# Controlling wind farms to enable market participation

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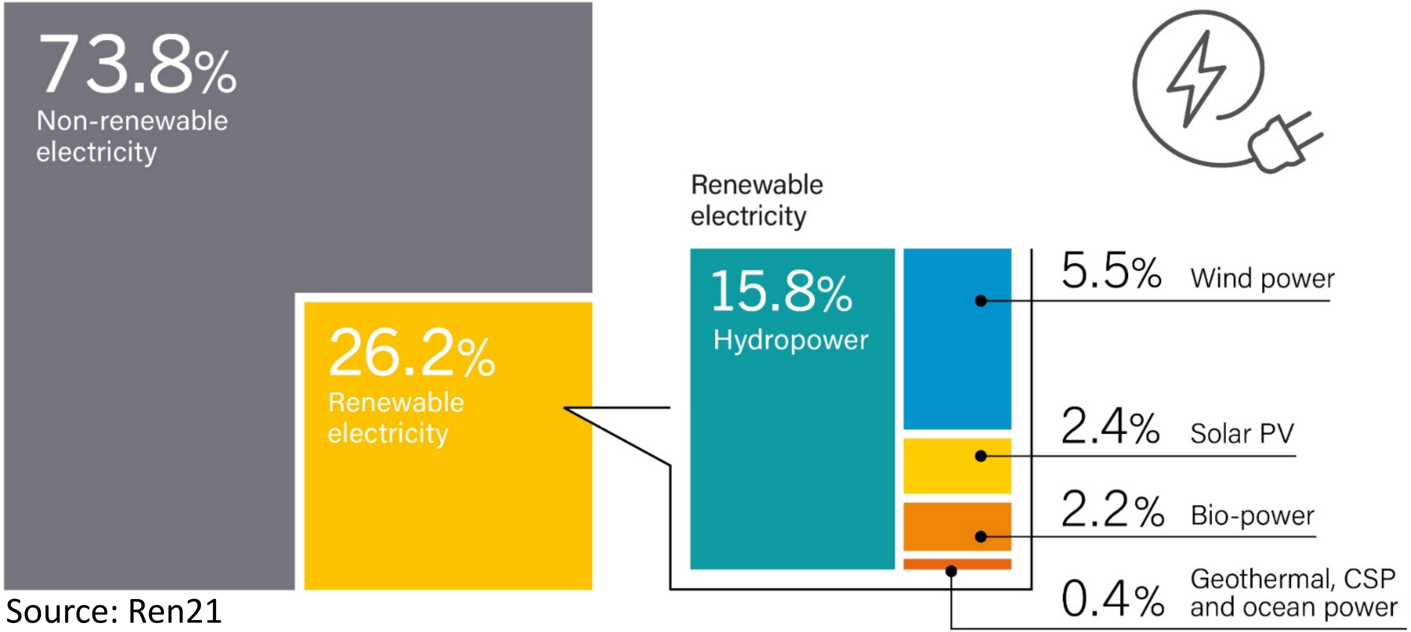
Support from the national science foundation is gratefully acknowledged

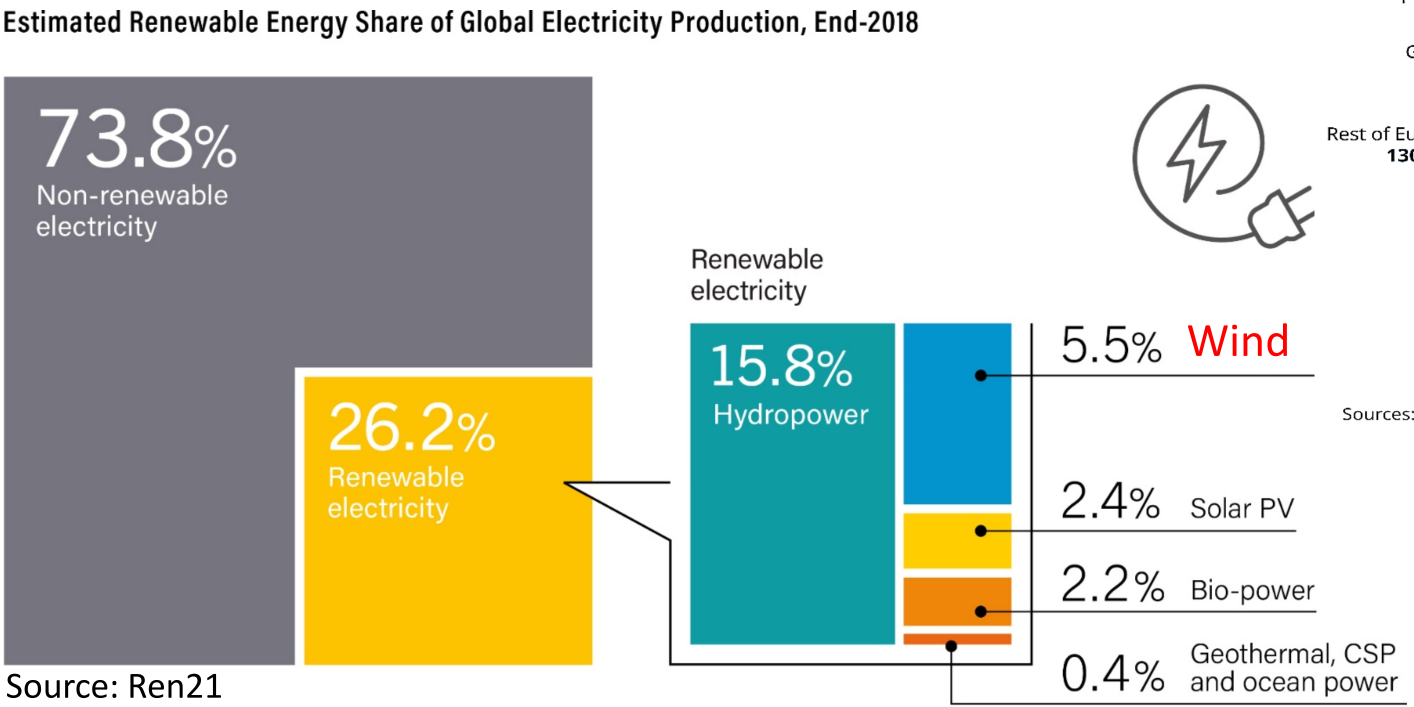
# Significance of renewably supplied electricity

Estimated Renewable Energy Share of Global Electricity Production, End-2018




Source: Ren21

# Significance of renewably supplied electricity

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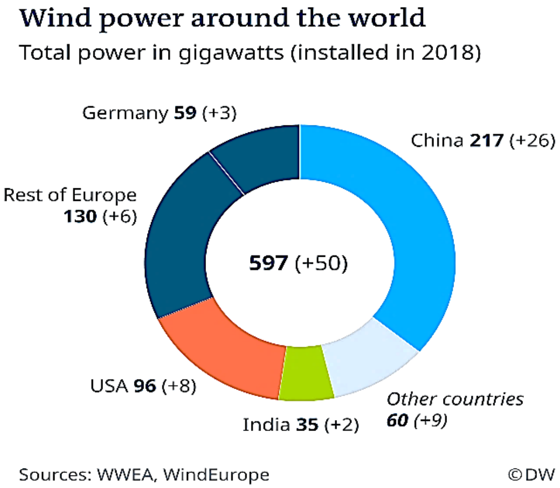
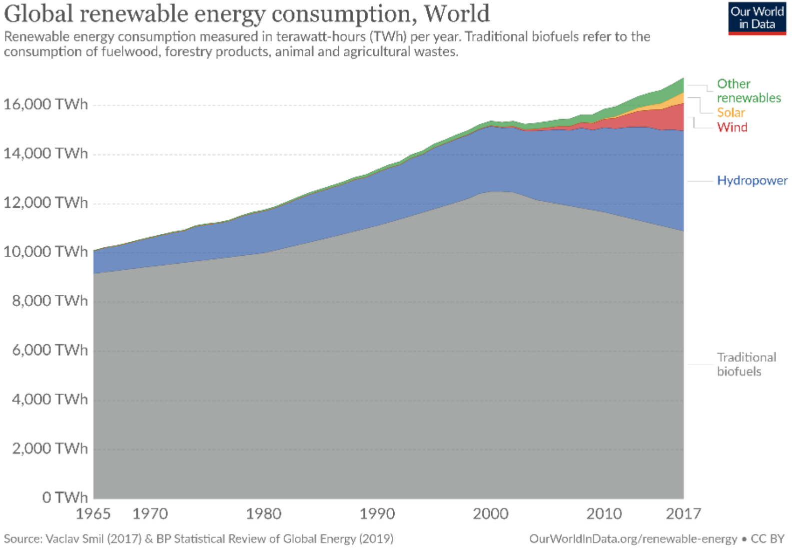


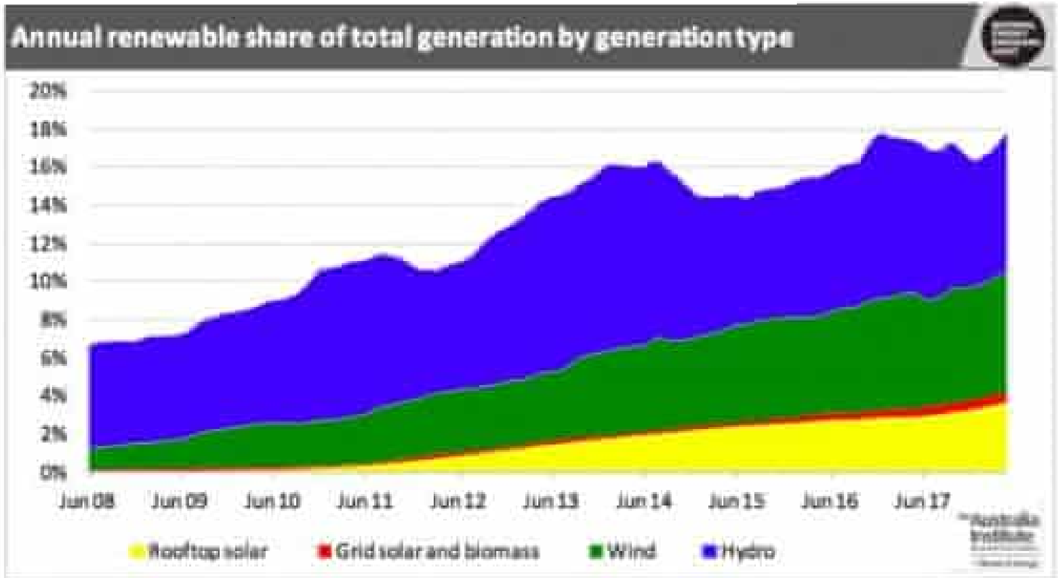
# Significant sustained wind energy growth

## Wind is becoming a significant proportion of world-wide electricity supply

### Global




### Australia






4

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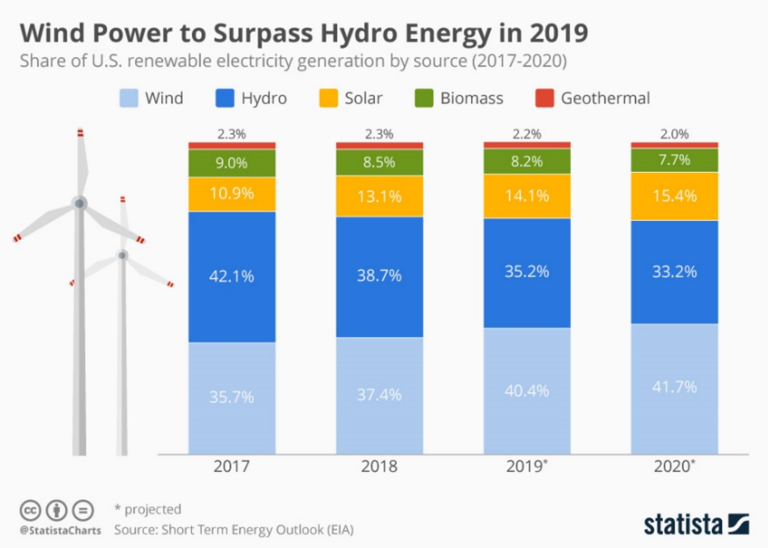


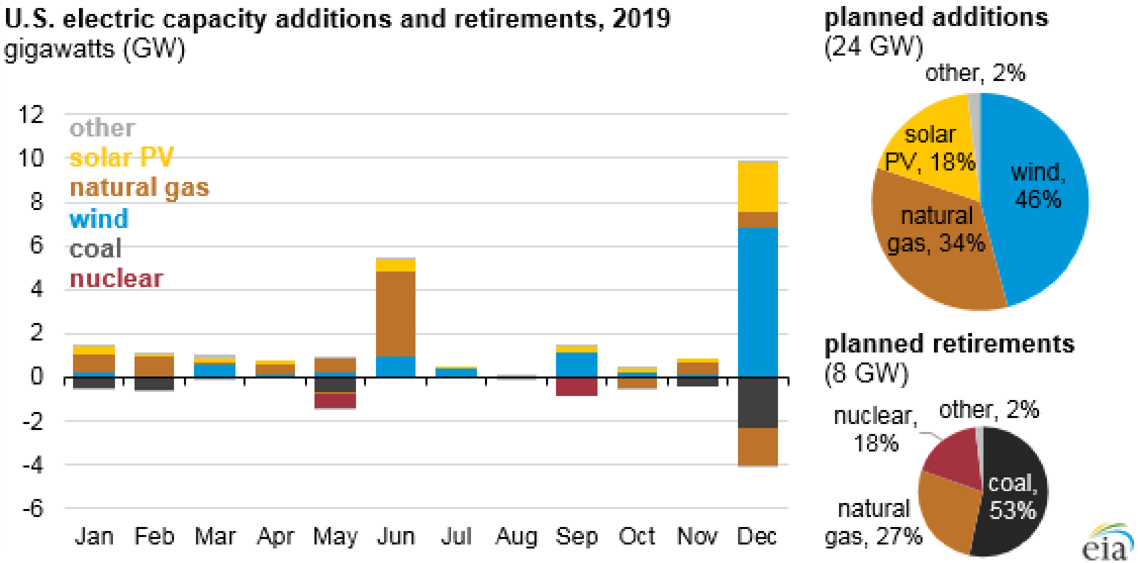

# Wind integration challenges- our model

*Model of wind as "negative demand/must take/free" poses fundamental system problem*

- Underlying assumption: niche supplier
- Incentive: maximize power output without regard for the grid


6

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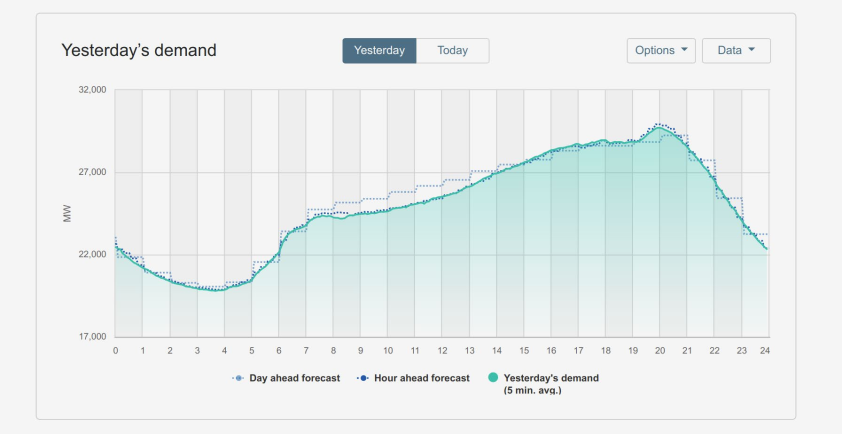


*What happens when wind penetration gets too high to make this model technically/economically feasible?*


7

# Wind integration challenges- our model

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- Underlying assumption: Niche supplier
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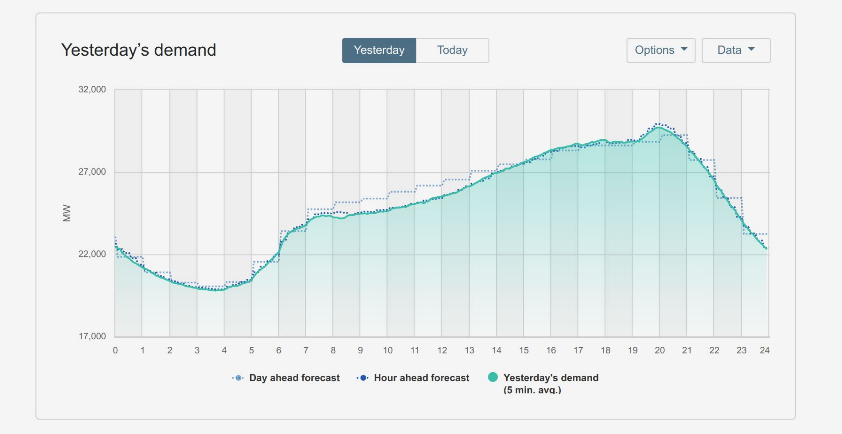



*What happens when wind penetration gets too high to make this model technically/economically feasible?*

*BIG SYSTEM PROBLEM!*

Goes far beyond balancing

- Reactive power
- Regulation
- Voltage support

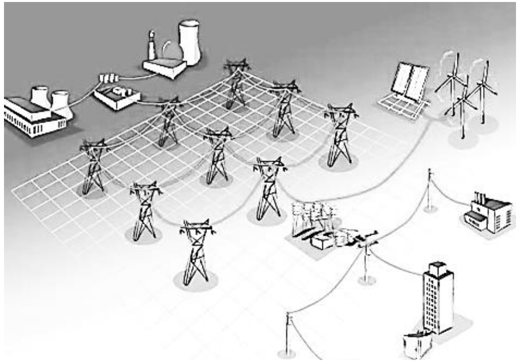

8

# Wind integration challenges

Wind is becoming a significant proportion of our electricity supply

- BUT it is still treated like a niche supplier "must take"
  - NO incentive to adjust output to track demand

Critical grid services that keep the system functioning properly (maintain balance, power quality etc.) are currently provided by conventional generators



- More wind means a smaller percentage of resources contributing
  1. *Conventional generators need to compensate (big economic issue!)*
  2. *Wind energy will be likely required to provide these services*

# Changing how we treat wind farms

*Two key issues that wind farm operators need to overcome for wind to move beyond current role as a "niche" energy provider*

1. Obtaining accurate predictions for wind farm power output levels over a wide range of conditions (A modeling problem)

2. Ensuring that wind farms can successfully operate within the current and anticipated energy markets of the future (A control problem)





10

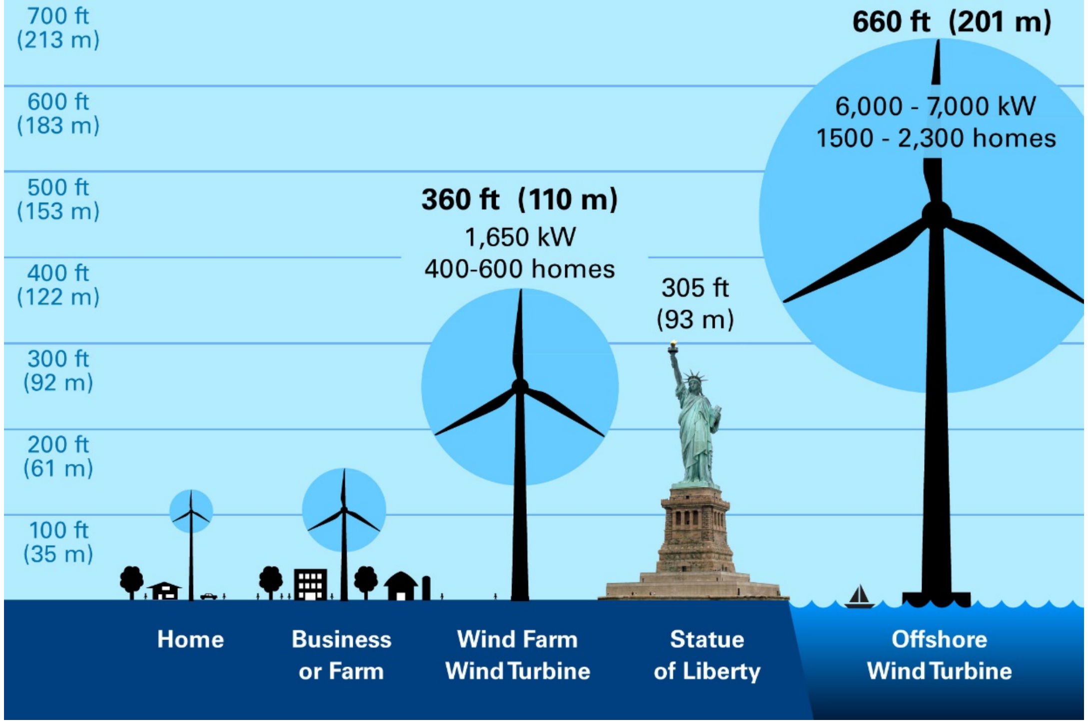
# Changing how we treat wind farms

*Two key issues that wind farm operators need to overcome for wind to move beyond current role as a “niche” energy provider*

1. Obtaining accurate predictions for wind farm power output levels over a wide range of conditions (A modeling problem)

2. Ensuring that wind farms can successfully operate within the current and anticipated energy markets of the future (A control problem)
    - Frequency regulation
    - Price arbitrage –aerodynamic storage

# Size and scale of the physical problem




- Recall frequency regulation for 30s to 30 minutes
- Typical turbine 100 m
- Operational speed 10 m/s
- Spacing 7D apart

Inter travel turbine time

$$\frac{700\text{ m}}{10\text{m/s}} = 70 \text{ seconds}$$

- 10 row farm 700 s (12 min)


12

# A control oriented wind farm model

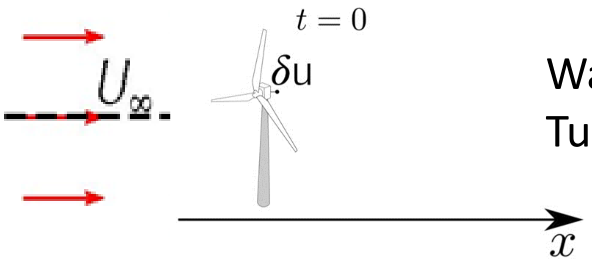
- Need a physical model that can account for the time-varying nature of wake interactions that is:

  1. Captures the behavior of the farm as the conditions change (e.g. changes in turbine inlet velocity)
  2. Simple enough to be implemented for real-time control (e.g. enable participation in energy markets)

Horns Rev 1: Photograph: Christian Steiness

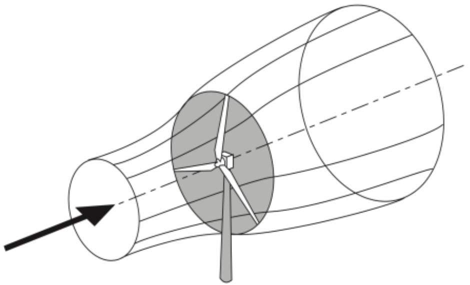
# Dynamic wake model for wind farm control

$$\underbrace{\frac{\partial \delta u_n}{\partial t} + U_\infty \frac{\partial \delta u_n}{\partial x}}_{\text{Linear advection}} = \underbrace{-w_n(x)\delta u_n(x,t)}_{\text{Linear wake expansion/diffusion}} + \underbrace{f(C_{Tn}'(t))G(x-s_n)}_{\text{turbine forcing}}$$



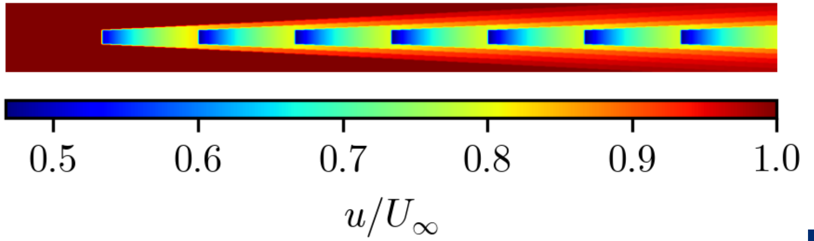

Wake growth: turbulent stress model

Turbine forcing: Momentum theory



Picture: Burton et al. (2011)

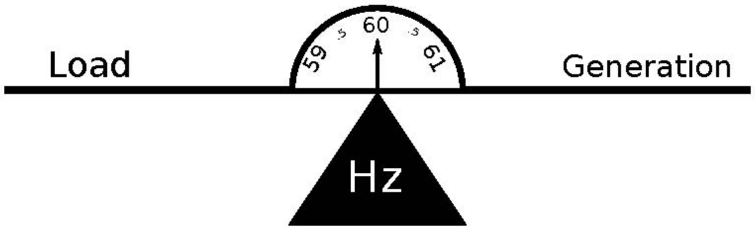
$$\hat{u}_n(t) = U_\infty - \int_0^L \left( \sum_{m=1}^{N} \delta u_m^2(x,t) \right)^{1/2} G(x-s_n)\,dx$$

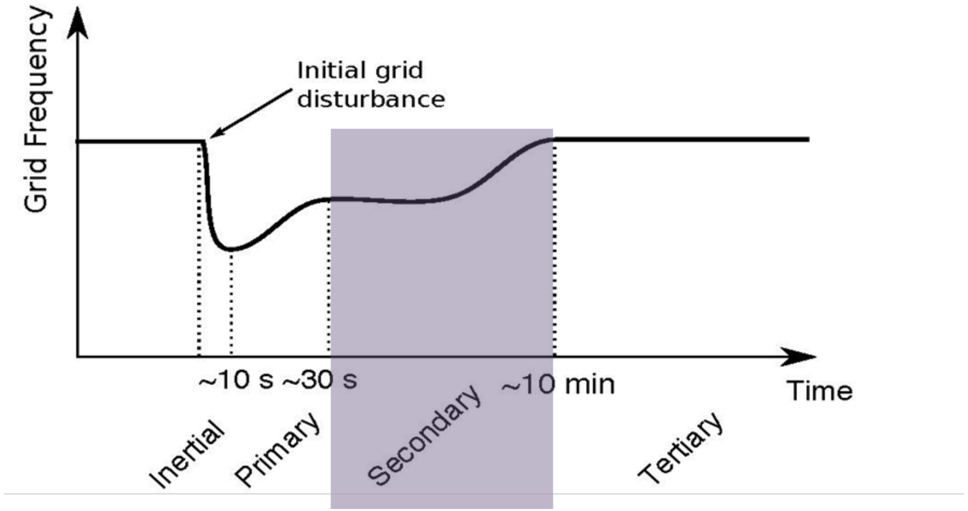



[Shapiro et al. 2017]

# Frequency regulation

- Generation and load imbalances affect grid frequency
- Frequency regulation services compensate for these imbalances



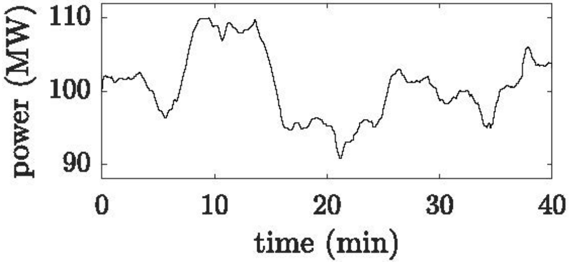




- Secondary regulation 30 sec to 10s of minutes

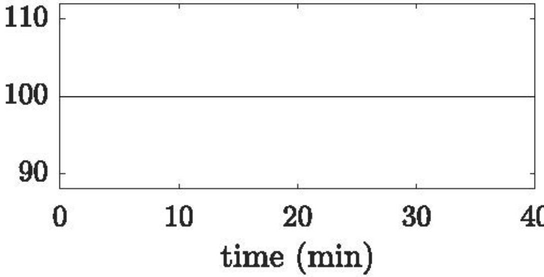
# Market: Secondary frequency regulation

- Generator plants follow a regulation signal from the grid operator to help keep the power grid in balance

$P_{\text{ref}}(t) = \text{power reference signal}$

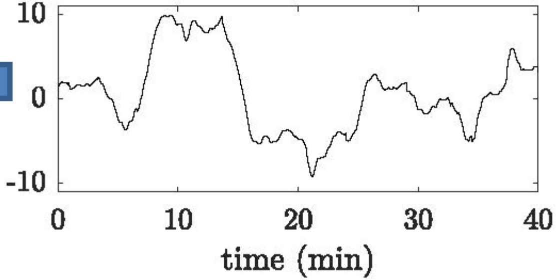



$P_0 = \text{scheduled bulk power}$

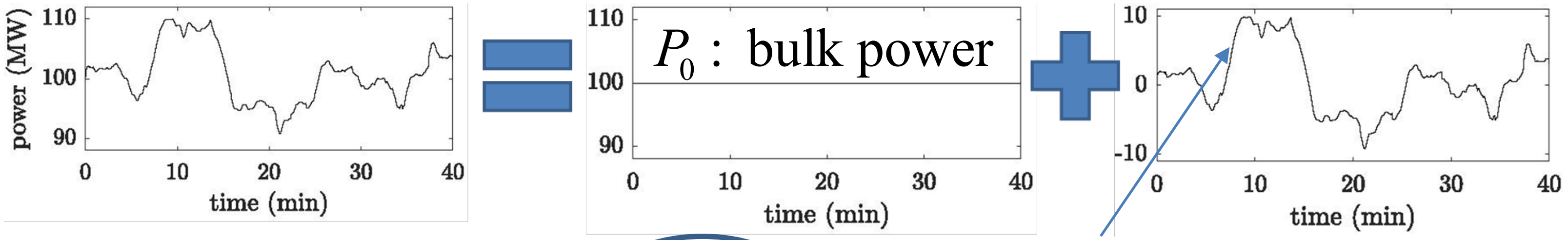



$\Delta P = \text{regulation power}$

$r(t) = \text{regulation signal}$



# Market: Secondary frequency regulation




$$P_{\text{ref}}(t) = P_0 + \Delta P r(t)$$

Up-ramping $\Delta P = \gamma P_{max}$

- Reduce bulk power supply (i.e. do not maximize power output) $P_0 = (1-\alpha) P_{max}$
  - Derate the turbine by some percentage $\alpha \times 100\%$
- Allows the farm to ramp up when needed by some amount $\Delta P = \gamma P_{max}$

- Previous work using wind turbines
  - [Buckspan et al. 2012, 2013; Aho et al. 2013, 2014; Jeong et al. 2014]

# Frequency regulation: economic trade-offs

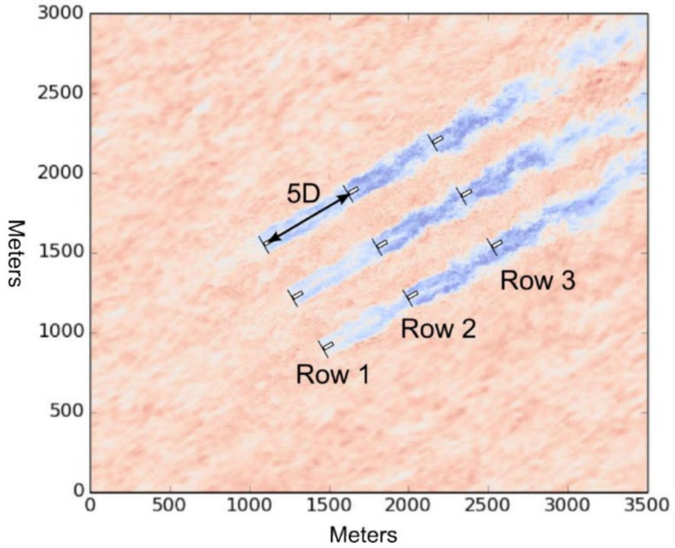
- Direct economic trade-off between bulk power supply and regulation
  - Ideally we want up-ramp capability $\Delta P = \gamma P_{max}$ where $\gamma > \alpha := \text{derate}$
- Rose and Apt (2014): Evaluated cost of using wind for regulation (in the current must take environment)
  - Assumed regulation capability (increased production) = derate amount
  - Compared cost of curtailment to up-regulation prices from ERCOT (Texas)
  - Regulation not cost effective for> 99% of the hours
- Ela et al. (2014)
  - Allowing wind to provide regulation reduces system costs by $19M in CA

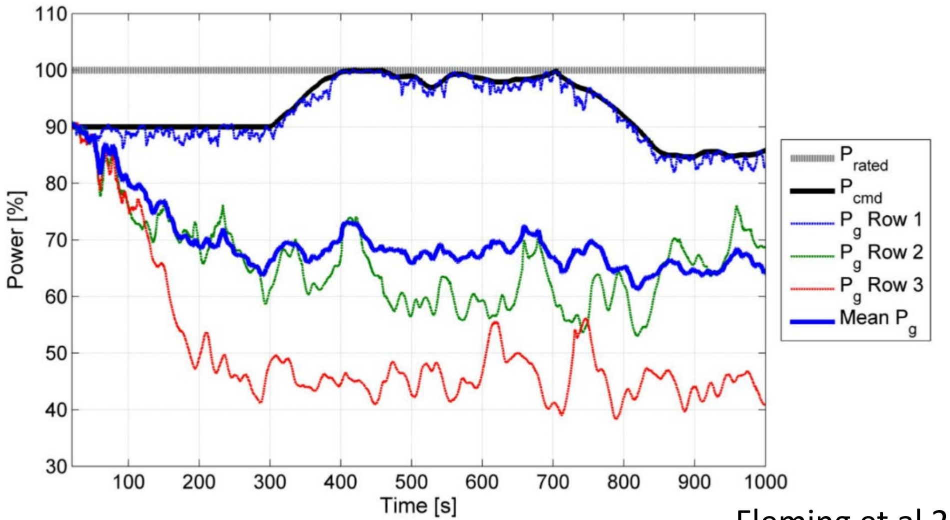
# Frequency regulation: technical challenges

- Previous work using wind turbines

  [Buckspan et al. 2012, 2013; Aho et al. 2013, 2014; Jeong et al. 2014]

- Failure to take wake effects into account (i.e. just controlling the turbines individually) fails even in small farms



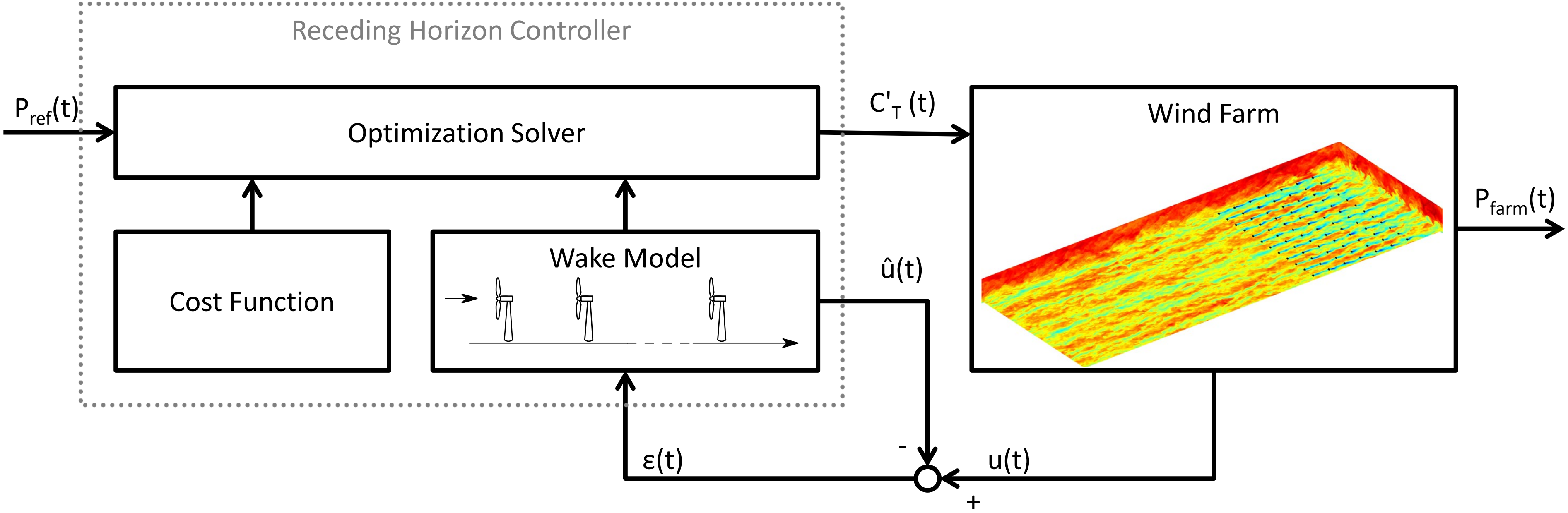




Fleming et al 2016


19

# Model-based controller for wind-farm frequency regulation

- Use the time-varying wake model, which captures both wake interactions and wake advection within a closed loop controller to enable a wind farm to participate in frequency regulation.

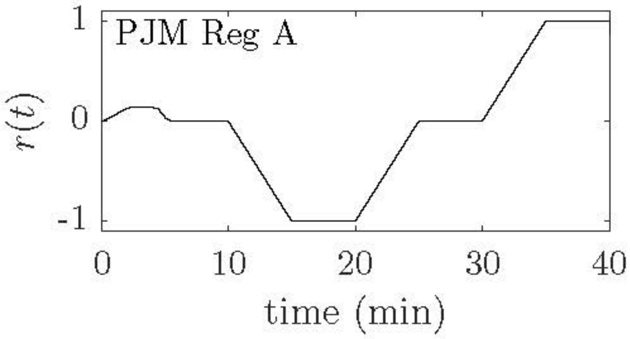


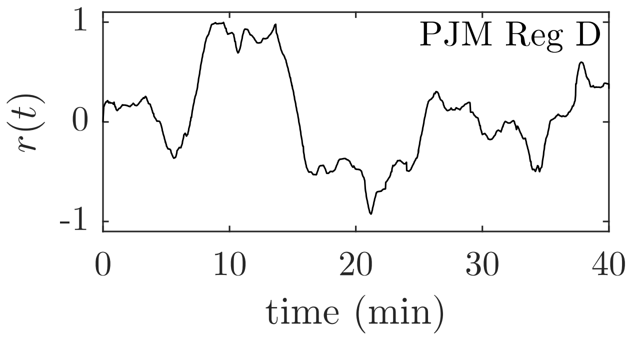


20

# Real world testing: PJM regulation market

- Signals are based on area control error (ACE),
  - a combined measure of power imbalance and frequency deviation
- PJM has two regulation markets




- Test on 48 cases (qualification and historical signals) for 8% regulation
  - Three different initial conditions in wind farm
  - Derates of 4% and 6%

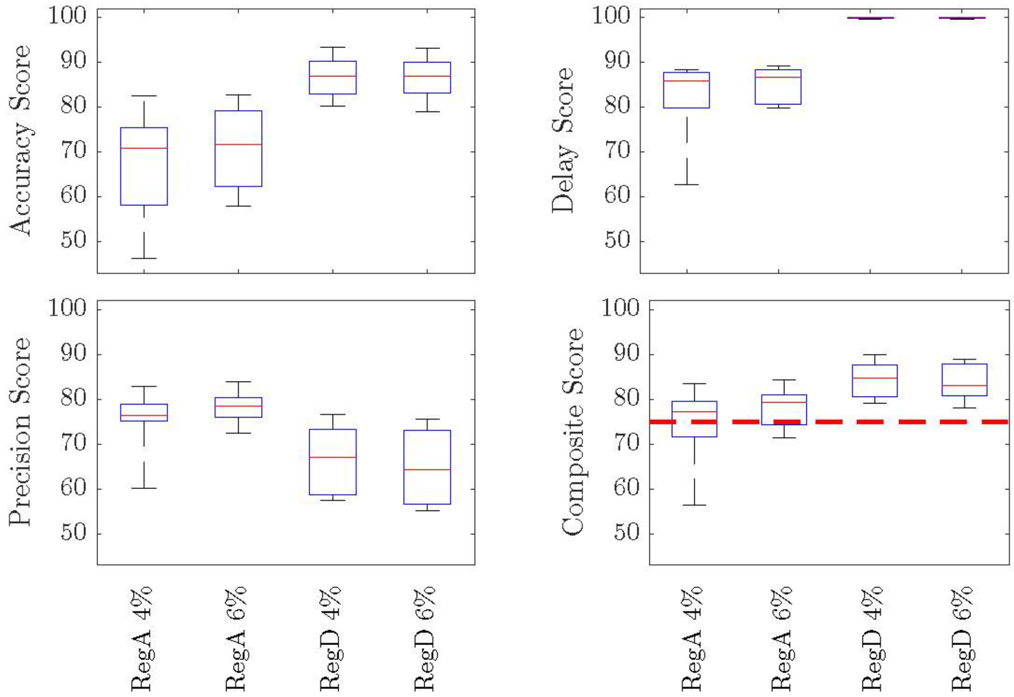
# Real world benchmarking- we qualify

$$P_{\mathrm{ref}}(t) = P_0 + \boxed{\Delta Pr(t)}$$

- We always pass!
- Better at RegD

$$P_{bulk} = (1-\alpha)P_{max}$$
$$\Delta P = \gamma P_{max} > \alpha P_{max}$$

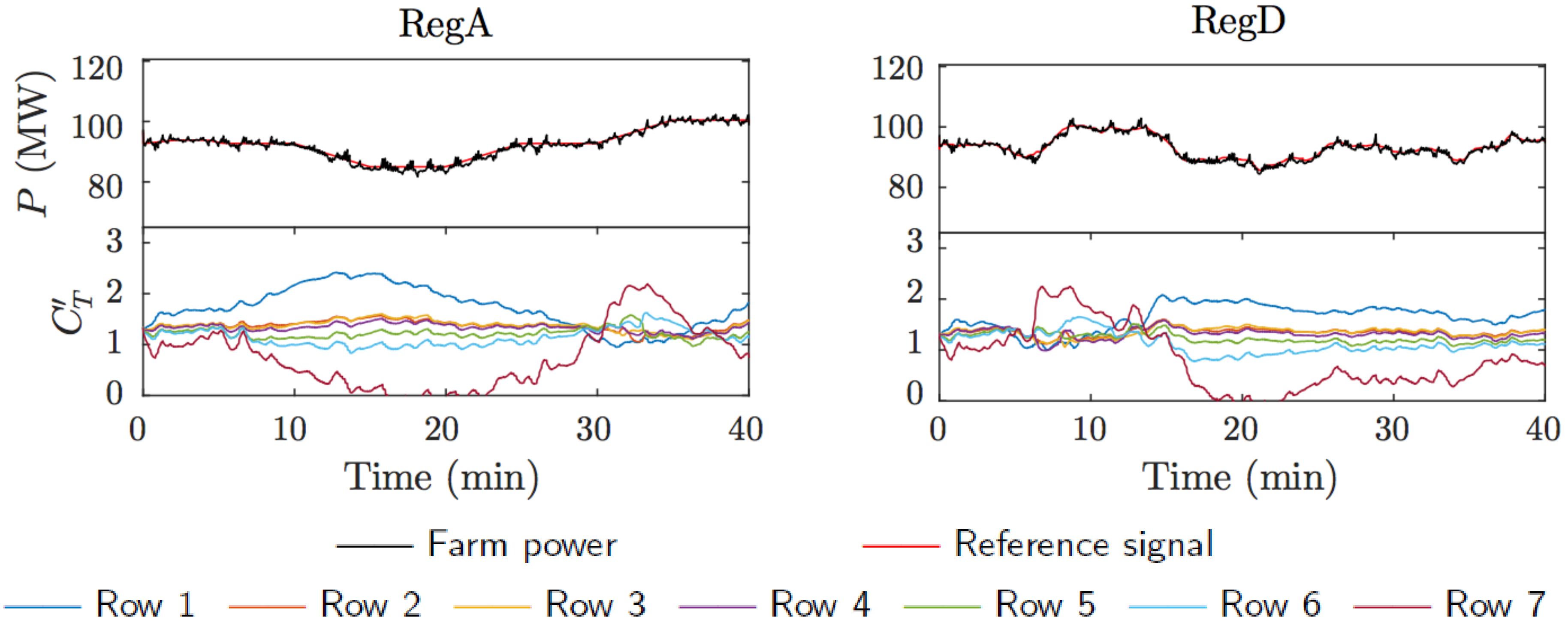
- Significantly less than full derate 4%<<8%
- More efficient means more $$$





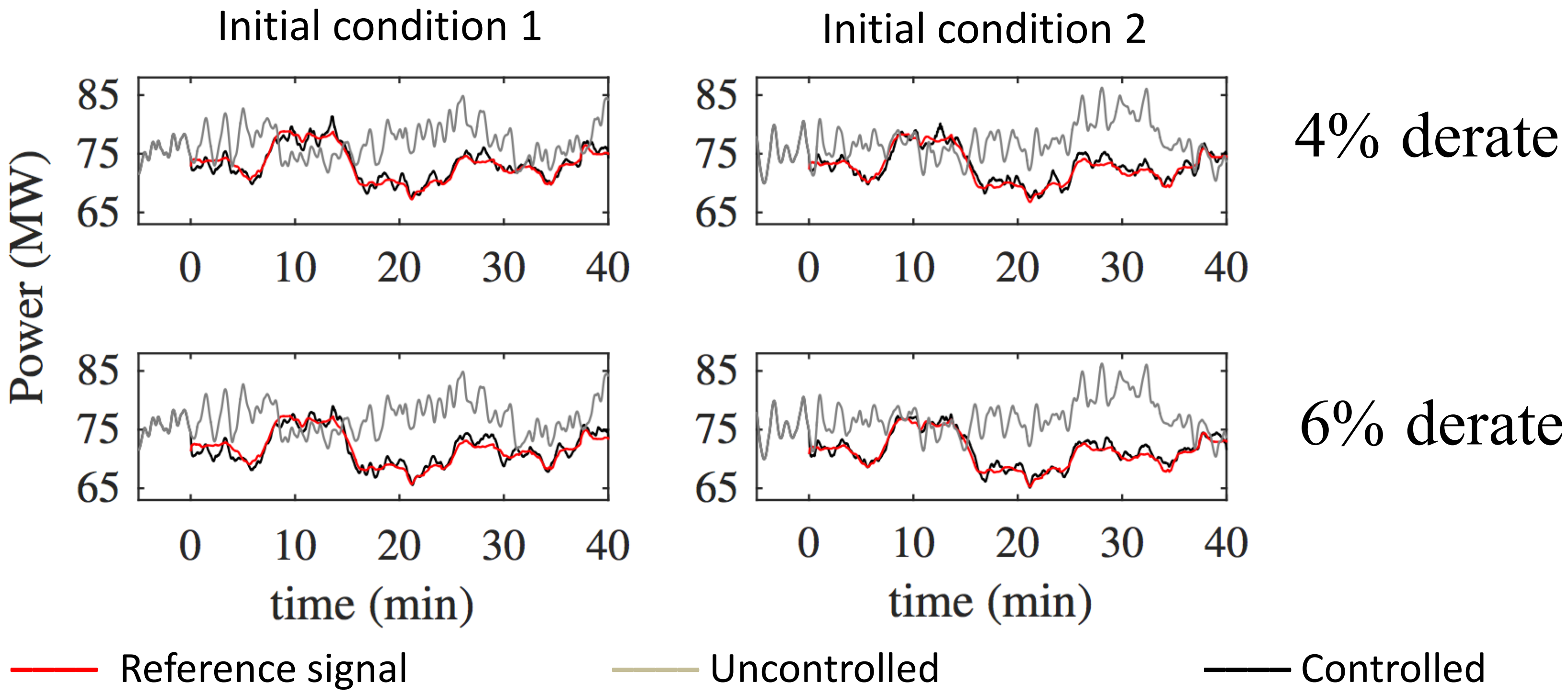
22

# Power tracking behavior



# Sample results: 8% regulation

$$P_{\text{ref}}(t) = P_0 + \boxed{\Delta Pr(t)}$$



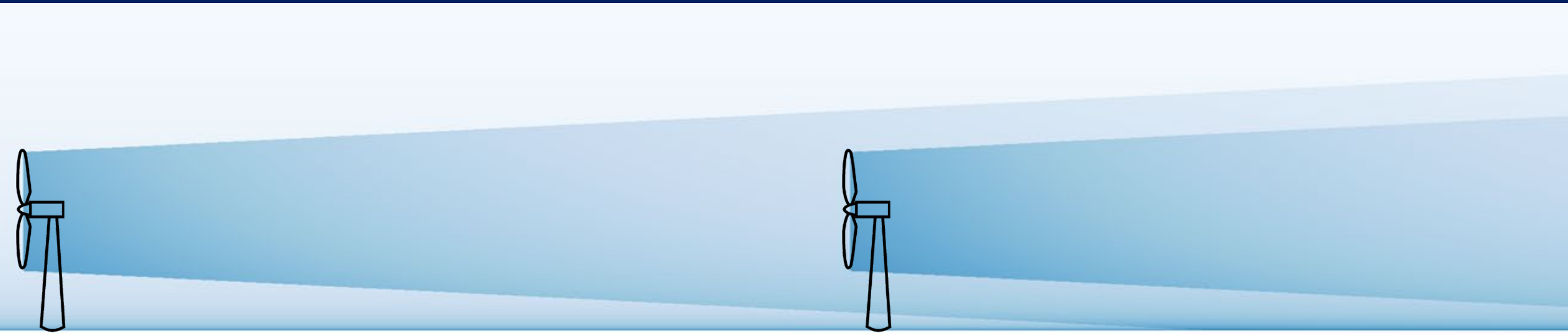
# Summary

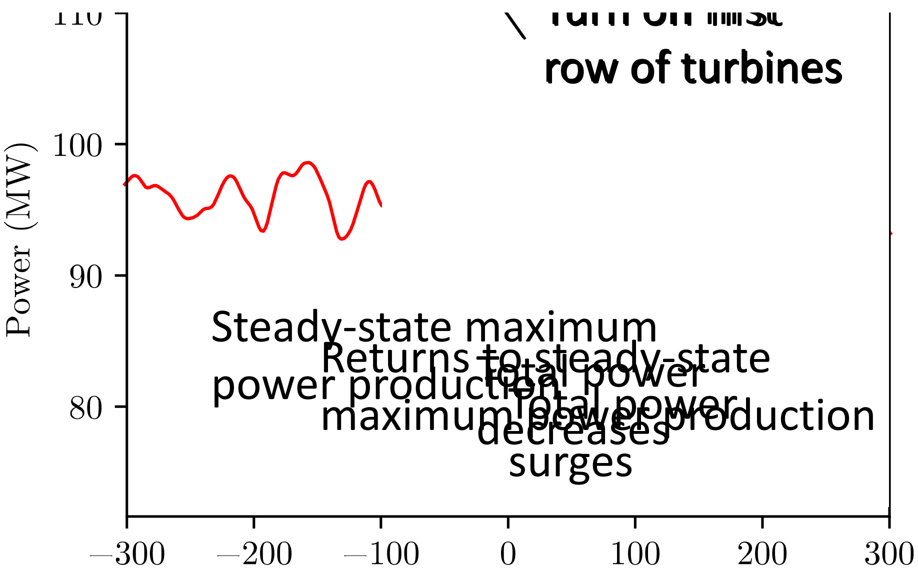
- Model-based receding horizon control shows promising results in allowing wind farms to track a power signal for secondary frequency regulation
  - Significantly reduces the bulk power opportunity cost (in LES with ADM)
  - Feedback (error correction) eliminates the need for a full flow field
  - Taking into account time-varying wake interactions is key

Assumptions

- Constant or steady wind condition for the problem timescale of interest –suitable with strong prevailing wind conditions
  - Requires wind farms to be able to decide when to participate based on forecasting
- Trajectory is given/known- this can be overcome

# Aerodynamic Storage






Storage efficiency is 45%

$$\alpha = \frac{\int_0^{90} P_{total} - P_{steadystate}}{\int_{-90}^{0} P_{steadystate} - P_{total}}$$

# Problem Setup

Maximize revenue

$$\max \quad \sum_{t=1}^{T} \lambda(t) \sum_{i=1}^{N} \delta_t P_i(t)$$

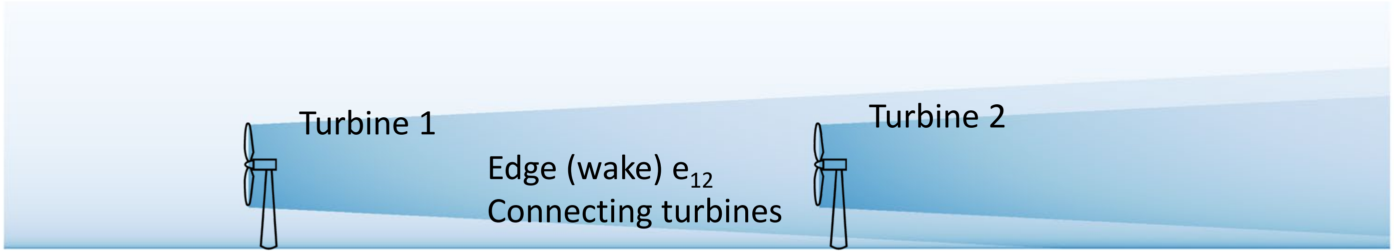
$\lambda : LMP$

subject to

$$P_j(t) \le P_{\text{rated}}(t) \quad \forall j \in \mathcal{N}$$ Rated power

$$0 \le P_1(t) \le P_1^{\max}(t)$$
$$0 \le P_2(t) \le P_2^{\max}(t) + \alpha P_{12}^{\text{stored}}(t)$$ Available power

$$P_{12}^{\text{stored}}(t + T_d) = P_1^{\max}(t) - P_1(t)$$ Power stored



# Problem Setup

Maximize revenue

$$\max \quad \sum_{t=1}^{T} \lambda(t) \sum_{i=1}^{N} \delta_t P_i(t)$$

$$\lambda : LMP$$

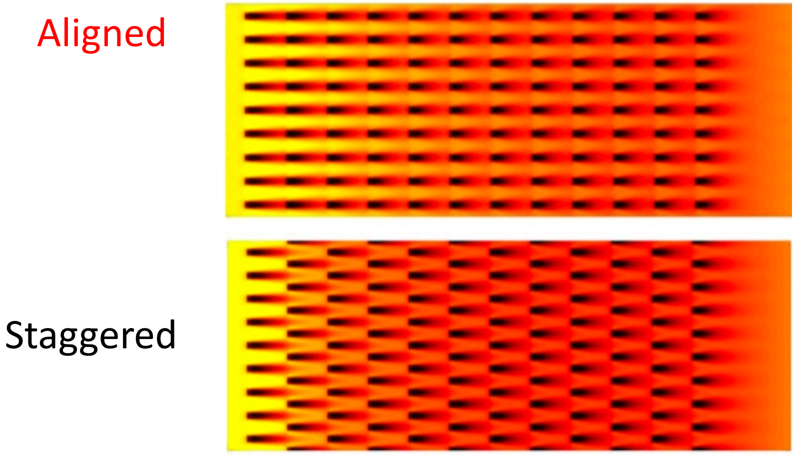
subject to wind farm constraints

Our feasibility study neglects subsidies and assumes

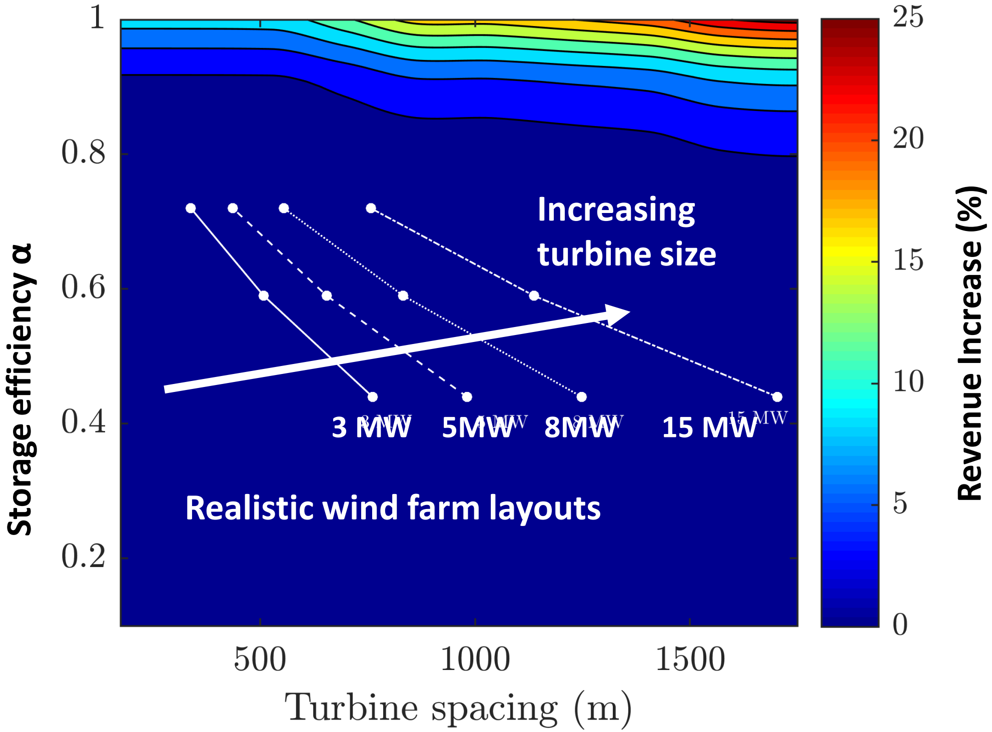
- Perfect knowledge of prices, wind speeds, etc.
- Regularly aligned wind farm arrangements
- Idealized wind farm aerodynamic model

# Efficiency and turbine spacing parameter sweep

- Historic price and wind data (low volatility)
- 84-turbine aligned wind farm




Stevens et al. (2014) *JRSE*




- Minimal revenue potential under historic price volatility

# Under higher price volatility

We expect price volatility to increase in the future.

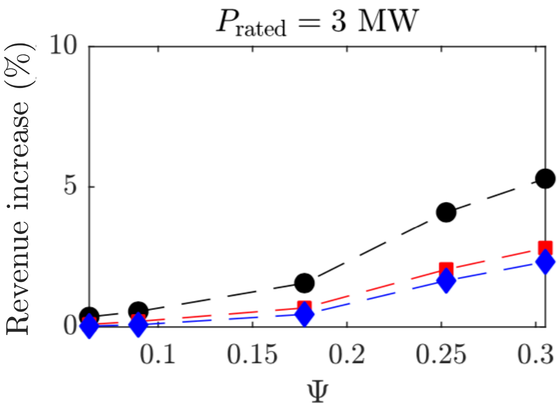
Introduce a price volatility index

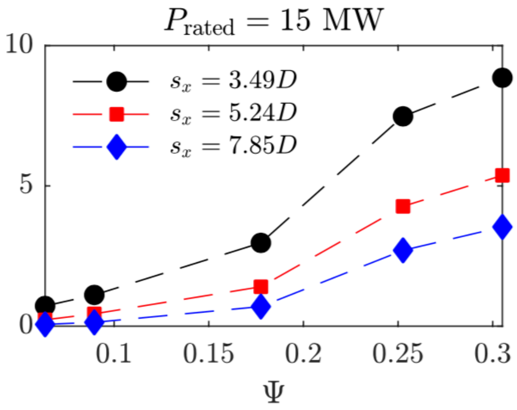
$$\Psi = 1 - \frac{1}{T}\int_0^T E_\lambda(t)\,dt$$

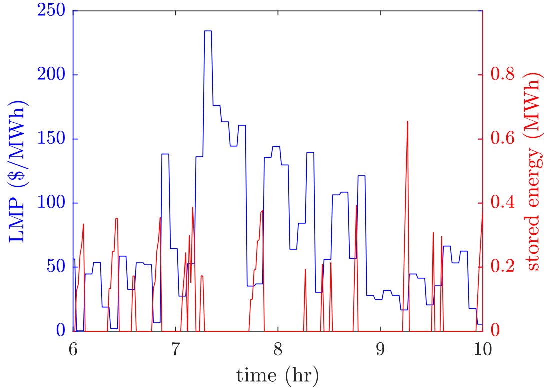
- Defined over adjacent clearing times to match aerodynamic time scales

$$E_\lambda(t) = \begin{cases} \exp\left(1 - \frac{\lambda(t+1)}{\lambda(t)}\right), & \text{if } \lambda(t) > 0 \ \& \ \frac{\lambda(t+1)}{\lambda(t)} > 1, \\ 0, & \text{if } \lambda(t) \leq 0 \ \& \ \lambda(t+1) > 0, \\ 1, & \text{otherwise,} \end{cases}$$

# Under higher price volatility




- Revenue increase is substantial
- Energy storage mechanism is responding to price fluctuations

# Summary

- Wind farms can do more than just maximize power output
  - Trade offs: Economics of wind operators versus the overall grid health
- Market models and economic models taking that into account might change the analysis and overall system impact of wind

# Acknowledgements

**Collaborators**
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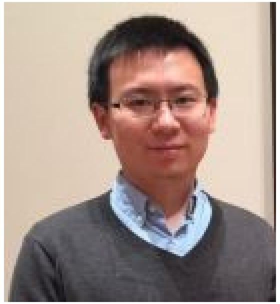
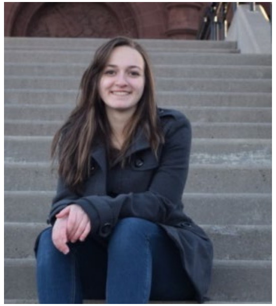
**Students and Postdocs**
Chengda Ji, Carl Shapiro, Genevieve Starke





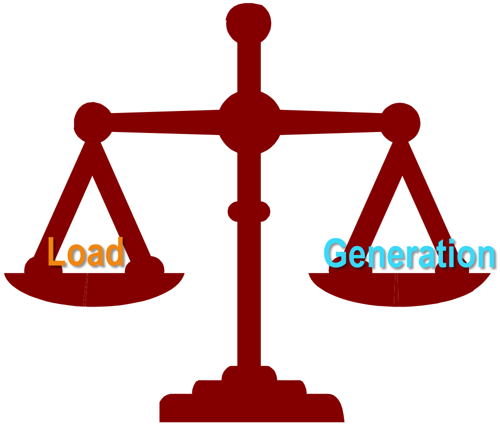


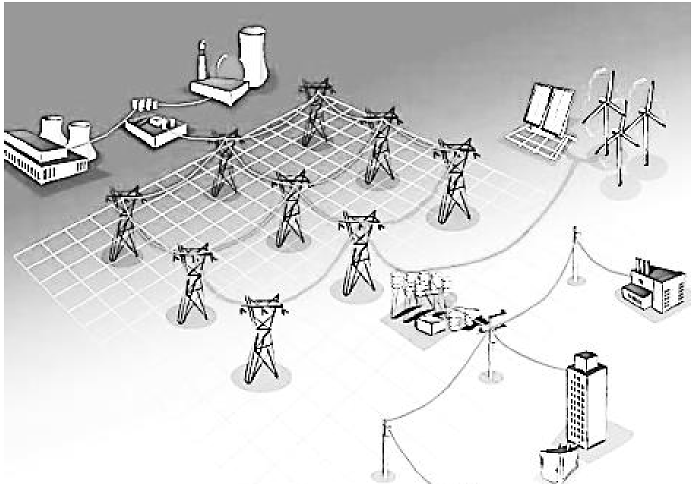
*Special thanks to Charles Meneveau for publically sharing the JHU LES code*

# Back-up slides

# Moving wind to main stream

- Obtaining accurate predictions for wind farm power output levels over a wide range of conditions (Build a better model ) ✓
- Ensure that wind farms can successfully operate within the current and anticipated energy markets of the future (Control the wind farm)
  - Markets that provide grid services




35