Grand Challenge Plant and Grid

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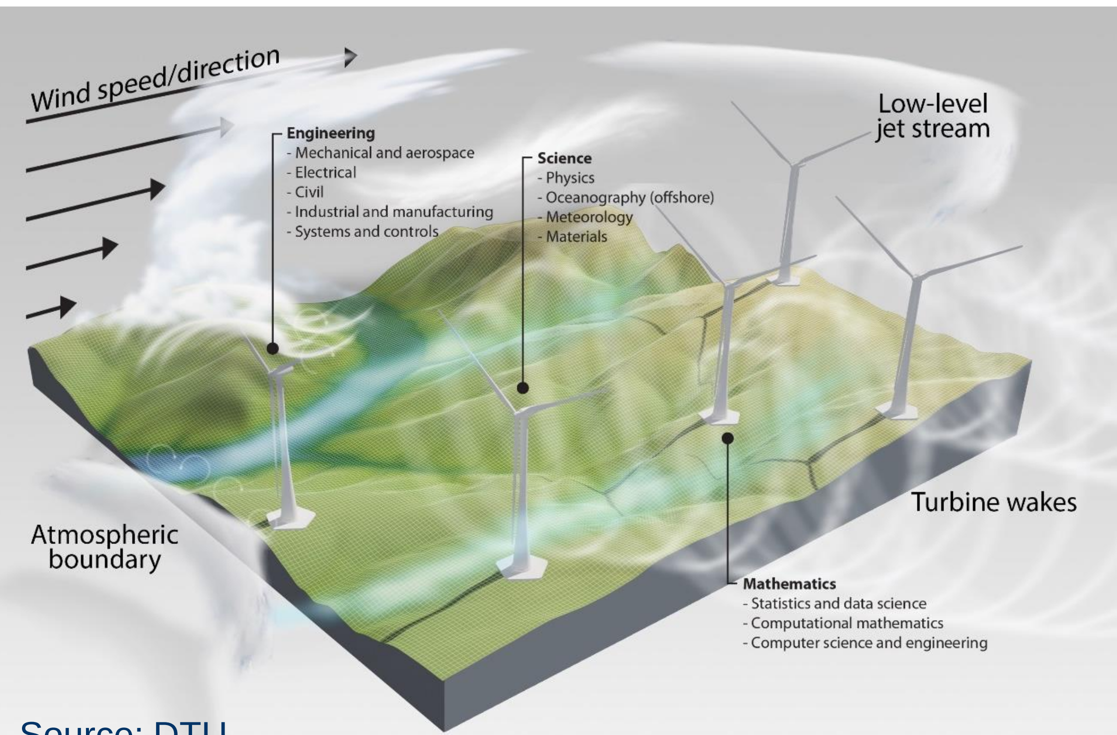

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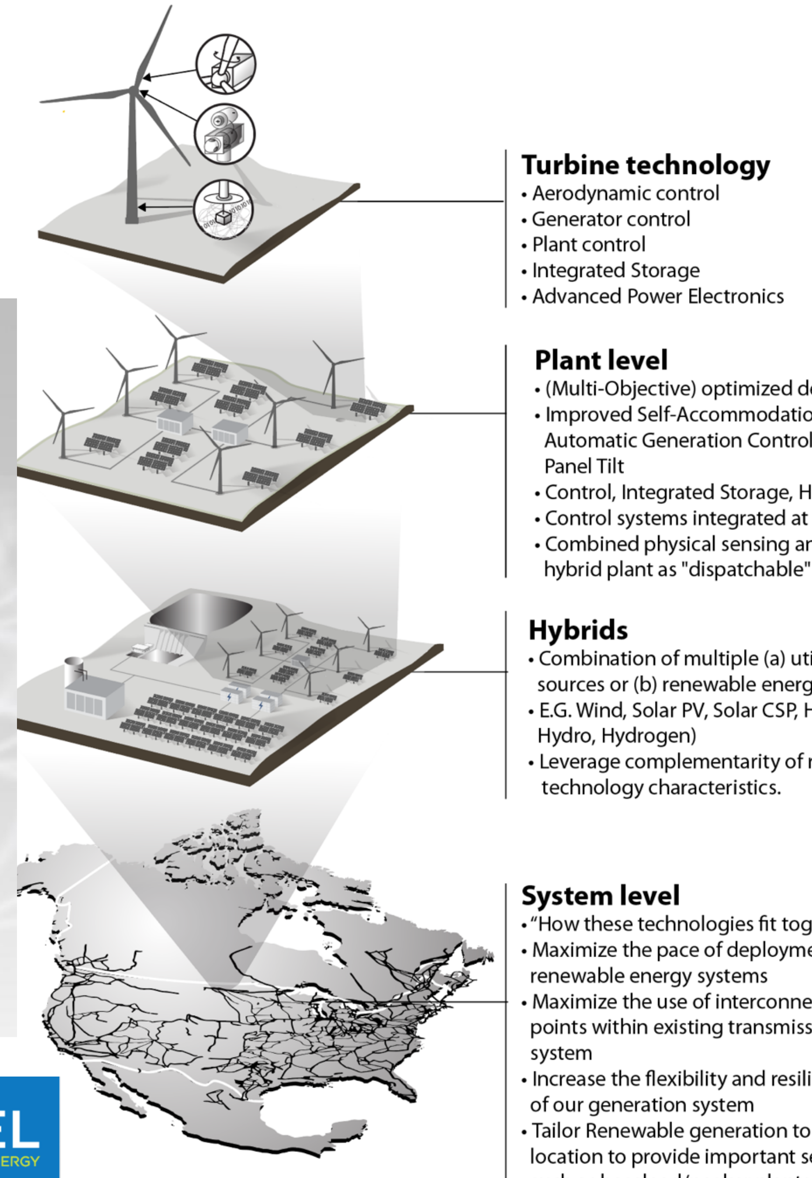

Grand challenge Plant

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Wind farm flow control: prospects and challenges

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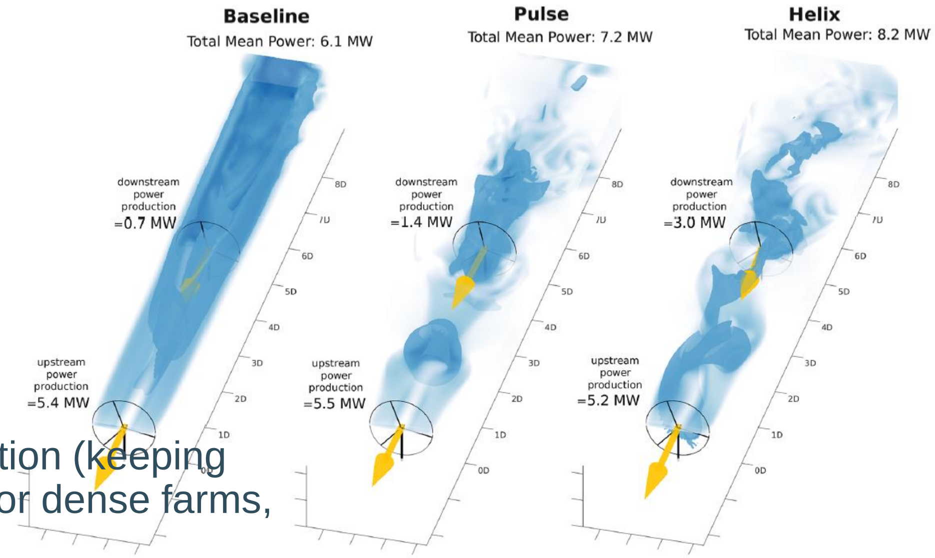
Challenges for wind-farm flow control

1. **WFFC physics.** Quasi-steady control: wake shape, over-induction, aspects of loads; dynamic control: wake mixing, … , Control of mesoscale effects?
2. **Algorithms and AI**. From open loop to closed loop. Selection of internal model, state estimation and virtual twins, what sensors are needed?
3. **Validation and implementation.** Various challenges in improving the LES – wind tunnel – field experiment validation process
4. **Co-design.** From LCOE to value based metric. Exploiting interaction between control and design; move away from control for AEP gain only

Insight in control flow physics



Quasi-static WFFC approach

changes turbine set-points at a relatively slow pace

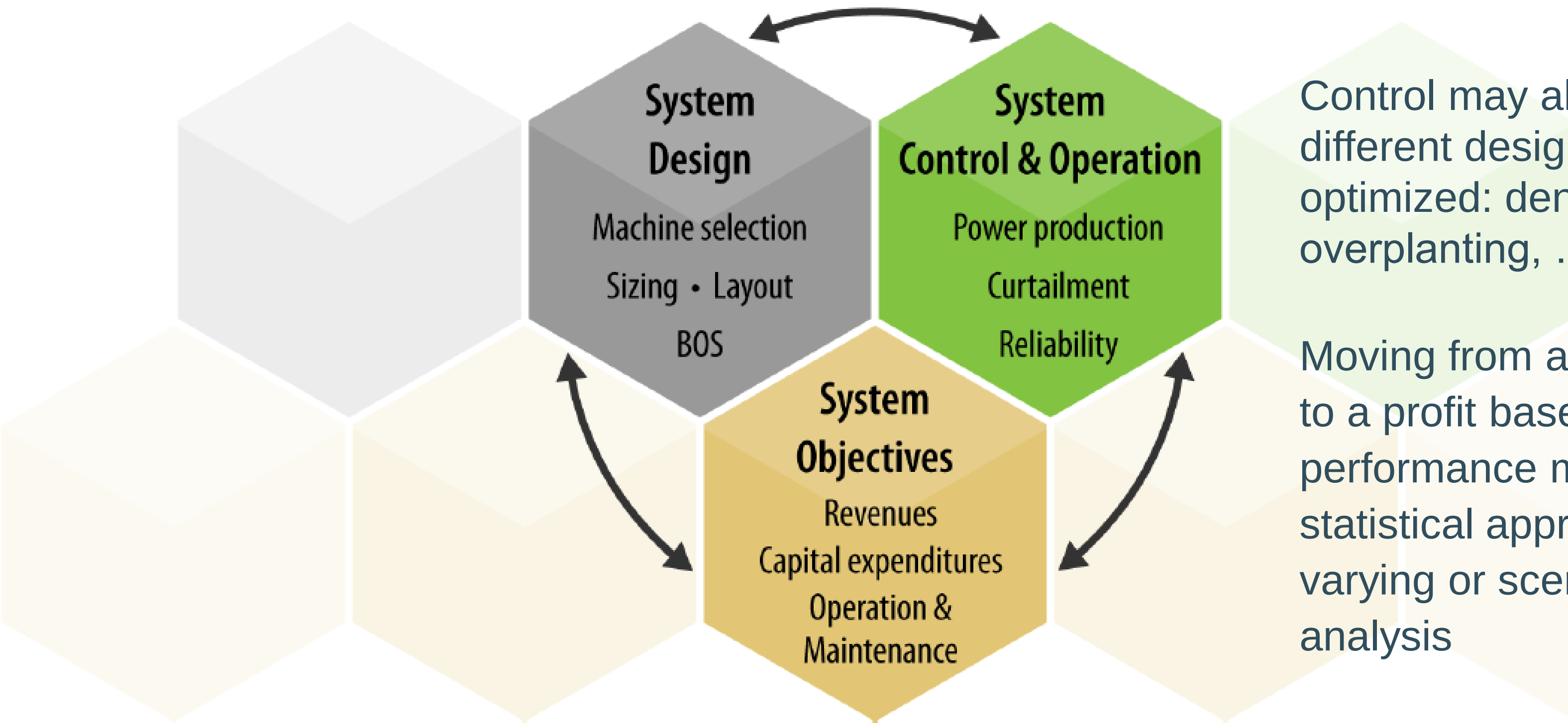
- Static induction control effective for load reduction (keeping energy ≈ same). Increased energy extraction for dense farms, over-induction?
- Static yaw control: probably most advanced in practice Shape and path of the wake under various atmospheric conditions? Effect on loads? Combination of yaw and induction control?

Dynamic WFFC approach *aims at including faster flow physics, more advanced approaches at directly influencing the wake mixing and turbulence*

- Wake dynamics Further insight for concepts (Dynamic Induction Control, Dynamic Yaw Control, Helix method), new approaches? Connections with instability modes of wakes? Wake dynamics of floating wind turbines (and consequences for WFFC)
- Boundary layer turbulence, entrainment *Can we control more than just the wake? Some theoretical results, but no tangible mechanism identified yet*

Mesoscale effects, blockage, and wind farm wakes *If farms can cause these effects, then there may be room for control* To date virtually unexplored

Integrating control with system design (co-design)



Control may allow for different designs when co-optimized: densification, overplanting, …

Moving from a LCOE based to a profit based performance metric: from a statistical approach to time varying or scenario-based analysis

Grand Challenge Grid

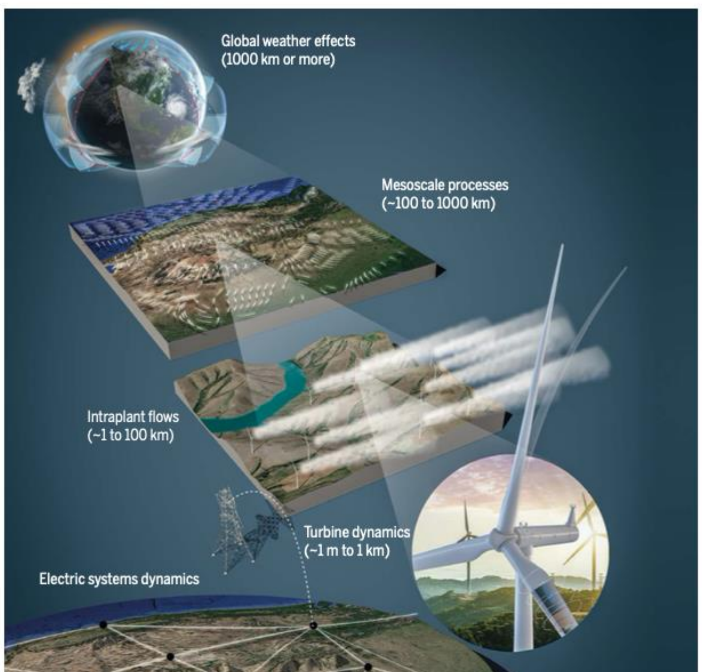
REVIEW SUMMARY

RENEWABLE ENERGY

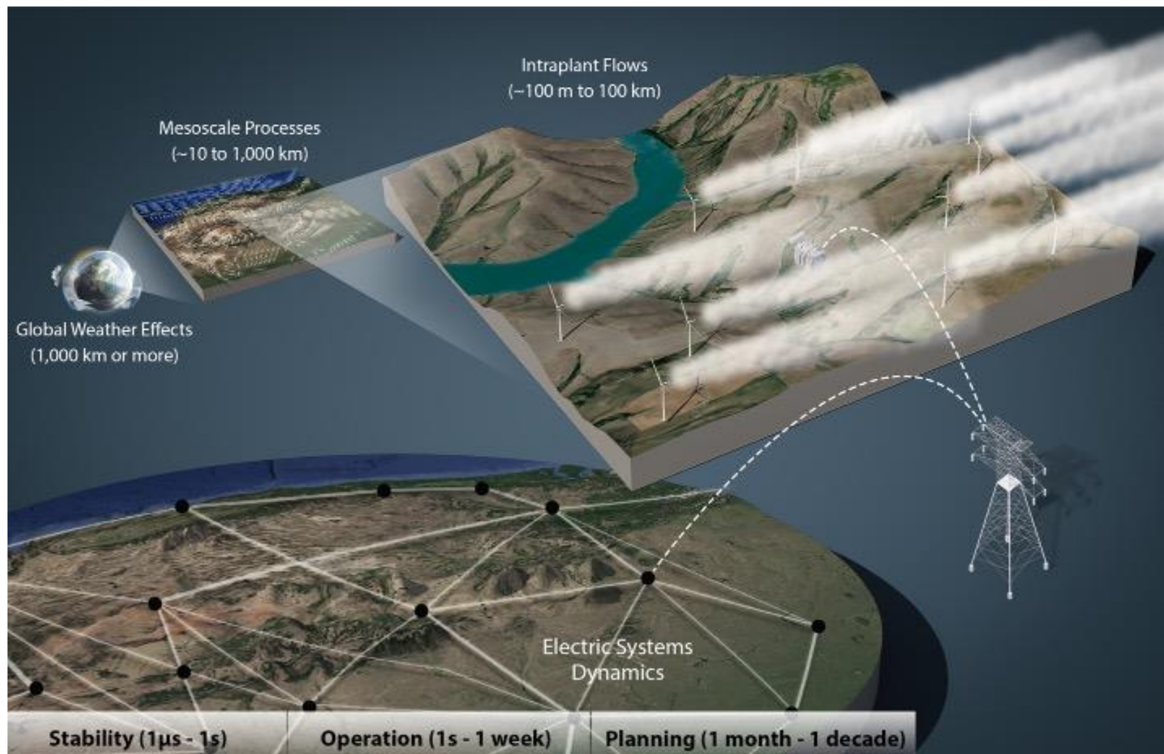
Grand challenges in the science of wind energy

Paul Veers*, Katherine Dykes*, Eric Lantz*, Stephan Barth, Carlo L. Bottasso, Ola Carlson, Andrew Clifton, Johney Green, Peter Green, Hannele Holttinen, Daniel Laird, Ville Lehtomäki, Julie K. Lundquist, James Manwell, Melinda Marquis, Charles Meneveau, Patrick Moriarty, Xabier Munduate, Michael Muskulus, Jonathan Naughton, Lucy Pao, Joshua Paquette, Joachim Peinke, Amy Robertson, Javier Sanz Rodrigo, Anna Maria Sempreviva, J. Charles Smith, Aidan Tuohy, Ryan Wiser

BACKGROUND: A growing global population and an increasing demand for energy services are expected to result in substantially greater deployment of clean energy sources. Wind energy is already playing a role as a mainstream source of electricity, driven by decades of scientific discovery and technology development. Additional research and exploration of design options are needed to drive innovation to meet future demand and functionality. The growing scale and deployment expansion will, however, push the technology into areas of both scientific and engineering uncertainty. This Review explores grand challenges in wind energy re-



Systems science and control of wind power plants to orchestrate wind turbine, plant, and grid formation operations to provide low cost energy, stability, resiliency, reliability and affordability in the future power system

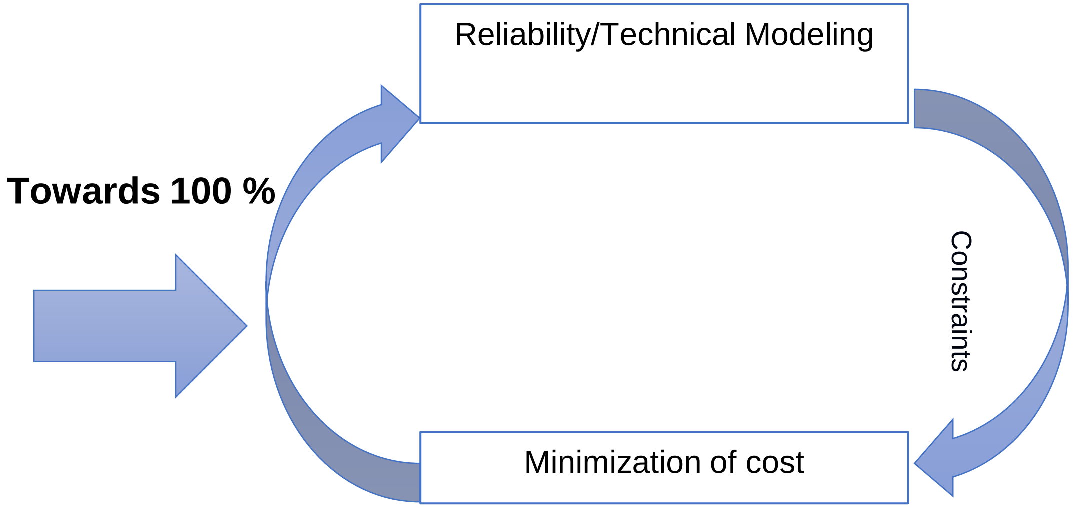


NREL
Transforming ENERGY

Energy transition – Grand challenge for the Grid

- Wind and PV becoming dominant in power systems
- Simultaneously electrification, other non sync technologies, energy sector coupling
- Cost effective Reliability as a fundamental objective
  - maintain supply-demand balance at all locations and at all times

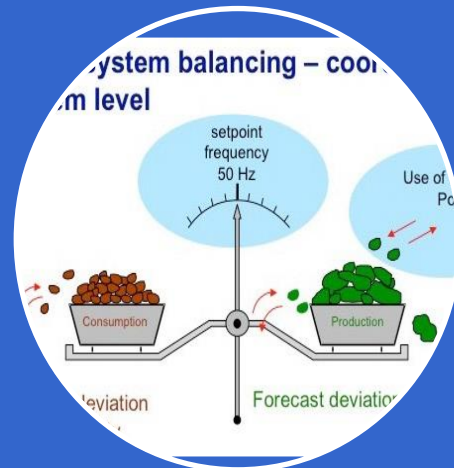
Cost reliability trade off



A real Grand Challenge for Grid

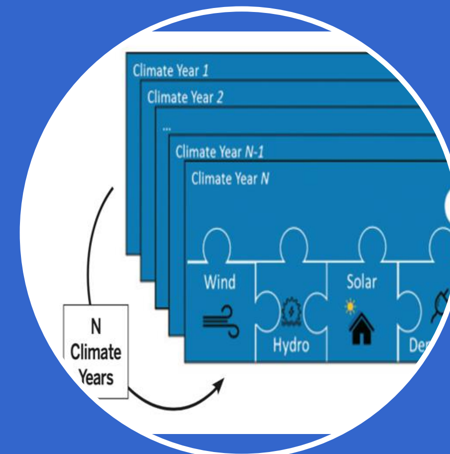
Stability

At times 100% inverters: non synchronous operation- resilience for disturbances and external events; control interactions



Short term balancing

Demand and supply in balance – flexibility challenge



Long term balancing

Increased weather dependency. No more fixed load paradigm – new planning tools for storage and demand side

seconds, minutes, hours, days seasons/years

Transmission is an enabler – easier for larger systems

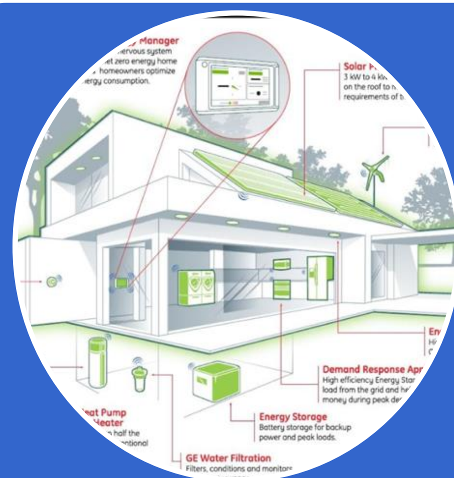
More complexity and amount of data is exploding - digitalisation

Wind based solutions

Stability:

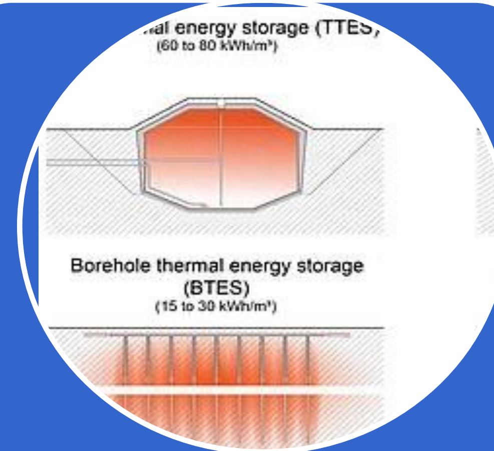
Grid forming inverters.
Exploit all capabilities of inverters.

Providing Freq, volt, stability services



Short term balancing:

use wind power plants for short term balancing – optimising wind power plants for less losses



Long term balancing:

diversify – low wind tech; hybrids with P2X long term storage;

no mass
all brains

Market design for wind

huge energy systems
power, heat, gas,…

Fundamental changes, system services needs

- Inverter Based Resources (IBR)s replacing synchronous machines changing the needs and service capabilities - also the resources “behind” the IBRs are changing – wind, solar,
- Generic “services” approach, focus on 8 fundamental ones, to get the full benefits of the new technologies, not to mimick what we already have storage, distributed etc.

System needs and services will evolve – a moving target.

Wind based solutions to be improved for capacity, freq and volt regulation. New capabilities / R&D for Damping, Angle Stability and Restoration, need storage. For protection, system changes required.

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Plant and Grid
High level Grand challenges

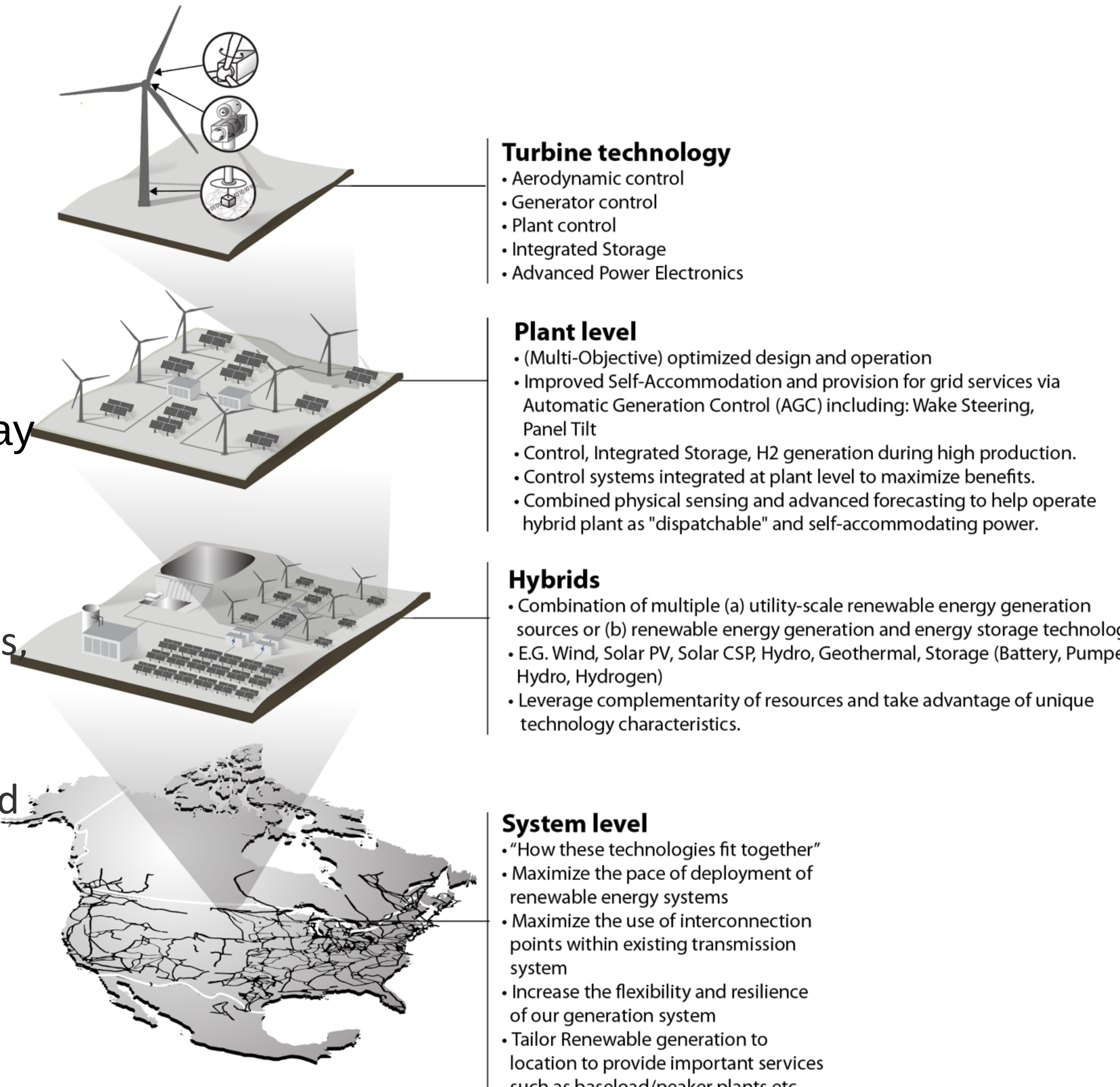
1. Flow control physics and AI & data driven modelling
2. Multi-objective optimization of the plant, including for hybrids, P2X (electricity/other output), and offshore grids
3. Next generation of wind plants – grid forming and interacting with other IBRs
4. Improve wind-based grid support
5. Integrated plant and flow control for optimized operation & grid services

Extra slides

Development of wind based solutions: wind turbines, wind power plants, and hybrids

For plants and hybrids:

- Metrics / design objective development, optimization techniques,…
- Integrating storage, and/or other RES. The control becomes more complex, and control interactions may appear.
- **Design: including new conversion services** like H2, NH3, methanol, liquid RE fuels, and heat to electricity. Assess the viability of electrolyzers and turbines, AC vs. DC shared electronics, etc. , also future offshore wind systems. Develop **large-scale, discrete optimization techniques** to handle a diverse set of design variables, for example, to



Need	Turbine	Plant	Hybrid
Energy (volume)	Yes. Increased capacity factor by design. This is covered elsewhere not the focus here.	Yes – some value over and above turbine level	Yes. Assuming storage then curtailed energy can be stored for later use,
Capacity (timing of energy)	Yes: utilizing also low wind turbines with larger rotors, more expensive and losing high winds but gaining on better value of energy generated (economic case for operators producing when others not) and increasing capacity value for the system. Quite marginal?	Yes, same as for turbines, probably marginal.	Yes: Assuming storage can be used to move the energy into more valuable time periods. Energy and power management challenges, more complex (generally about hybrids)
Frequency control	Yes - at high shares wind/solar will be partly curtailed. when there is value in generated energy – less competitive. R&D needed? faster sync inertia still some. Grid-forming operation of wind turbines impact on the drivetrain?	Yes – some more over and above turbine level. Flow control, wake steering to reduce losses for providing active power services (not much impact for the faster services?)	Yes: Assuming storage is part of the hybrid story then it gives you the up and down capability without having to curtail. State-of-the-art already? Research content?
Voltage Control	Yes. Capability already demonstrated, but not used much in other than weak grids. Part of grid forming research	Yes. What is the value add over and above turbine? Statcom possible to add. Grid forming case same for plant level as turbine?	Yes: What is the value add over and above turbine and/or plant level?
Angle Stability	Yes –active power control, needs energy source. Note: more critical in beginning, when sync gens less to provide service, when hardly any sync gens then also need is less.	Same as turbine level – or easier?	Same at the hybrid level – or easier?
Damping	Yes: Needs an energy source so when wind is curtailed it can contribute this service. Competitiveness ok when energy has low value (surplus energy in the system).	Maybe: What is the value add over and above turbine level ?	Yes. Assuming storage is part of the hybrid story.
Protection	No. Power Electronics issue – by over rating them but this is expensive. Therefore, probably a no. Wind turbines and farms are expected to produce current in to low voltage events (faults) but to nothing like conventional plant. To system section: unknown, deep change is needed in protection relays once the conventional plant are all gone	No	No
Restoration	Maybe. But ONLY when the wind is blowing. Grid forming.	Maybe. What is the value add at the plant level?	Yes. Assuming storage is part of the hybrid story.

Main messages

- Wind turbines/plants are very performant generators with high controllability. Capabilities demonstrated for most services and already contributing to main grid support services.
  - grid forming…may require changes in the technology, hardware and software. Power electronics research, deployed in wind turbines.
- Simultaneous changes of future power systems – increasing VRE and electrification - lead to a high dimensional situation where maintaining supply demand balance reliably and at least cost is a multidimensional energy systems integration challenge:
  - Integrated design & operation needed!
  - Understanding system needs and technology boundaries is required
  - Transmission grid an enabler, and offshore grids have many R&D needs
- Plant controls have potential to enhance capabilities – need to strike a balance between driving down LCOE and potentially undermining the cost effectiveness or ability of providing other services
- Hybrids with storage can greatly enhance capabilities