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Sensitivity Analysis of Offshore Wind Cost of Energy

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Abstract

No matter the source, offshore wind energy plant cost estimates are significantly higher than for land-based projects. For instance, an NREL review on the 2010 cost of wind energy found baseline cost estimates for land-based wind energy systems to be 71 dollars per megawatt-hour ($/MWh), versus 225 $/MWh for offshore systems.[1] There are many ways that innovation can be used to reduce the high costs of offshore wind energy. However, the use of such innovation can impact the cost of energy in counterintuitive ways because of the highly coupled nature of the system.

In 2011–2012, the National Renewable Energy Laboratory (NREL) began developing a wind energy systems engineering software tool to support offshore wind energy system analysis.[2] The tool combines engineering and cost models to represent an entire offshore wind energy plant and to perform system cost sensitivity analysis and optimization. Initial results were collected by applying the tool to conduct a sensitivity analysis on a baseline offshore wind energy system using 5-MW and 6-MW NREL reference turbines. Results included information on rotor diameter, hub height, power rating, and maximum allowable tip speeds.

Introduction

Wind energy is a complex system that involves input from various stakeholders and designers. Figures 1 illustrates a systems engineering perspective of the wind energy system.

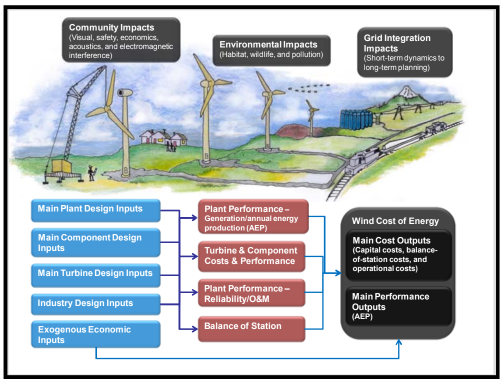


Illustration by Rick Hinrichs, PWT Communications

Figure 1: Wind energy system design depends on many variables for components, turbines, and plants, and the related design decisions all affect ultimate performance, cost, and the community.

The industry has recognized the highly coupled nature of wind energy systems over the last several decades. Attempts have been made to better integrate overall wind plant design, starting from the wind climate and field down to the logistics of plant development and operation. But, a design change in one aspect of the system can impact the overall system performance and cost in significant ways. Despite the highly complex and coupled nature of wind energy systems, the design and study of wind plants is often a relatively decoupled process. Insight could be gleaned from a truly integrated analysis of wind turbine and plant performance. For this reason, NREL created a flexible software tool that uses models of various levels of detail and accuracy to represent a full wind plant and to enable the analysis, design, and optimization of a full wind plant system.

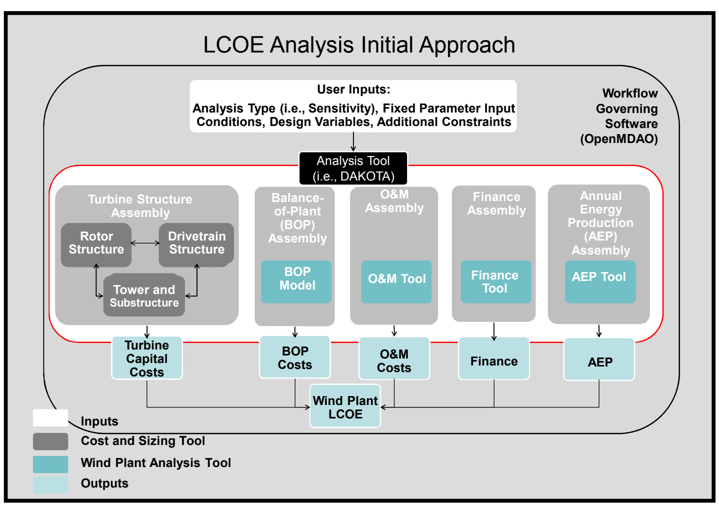
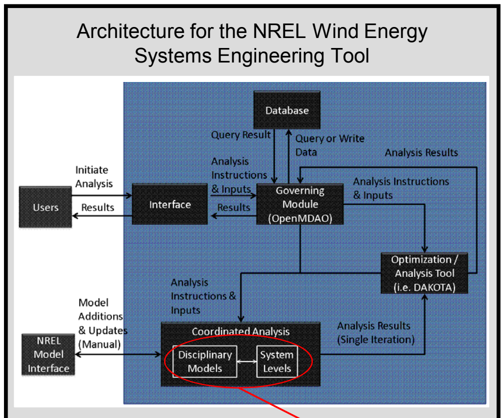


Illustration by Katherine Dykes, NREL

Figure 3: The initial tool development is based on the integration of wind plant cost models and engineering-based wind turbine component cost and sizing models, using a system LCOE analysis framework. This allows for study of how a design parameter change in one part of the system causes changes throughout the system to impact LCOE. For example, changes in the rotor diameter affect not only energy output from a single turbine, but overall rotor weight, thereby increasing loads from the rotor that feed through the nacelle and into the tower. The increased rotor loads can then affect the downstream component size, performance, and cost. This affects operation, maintenance, and replacement costs. The size of turbine components can also affect the plant logistics and layout. The decisions concerning logistics and plant layout will impact both balance-of-plant (BOP) and O&M costs. Thus, a full system analysis is developed through the proper integration of the models as shown in Figure 3—though the detail of each individual model may change for a given analysis.

NREL Wind Energy Systems Engineering Tool

Shown below in Figure 2, the NREL wind energy systems engineering tool combines engineering and cost analysis models at all levels of the turbine—from component to plant—to perform system-level analyses such as uncertainty quantification and optimization. The initial models are relatively simple. Ultimately, multiple levels of detail and accuracy will be incorporated into the tool to support a variety of analyses. In addition, the tool integrates with NREL's and other wind energy models into an architectural framework for analysis that is based on the National Aeronautics and Space Administration's (NASA's) Open Multi-Disciplinary Analysis and Optimization (OpenMDAO) software. In addition, the tool incorporates the use of Sandia National Laboratories' Design Analysis Kit for Optimization and Terascale Applications (DAKOTA) to perform advanced analysis ranging from optimization to uncertainty quantification.



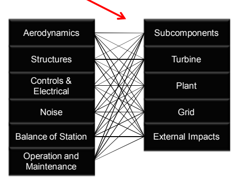


Figure 2: The diagram shows the composition of the NREL wind energy systems engineering tool as described above. It involves phased integration of engineering and cost models for wind energy within a governing architecture based on NASA's OpenMDAO and Sandia's DAKOTA software.

Illustration by Katherine Dykes, NREL

In each phase of the tool development, a critical objective is to have a full system representation for levelized cost of energy (LCOE) analysis. A key advantage of the tool is its ability to meet a wide range of user needs by providing a diverse selection of models. Depending on the analysis objectives, a variety of model configurations can be used, from a full-blown, complex optimization of a wind turbine and plant to wind plant financial analysis for a particular site. The key attribute of the tool is that specific models for different parts of the system can be selected based on the particular analysis to reduce computational complexity. As illustrated in Figure 3, the tool development entails the use of models for each aspect of a wind plant. Subsequent development will build upon the foundation with increasing levels of model accuracy. Objectives of the analysis in this study include demonstration of the tool for sensitivity analysis on key global design parameters that impact LCOE.

Sensitivity Analysis and Results

In this first year of development, the initial tool and simplified model set were used to investigate the sensitivity of overall wind plant performance and cost for an offshore wind site. Key design parameters studied included rotor diameter, hub height, power rating, and maximum allowable tip speeds. Figure 4 shows the analysis and how information flows from model to model.

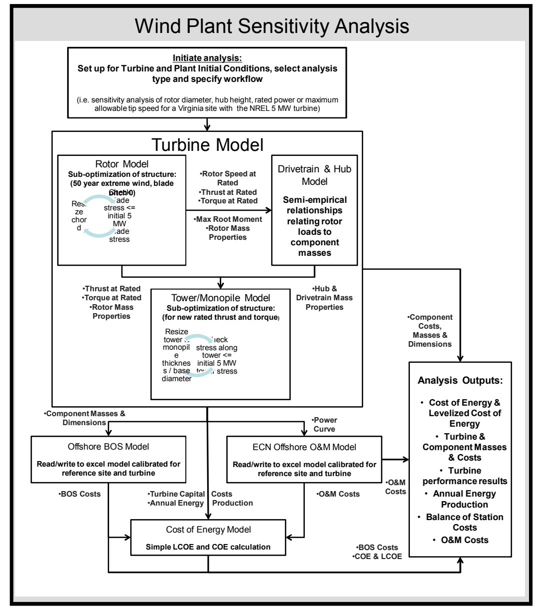


Illustration by Katherine Dykes, NREL

Figure 4: The sensitivity analysis is performed within the tool. The models are integrated together using OpenMDAO and analysis is performed with DAKOTA software.

Table 1 shows the directional impact of each design parameter on cost of energy. Some unexpected results appear that are related to the direction of change for each of the sensitivities, representing roughly a +/- 10% in the overall magnitude of each of the design parameters. The impact of hub height in increasing overall cost of energy reflects increased capital costs that outweigh increases in energy production. Increasing the rotor diameter and decreasing the generator size improves cost of energy, but so does the reverse case (unexpectedly). This result reflects significant dependencies of certain models, such as the balance of plant, on specific design parameters and provides insight into areas of potential model improvement. Similar findings were discovered for the maximum tip speed sensitivity, though impacts on overall cost of energy were small in this case because operational tip speeds at rated power were below the initial maximum.

Table 1: Initial results of analysis. Directional impacts are unexpected and reflect the simplified state of the current simple model set as opposed to actual expected impacts from design changes.

Design Parameter	Direction Change	Cost-of-Energy Impact
Rotor Diameter	Up	Down--
	Down	Down-
Hub Height	Up	Up+
	Down	Down-
Rated Power	Up	Down-
	Down	Down--
Maximum Tip Speed	Up	Up+
	Down	No Change

Conclusions

A systems engineering approach to wind plant analysis on cost and performance was demonstrated. Subsequent work will improve individual model fidelity as well as the overall system modeling capability for a variety of analyses.

References

[1] Tegen, S.; Hand, M.; Maples, B.; Lantz, E.; Schwabe, P.; Smith, A. (2012). *2010 Cost of Wind Energy Review*. NREL/TP-5000-52920.

[2] Dykes, K.; Meadows, R.; Felker, F.; Graf, P.; Hand, M.; Lunacek, M.; Michalakes, J.; Moriarty, P.; Musial, W.; Veers, P. (2011). "Applications of Systems Engineering to the Research, Design, and Development of Wind Energy Systems." 92 pp.; NREL Report No. TP-5000-52616.

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