An Integrated Platform for Wind Plant Operations: From Atmosphere to Electrons to the Grid

Elina Spyrou, Jennifer King, Andrew Kumler, Christopher Bay, Yingchen Zhang, Vahan Gevorgian, and Dave Corbus

FERC Technical Conference regarding Increasing Market and Planning Efficiency and Enhancing Resilience through Improved Software

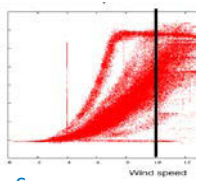
June 25, 2020

Questions: Elina.spyrou@nrel.gov ; Jennifer.King@nrel.gov; David.Corbus@nrel.gov

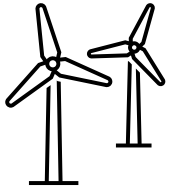
Contents

Background: Wind Plant Operations

Example model



Source: https://www.spp.org/documents/28867/energymeteo_spp_qa.pdf



Bids for energy and ancillary services

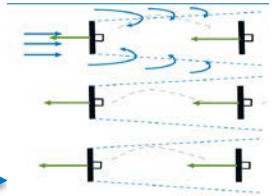
Market

Accounts for congestion

Awards for energy and ancillary services

What can affect delivery?

Weather uncertainty



Wake dynamics in the example model are ignored

Deviation from market award

What is the impact of deviation?

- Balancing market settlements
- Over-/under-generation **penalties**
- **Disqualification** if behavior persists.

Background: Status Quo and Forward-Looking Scenarios

Status quo:

- "Only a handful of wind generators have opted to qualify for the ancillary services provision in ERCOT, and their participation in regulation markets is currently minimal (Matevosjana 2018)" [1].
- "Risk is higher for generators selling day-ahead…the potential of incurring a forced outage and having to buy back energy at real-time prices" [2].

Forward-looking scenarios:

- Prices for ancillary services might increase under high variable renewable energy scenarios [3].

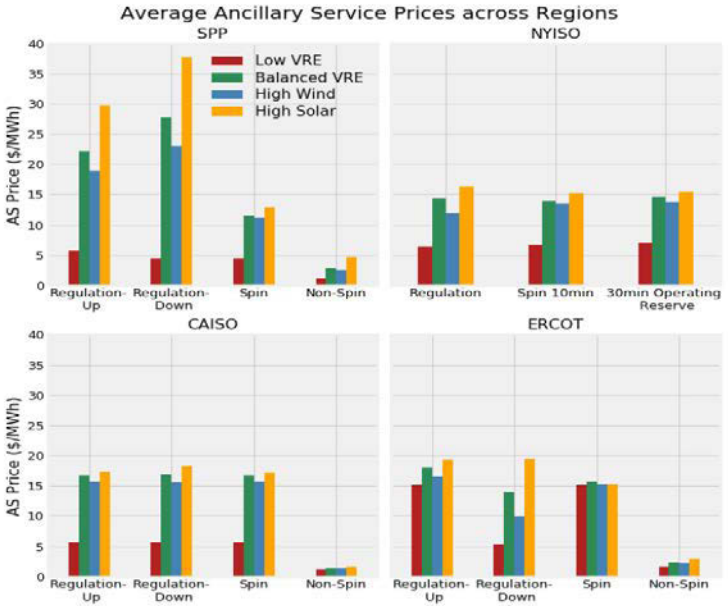


Figure 1. Ancillary service prices under varying renewable penetration scenarios [3]

1. I Chernyakhovskiy, S. Koebrich, V. Gevorgian, and J. M. Cochran, *Grid-Friendly Renewable Energy: Solar and Wind Participation in Automatic Generation Control Systems* (NREL/TP-6A20-73866) (Golden, CO: National Renewable Energy Laboratory, 2019).
2. Potomac Economics, *2018 State of the Market Report for the ERCOT Electricity Markets: Independent Market Monitor for ERCOT* (June 2019).
3. J. Seel, A. D. Mills, and R. H. Wiser, "Impacts of High Variable Renewable Energy Futures on Wholesale Electricity Prices, and on Electric-Sector Decision Making (LBNL-2001163) (Berkeley, CA: Lawrence Berkeley National Laboratory, 2018).

Research Question

A

Can we develop a platform that integrates:

- Forecasting tools to account for weather uncertainty
- With aerodynamic models to account for wake dynamics
- And economic models to account for impact of deviations

B

to advise on **bidding and operation** for a *"price-maker"* wind power plant so that its **value** streams for energy and ancillary services increase?

Design of the A2E2G Integrated Platform

A

The A2E2G will be a holistic Python tool with two modules that can be run in parallel and possibly interact to:

- Advise on market participation
- Control and operate a wind power plant in real time.

Advise on market participation:

Time series:
Wind speed
Wind direction
Turbulence intensity

Time series:
Forecasted power production and imbalance prices

Output: Advisory bidding decisions

Real-time control and operation:

Time series:
Wind speed
Wind direction
Turbulence intensity

Time series:
Power limit
Yaw set points

Output: Control signal

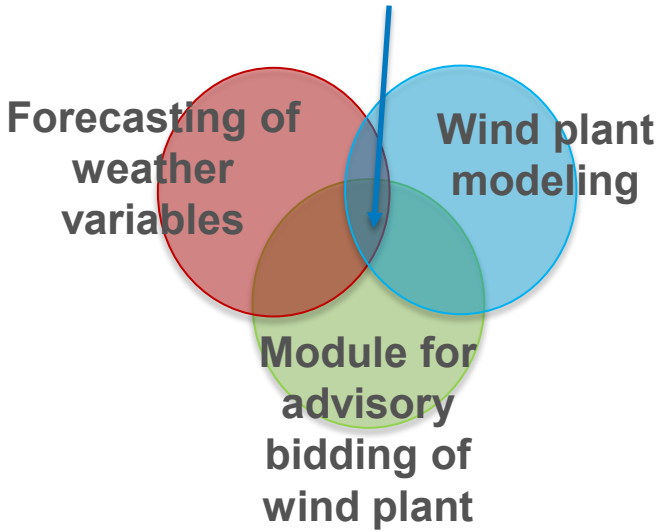
4. Jennifer King, Paul Fleming, Luis Martínez-Tossas, Rafael Mudafort, Eric Simley, and Mike Lawson, "FLORIS (FLOw Redirection and Induction in Steady State): A Brief Tutorial Christopher Bay," presented at the 5th Wind Energy Systems Engineering Workshop, Pamplona, Spain, October 2–4, 2019 (NREL/PR-5000-75661).

A2E2G Integrated Platform: Novel Features

A

Probabilistic forecasts

A2E2G integrated platform:



Modeling of wake dynamics to:

- Forecast probability distribution functions of wind power dynamically
- Capture the value of wake steering for real-time controls.

Bid curves that consider:

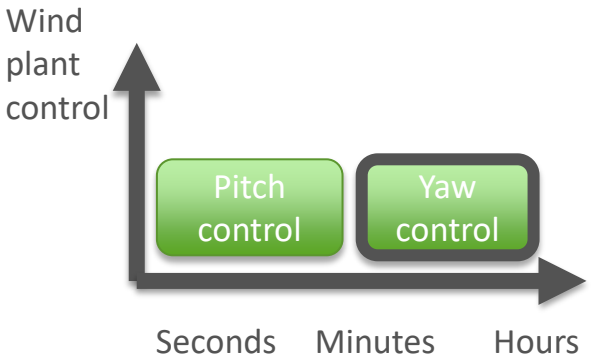
- Probabilistic forecasts for wind power
- Expected imbalance costs
- Compliance performance targets for ancillary services.

A2E2G Integrated Platform: Forecasting and Wake Steering

A

- Current focus: 1) Regulation [5]–[7] 2)Day-ahead forecasting

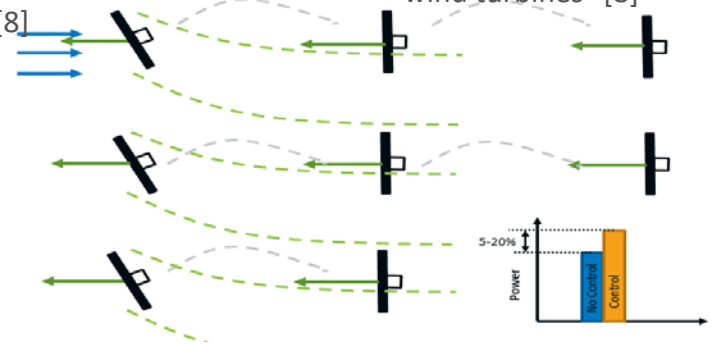
Note: We plan to expand to other horizons and products.



Wake steering: Explanation

"Intentionally misaligning turbines' nacelle positions relative to the wind direction" [8]

"steering their wakes away from downstream wind turbines" [8]



"the total power produced by the wind farm can be increased as a result of the higher wind speeds experienced by downstream turbines" [8]

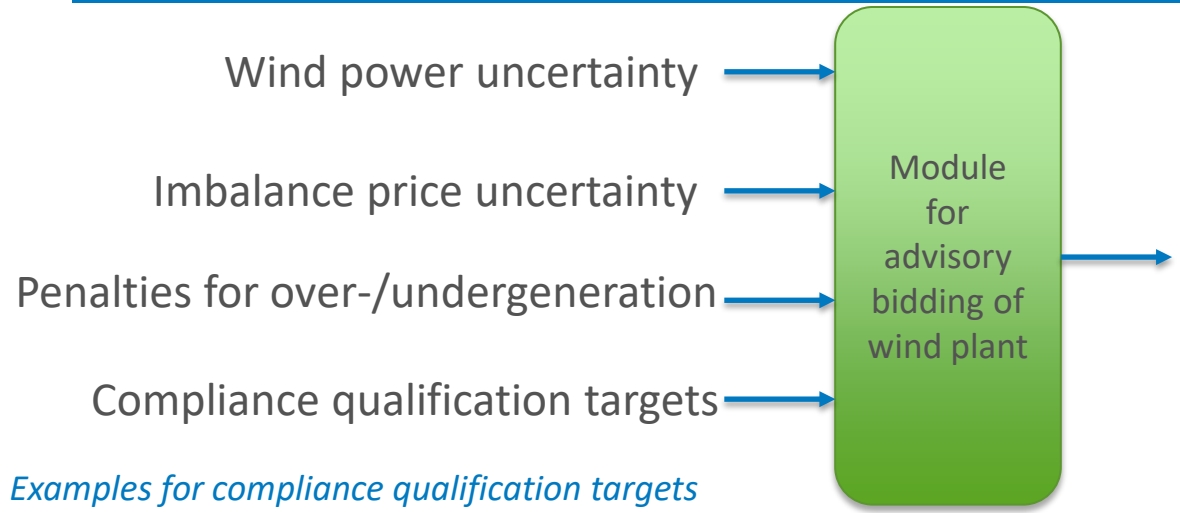
5. E. Rebello, D. Watson, and M. Rodgers, "Ancillary Services from Wind Turbines: AGC from a Single Type 4 Turbine," *Wind Energy Science Discussions* (2019): 1–17, https://doi.org/10.5194/wes-2019-26.

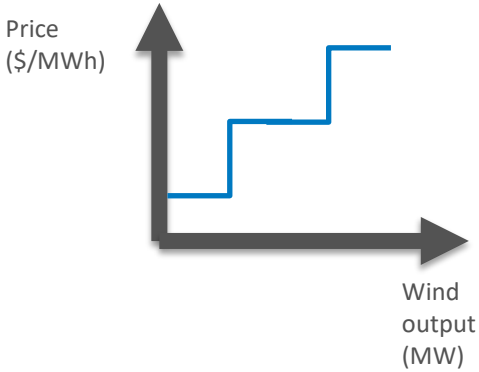
6. E. Rebello, D. Watson, and M. Rodgers, "Performance Analysis of a 10-MW Wind Farm in Providing Secondary Frequency Regulation: Experimental Aspects," *IEEE Transactions on Power Systems* 34, no. 4 (2019): 3090–3097, https://doi.org/10.1109/TPWRS.2019.2891962.

7. C. R. Shapiro, J. Meyers, C. Meneveau, and D. F. Gayme, "Wind Farms Providing Secondary Frequency Regulation: Evaluating the Performance of Model-Based Receding Horizon Control," *Journal of Physics: Conference Series* 753, no. 5 (2016): 052012.

8. E. Simley, P. Fleming, and J. King, "Design and analysis of a wake steering controller with wind direction variability," *Wind Energ. Sci.*, no.5, 2020: 451–468.

Bidding Module: Design





Examples for compliance qualification targets

Source: [9]

(b) An IRR or IRR Group must have a GREDP less than the greater of X% or Y MW for 85% of the five-minute clock intervals in the month during which the Resource or a member IRR of an IRR Group was carrying an Ancillary Service Resource Responsibility.

Source: [10]

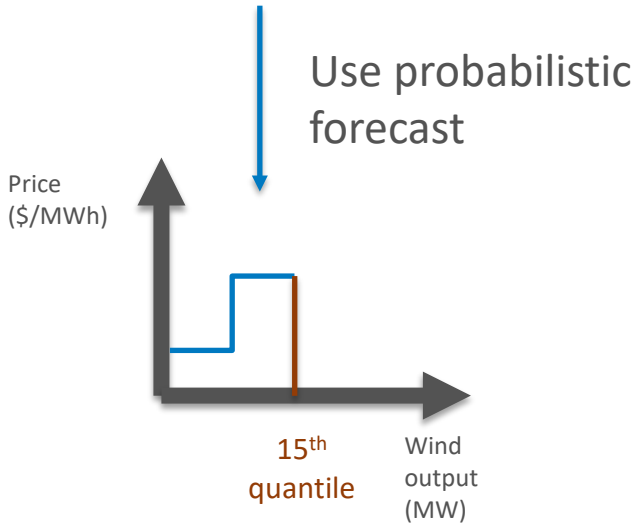
When the historical performance score falls below 40 percent by signal type, PJM will notify the resource owner and the resource will no longer be eligible to offer into the regulation market for the applicable signal type.

9. ERCOT, Nodal Protocols, March 1, 2019.
10. PJM, *PJM Manual 12: Balancing Operations—Revision 40* (Norristown, PA, March 26, 2020).

Bidding Module: Examples

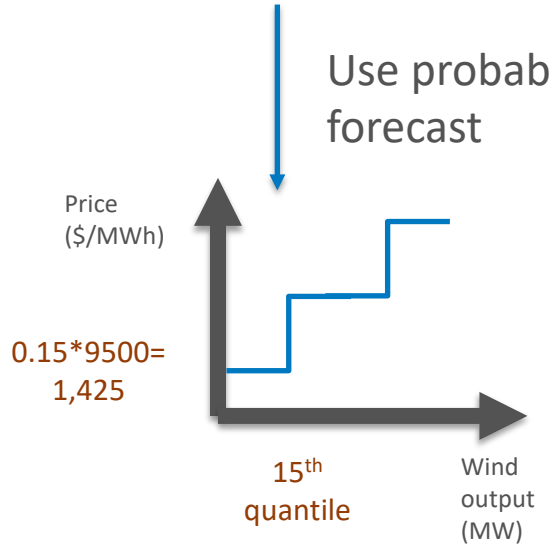
Example 1: Compliance qualification target

A resource disqualifies from providing regulation when they deviate outside the tolerance window more than 15% of the time.



Example 2: Imbalance price expectation [11]

Assume that our **imbalance price modeling** suggests that the imbalance price will be $9,500/MWh.



11. C.J. Dent, J.W. Bialek, and B.F.Hobbs, "Opportunity cost bidding by wind generators in forward markets: Analytical results," *IEEE Transactions on Power Systems*, no. *26*(3), (2011): 1600-1608

Research Question

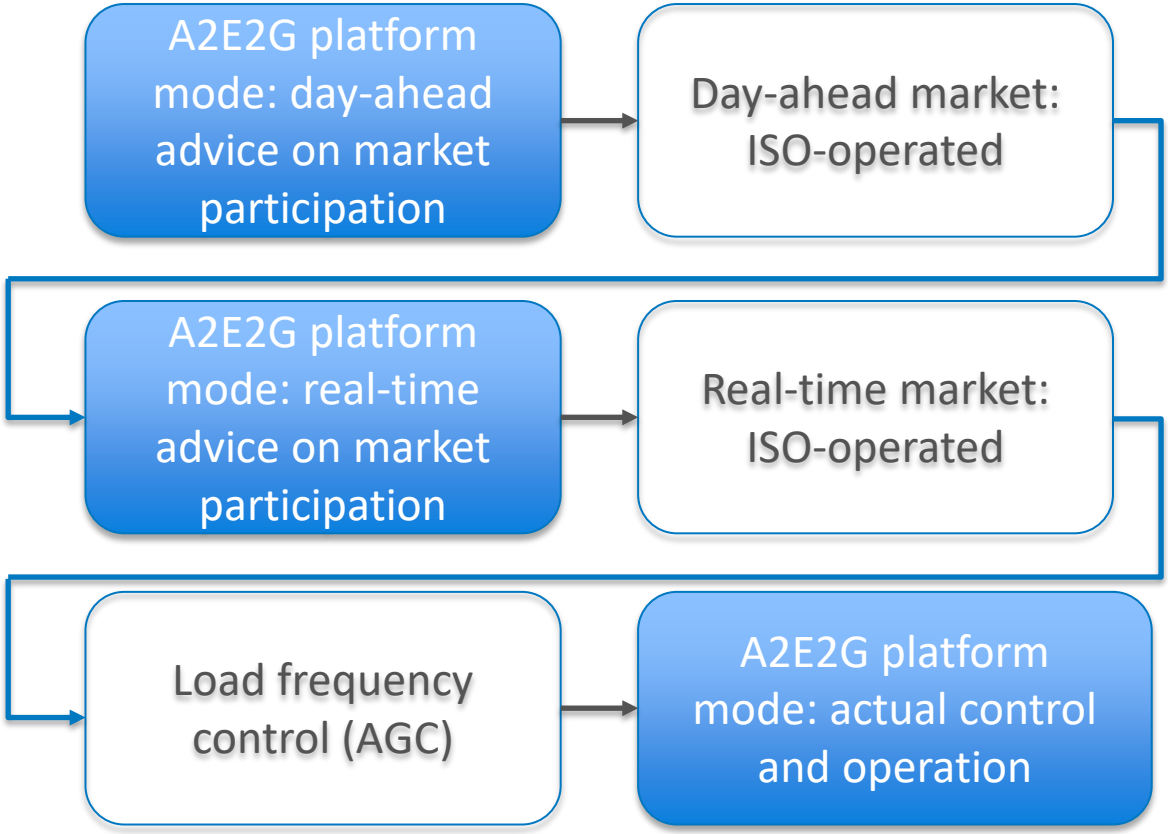
A Can we develop a platform that integrates:

- Forecasting tools to account for weather uncertainty
- With aerodynamic models to account for wake dynamics
- And economic models to account for impact of deviations

B to advise on **bidding and operation** for a wind power plant so that its **value** streams for energy and ancillary services increase?

B

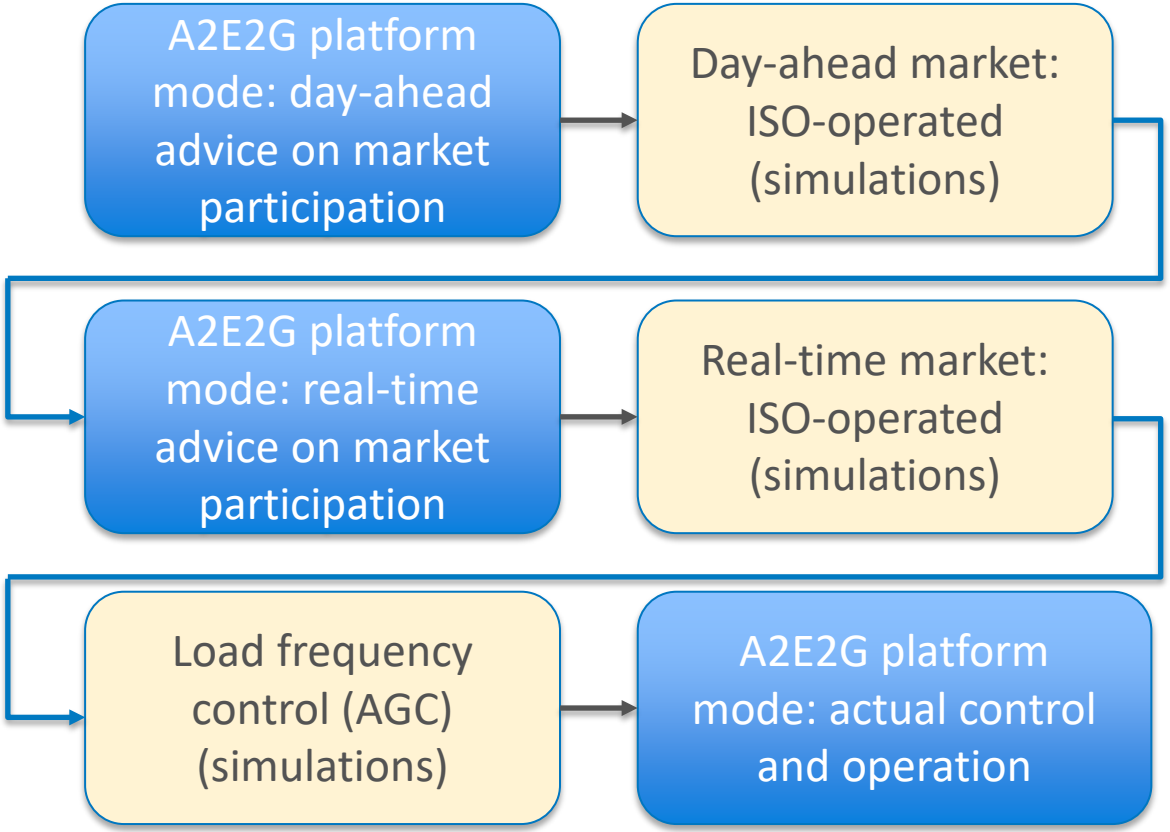
Performance of the A2E2G Integrated Platform: Use Case



B

Performance of the A2E2G Integrated Platform: Testing

We are conducting simulations to demonstrate the platform and its capabilities.



B Simulations for Testing A2E2G Integrated Platform

Simulations of day-ahead and real-time market and load frequency control

This presentation: Price-taker

Desktop analysis based on historical prices and regulation deployment from ERCOT

Starting Fall 2020: "Price-maker"

Market simulations that endogenously consider updated wind bids

Demonstration of capability by estimating frequency and magnitude of deviations from independent system operator (ISO) signal

Demonstration of value through estimates of short-term revenues from market participation

Note: highly depends on market design

B

Example for Demonstration of Capability

Facilitation of market participation

Real-time control and operation

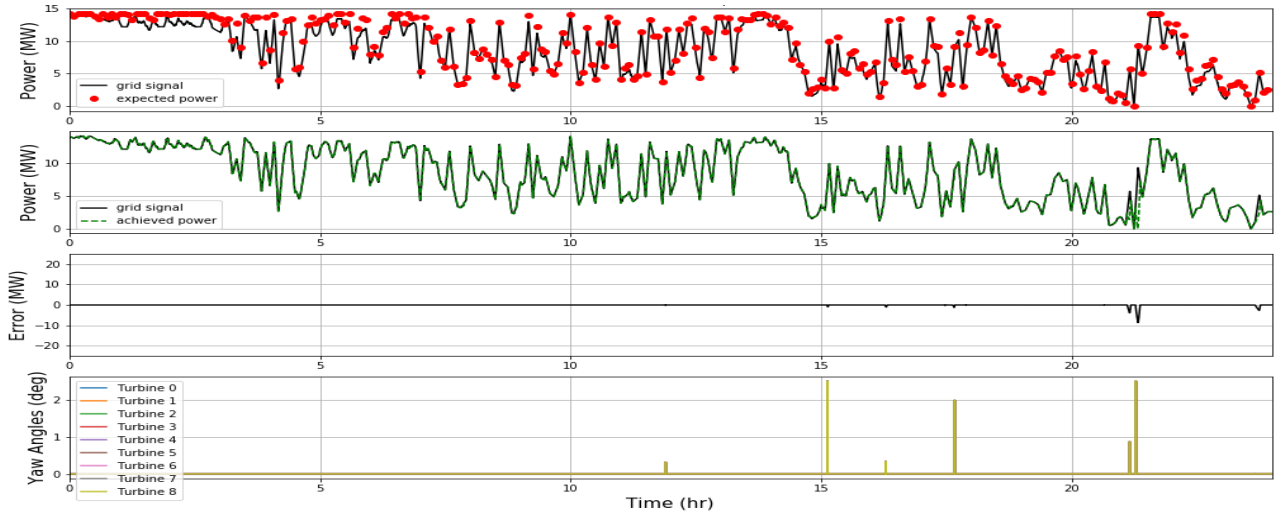
Forecasting of weather variables → FLORIS: Turbine & wake dynamics → Module for advisory bidding of wind plant → Energy and regulation awards → Load frequency control → Most recent forecast and actuals → FLORIS: **Wake steering** → Wind turbine controller

Figures and statistics on performance: example with perfect foresight for a 3 by 3 wind farm with GE turbines at 1.5 MW

LFC sends signals that are within the wind plant's capability

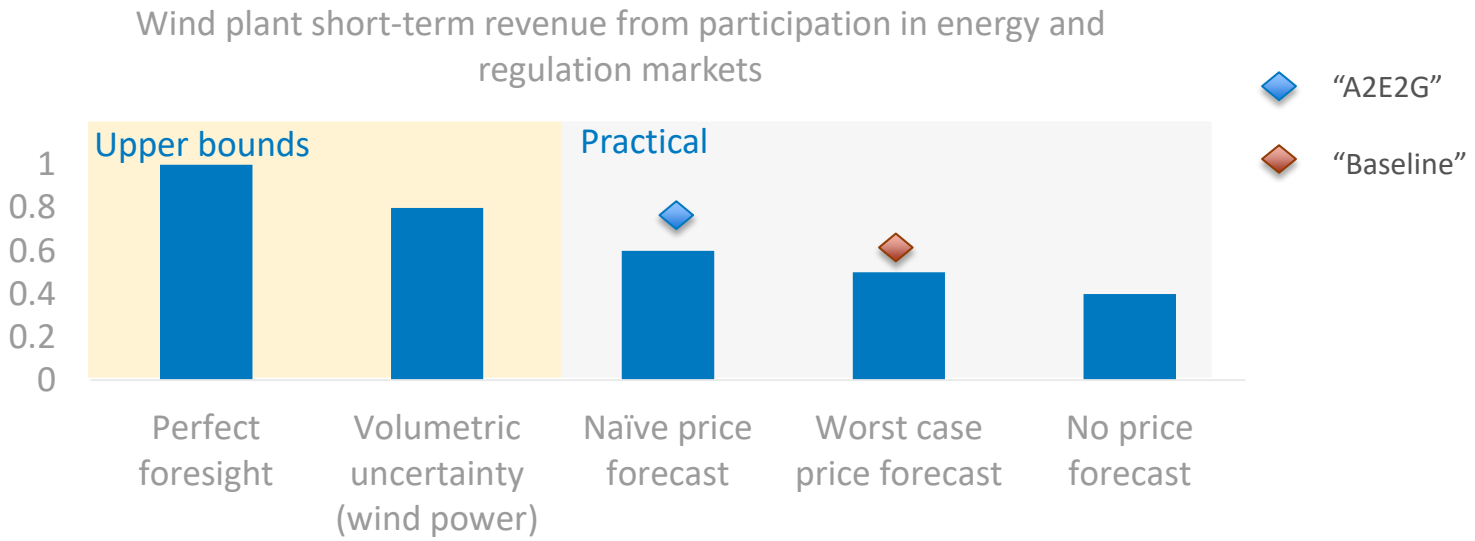
Wind plant can follow the grid signal **almost perfectly**

FLORIS output (power and yaw) == input for turbine controller



B Example for Demonstration of Value: Design (1/4)

Hypothetical wind plant with capacity at 1/1000 system-wide ERCOT



Day-ahead wind power forecast	Actual 5-minute data	**Day-ahead forecast (ERCOT)**	Day-ahead forecast	Day-ahead forecast	Day-ahead forecast
Forecast for imbalance prices	Day-of real-time prices	Day-of real-time prices	**Empirical probability distribution function for same hour in 2019—worst case**	**Price cap ($9,500/MWh)**	**Price taker at $0/MWh in day-ahead**

Note: Same real-time prices used for evaluation

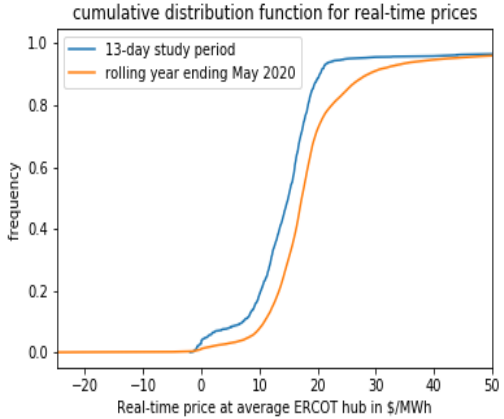
B

Example for Demonstration of Value: Limitations (2/4)

Revenue streams considered: (1) day-ahead energy and regulation, (2) real-time energy, (3) metered/deployment, (4) over-/undergeneration penalty

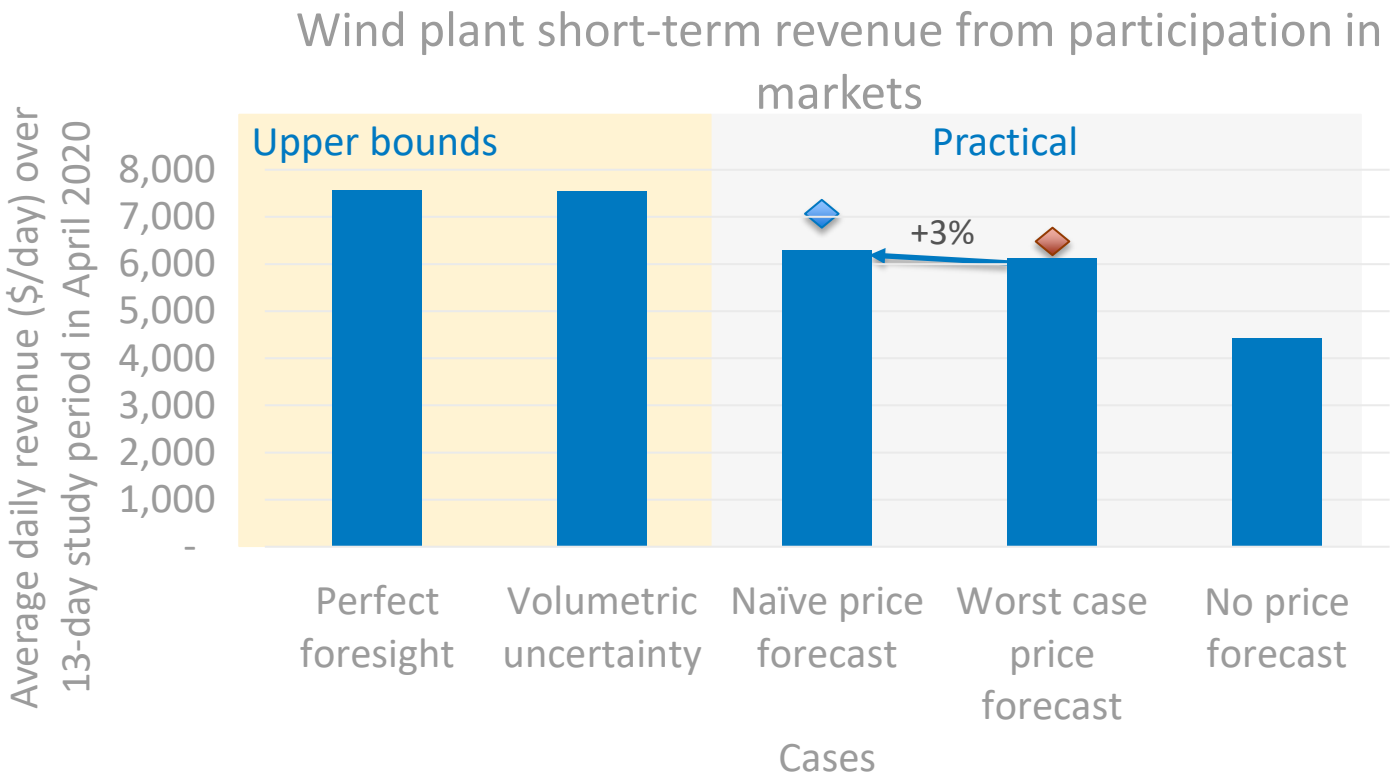
13-day study period because of data availability (We are working to extend it.)

One example for limitation by short study period



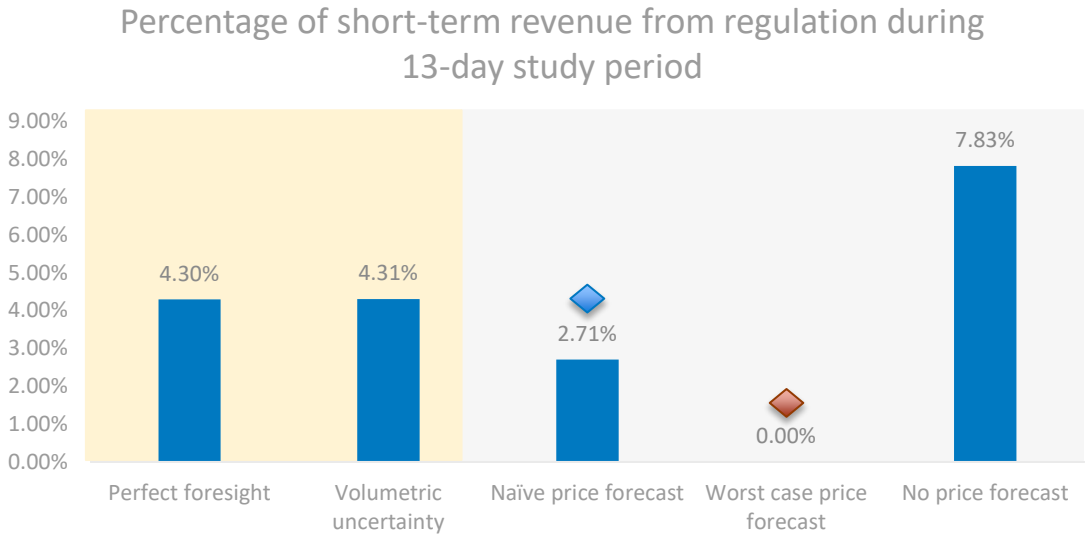
The 13-study period does not capture the tails, e.g., 3.4% of intervals have price >$50/MWh in study period vs. 4% in rolling year.

Example for Demonstration of Value: Discussion (3/4)



- Case to be facilitated by A2E2G platform—during limited study period:
  - **+3%** short-term revenue
  - **Participation in energy and regulation markets.**
- The "worst-case price forecast" results in **no participation in day-ahead.**

Example for Demonstration of Value: Discussion (4/4)



During the limited study period, we observe how the A2E2G platform could facilitate participation in regulation products and capture some value for the wind plant from that participation (assuming it is valuable for the system).

Note: During the 13-day study period under the naïve price forecast case, regulation-up was provided only 1 hour in the day-ahead market.

Ongoing and Future Research

- The A2E2G platform could increase **value** streams for wind plants and/or lead to system benefits by accurately estimating their **capability** of providing energy and other products.
- The focus of our ongoing and future research is:
  - Testing with realistic configurations, e.g., Biglow Canyon Wind Farm in Oregon
  - Expanding A2E2G capabilities to:
    - Include improved probabilistic forecast that accounts for wake steering and estimations of price uncertainty that consider market interactions
    - Consider hybrid systems including solar and storage.
  - System-wide analysis to study:
    - **Forward-looking scenarios** with higher renewable penetrations and broad participation of renewables in ancillary services
    - System benefits from the use of A2E2G informed strategies.

Q&A

www.nrel.gov

NREL/PR-5D00-77097

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 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.