Grand Challenges and Wind Energy Systems Engineering beyond LCOE:

Wind energy economic, social, environmental value

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Wind Energy Systems Engineering Workshop

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The Question hasn’t changed: What will it take to achieve 50% or more of the global electricity supply from wind energy?

We still need answers…

From 0.6 to 6 TW of wind globally

The “OG” Grand Challenges of Wind Energy Science included:

- The **physics of atmospheric flow**, especially in the critical zone of wind power plant operation
- The **system dynamics and materials** of the largest, most flexible machines that have yet to be built
- **Optimization and control of fleets of wind plants** made up of hundreds of individual generators working **to support the electric grid**

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REVIEW

Grand challenges in the science of wind energy

Paul Veers[1,*], Katherine Dykes[2,*], Eric Lantz[1,*], Stephan Barth[3], Carlo L. Bottasso[4], Ola Carlson[5], Andrew Clifton[6], Johney Gr...

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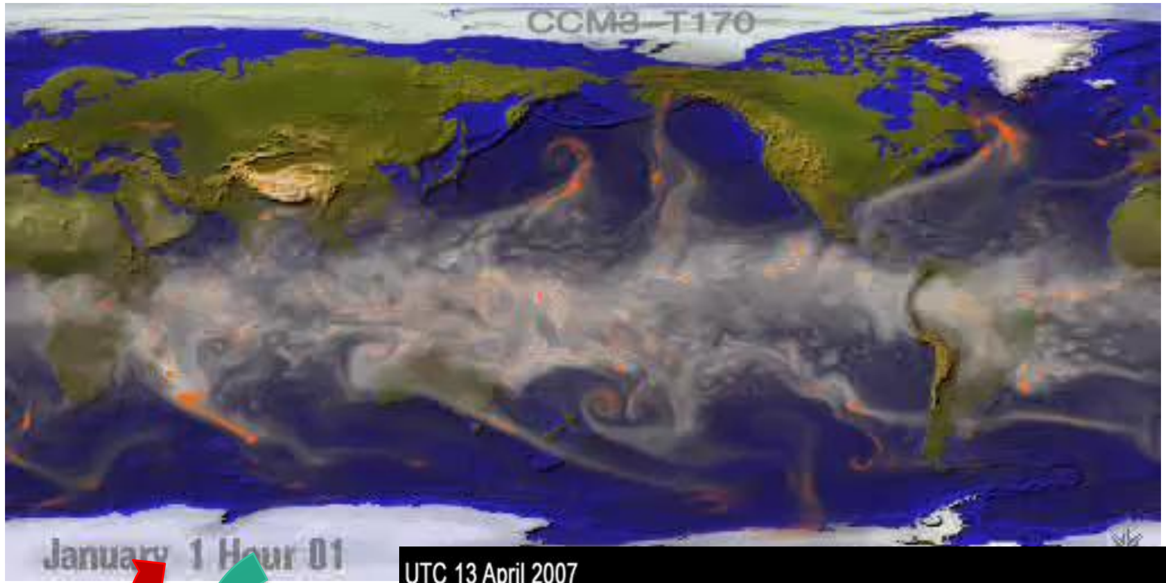
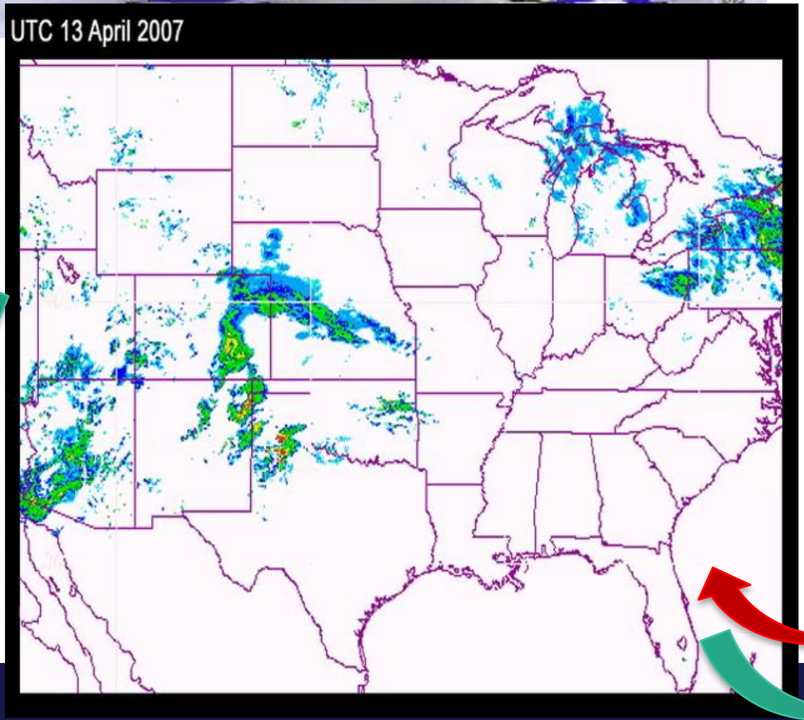
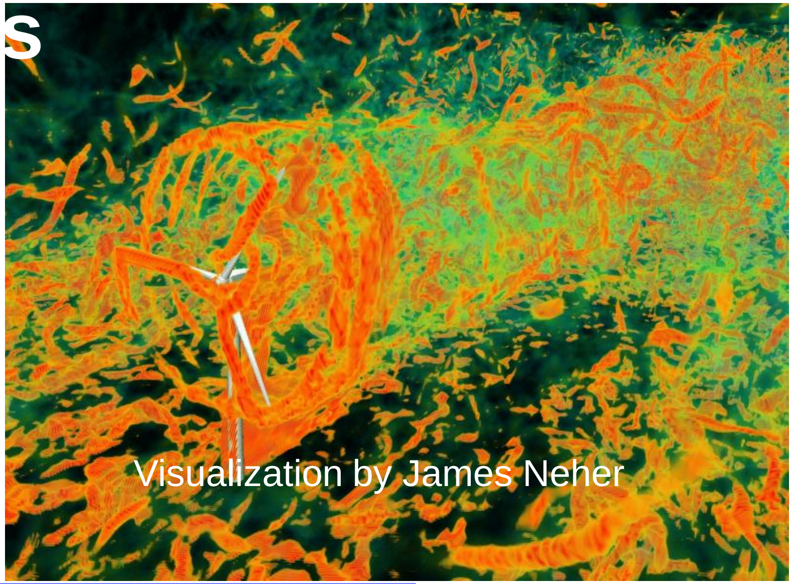
https://science.sciencemag.org/content/early/2019/10/09/science.aau2027

Grand Challenge 1: The Wind (and Sea)



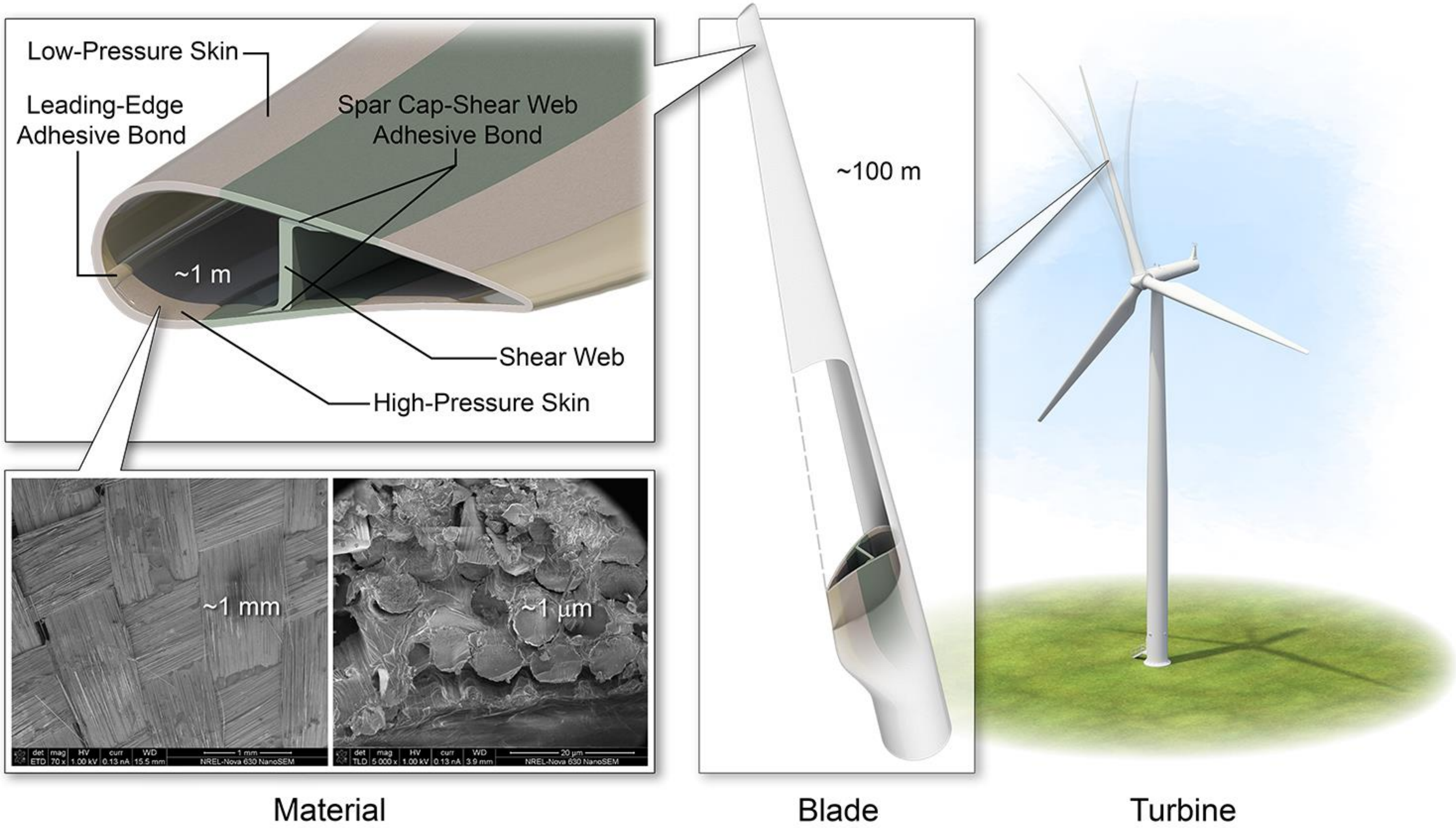


Courtesy Sue Haupt of NCAR and colleagues

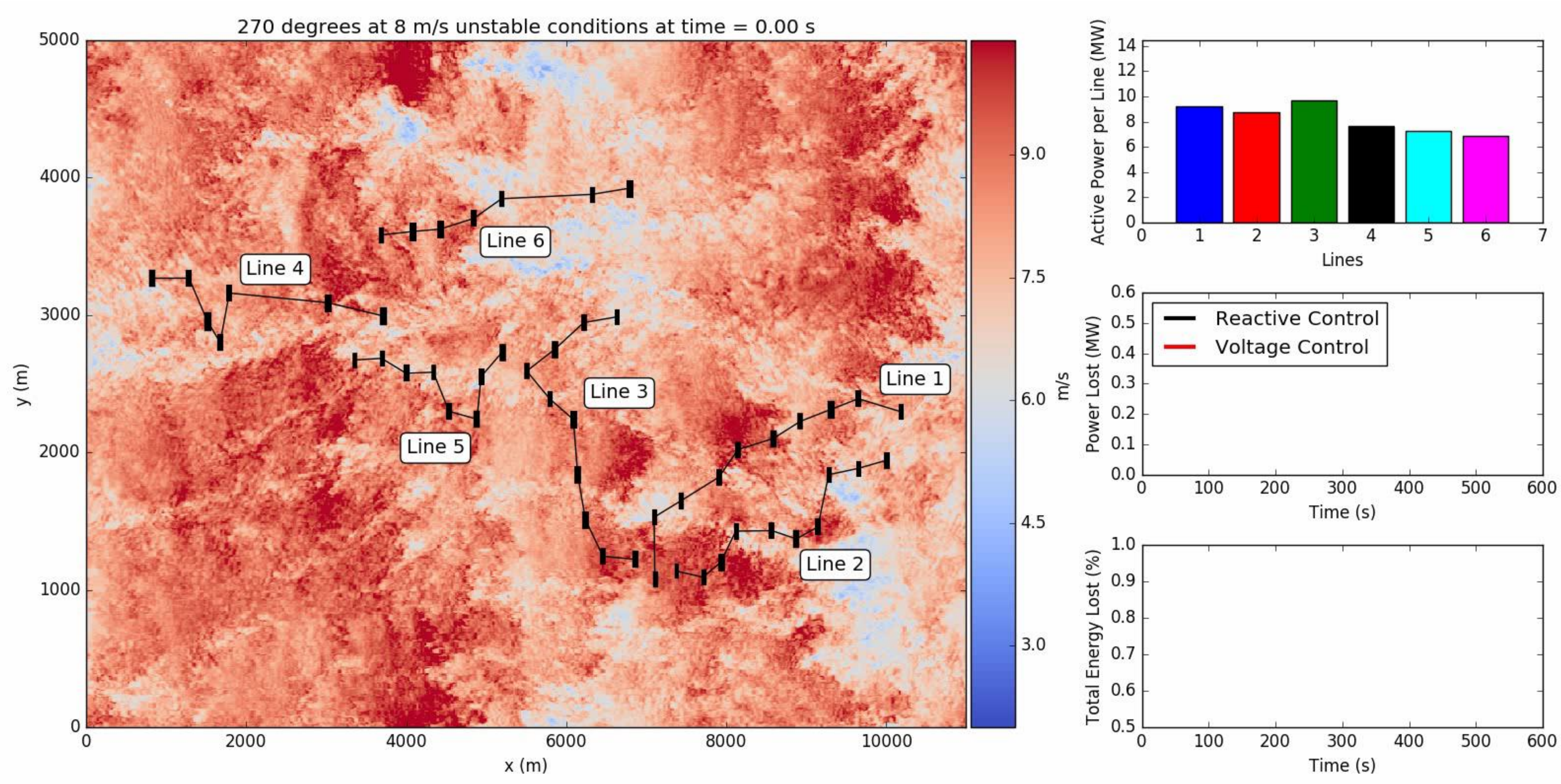


Courtesy Jeff Mirocha, LLNL

Grand Challenge 2:
Wind Turbines, the Largest Rotating Machines on Earth



Grand Challenge 3: Fleets of Wind Farms Driving The Grid

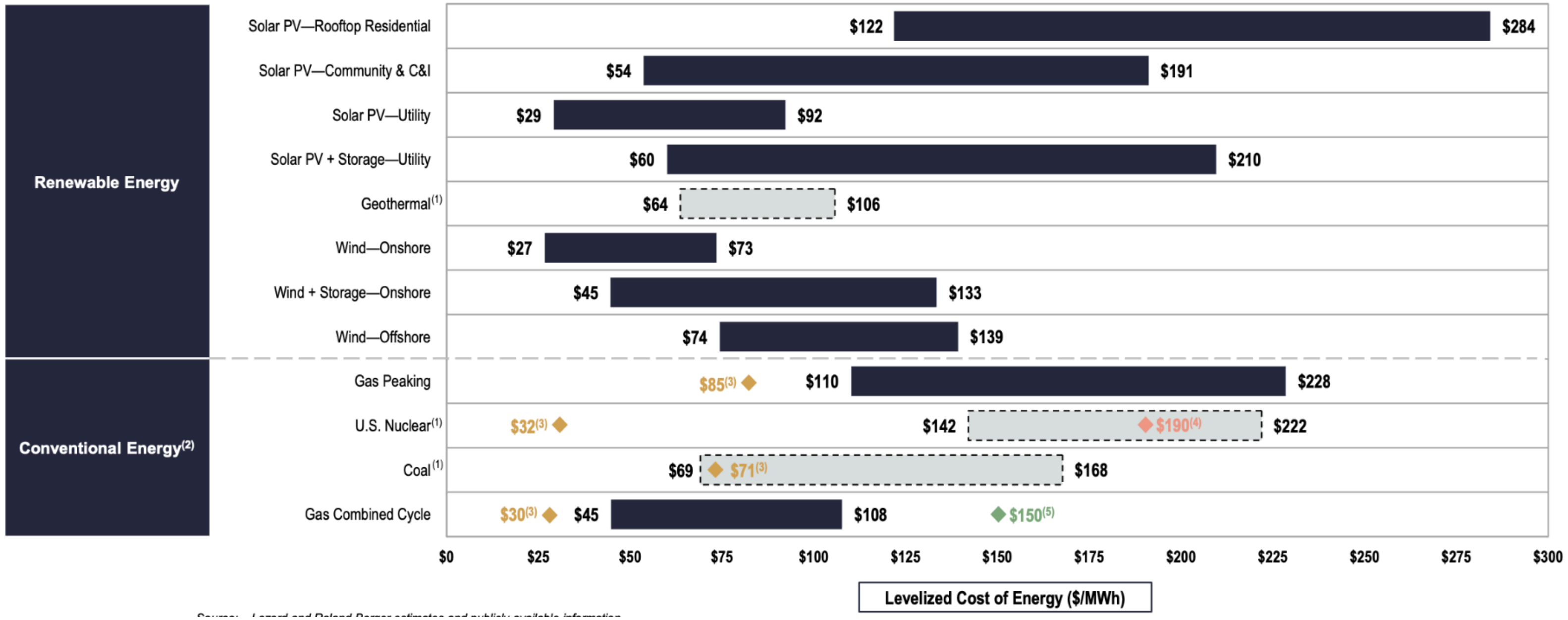


Courtesy Patrick Moriarty, NREL

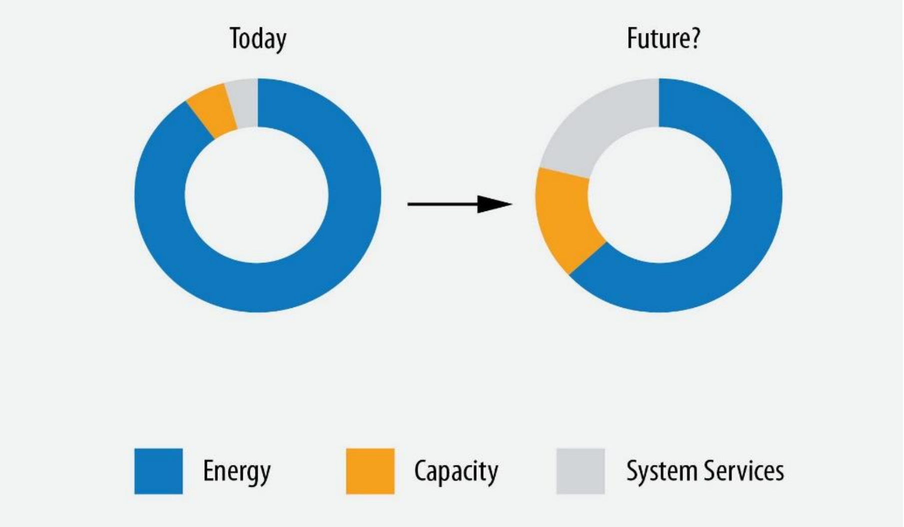
Optimal electrical control depends on atmospheric conditions and grid

Persistent Challenges: To Realize the Potential of the Resource, Costs Will Need to Continue to Fall

Wind energy still competitive in many places globally on LCOE



Source: Lazard June 2024



But markets are changing and LCOE will not be enough

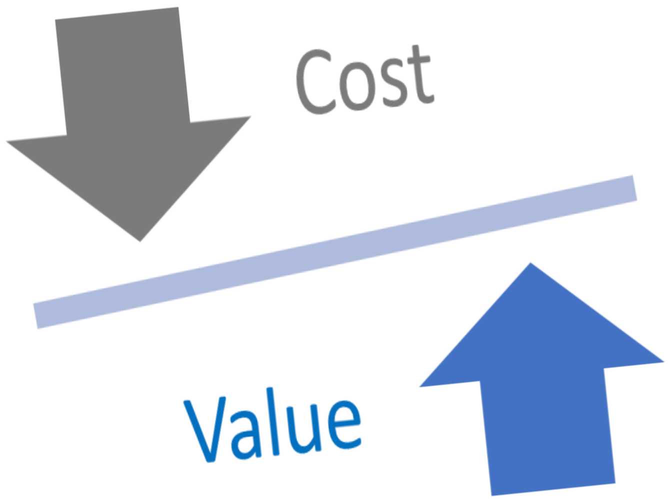
Source: Dykes et al 2019 based on Ahlstrom et al 2015

Persistent Challenges: Options for wind energy in a changing environment

Success of wind energy in the future:

- If storage, power-to-x ubiquitous, highly elastic demand, then do nothing, focus on cheap electrons (**LCOE**)

- If dispatchability, capacity value dominate revenue, then rethink options and increase value of wind energy (**Beyond LCOE**)



Persistent Challenges: But there is more!

- Local:
  - – Community impacts
  - – Environmental habitats and species

- Regional / national:
  - – Supply chain and workforce
  - – Cybersecurity
  - – Energy security

- Global:
  - – Emissions, waste, materials, energy impacts

From 0.6 to 6 TW of wind globally

- The Grand Challenges of Wind Energy Science include:
  - The **physics of atmospheric flow**, especially in the critical zone of wind power plant operation
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  - **Optimization and control of fleets of wind plants** made up of hundreds of individual generators working **to support the electric grid**


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What makes for a successful business case for wind energy?

Beyond LCOE means many things: economics, supply chain, cybersecurity, environmental, social, and so on…

New Generations of Wind Energy Face Different New* Requirements / “Needs”

and these are typically additive

Generation 1: Pioneering

- Produce electricity
- Don’t break

Generation 2: Industrializing

- Compete on cost
- Adhere to grid requirements
- Limit adverse local environmental and social impacts

Generation 3: Mainstreaming

- Compete on (economic) value
- Serve the system
- Contribute to global climate and environmental objectives
- Contribute to broader sector development and a just energy transition

Generation 4: System Defining

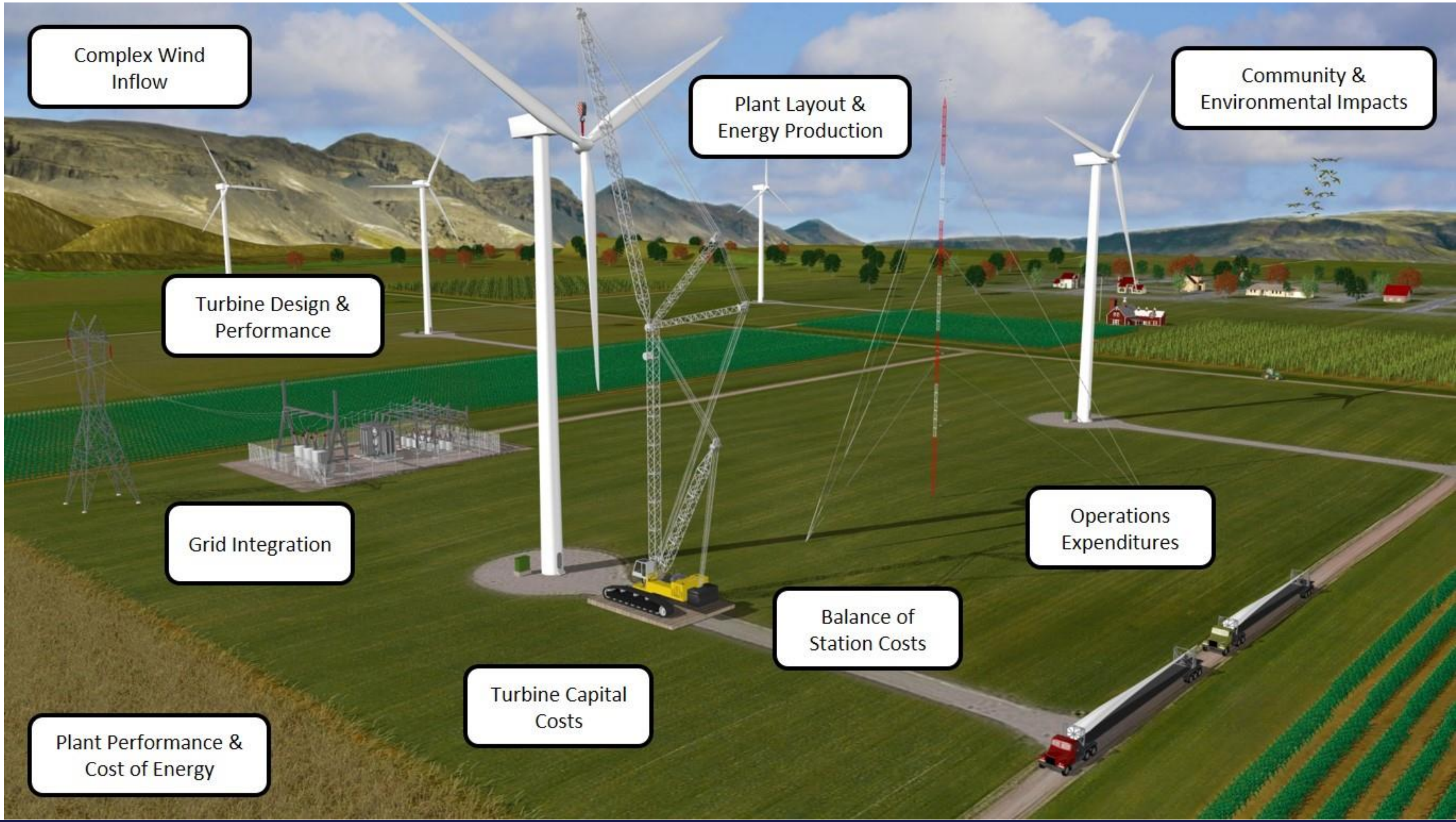
- Compete on non-price (non-economic) criteria
- Form the system
- Lead decarbonization of the global energy system
- Realize benefits to the environment and communities

You are Here

Wind Generations, Source: Kitzing, Torque 2023

The Answer is?
Systems Engineering for Wind Energy!

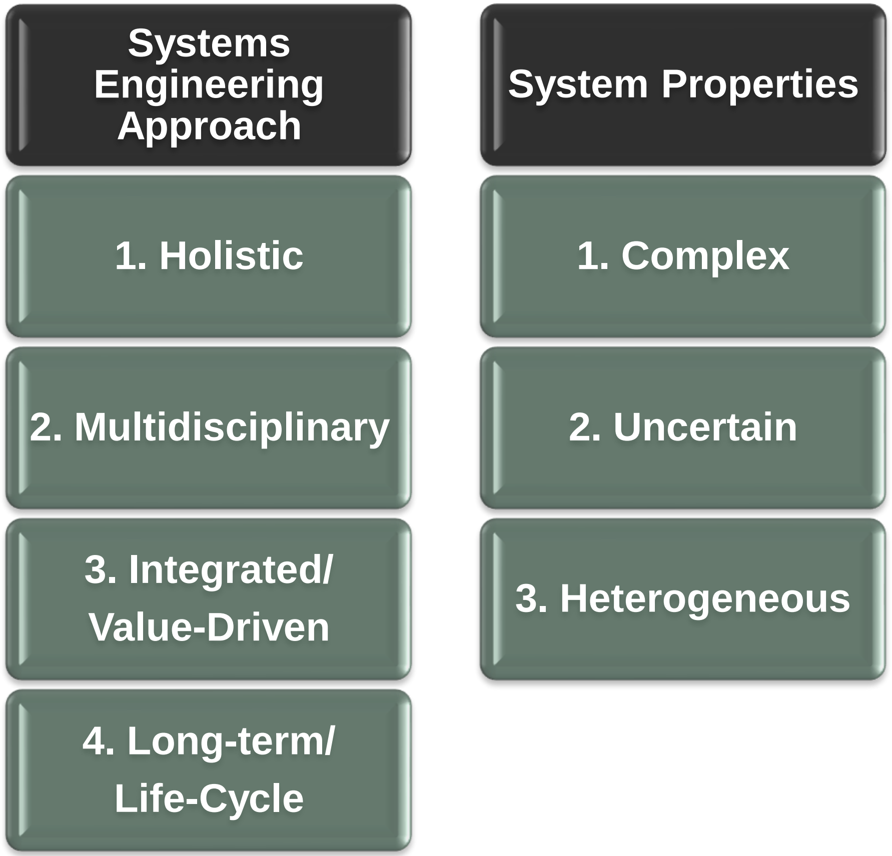
Wind energy systems are complex and couple many sub-systems and components together, described by numerous physical phenomena and disciplines (from the atmosphere to the electrons)



The Answer is?
Systems Engineering for Wind Energy!

- Various methods of systems engineering applied to aerospace, automotive and other technologies
  - Design optimization and concurrent engineering
  - Supply chain management
  - Reliability engineering
  - Cost engineering

- Target broad system boundaries (component to turbine to plant to grid)



Source: Dykes et al 2011

How do we rethink wind farm design and operation for objectives of value?

System Design, Operation and Control for Beyond LCOE Metrics

First: A History Lesson

Energy Optimization Software: A bad idea in practice

- RES has developed various optimization software over the years

SIMPLEX ALGORITHM (> 10 years ago) → GENETIC ALGORITHM (8 years ago) → SIMULATED ANNEALING (7 years ago) → SOFTWARE DISCONTINUED (2010)

- Why did we discontinue it?
  - Complex site constraints
    - Software could deal with this, but very time consuming entering all into software
    - Inevitably some ‘real world’ constraint missed (less value in the optimization)
      - Contractual: E.g. Landowner ‘A’ has stipulation of minimum MW
      - ALTA survey (late in dev. cycle) reveals pipelines, easements, microwaves, etc
      - Many times governed by noise constraints: Complex analysis in itself
  - Wake models and wind flow models don’t have required level of accuracy
    - See following slides: Can’t do an optimization if the inputs (models) aren’t correct
  - Many layouts end up ‘designing themselves’ and when they don’t ….
  - …. an experienced practitioner can get extremely close to the optimized solution

1st Wind Energy Systems Engineering Workshop Presentation

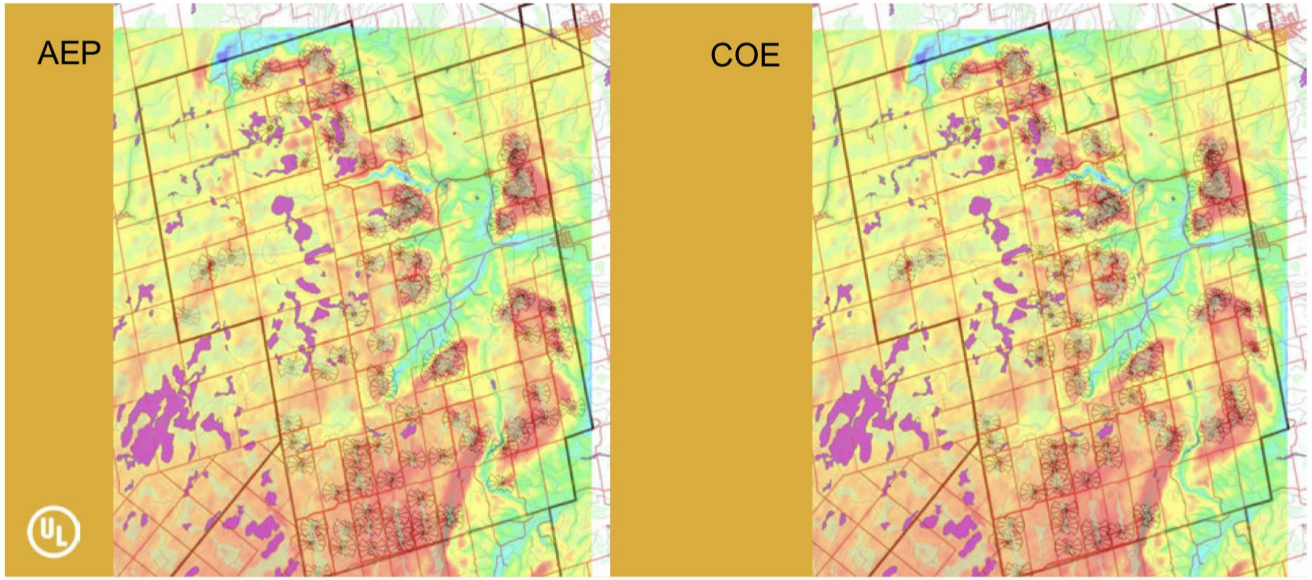
https://www.nrel.gov/wind/assets/pdfs/se_workshop_oliver.pdf

Systems Engineering: Proving our worth

- Built in key cost elements necessary to move from AEP to LCOE optimization applied to wind turbine and farm design

Objective Function	Net Energy [GW]	BOP Cost [$]	LCOE [$/MW]
AEP	1101 100%	51 100%	38.49 100%
COE	1096 99.6%	46 90.2%	38.3 99.5%
IRR	1094 99.4%	46 90.2%	38.38 99.7%

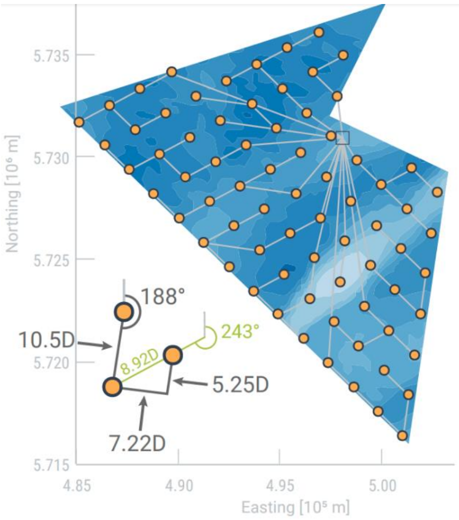
Results

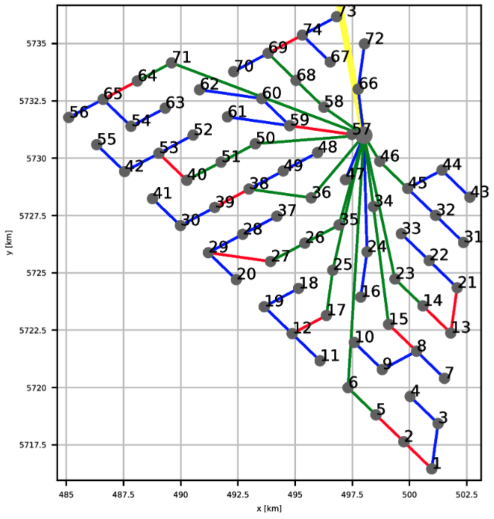


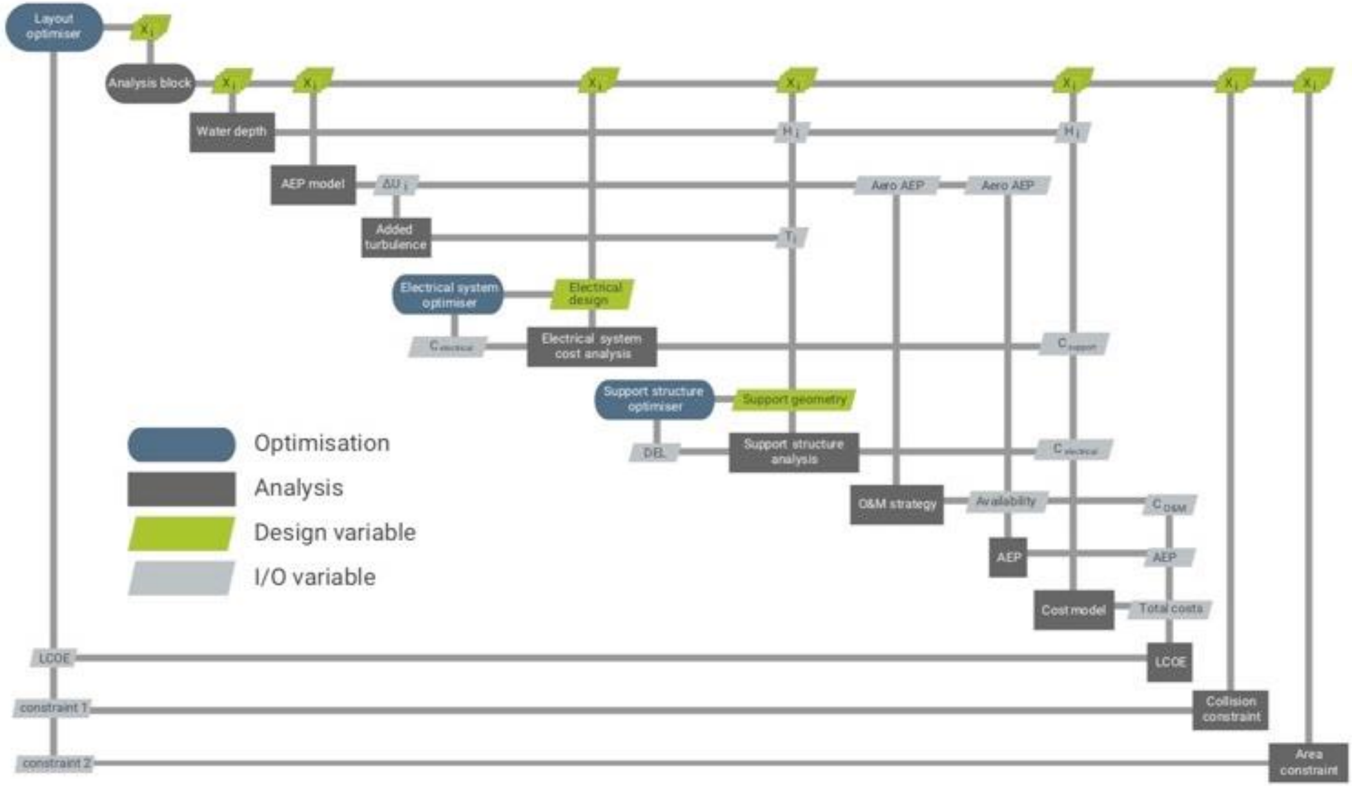
Source: 4th Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se17-8-ul-renewables.pdf

Systems Engineering:
More and More Advanced Optimization

- Optimization use in site design now widespread
- More sophisticated modelling for energy, site suitability, control strategies, foundation design, electrical infrastructure, logistics, and so on...







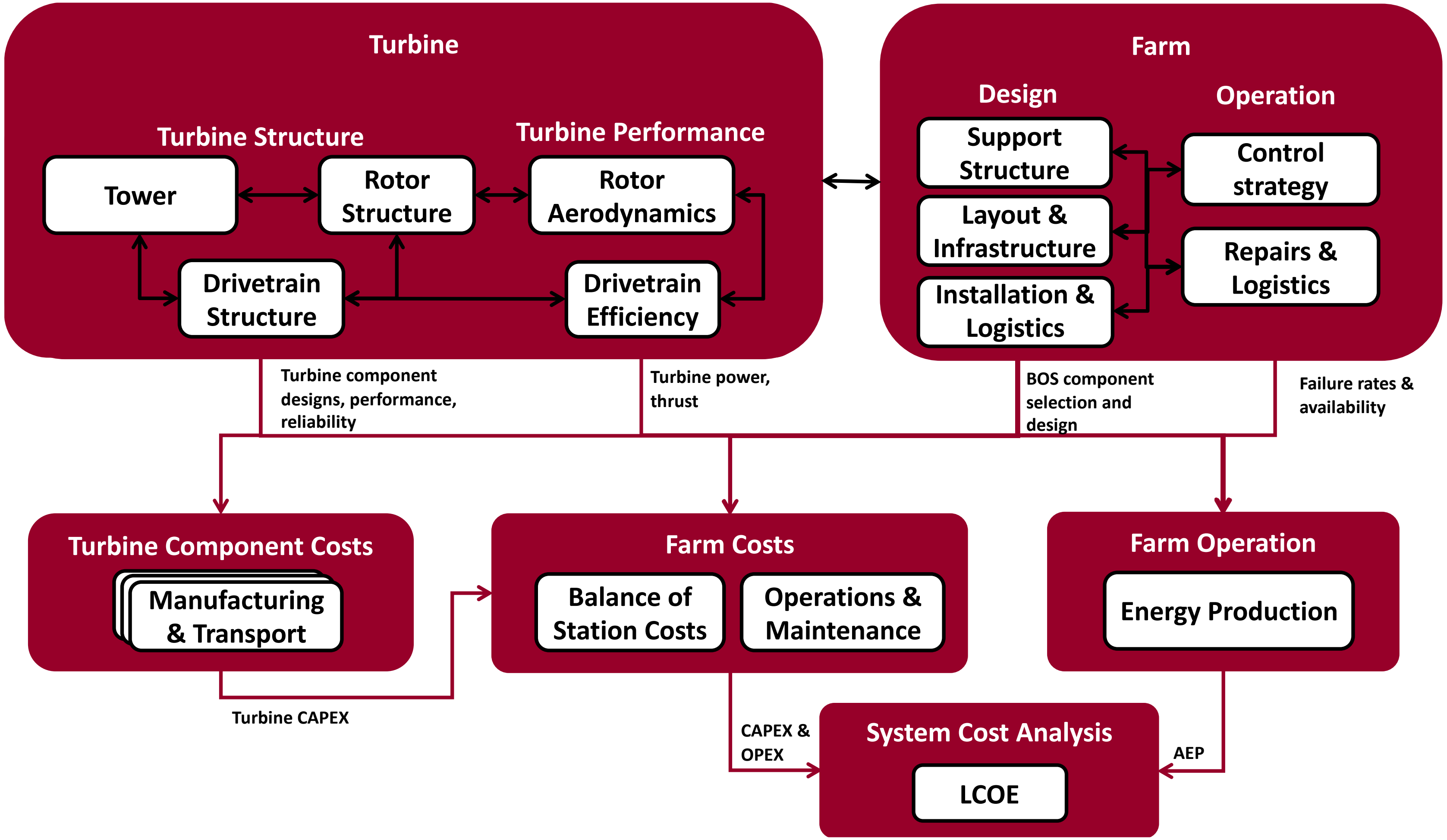
Example wind plant layout optimization workflow for an offshore reference wind plant (Source: Sanchez Perez-Moreno et al 2017)

LCOE:
A Gold Standard in Innovation and Technology Evaluation

$$LCOE = \frac{CAPEX * FCR + OPEX}{AEP}$$

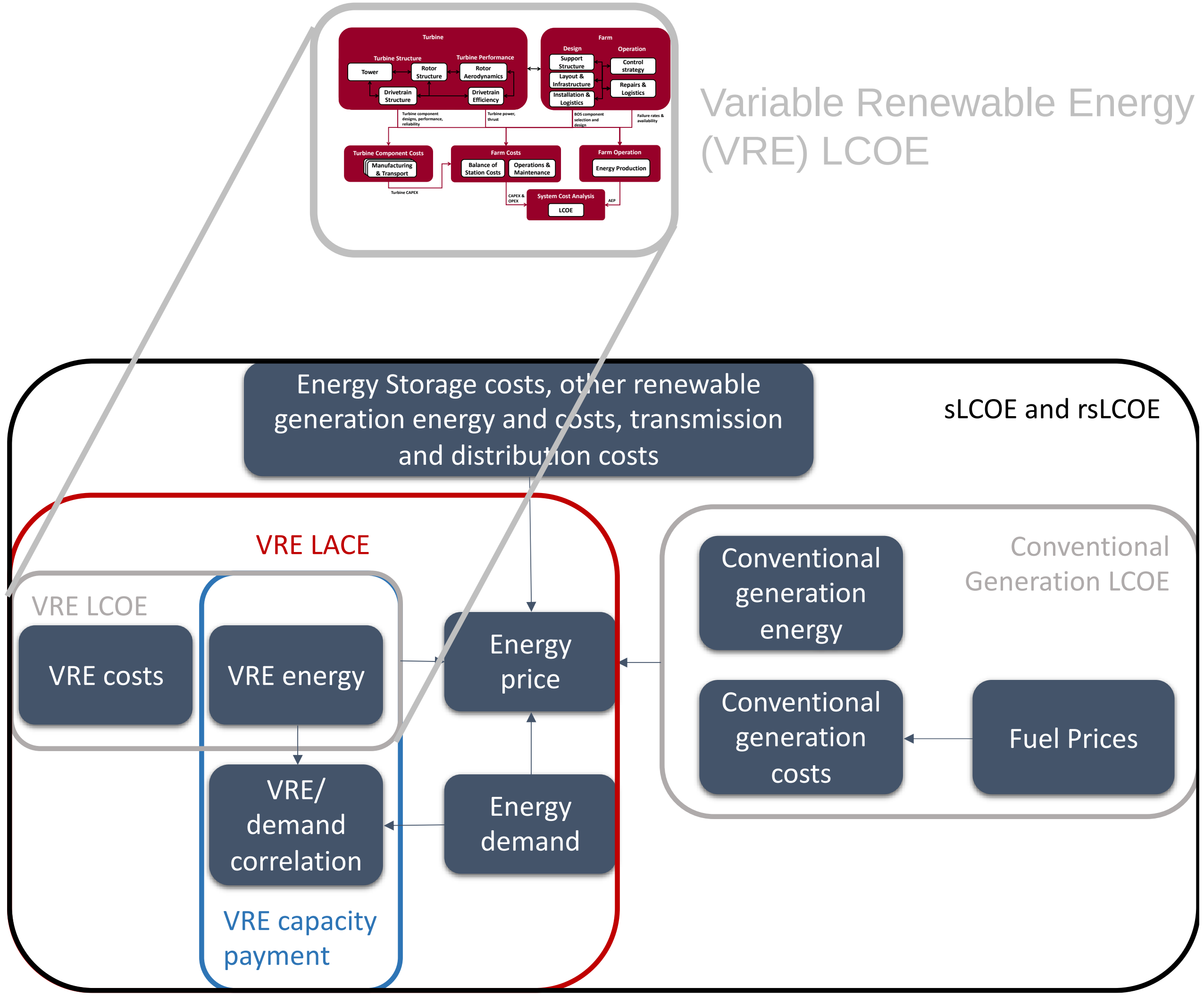
– LCOE is complex and involves a large scope and timeframe with many sub-systems and disciplines including both physical and cost modelling of the system

– Significant couplings (e.g. farm layout → support structures, collection system, energy production)



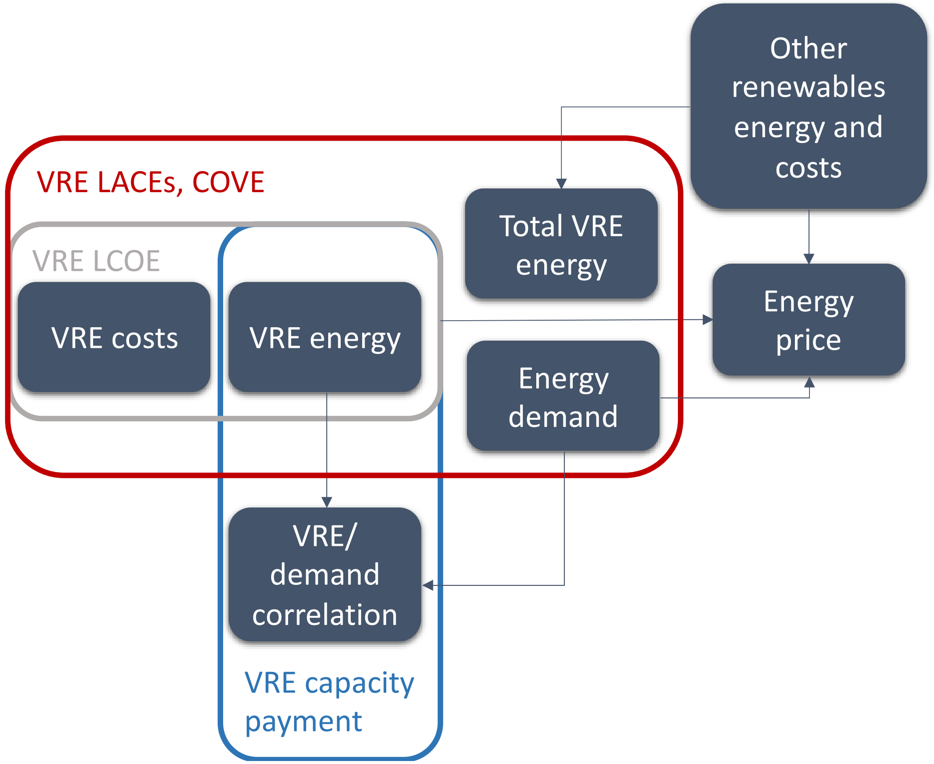
From LCOE to Beyond LCOE

- LCOE is complex, but going *Beyond* LCOE adds further complexity:
  - Time-varying revenues from markets – that also evolve over time
  - System context in terms of generation mix, transmission infrastructure, demand profile
  - Evolving policy and regulatory context
  - Effects of uncertainties from many sources
- Can move to metrics such as System LCOE (sLCOE)



From sLCOE to COVE

- sLCOE is difficult to assess:
  - Heterogeneous: generation mix, transmission infrastructure, demand elasticity, storage, sector-coupling, etc
  - Uncertain: system technical, market and regulatory characteristics evolve over time
- Use statistical / surrogate models to address system complexity (and explicitly address uncertainty if you can)
- Cost of Valued Energy (COVE) is a stastical model relating revenue to share of wind in an energy system



Simpson J, Loth E and Dykes K 2020 Cost of valued energy for design of renewable energy systems Renewable Energy 153 290 – 300 ISSN 0960-1481

Metrics for Beyond LCOE system design and operation

LCOE-world metrics	Beyond-LCOE-world metrics
AEP	Levelized Revenue of Energy (LROE)[1]
LCOE	COVE[2]
Capacity Factor (CF)	Capacity Value

- Analogues of traditional LCOE-world metrics can be made in the new Beyond-LCOE-world
- Metrics from each column will push wind and renewable machine and plant design, operation and control optimization in different directions

[1]*Philipp Beiter, Lena Kitzing, Paul Spitsen, Miriam Noonan, Volker Berkhout, Yuka Kikuchi, "Toward global comparability in renewable energy procurement," Joule, 2021, ISSN 2542-4351,* https://doi.org/10.1016/j.joule.2021.04.017 .

[2]*Simpson J, Loth E and Dykes K 2020 Cost of valued energy for design of renewable energy systems Renewable Energy 153 290 – 300 ISSN 0960-1481*

Examples of Beyond LCOE Across the Full Life-Cycle – Engineering the Business Case

Site / Technology Selection

- Storage
- Power-to-x
- Additional energy technologies
- Turbine type(s)

Technology Sizing

- Capacity of each generation and storage asset
- Electrical system topology

Site Design

- Detailed site layout
- Detailed collection and balance of system design

Project Operation

- Lifetime operation of the project balancing revenues and ccosts

Real Challenges!

Beyond LCOE Case Study: Sizing

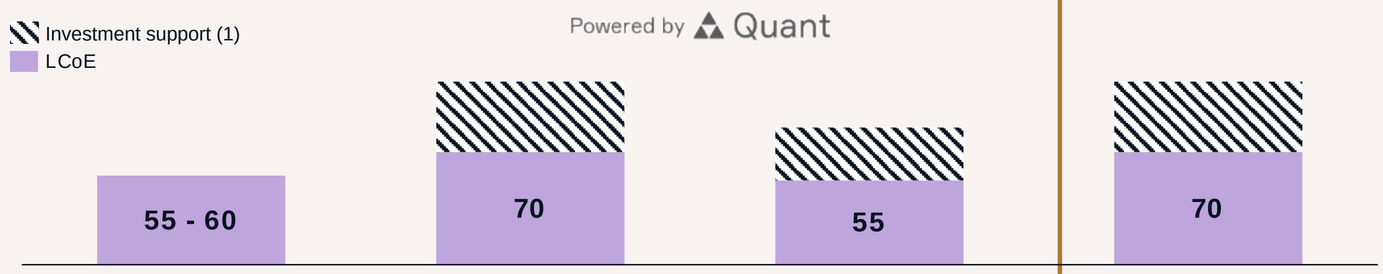
- Sweden's government is considering aggressive nuclear subsidies (75% CAPEX!) at a contract price of 70 EUR/MWh

- Does Sweden *need* nuclear? What if the subsidies were technology agnostic?

- How would we optimize the design of a wind + storage system to meet different "functional requirements" for the grid while still turning a profit?

Analysis of Offshore Wind + Storage for Baseload in Sweden

	Baseline	Scenario 1	Scenario 2	Scenario 3
Grid connection, (MW)				
OSW capacity, (MW)				
Battery energy, (MWh)[2]				
LCoE, Real 2024, (EUR/MWh)[3]	55 - 60	70	55	70
Capacity factor, (%)	50%	80%	80%	85%
100% Grid Feed freq. (proxy to baseload), (%)[4]	N/A	65%	65%	80%



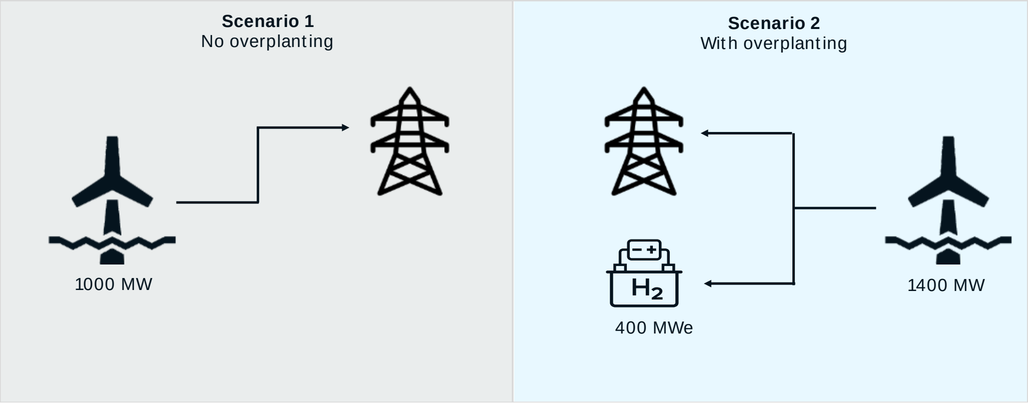
Source: Aegir Insights

Beyond LCOE Case Study: Design

- Denmark launched offshore wind tenders with a unique structure:
  – 6 tenders each of minimum ~1 GW capacity (and 1 GW grid interconnection capacity)
  – Overplanting opportunities planned for H2 production (up to roughly 10 GW potential)

- How do you design a plant layout considering optional overplanting capacity? How does that factor into your LCOE and make (or break) the business case? How do the risks change and what (real) options might developers use?

Analysis of Overplanting for Danish Offshore Wind Tenders



Powered by Quant

Hydrogen offtake price	Likeliness of profitability in scenario 1	Required LCOE reduction to get profitability in scenario 1	Likeliness of profitability in scenario 2	Required LCOE reduction to get profitability in scenario 2
Benchmark 4 EUR/kg	Low High		Low High	
Optimistic 7 EUR/kg	Low High		Low High	

Source: Aegir Insights

Beyond LCOE Case Study: Operation

- Kriegars Flak II project recently cancelled citing adverse market conditions. Can we make the business case by adding batteries by participating in multiple markets?

- Shifting to operation for multiple markets yields a better NPV and IRR, but the LCOE is worse because you are allowing for curtailment (i.e. no longer maximizing for AEP).

- Battery storage provides additional revenue opportunity by adjusting the timing of electricity generation (i.e. via arbitrage)

Analysis of Onshore Wind + Storage Operation for Different Markets

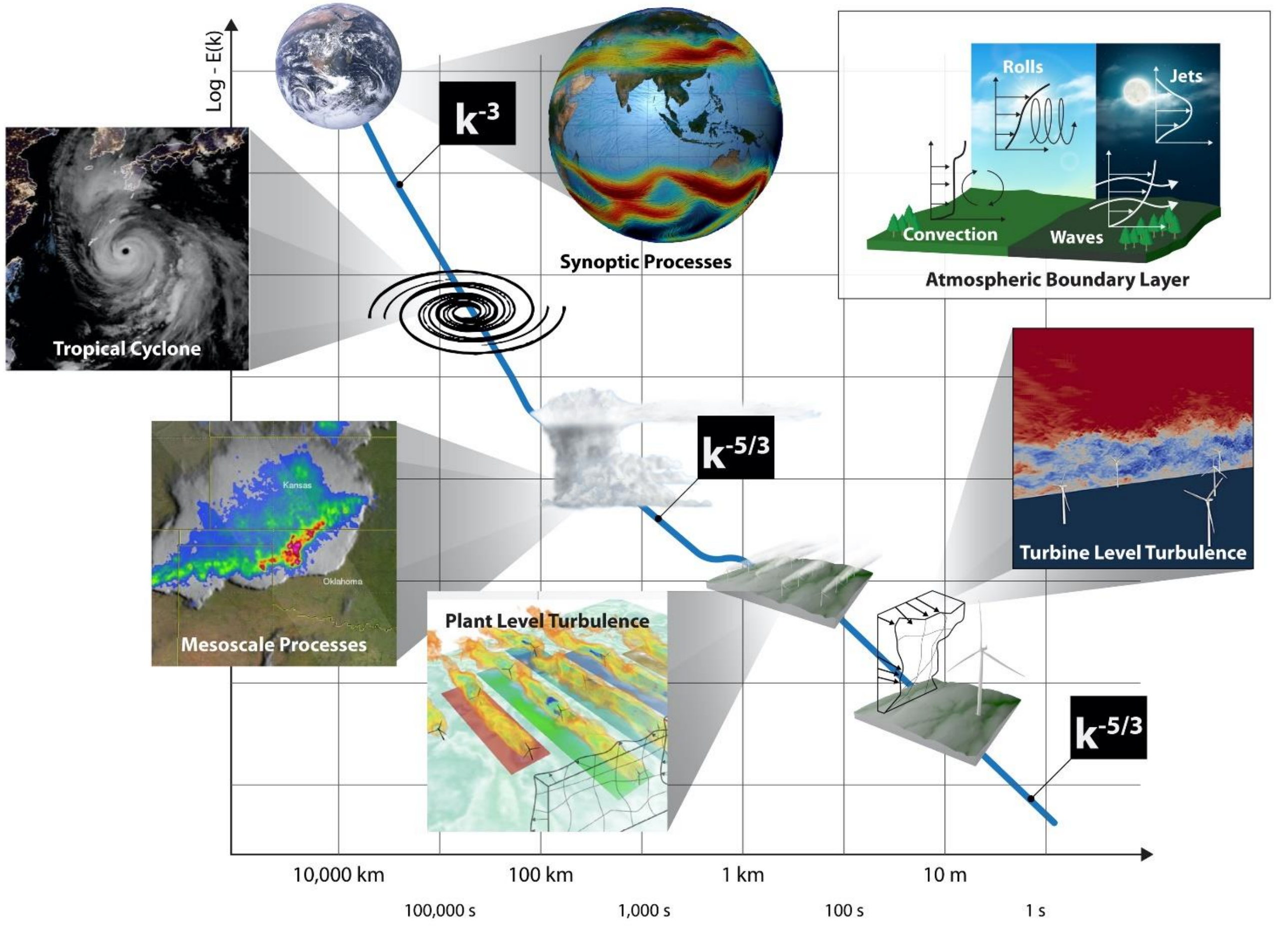
	No Balancing	With Balancing markets
Capacity (Wind)		
Battery Power		
Battery Duration		
CAPEX delta from base, %		
NPV, EURm		
IRR		
Revenues, EURm		
LCOE, EUR/MWh		

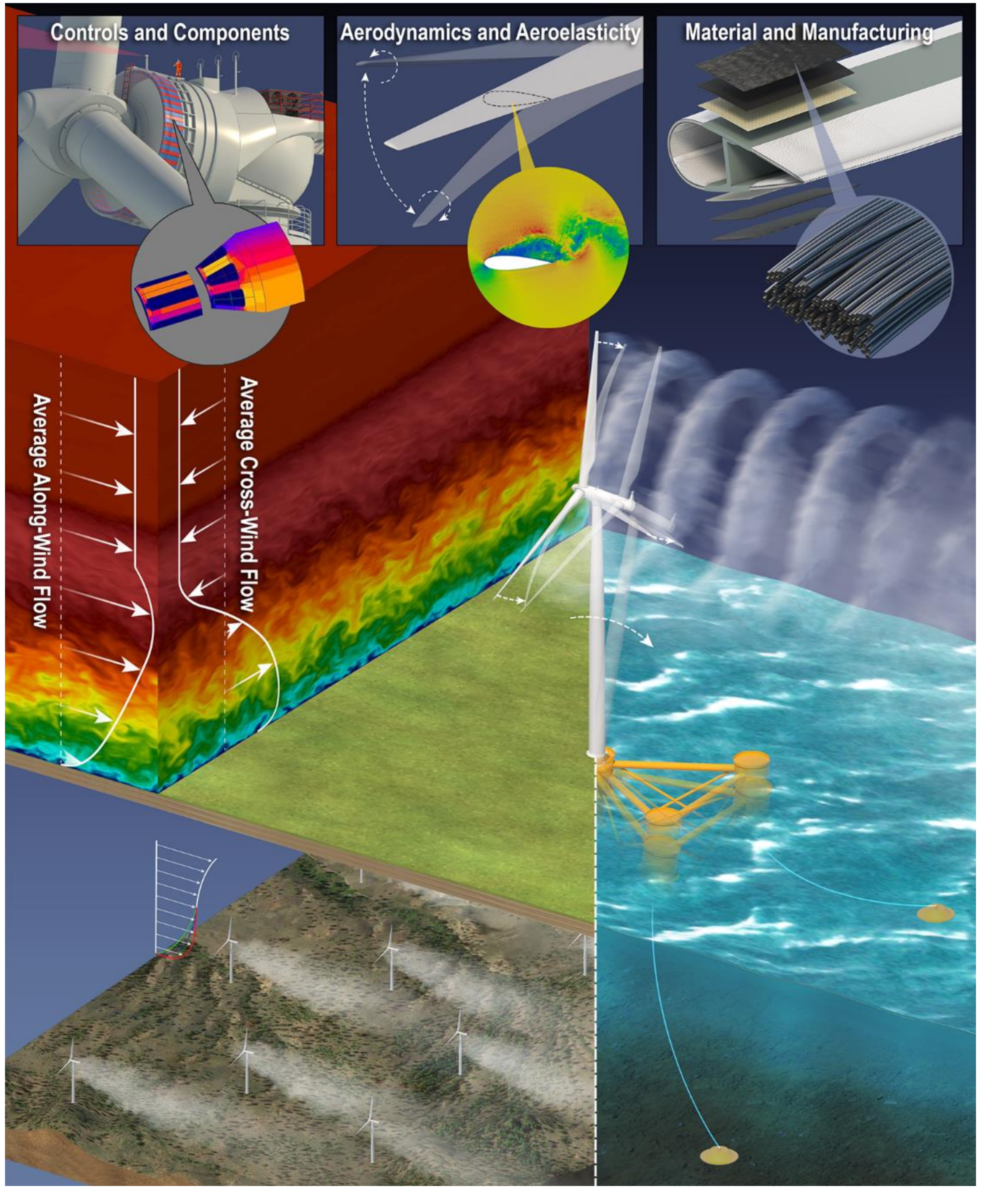
Source: Aegir Insights

Where do we go from here?

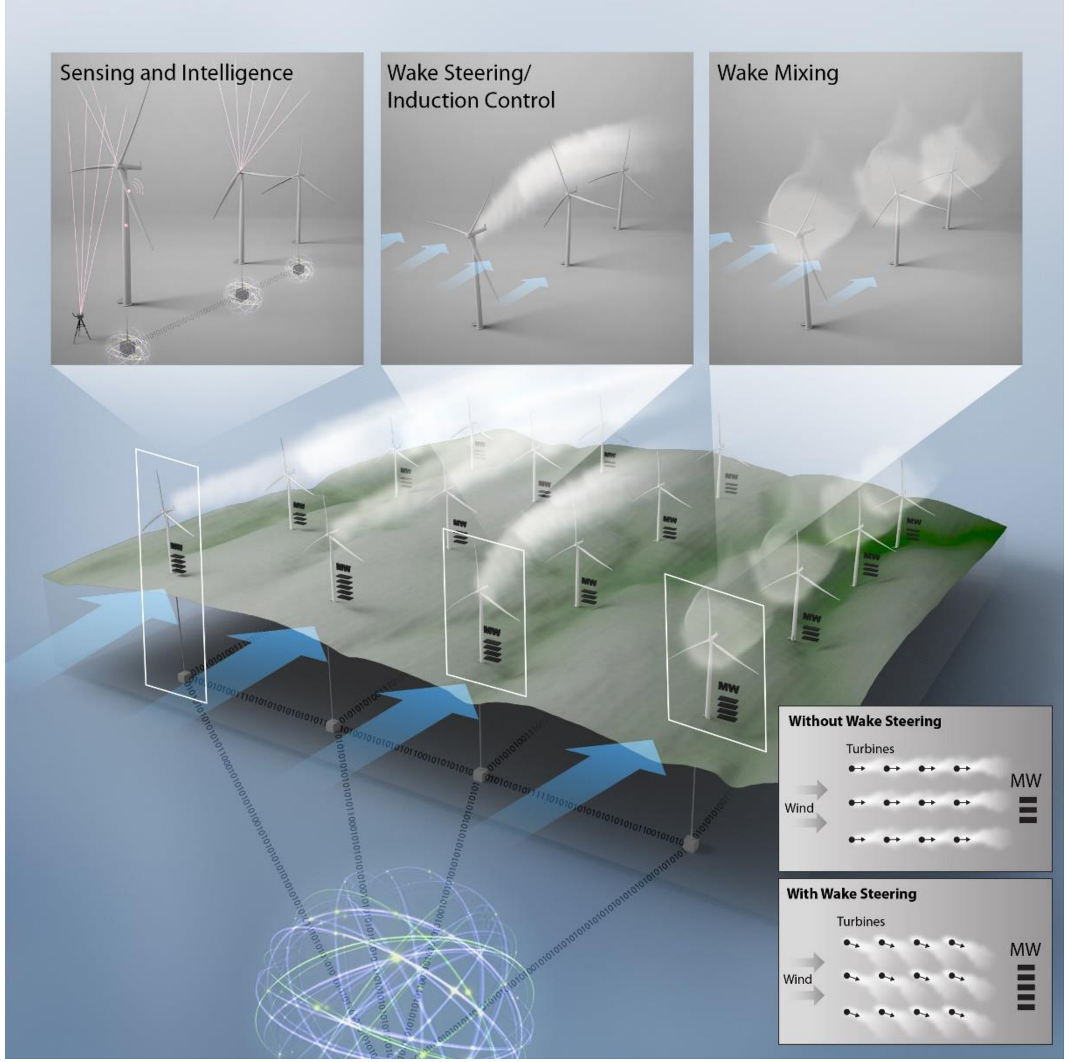
Summary and Outlook

Futher development on the grand challenges: Atmosphere and Turbine

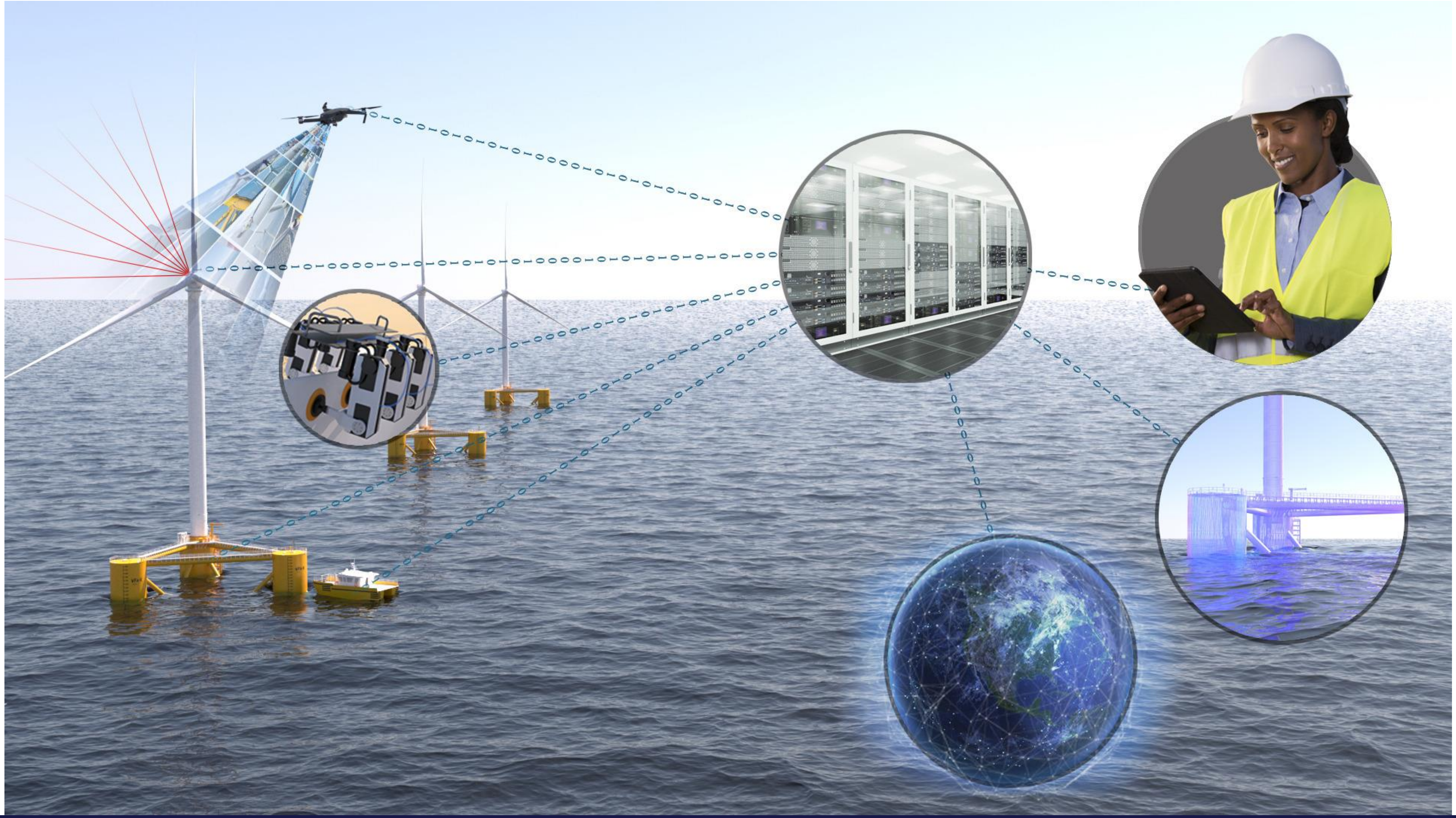


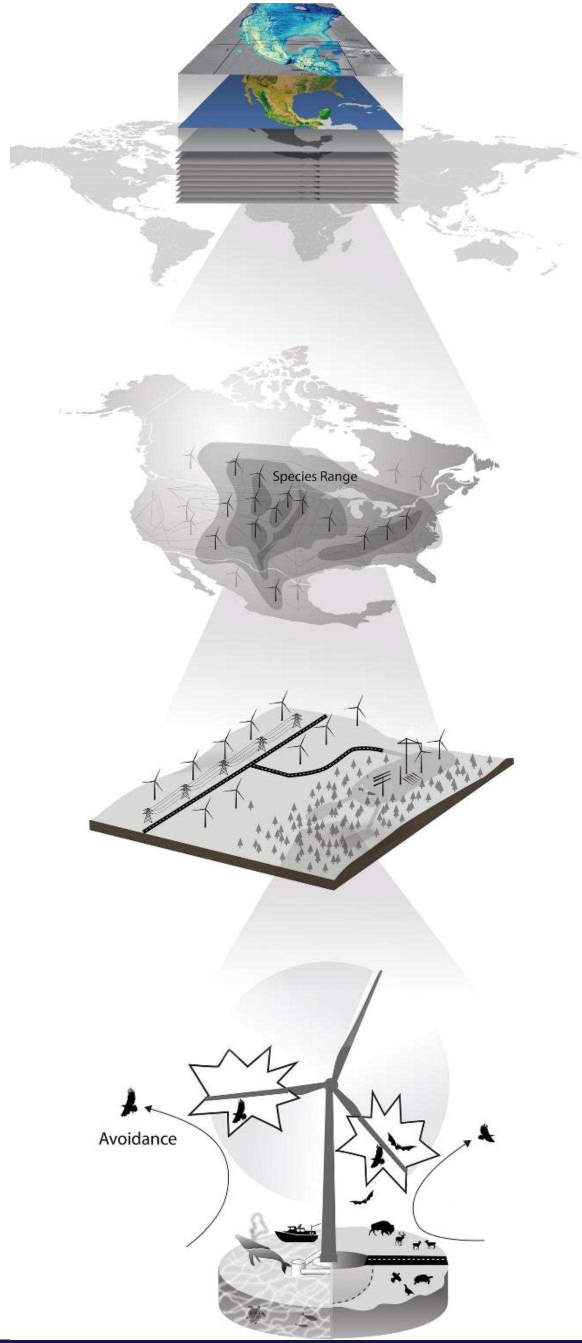


Further development on grand challenges: Plant Controls and Grid



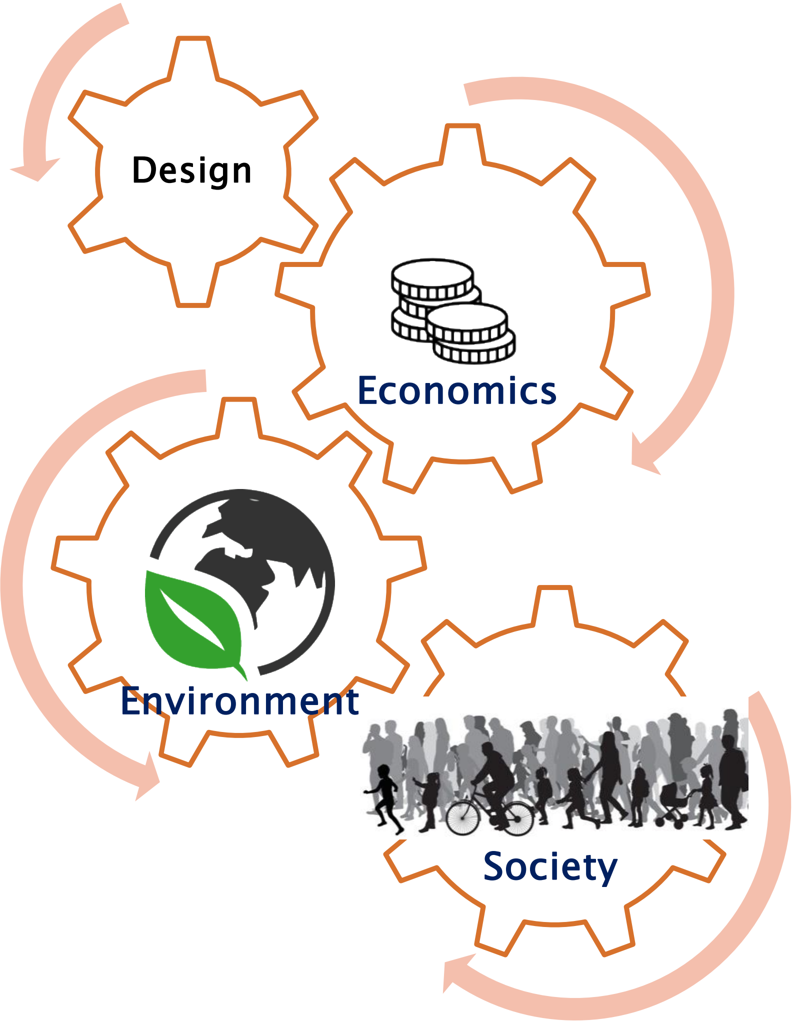
Further development on grand challenges: beyond science- the digital and the physical worlds





What's needed?

- Short answer: everything!
  - Continued drive on LCOE and cost competitiveness
  - Increasing focus on profitability in dynamic markets with high shares of renewable energy
  - Addition of non-price/non-economic criteria in early-stage development and design through the full project life-cycle
  - **Systems engineering holds the key as an integrating methodology / paradigm across disciplines**



Source: Bottasso, NAWEA 2023

Thank You