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NATIONAL RENEWABLE ENERGY LABORATORY

Engineering Challenges of Airborne Wind Technology

Dr. Fort Felker

Director, National Wind Technology Center

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Potential Benefits of Airborne Wind Energy Systems

- Excellent wind resource
- High capacity factors and reduced variability
- Can extract wind energy over instead of on difficult terrain
- Reduced environmental impact
- May eliminate or mitigate land use conflicts

Having a Better Mousetrap is Not Enough!

- Potential benefits must be so compelling that hundreds of millions of dollars can be put at risk
- Technology must be sufficiently mature that it can pass a critical Due Diligence examination
- Technology must be sufficiently mature that insurance can be acquired at acceptable rates
  - Must insure the system against accidental loss
  - Must protect the owners from accident liability
- Increased cost of project financing for immature technologies can be fatal
- Engineering challenge to sufficiently advance Technology Readiness Level so that financial needs are met

Unique Niche for Airborne Wind Systems

Airborne wind needs:

- Low cost of wind turbines
- High reliability of aircraft

Reliability Requirements

- Reliability affects
  - Safety
  - Public perception
  - System development nonrecurring costs
  - Operations and maintenance costs
  - Power production (revenue!)
- Need a comprehensive approach to system reliability to address these diverse needs
- Need clear definition of all reliability requirements
- Reliability is expensive!

Risk Management

- Development, deployment and operation of airborne wind energy systems have unique risks

  Examples:
  - If you exclude certain weather from your design environment, how do you know it's coming?
  - Who decides to recover?
  - How much time is required to recover the system?
- Must follow a rigorous risk reduction process as these systems are developed
- Different set of issues for system operations, but need for risk management remains

Design and Verification Standards

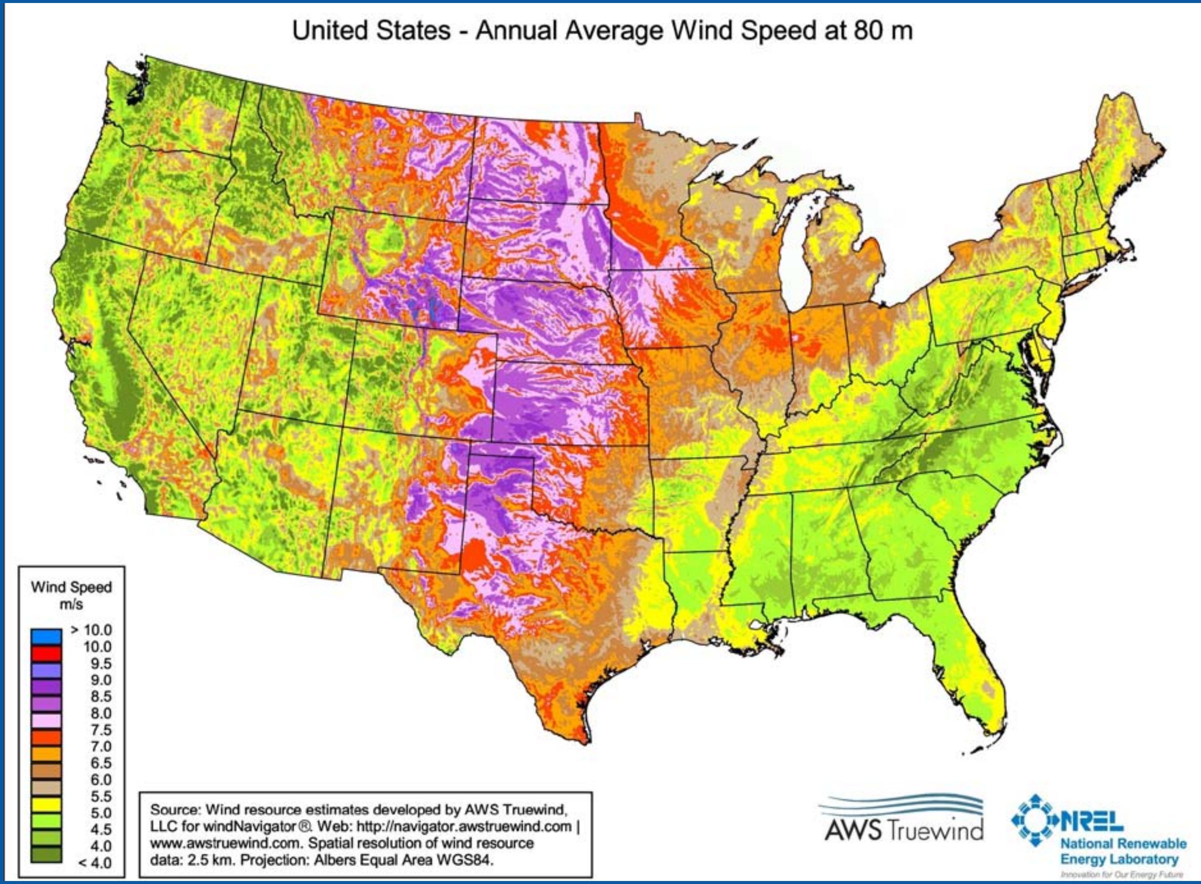
- Complete set of standards for design, verification, manufacture and operations of aircraft – Title 14 of the Code of Federal Regulations
- Modest set of standards for wind turbines – International Electrotechnical Commission 61400
- <u>Nothing</u> exists for airborne wind energy systems
- No basis for Certification or 3rd party assessment of designs (who is Certifying body?)
- Serious bar to rigorous Due Diligence process
- Must get started defining standards immediately – it takes time!

Resource Assessment

To start, mesoscale models developed for wind turbines can be “queried” at higher elevations

Need much more than average wind speed!

- Wind speed probability distribution
- Turbulence
- Vertical shear
- Extreme winds
- Extreme coherent gusts
- Temperatures
- Probability of thunderstorms, hail, icing, tornados, hurricanes



Design Environment

- Different issue than resource assessment!
- Design environment involves choices:

  Will the system be operated in
  - Thunderstorms and lightning
  - Hail
  - Icing
  - Tornados
  - Hurricanes
  - Severe storms (how severe?)
  - High winds (how high?)
- What is the maximum operating wind speed? What is the minimum?
- What is the design envelope for turbulence, gusts, etc?

Design Load Cases

- Definition of comprehensive set of Design Loads Cases is critical
- Must encompass sufficient range of conditions to adequately address entire system lifetime
  - Operational cases, static and dynamic
  - Launch and recovery process
  - Adverse operational environments (e.g. flutter with icing present)
  - Extreme events
  - Partial failure cases
  - Electrical and control system faults
- Must constantly recalculate Design Loads Cases are system configuration evolves

Margins of Safety

- Must establish structural margins of safety
- Aircraft use 1.5. Wind turbines use different factors on loads and on structure
- Must define approach for fatigue analysis
  - Design life
  - Fail safe
  - On condition
  - Damage tolerant
- What is required margin for flutter?
- Want most likely system failures to be handled routinely without loss of entire flight vehicle. Must define these failure cases.
- How much damping is required to be present for normal operational aero-servo-elastic modes?

Simulation and Analysis

- Impossible to test all design conditions
- Must have a complete set of simulation and analysis tools to predict
  - Steady and dynamic loads
  - Aero-servo-elastic stability
  - Stability and control (flight dynamics)
  - Dynamics of launch and recovery process
  - Dynamic response to faults and failures
- These tools must be validated with test data for wide range of conditions for the actual system configuration
- Must validate the tools <u>and</u> the input data

Control Systems

- Control system attributes:
  - Autonomous with ground override
  - Redundant and fault tolerant
  - Must automate launch and recovery
  - Will need to sense operational environment and adapt
- Development of control systems for aircraft has become long expensive process
- Need for autonomy complicates control system development for airborne wind systems
- Having a system that appears to work correctly is only half the battle – must then document, validate, and demonstrate to 3rd party

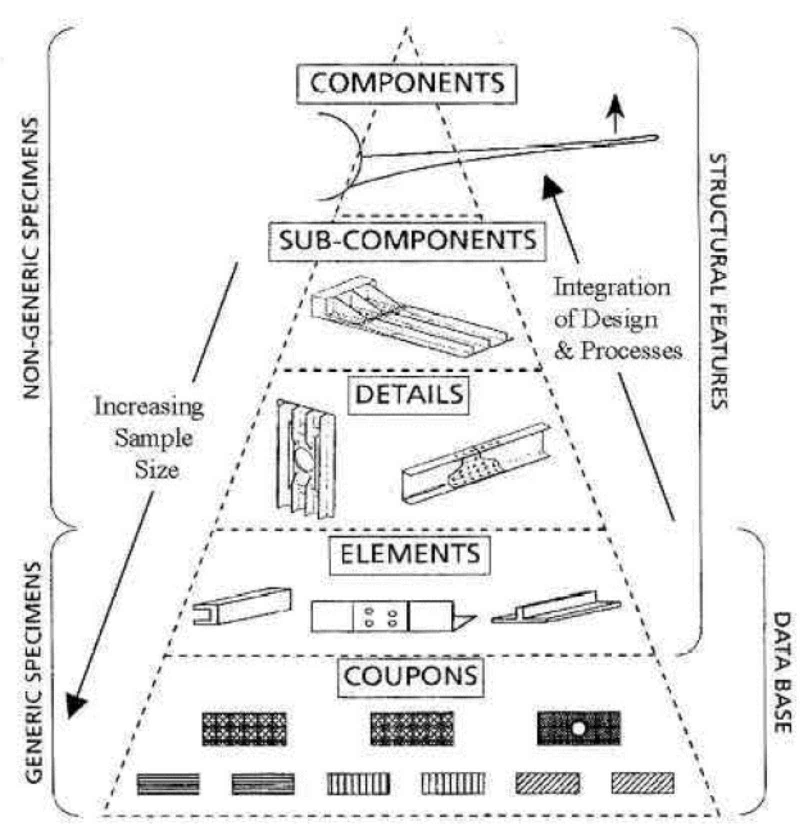
Aero-servo-elastic Stability

- Systems will inevitably grow in size, and become more flexible
- Aeroelastic stability will eventually become a design driver
- Airborne wind energy systems have relatively low Mach numbers
- Linear potential flow analysis, with Prandtl-Glauert corrections, should be sufficient
- Commercial versions of NASTRAN available with required aerostructural modeling capability
- Still requires lengthy and difficult process to build and verify models for novel configurations
- Little knowledge of modes of instability of novel configurations

Verification and Validation

- No substitute for testing
- Companies that have a robust program of component and field testing are more likely to succeed
- Consider establishment of 1-year and 5-year field tests as important milestones
- Need to complete comprehensive set of component Highly Accelerated Life Tests (HALT)
- Sufficient instrumentation required to validate simulation results, and predict fatigue life
- Should partner with 3rd-party test facilities to provide independence and credibility

Comprehensive Testing Required



Environmental Impacts

- Environmental impacts cannot be ignored – to produce 1% of US electricity requires 15,000 1MW systems
- Many lessons to be learned from wind industry
- Form and fund direct partnerships with environmental advocacy groups to guide approach (e.g. Audubon Society)
- Be sure to address human impacts as well, such as change in "Viewscape"
- Environmental impact assessments are data driven – go get the needed data!
- Common issues across companies and technologies – should collaborate

Lifecycle Cost Modeling

- With all these details settled, can now assess overall costs
  - Development cost
  - Manufacturing and deployment cost
  - Cost of financing
  - Operations and maintenance cost
  - Replacement cost
  - Decommissioning cost
- Use systems engineering model to optimize
- Use model to inform directions for future R&D investment

Summary and Recommendations

- Must explicitly define all system reliability requirements
- Use an integrated risk management approach to meet these requirements
- Certification Standards urgently needed to
  - Define design environment
  - Define design loads cases
  - Define margins of safety
  - Permit 3rd party assessment and Certification
- Major effort required to develop and validate simulation tools
- Test, test, test, test, test
- Test some more

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Thank you!

Questions?

Dr. Fort Felker
Center Director
National Wind Technology Center

Contact Information:
Phone: 303-384-6905
Email: fort.felker@nrel.gov