for all servicing equipment and any modeled port, by default None.
- **non\_operational\_end** (*str* / *datetime.datetime* / *None*) – The ending month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of prohibited operations. When defined at the environment level, an undefined or earlier ending date will be overridden for all servicing equipment and any modeled port, by default None.
- **reduced\_speed\_start** (*str* / *datetime.datetime* / *None*) – The starting month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of reduced speed operations. When defined at the environment level, an undefined or later starting date will be overridden for all servicing equipment and any modeled port, by default None.
- **reduced\_speed\_end** (*str* / *datetime.datetime* / *None*) – The ending month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of reduced speed operations. When defined at the environment level, an undefined or earlier ending date will be overridden for all servicing equipment and any modeled port, by default None.
- **reduced\_speed** (*float*) – The maximum operating speed during the annualized reduced speed operations. When defined at the environment level, an undefined or faster value will be overridden for all servicing equipment and any modeled port, by default 0.0.
- **random\_seed** (*int* / *None*) – The random seed to be passed to a universal NumPy `default_rng` object to generate Weibull random generators, by default None.
- **random\_generator** (*np.random.\_generator.Generator* / *None*) – An optional numpy random generator that can be provided to seed a simulation with the same generator each time, in place of the random seed. If a `random_seed` is also provided, this will override the random seed, by default None.

# Overarching Configuration File: Answer

```
library > project > config > morro_bay_in_situ.yaml > ...
1  name: COREWIND Morro Bay In Situ
2  library: library
3  weather: central_ca.csv
4  service_equipment:
5    - ctv1.yaml
6    - ctv2.yaml
7    - ctv3.yaml
8    - ctv4.yaml
9    - ctv5.yaml
10   - ctv6.yaml
11   - ctv7.yaml
12   - cab.yaml
13   - dsv.yaml
14   - ahv.yaml
15   - hlv1.yaml
16  layout: morro_bay_9D_layout.csv
17  port_distance: 60 # 20/100 for West of Barra Island; 10 for Gran Canaria Island
18  inflation_rate: 0
19  workday_start: 6
20  workday_end: 22
21  start_year: 2002
22  end_year: 2021
23  project_capacity: 1200
24  |
```

# Layout

- Create a layout CSV file in `<library>/project/plant/` using the file name you used for “layout” in `base.yaml`
- Open it in Excel, Numbers, or whatever you prefer for editing tabular data
- Add the columns you see to the right:  
[https://wisdem.github.io/WOMBAT/examples/how\\_to.html#windfarm-layout](https://wisdem.github.io/WOMBAT/examples/how_to.html#windfarm-layout)
- Create the first string for each substation with the information that we have (fill in optional pieces as you please)—layout on Slide 17
- NOTE: “subassembly” and “upstream\_cable” just need the file names

## **id (required)**

Unique identifier for the asset; no spaces allowed.

## **substation\_id (required)**

The id field for the substation that the asset connects to; in the case that this is a substation, then this field should be the same as id; no spaces allowed.

## **name (required)**

A descriptive name for the turbine, if desired. This can be the same as id.

## **type (optional)**

One of “turbine” or “substation”. This is required to accurately model a multi-substation wind farm. The base assumption is that a substation connects to itself as a means to model the export cable connecting to the interconnection point, however, this is not always the case, as substations may be connected through their export systems. Using this field allows for that connection to be modeled accurately.

## **longitude (optional)**

The longitudinal position of the asset, can be in any geospatial reference; optional.

## **latitude (optional)**

The latitude position of the asset, can be in any geospatial reference; optional.

## **string (required)**

The integer, zero-indexed, string number for where the turbine will be positioned.

## **order (required)**

The integer, zero-indexed position on the string for where the turbine will be positioned.

## **distance (optional)**

The distance to the upstream asset; if this is calculated (input = 0), then the straightline distance is calculated using the provided coordinates (WGS-84 assumed).

## **subassembly (required)**

The file that defines the asset’s modeling parameters.

## **upstream\_cable (required)**

The file that defines the upstream cable’s modeling parameters.

## **upstream\_cable\_name (optional)**

The descriptive name to give to the cable that will be used during logging. This enables users to use a single cable definition file while maintaining the naming conventions used for the wind farm being simulated.

# Layout: Answer

4 strings per substation, plus a connection between them and the interconnection point (unmodeled)

Zero-indexing is required for string/order

	A	B	C	D	I	J	K	L	M	N	O	P
1	id	substation_id	name	type	longitude	latitude	string	order	distance	subassembly	upstream_cable	upstream_cable_name
2	SS1	SS2	SS1	substation	-121.6445116	35.40616396	9	0		corewind_substation.yaml	corewind_export.yaml	EXP00
3	SS2	SS2	SS2	substation	-121.6458132	35.32827984	9	1		corewind_substation.yaml	corewind_export.yaml	EXP01
4	WTG_0000	SS1	WTG_0000	turbine	-121.6678132	35.4356351	0	0		corewind_15MW.yaml	corewind_array.yaml	ARR00
5	WTG_0001	SS1	WTG_0001	turbine	-121.6916045	35.43589529	0	1		corewind_15MW.yaml	corewind_array.yaml	ARR01
6	WTG_0002	SS1	WTG_0002	turbine	-121.7153961	35.43615079	0	2		corewind_15MW.yaml	corewind_array.yaml	ARR02
7	WTG_0003	SS1	WTG_0003	turbine	-121.739188	35.43640161	0	3		corewind_15MW.yaml	corewind_array.yaml	ARR03
8	WTG_0004	SS1	WTG_0004	turbine	-121.7629802	35.43664773	0	4		corewind_15MW.yaml	corewind_array.yaml	ARR04
9	WTG_0005	SS1	WTG_0005	turbine	-121.7867727	35.43688918	0	5		corewind_15MW.yaml	corewind_array.yaml	ARR05
10	WTG_0006	SS1	WTG_0006	turbine	-121.8105655	35.43712593	0	6		corewind_15MW.yaml	corewind_array.yaml	ARR06
11	WTG_0007	SS1	WTG_0007	turbine	-121.8343586	35.437358	0	7		corewind_15MW.yaml	corewind_array.yaml	ARR07
12	WTG_0008	SS1	WTG_0008	turbine	-121.8581519	35.43758538	0	8		corewind_15MW.yaml	corewind_array.yaml	ARR08
13	WTG_0009	SS1	WTG_0009	turbine	-121.8819455	35.43780807	0	9		corewind_15MW.yaml	corewind_array.yaml	ARR09

	A	B	C	D	I	J	K	L	M	N	O	P
44	WTG_0400	SS2	WTG_0400	turbine	-121.6690938	35.35775062	4	0		corewind_15MW.yaml	corewind_array.yaml	ARR40
45	WTG_0401	SS2	WTG_0401	turbine	-121.6928623	35.35801007	4	1		corewind_15MW.yaml	corewind_array.yaml	ARR41
46	WTG_0402	SS2	WTG_0402	turbine	-121.7166311	35.35826484	4	2		corewind_15MW.yaml	corewind_array.yaml	ARR42
47	WTG_0403	SS2	WTG_0403	turbine	-121.7404001	35.35851493	4	3		corewind_15MW.yaml	corewind_array.yaml	ARR43
48	WTG_0404	SS2	WTG_0404	turbine	-121.7641695	35.35876036	4	4		corewind_15MW.yaml	corewind_array.yaml	ARR44
49	WTG_0405	SS2	WTG_0405	turbine	-121.7879391	35.35900111	4	5		corewind_15MW.yaml	corewind_array.yaml	ARR45
50	WTG_0406	SS2	WTG_0406	turbine	-121.811709	35.35923719	4	6		corewind_15MW.yaml	corewind_array.yaml	ARR46
51	WTG_0407	SS2	WTG_0407	turbine	-121.8354792	35.35946859	4	7		corewind_15MW.yaml	corewind_array.yaml	ARR47
52	WTG_0408	SS2	WTG_0408	turbine	-121.8592497	35.35969532	4	8		corewind_15MW.yaml	corewind_array.yaml	ARR48
53	WTG_0409	SS2	WTG_0409	turbine	-121.8830204	35.35991738	4	9		corewind_15MW.yaml	corewind_array.yaml	ARR49

# Servicing Equipment

- 7 CTVs, 1 Anchor Handling Vessels, 2 Support Operating Vessels (SOV) with ROV, 1 Heavy Lift Vessel, 2 Tugboats
- Modifications needed: No SOVs (yet) in WOMBAT, so we will model 2 ROVs
- 2 classes of vessels—scheduled and unscheduled—so how would we classify the vessels in the first bullet?
- <https://wisdem.github.io/WOMBAT/API/types.html#scheduled-service-equipment>
- <https://wisdem.github.io/WOMBAT/API/types.html#unscheduled-service-equipment>

# Scheduled Servicing Equipment

- D4.2, p. 18
- Create a YAML configuration file in “<library>/vessels/”, for a single CTV.

<https://wisdem.github.io/WOMBAT/API/types.html#scheduled-service-equipment>

- **name** (*str*) – Name of the piece of servicing equipment.
- **equipment\_rate** (*float*) – Day rate for the equipment/vessel, in USD.
- **n\_crews** (*int*) – Number of crew units for the equipment.

## Note

The input to this does not matter yet, as multi-crew functionality is not yet implemented.

- **crew** (*ServiceCrew*) – The crew details, see [ServiceCrew](#) for more information. Dictionary of labor costs with the following: **n\_day\_rate**, **day\_rate**, **n\_hourly\_rate**, and **hourly\_rate**.
- **start\_month** (*int*) – The day to start operations for the rig and crew.
- **start\_day** (*int*) – The month to start operations for the rig and crew.
- **start\_year** (*int*) – The year to start operations for the rig and crew.
- **end\_month** (*int*) – The month to end operations for the rig and crew.
- **end\_day** (*int*) – The day to end operations for the rig and crew.
- **end\_year** (*int*) – The year to end operations for the rig and crew.

## Note

if the rig comes annually, then the enter the year for the last year that the rig and crew will be available.

- **capability** (*str*) – The type of capabilities the equipment contains. Must be one of:
  - RMT: remote (no actual equipment BUT no special implementation)
  - DRN: drone
  - CTV: crew transfer vessel/vehicle
  - SCN: small crane (i.e., field support vessel)
  - LCN: large crane (i.e., heavy lift vessel)
  - CAB: cabling vessel/vehicle
  - DSV: diving support vesselPlease note that “TOW” is unavailable for scheduled servicing equipment
- **mobilization\_cost** (*float*) – Cost to mobilize the rig and crew.
- **mobilization\_days** (*int*) – Number of days it takes to mobilize the equipment.
- **speed** (*float*) – Maximum transit speed, km/hr.
- **speed\_reduction\_factor** (*float*) – Reduction factor for traveling in inclement weather, default 0. When 0, travel is stopped when either **max\_windspeed\_transport** or **max\_waveheight\_transport** is reached, and when 1, **speed** is used.
- **max\_windspeed\_transport** (*float*) – Maximum windspeed for safe transport, m/s.
- **max\_windspeed\_repair** (*float*) – Maximum windspeed for safe operations, m/s.

- **max\_waveheight\_transport** (*float*) – Maximum waveheight for safe transport, m, default 1000 (land-based).
- **max\_waveheight\_repair** (*float*) – Maximum waveheight for safe operations, m, default 1000 (land-based).
- **workday\_start** (*int*) – The starting hour of a workshift, in 24 hour time.
- **workday\_end** (*int*) – The ending hour of a workshift, in 24 hour time.
- **crew\_transfer\_time** (*float*) – The number of hours it takes to transfer the crew from the equipment to the system, e.g. how long does it take to transfer the crew from the CTV to the turbine, default 0.
- **onsite** (*bool*) – Indicator for if the servicing equipment and crew are based onsite.

## Note

If based onsite, be sure that the start and end dates represent the first and last day/month of the year, respectively, and the start and end years represent the first and last year in the weather file.

- **method** (*str*) – Determines if the equipment will do all maximum severity repairs first or do all the repairs at one turbine before going to the next, by default severity. Must be one of “severity” or “turbine”.
- **port\_distance** (*int* | *float*) – The distance, in km, the equipment must travel to go between port and site, by default 0.
- **non\_operational\_start** (*str* | *datetime.datetime* | *None*) – The starting month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of prohibited operations. When defined at the environment level, an undefined or later starting date will be overridden, by default None.
- **non\_operational\_end** (*str* | *datetime.datetime* | *None*) – The ending month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of prohibited operations. When defined at the environment level, an undefined or earlier ending date will be overridden, by default None.
- **reduced\_speed\_start** (*str* | *datetime.datetime* | *None*) – The starting month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of reduced speed operations. When defined at the environment level, an undefined or later starting date will be overridden, by default None.
- **reduced\_speed\_end** (*str* | *datetime.datetime* | *None*) – The ending month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of reduced speed operations. When defined at the environment level, an undefined or earlier ending date will be overridden, by default None.
- **reduced\_speed** (*float*) – The maximum operating speed during the annualized reduced speed operations. When defined at the environment level, an undefined or faster value will be overridden, by default 0.0.

# Scheduled Servicing Equipment: Answer

```
library > vessels > vs ctv1.yaml > ...
1 name: Crew Transfer Vessel 1
2 equipment_rate: 3500
3 capability: CTV
4 speed: 37.04 # 20 knots
5 strategy: scheduled
6 max_windspeed_transport: 99
7 max_windspeed_repair: 99
8 max_waveheight_transport: 2
9 max_waveheight_repair: 2
10 onsite: True
11 mobilization_cost: 0
12 mobilization_days: 0
13 port_distance: 30
14 # workday_start: 0
15 # workday_end: 24
16 start_month: 1
17 start_day: 1
18 end_month: 12
19 end_day: 31
20 start_year: 2002
21 end_year: 2021
22 crew_transfer_time: 0.25
23 n_crews: 1
24 crew:
25   day_rate: 0 # crew comes with vessel
26   n_day_rate: 0
27   hourly_rate: 0
28   n_hourly_rate: 0
29 # capex: 3000000
30 |
```

# Unscheduled Servicing Equipment

- **name** (*str*) – Name of the piece of servicing equipment.
- **equipment\_rate** (*float*) – Day rate for the equipment/vessel, in USD.
- **n\_crews** (*int*) – Number of crew units for the equipment.
- **crew** (*ServiceCrew*) – The crew details, see [ServiceCrew](#) for more information. Dictionary of labor costs with the following: **n\_day\_rate**, **day\_rate**, **n\_hourly\_rate**, and **hourly\_rate**.
- **charter\_days** (*int*) – The number of days the servicing equipment can be chartered for.
- **capability** (*str*) – The type of capabilities the equipment contains. Must be one of: - RMT: remote (no actual equipment BUT no special implementation) - DRN: drone - CTV: crew transfer vessel/vehicle - SCN: small crane (i.e., field support vessel) - LCN: large crane (i.e., heavy lift vessel) - CAB: cabling vessel/vehicle - DSV: diving support vessel - TOW: tugboat or towing equipment - AHV: anchor handling vessel (tugboat that doesn't trigger tow-to-port)
- **speed** (*float*) – Maximum transit speed, km/hr.
- **tow\_speed** (*float*) – The maximum transit speed when towing, km/hr.

## Note

This is only required for when the servicing equipment is tugboat enabled for a tow-to-port scenario (capability = "TOW")

- **speed\_reduction\_factor** (*float*) – Reduction factor for traveling in inclement weather, default 0. When 0, travel is stopped when either **max\_windspeed\_transport** or **max\_waveheight\_transport** is reached, and when 1, **speed** is used.
- **max\_windspeed\_transport** (*float*) – Maximum windspeed for safe transport, m/s.
- **max\_windspeed\_repair** (*float*) – Maximum windspeed for safe operations, m/s.
- **max\_waveheight\_transport** (*float*) – Maximum waveheight for safe transport, m, default 1000 (land-based).
- **max\_waveheight\_repair** (*float*) – Maximum waveheight for safe operations, m, default 1000 (land-based).
- **mobilization\_cost** (*float*) – Cost to mobilize the rig and crew, default 0.
- **mobilization\_days** (*int*) – Number of days it takes to mobilize the equipment, default 0.

- **strategy** (*str*) – For any unscheduled maintenance servicing equipment, this determines the strategy for dispatching. Should be one of "downtime" or "requests".
- **strategy\_threshold** (*str*) – For downtime-based scenarios, this is based on the operating level, and should be in the range [0, 1]. For request-based scenarios, this is the maximum number of requests that are allowed to build up for any given type of unscheduled servicing equipment, should be an integer  $\geq 1$ .
- **workday\_start** (*int*) – The starting hour of a workshift, in 24 hour time.
- **workday\_end** (*int*) – The ending hour of a workshift, in 24 hour time.
- **crew\_transfer\_time** (*float*) – The number of hours it takes to transfer the crew from the equipment to the system, e.g. how long does it take to transfer the crew from the CTV to the turbine, default 0.
- **onsite** (*bool*) – Indicator for if the rig and crew are based onsite.

## Note

if the rig and crew are onsite be sure that the start and end dates represent the first and last day/month of the year, respectively, and the start and end years represent the first and last year in the weather file.

- **method** (*str*) – Determines if the ship will do all maximum severity repairs first or do all the repairs at one turbine before going to the next, by default severity. Should be one of "severity" or "turbine".
- **unmoor\_hours** (*int* / *float*) – The number of hours required to unmoor a floating offshore wind turbine in order to tow it to port, by default 0.

## Note

Required for the tugboat/towing capability, otherwise unused.

- **reconnection\_hours** (*int* / *float*) – The number of hours required to reconnect a floating offshore wind turbine after being towed back to site, by default 0.

## Note

Required for the tugboat/towing capability, otherwise unused.

- D4.2, p. 18
- Create a YAML configuration file in "`<library>/vessels/`", for the heavy lift vessel and tugboat.

<https://wisdem.github.io/WOMBAT/API/types.html#unscheduled-service-equipment>

- **port\_distance** (*int* / *float*) – The distance, in km, the equipment must travel to go between port and site, by default 0.
- **non\_operational\_start** (*str* / *datetime.datetime* / *None*) – The starting month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of prohibited operations. When defined at the environment level or the port level, if a tugboat, an undefined or later starting date will be overridden, by default None.
- **non\_operational\_end** (*str* / *datetime.datetime* / *None*) – The ending month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of prohibited operations. When defined at the environment level or the port level, if a tugboat, an undefined or earlier ending date will be overridden, by default None.
- **reduced\_speed\_start** (*str* / *datetime.datetime* / *None*) – The starting month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of reduced speed operations. When defined at the environment level or the port level, if a tugboat, an undefined or later starting date will be overridden, by default None.
- **reduced\_speed\_end** (*str* / *datetime.datetime* / *None*) – The ending month and day, e.g., MM/DD, M/D, MM-DD, etc. for an annualized period of reduced speed operations. When defined at the environment level or the port level, if a tugboat, an undefined or earlier ending date will be overridden, by default None.
- **reduced\_speed** (*float*) – The maximum operating speed during the annualized reduced speed operations. When defined at the environment level, an undefined or faster value will be overridden, by default 0.0.

# Unscheduled Servicing Equipment: Answer

```
library > vessels > %>% hlv1.yaml > {} crew
1 name: Heavy Lift Vessel 1
2 equipment_rate: 290000
3 capability: LCN
4 speed: 20.37 # 11 knots
5 strategy: requests
6 strategy_threshold: 1
7 max_windspeed_transport: 10
8 max_windspeed_repair: 10
9 max_waveheight_transport: 2
10 max_waveheight_repair: 2
11 onsite: false
12 mobilization_cost: 325000
13 mobilization_days: 10
14 workday_start: 0
15 workday_end: 24
16 charter_days: 20
17 crew_transfer_time: 0.25
18 n_crews: 1
19 crew:
20   day_rate: 0
21   n_day_rate: 0 # crew comes with the vessel
22   hourly_rate: 0
23   n_hourly_rate: 0
24
```

```
library > vessels > %>% tugboat1.yaml > {} crew
1 name: Tugboat 1
2 equipment_rate: 30000
3 # mobilization_cost: 200000
4 capability: [TOW]
5 speed: 37.04 # 20 knots
6 strategy: requests
7 max_windspeed_transport: 99
8 max_windspeed_repair: 99
9 max_waveheight_transport: 2.5
10 max_waveheight_repair: 2.5
11 onsite: false
12 port_distance: 0 # automatically set from the port configuration
13 # workday_start: 6
14 # workday_end: 18
15 strategy_threshold: 1 # needs to be here, but doesn't do anything
16 charter_days: 3 # needs to be here, but doesn't do anything
17 tow_speed: 9.26 # 5 knots
18 unmoor_hours: 2
19 reconnection_hours: 4
20 crew_transfer_time: 0.25
21 n_crews: 1
22 crew:
23   day_rate: 0 # crew comes with vessel
24   n_day_rate: 0
25   hourly_rate: 0
26   n_hourly_rate: 0
27
```

# Substations

- D4.2, pp. 13–17
- Create a YAML file in `<library>/substations/` using the file name you used in “subassembly” for your layout file
- Create the maintenance and failure configurations for the offshore substation

## Substations

The substation model relies on two specific inputs, and one subassembly input (transformer).

### **capacity\_kw**

The capacity of all turbines in the windfarm, neglecting any losses. Only needed if a \$/kw cost basis is being used.

### **capex\_kw**

The \$/kw cost of the machine, if not providing absolute costs.

Additional keys can be added to represent subassemblies, such as a transformer, in the same format as the generator example above. Similarly, a user can define as many or as few of the subassemblies as desired with their preferred naming conventions

The following is an example of substation YAML definition with no modeled subassemblies.

```
capacity_kw: 670000
capex_kw: 140
transformer:
  name: transformer
  maintenance:
  -
    description: n/a
    time: 0
    materials: 0
    service_equipment: CTV
    frequency: 0
  failures:
  1:
    scale: 0
    shape: 0
    time: 0
    materials: 0
    service_equipment: [CTV]
    operation_reduction: 0
    level: 1
    description: n/a
```

- **time** (*float*) – Amount of time required to perform maintenance, in hours.
- **materials** (*float*) – Cost of materials required to perform maintenance, in USD.
- **frequency** (*float*) – Optimal number of days between performing maintenance, in days.
- **service\_equipment** (*list[str] | str*) – Any combination of the following `Equipment.capability` options.
  - RMT: remote (no actual equipment BUT no special implementation)
  - DRN: drone
  - CTV: crew transfer vessel/vehicle
  - SCN: small crane (i.e., field support vessel)
  - LCN: large crane (i.e., heavy lift vessel)
  - CAB: cabling vessel/vehicle
  - DSV: diving support vessel
  - TOW: tugboat or towing equipment
  - AHV: anchor handling vessel (tugboat that doesn't trigger tow-to-port)
- **system\_value** (*Union[int, float]*) – Turbine replacement value. Used if the materials cost is a proportional cost.
- **description** (*str*) – A short text description to be used for logging.
- **operation\_reduction** (*float*) – Performance reduction caused by the failure, between (0, 1]. Defaults to 0.

#### ⚠ Warning

As of v0.7, availability is very sensitive to the usage of this parameter, and so it should be used carefully.

- **level** (*int, optional*) – Severity level of the maintenance. Defaults to 0.

- **scale** (*float*) – Weibull scale parameter for a failure classification.
- **shape** (*float*) – Weibull shape parameter for a failure classification.
- **time** (*float*) – Amount of time required to complete the repair, in hours.
- **materials** (*float*) – Cost of the materials required to complete the repair, in \$USD.
- **operation\_reduction** (*float*) – Performance reduction caused by the failure, between (0, 1].

#### ⚠ Warning

As of v0.7, availability is very sensitive to the usage of this parameter, and so it should be used carefully.

- **level** (*int, optional*) – Level of severity, will be generated in the `ComponentData.create_severities` method.
- **service\_equipment** (*list[str] | str*) – Any combination of the following `Equipment.capability` options:
  - RMT: remote (no actual equipment BUT no special implementation)
  - DRN: drone
  - CTV: crew transfer vessel/vehicle
  - SCN: small crane (i.e., field support vessel)
  - LCN: large crane (i.e., heavy lift vessel)
  - CAB: cabling vessel/vehicle
  - DSV: diving support vessel
  - TOW: tugboat or towing equipment
  - AHV: anchor handling vessel (tugboat that doesn't trigger tow-to-port)
- **system\_value** (*Union[int, float]*) – Turbine replacement value. Used if the materials cost is a proportional cost.
- **replacement** (*bool*) – True if triggering the failure requires a subassembly replacement, False, if only a repair is necessary. Defaults to False
- **description** (*str*) – A short text description to be used for logging.
- **rng** (*np.random.\_generator.Generator*) –

Left:

## Maintenance

<https://wisdem.github.io/WOMBAT/API/types.html#maintenance-tasks>

Right: Failure

<https://wisdem.github.io/WOMBAT/API/types.html#failures>

# Substations: Answer

```
library > substations > corewind_substation.yaml > {} transformer
1 capacity_kw: 600
2 capex_kw: 120 # 120,000 EUR/MW; https://guidetoanoffshorewindfarm.com/wind-farm-costs
3 transformer:
4   name: transformer
5   maintenance:
6     -
7       description: oss annual inspection
8       time: 24
9       materials: 500
10      service_equipment: CTV
11      frequency: 365
12      level: 1
13      # n_technicians: 4
14 failures:
15   2:
16     scale: 5
17     shape: 1
18     time: 12
19     materials: 2000
20     service_equipment: CTV
21     operation_reduction: 0
22     level: 2
23     description: oss minor repair
24     # n_technicians: 2
25   4:
26     scale: 100
27     shape: 1
28     time: 60
29     materials: 100000
30     service_equipment: CTV
31     operation_reduction: 0
32     level: 4
33     description: oss major repair
34     # n_technicians: 5
35
```

# Turbines

- D4.2, pp. 13–17
- Create a YAML file in <library>/turbines/ using the file name you used in “subassembly” for your layout file
- What subassemblies should we consider for the turbine model?
- Create the maintenance and failure configurations for the hydraulic system (ballast pump and pitch system)

Right:

[https://wisdem.github.io/WOMBAT/examples/how\\_to.html#turbines](https://wisdem.github.io/WOMBAT/examples/how_to.html#turbines)

## Substations

The substation model relies on two specific inputs, and one subassembly input (transformer).

### capacity\_kw

The capacity of all turbines in the windfarm, neglecting any losses. Only needed if a \$/kw cost basis is being used.

### capex\_kw

The \$/kw cost of the machine, if not providing absolute costs.

Additional keys can be added to represent subassemblies, such as a transformer, in the same format as the generator example above. Similarly, a user can define as many or as few of the subassemblies as desired with their preferred naming conventions

The following is an example of substation YAML definition with no modeled subassemblies.

```
capacity_kw: 670000
capex_kw: 140
transformer:
  name: transformer
  maintenance:
  -
    description: n/a
    time: 0
    materials: 0
    service_equipment: CTV
    frequency: 0
  failures:
  1:
    scale: 0
    shape: 0
    time: 0
    materials: 0
    service_equipment: [CTV]
    operation_reduction: 0
    level: 1
    description: n/a
```

# Turbines: Answer

```
library > turbines > corewind_15MW.yaml > {} drive_train > {} failures
```

```
1 capacity_kw: 15000
2 capex_kw: 1300
3 power_curve:
4   file: 2020ATB_NREL_Reference_15MW_240.csv
5   bin_width: 1
6 > electrical_system: ...
77 > hydraulic_system: ...
127 > yaw_system: ...
167 > rotor_blades: ...
207 > generator: ...
248 > supporting_structure: ...
327 > drive_train: ...
367
```

```
77 hydraulic_system:
78   name: hydraulic_system
79   maintenance:
80     - description: n/a
81       time: 0
82       materials: 0
83       service_equipment: CTV
84       frequency: 0
85   failures:
86     1:
87       scale: 1.214
88       shape: 1
89       time: 18
90       materials: 500
91       service_equipment: CTV
92       operation_reduction: 0
93       level: 1
94       description: minor pitch system repair
95       # n_technicians: 2
96     2:
97       scale: 100
98       shape: 1
99       time: 8
100      materials: 1000
101      service_equipment: CTV
102      operation_reduction: 0
103      level: 2
104      description: minor ballast pump repair
105      # n_technicians: 2
106     3:
107       scale: 5.587
108       shape: 1
109       time: 30
110      materials: 1900
111      service_equipment: CTV
112      operation_reduction: 0.0
113      level: 3
114      description: major pitch system repair
115      # n_technicians: 3
116     5:
117       scale: 1000
118       shape: 1
119       time: 75
120      materials: 14000
121      service_equipment: LCN
122      operation_reduction: 0
123      replacement: true
124      level: 5
125      description: major pitch system replacement
126      # n_technicians: 4
127 > yaw_system:
```

# Cables

- D4.2, pp. 13–17
- Create a YAML file in <library>/cables/ using the file name you used in “upstream\_cable” for your layout file
- Create the maintenance and failure configurations for the export cables

Right:

[https://wisdem.github.io/WOMBAT/examples/how\\_to.html#cables](https://wisdem.github.io/WOMBAT/examples/how_to.html#cables)

## Substations

The substation model relies on two specific inputs, and one subassembly input (transformer).

### capacity\_kw

The capacity of all turbines in the windfarm, neglecting any losses. Only needed if a \$/kw cost basis is being used.

### capex\_kw

The \$/kw cost of the machine, if not providing absolute costs.

Additional keys can be added to represent subassemblies, such as a transformer, in the same format as the generator example above. Similarly, a user can define as many or as few of the subassemblies as desired with their preferred naming conventions

The following is an example of substation YAML definition with no modeled subassemblies.

```
capacity_kw: 670000
capex_kw: 140
transformer:
  name: transformer
  maintenance:
  -
    description: n/a
    time: 0
    materials: 0
    service_equipment: CTV
    frequency: 0
  failures:
  1:
    scale: 0
    shape: 0
    time: 0
    materials: 0
    service_equipment: [CTV]
    operation_reduction: 0
    level: 1
    description: n/a
```

# Cables: Answer

```
library > cables > corewind_export.yaml > {} failures
1  name: export cable
2  maintenance:
3  -
4    description: export cable subsea inspection
5    time: 12
6    materials: 500
7    service_equipment: DSV
8    frequency: 730
9    level: 1
10   # n_technicians: 5
11 failures:
12   6:
13     scale: 50
14     shape: 1
15     time: 60
16     materials: 30000
17     operation_reduction: 0
18     service_equipment: [CAB]
19     replacement: false
20     level: 4
21     description: export cable major repair
22     # n_technicians: 5
23
```

# Hands On With WOMBAT

---

# Running a Simulation

- Final questions on setup before moving forward?
- From the terminal, launch a Jupyter Lab session: “jupyter lab”
- I’ll switch over the example notebook that’s set up to finish out the workshop

# WAVES

---

Combining ORBIT, WOMBAT, and FLORIS  
in a single model

# WAVES

- Release coming soon at: <https://github.com/NREL/WAVES>
- Combine capital expenditures (CapEx–ORBIT), OpEx (WOMBAT), and annual energy production (AEP–FLORIS) into a single model API that creates the required input and output connections to properly consider project financials, LCOE, and real-world energy production (availability and wakes)

# Future of WOMBAT

---

What's on the horizon for WOMBAT  
over the next few years?

# Potential Future Work

## Model Development

- Model tow-to-port simulations at a higher resolution
- Improved repair timing
- Date-based maintenance
- Single file/dictionary configuration like ORBIT and FLORIS
- Multicrew handoff
- Other ideas? Add them to the Issues board:  
<https://github.com/WISDEM/WO-MBAT/issues>

## Validation and Review

- Floating Wind model comparison publication in 2024 to update the state of O&M modeling
- Develop a baseline land-based, fixed offshore, and floating offshore wind data set for easier modeling

# Thank you

---

[www.nrel.gov](http://www.nrel.gov)

NREL/PR-5000-87913

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

