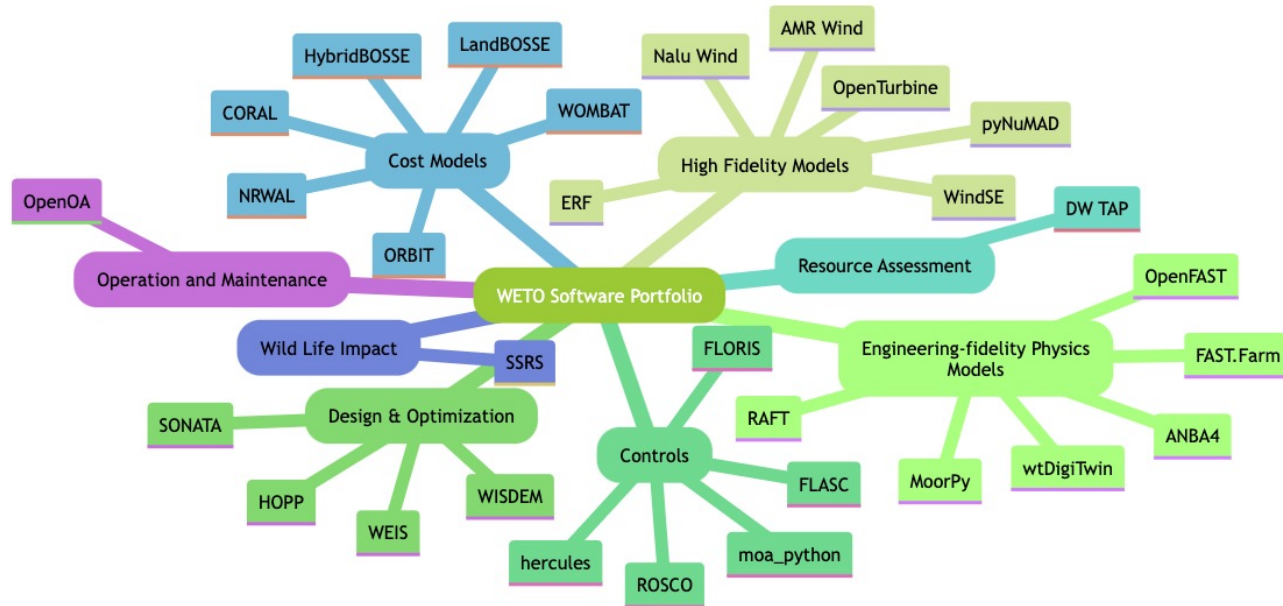




The WETO Software Portfolio

Rafael Mudafort, Derek Slaughter
November 2, 2023

Wind Energy Research Software

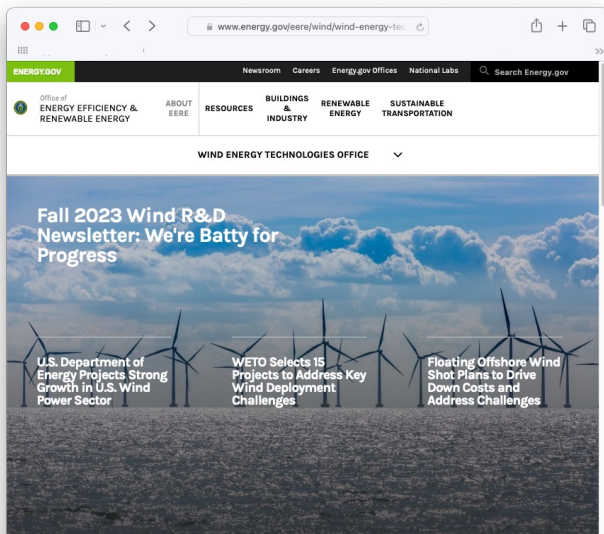


Agenda

- 1 Holistic Modeling Project overview
- 2 WETO Software Portfolio introduction
- 3 Upcoming: Coordinated roadmap + development
- 4 Open ended discussion

Holistic Modeling Project

WETO Software Portfolio Coordination



The **Wind Energy Technologies Office** invests in wind energy research, development, demonstration, and deployment activities that enable and accelerate the innovations needed to advance offshore, land-based, and distributed wind systems; reduce the cost of wind energy; drive deployment in an environmentally conscious manner; and facilitate the integration of high levels of wind energy with the electric grid.

WETO Wind Energy Technology Software invests in the energy research, development, demonstration, and deployment activities that enable and accelerate the innovations needed to advance offshore, land-based, and distributed wind systems; reduce the cost of wind energy; drive deployment in an environmentally conscious manner; and facilitate the integration of high levels of wind energy with the electric grid.



Lawrence Berkeley National Laboratory

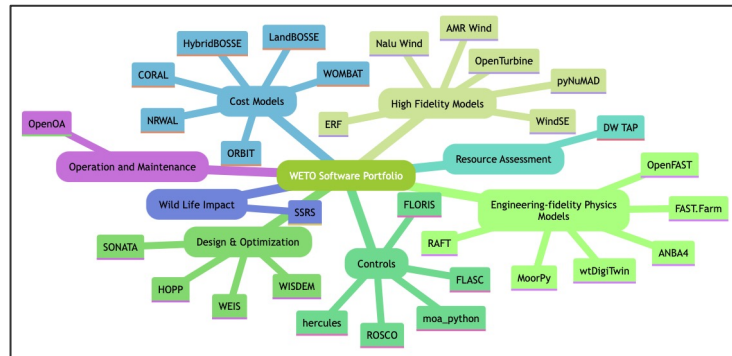


Holistic Modeling Project

WETO Software Portfolio Coordination

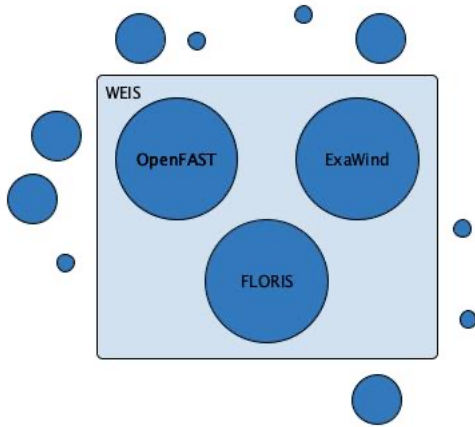
WETO Mission

The **Wind Energy Technologies Office** invests in wind energy research, development, demonstration, and deployment activities that enable and accelerate the innovations needed to advance offshore, land-based, and distributed wind systems; reduce the cost of wind energy; drive deployment in an environmentally conscious manner; and facilitate the integration of high levels of wind energy with the electric grid.

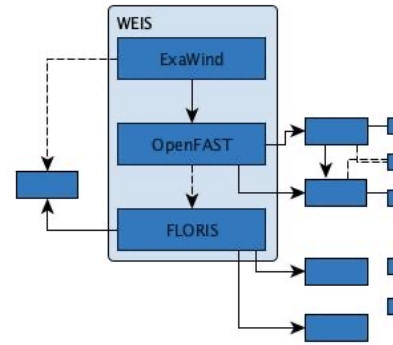


Holistic Modeling Project Overview

Current: Collection of tools covering a variety of topics; loosely organized and somewhat coupled



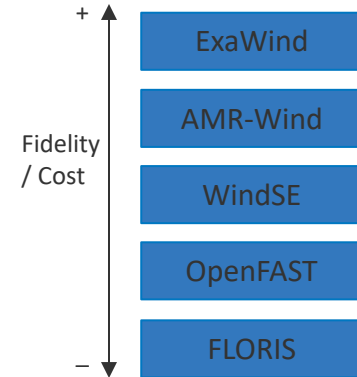
Target: Tech stack covering defined topics across established fidelities; coupled where relationships allow; capabilities exploration and tool selection



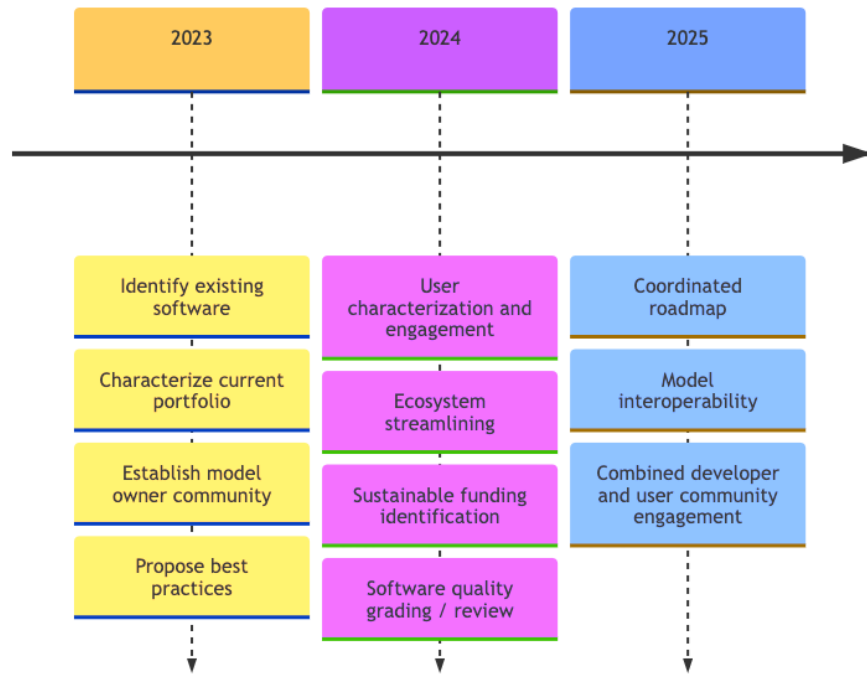
Compare and relate based on attributes:

- Current funding level
- Release activity
- Documentation maturity
- Fidelity of physics
- Primary use

Capability - Aerodynamics
Tools Selection:

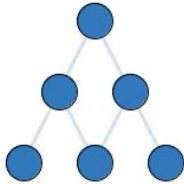


Holistic Modeling Project Overview



Holistic Modeling Project Year 1

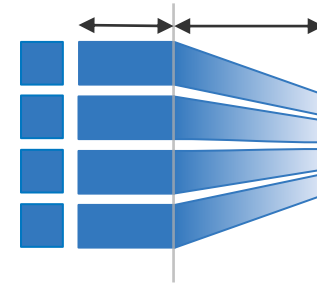
Model Listing &
Capabilities Dashboard



Software Development
Best Practices

- Quality
- Maintenance
- Usability
- Extensibility
- Robustness

Portfolio Coordination



* Frameworks established in FY23 within ongoing updates in FY24 and FY25

Software Listings

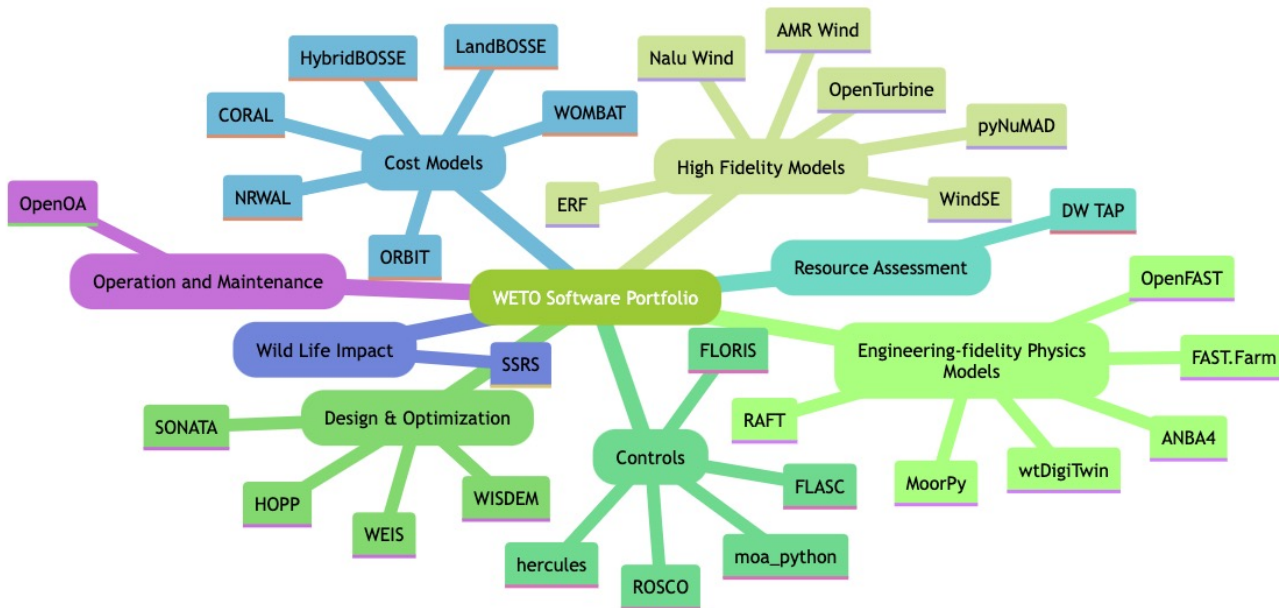
<https://a2e.energy.gov/code/repo>

The screenshot shows the WETO Software Stack Dashboard search results page. The header includes the WETO logo and navigation links for Projects, Data, Publications, Code, Metrics, and FAQ. A search bar is present with the text "Search". The main content area displays search results for "35 repositories found (page 1 of 2)". The results are organized by Organization, License, and Language. The "OpenFAST / openfast" repository is highlighted, showing its description, license (Apache-2.0), and activity metrics (Issues: 243, Pull Requests: 7, Contributors: 85, Forks: 417). A line graph shows activity over time, and a status bar indicates "Development Pipeline: passing" and "docs: passing".

<https://nrel.github.io/WETOStack>

The screenshot shows the WETO Software Stack Software Listing page. The header includes the WETO Software Stack logo and navigation links for Workshop, Portfolio Analysis, and Software Development. The main content area is titled "Software Listing" and contains a description of the software set. It lists two groups of software projects: "WETO-funded software" and "Other projects funded by various agencies and mechanisms". A list of active support projects is provided, including OpenFAST, FAST.Farm, MoorPy, wtDigiTwin, RAFT, and ANBA4. The page also lists high fidelity models (AMR-Wind, Nalu-Wind, OpenTurbine, ERF, WindSE, pyNumAD) and design and optimization projects.

WETO Software Portfolio

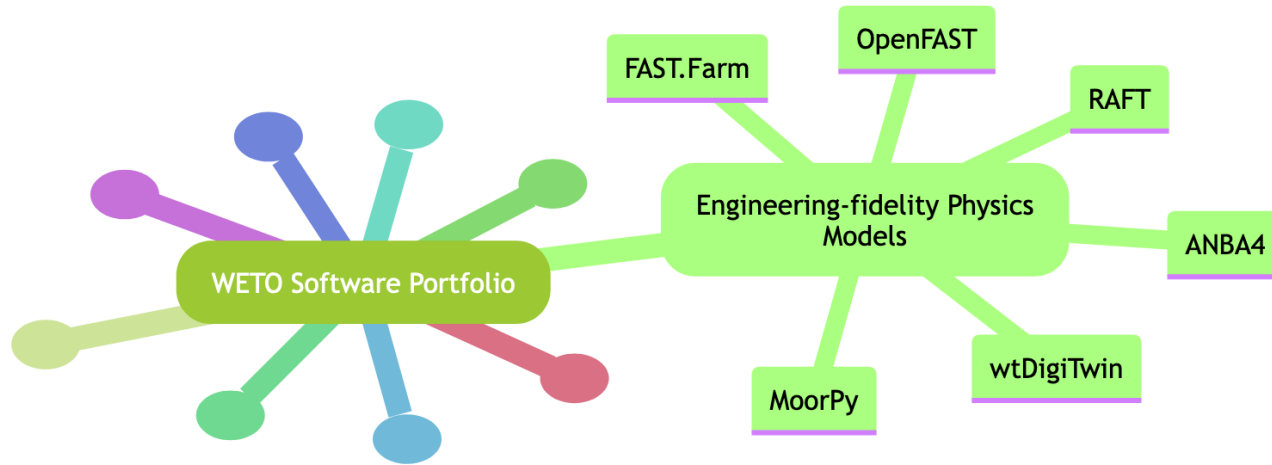


Active funding, active development: **30 projects + 20%?**

Technical Areas

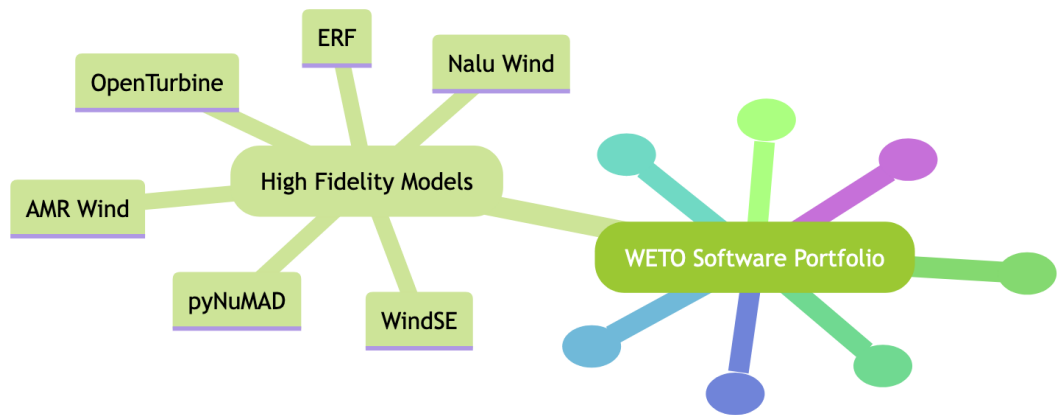
- Engineering-fidelity Physics Models
- High Fidelity Models
- Design & Optimization
- Controls
- Resource Assessment
- Cost Models
- Wildlife Impact
- Operation and Maintenance

Engineering-fidelity Physics Models



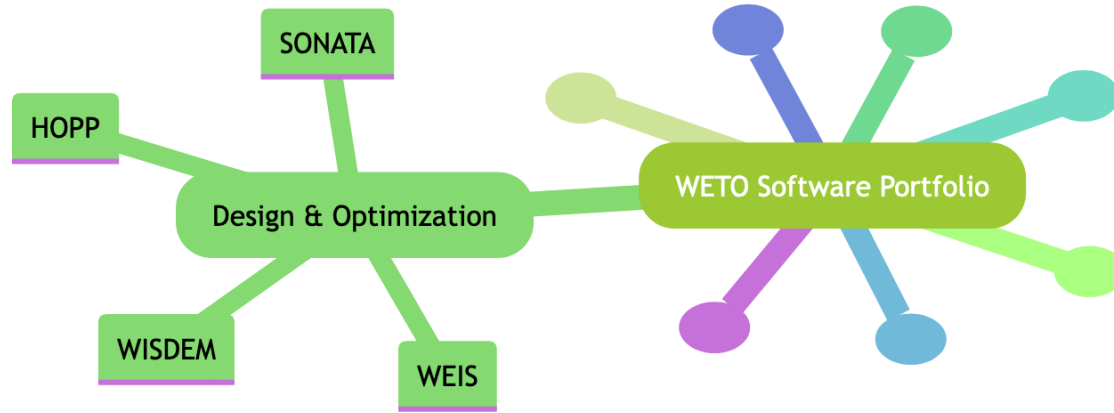
- OpenFAST [openfast/openfast](https://openfast.github.io/openfast/) - Multi-physics tool for simulating the coupled dynamic response of wind turbines.
- FAST.Farm [openfast/openfast](https://openfast.github.io/openfast/) - Mid-fidelity wind farm simulator that uses OpenFAST as a turbine model.
- MoorPy [nrel/moorpy](https://nrel.github.io/moorpy/) - Quasi-static mooring model and a suite of associated functions for mooring system analysis.
- wtDigiTwin [ebranlard/wtDigiTwin](https://ebranlard.github.io/wtDigiTwin/) - Digital twin model for wind turbine
- RAFT [WISDEM/RAFT](https://wisdem.github.io/RAFT/) - Library for frequency-domain analysis of floating wind turbines.
- ANBA4 [ANBA4/anba4](https://anba4.github.io/anba4/) - Computes the 6x6 stiffness/mass matrices of arbitrarily complex composite beam cross sections

High Fidelity Models



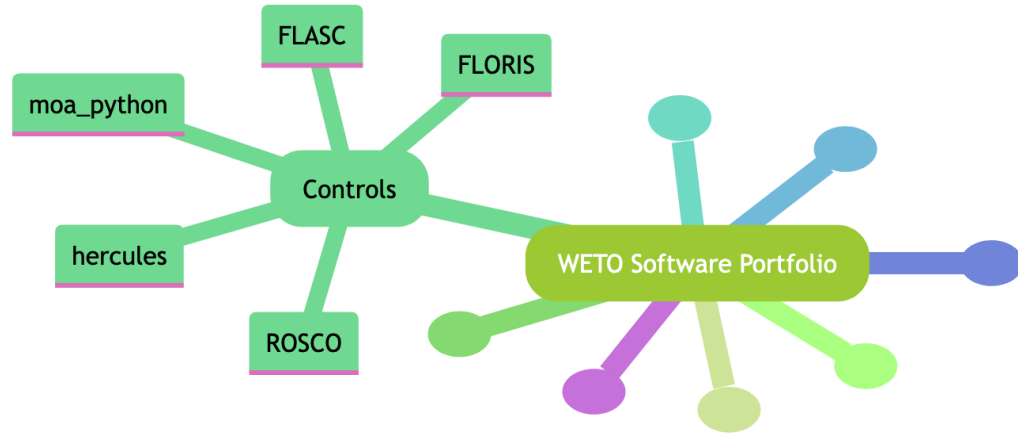
- AMR-Wind [exawind/amr-wind](https://exawind.com/amr-wind) - Massively parallel, block-structured adaptive-mesh, incompressible flow solver for wind turbine and wind farm simulations.
- Nalu-Wind [exawind/nalu-wind](https://exawind.com/nalu-wind) - Generalized, unstructured, massively parallel, incompressible flow solver for wind turbine and wind farm.
- OpenTurbine [exawind/openturbine](https://exawind.com/openturbine) - Wind turbine structural dynamics simulation code for land-based and offshore wind turbines specifically designed to couple with low-fidelity aerodynamic/hydrodynamic models (OpenFAST) and high-fidelity computational fluid dynamics (CFD) models (ExaWind).
- ERF [erf-model/ERF](https://erf-model.com/ERF) - Compressible Navier-Stokes solver on an Arakawa C-grid for large-scale weather modeling.
- WindSE [nrel/windse](https://nrel.com/windse) - Python package that uses a FEniCS backend to perform wind farm simulations and optimization.
- pyNuMAD [sandialabs/pyNuMAD](https://sandialabs.com/pyNuMAD) - Simplifies the process of creating a three-dimensional model of a wind turbine blade by providing an intermediary between raw blade data and analytical platforms (ANSYS, Cubit, OpenFAST, etc).

Design & Optimization



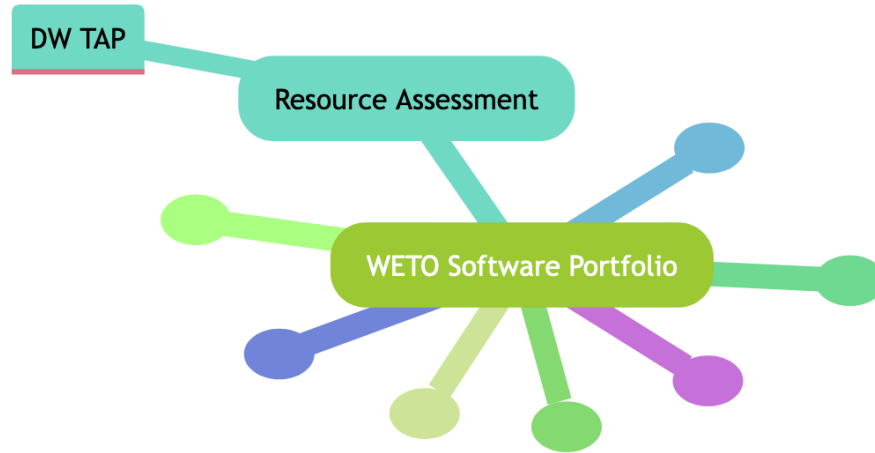
- WEIS wisdem/weis - Wind Energy with Integrated Servo-control performs multi-fidelity co-design of wind turbines to enable design optimization of floating offshore wind turbines.
- WISDEM wisdem/wisdem - Set of wind turbine and plant cost and energy production models along with financial models for assessing overall wind plant cost of energy.
- HOPP [NREL/HOPP](http://nrel/hopp) - Assesses optimal designs for the deployment of utility-scale hybrid energy plants, particularly considering wind, solar and storage.
- SONATA [ptrbortolotti/SONATA](http://ptrbortolotti/sonata) - Toolbox for Multidisciplinary Rotor Blade Design Environment for Structural Optimization and Aeroelastic Analysis.

Controls



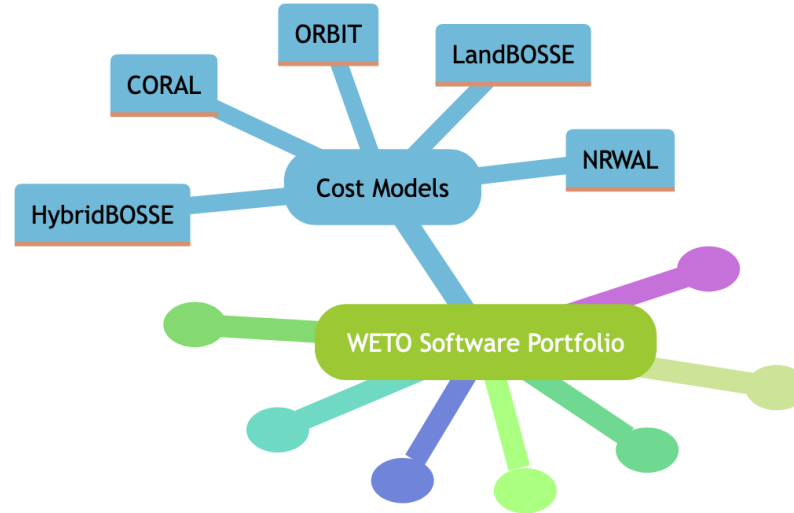
- ROSCO [NREL/ROSCO](https://nrel.github.io/ROSCO/) - Reference controller with industry-standard functionality and generic tuning
- FLORIS [nrel/floris](https://nrel.github.io/floris/) - Controls-focused wind farm simulation software incorporating steady-state engineering wake models into a performance-focused Python framework.
- FLASC [nrel/flasc](https://nrel.github.io/flasc/) - Suite of analysis tools for SCADA data filtering, analysis, wind farm model validation, field experiment design, and field experiment monitoring.
- hercules [nrel/hercules](https://nrel.github.io/hercules/) - Wind farm emulator for controls testing with LES models.
- moa_python [nrel/moa_python](https://nrel.github.io/moa_python/) - Wind farm performance post processing and analysis tool.

Resource Assessment



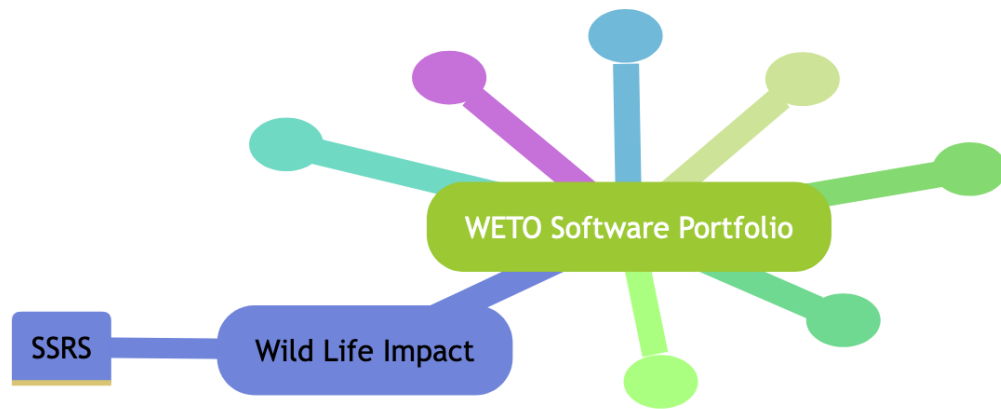
- DW TAP [NREL/dw-tap-app](https://www.nrel.gov/dw-tap-app) - A simple tool for cost-effectively and accurately assessing wind resources without having to physically take direct measurements in the field.

Cost Models



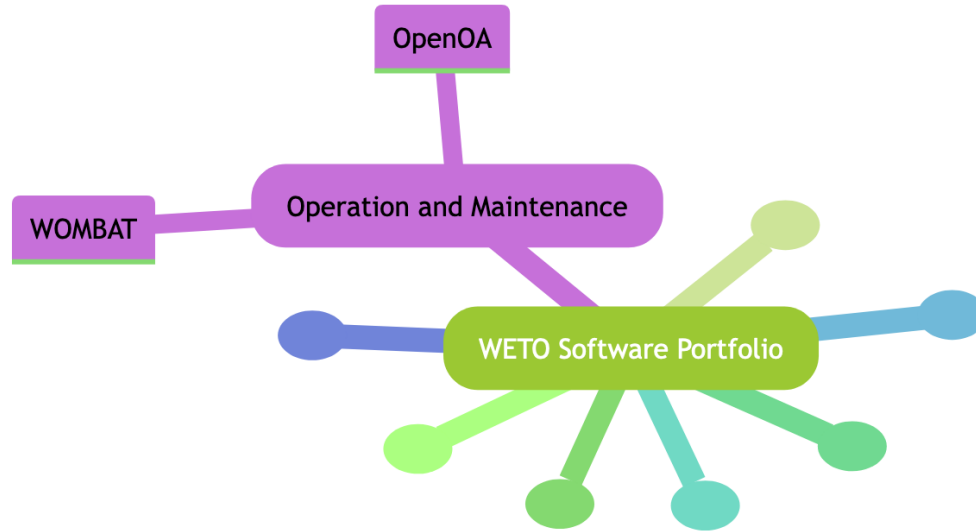
- LandBOSSE [WISDEM/LandBOSSE](#) - A systems engineering tool that estimates the balance-of-system (BOS) costs associated with installing utility scale wind plants.
- HybridBOSSE [NREL/HybridBOSSE](#) - A tool for estimating BOS costs for hybrid power plants
- ORBIT [WISDEM/ORBIT](#) - A model to study the cost and times associated with Offshore Wind Balance of System (BOS) processes.
- CORAL [NREL/CORAL](#) - Concurrent ORBIT for shared Resource Analysis Library
- NRWAL [NREL/NRWAL](#) - A library of offshore wind cost equations

Wildlife Impact



- SSRS [NREL/SSRS](#) - A stochastic agent-based model for predicting raptor movements through an orographic updraft field estimated using the spatially varying wind conditions and ground features (altitude, slope, aspect).

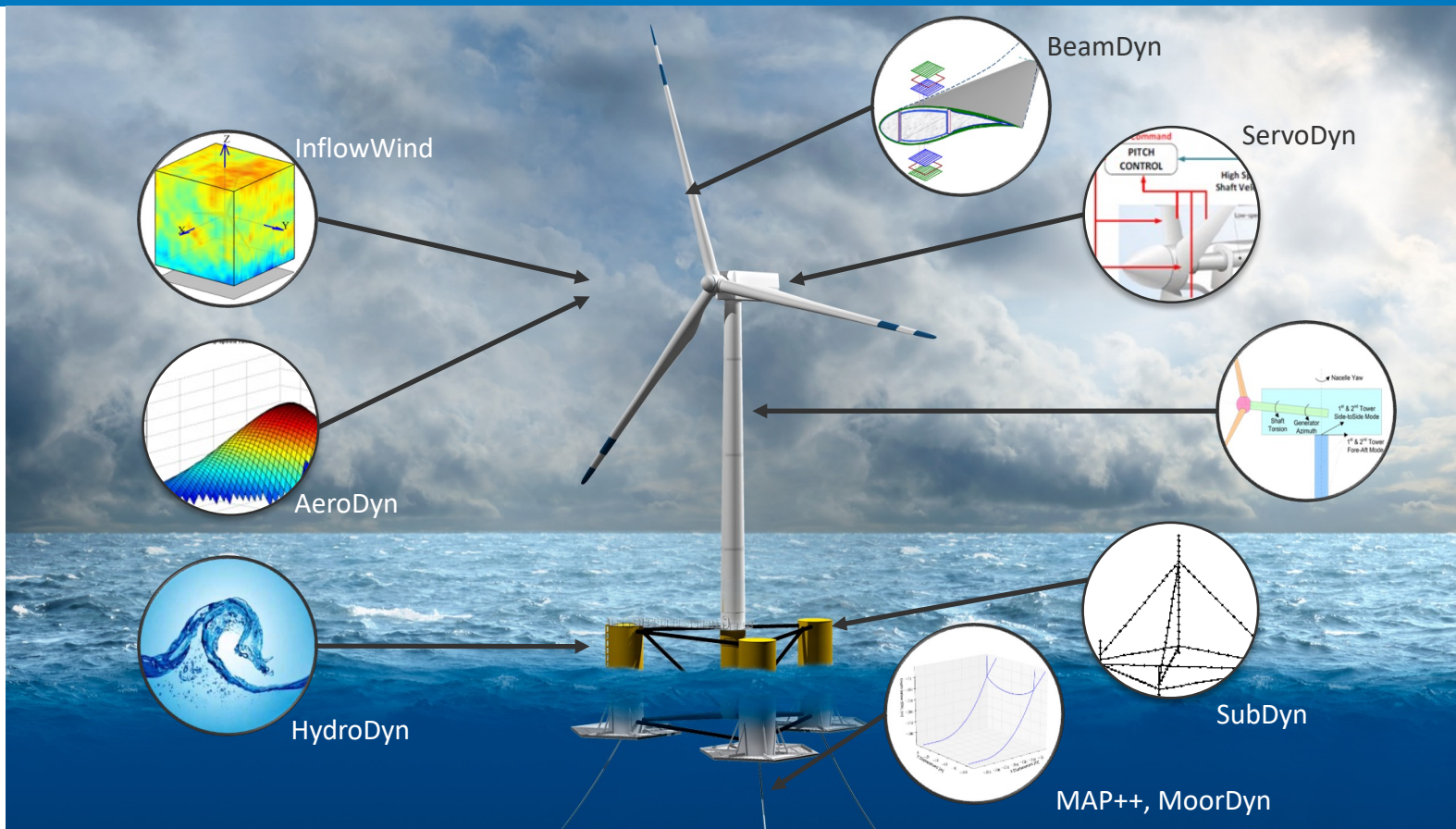
Operation and Maintenance



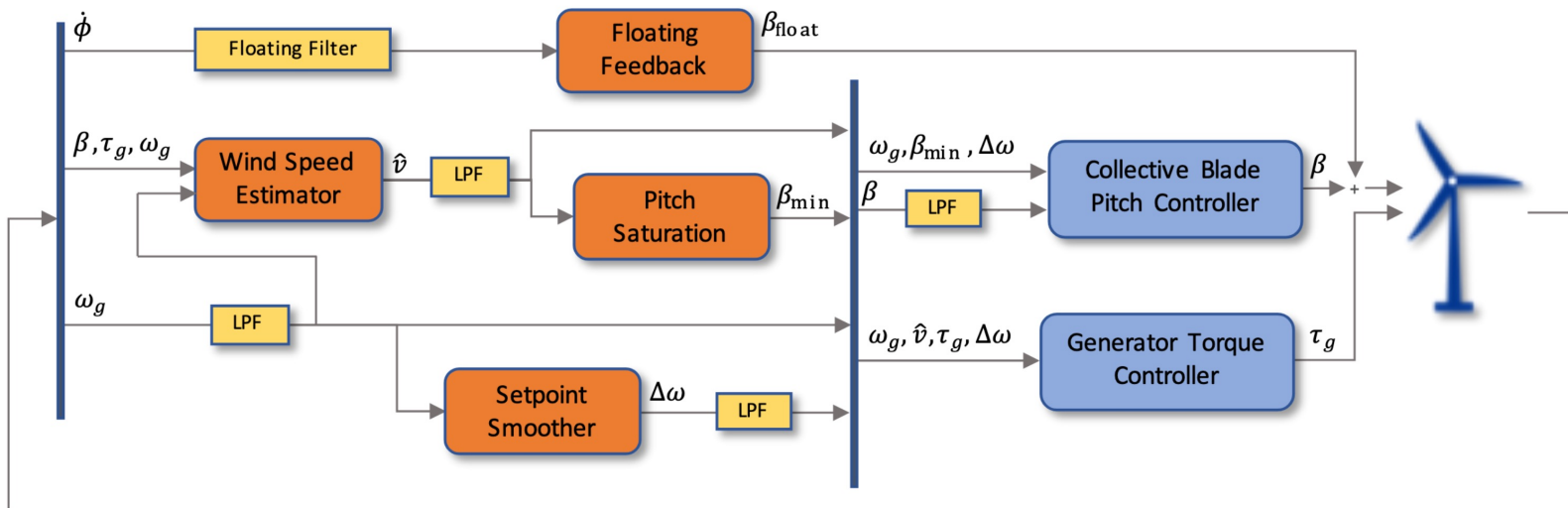
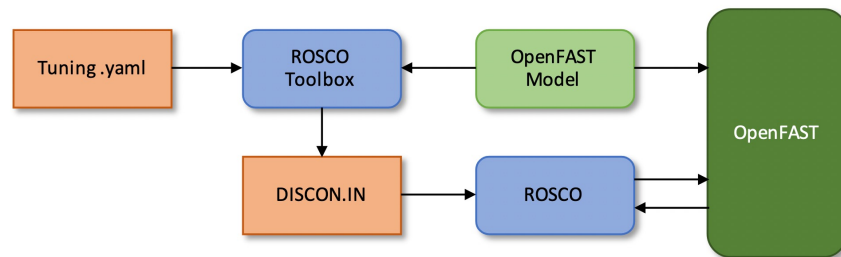
- WOMBAT [WISDEM/WOMBAT](#) - A library to simulate the operation and maintenance phase (O&M) of distributed, land-based, and offshore windfarms using a discrete event simulation framework.
- OpenOA [nrel/openoa](#) - A framework for working with large time-series data from wind plants, such as SCADA.

Capability Areas

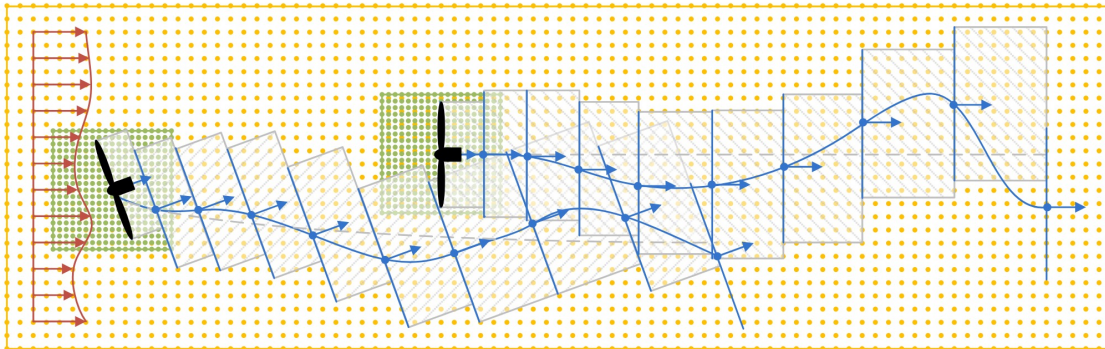
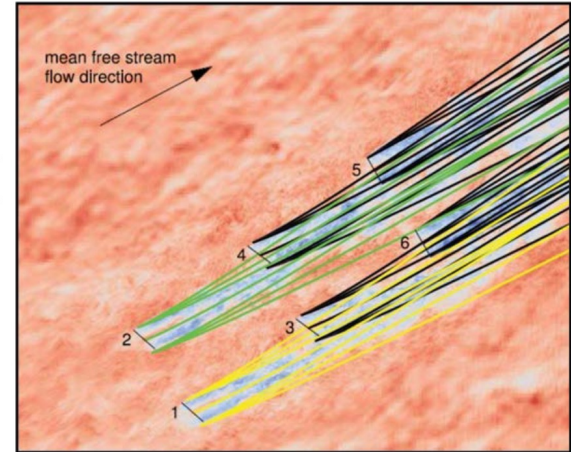
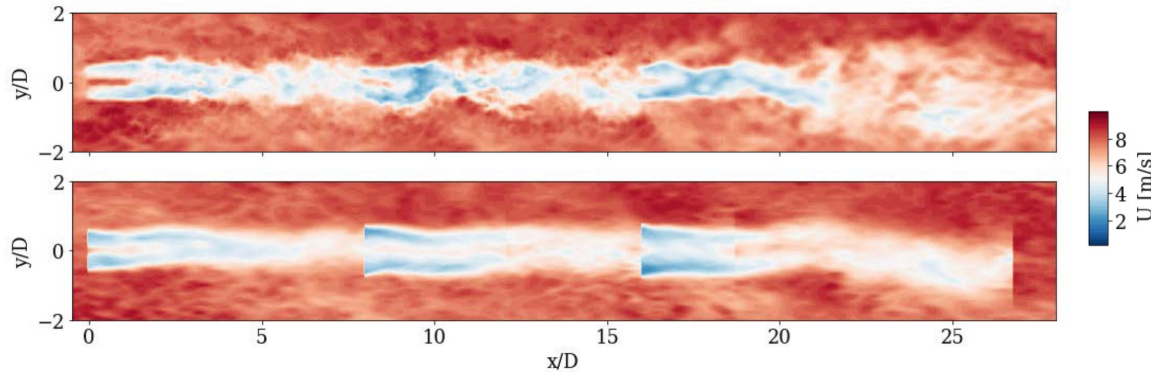
OpenFAST – Multi-physics Wind Turbine Simulation



ROSCO - Open-Source Controller for OpenFAST



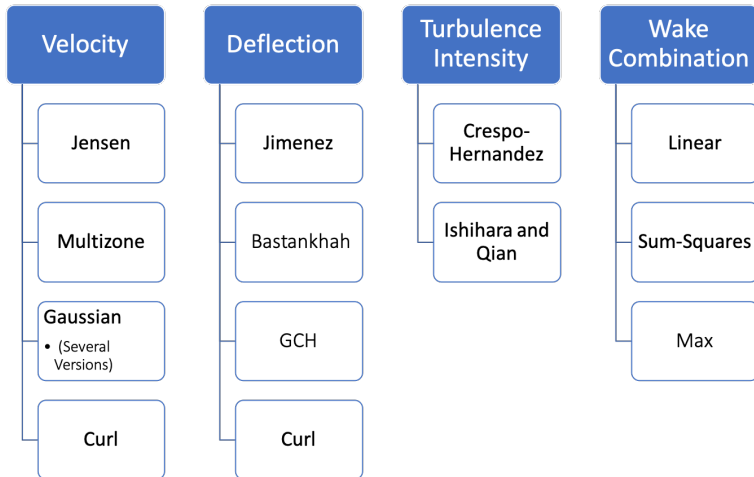
FAST.Farm – Wind Farm Simulation



FLORIS – Wind Farm Control and Design Tool

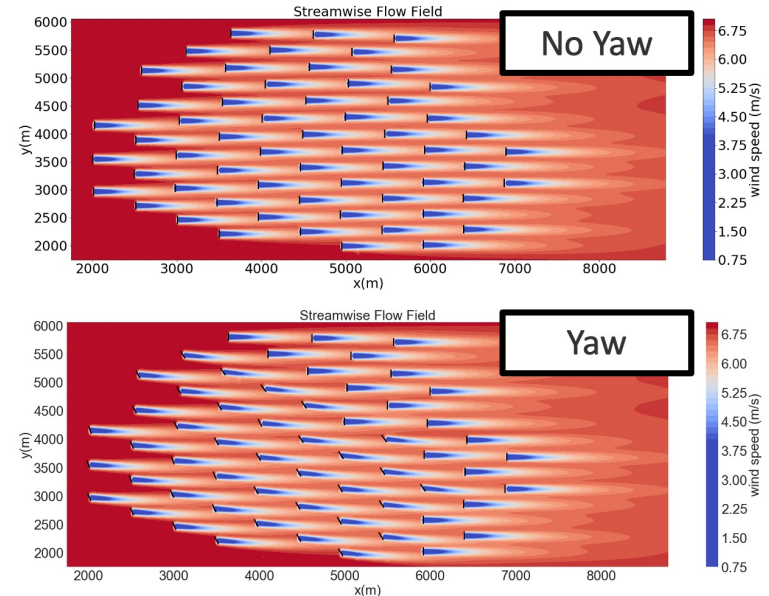
Design and analysis tools

- Controls design and analysis
- Site layout optimization and codesign
- Analysis of energy production



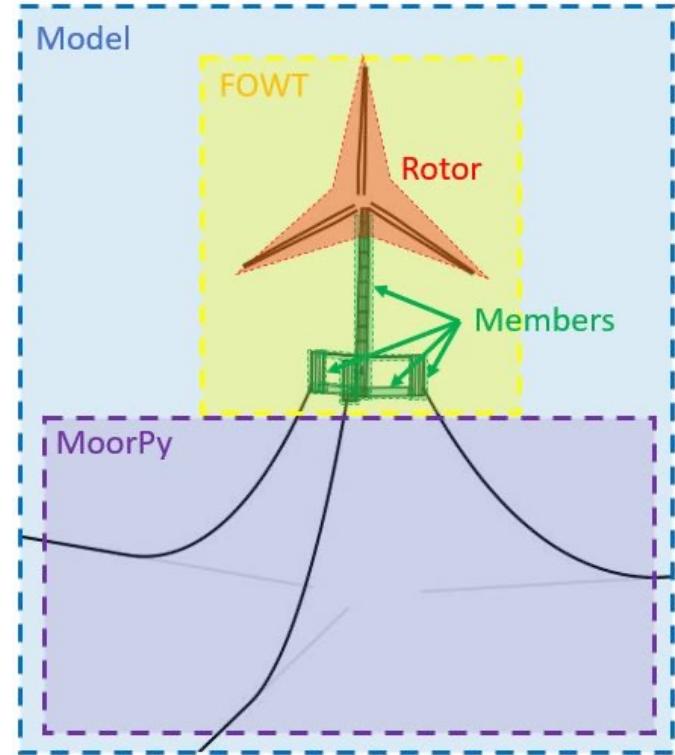
Wake Modeling

- Wake velocity, deflection, combination
- Turbulence propagation



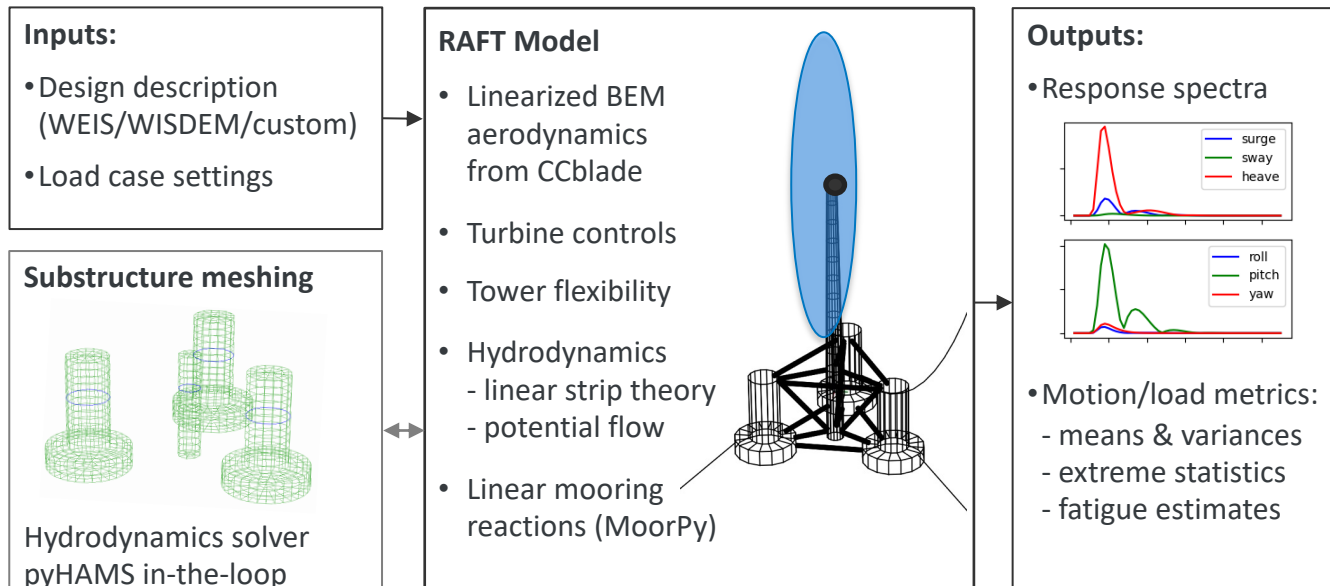
MoorPy - Quasi-Static Mooring Toolset

- Used by RAFT for mooring simulation



RAFT - Response Amplitudes of Floating Turbines

- Frequency-domain dynamics model for support structure optimization
- Level 1 model within WEIS, providing dynamics to complement WISDEM



Impact:

- Efficient (~1 minute) dynamics evaluation for rapid floating wind design optimization

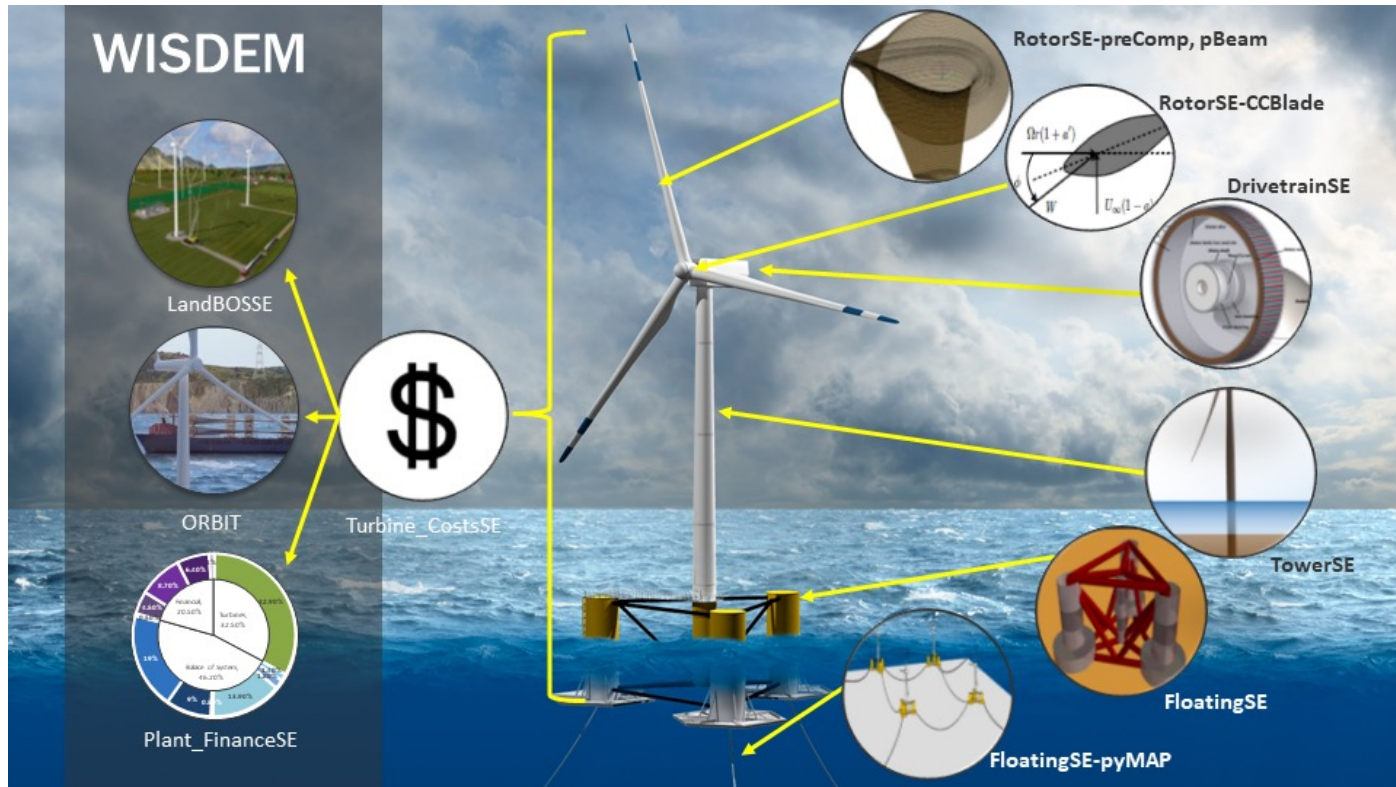
Current Funding:

- [ATLANTIS – WEIS](#)

Roadmap:

- Complete aerodynamics and control for [WEIS](#)
- Expanded aerodynamic, control, and structural modeling
- Multi-fidelity coupling

WISDEM – Wind Plant COE Assessment



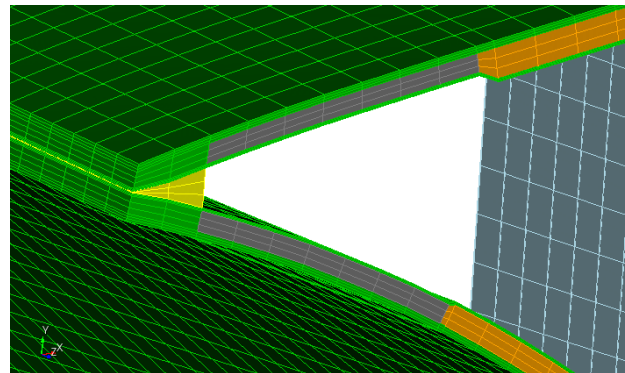
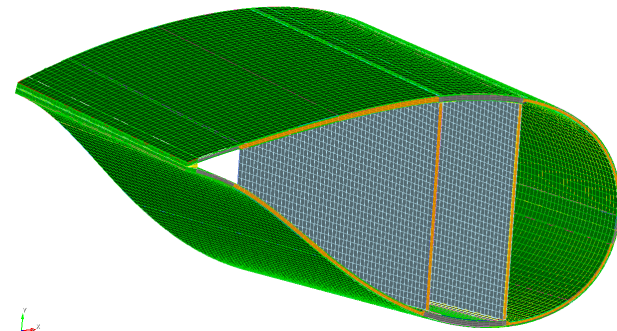
pyNuMAD – Blade Design



- Creates blades for beam, shell, and solid models
- Branched from NuMAD but with increased fidelity, robustness, and usability
- Currently interfaces with

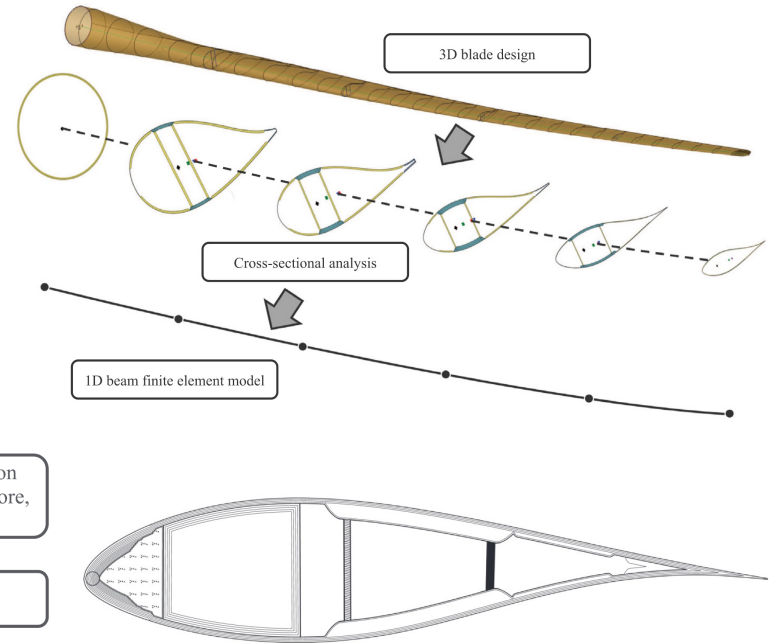
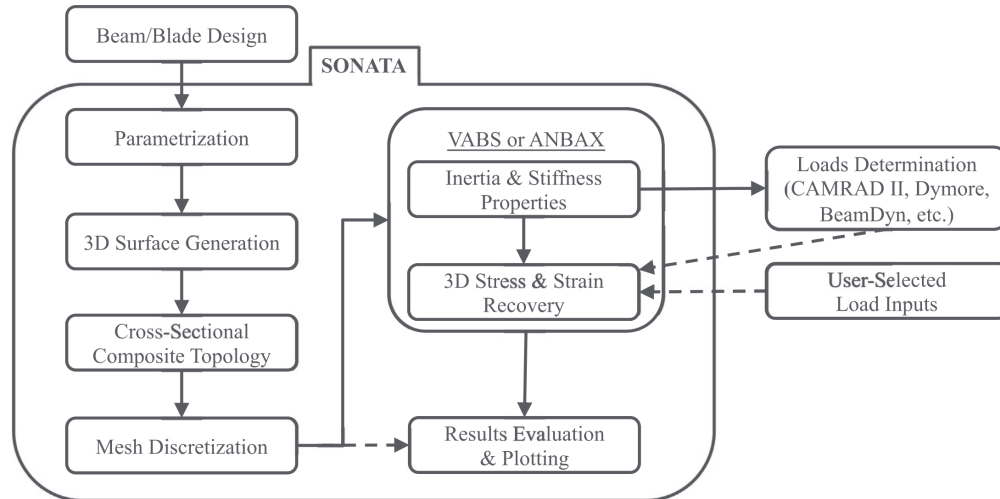


BeamDyn



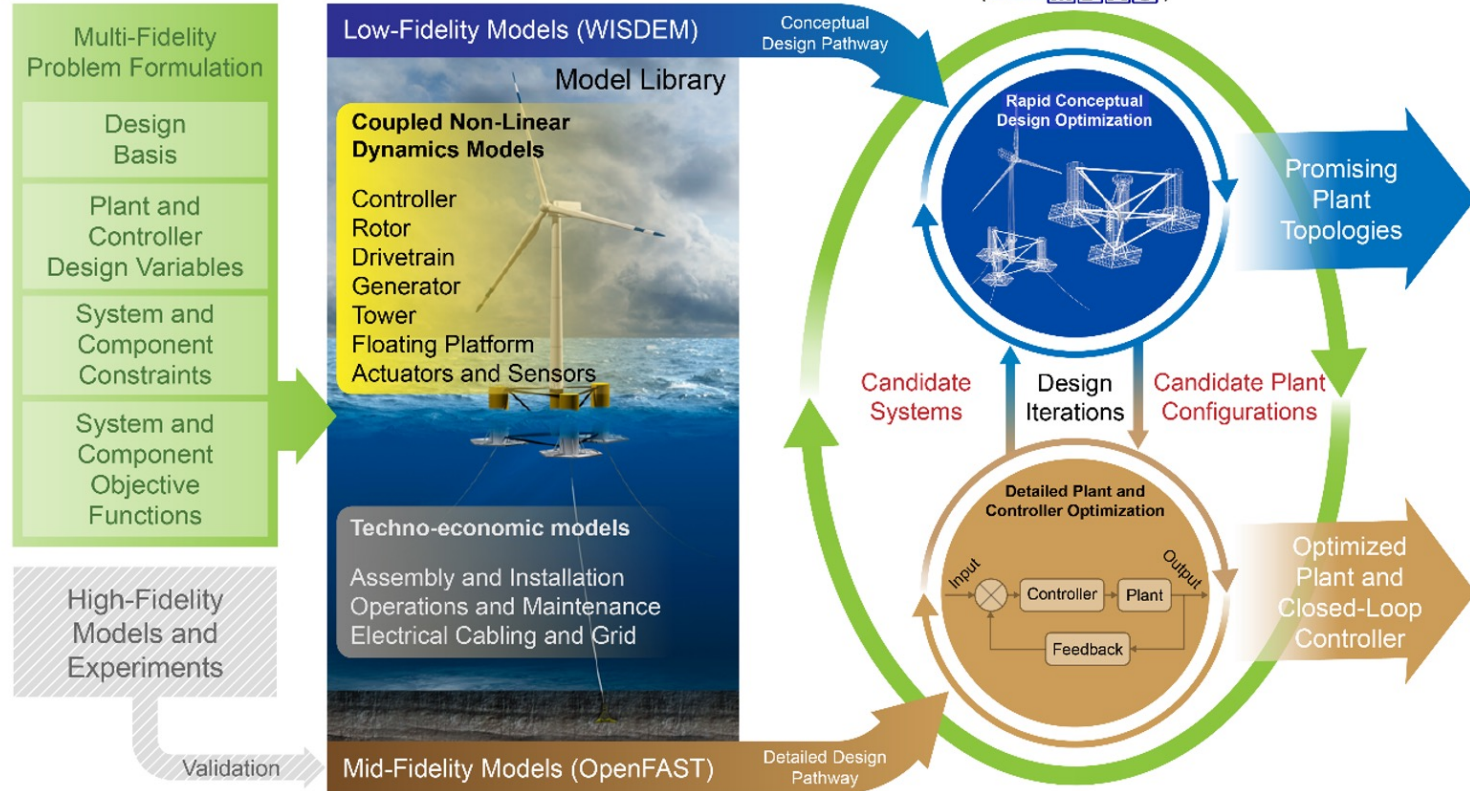
SONATA – Blade Cross-Section Design

- Uses structural solvers – VABS and ANBA4

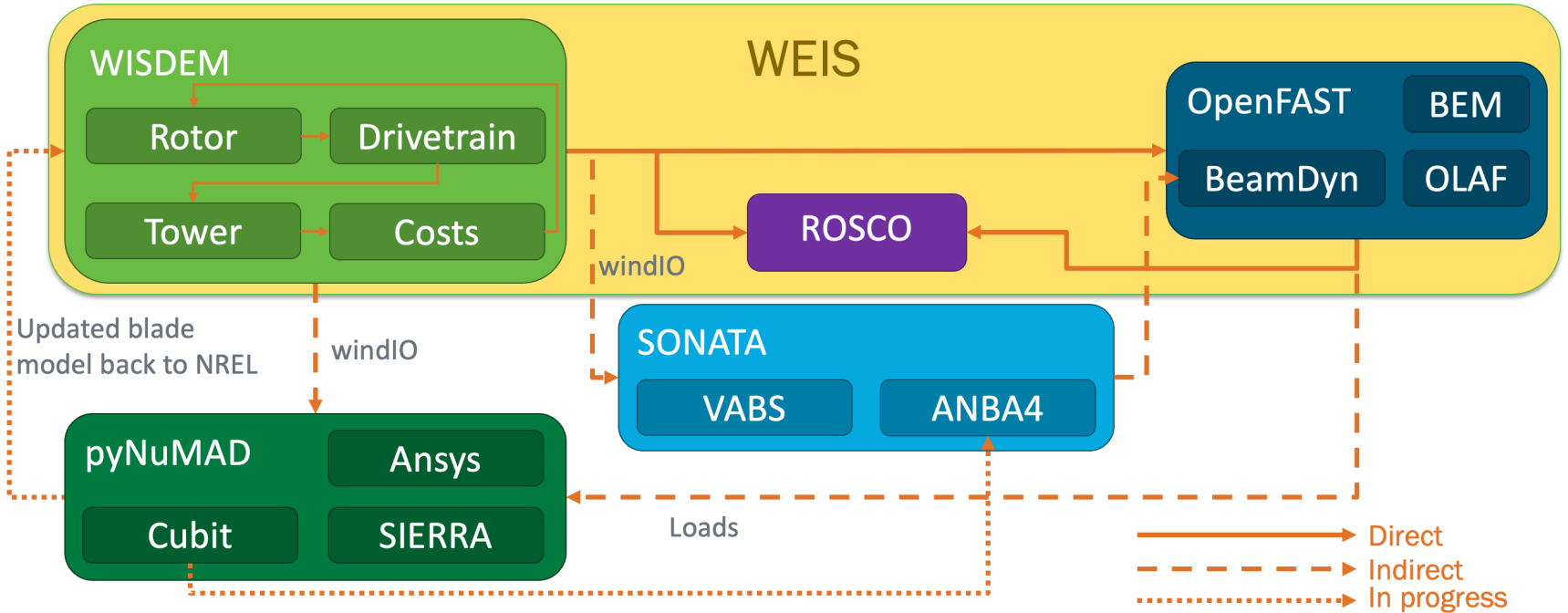


WEIS – Wind Turbine Multi-fidelity Co-Design

Wind Energy with Integrated Servo-Control (WEIS)

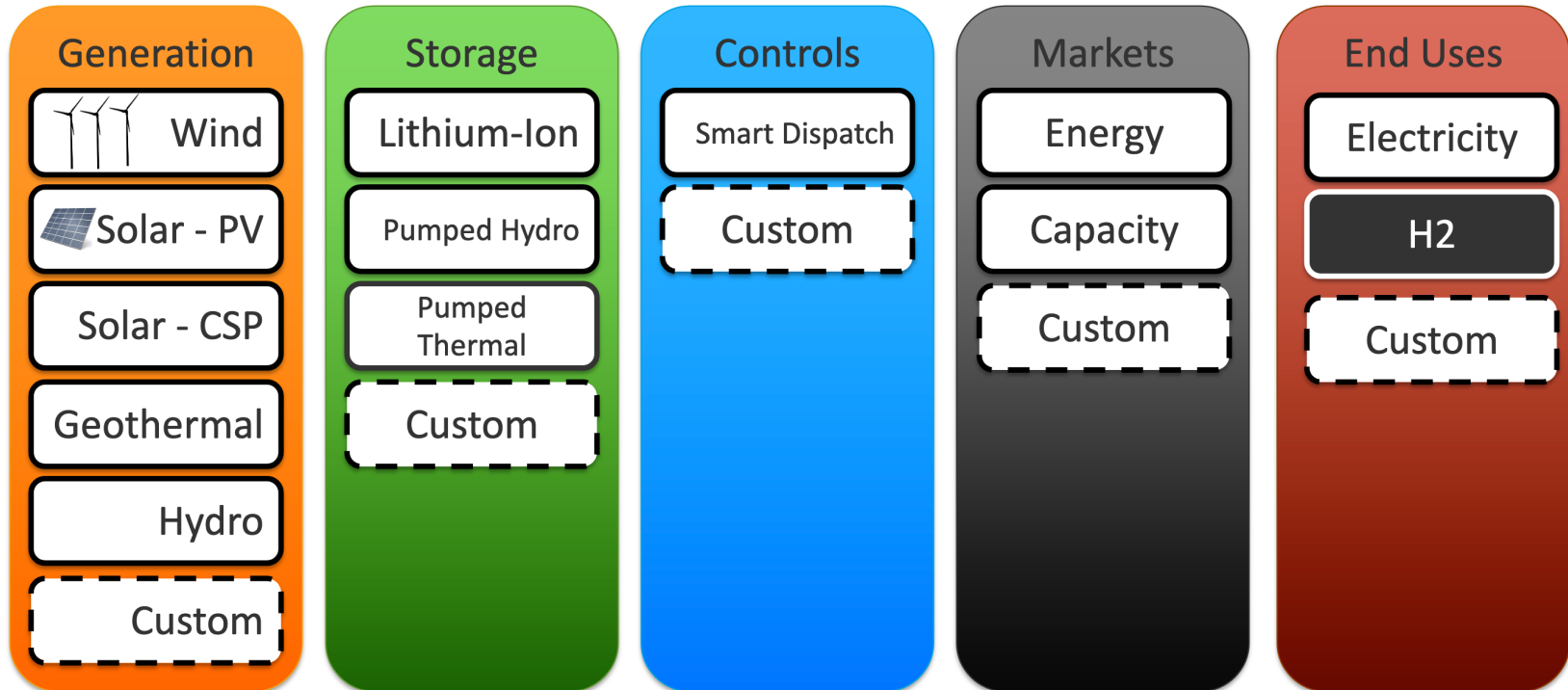


WEIS Interdependencies



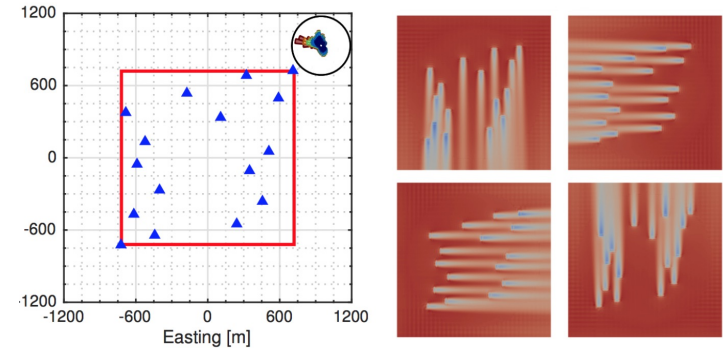
HOPP – Hybrid Optimization & Performance Platform

Optimize co-located, utility-scale hybrid plants down to the component level for different markets

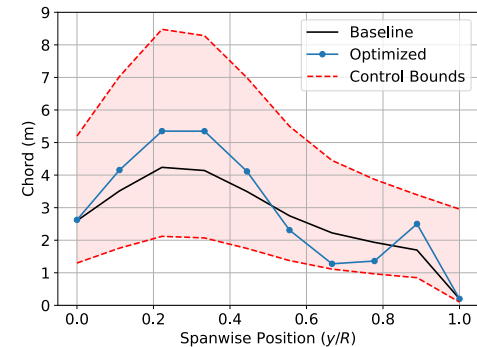


WindSE – Wind Farm Simulation & Optimization

- WindSE is an open-source, Python package for wind plant simulation and optimization
- Supports both **steady and unsteady simulations** modeling turbines using **actuator disks and actuator lines**
- Adjoint gradient calculation enables performing optimizations with many controls
- **Current bottleneck:** how to perform optimizations of unsteady problems simulated with many timesteps and high spatial resolution
- Missed opportunities: unable to perform layout optimizations using higher-fidelity actuator lines with controls at the level of individual turbines



Layout optimization using steady-state solver to maximize power



Chord profile optimization using unsteady solver to maximize lateral wake deflection during yawed operation NREL | 33

AMR-Wind / Nalu-Wind / ERF / OpenTurbine

AMR-Wind

- Incompressible / anelastic fluid equations
- Structured-grid finite volume with MR
- Built on AMReX, a framework for block-structured adaptive mesh refinement

Nalu-Wind

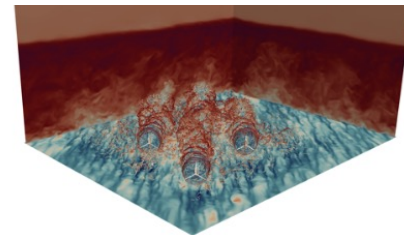
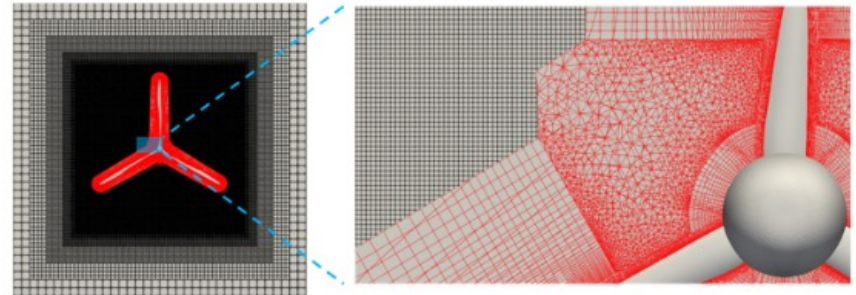
- Fluid-solid interaction
- Unstructured-grid finite volume
- Built on Trilinos

OpenTurbine

- Whole-turbine structural simulation code

ERF

- Compressible fluid equations
- Structured-grid finite volume with MR
- Built on AMReX



Questions?

Portfolio Analysis Tools

<https://nrel.github.io/WETOStack>

The screenshot shows the 'Modeling' section of the WETOStack interface. It features a code cell with Python code for a DataFrame processor. Below the code, there is a table with 11 rows and 7 columns. The table headers are: Index, scope, system_type, system_location, time_domain, io4, and tags. The rows list various software projects like hercules, fastfarm, weis, openfast, etc., with their respective attributes.

Index	scope	system_type	system_location	time_domain	io4	tags	
1	hercules	['turbine', '...	['hawt']	['land', 'fixed_offshor...	dynamic	true	['arn-wind', 'large eddy simulation'...
2	fastfarm	['farm', 'tur...	['hawt']	['land', 'fixed_offshor...	dynamic	true	['dynamic wake meandering', 'pola...
3	weis	['turbine']	['hawt']	['land', 'fixed_offshor...	dynamic	true	['mid-fidelity engineering models', ...
4	openfast	['turbine', '...	['hawt', 'vawt']	['land', 'fixed_offshor...	dynamic	true	['modularization framework', 'nonli...
5	dw_tap	['turbine', '...	['any']	['land']	dynamic	false	['distributed wind', 'obstacle model...
6	openoa	['turbine', '...	['hawt']	['land', 'fixed_offshor...	dynamic	false	['operational analysis', 'gap analysi...
7	windse	['turbine', '...	['hawt']	['land', 'fixed_offshor...	['steady', 'dynamic']	false	['steady state Reynolds-averaged ...
8	wombat	['turbine', '...	['hawt']	['any']	steady	false	['operations and maintenance', 'dis...
9	dwind	['turbine', '...	['any']	['land']	dynamic	false	['distributed wind', 'distributed futu...
10	flasc	['turbine', '...	['hawt', 'any']	['land', 'fixed_offshor...	steady	false	['steady state analytical engineerin...
11	floriv	['turbine', '...	['hawt']	['land', 'fixed_offshor...	steady	false	['Petascale state', 'analytical wake mo...

The screenshot shows the 'Dependencies' section of the WETOStack interface. It includes a text description of the network and a connectivity diagram. The diagram, titled 'WETO Software Portfolio Connectivity', shows a network of software projects. Solid lines represent direct connections, and dashed lines represent indirect connections. The legend indicates that solid lines are for 'Direct' and dashed lines are for 'Indirect'.

By collecting data on the projects within the WETO portfolio that use other tools within the portfolio, we can get a sense for the software projects that are at the "core" of the capabilities.

This network is divided into two types of connectivity:

1. **Direct connections** are software that are connected within the code, so they may communicate directly through APIs, share memory, and be distributed as a bundle.
2. **Indirect connections** are software that require the outputs of other tools in order to construct their inputs. These are connected through workflows rather than code.

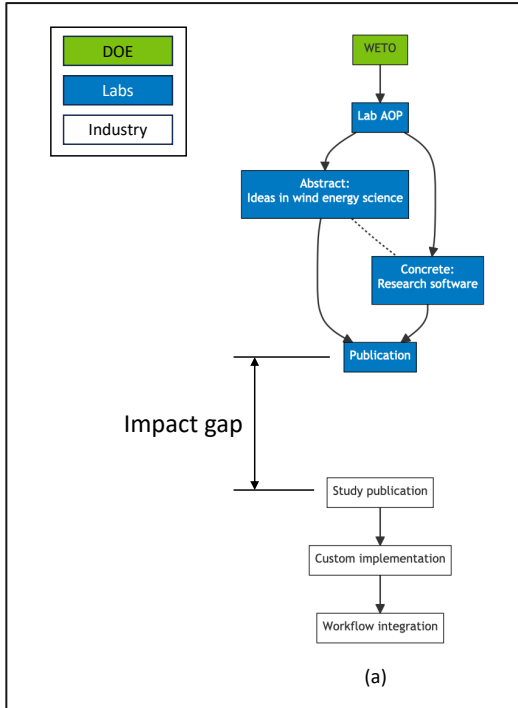
WETO Software Portfolio Connectivity

..... Direct
----- Indirect

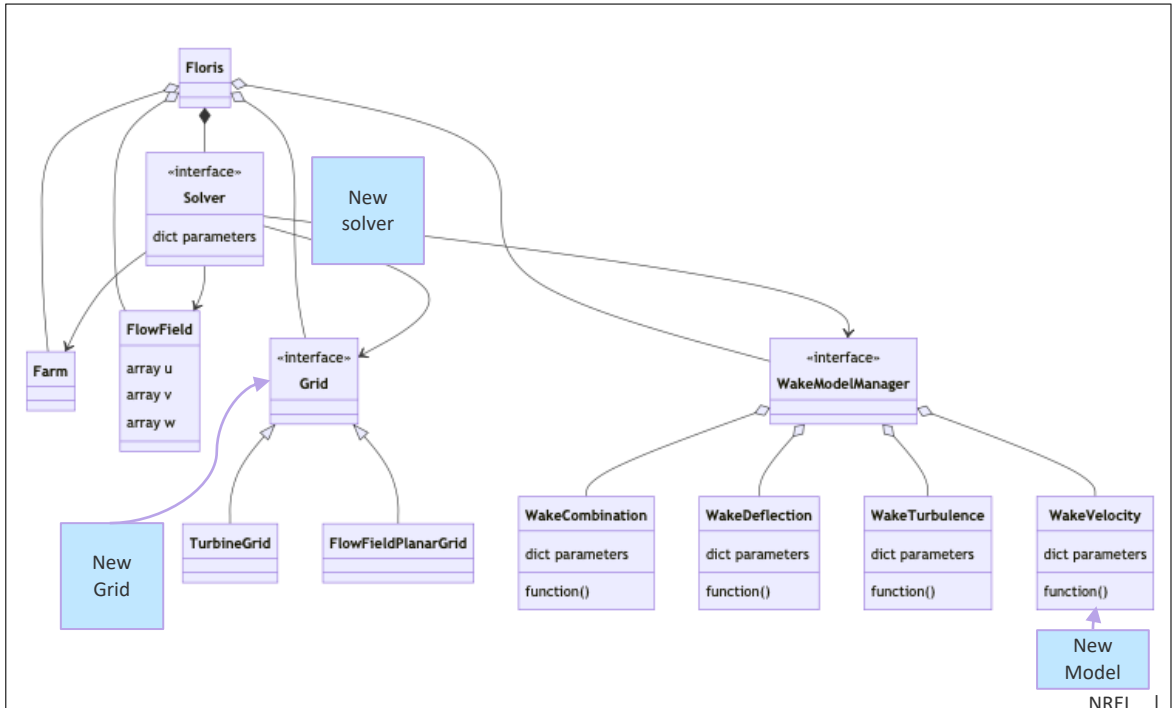
WETO Software Best Practices

https://nrel.github.io/WETOStack/best_practices.html

Usability - Practitioner



Usability - Developer



Holistic Modeling Upcoming

- User survey in early 2024
- **User-focused workshop in May/June 2024** ← Rafael.Mudafort@nrel.gov
- Ecosystem streamlining
 - Improved dependency management
 - Consolidate or decouple, as needed
- Software quality grading and review system
- Refine and expand portfolio analyses

- All activities will be documented on the WETOSStack repository!
<https://nrel.github.io/WETOSStack>

Q&A / Open Discussion

Rafael.Mudafort@nrel.gov
github.com/NREL/WETOStack

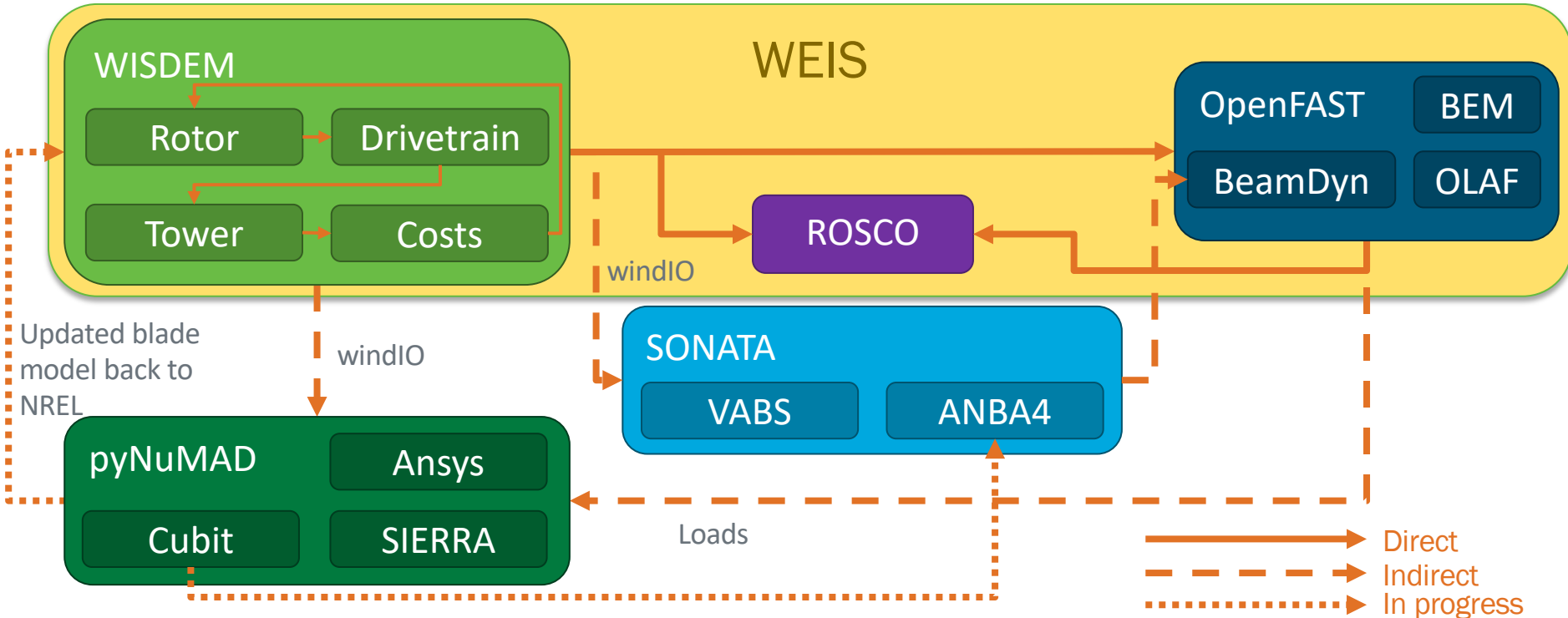
- Where do you see the strengths and gaps in the WETO Software Portfolio?
- Regarding WETO software, what is appealing and what is currently lacking?



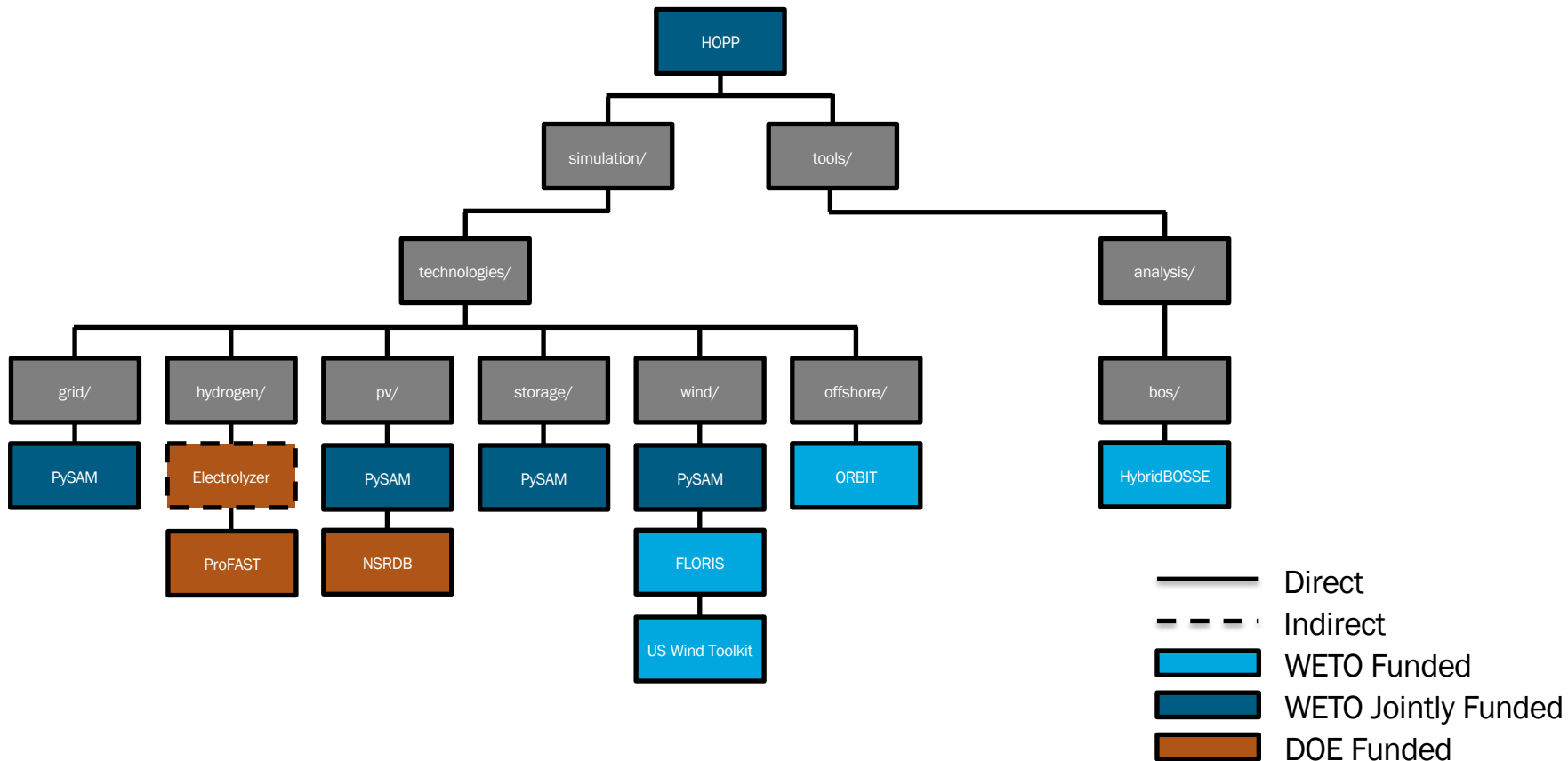
Design and Optimization: Big Adaptive Rotor

The Toolchain used in the Design Studies of the BAR Project

Sequential design process at increasing fidelity, using open-source tools

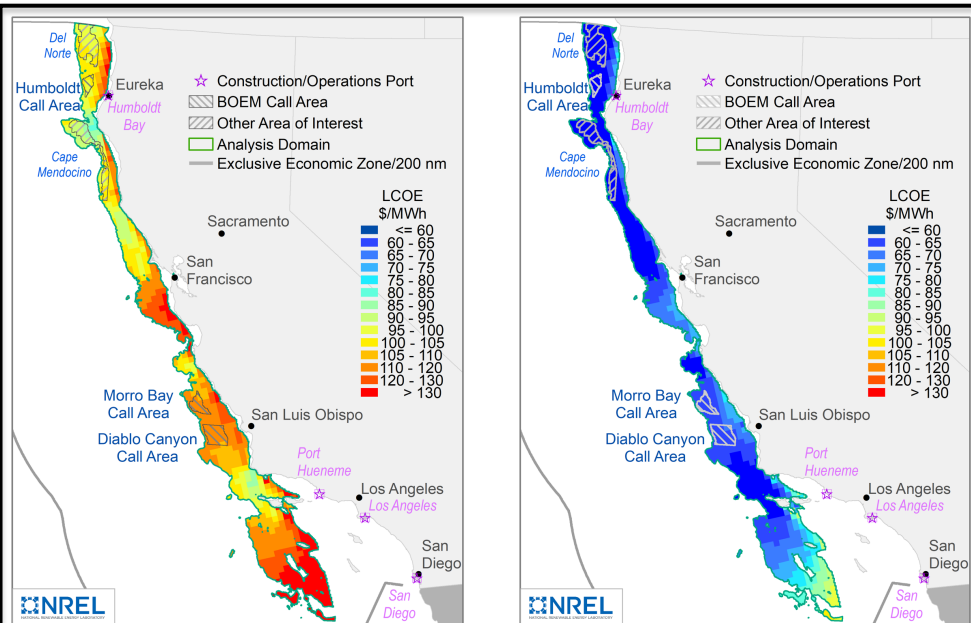


HOPP – Hybrid Optimization Performance Platform

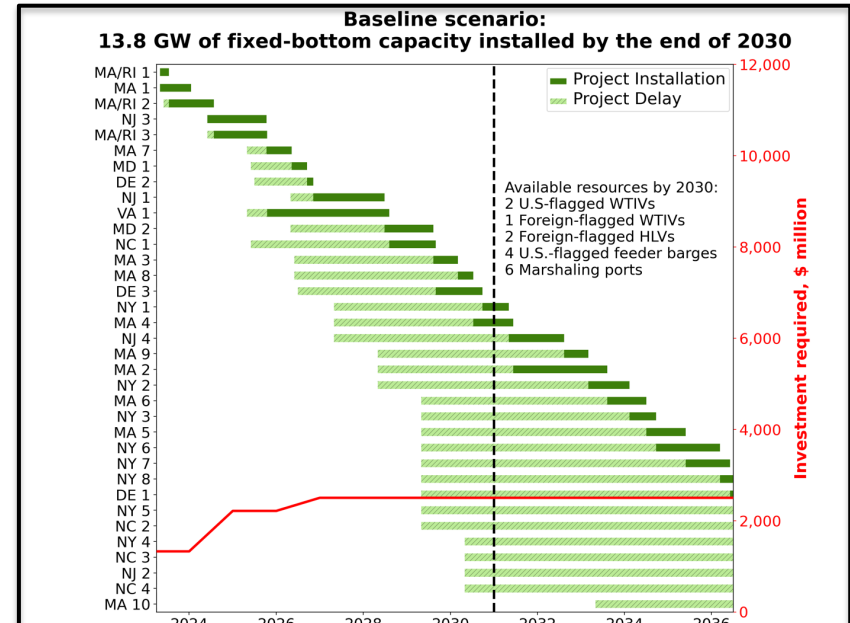


Techno-Economic Analysis

NREL develops open-source techno-economic modeling tools to evaluate high-impact cost, technology, logistics, and supply chain questions for offshore wind energy



Levelized cost of energy for offshore wind in California for a commercial operation date in 2019 (left) and 2032 (right). From [Beiter, et al, 2020](#)



Evaluation of deployment bottlenecks due to port and vessel supply limitations. From [Shields et al. \(2023\)](#)

Primary research questions and relevant tools

- How do technology and process innovations impact the costs, logistics, risks, and performance of individual projects?

Project scale cost and logistics

- LandBOSSE
- ORBIT
- WOMBAT
- HybridBOSSE

Future cost projections

- FORCE

Regional/national scale

- NRWAL
- CORAL

Primary research questions and relevant tools

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- How could costs evolve over time given technology choices and broader industry development?

Project scale cost and logistics

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Primary research questions and relevant tools

- How do technology and process innovations impact the costs, logistics, risks, and performance of individual projects?
- How could costs evolve over time given technology choices and broader industry development?
- What drives costs and deployment bottlenecks throughout the broader industry?

Project scale cost and logistics

- LandBOSSE
- ORBIT
- WOMBAT
- HybridBOSSE

Future cost projections

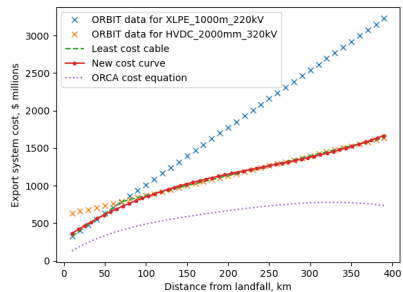
- FORCE

Regional/national scale

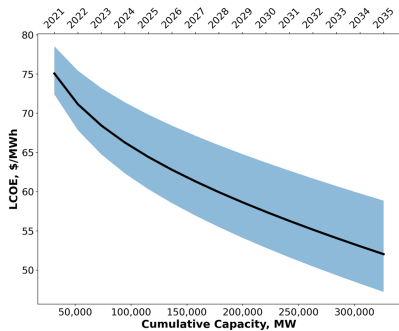
- NRWAL
- CORAL

Model integration with broader NREL tool sets

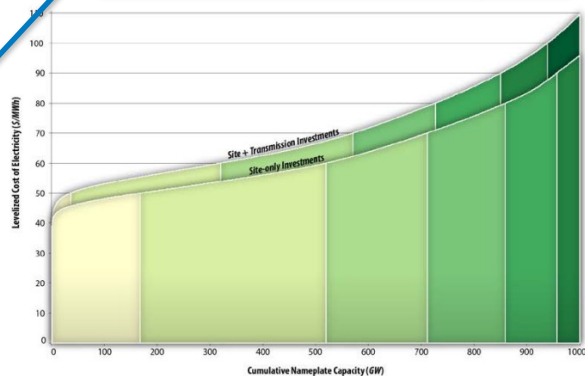
Design space of project costs



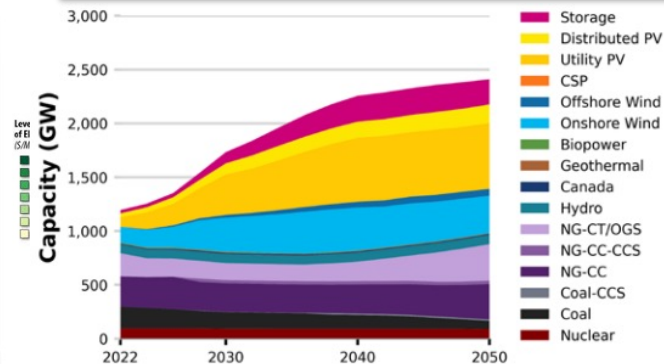
Cost projections



Supply curves (reV)



Capacity expansion (ReEDS)



WETO models
All technology