NAWEA/WindTech ~~2021~~ 2022

Grand Challenges of Wind Energy Science – The Grid

October 13, 2021

NAWEAWindTech2021.org/interim/

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NAWEA
NORTH AMERICAN WIND ENERGY ACADEMY

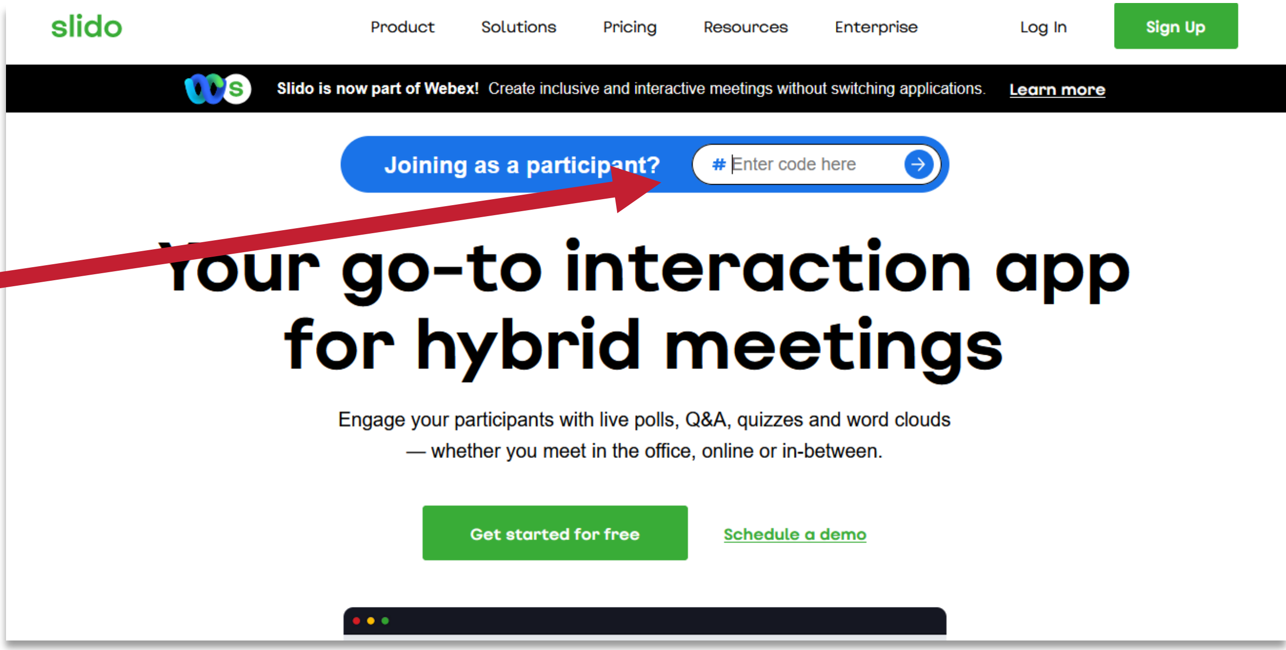
NAWEA/WindTech 2021

The North American Wind Energy Academy (NAWEA) brings together researchers, educators, policymakers, and industry members to advance research, provide educational opportunities, and disseminate unbiased information to facilitate our transformation to carbon-free energy in North America.

Thanks to **Wind-U** and the University of Delaware Center for Research in Wind (**CReW**) for hosting this webinar series!

Logistics for Q&A

- In another browser window, go to: SLIDO.COM
- Enter the Code: nawea5
- We will not monitor the Zoom Chat for questions



NAWEAWindTech2021.org/interim/

- **NAWEA/WindTech 2021** is postponed to 2022 due to the COVID-19 pandemic
- **Interim Webinar Series** offers high-level, impactful presentations
  - 23 Sept – Keynote: Critical partnerships for a carbon-free energy future
  - 29 Sept – Wind turbines and wind plants
  - 30 Sept – Transdisciplinary approaches to accelerate the wind power transition
  - 6 Oct – A conversation with DOE Secretary Jennifer Granholm
  - 13 Oct – Grand challenges of wind energy science – The Grid
  - 19 Oct – Offshore wind
  - 27 Oct – Recent research advances in atmospheric and ocean sciences
- **Free of charge** but registration is required

For Q&A, go to **Slido.com** and enter Code **#nawea5**

Grand Challenge 3: Grid

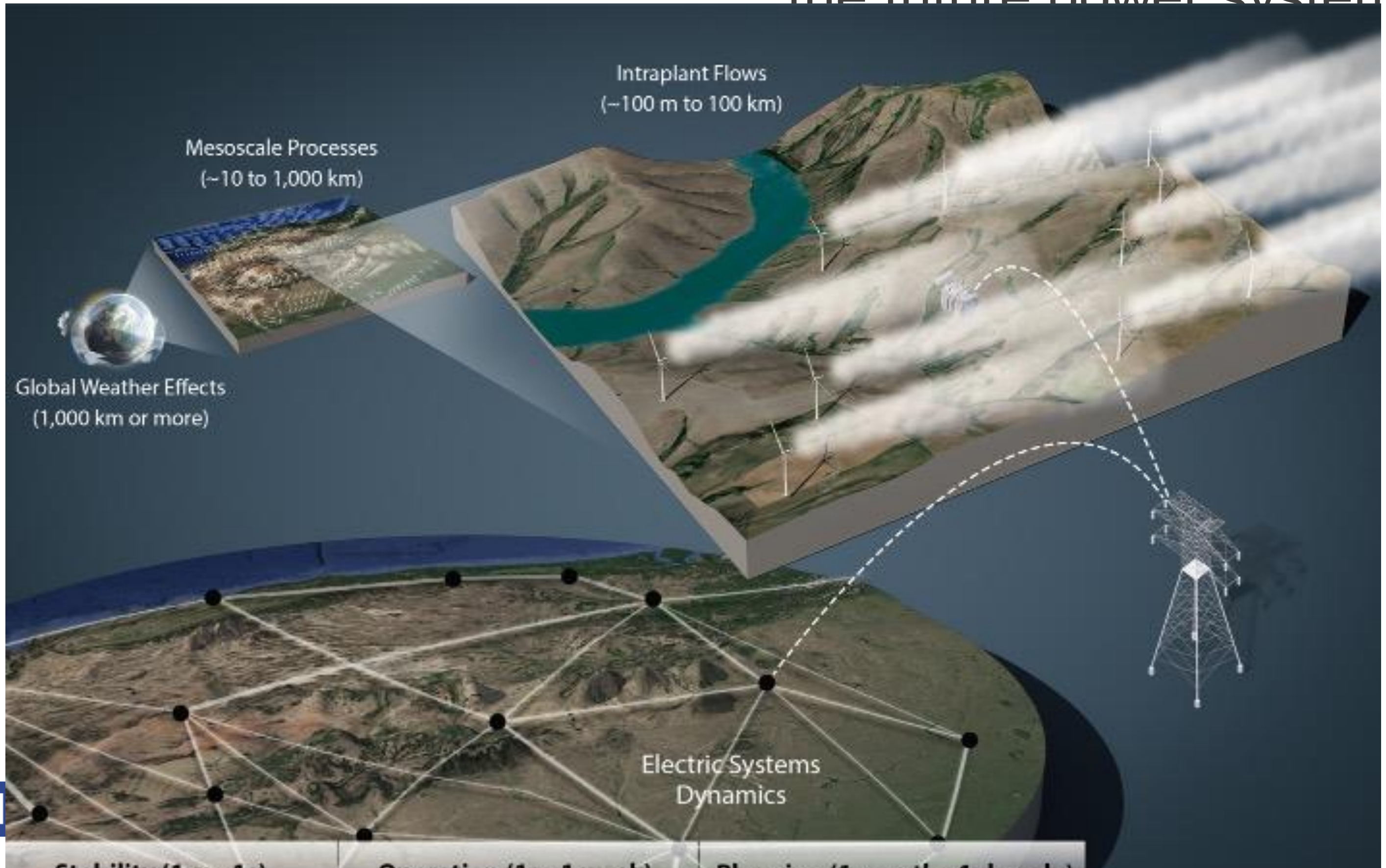
REVIEW SUMMARY

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

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



Development of wind turbines, wind power plants, also hybrids

Grand Challenges for Wind Energy Science

Balancing the Future Grid

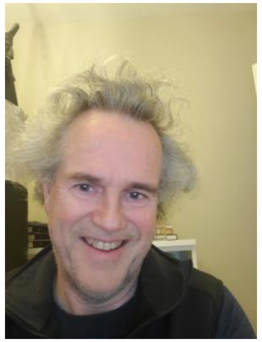
Mark O'Malley – Global Power System Transformation Consortium & Energy Systems Integration Group

Hannele Holttinen – Recognis Oy & IEA Wind Task 25

Katherine Dykes – Technical University of Denmark

Nicolaos A. Cutululis – Technical University of Denmark

Jennifer King – National Renewable Energy Laboratory



North America Wind Energy Academy, Oct. 13, 2021

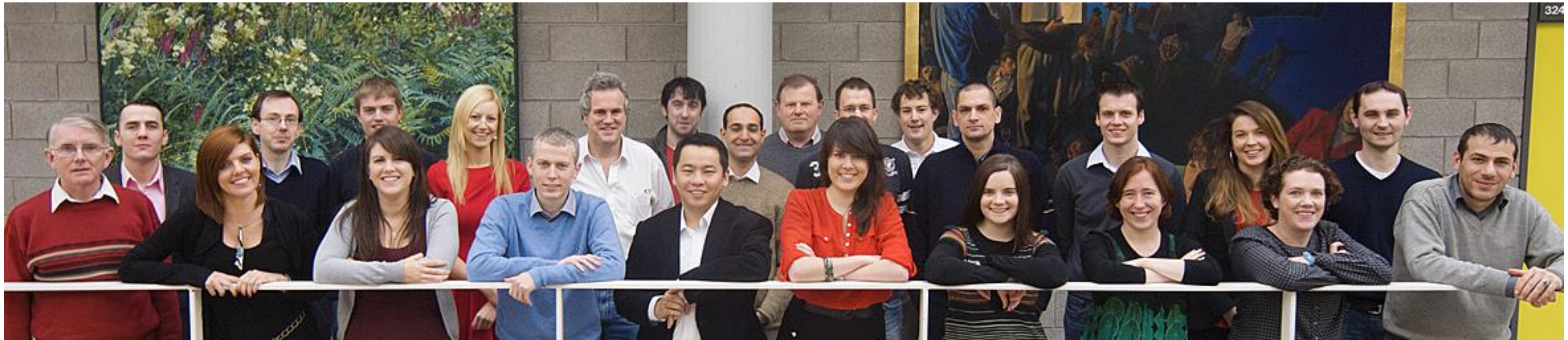
Grid Integration Challenges and Solutions

Mark O'Malley

North American Wind Energy Academy
Amherst, MA, USA

August 8th, 2012

www.ucd.ie/erc



Decarbonisation and the Integrated Energy System

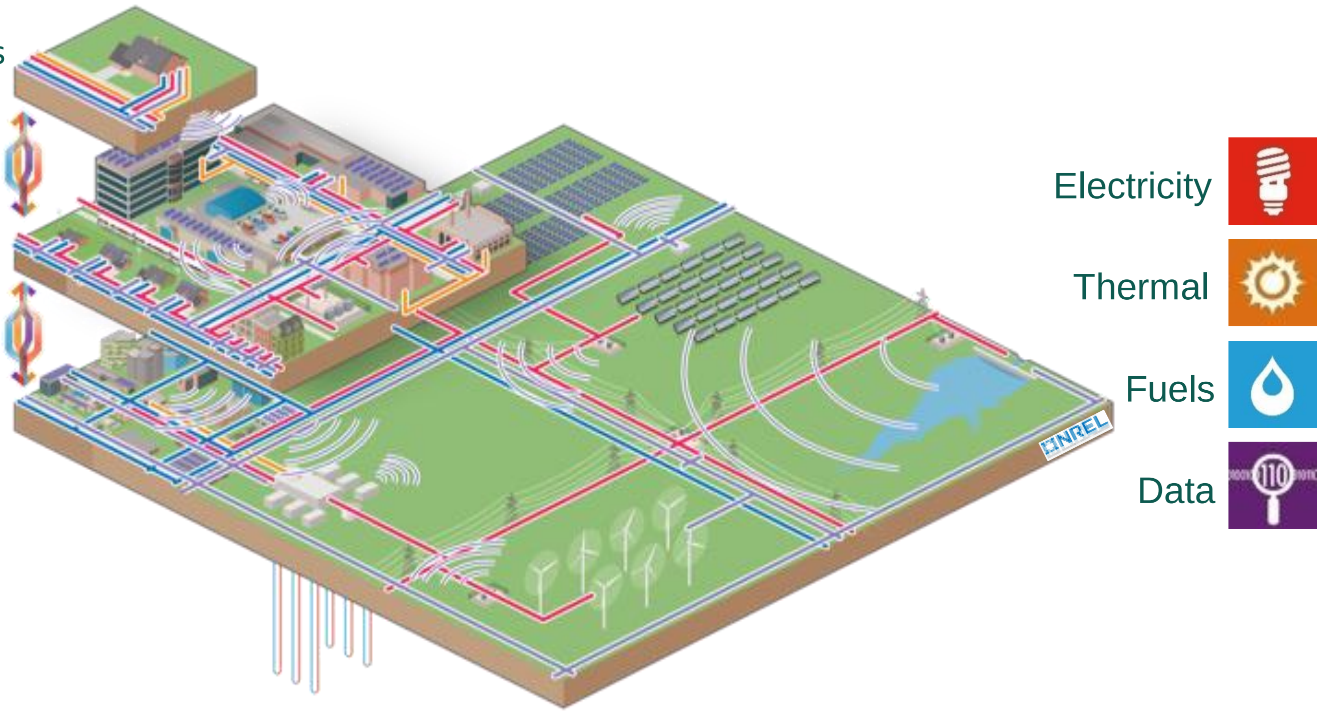
Energy Source

Fossil | Nuclear | Renewable

Single Technologies and Locations

Campus, City Community

Regional, National, Continental



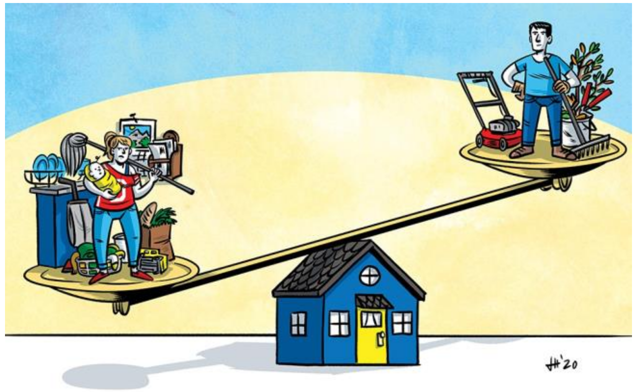
Residential | Commercial | Industry | Mobility

Energy Use Sector

Decarbonization

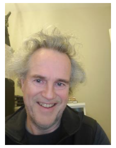
- **Wind (& Solar PV)**
- **Electrification**
- Hydro
- Biomass
- Nuclear
- CCS
- Negative emissions
- etc.

O'Malley, M.J., Kroposki, B., Hannegan, B., Madsen, H., Andersson, M., D'haeseleer, W., McGranaghan, M., Dent, C., Strbac, G., Baskaran, S. and Rinker, M., "Energy System Integration Defining and Describing the Value Proposition", NREL Technical Report NREL/TP-5D00-66616, June 2016. DOI: 10.2172/1257674



Balanced Outline

Setting the Scene – Mark O'Malley



Grid & System Options – Accommodating Wind Hannele Holttinen

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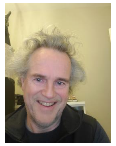
Hybrids – To Benefit Wind and the System – Jennifer King

Wrap Up & Conclusions – Mark O'Malley



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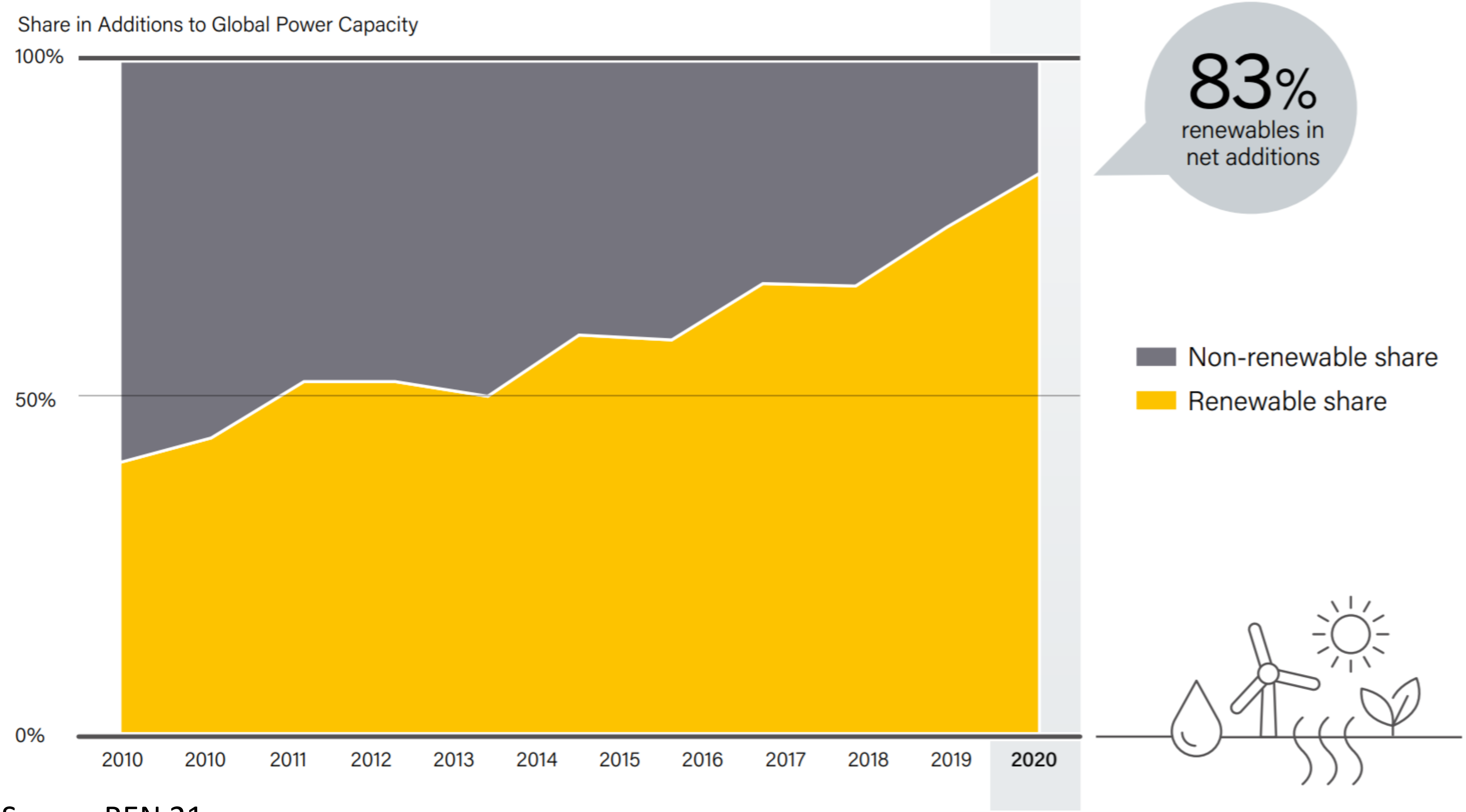
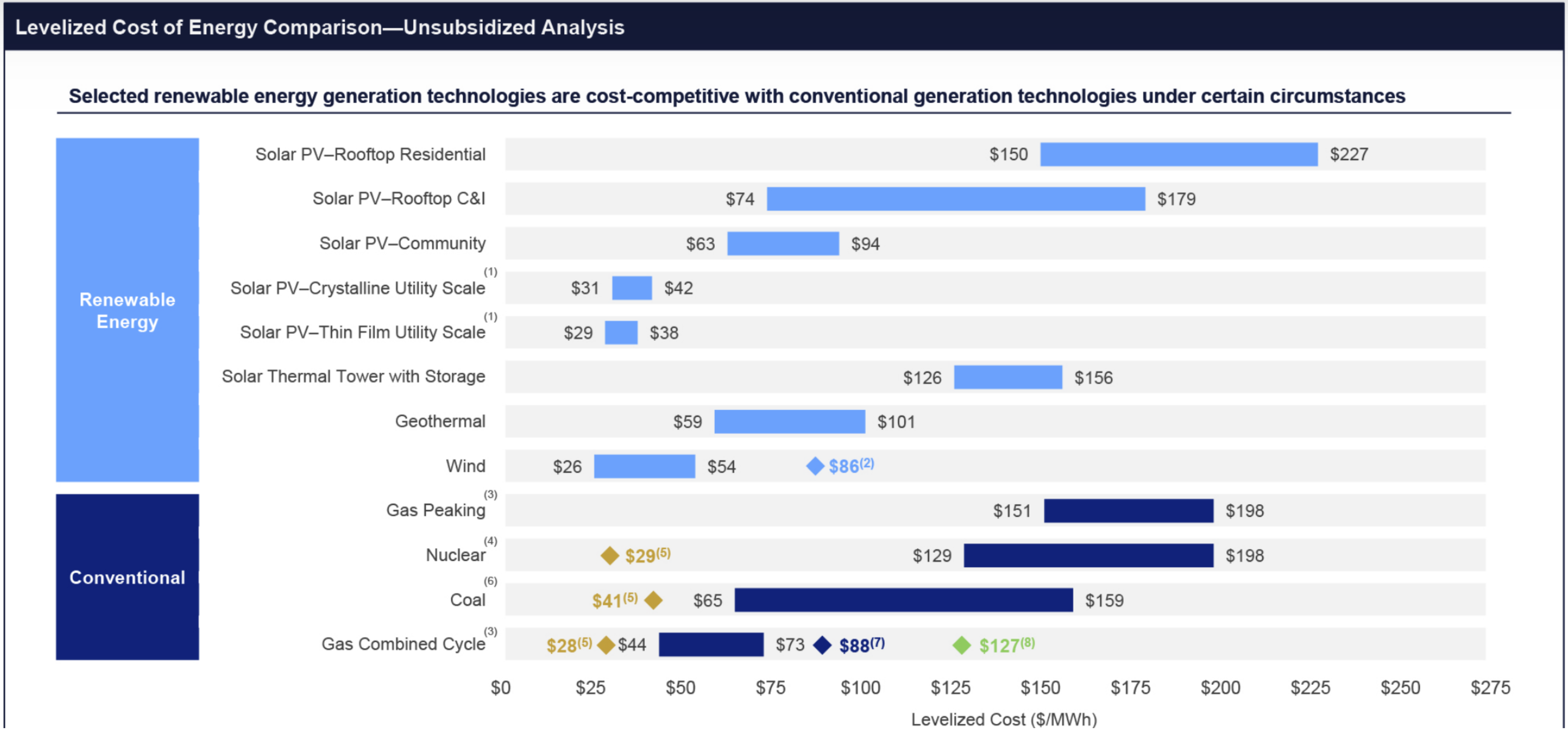
The trend is unstoppable – towards 100 %



Source REN 21

Low cost & clean an unbeatable combination



Source: Lazard, LCOE, Version 14, 2020

The two extremes and the balance in between

EDF scientific chief: A 100% renewable energy system is impossible

By Pavol Szalai | EURACTIV.sk Jul 15, 2016

GRID OPTIMIZATION

[redacted] Drops Lawsuit Against Critics of His 100% Renewables Plan

The Stanford researcher didn't get what he demanded, but says he "brought the false claims to light."

JULIAN SPECTOR | FEBRUARY 26, 2018

https://www.esig.energy/esig-releases-toward-100-renewable-energy-pathways-key-research-needs-report/

21st April 2021

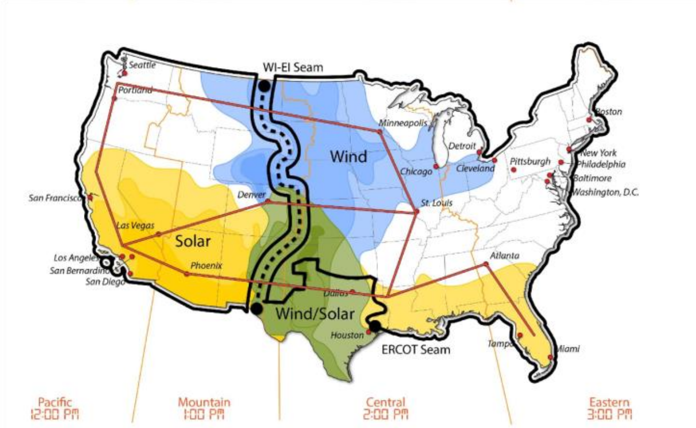
https://globalpst.org/

https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf

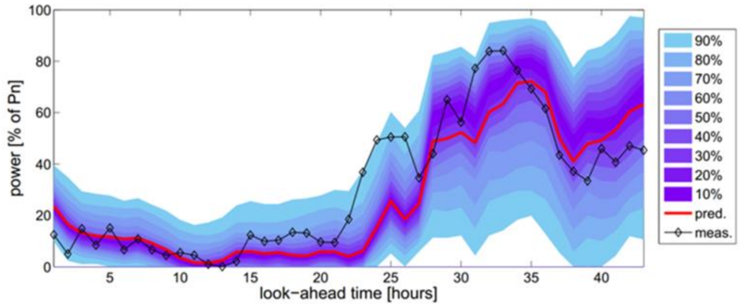
Summary G-PST Research Agenda

Research Program	Description	Number of Questions
Inverter Design	Development of capabilities, services, design methodologies and standards for IBRs.	10
Tools and Methods	New tools and methods required to ensure reliability, security, and stability in power systems.	9
Control Room of the Future	Development of new technologies and approaches for enhanced real-time visibility and analysis in power system operator control rooms.	17
Planning	New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix.	15
Black Start	Creating new procedures for black starting and restoring a power system with high or 100% IBR penetrations.	1
Services	Quantifying the technical service requirements required of future power system to maintain the supply-demand balance reliably and at least cost.	7

Characteristics of variable renewable energy resources

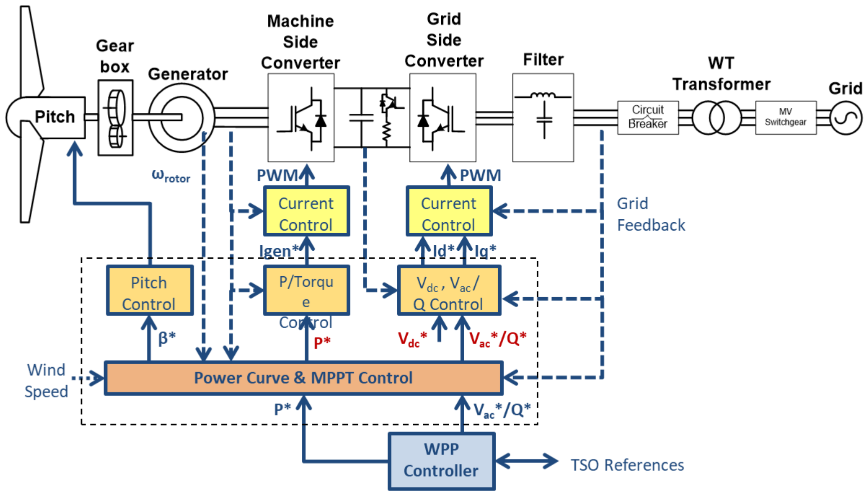


NARIS, National Renewable Energy Laboratory



Pinson, P., Madsen, H, Nielsen, H., Papaefthymiou, G. and Klöckl, B., From probabilistic forecasts to statistical scenarios of short-term wind power production, Wind Energy, volume 12, issue 1, January 2009

- Spatially disperse
- Variable and somewhat difficult to predict
- Inverter Based Resources (IBR)
- Zero marginal cost



Nicolaos Cutululis – Technical University of Denmark

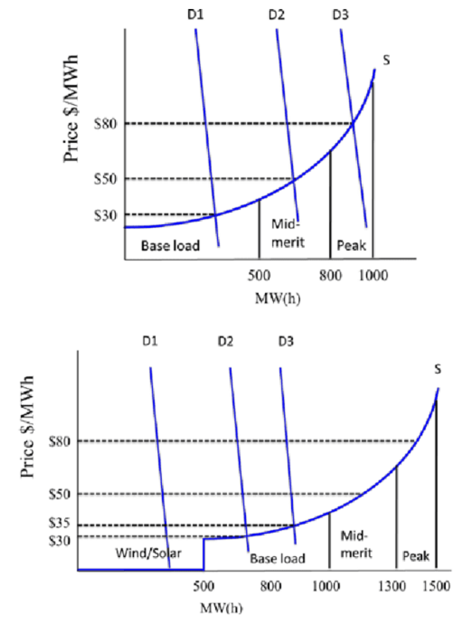
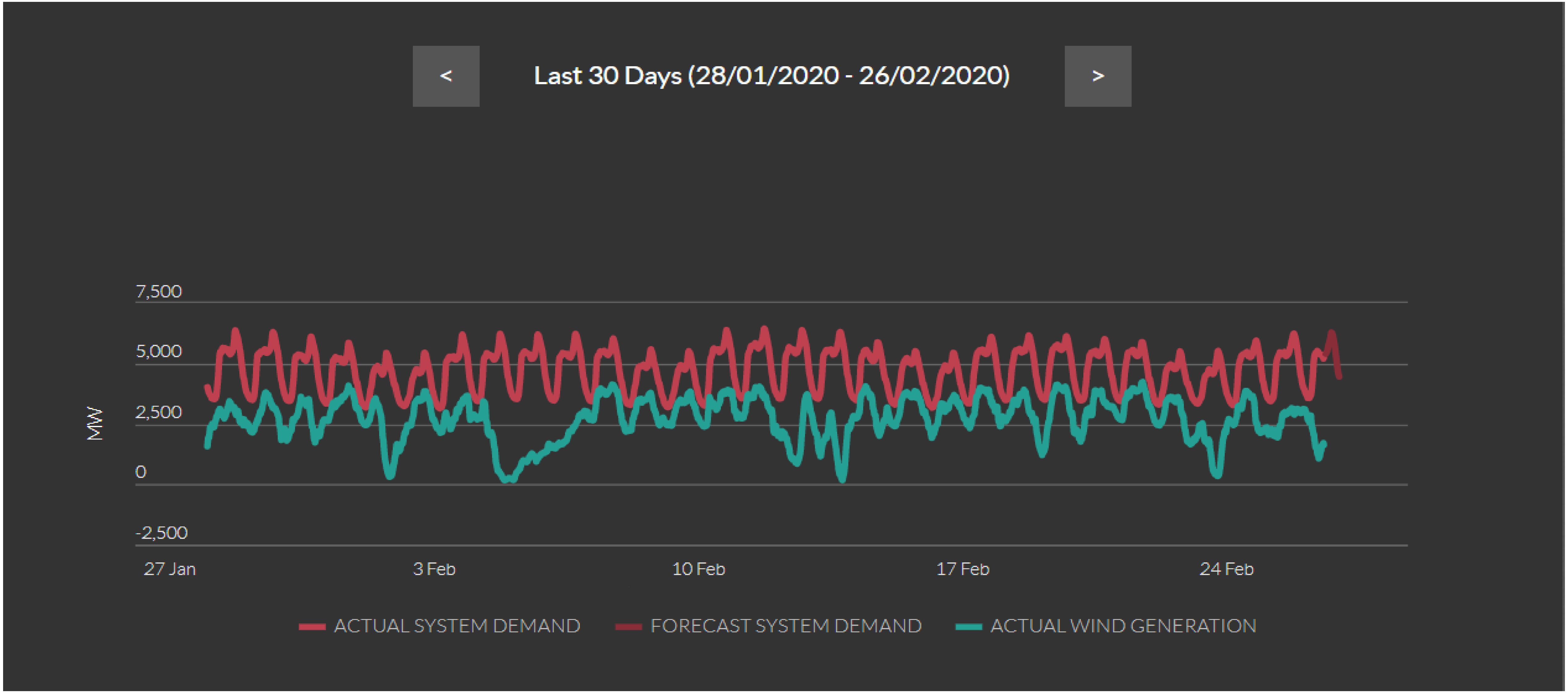


Figure 1. Impact of variable renewable generation on market prices.

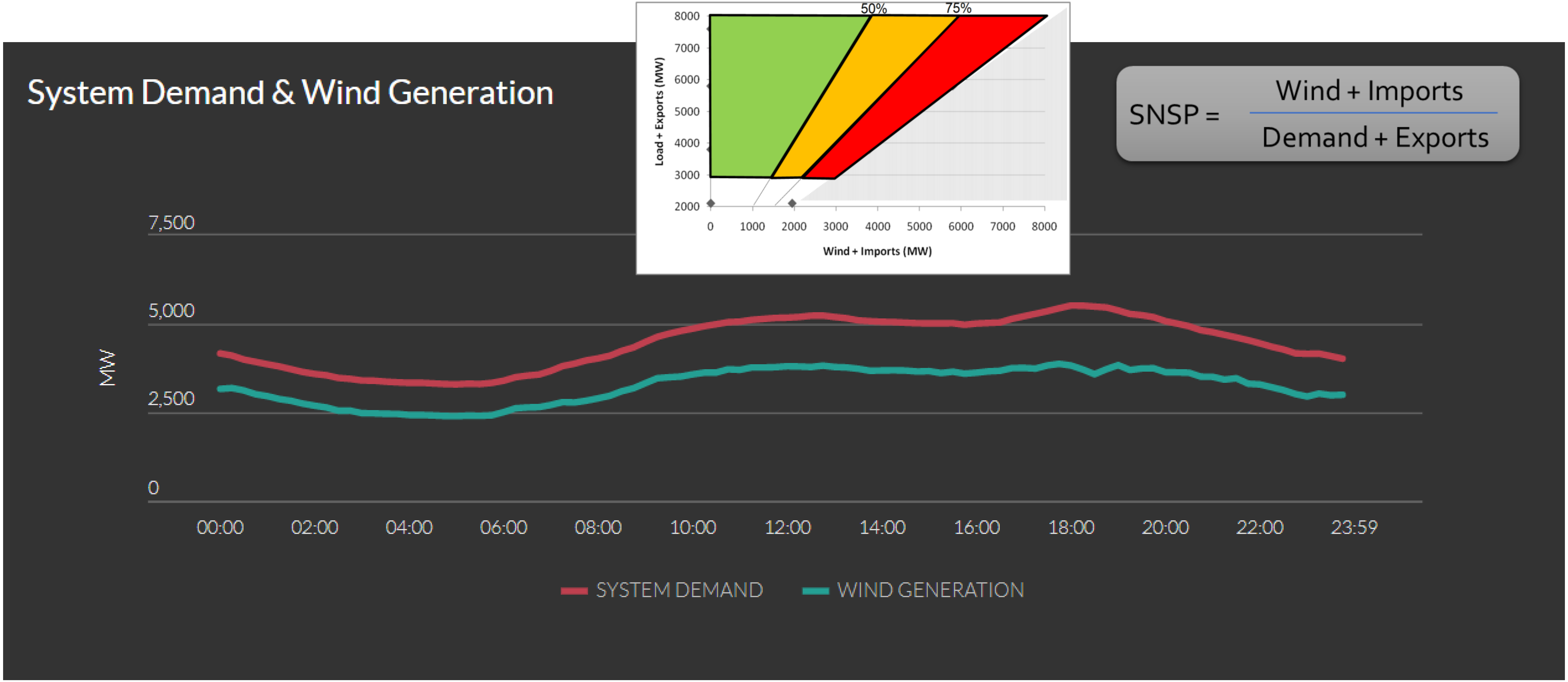
Bethany A. Frew, Michael Milligan, Greg Brinkman, Aaron Bloom, Kara Clark, and Paul Denholm, "Revenue Sufficiency and Reliability in a Zero Marginal Cost Future, International Workshop on Large-Scale Integration of Wind Power into Power Systems Vienna, Austria November 15–17, 2016.

Ireland Feb 2020



http://smartgriddashboard.eirgrid.com/

Ireland 15th February 2020



$$\text{SNSP} = \frac{\text{Wind + Imports}}{\text{Demand + Exports}}$$

http://smartgriddashboard.eirgrid.com/

Dispatch down increases the LCOE of wind

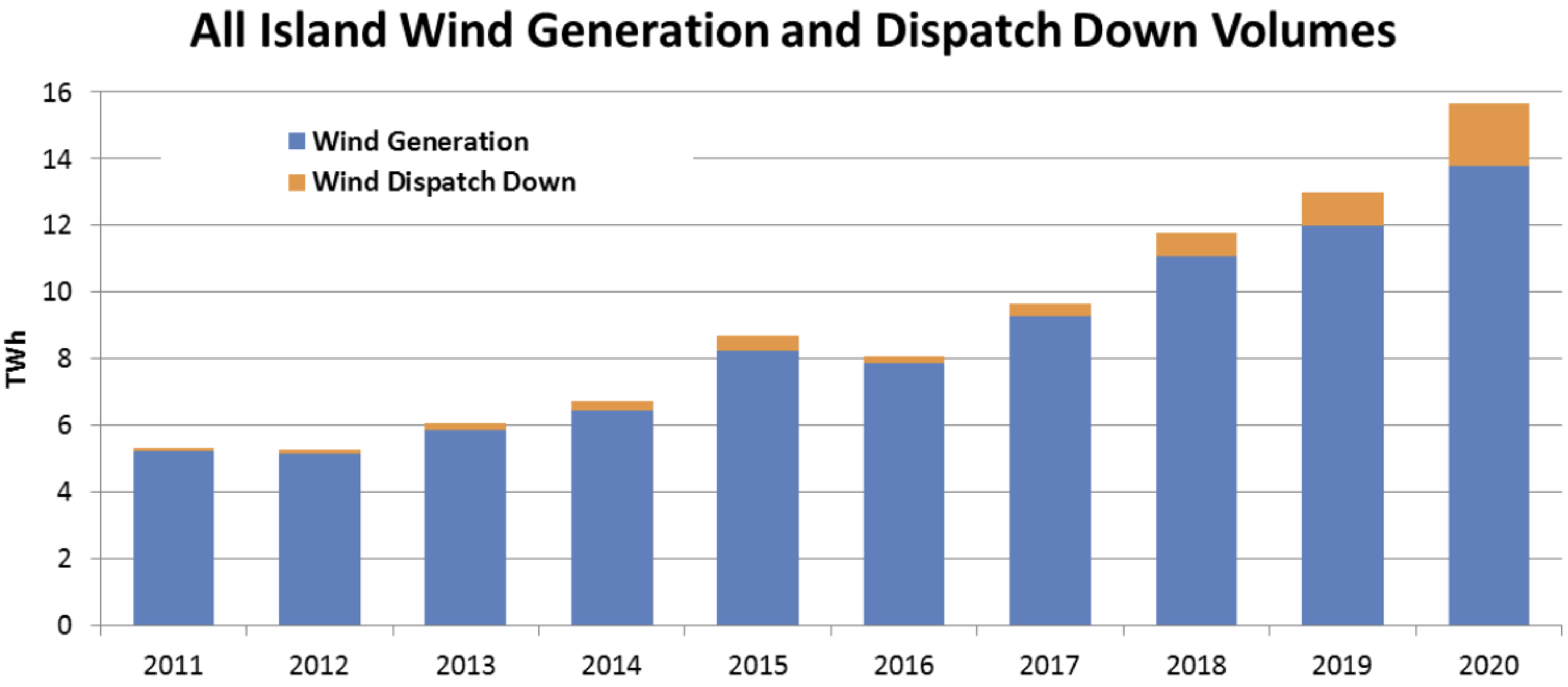
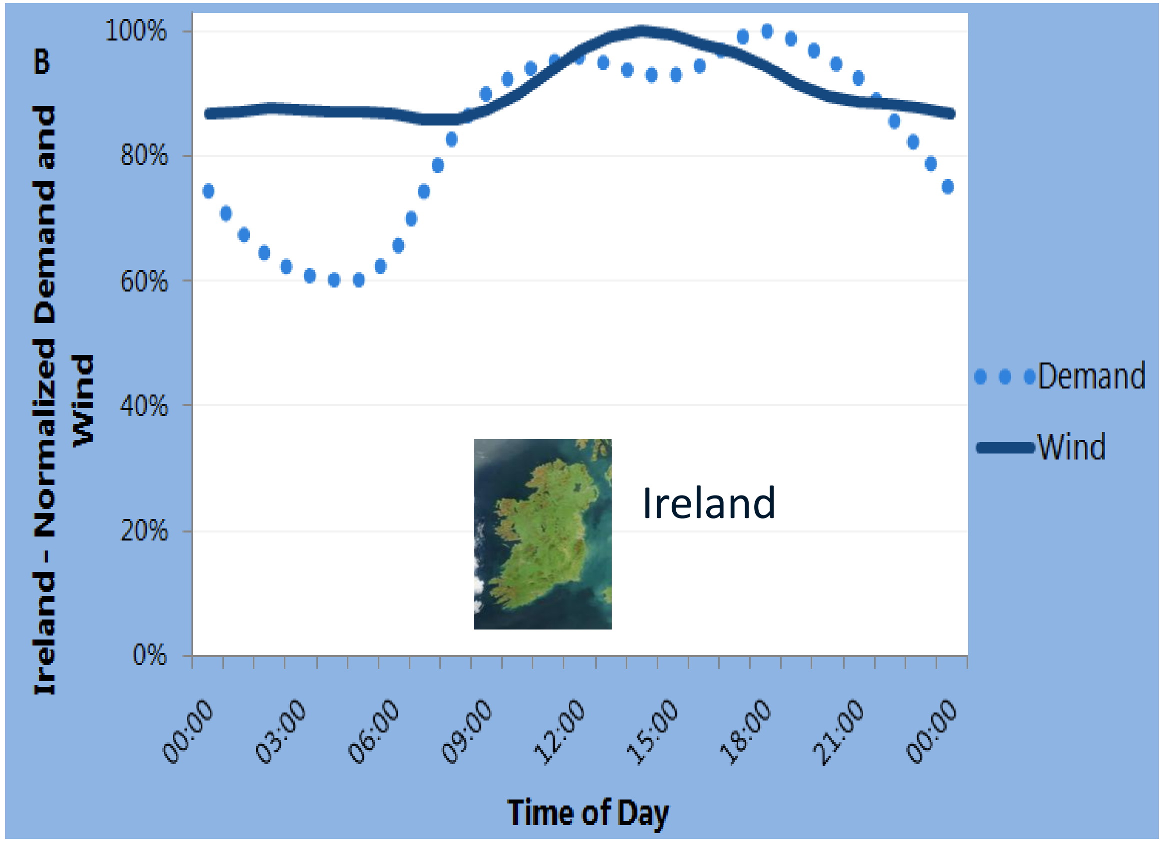
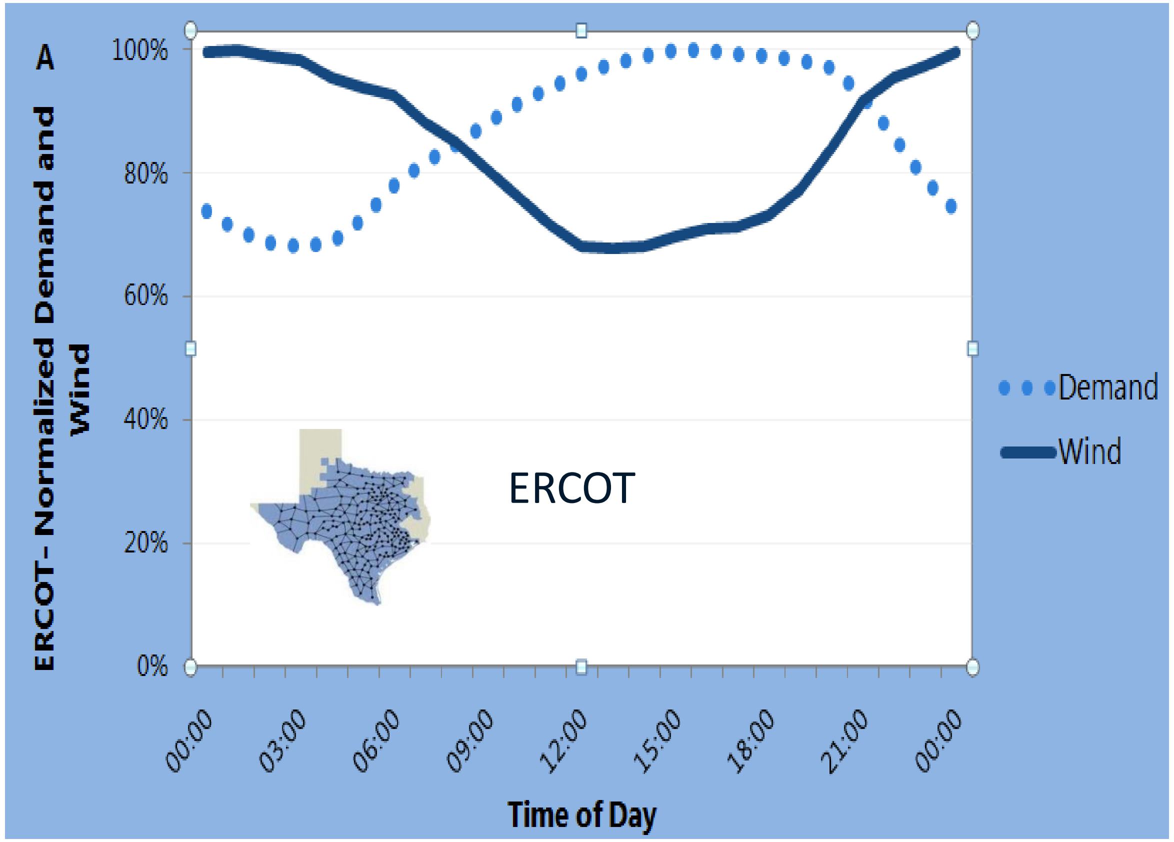


Figure 1: All Island Annual Wind Generation and Dispatch Down Volumes

http://www.eirgridgroup.com/site-files/library/EirGrid/Annual-Renewable-Constraint-and-Curtailment-Report-2020.pdf

Every system is different





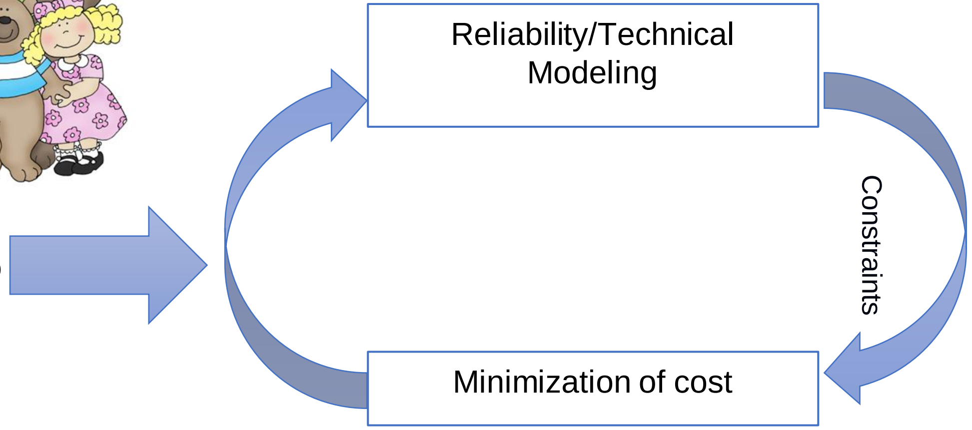
AEMO, Australian Energy Market Operator, "Wind Integration In Electricity Grids: International Practice And Experience" Work Package 1, 2011.
http://www.aemo.com.au/~/media/Files/Other/planning/0400-0049%20pdf.pdf

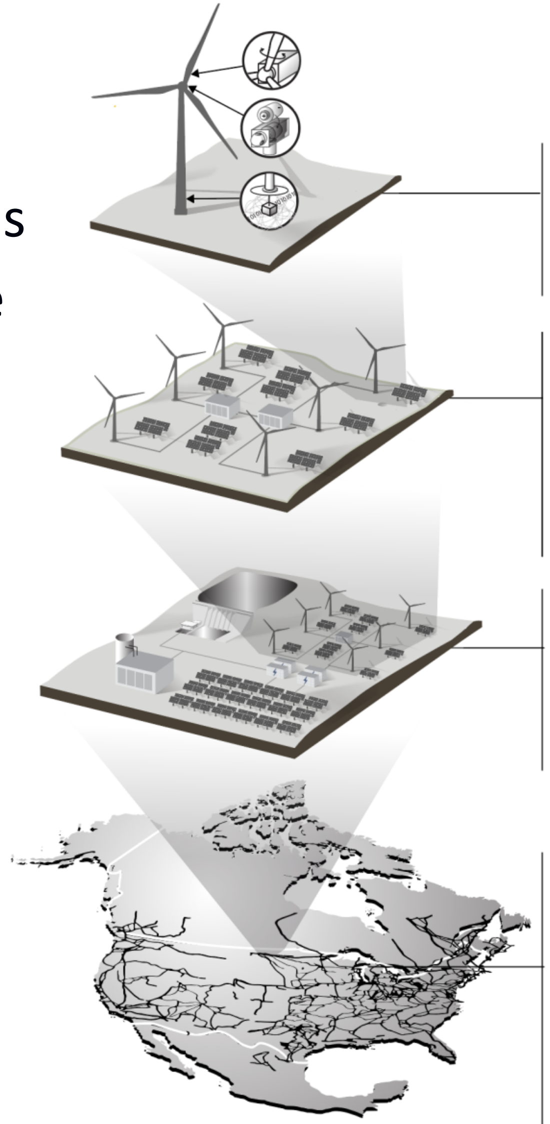
Integrated design & operation of wind and other grid technologies

Cost effective Reliability of the Grid

The fundamental objective of an electricity system is to cost-effectively maintain supply-demand balance reliably at all locations and at all times.

Cost reliability trade off





Turbine technology
- Aerodynamic control
- Generator control
- Plant control
- Integrated Storage
- Advanced Power Electronics

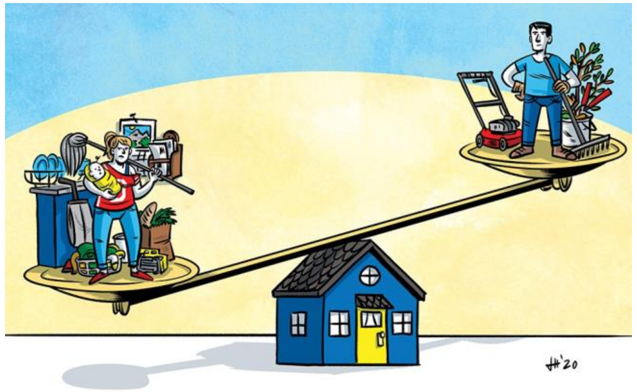
Plant level
- (Multi-Objective) optimized design and operation
- Improved Self-Accommodation and provision for grid services via Automatic Generation Control (AGC) including: Wake Steering, Panel Tilt
- Control, Integrated Storage, H2 generation during high production.
- Control systems integrated at plant level to maximize benefits.
- Combined physical sensing and advanced forecasting to help operate hybrid plant as "dispatchable" and self-accommodating power.

Hybrids
- Combination of multiple (a) utility-scale renewable energy generation sources or (b) renewable energy generation and energy storage technologies
- E.G. Wind, Solar PV, Solar CSP, Hydro, Geothermal, Storage (Battery, Pumped Hydro, Hydrogen)
- Leverage complementarity of resources and take advantage of unique technology characteristics.

System level
- "How these technologies fit together"
- Maximize the pace of deployment of renewable energy systems
- Maximize the use of interconnection points within existing transmission system
- Increase the flexibility and resilience of our generation system
- Tailor Renewable generation to location to provide important services such as baseload/peaker plants etc.

Summary

- In is no longer a purely LCOE challenge
- Balancing the grid with increased wind (& solar PV) is a critical challenge
- This can be done anywhere in the system including within the wind technology
- There are “best” places to do it and “best” is system specific
- It is an “integrated” problem and we will explore some of these challenges below



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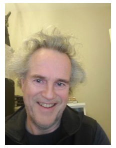

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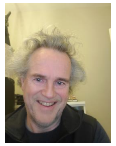

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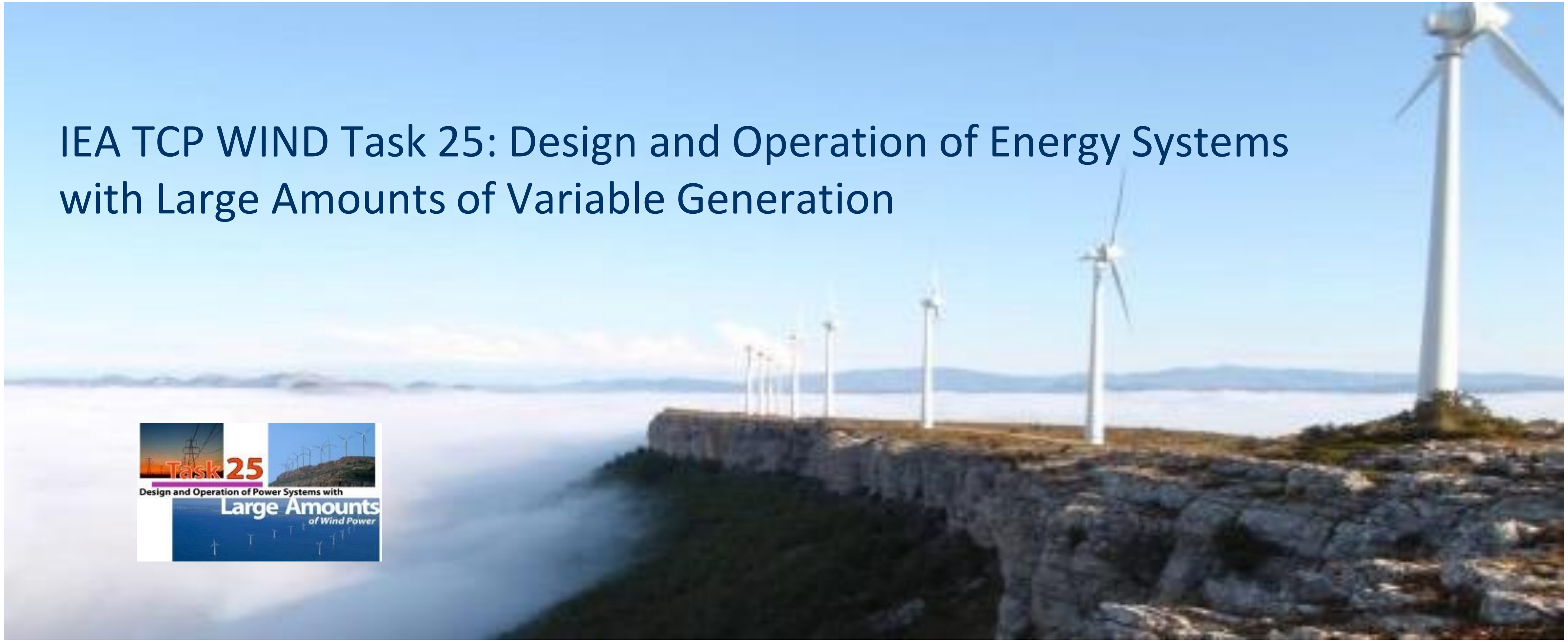
Grand Challenges – grid and system options



IEA TCP WIND Task 25: Design and Operation of Energy Systems with Large Amounts of Variable Generation

Hannele Holttinen, Operating Agent Task25

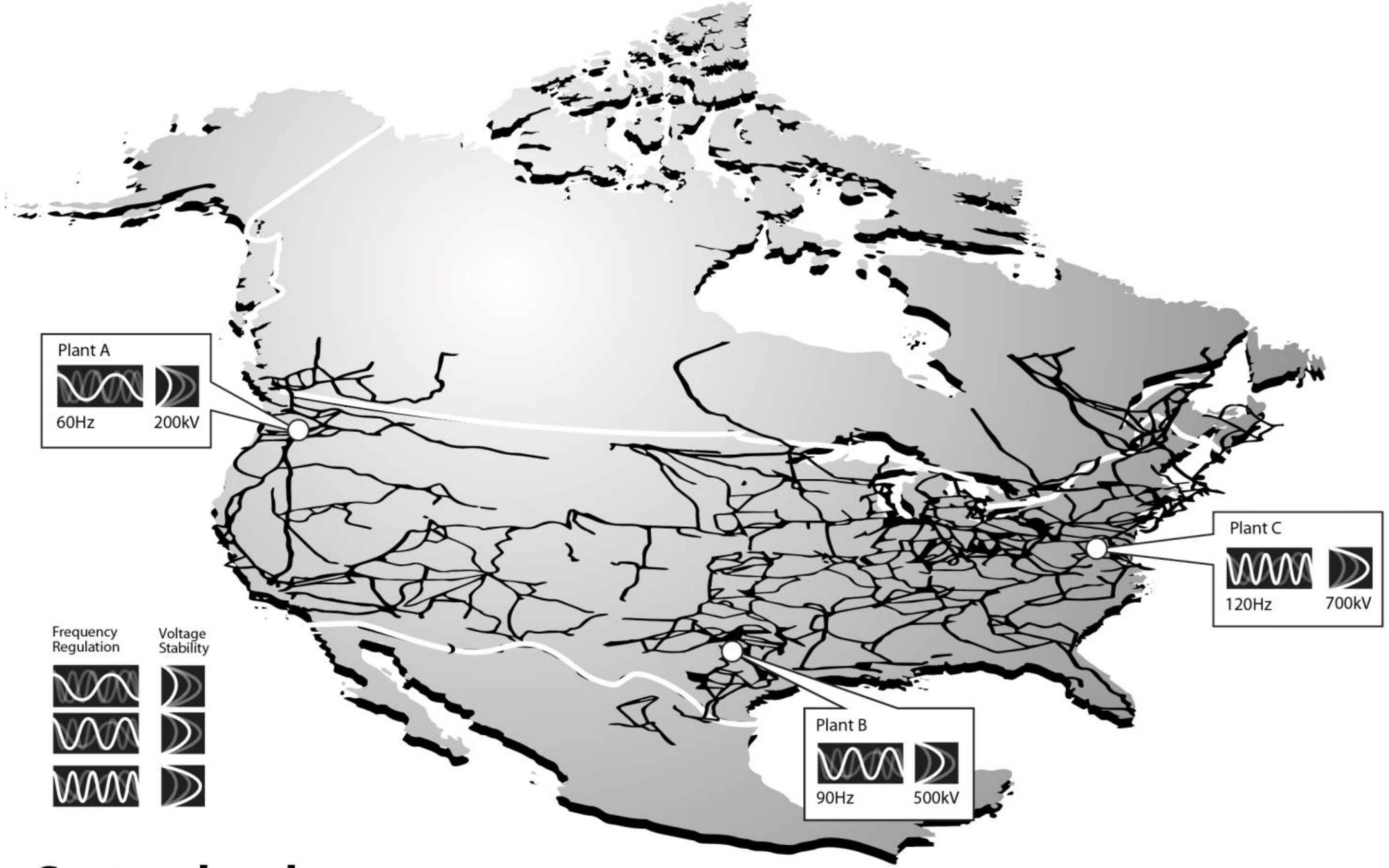
Partner, Recognis Oy

NAWEA, 13th Oct, 2021

recognis

iea wind

What if grid/system evolved to take variable generation



System level

- "How these technologies fit together"
- Maximize the pace of deployment of renewable energy systems
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Contents

Challenges

- Stability
- Balancing and
- Adequacy

Solutions

- Transmission
- Storage
- Demand flexibility
- Generation (thermal, wind, solar PV etc.)

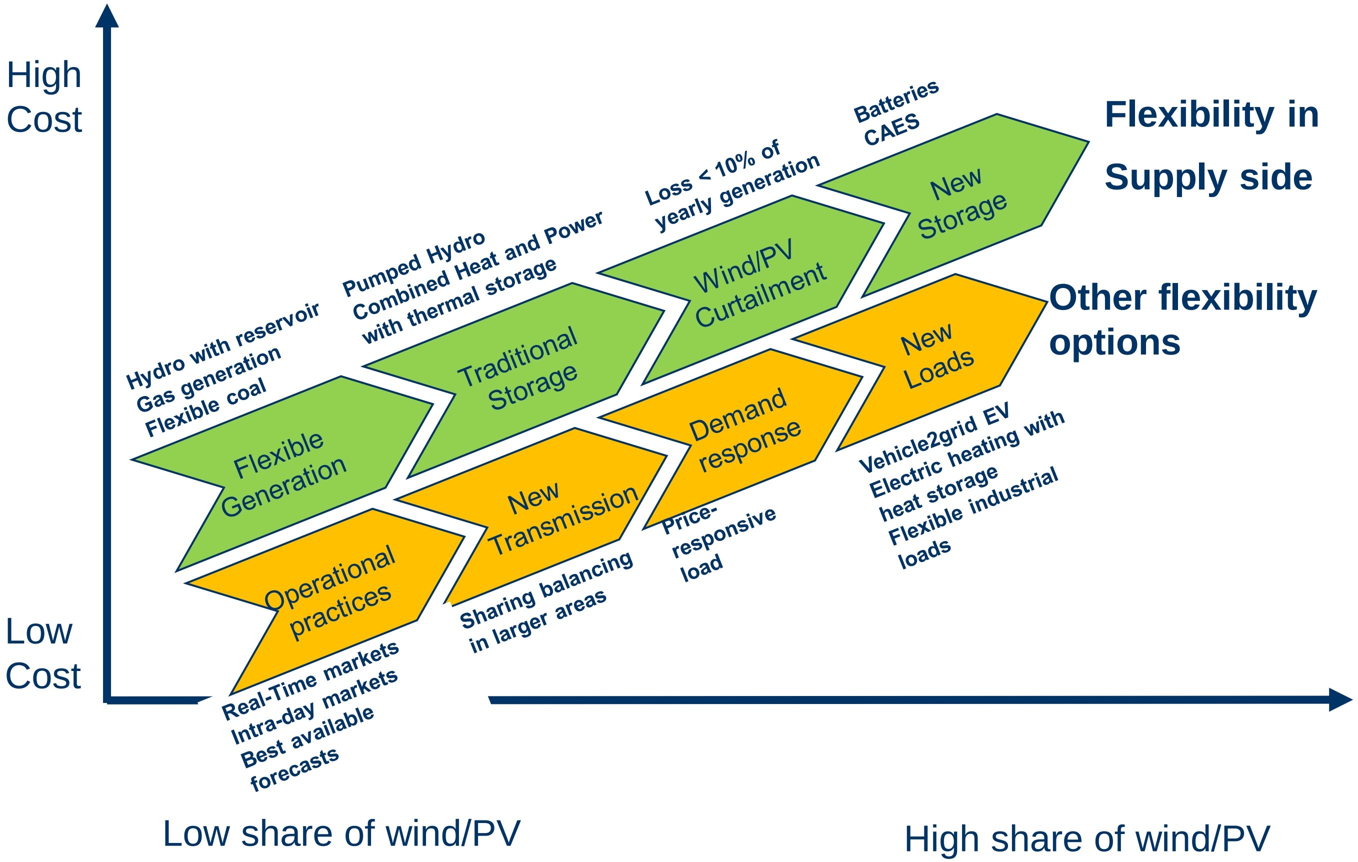
Stability challenge – and solutions

Going towards 100% renewables: new paradigm for non synchronous system operation?

Challenge: maintaining inertia, minimum fault level requirements, system strength, voltage stability, without synchronous machines running

- Grid sources of synchronous inertia (i.e. synchronous condensers) and reactive/active power management (STATCOMs, FACTs, HVDC VSC,..)
- Use wind and solar, loads and electrical storage for system support services provided by generators today. Grid forming technology.
- Speed up frequency response

Balancing challenge: Using all the flexibility solutions we know



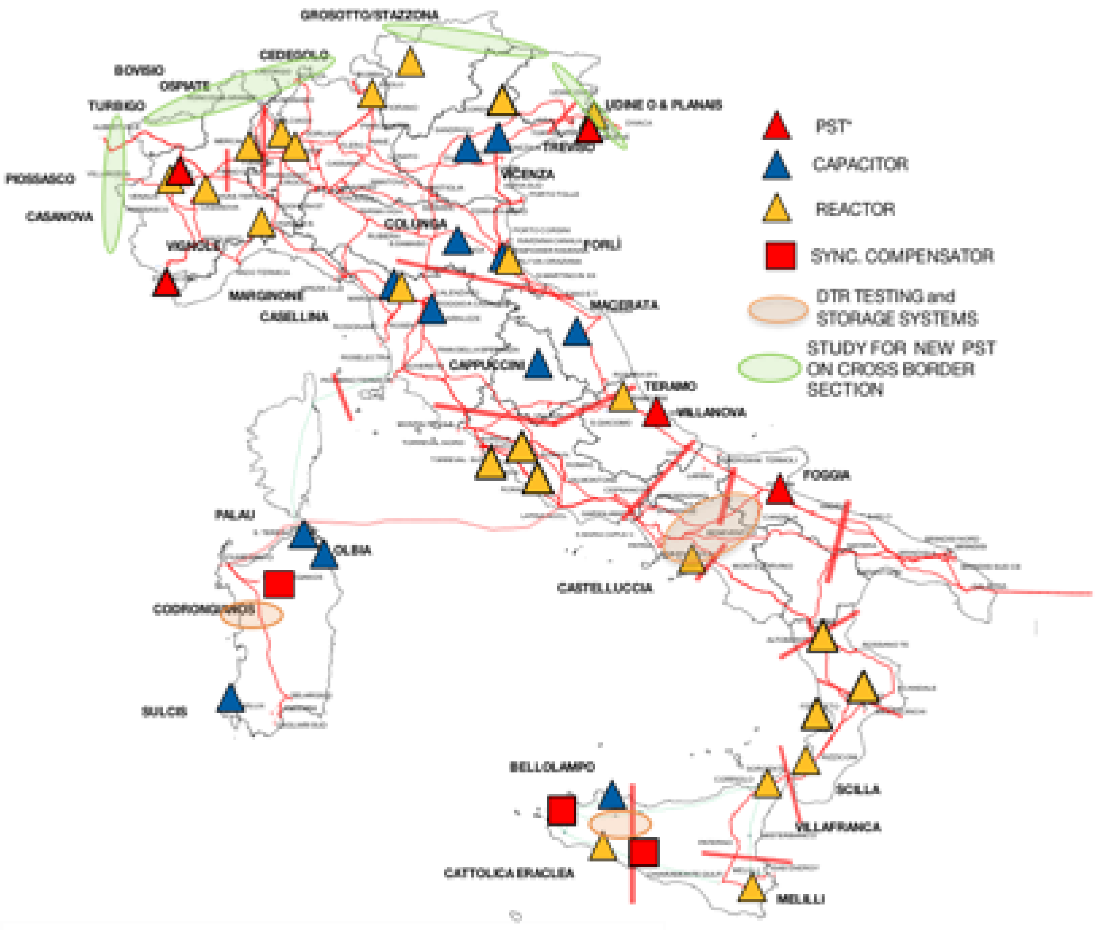
Flexibility sources will compete, and complement (short/long term flexibility)

- Generation
  - Thermal power: retrofits to increase flexibility, options to link with heat storage
  - Hydro power: pumped hydro for short and medium term storage, large reservoirs enable also long term storage
  - Wind and solar, through smart curtailments
- Storage
  - Batteries provide short-term balancing over one to few hours
- Demand response
  - Short-term flexibility from existing loads
  - longer-term flexibility from Power2X loads

How much these options are needed is system specific – and how much transmission can be increased

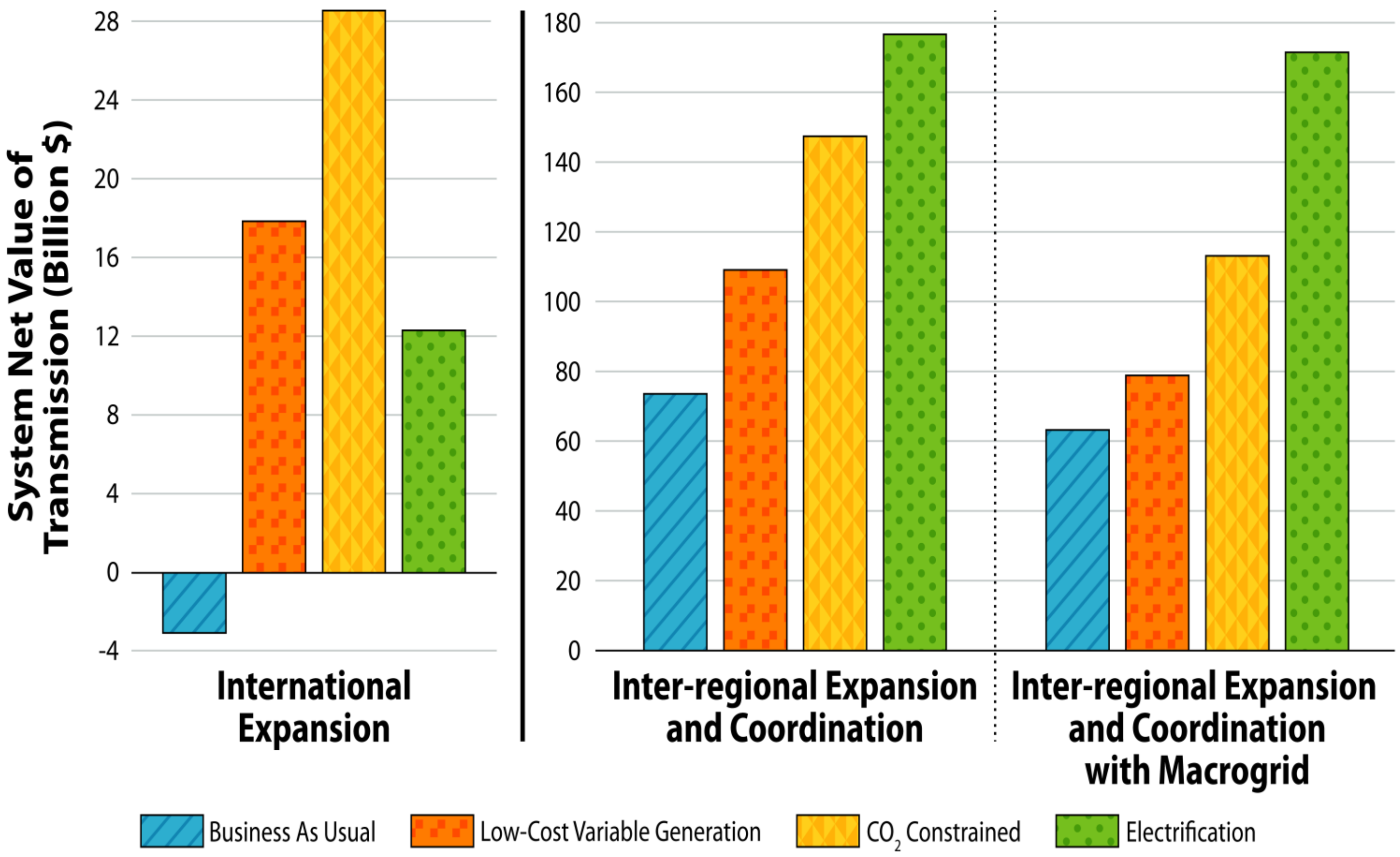
Operational practices matter

- Sharing balancing – larger areas
- Faster operation – trend towards dynamic reserve setting closer to real time, and probabilistic methods
- Congestion management
  - Use existing grid to its limits: Setting security margins with stochastic weather forecasts; Dynamic line ratings; Advanced power flow control; Topology optimisation
- TSO-DSO coordination
  - Flexibility from distributed resources while ensuring secure operation of DS



Example of grid investments to active and reactive power management in Italy (DTR = dynamic transmission rating). (Terna)

With more wind (and solar) deployment, inter-regional coordination and expansion are more beneficial

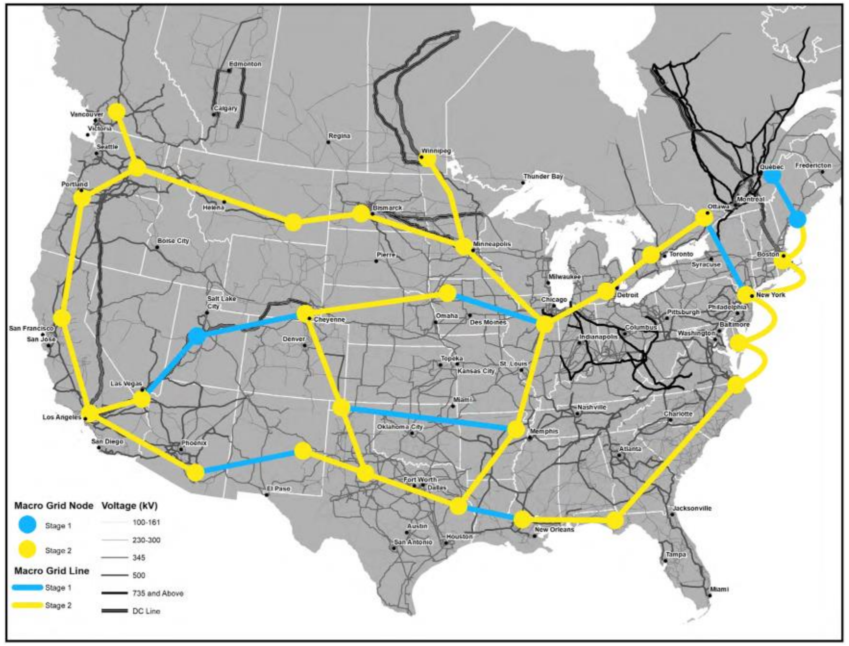


Continent-wide net value of transmission expansion for the four scenarios in the NARIS study.

Source: Brinkman et al., 2021. The North American Renewable Integration Study: A U.S. Perspective. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-79224. https://www.nrel.gov/docs/fy21osti/79224.pdf

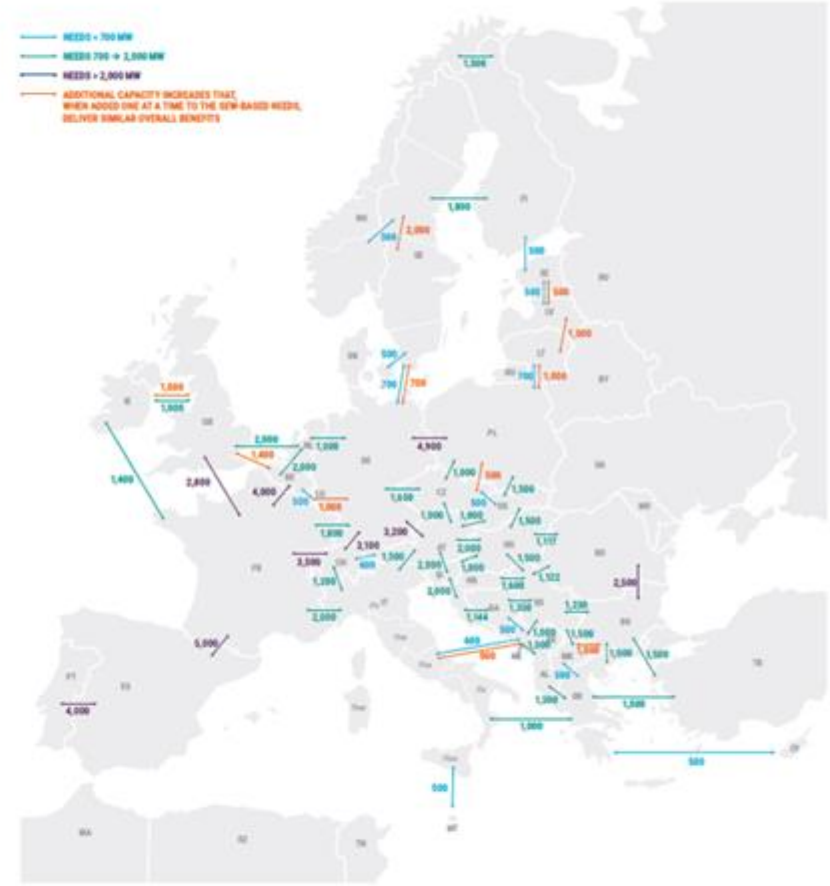
Transmission planning

- Regional transmission planning
  - Macro-grid discussions in US
  - Enhance existing corridors in Europe



Conceptual macro-grid to unite the US power systems.

Source: ESIG. 2021. Transmission Planning for 100% Clean Electricity. https://www.esig.energy/wp-content/uploads/2021/02/Transmission-Planning-White-Paper.pdf

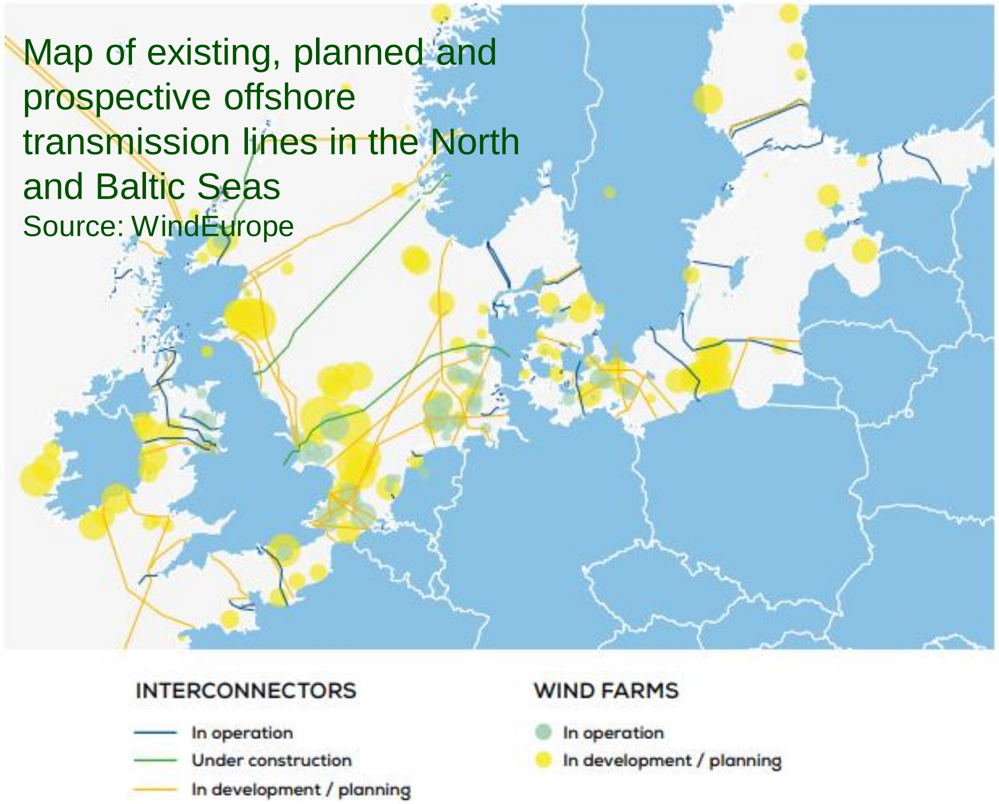


Europe-wide grid architecture for a low-carbon future, as identified by a recent ENTSO-E ten year network development plan (TYNDP).

Source: “Completing the Map 2020 – Power System Needs in 2030 and 2040; https://tyndp.entsoe.eu/ .

Offshore grids

- Meshed grids, hubs, and energy islands
  - HVDC technology improvements to increase cost effectiveness, reliability, and land-based grid support
  - multi-vendor interoperability



Map of existing, planned and prospective offshore transmission lines in the North and Baltic Seas
Source: WindEurope

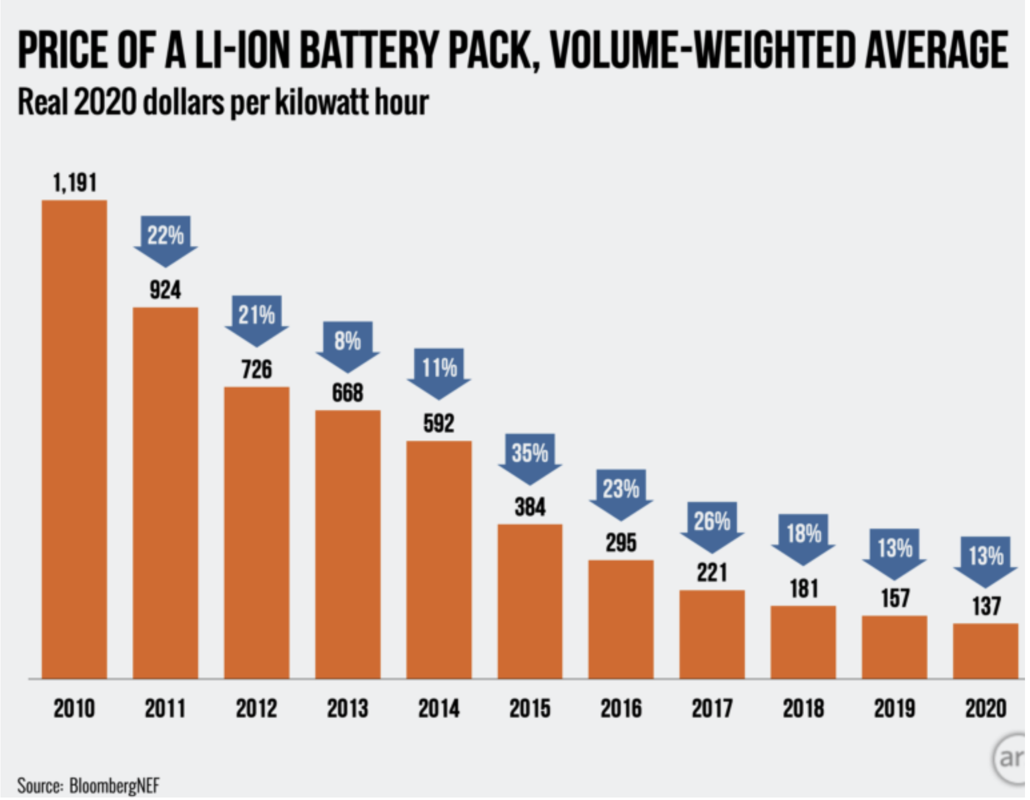
North Sea Wind Power Hub joint initiative started by system operators TenneT TSO B.V. (Netherlands), Energinet (Denmark), and TenneT TSO GmbH (Germany), with transmission interconnectors (left), Energy Island concept (middle) and the option of increased regional interconnection (right).

Technology development of transmission

- macro-grids and offshore grids: how we plan and operate the “hybrid AC/DC systems”
- new technology development
  - high temperature conductor
  - low-cost, high-capacity underground transmission cables
  - superconducting

Storage opportunities

- Cost reductions trend looks promising
- more types of storage than just batteries, important for longer duration storage



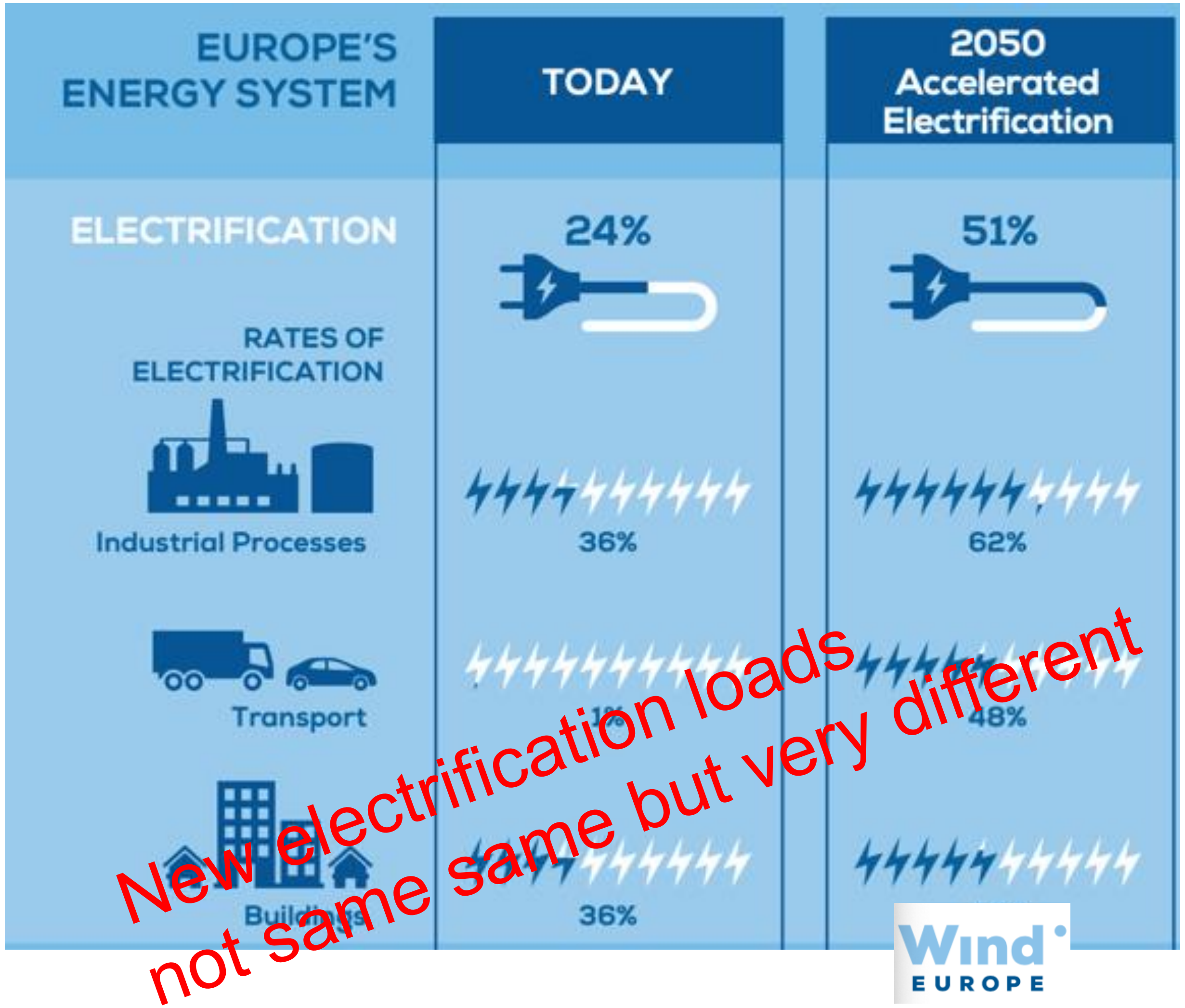
Digitalisation – opportunities for demand response

- Smart grids:
  enabling distributed resources, prosumers, HEMS/BEMS operating with price signals

same same but different than existing demand

Energy transition - opportunities

- Load transition: changing the fixed load paradigm. What if we can dispatch load to the generation available?
- Seasonal thermal storage; electrolyser loads



Long term flexibility challenge

- Traditionally build gas turbines for back up – use as peakers <1000h/a
  - With wind/solar dominating, this will be expensive.
- Two other pathways possible:
  - Load becomes flexible – also in weeks time scale, electrolysers for power2X, thermal storages for heat etc
  - Electric storage becomes very cheap, and new seasonal options for storage developed
- Probably a mix of these three?

Need for research

- Stability: better understanding, which requires improved simulation tools and generator models and better predictive tools and metrics
- System operation: agile market rules to make revenue from solutions that are optimal for the system – also taking benefits from local trade
- Adequacy: new methods to optimise the varying generation and flexible loads (from LOLP metrics)

Not all challenges need to be tackled by wind power plants
- but there are a lot of opportunities for wind power plants to support the future grid

Thank you!

Hannele Holttinen

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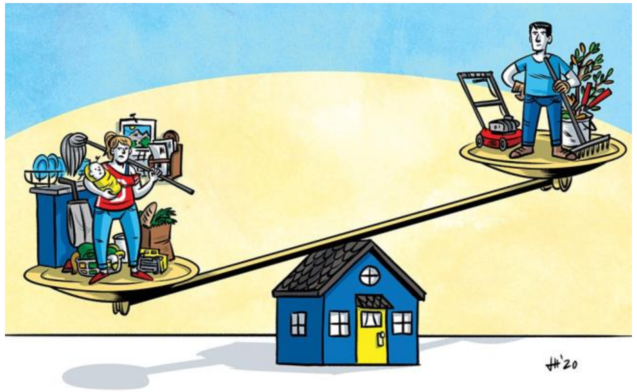
https://iea-wind.org/task25/



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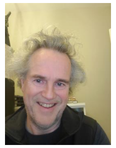

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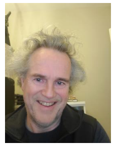

Q & A – SLIDO - All

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Value-based Wind Turbine and Farm Optimization of Design and Operation

Katherine Dykes, DTU Wind Energy
(along with input from many others from DTU Wind Energy and beyond)

NAWEA 2021 Online Webinar
October 13th, 2021

Outline

- LCOE based optimization for wind energy applications (traditional objectives)
- Objectives for wind energy optimization beyond LCOE
- Value-based optimization for wind energy applications (new objectives)

How do we use optimization to increase competitiveness of wind by reducing LCOE?

Wind Farm Design, Operation and Control Past and Present

Wind Plant Optimization
Background and Motivation

- Complexity of wind farms:
  - Many disciplines – aerodynamics, structures, electrical, etc
  - Many stakeholders – supply chain, developers, financiers, environmentalists, communities
  - Long time scales – operation over several decades
  - Large scope – activity within a single component to interaction of turbines within the plant to interaction of plant with the grid

- With such a complex dynamically coupled system, how do we evaluate how changes will affect overall *system* performance and cost?

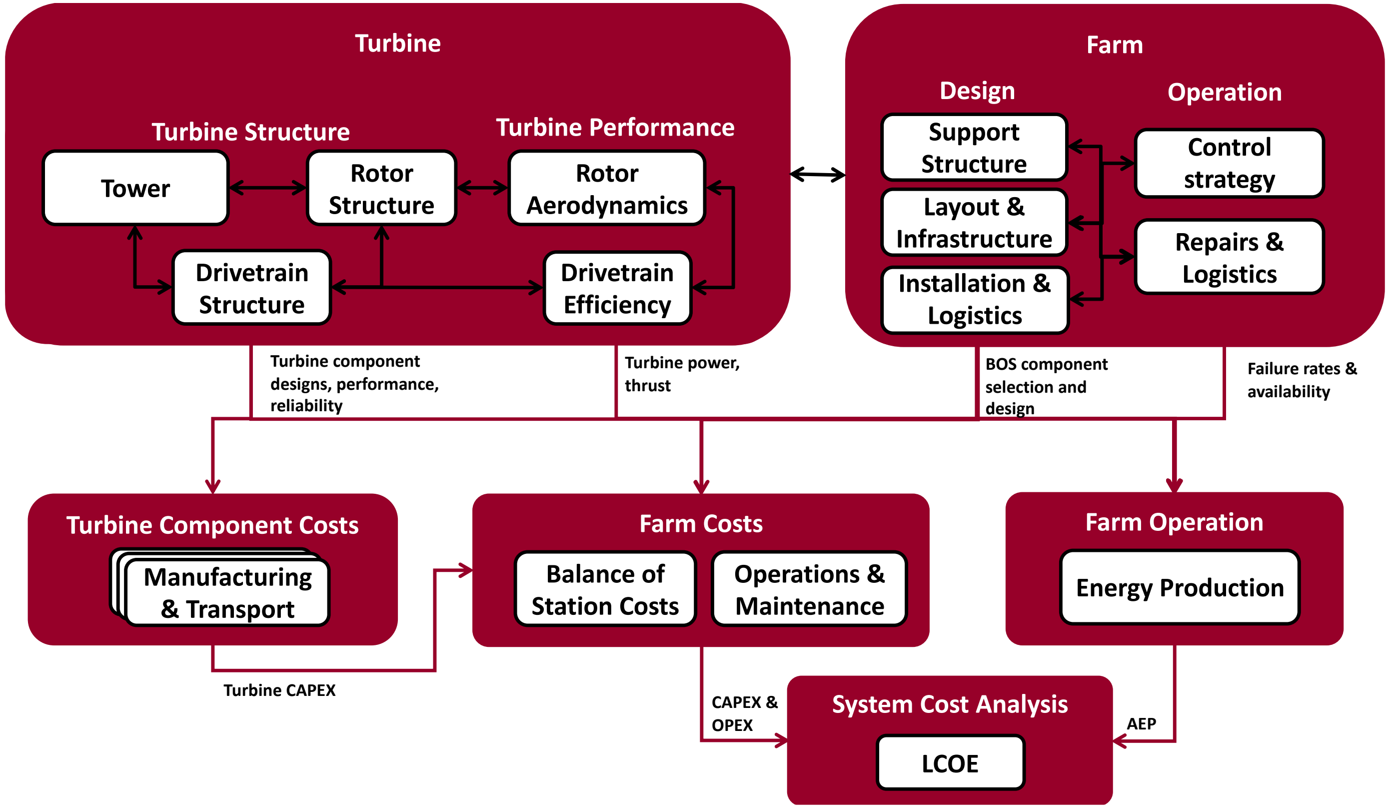
LCOE:
A Gold Standard in Innovation and Technology Evaluation

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

– 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
  - E.g. control strategy → energy production, reliablity

– LCOE depends on the resource, technology, site design, local conditions and more



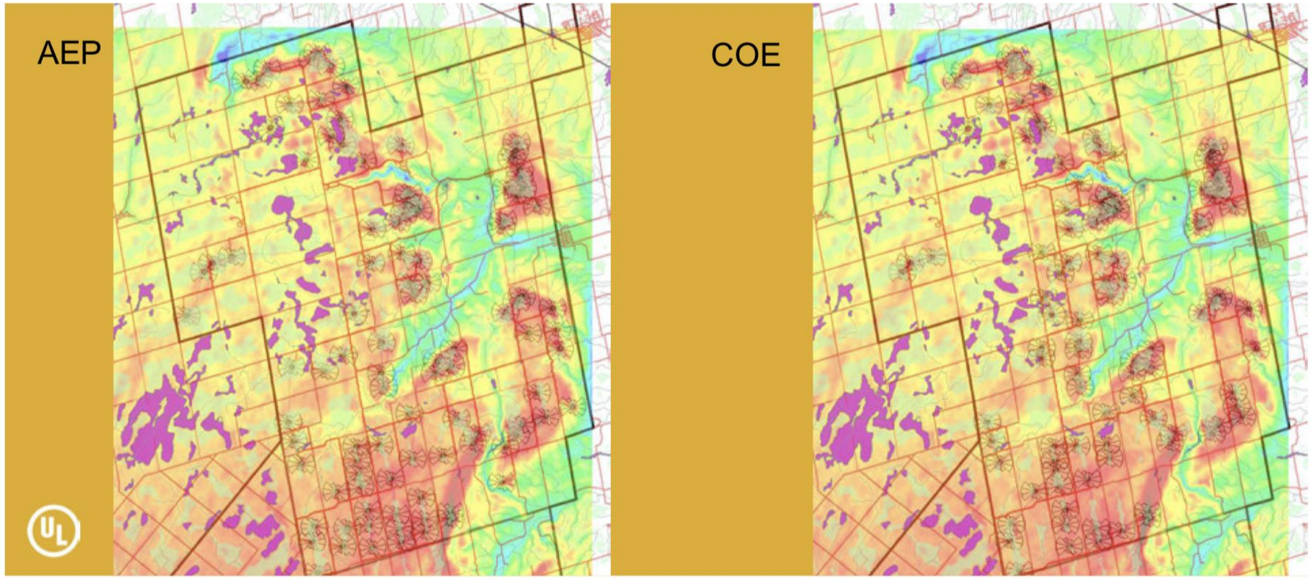
Historical Wind Plant Optimization (2000 – 2015)
From AEP to LCOE

- Slowly built trust in optimization with research and industry experience
- AEP optimization insufficient but cost models are cumbersome
- Compromise: simple models for major cost elements (electrical and road infrastructure)

Openwind®

Results

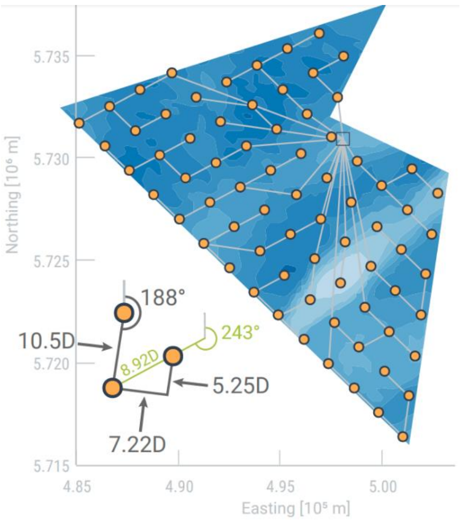
Objective Function	Net Energy [GW]	BOP Cost [$]	LCOE [$/MW]
AEP	1101 100%	51 100%	38.49 100%
COE	1096 99.6%	46 90.2%	38.3 99.5%
IRR	1094 99.4%	46 90.2%	38.38 99.7%

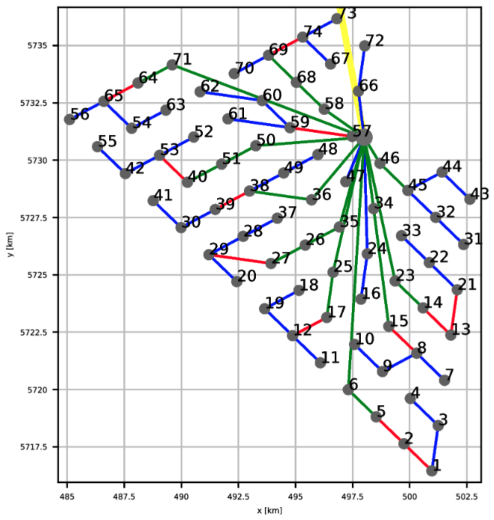


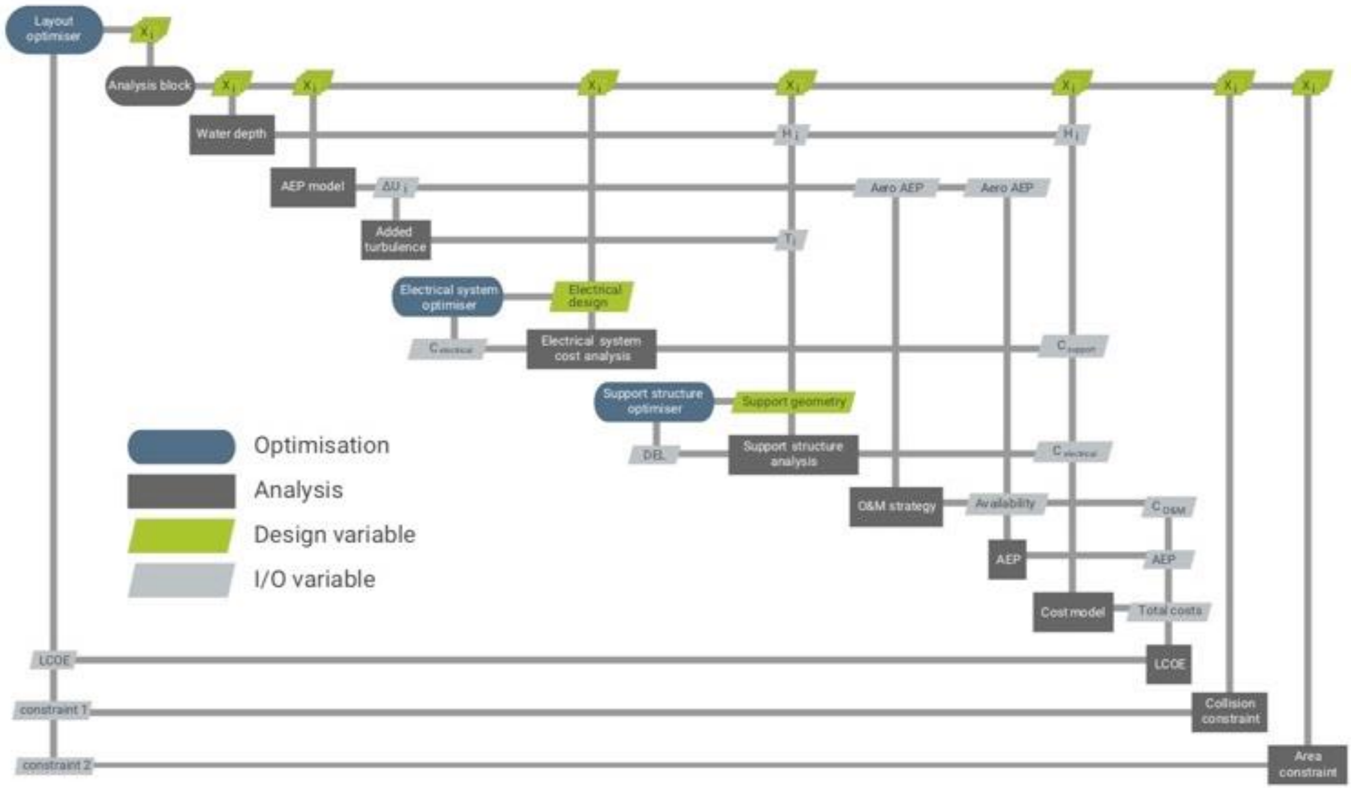
4th Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se17-8-ul-renewables.pdf

Recent Wind Plant Optimization
More advanced LCOE optimization

- Optimization use in site design now widespread
- Emphasis shifts to more advanced modeling of LCOE components – and also addressing offshore sites





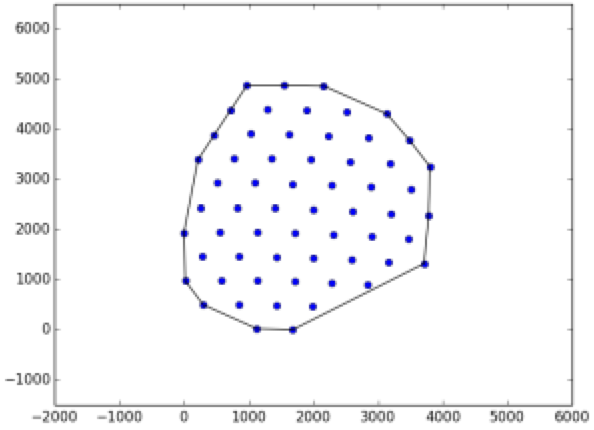


Example wind plant layout optimization workflow for an offshore reference wind plant (Source: Sanchez Perez-Moreno et al 2017)

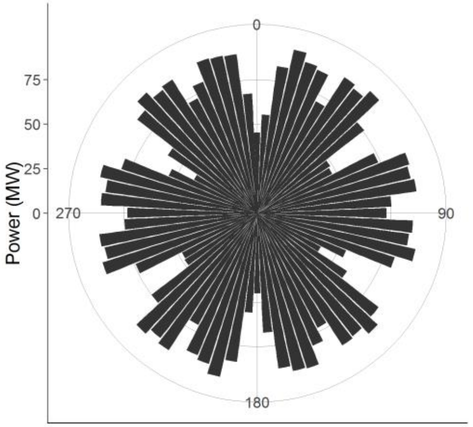
Recent Wind Plant Optimization
Control strategies

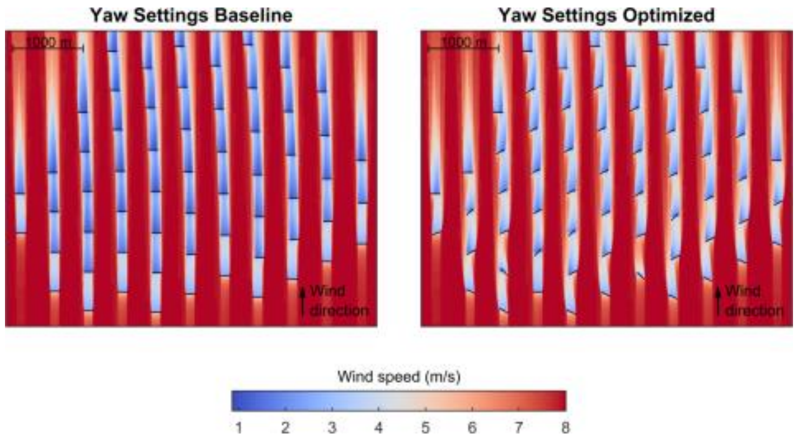
- As control paradigm shifts from turbine to plant, so do opportunities to consider plant control strategies in the upfront design process

Baseline Layout



Baseline Power Production





- **Baseline**: fixed (original) positions, turbines all yawed in mean wind direction
- **Optimized yaw**: fixed (original) positions, turbines optimally yawed for each wind direction
- **Optimized location**: position optimized, turbines all yawed in mean wind direction
- **Combined optimization**: simultaneously optimized position and yaw for each wind direction.

Gebraad, P.; Thomas, J.; Ning, A.; Fleming, P.; Dykes, K. (May 2016) Maximization of the Annual Energy Production of Wind Power Plants by Optimization of Layout and Yaw-Based Wake Control. Wind Energy, doi:10.1002/we.1993.

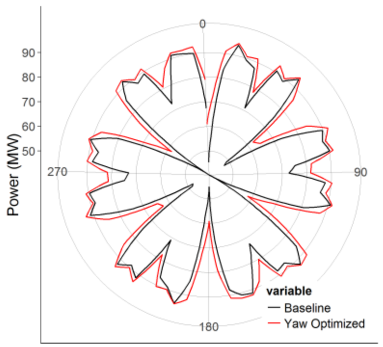
Fleming, P.A.; Ning, A.; Gebraad, P.M.O.; Dykes, K. (2015). Wind plant system engineering through optimization of layout and yaw control. Wind Energy.

Recent Wind Plant Optimization
Control strategies

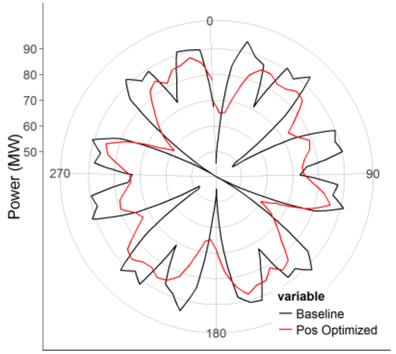
- Considering wake steering strategies in the design process can increase AEP, reduce costs, or both

	Baseline	YawOpt	PosOpt	Combined
Mean power (MW)	78.86	84.91	78.86	78.84
Area (km^2)	14.53	14.53	12.45	8.96
Power density (W/m^2)	5.43	5.84	6.33	8.80
AEP(GWh)	1040.3	1094 (+5.2%)	1055.8 (+1.5%)	1095 (+5.3%)

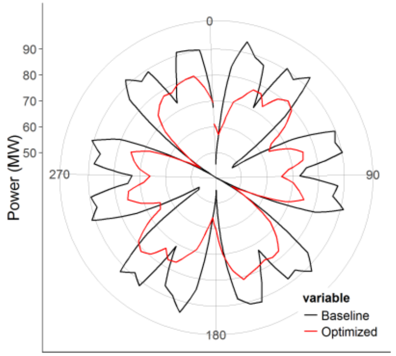
Yaw Optimized

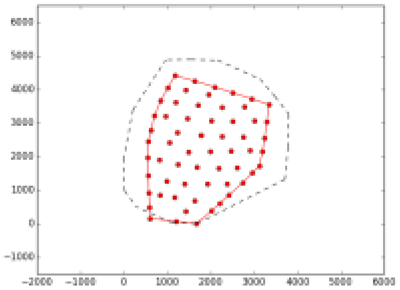


Position Optimized



Combined





Final versus initial layout perimeter with higher power density

Gebraad, P.; Thomas, J.; Ning, A.; Fleming, P.; Dykes, K. (May 2016) Maximization of the Annual Energy Production of Wind Power Plants by Optimization of Layout and Yaw-Based Wake Control. Wind Energy, doi:10.1002/we.1993.

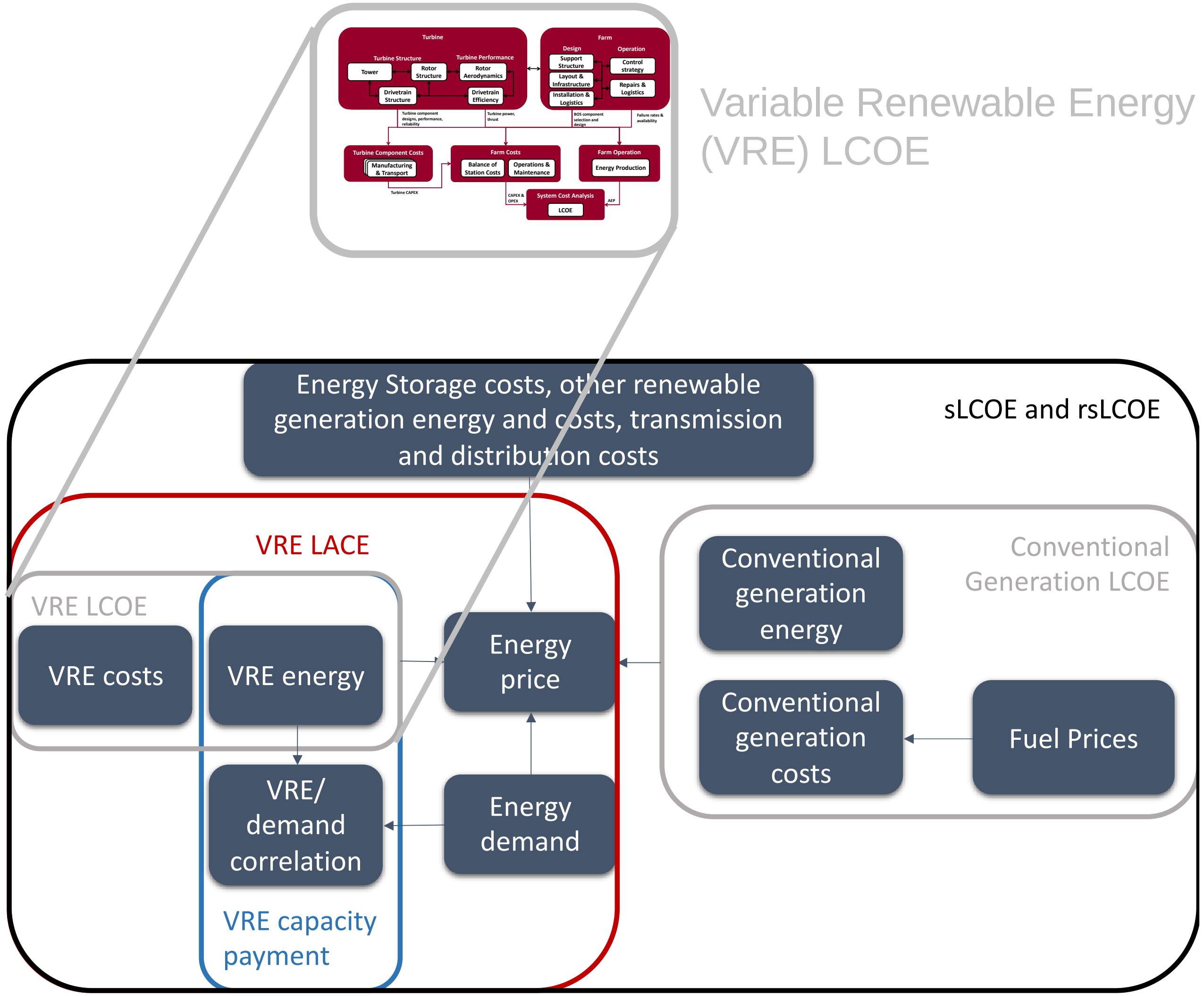
Fleming, P.A.; Ning, A.; Gebraad, P.M.O.; Dykes, K. (2015). Wind plant system engineering through optimization of layout and yaw control. Wind Energy.

How do we rethink wind farm design and operation to beyond LCOE?

Wind Farm Design, Operation and Control for the Future

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)

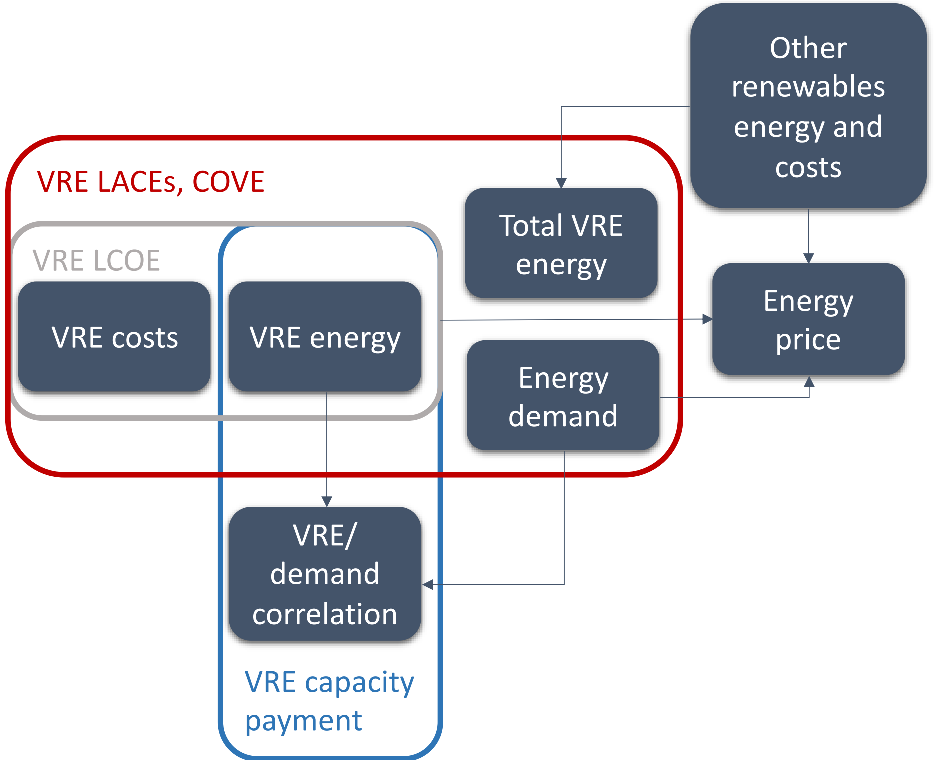


From sLCOE to COVE

- 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*

How do value objectives affect wind project design and operation?

DTU Wind Energy System Design, Operation and Control for Beyond LCOE Metrics

Wind/Renewable Energy Project Life-Cycle

Technology Design / Innovation	Site / Technology Selection	Technology Sizing	Site Design	Project Operation
• Turbine design • Innovation concepts (hardware and control)	• Storage • Power-to-x • Additional energy technologies • Turbine type(s)	• Capacity of each generation and storage asset • Electrical system topology	• Detailed site layout • Detailed collection and balance of system design	• Lifetime operation of the project balancing revenues and ccosts

Beyond LCOE Case Study: Technology Design / Innovation

Technology Design / Innovation → Site / Technology Selection → Technology Sizing → Site Design → Project Operation

- **LowWind (LW) turbine**
- High generation at low wind speeds
- Lower cut-off lowers CAPEX

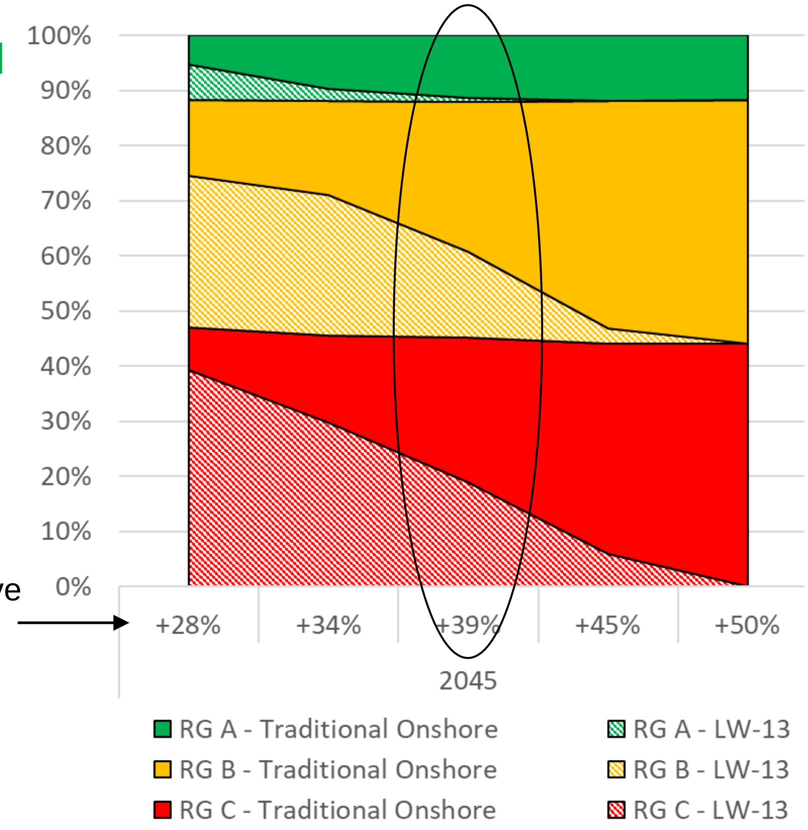
- High market share if CAPEX < 40 % higher compared to traditional turbine
- Also reduces transmission expansion needs

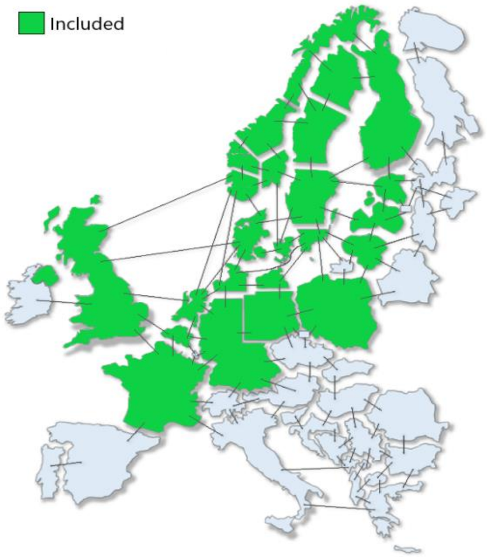
High wind areas

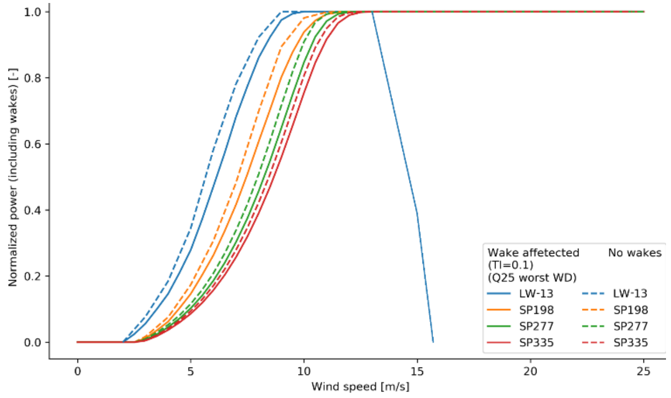
Mid wind areas

Low wind areas

CAPEX relative to a standard turbine







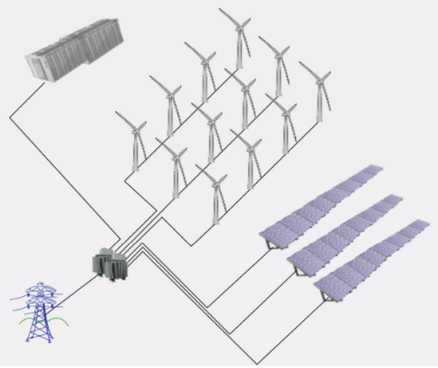
P. Swisher, et al., "Competitiveness of a low specific power, low cut-out wind speed wind turbine in North and Central Europe towards 2050", *TechRxiv, Preprint*, 2021 (https://doi.org/10.36227/techrxiv.14267960.v1)

Beyond LCOE Case Study: Technology Selection and Sizing

Technology Design / Innovation | Site / Technology Selection | Technology Sizing | Site Design | Project Operation

Sizing of Wind-Solar-Storage Hybrid Power Plant

Case Study – Indian Peak Power Plant



Grid Connection (contracted capacity) = 300 MW

	Solar Contracted capacity	Wind Contracted capacity	Wind Solar Optimized	**Optimal Solution**	Unit
Wind	-	300	129	171	MW
Solar	300	-	347	378	MW
Battery energy	-	-	-	271	MWh
Battery power	-	-	-	83	MW
Potential wind-solar energy at nominal capacity	617	775	1047	1219	GWh
HPP Annual energy production	617	775	1026	1199	GWh
Capacity factor	23	29	39	46	%
Full load hours	2057	2584	3421	3997	Hours
Total curtailment	0	0	21	20	GWh
Potential wind-solar energy curtailed	0	0	2	2	%
LCOE	29	38	32	39	EUR/MWh
NPV	37	36	72	82	MEUR

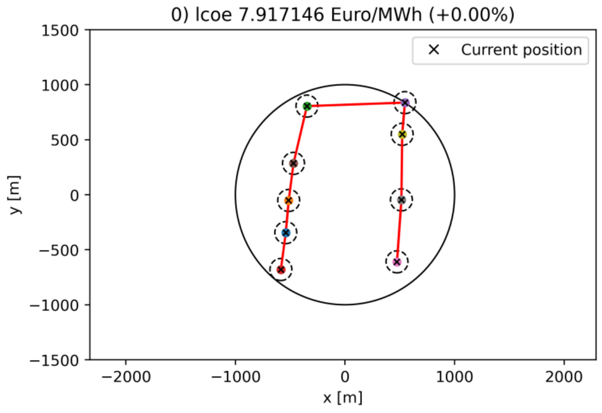
Alessandra Cossu "Optimal sizing of hybrid power plant" *Master Thesis, DTU Wind Energy, 2020*

Beyond LCOE Case Study: Site Physical Design

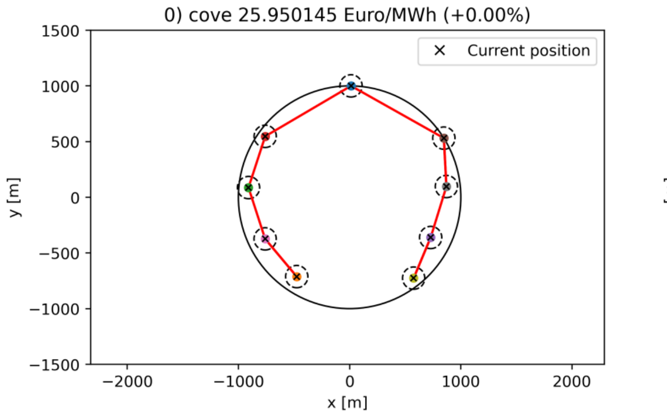
Technology Design / Innovation → Site / Technology Selection → Technology Sizing → **Site Design** → Project Operation

- How does selection of AEP versus LROE, LCOE versus COVE affect the design of a wind farm?

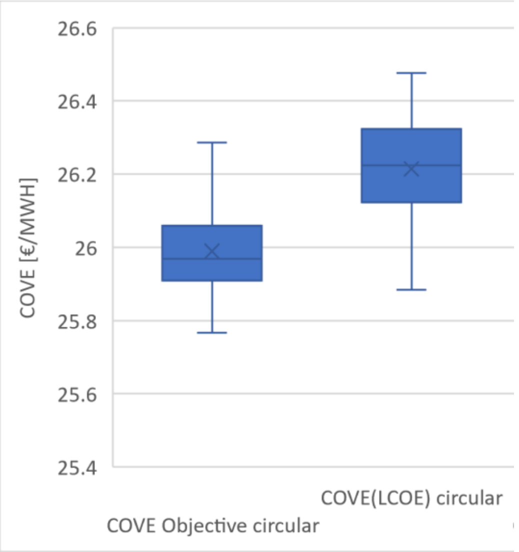
- IEA Wind Task 37 Reference Site designed for each objective:
  - Metrics drive designs systematically in different ways
  - Value based objective more heavily favor larger turbine spacings despite impact to balance of system costs

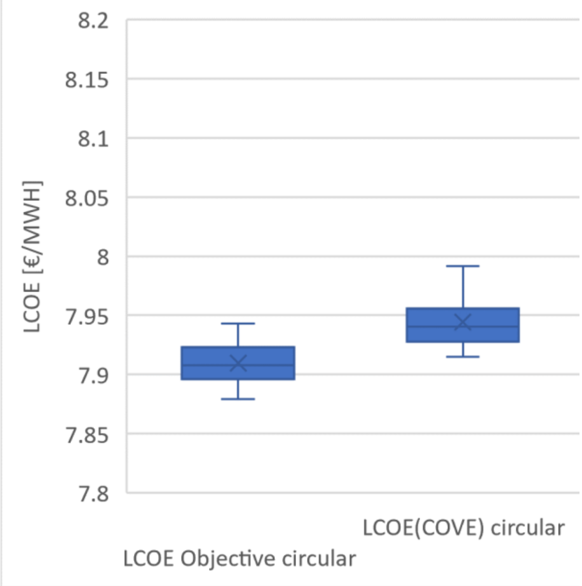


(a) Main pattern representative



(a) Main pattern representative





Wawrzyniak, S. J. Optimization of wind farm layout design for value-based and profitability-based objectives , MS Thesis, DTU Wind Energy, 2021.

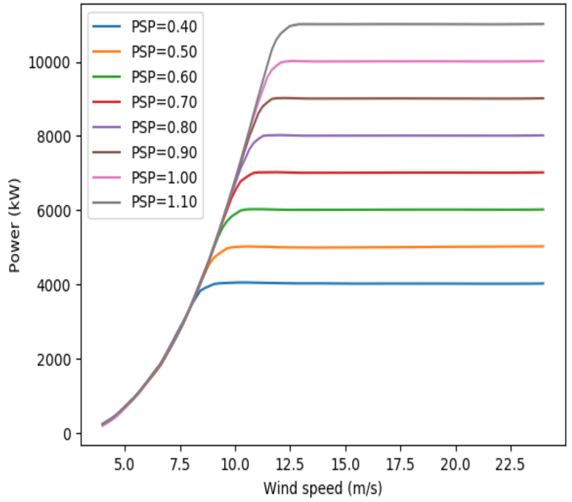
Supervised by Katherine Dykes, Lena Kitzing, and Philipp Beiter

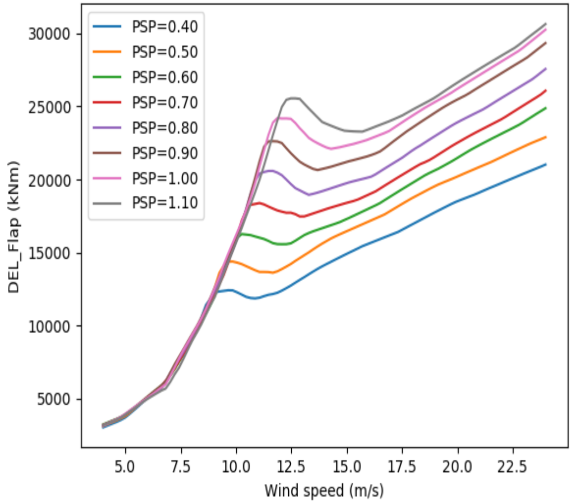
Beyond LCOE Case Study: Operation

Technology Design / Innovation → Site / Technology Selection → Technology Sizing → Site Design → **Project Operation**

Optimization of turbine operation balancing revenue and reliability:

- Optimization of a single turbine operational setpoints (Power boosting and de-rating) under Damage Equivalent Load (DEL) constraints
- Unconstrained optimization results in full derating under negative prices and full power boosting under positive prices
- Constrained trades-off power-boosting / higher loads for high electricity prices with derating / lower loads at negative and low prices





Constrained / Unconstrained	Site	Base Revenue (DKK/hour)	Avg. Optimised Revenue	Avg. Rev Imp (%)	Max. Optimised Revenue	Max. Rev Imp (%)	Min. Optimised Revenue	Std. dev. of Opt. Revenue	Std. dev. of Opt. Revenue (%)	Successful Opt Runs (out of 100)
Constrained	Bovling	1,119	1.0217	**2.535**	1.0273	**3.031**	1.0123	0.00275	0.2690%	33
	Made_3	1,115	1.0297		1.0333		1.0226	0.00269	0.2614%	39
	Vesternæs_1	1,153	1.0246		1.0303		1.0174	0.00347	0.3387%	78
Unconstrained	Bovling	1,119	1.0481	**4.663**	1.0497	**4.835**	1.0442	0.00092	0.0879%	100
	Made_3	1,115	1.0498		1.0514		1.0471	0.00087	0.0831%	100
	Vesternæs_1	1,153	1.0420		1.0440		1.0388	0.00119	0.1141%	100

Thorsen, A. Wind Turbine Operational Strategies for Increasing Value of Energy, MS Thesis, DTU Wind Energy, 2020.

& Philips, E. Optimization of wind farm operational strategy for revenue and reliability, MS Thesis, DTU Wind Energy, 2020.

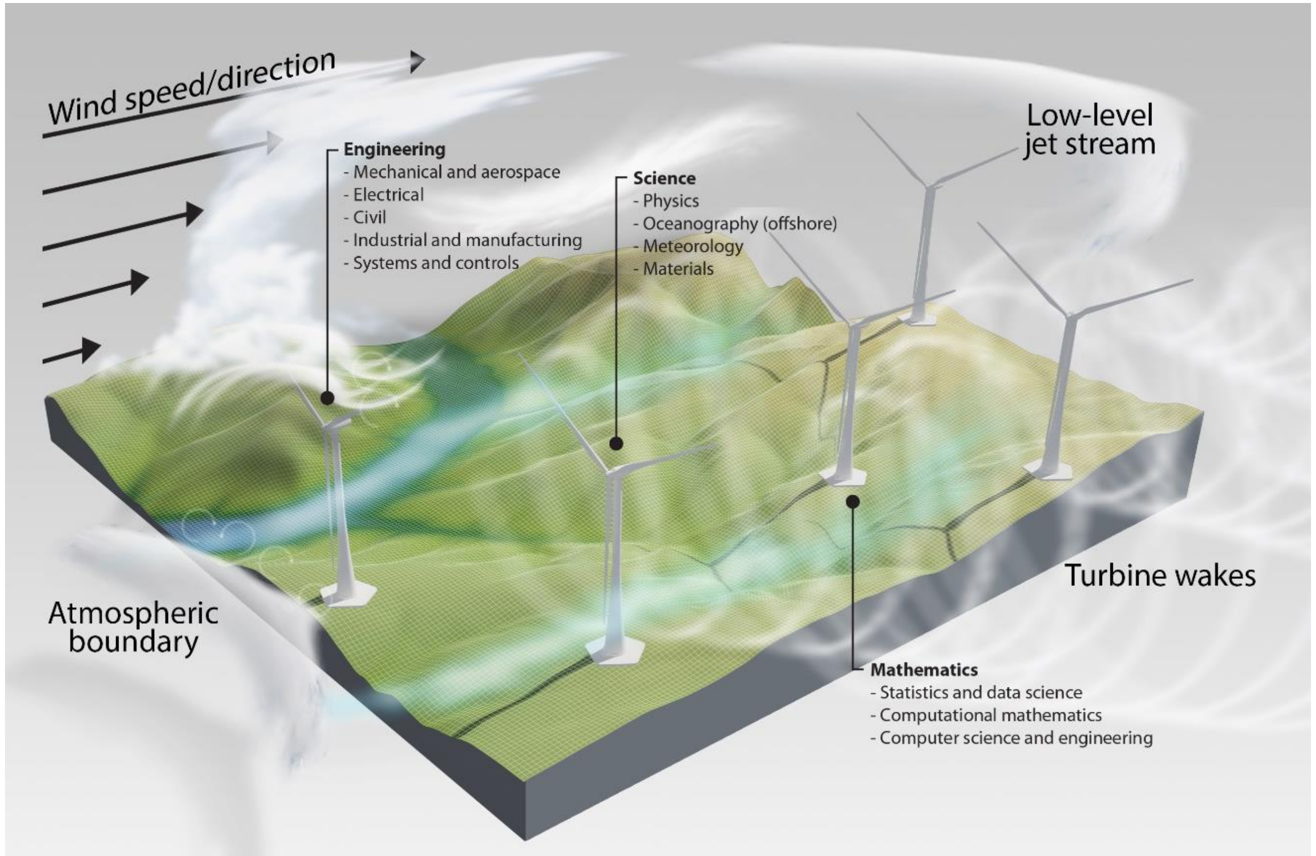
Supervised by Søren Juhl Andersen, Juan Pablo Murcia Leon and Katherine Dykes

Where do we go from here?

Summary and Outlook

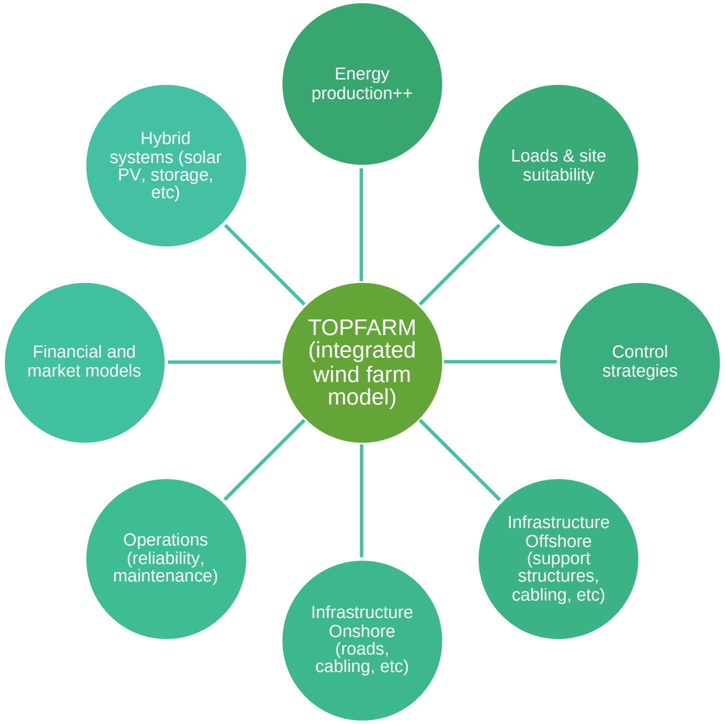
What’s needed?

- There remains a **great deal of work to drive Wind Power** to its full potential
- Much of the need is in **fundamental knowledge that can catalyze subsequent innovations** in the public and private sectors
- **A lot of work is needed!** Metrics / design objective development, application in wind farm turbine and farm R&D, design and operation, investigation of new innovations, optimization techniques and more!

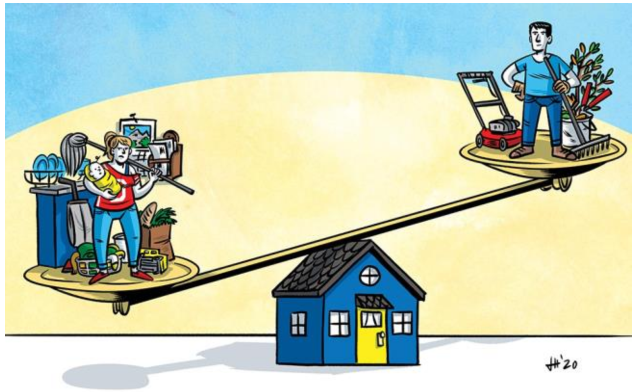


Thank You

TOPFARM :DTU Wind Energy software platform for optimization of wind farm and renewable energy park design and operational strategies in both onshore and offshore applications

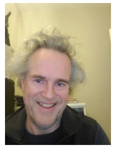


https://github.com/DTUWindEnergy/TOPFARM



Balanced Outline

Setting the Scene – Mark O'Malley



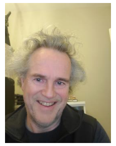
Grid & System Options – Accommodating Wind
Hannele Holttinen

Optimisation of Wind Power – Maximising its Value – Katherine Dykes

Stability – Wind Power Playing its Part – Nicolaos A. Cutululis

Hybrids – To Benefit Wind and the System – Jennifer King

Wrap Up & Conclusions – Mark O'Malley



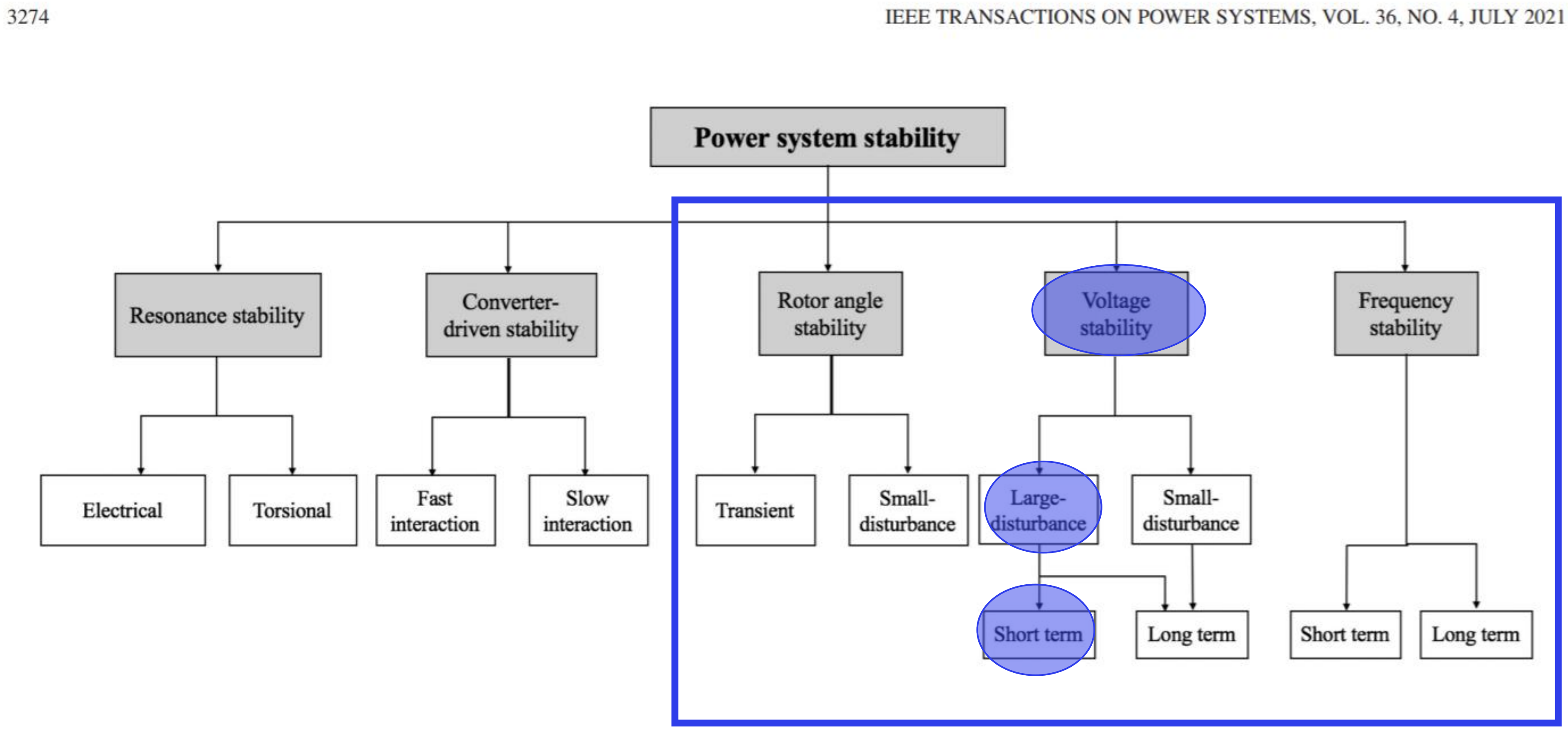
Q & A – SLIDO - All

Slido.com and enter Code **#nawea5**

Nicolaos A. Cutululis

Grand Challenges for Grid Integration – stability

Stability in power systems

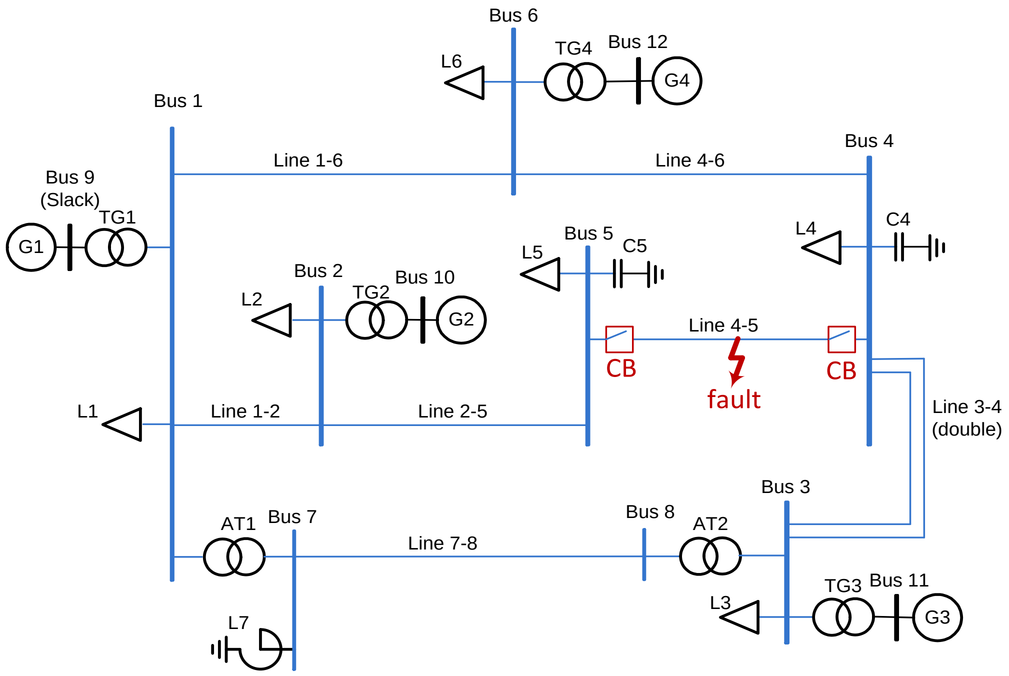


Fault ride through (FRT)

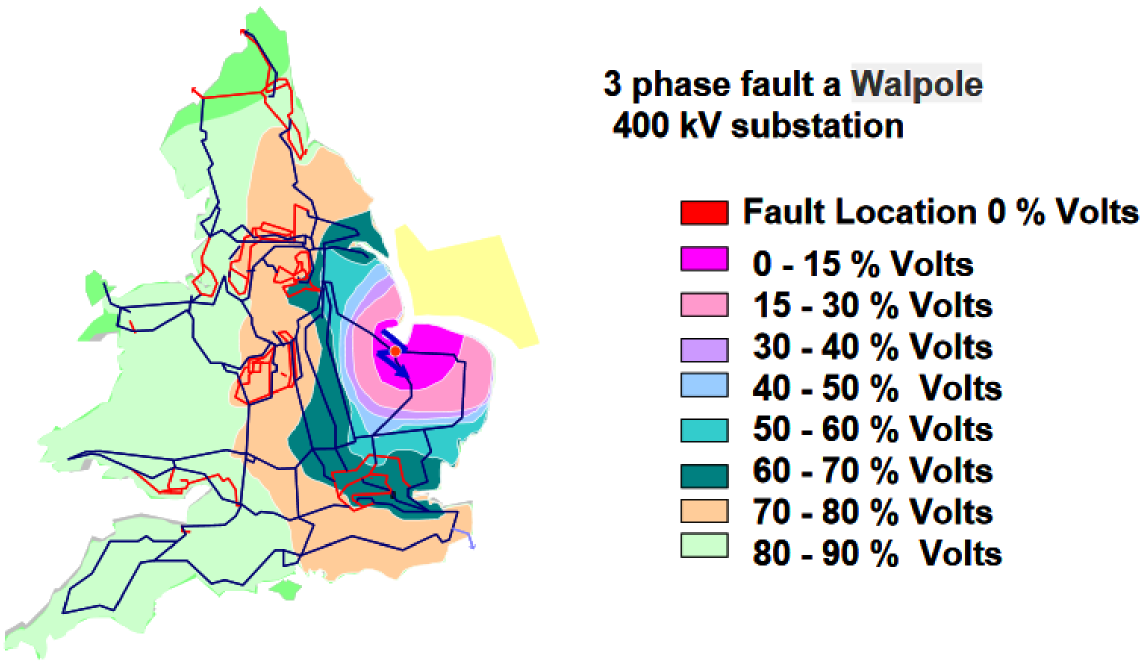
Requirements and specifications usually defined in grid codes

Fault ride-through (FRT)

- Power system protection relays (overcurrent, differential, distance) → detect the fault
- Circuit breakers (CBs) clear the fault → disconnect the faulted sections



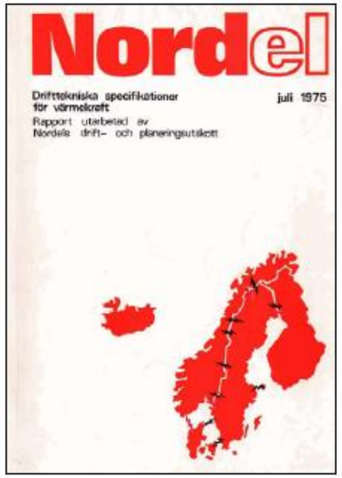
FRT – Regional voltage collapse (England)



Securely cleared fault within e.g. 100 milliseconds

Facilities (generators) should *survive* (i.e. ride-through) the fault & inject *fault* current…!!!

Control – FRT requirements *through time*



- **1975**

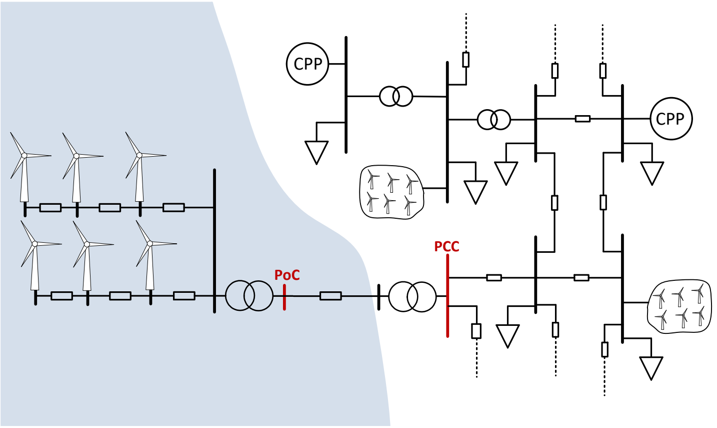
Technical Operation Specifications for Thermal Plants:
Plants should be able to withstand a ‘deep voltage transient’

- **early 1990s**

Recommendations for wind power:
FRT not mentioned **minor attention – not considered important**

- **late 1990s**

Stay connected (fault ride through – FRT) **as wind share increases**



- **2003-2007**

Grid codes for large scale wind power:
Reactive current injection **to avoid voltage collapse & help protection**

- **2008-2010**

Grid codes for large scale wind power:
Post-fault P ramp-up **to avoid frequency collapse**

- **2015**

Negative sequence current **to balance and detect asymmetrical faults**

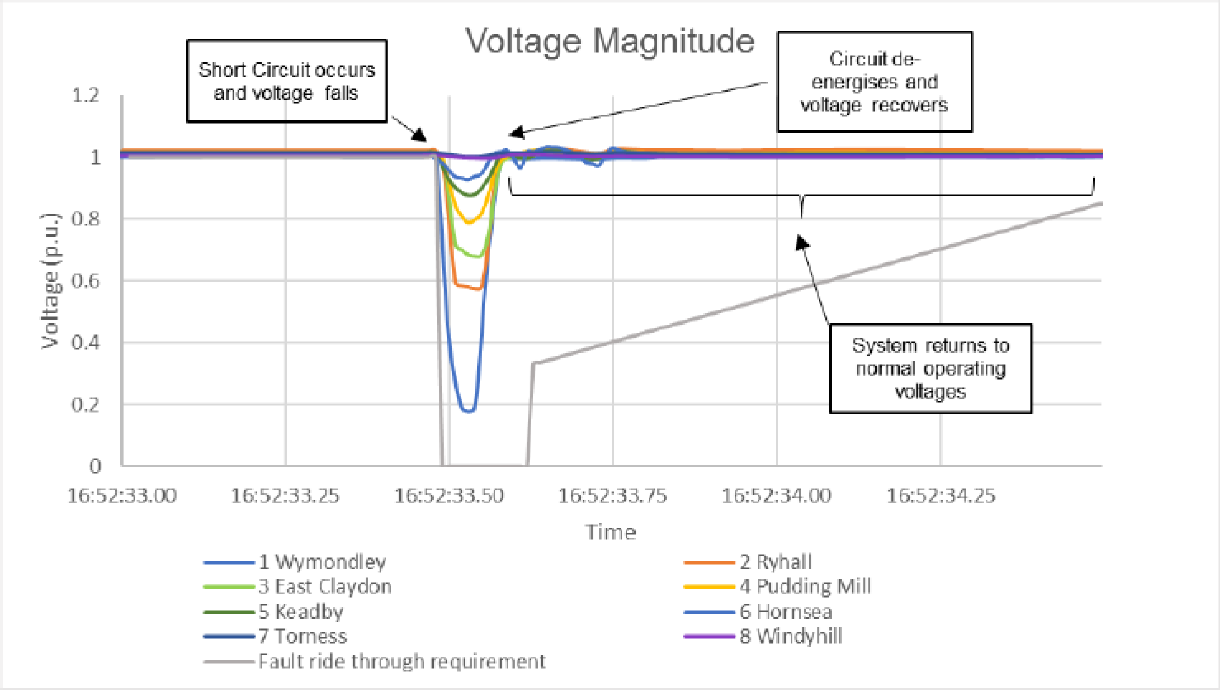
Grid codes: The Manufacturer´s Nightmare, Peter Wibek Christensen, EWEC 2010, Warsaw - April 22. 2010
http://www.ewea.org/ewec2010/fileadmin/ewec2010_files/documents/side_events/Peter_Wibaek_Christensen.pdf

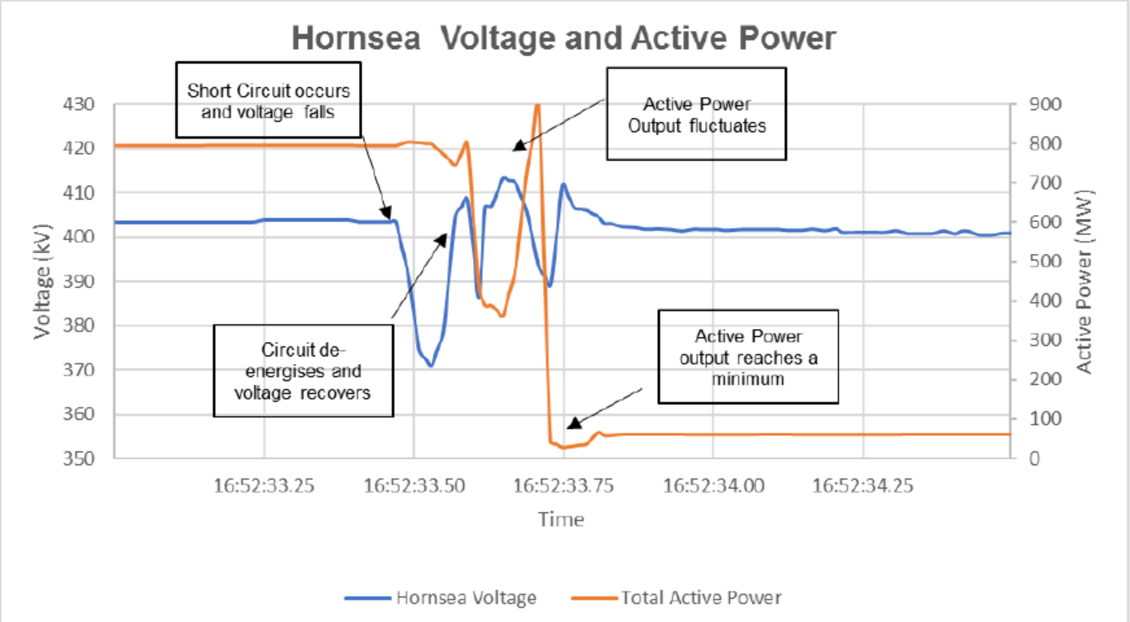
Wind power has been successfully performing FRT for many years

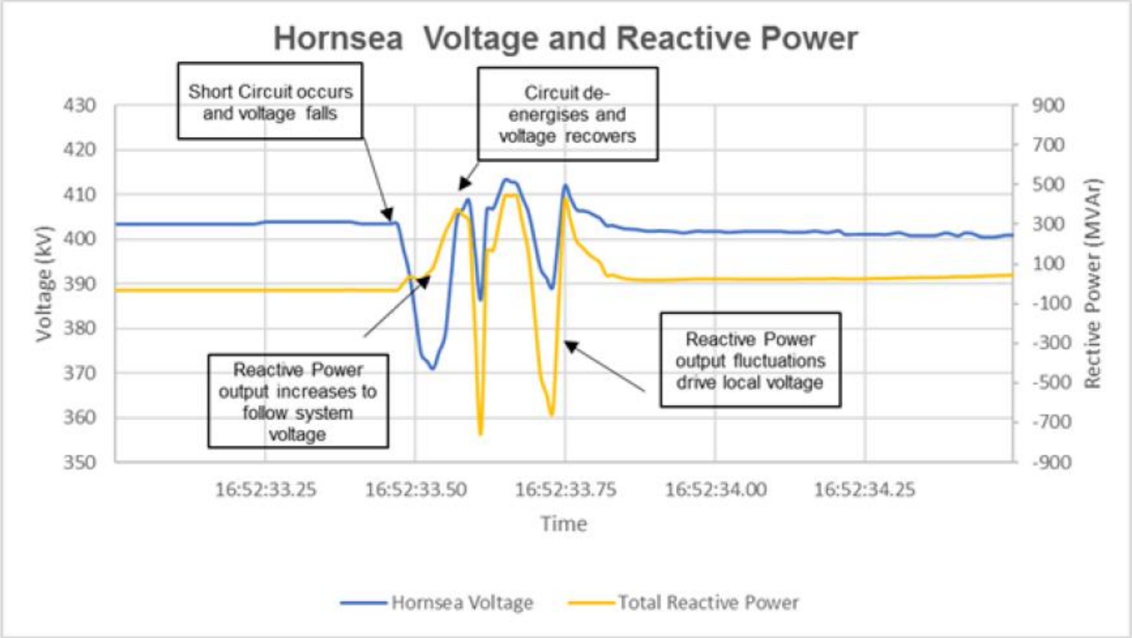
however…

A recent event in UK 9th of August 2019

- Due to harsh weather, fault(s) occurred



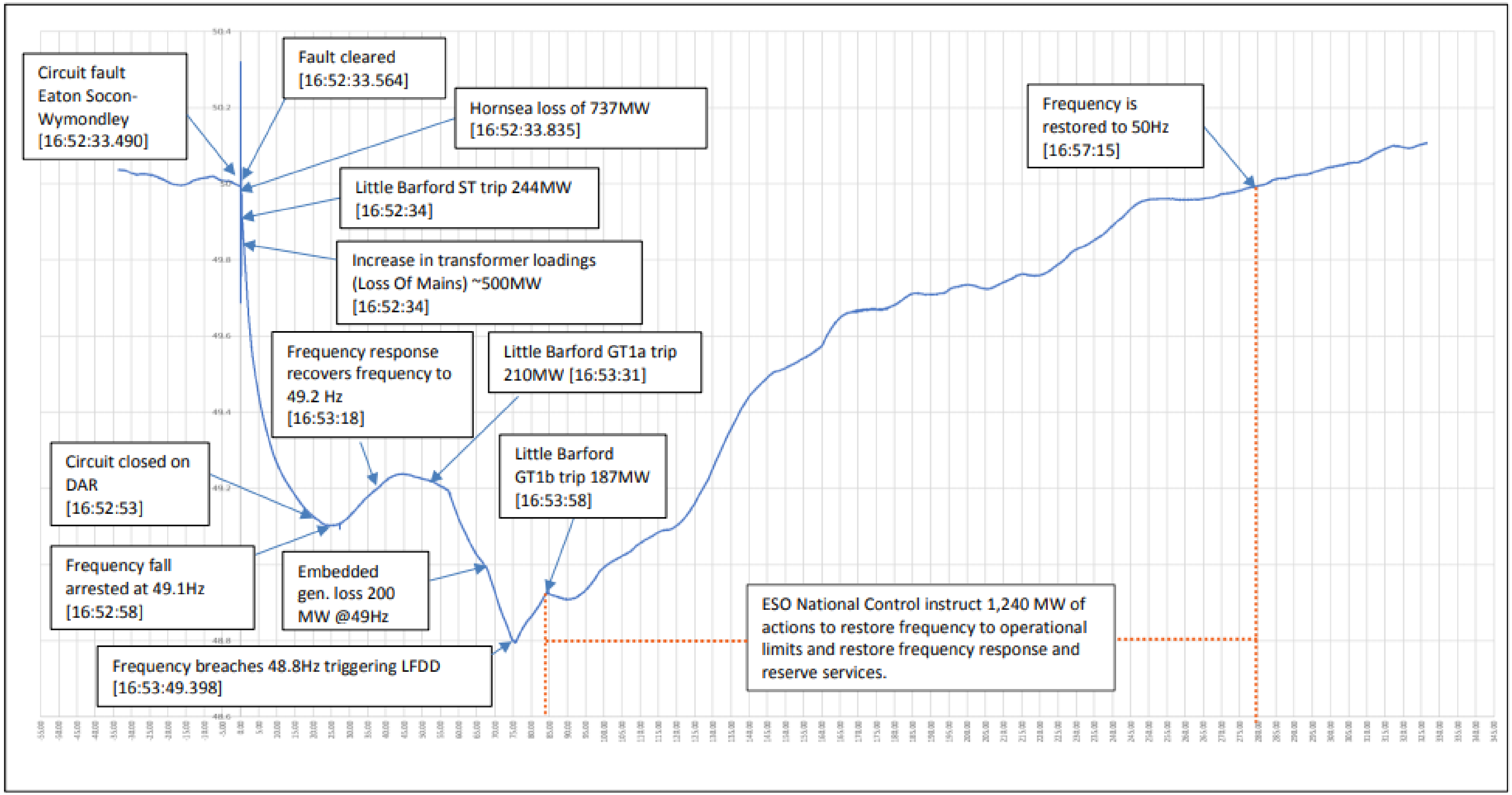




https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_final.pdf
https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_appendices_-_final.pdf

A recent event in UK
9th of August 2019

- Post-fault
  - →Trippings
  - →Frequency drop
  - → Load shedding



https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_final.pdf

Why this happened?

The wind turbine settings were standard settings from the manufacturer. During the incident, the turbine ***controllers*** *reacted* ***incorrectly*** *due to an insufficiently damped* ***electrical resonance*** *in the sub-synchronous frequency range, so that the local Hornsea voltage dropped and the turbines shut themselves down.*

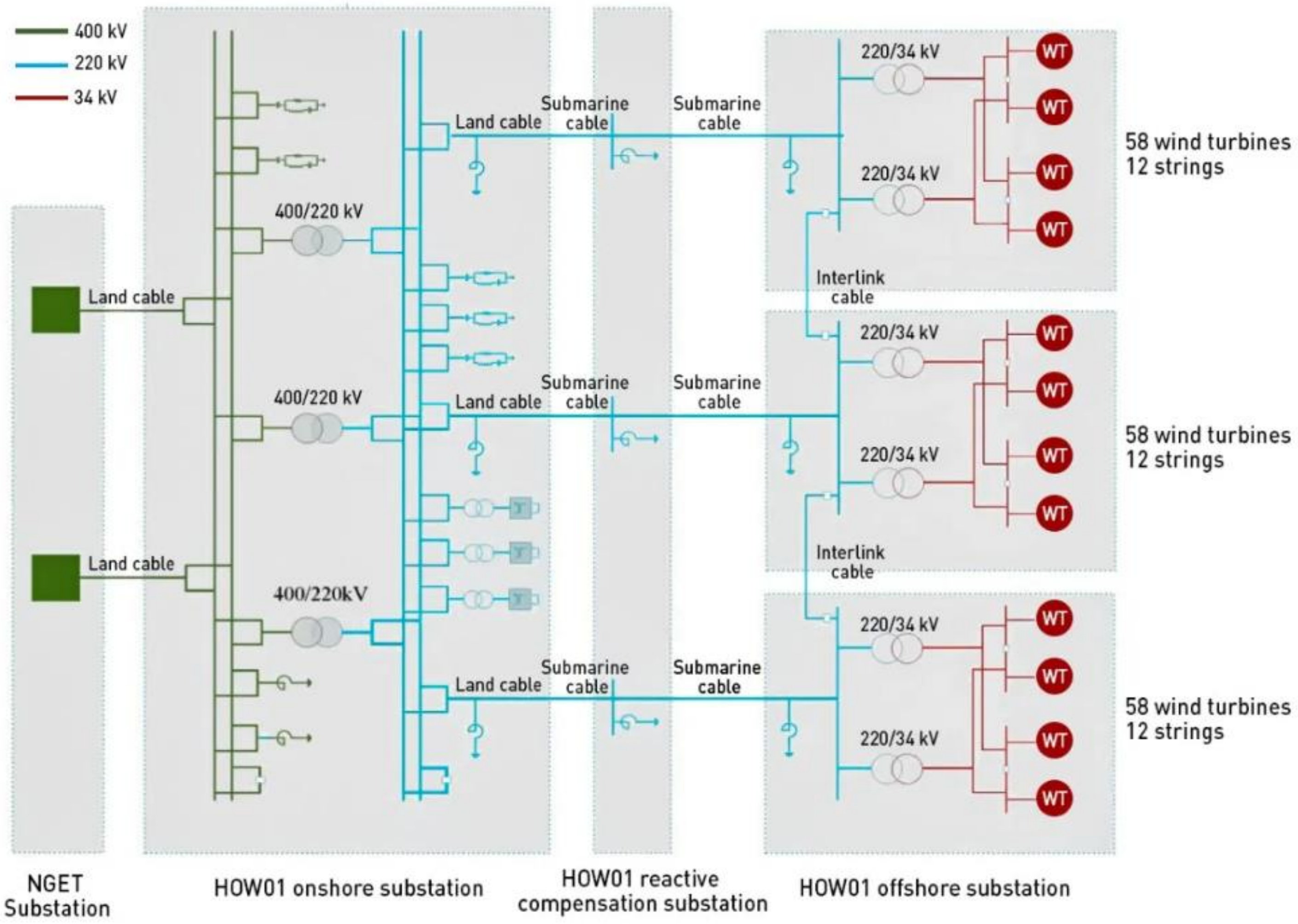
https://www.nationalgrideso.com/document/152346/download

Hornsea ONE WPP

Hornsea ONE WPP:

- 174 WTs X 7.0 MW → 1.218 MW
- Three clusters (58 WTs each, 12 strings)
- Export cables of app. 170-190 km

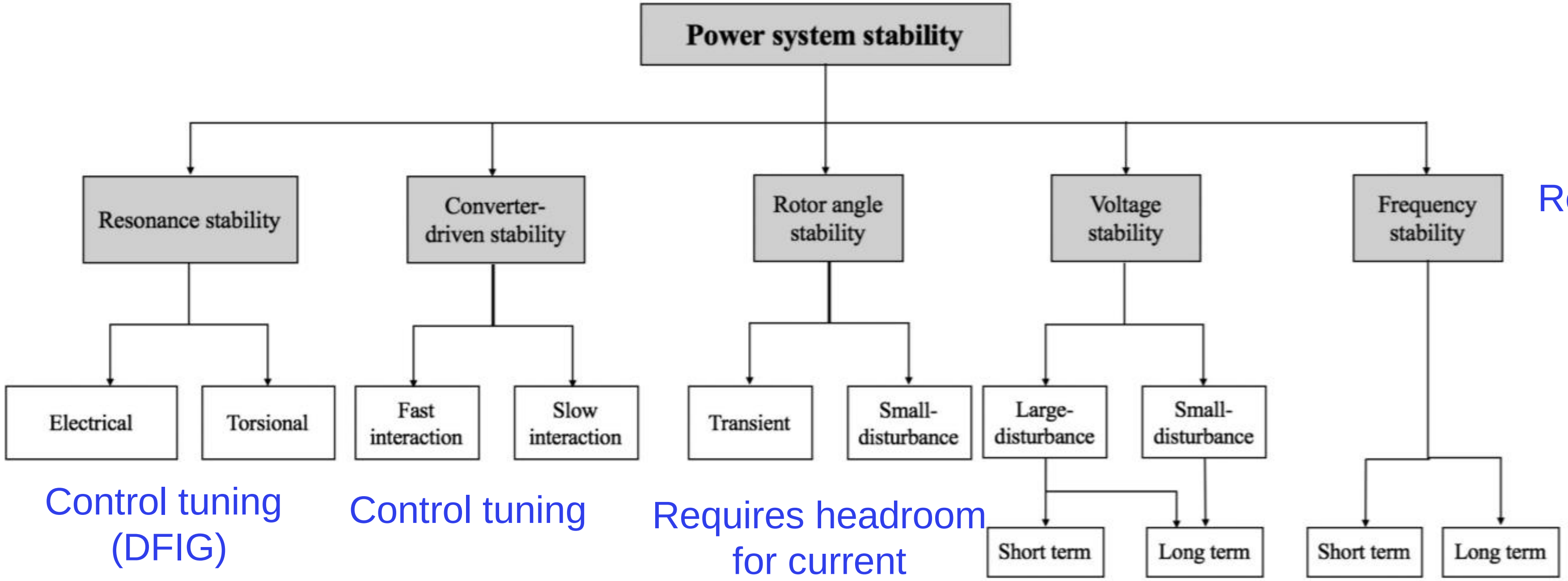
- Interlink cables
- Mid-point compensation (extra platform)
- Compensation units:
  - Passive - shunt reactors
  - Active – STATCOM
- Filters: C-type



Source: Active Filtering in a Large-Scale STATCOM for the Integration of Offshore Wind Power - Lehmann et al

Stability in power systems – can wind contribute?

3274 IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 36, NO. 4, JULY 2021



Requires operation below MPP

Control tuning (DFIG)

Control tuning

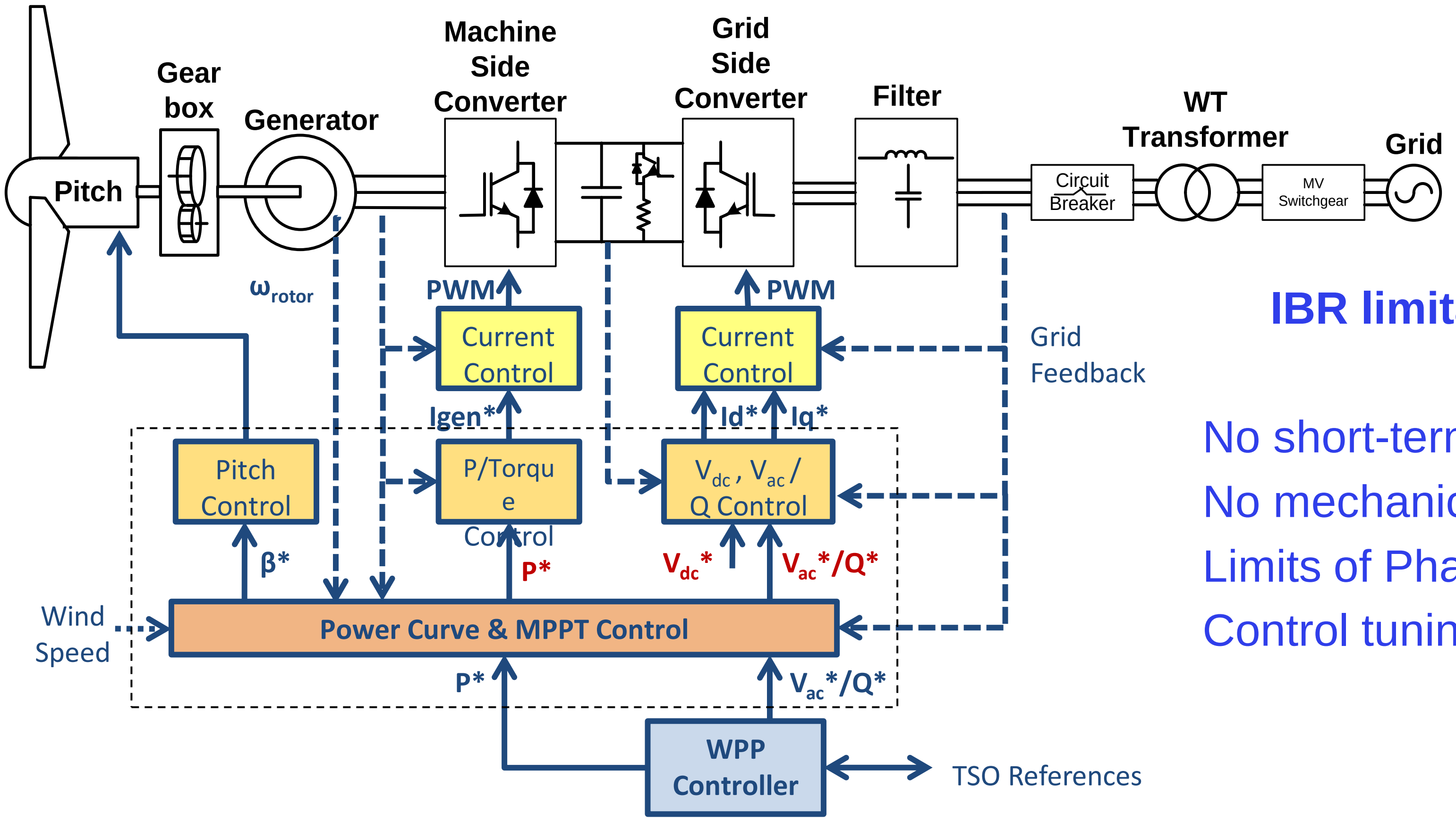
Requires headroom for current

Requires headroom for current

Wind power – limitations in providing services

VRE limitations

Power & energy availability



IBR limitations

No short-term rating

No mechanical inertia

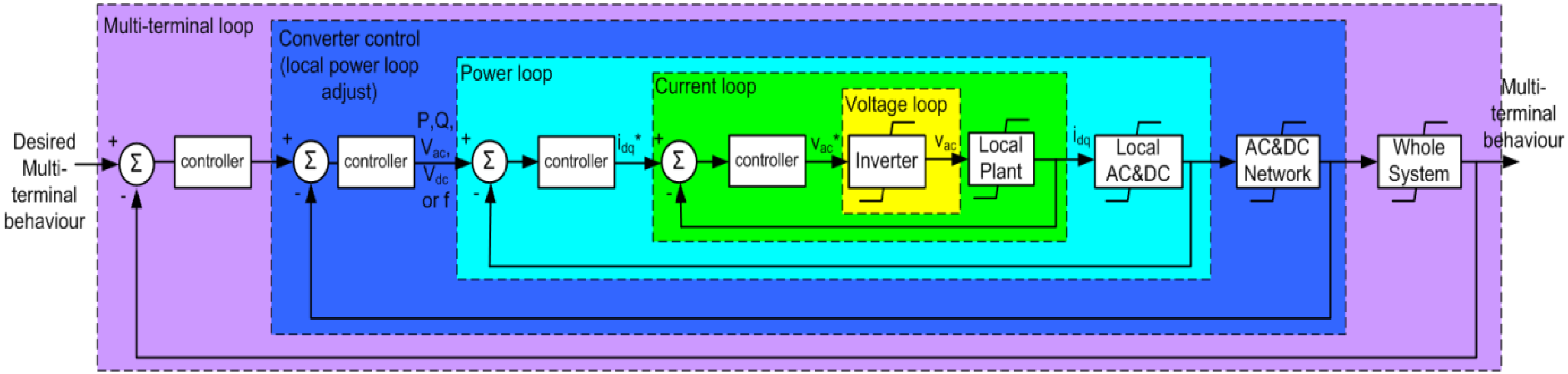
Limits of Phase-Lock

Control tuning

Converters - limits of control speed

"…all brains, no mass"

- Different control levels must be partitioned: typically 4-10x difference in speed
- IGBT switching limited to 1 to 20 kHz range
- Walking down the control levels, this sets limits on subordinate control loops speeds
- Also need to avoid key other frequencies (e.g. 50Hz)



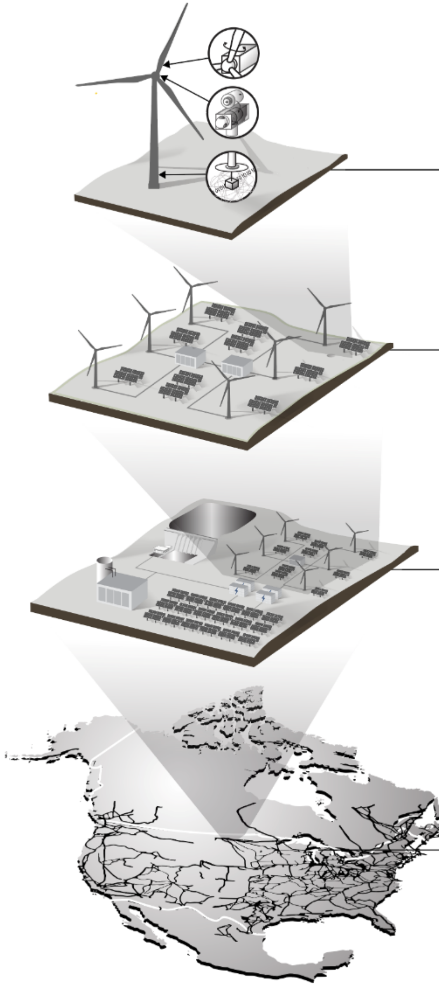
EES-UETP, HVDC and HVDC Grids for Future Transmission, Prof. Mike Barnes, 2018

How can we overcome the limitations?

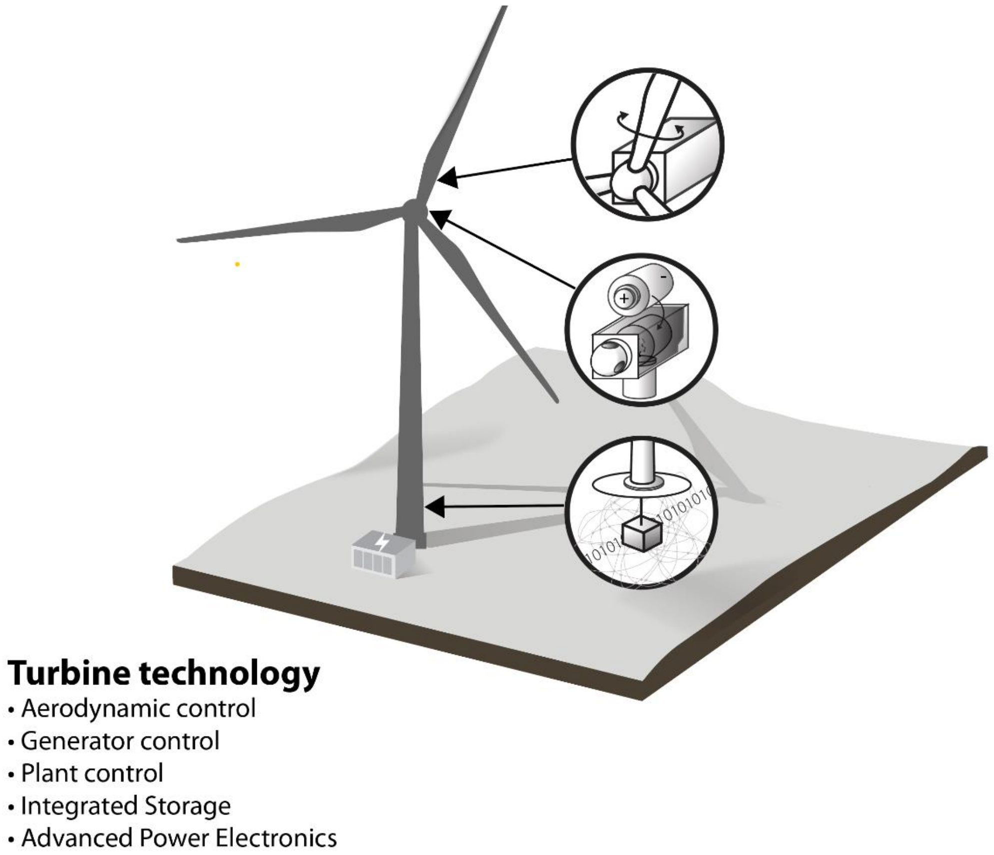
By teaming up!

Wind power can not address all the challenges alone

…but together with other RES or grid assets can significantly improve performance



Wind turbine level



Integrating storage in the DC link or at the transformer side could address the power availability

…but probably not energy availability

Plant or hybrid

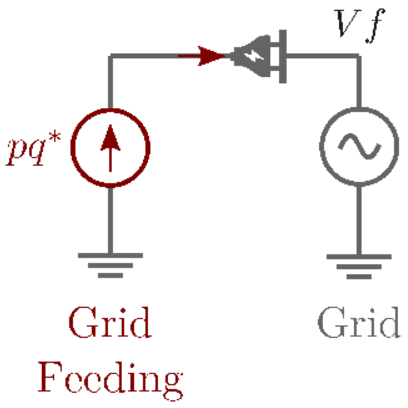
Integrating storage and/or other RES would address the power & energy availability

The control becomes more complex, and control interactions may appear

Energy management systems needed

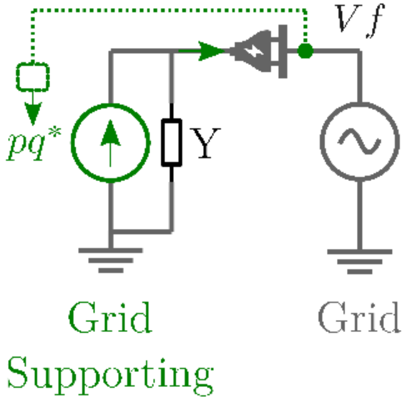
Wind turbines/plants control

First generation



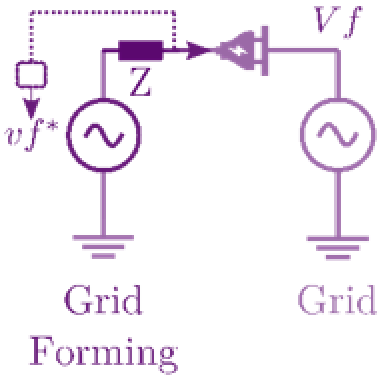
- Focus on MPPT
- Ability of controlling P & Q
- Needs energized and strong grid
- Minor contribution to system stability

Second generation



- (still) Focus on MPPT
- Ability of controlling P & Q
- Support F & V
- Needs energized and (strong) grid
- Increased contribution to system stability

Next generation



- (maybe) MPPT, more “on demand”
- Ability of controlling P & Q
- Create F & V
- ~~Needs energized and strong grid~~
- Major contribution to system stability

Main messages

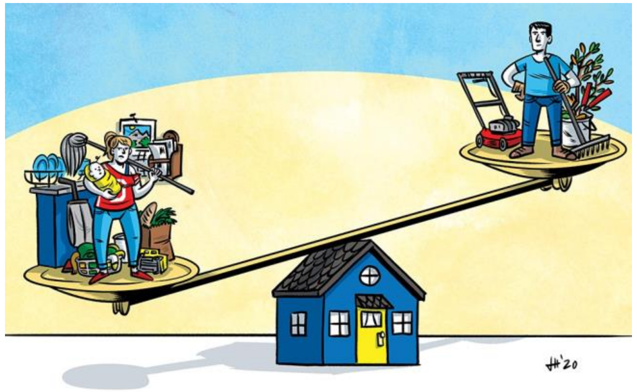
- Wind turbines/plants are very performant generators with very high controllability and have been contributing to system stability for some time now

- They can develop into the back-bone (forming the grid) generators of Europe’s net-zero power grid…but doing so may require changes in the technology, hardware and software

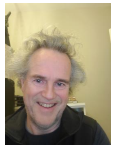
- Integrated design & operation needed!

- Understanding better the system needs and technology boundaries is required

DTU



Balanced Outline



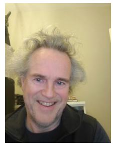
Setting the Scene – Mark O'Malley

Grid & System Options – Accommodating Wind
Hannele Holttinen

Optimisation of Wind Power – Maximising its Value – Katherine Dykes

Stability – Wind Power Playing its Part – Nicolaos A. Cutululis

Hybrids – To Benefit Wind and the System – Jennifer King



Wrap Up & Conclusions – Mark O'Malley

Q & A – SLIDO - All

Slido.com and enter Code **#nawea5**

<u>Main Risks/Challenges:</u> Adding large interstate & interregional transmission capacity has historically been a significant risk to renewable energy project development.

<u>Strategic Opportunity:</u> Transition renewables to a ***Dispatchable*** renewable generation source to fully use the existing grid distribution infrastructure, minimize additional transmission capacity expansion, and **provide ancillary grid services not currently available**

Technical Approach: Couple renewable sources & energy storage to meet the domestic energy demand across timescales and sectors with minimal required capacity reserves

Our Working Premise: We can meet the 100% goal by 2035 with minimal new transmission, minimize the strategic risk and achieve the Presidents Goal

As we prepare for a future of 100% renewable energy…

Hybrid plants will have to play a crucial role in providing services across a **range of timescales (sub-seconds to day-ahead)**.


How do we design hybrid plants with such capabilities?
“Design for Operation”

__Objective:__ Develop **modeling** and **optimization** techniques to design, operate, and analyze hybrid power plants for grid services across a range of timescales from sub-second to day-ahead services.

<u>Innovation</u>: Understand and exploit the dynamic interactions of technologies across timescales to design disruptive hybrid energy systems.

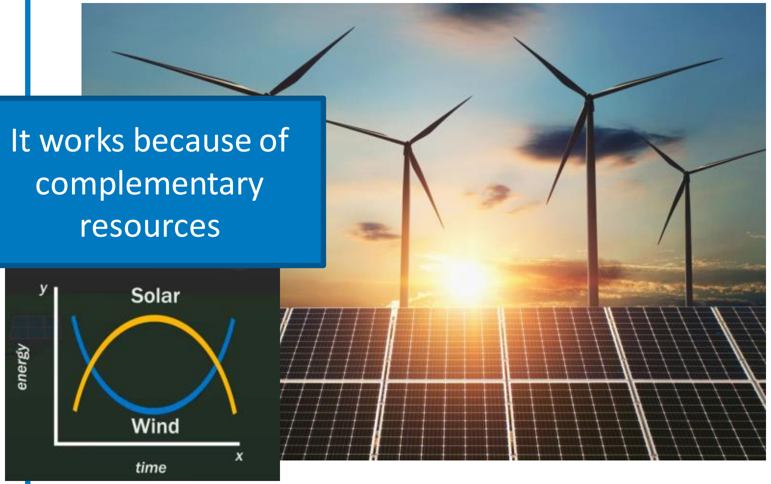
What is a Hybrid System?

Combinations of *mature* technologies can provide services needed to reach goal

Adding solar to existing onshore wind

(Maximize current interconnects)

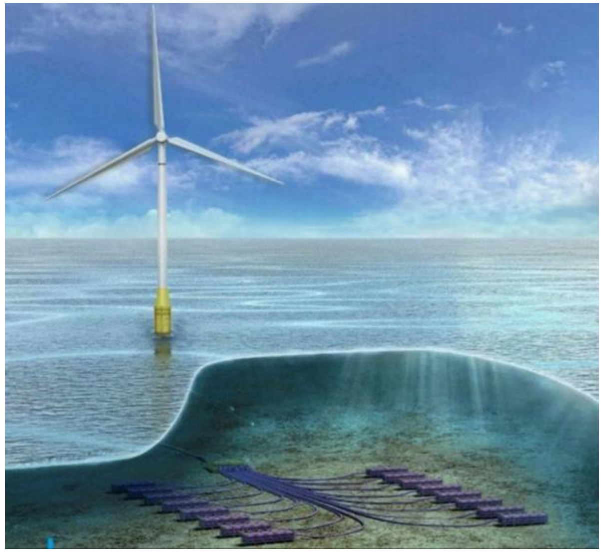
It works because of complementary resources



Easy win – add 30+ GW of solar to wind in next few years

*Major hold up is policy

Offshore Wind + Storage



Enables long term storage and grid-independent utility scale energy systems.

Wind-solar-storage

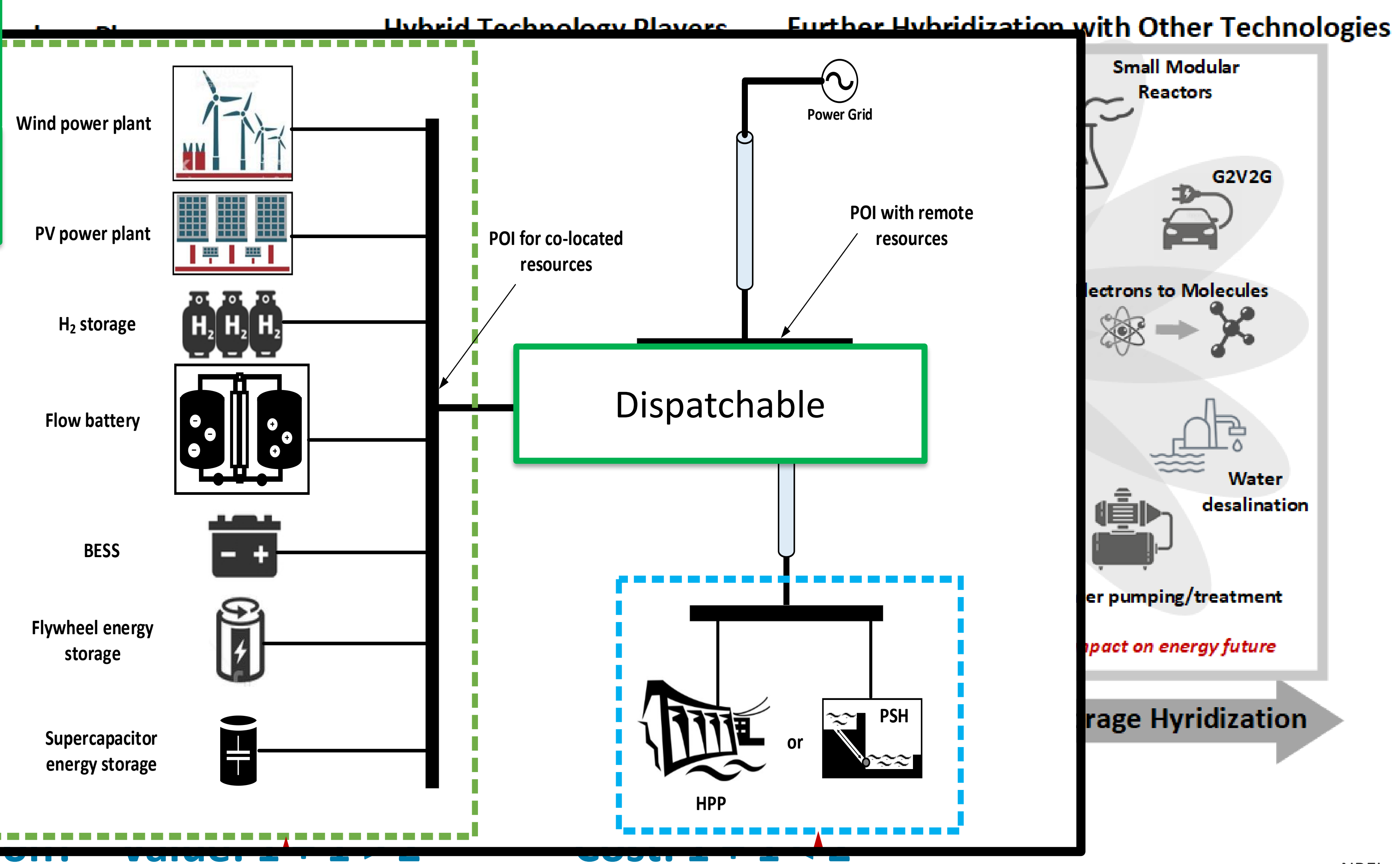
(Greenfield)

Optimal design for a highly customized system to achieve different services.

g Beyond Traditional Variable-Generation Renewable Energy Plants

Atmospheric Sciences

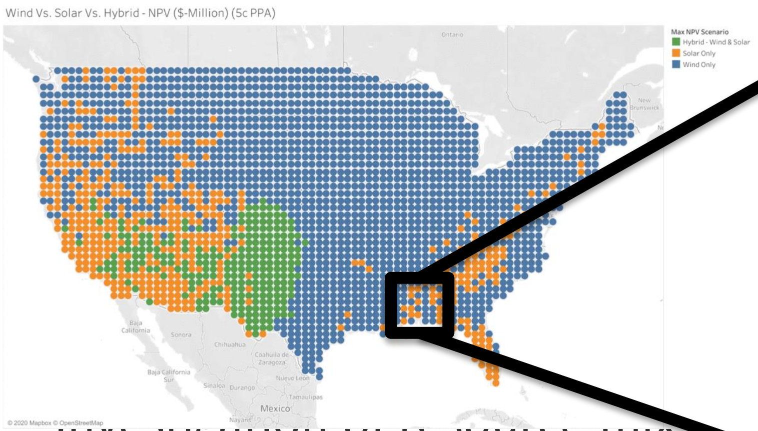
Generation



Why hybridiza

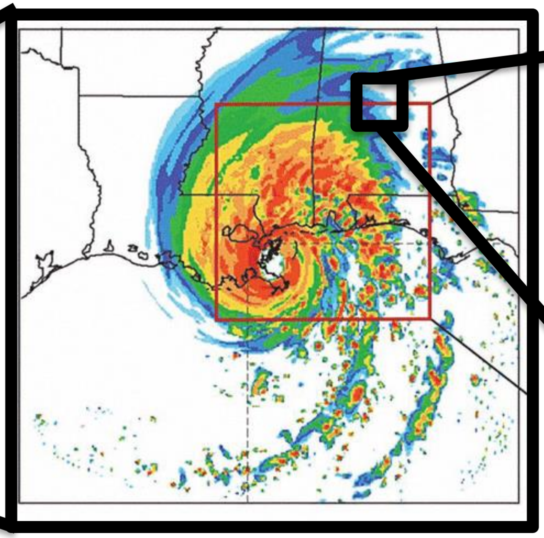
Facilitate Large-Scale Deployment of Hybrids

Techno-Economic Analysis



Investigation of resource mix and deployment. Balance between battery storage and alternative fuels.

System and Plant level design and control



Optimally design and operate plants to achieve different objectives

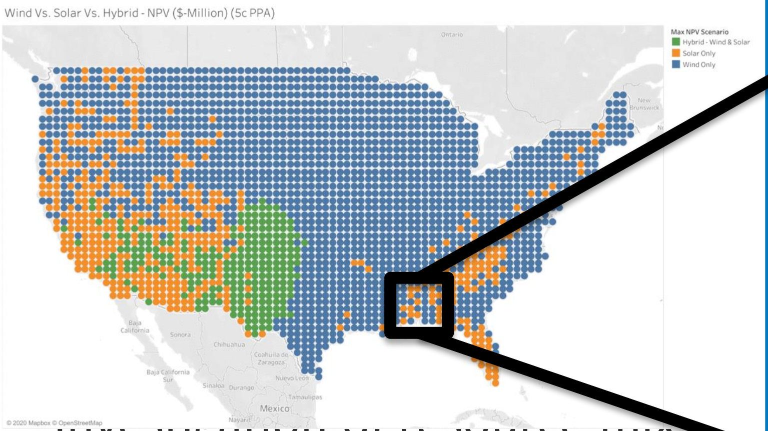
Hardware and Grid Strength

Support a grid that is 100% inverter-based. Need for inertia, blackstart capabilities.

System and Plant Level Design and Control

Nicolaos Cutululis will discuss

Techno-Economic Analysis



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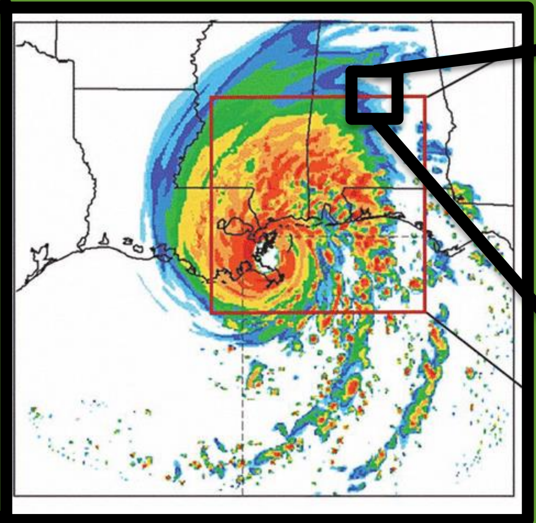


Optimally design and operate plants to achieve different objectives.

Hardware and Grid Strength

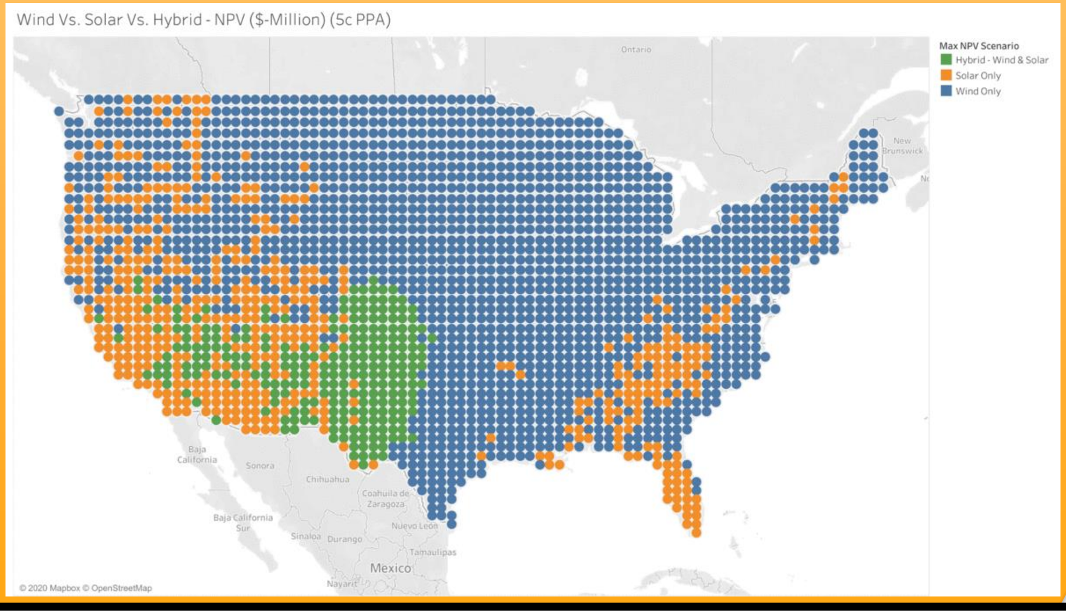
Support a grid that is 100% inverter-based. Need for inertia, blackstart capabilities.

Wind-Based Hybrids

Analysis

Where to build co-located hybrid plants?

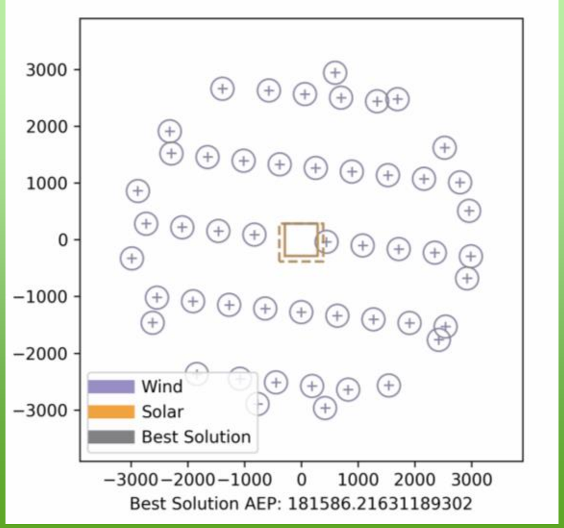
- Resources are complementary
- Overbuild (Ex: 200MW plant at 100MW interconnect)
- Include storage



Strong solar during day and strong wind at night

Optimization

Optimize hybrid plants down to the *component* levels



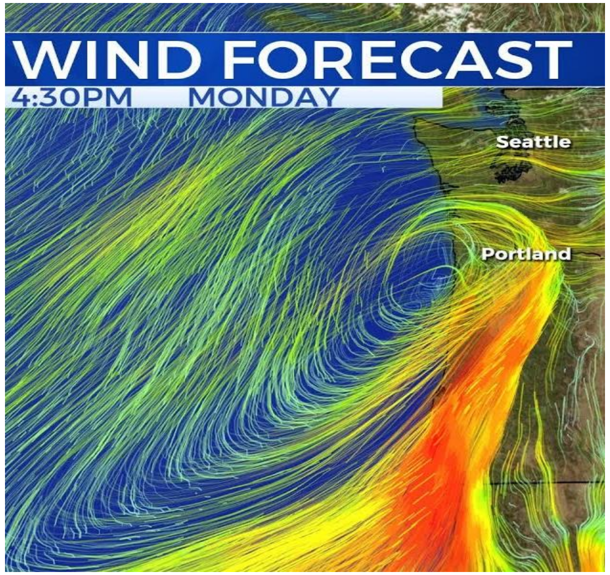
Intelligent Controller

- **Wind-solar-storage** dispatch algorithms developed in HOPP
- Operation of plants down to the **1-minute timescale (R&D efforts to go to sub-second)**
- Improve performance of hybrid power plants by > 5%

Control Functions

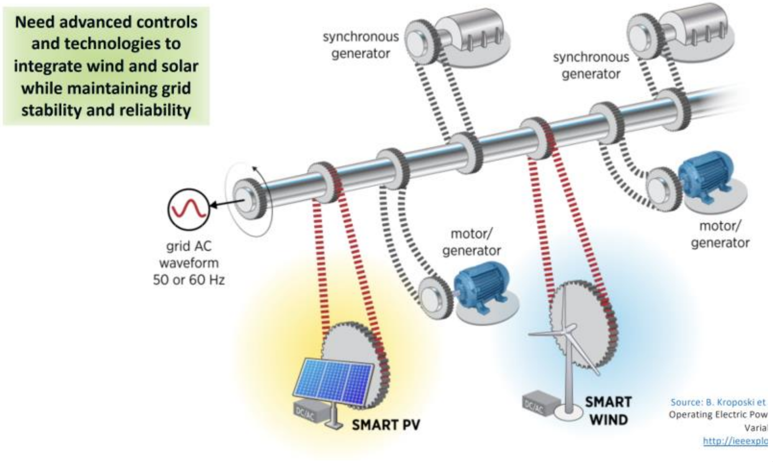
Optimization

Dispatchable energy services and flexibility services with resource forecast



Fast Control

Essential and advanced reliability services (AGC, FFR, Synthetic Inertia, etc.)

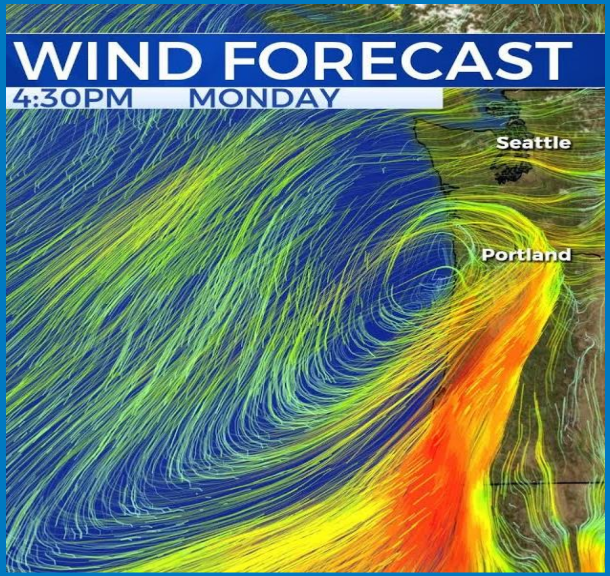


Transient performance and resiliency services (grid-forming, blackstart, islanded systems etc.)

Control Functions

Optimization | **Fast Control**

Dispatchable energy services and flexibility services with resource forecast



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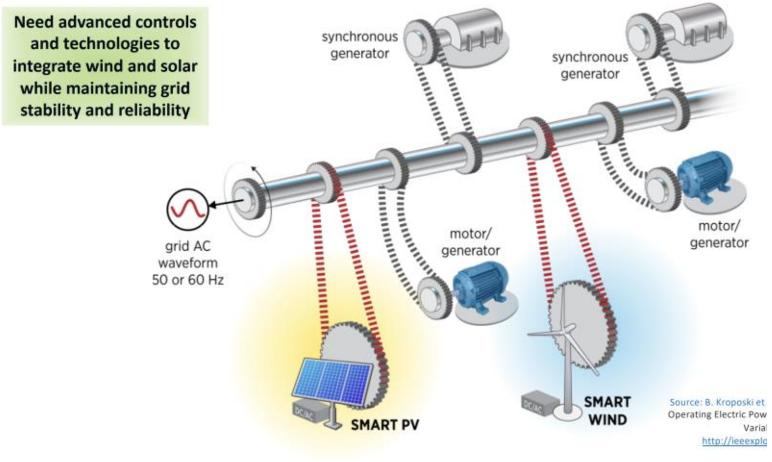
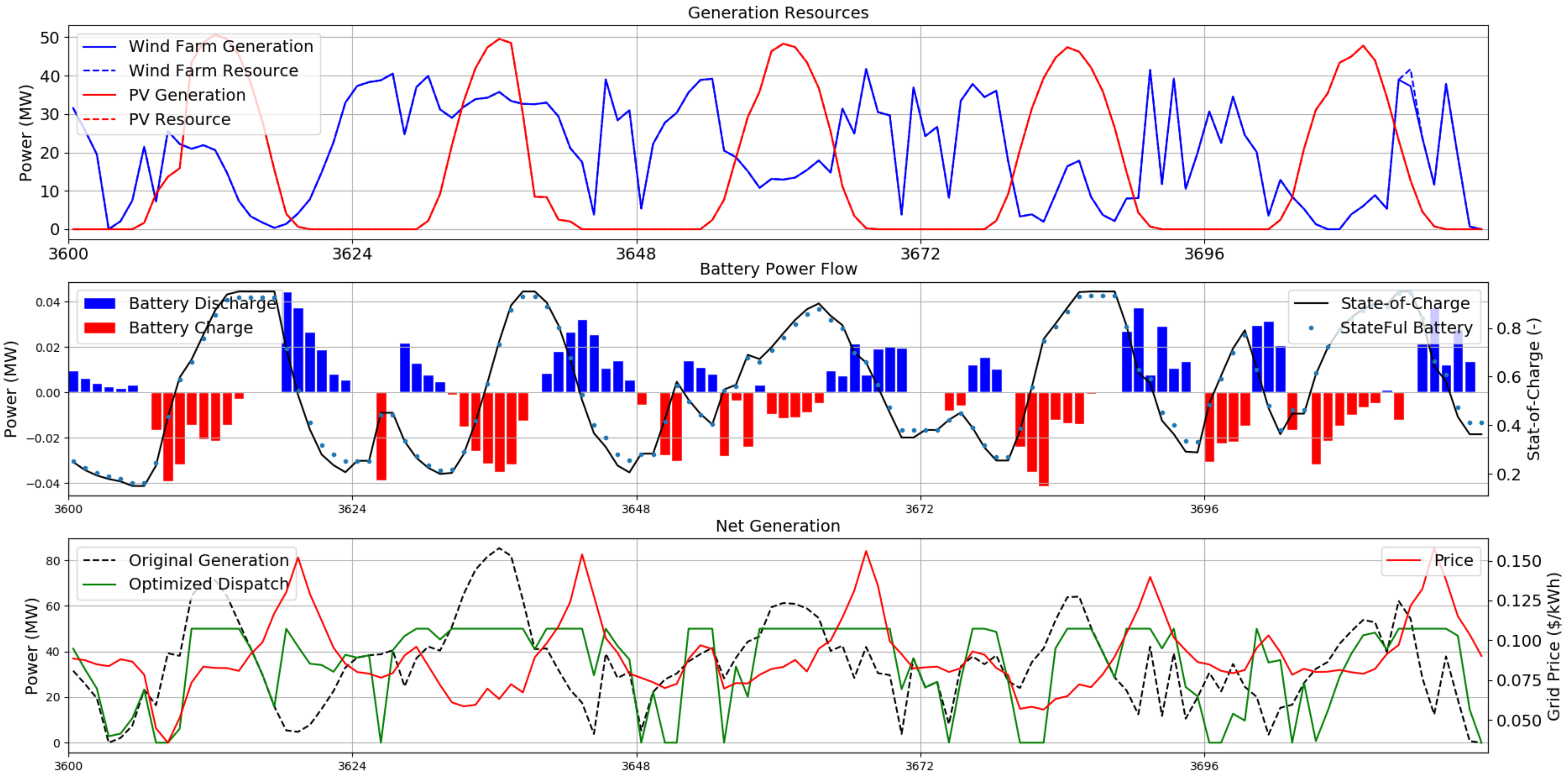


Transient performance and resiliency services (grid-forming, blackstart, islanded systems etc.)

Detailed Battery Dispatch Optimization



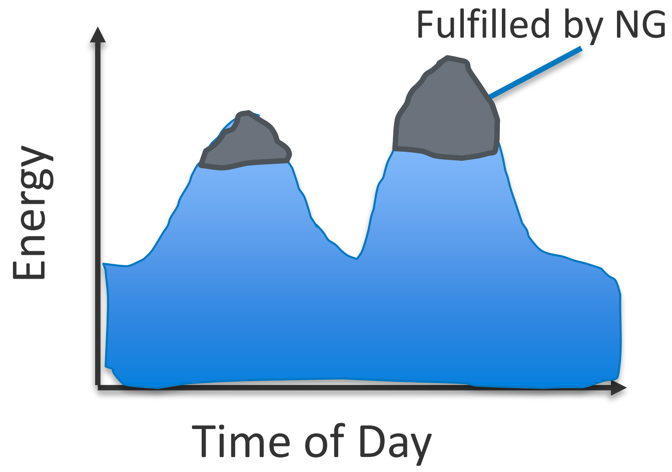
Design Plants to Provide a Range of Services

Each will require different designs and operational strategies

Firm Power

Hybrids can replace coal and natural gas to provide local baseload.

Time Dependent Power



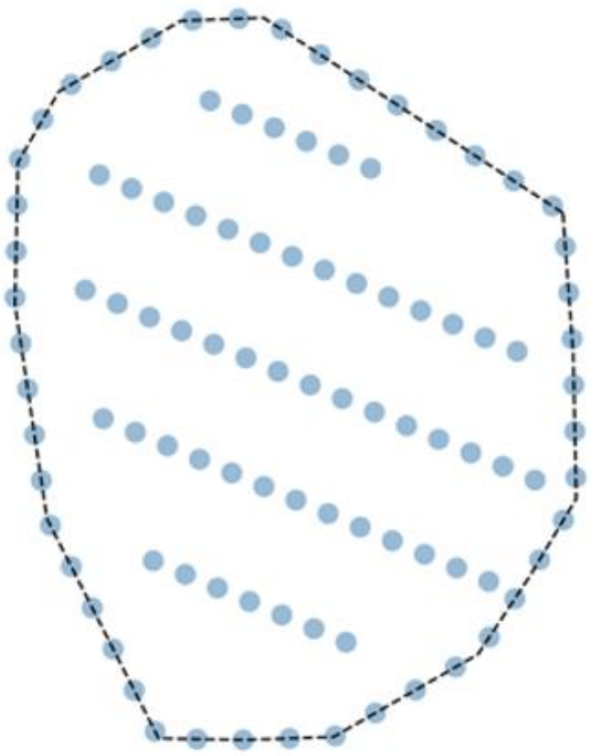
Guaranteed power at the most vulnerable parts of the day

Grid Services

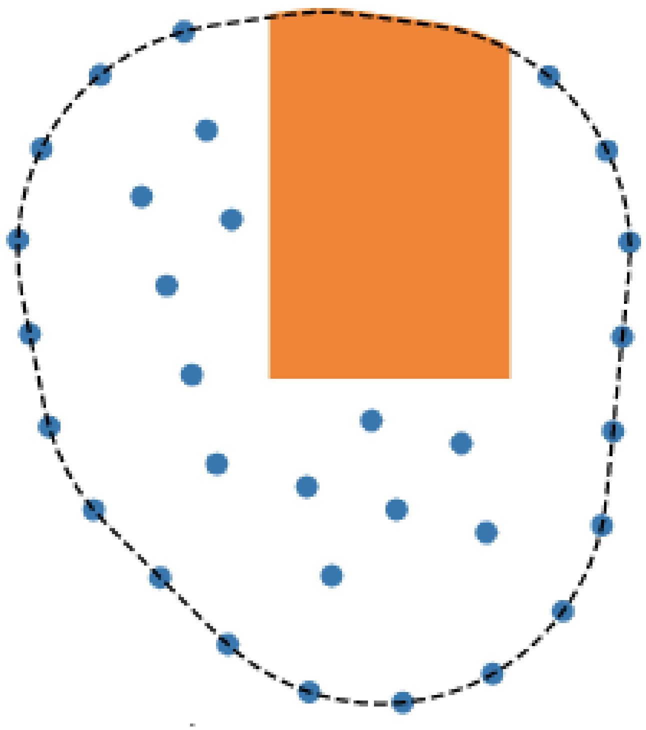
Frequency response
Active generation control
Ramping up/down
Bulk energy

Problem Setup to Enable Multi-Timescale Hybrids

Boundary-grid for wind



Single rectangle for solar

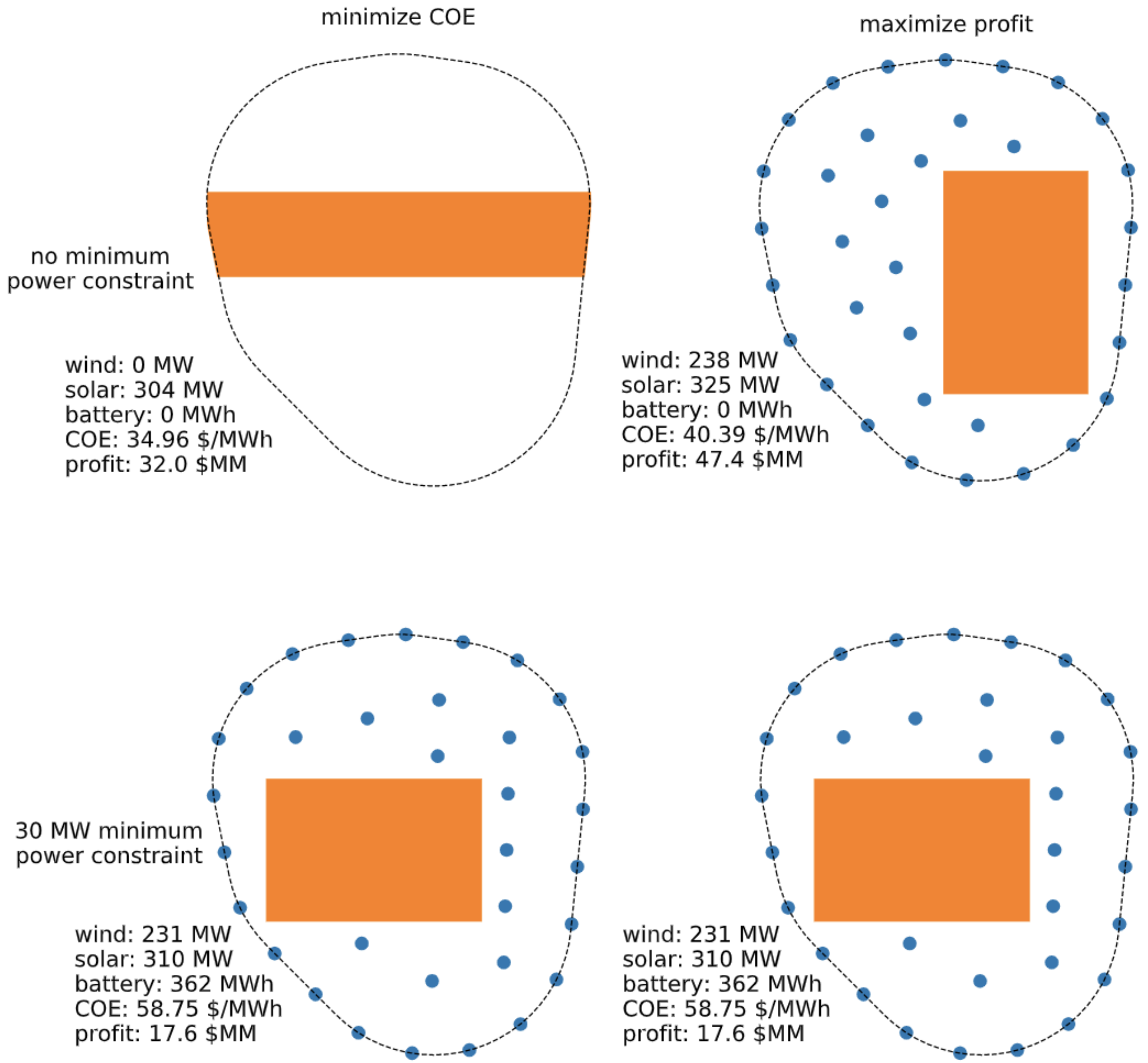


16 total design variables

	design variable
wind	number of boundary turbines boundary turbine start location number of grid rows number of grid columns grid row spacing grid column spacing grid shear grid rotation grid center x grid center y grid boundary setback
solar	array center x array center y array height array width
battery	battery storage capacity

Lead: PJ Stanley

Different Objective Functions



- Highly dependent on resource available
- Highly dependent on objective function
- Need optimization approaches that handle multiple timescales
- Challenging design problem that requires knowledge of the control strategy.

Additional Benefits of Hybrids

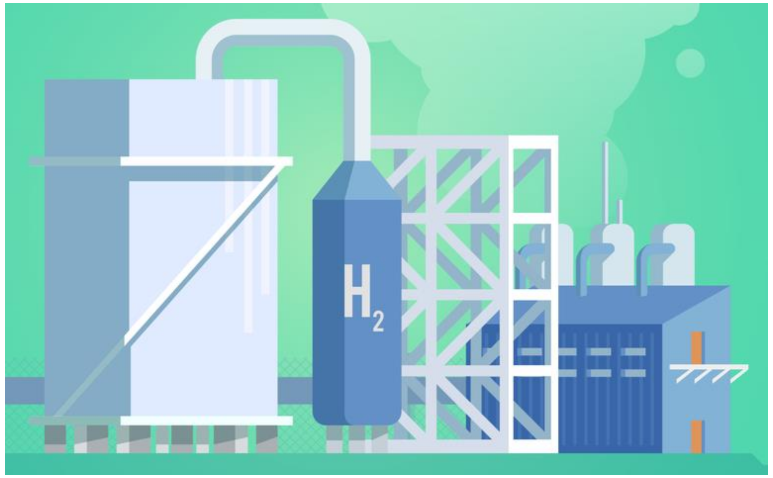
Firm power does not mean ONLY electricity

Firm Power - Electricity

Hybrids can replace coal and natural gas to provide local baseload.

H2 (dual-purpose)

(Ammonia, etc.)



Long-term storage, decarbonizing transportation, drive demand

Other Value Streams

(Carbon capture, desalination)

If grid connected, use excess energy to sell to the grid.

The cheaper we can make electricity means the faster these markets are unlocked

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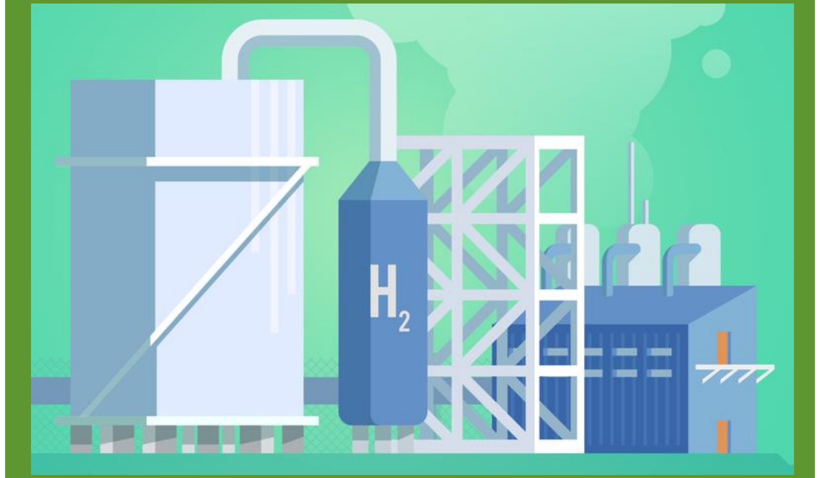

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End to End Analysis

Lead: Aaron

System Si

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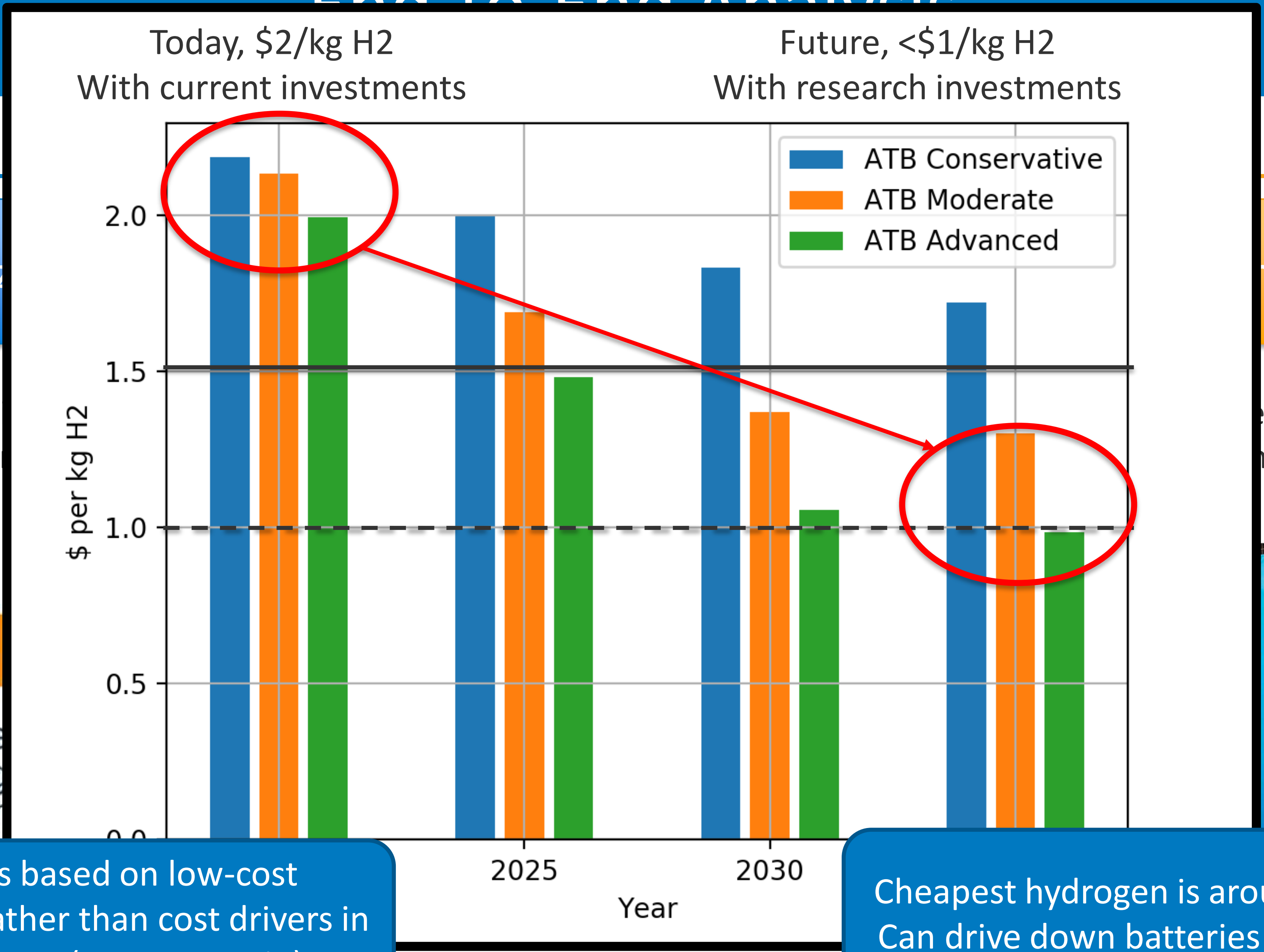


Analysis based on low-cost electricity rather than cost drivers in electrolyzer (Iowa scenario)

Cheapest hydrogen is around $1/kg
Can drive down batteries deployed

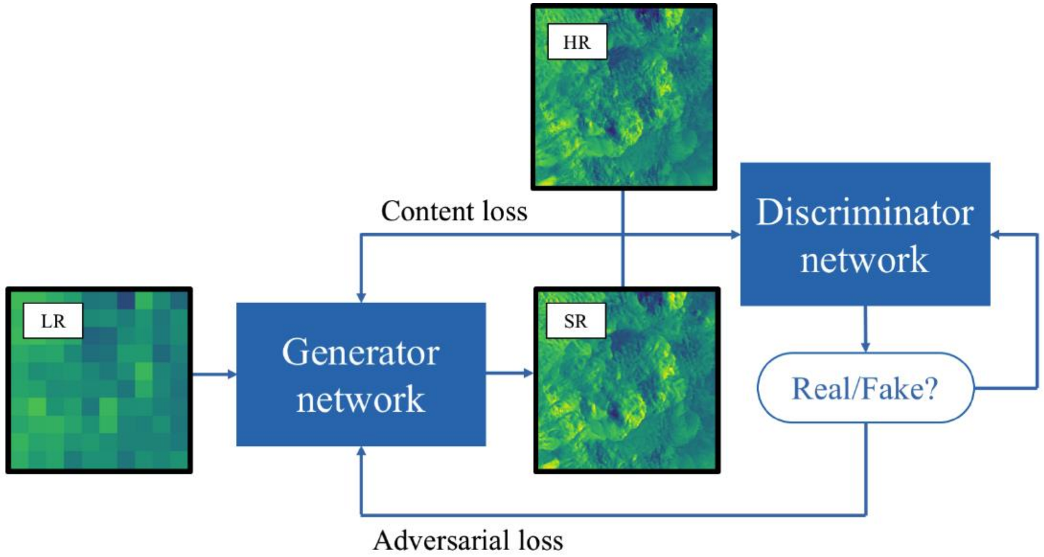
rogen

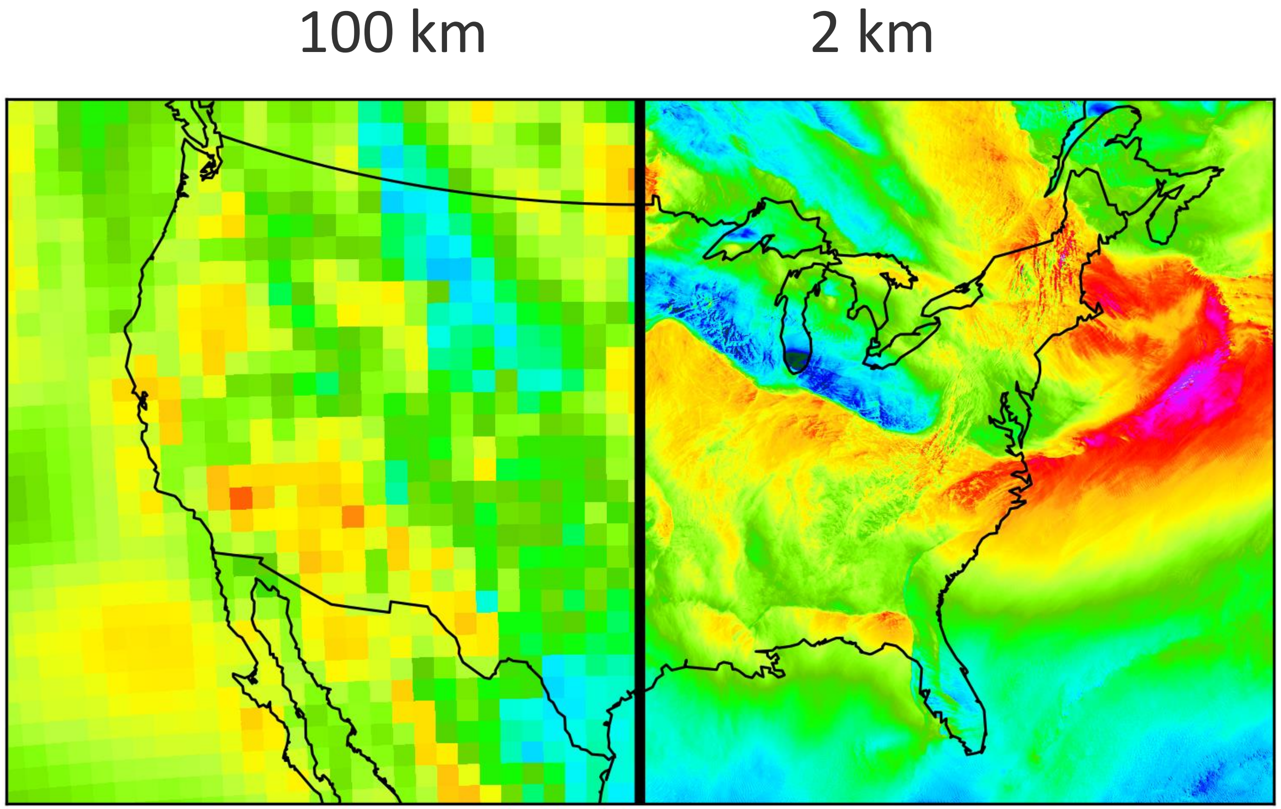
en analysis
nalysis.

Analysis with Deep Learning Capabilities: Climate Downscaling Challenge

Climate models are typically run at ~100km resolution, but ~2 km resolution is required for renewable energy resource assessments.

De-risk investments in changing climate scenarios





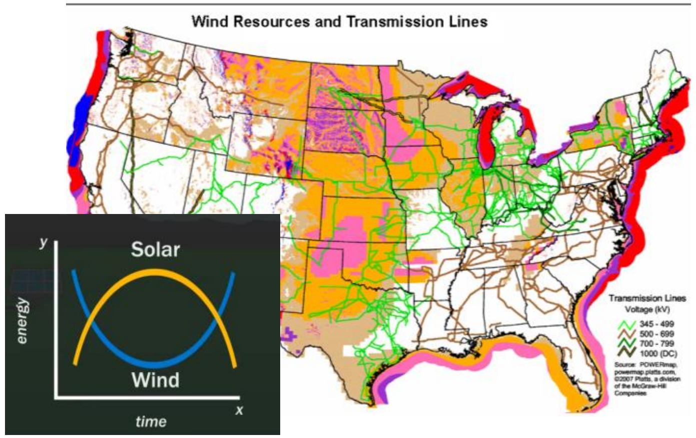
Stengel, Glaws, Hettinger, and King, Proc. of the Natl Acad. Sciences, 2020

Wind will play a major role

Path to Ultra-low-cost electricity

Through new technology innovations

Utilities are moving in this direction



Asking for developers to add hybrid plants

Wind Innovations will drive the development of hybrids

Offshore, tall towers, etc.

Research Needs – System Design

Modeling, analysis, and optimization of **offshore wind systems**

Design of conversion services, including H2, NH3, methanol, liquid RE fuels for the transportation sector such as aviation and marine, and heat to electricity

Framework to assess the viability of the **design of disruptive technologies** such electrolyzers and turbines, AC vs. DC shared electronics, etc.

Develop **large-scale, discrete optimization techniques** to handle a diverse set of design variables

Demonstrate the value proposition of designing and operating an optimal wind-based hybrid plant with a large industry player

Research Needs – Intelligent Controller

Determine **different objectives** and corresponding designs that need to be developed and solved for wind-based hybrid power plants.

Integrate state-of-the-art forecasting for wind and solar, and integrate forecasting techniques across a range of timescales.

Develop **resilience-based controllers** for wind-based hybrid plants operating in a region.

Advanced coordinated controls of connected technologies that incorporate **atmospheric effects** and technology interactions

Integrate controller with design to **minimize storage across a region**.

Research Needs – AI/ML

Open-source dispatchable wind plant **intelligent controller**

Design AI/ML controllers for improving dispatchability.

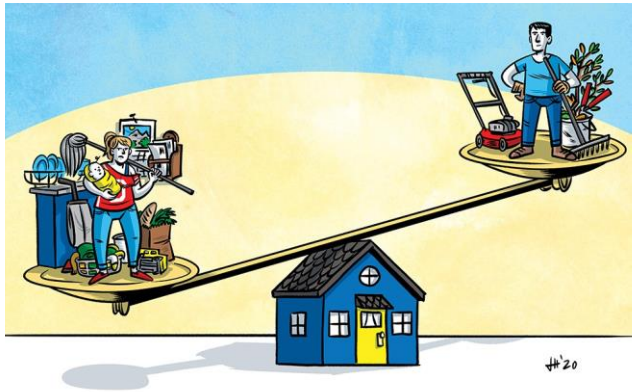
Validation of the dispatchable wind plant using the ARIES campus

Open-source data to accelerate validation of models and dispatchable wind controllers

Data-driven AI/ML solutions to design and control problems that can be deployed to edge devices co-located with dispatchable wind plants

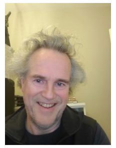
Goal: 100% clean electricity by 2035

- Wind-based hybrids can **significantly mitigate the risk and dependency** on additional, new interstate and inter-regional transmission investments for 100% clean energy future.
- Wind-based hybrid systems can **maximize the use of existing interconnections** and can provide cost effective alternatives.
- Wind-based hybrids can facilitate new markets for **cost-effective alternative RE fuels** (e.g. H2, ammonia, zero net carbon emission fuels.)
- New wind technology innovations, with hybrid designs, **can play a major role** in achieving these goals.



Balanced Outline

Setting the Scene – Mark O'Malley



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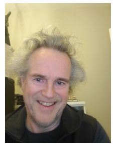
Wrap Up & Conclusions – Mark O'Malley



Q & A – SLIDO - All

Slido.com and enter Code **#nawea5**

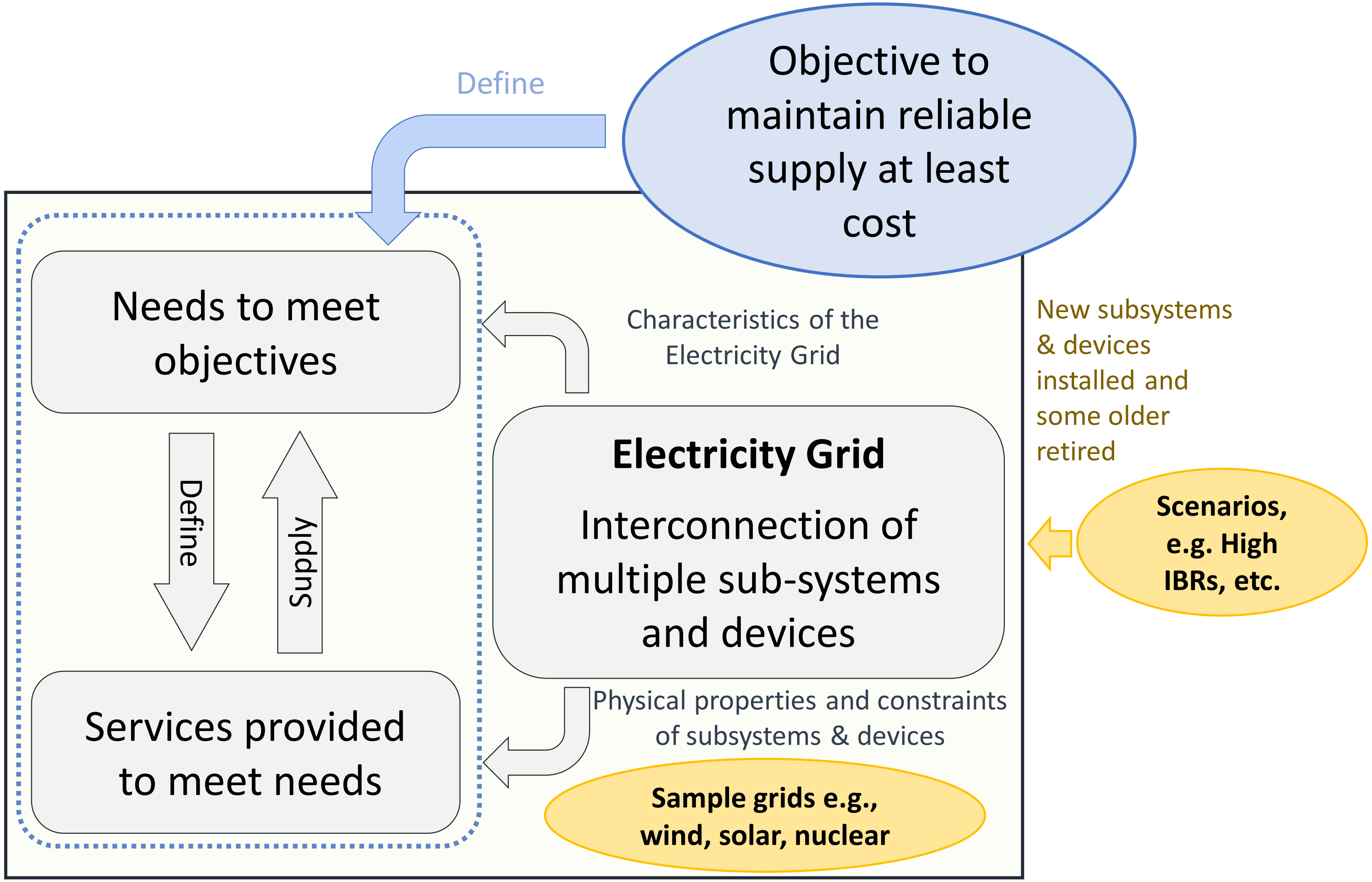
Summary G-PST Research Agenda

Research Program	Description	Number of Questions
Inverter Design	Development of capabilities, services, design methodologies and standards for IBRs.	10
Tools and Methods	New tools and methods required to ensure reliability, security, and stability in power systems.	9
Control Room of the Future	Development of new technologies and approaches for enhanced real-time visibility and analysis in power system operator control rooms.	17
Planning	New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix.	15
Black Start	Creating new procedures for black starting and restoring a power system with high or 100% IBR penetrations.	1
Services	Quantifying the technical service requirements required of future power system to maintain the supply-demand balance reliably and at least cost.	7

Wrap up and Conclusions – Based on the SLIDO Questions & presentations

- Every system is different & it is a moving target
- Risk is a very important aspect of all this
- Wind is just one part of a rapidly changing energy system – we (the broader energy research community) need to look at this holistically
- Nobody can solve all these questions team work globally and disciplinary is required
- The value “services” based approach is replacing a cost based approach
- Time scales are important – we are looking at all timescales
- Different Objectives – System, Wind etc.
- Solution Space is getting bigger - Energy System
- Policy, regulation etc. are and can be important drivers

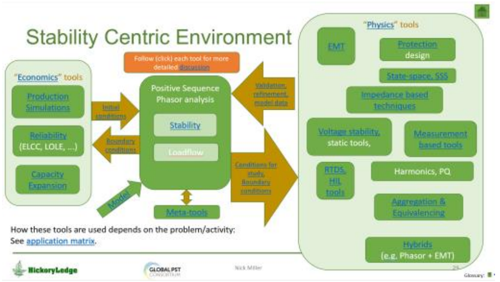
Defining Needs & Services



clear signal to the market/manufacturers to what is needed and enables efficient operation of the electricity grid by the system operator.

- Robust and economic across all systems/scenarios
- Across all time scales milliseconds to seasons
- Forward looking
- Non-discriminatory
- etc.

What is changing and why take a services perspective



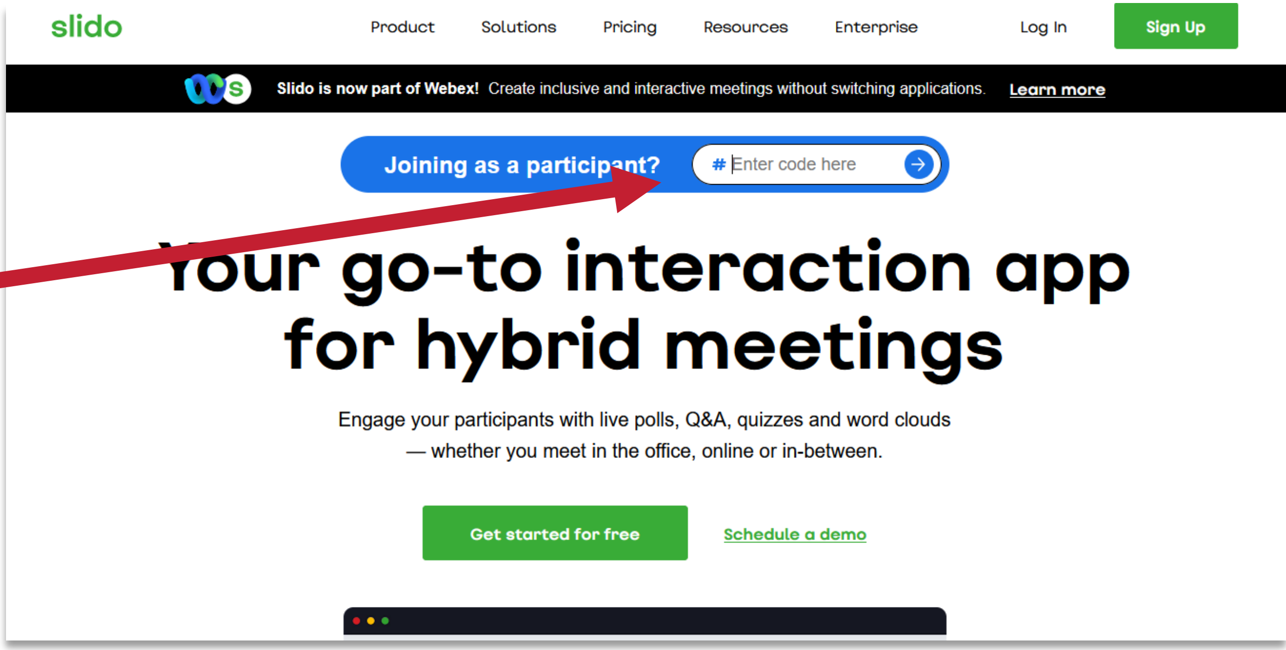
- IBRs replacing synchronous machines changing the needs and service capabilities
- IBRs are not the only change – the resources "behind" the IBRs are also changing – wind, solar, storage, distributed etc.

- Taking a "services" approach is generic and avoids technology specific solutions
- Need a rigorous holistic approach
- To get the full benefits of the new technologies this is where the focus should be otherwise, we will end up just mimicking what we already have

nationalgridESO

Logistics for Q&A

- In another browser window, go to: SLIDO.COM
- Enter the Code: nawea5
- We will not monitor the Zoom Chat for questions



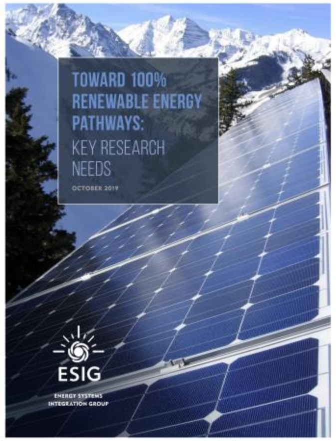
Acknowledgements & Further Reading

https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf

Acknowledgements

- Paul Veers, NREL
- Tom Acker, NAU
- etc.

https://globalpst.org/



https://globalpst.org/wp-content/uploads/Toward-100-Renewable-Energy-Pathways-Key-Research-Needs.pdf

Joule

CellPress

Perspective

The challenges of achieving a 100% renewable electricity system in the United States

Paul Denholm, Douglas J. Arent, Samuel F. Baldwin, Daniel E. Bilello, Gregory L. Brinkman, Jaquelin M. Cochran, Wesley J. Cole, Bethany Frew, Vahan Gevorgian, Jenny Heeter, Bri-Mathias S. Hodge, Benjamin Kroposki, Trieu Mai, Mark J. O'Malley, Bryan Palmintier, Daniel Steinberg, and Yingchen Zhang

SUMMARY

Context & scale

https://www.cell.com/joule/fulltext/S2542-4351(21)00151-3?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2542435121001513%3Fshowall%3Dtrue

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