Design and Operation of Energy Systems with Large Amounts of Variable Generation

IEA Wind TCP Task 25

Technical report presentation, 20 Jan, 2022,

ESIG webinar

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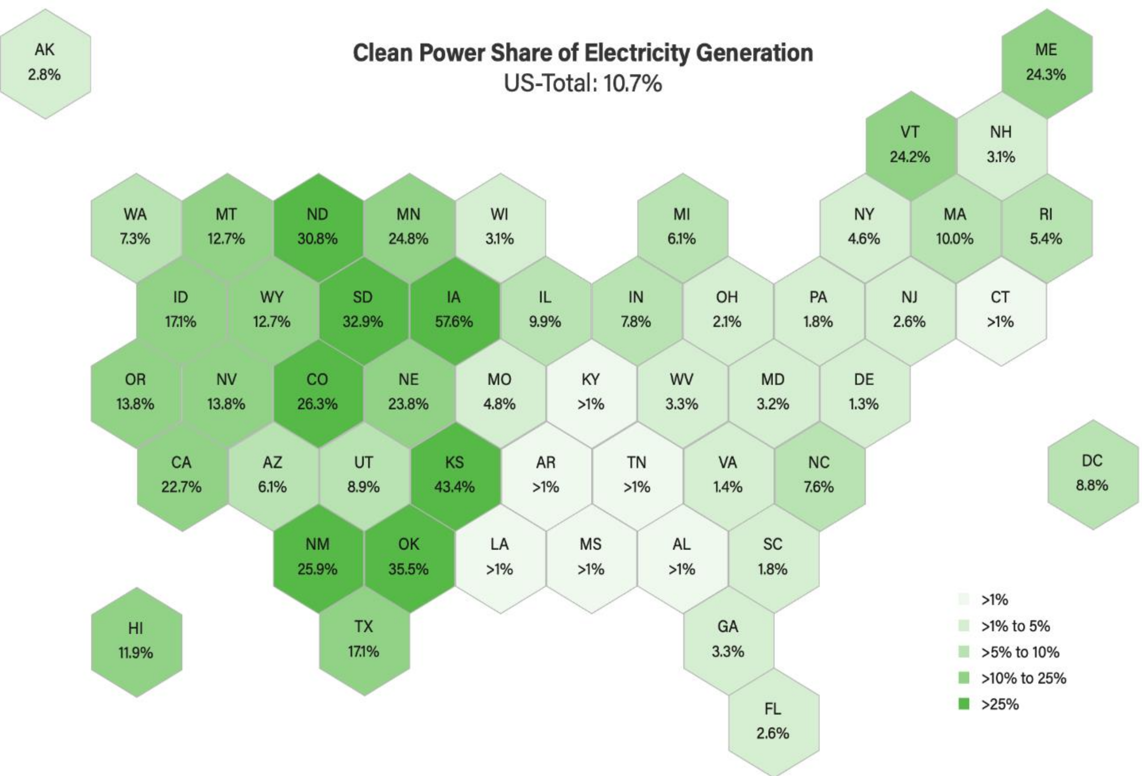
iea wind

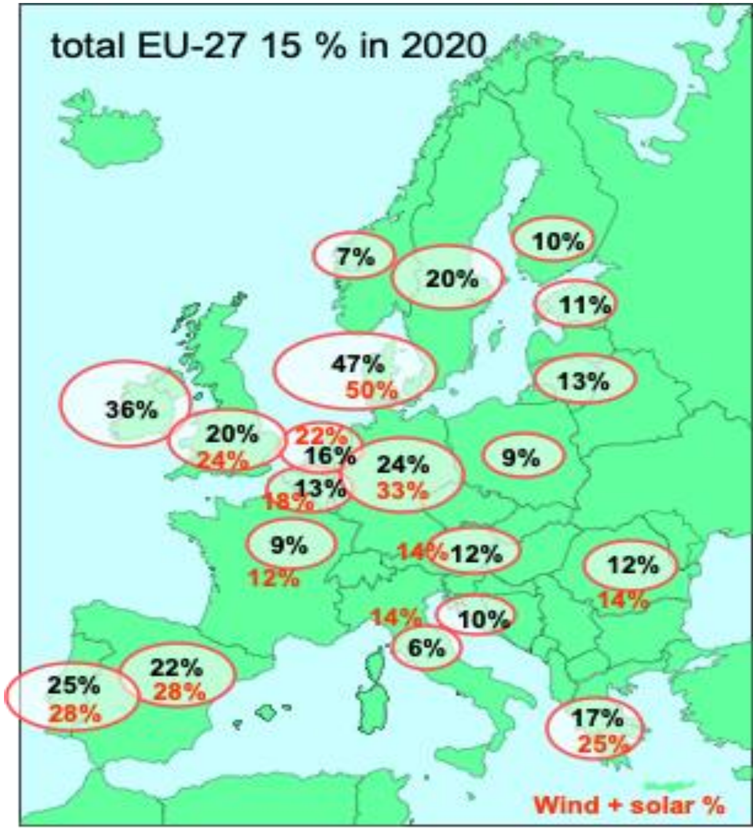
Agenda

- Presentation of the report
    1. Introduction
    2. Variability and Uncertainty of wind and solar at Power system level
    3. Transmission planning
    4. Ensuring long term reliability: assessing resource adequacy
    5. Ensuring short term reliability: operating reserves and stability
    6. Maximising the value of wind in operations: curtailments, grid support services, operational practices and flexibility
    7. Pushing the limits: towards 100% shares of renewables
    8. Conclusions
- Q&A

1. Higher wind (and solar) shares …

11 states in the US and 9 in the EU >20% share of VG

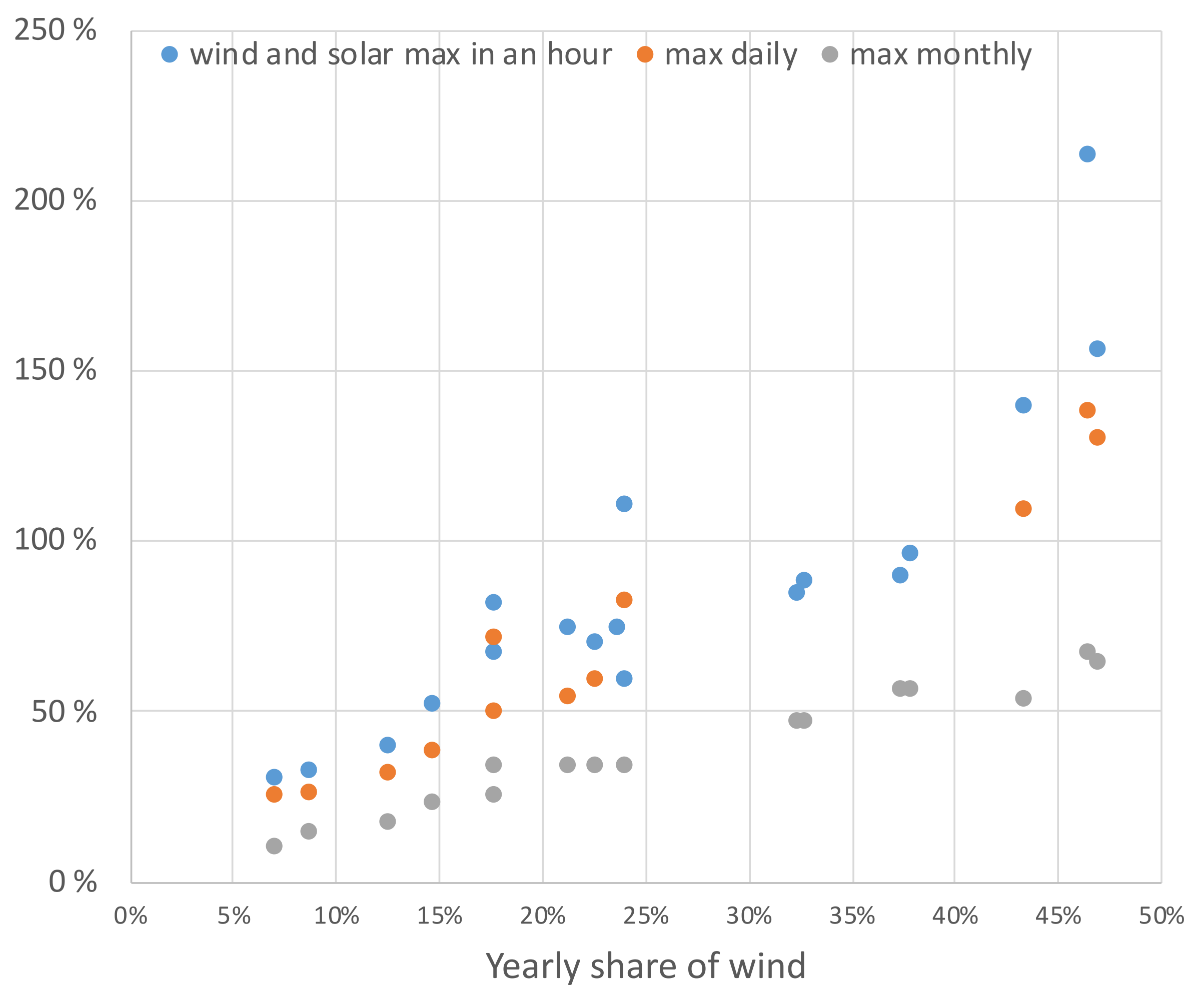




Source: ACP

..mean increasing instant shares

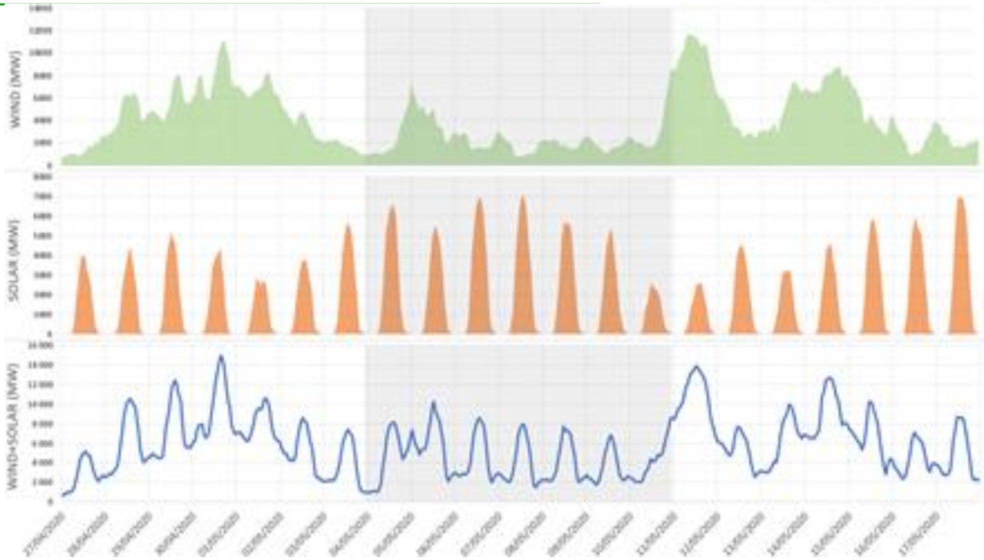
- challenges when >50% in synchronous power system (Island of Ireland, Texas, GB)
- larger power systems still 10-15% share of wind & solar

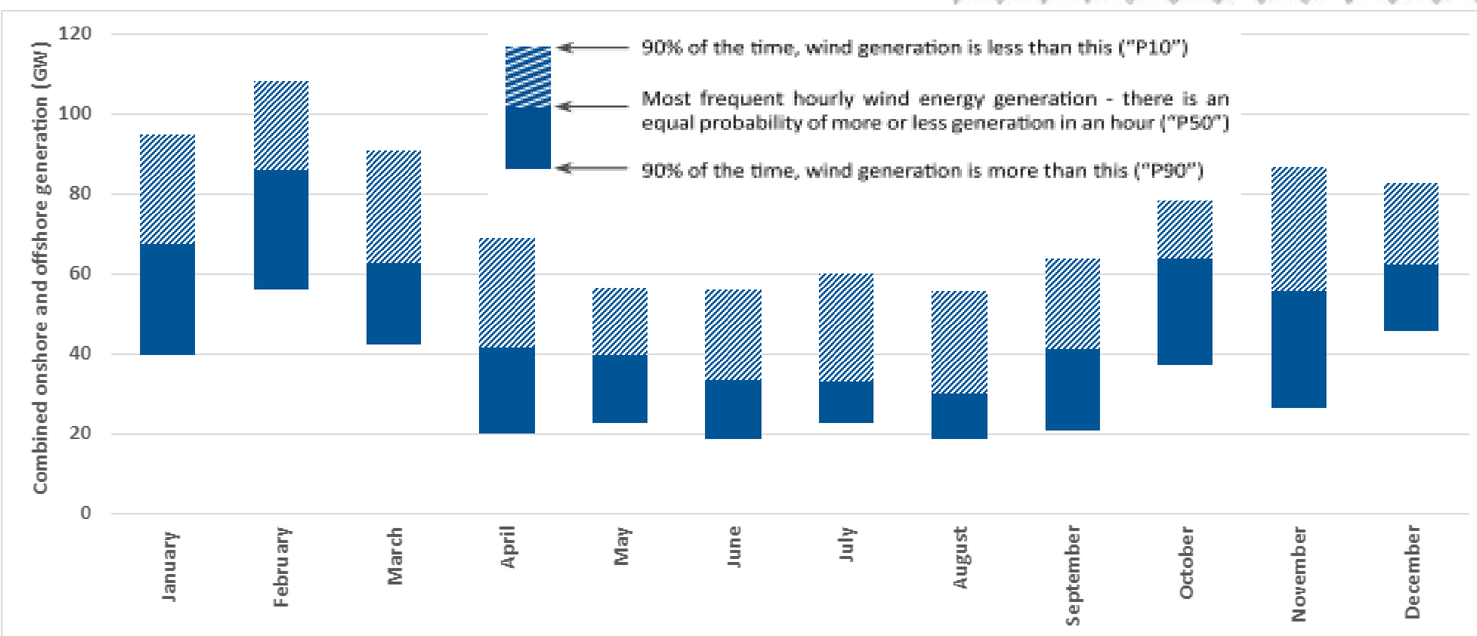


2. Impacts of variability and uncertainty

- wind smoothing impact (size of area, dispersion)
- wind and solar complementarity

  3 weeks in France, from ENTSO-E data:

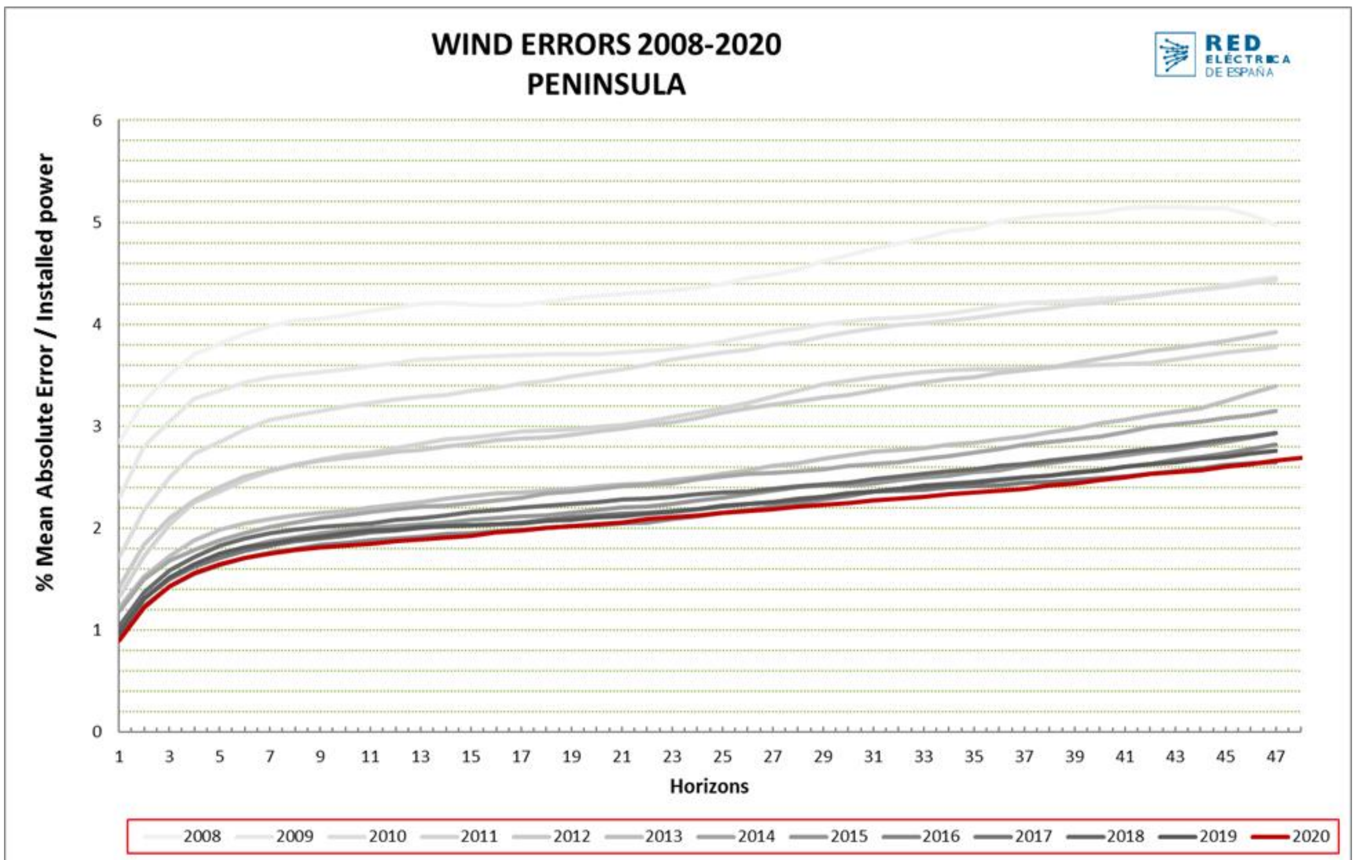




Wind Europe, year 2020 hourly data for EU-28 (~200 GW) data source ENTSO-E

Improvements in data and models

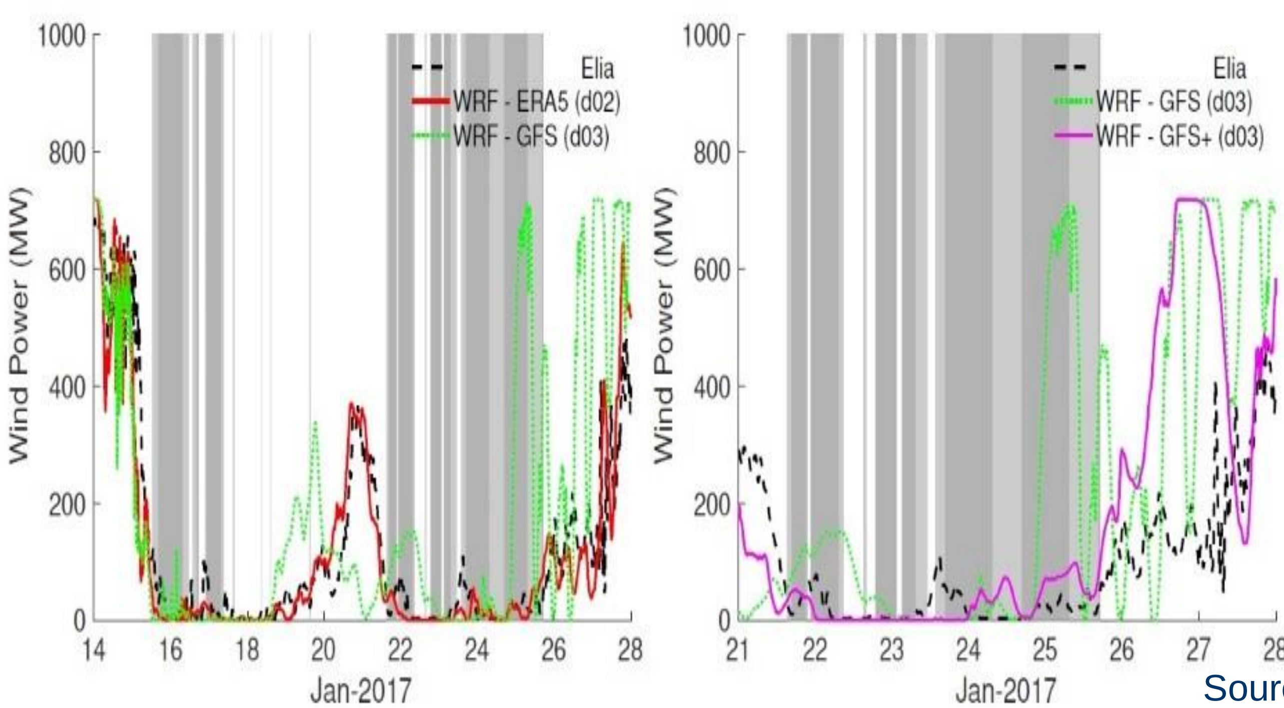
- Simulated weather data has improved: future wind scenario output time series for models
- Forecasts continue to improve



Source: REE, Spain

Capturing extreme events

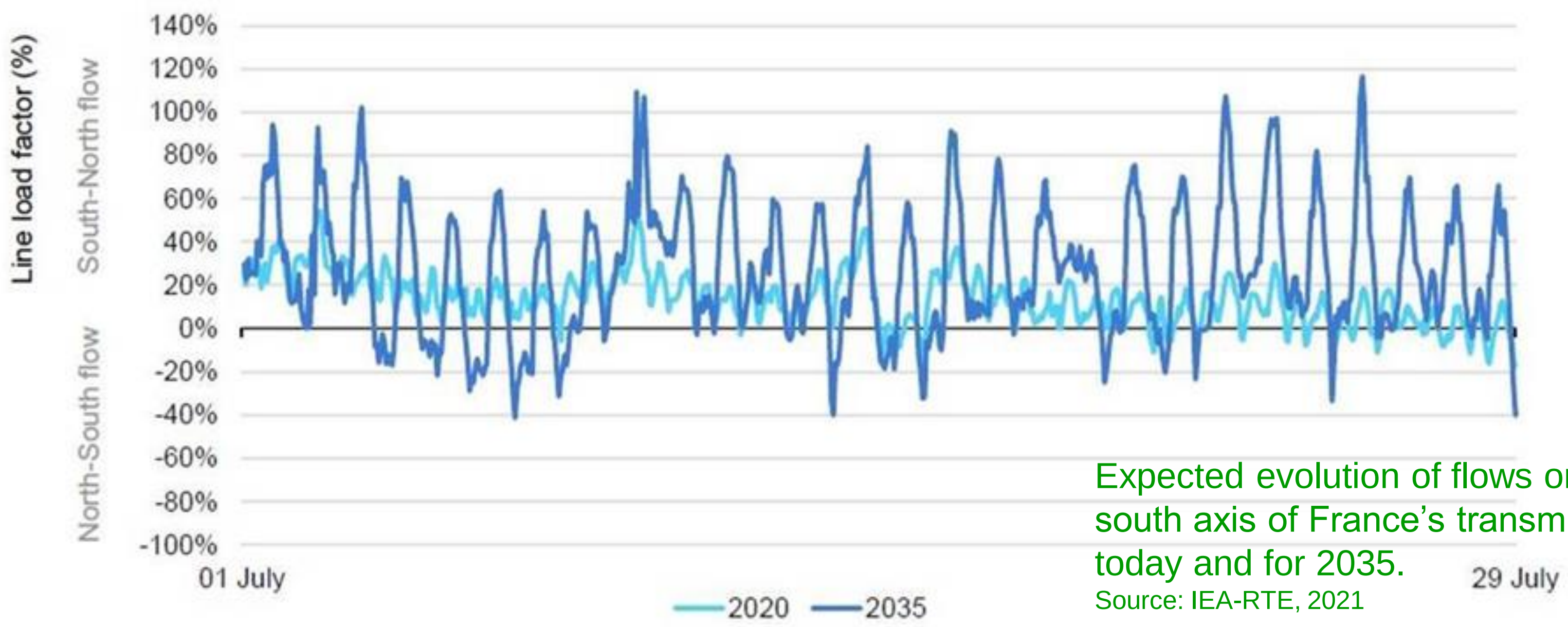
- Ramp forecasting
- storms: synoptic scale weather during dates with large forecast errors
- dunkelflaute: longer low wind events predicted 3-4 days in advance



Source: TUDelft, Li, et al. 2021

3. Transmission planning

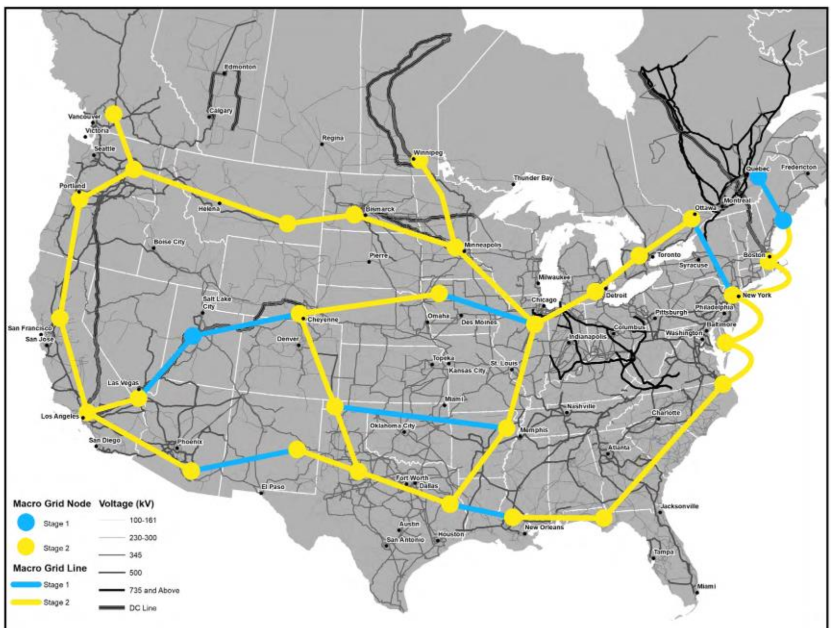
- Greater deployment of wind (and solar) yields higher line utilization, indicating greater benefit and additional need for transmission
- Investments can be partly integrated into renewals of aging assets
- Public engagement with citizens is key for social acceptance
  - In Ireland and Germany, a stepwise process has been developed to increase transparency



Expected evolution of flows on a north-south axis of France's transmission grid, today and for 2035.
Source: IEA-RTE, 2021

Regional transmission planning

- Macro-grid discussions in US
- Enhancing existing corridors in Europe



Conceptual macro-grid to unite the US power systems.

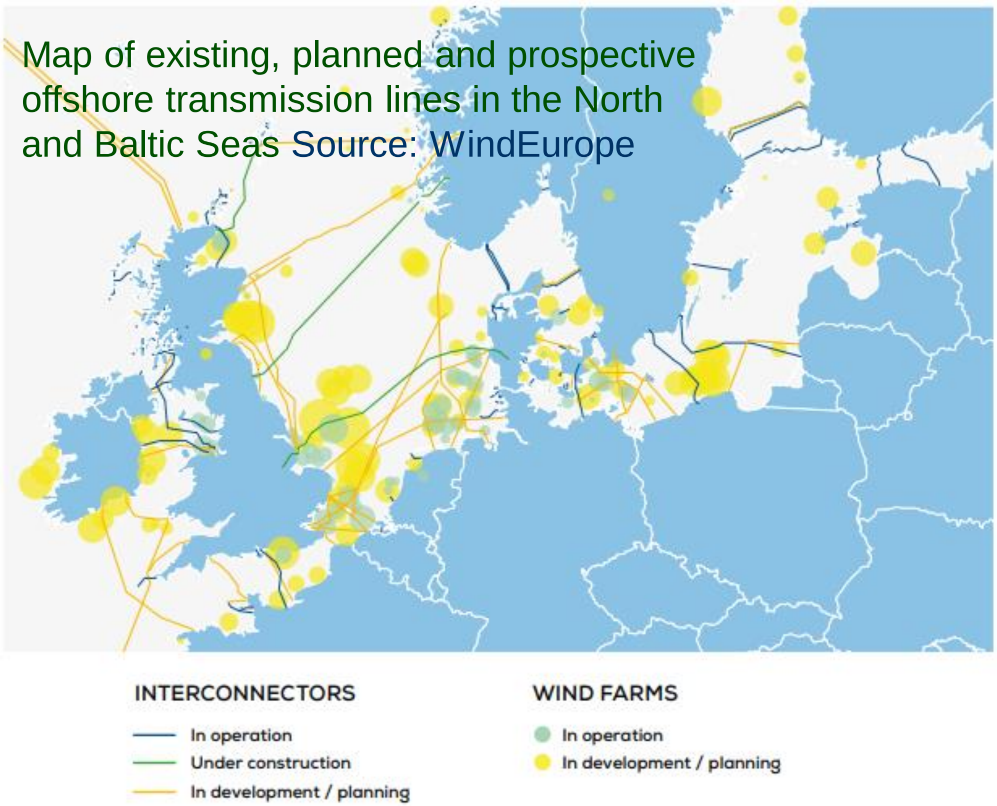
Source: ESIG. 2021. Transmission Planning for 100% Clean Electricity. https://www.esig.energy/wp-content/uploads/2021/02/Transmission-Planning-White-Paper.pdf

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; ENTSO-E, Nov 2020).

TSOs also planning offshore grids

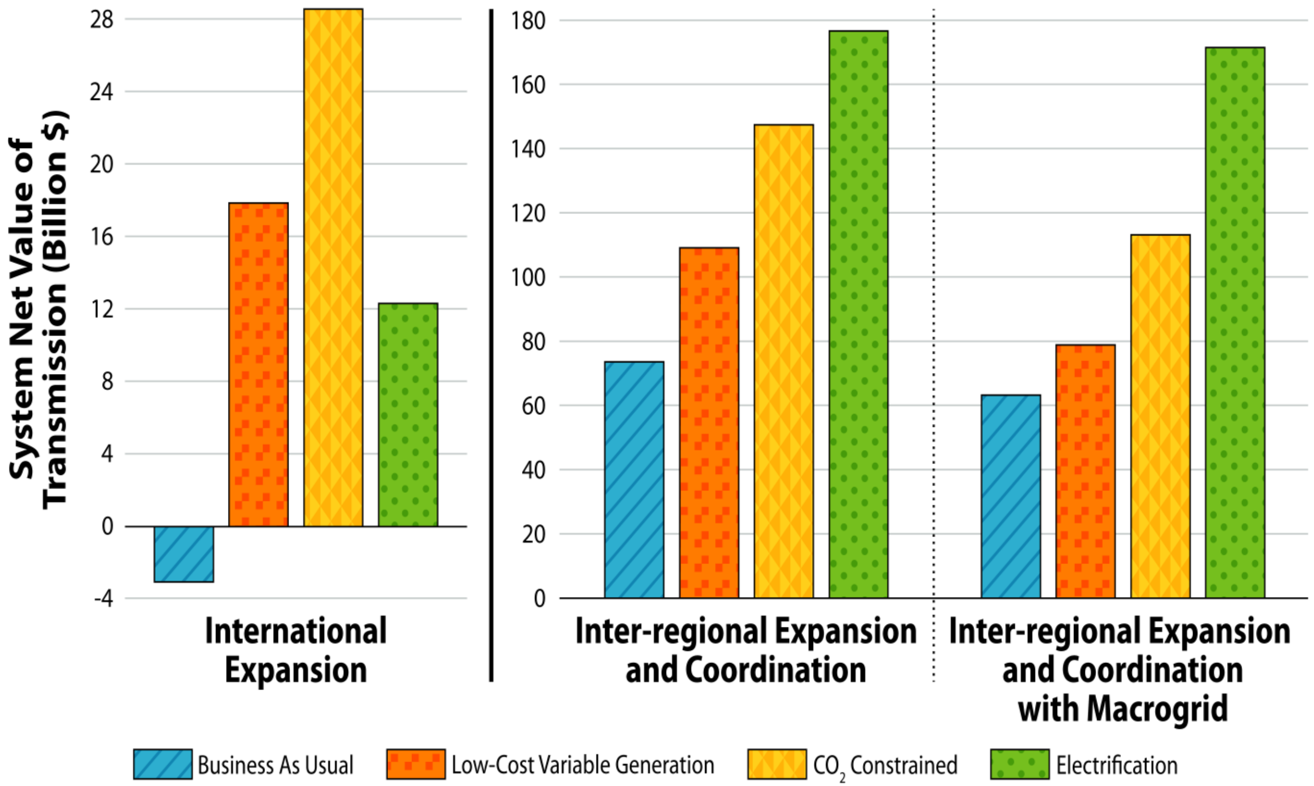
– Meshed grids, hubs, and energy islands
– HVDC technology improvements to increase cost effectiveness, reliability, and land-based grid support



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).

More wind and solar … more benefits in inter-regional coordination & expansion



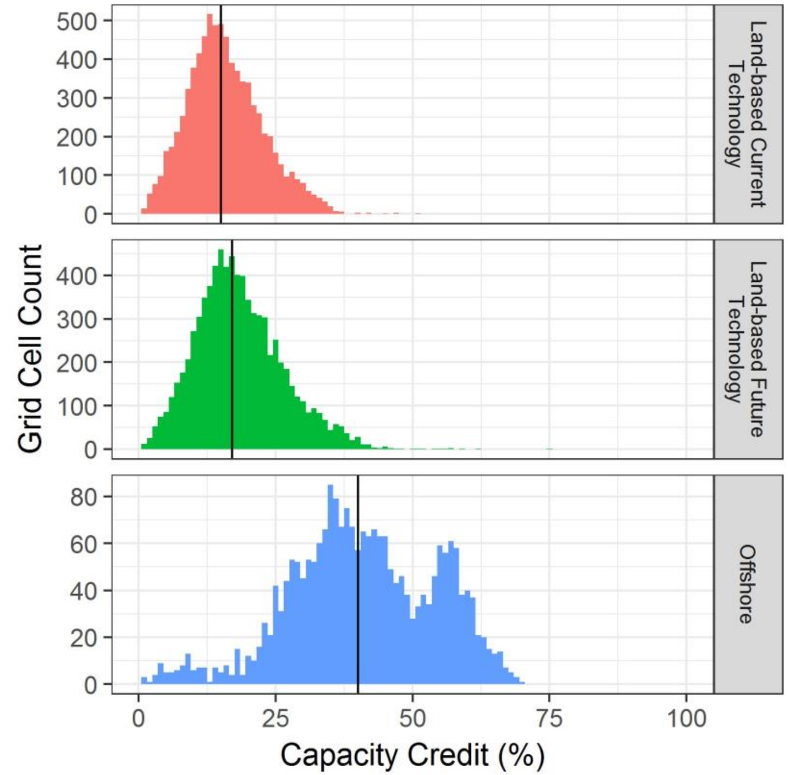
Continent-wide net value of transmission expansion for the four scenarios in the NARIS study.

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.

4. Ensuring long-term reliability and security of supply

Capacity value (capacity credit) of wind

- Decreases with increasing wind share, but trend less pronounced across larger geographic areas
- More years of data are needed for robust results
- Ideally calculated with probabilistic methods, LOLP, ELCC, etc.
- Used as inputs for planning models and capacity markets

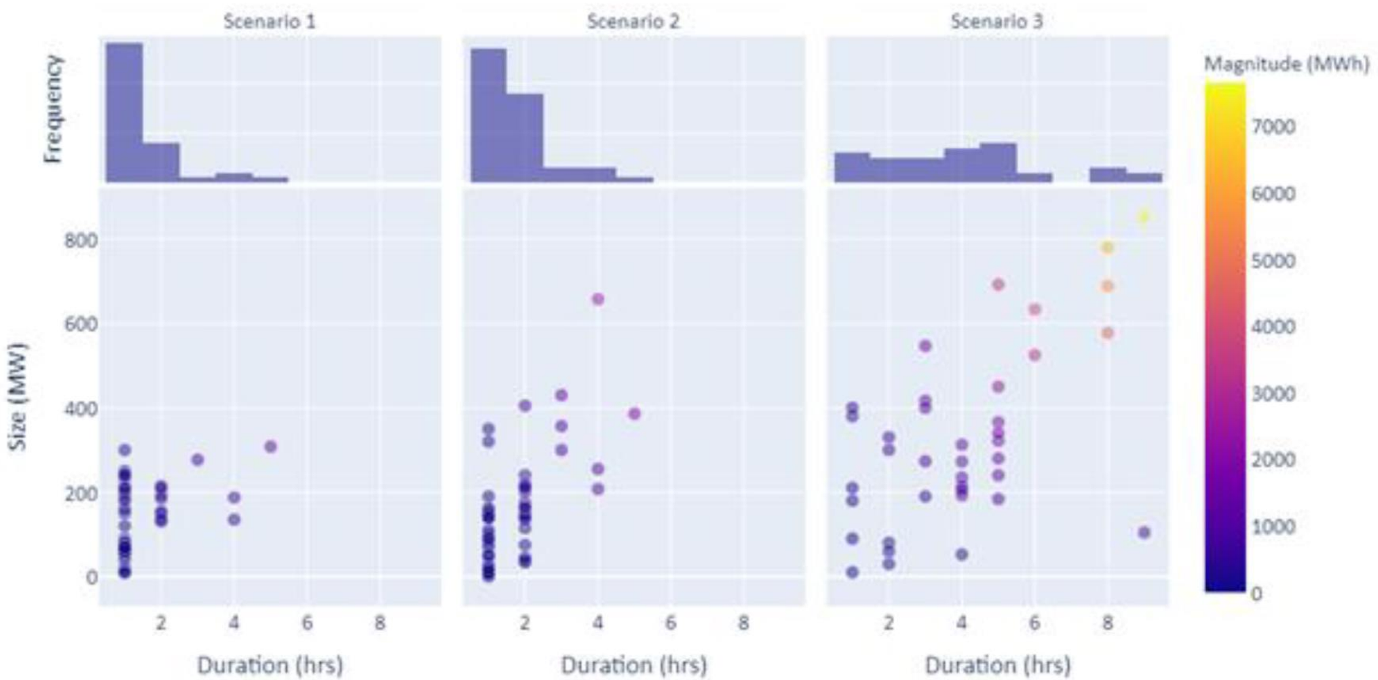


Capacity credit of wind in the Western United States. The average capacity credit is16% for land-based turbines and 41 % for offshore turbines.

Source: Jorgenson, J., Awara, S., Stephen, G., Mai, T., 2021. A systematic evaluation of wind's capacity credit in the Western United States. *Wind Energy* 24, 1107–1121. https://doi.org/10.1002/we.2620

Resource adequacy in future systems

- Improvements to metrics, methods, and/or tools are needed to:
  - Include coordination with neighbouring areas
  - Reflect extreme events, including correlated outages and multiple years of data
  - Capture magnitude, duration, frequency, and timing of potential loss of load
  - Model chronology, which is essential for resources like load participation and storage

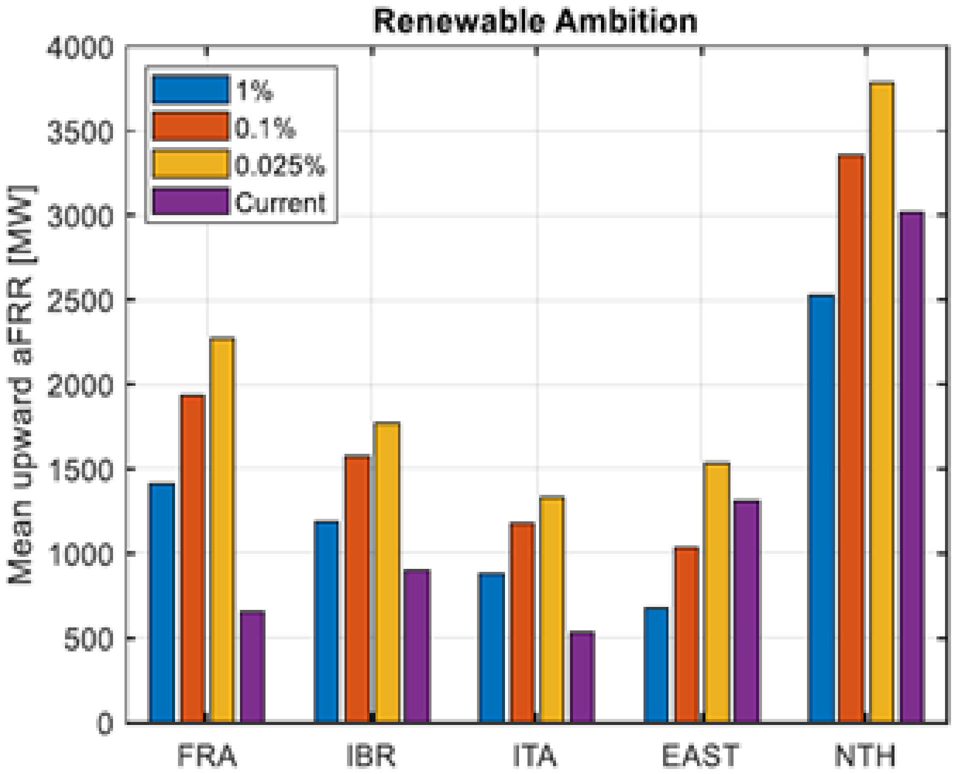


Plots of size, duration, frequency of shortfall events. Each scenario has a different resource mix but the same LOLE (i.e., number of dots).

Source: ESIG. 2021. Redefining Resource Adequacy. https://www.esig.energy/resource-adequacy-for-modern-power-systems/

5. Ensuring short term reliability: Operating reserve

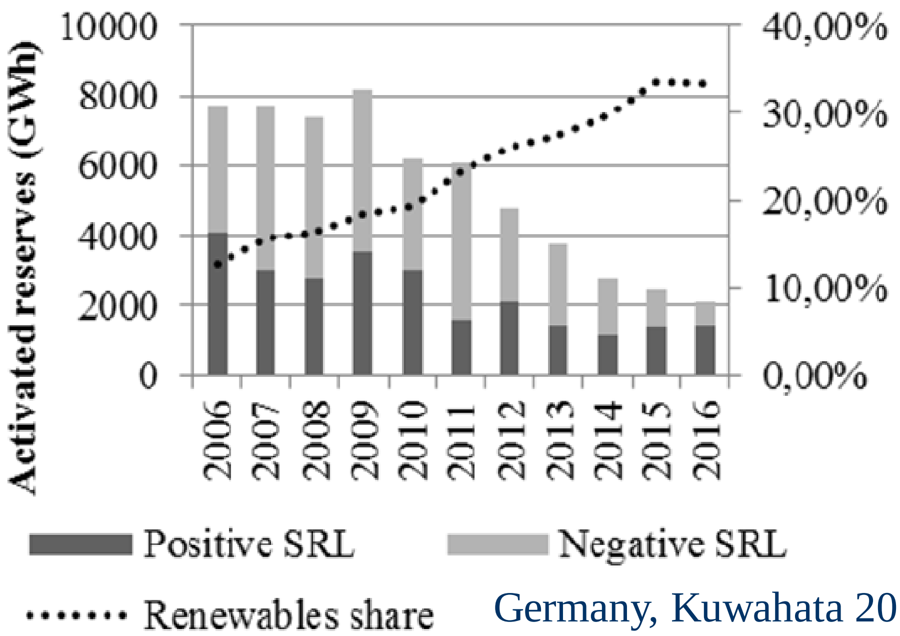
- Adding wind and solar uncertainty requires more short-term reserves
- How much?
  - Reliability level has an impact
- Trend towards dynamic reserve setting – closer to real time, and probabilistic methods



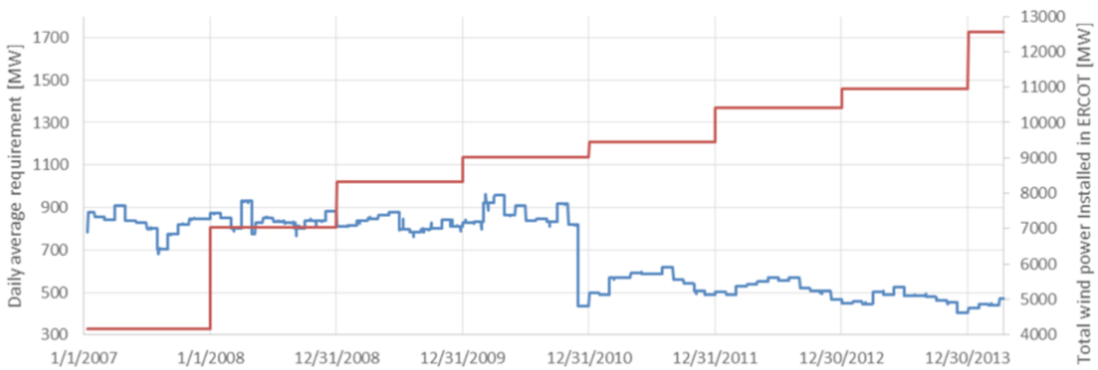
Source: EU-SysFlex project

Operating reserve - experience

Changing operational practices – sharing reserves with neighbours, faster operation – reduces need for short-term reserve more than additional wind



Germany, Kuwahata 2017



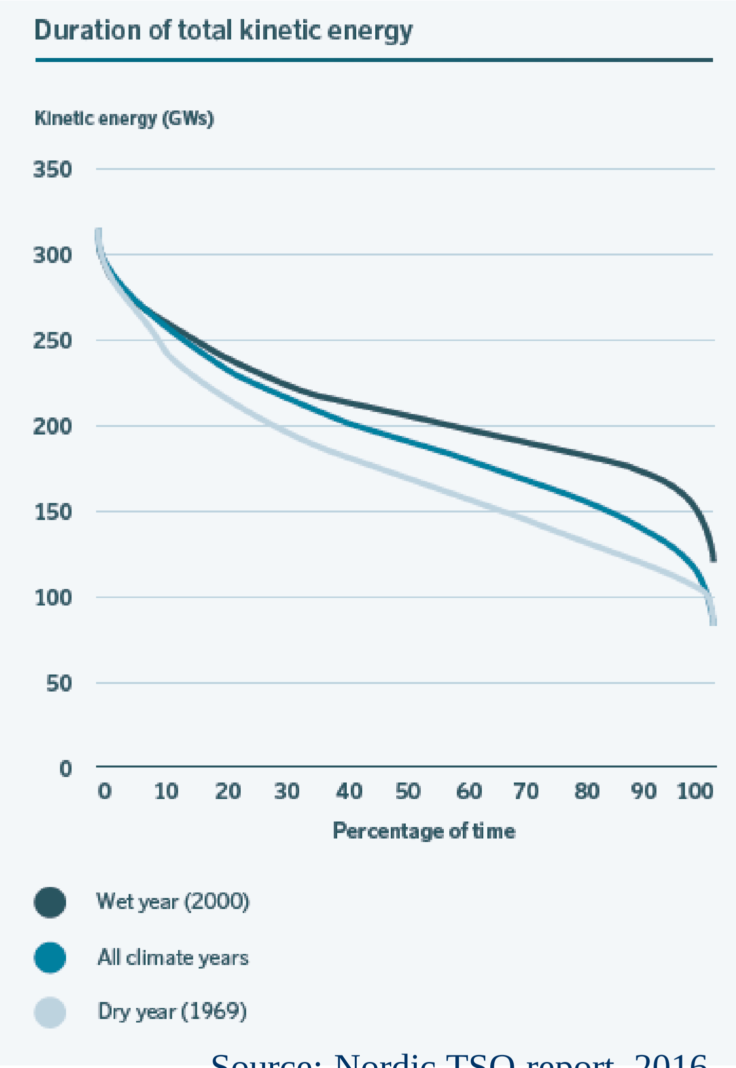
Source: ERCOT

4. Ensuring long-term reliability: Stability. Concerns so far:

- Responses to fault situations – grid code settings:
  - FRT; South Australia 2016 consecutive faults in storm
  - Solar: 50.2 Hz issue with German PV; California 2016 Blue cut event, initiated NERC WG
- More recently: control interactions
  - UK 2019 Hornsea WPP control settings
  - Australia investigations which IBRs contribute negatively/positively to system damping in observed oscillation modes
  - so far, local incidents, in the future … need to assess

Frequency stability

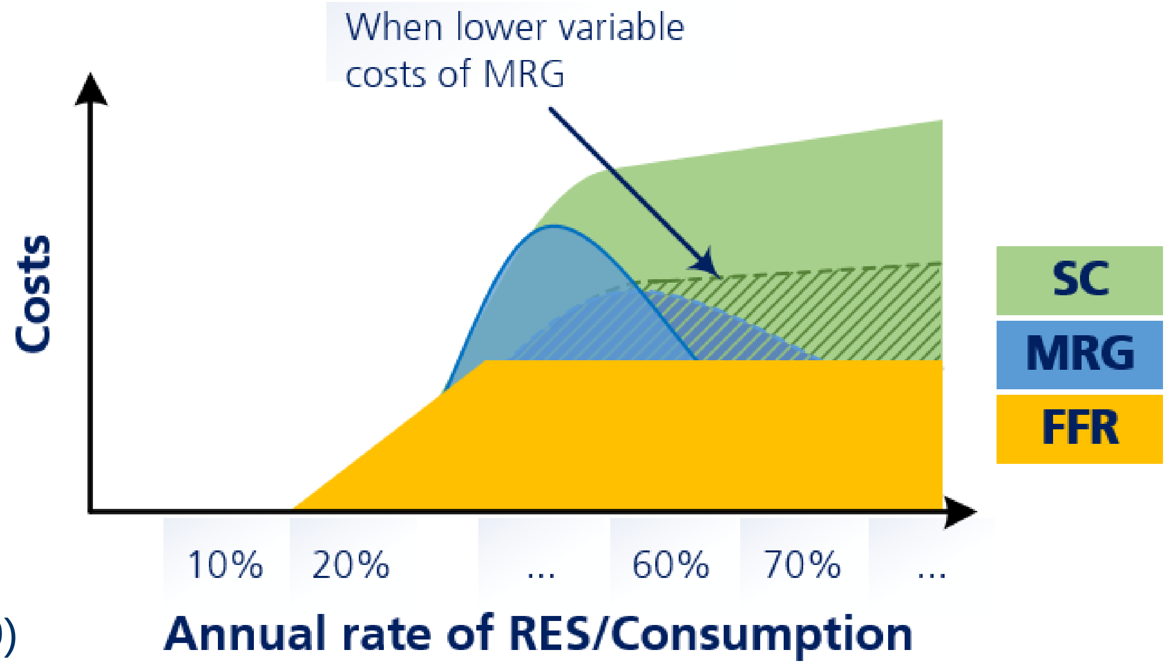
- Small system: Ireland case: limiting wind, SNSP
- Medium size systems: Nordic, Texas, GB new tools to monitor inertia real-time/day-ahead
- Large systems:
  - US MISO – not an issue at <60% average share of wind and solar
  - European system: system splits could happen (Iberia, EU SYSflex) Mitigation: cross-border flow limits, ensuring DC connections



Source: Nordic TSO report, 2016

Supporting frequency stability

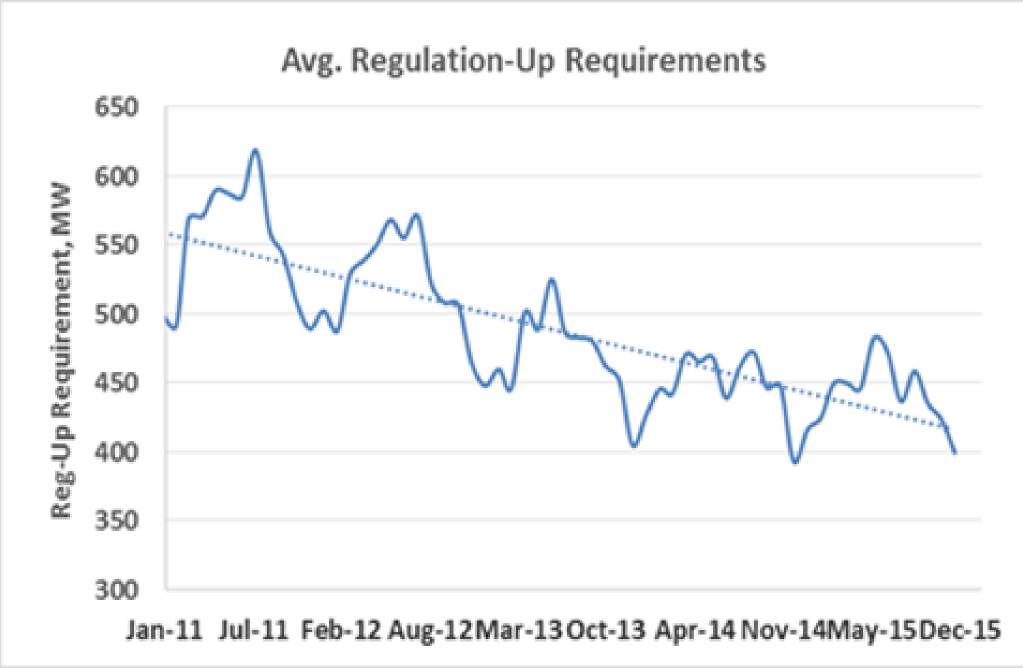
- Maintain online inertia by keeping synchronous machines running (MRG) or other sources of synchronous inertia (SC, synchronous condensers)
- Speed up frequency response, Faster primary frequency response (on sync machines), Fast frequency response (FFR)



Source: EdF (Primes et al. 2019)

Faster response is more valuable

- ERCOT, Texas: FFR (0.5 s) High wind, low load: 1,400 MW of FFR provides same response (and reliability impact) as 3,300 MW of PFR
- Hydro Quebec event 28 Dec. 2015, frequency nadir of 59.08 Hz, wind power plants response contributed to recovery of system frequency



Texas experience, less need for secondary frequency support after changes in operational practices - wind power plants fast response also helping the need for secondary service (Source: Julia Matevosjana, ERCOT)

Voltage stability

- Replacement of rotating, sync generators with IBRs decreases short-circuit currents and widens area of voltage disturbance

- Transient stability issues with a reduction in synchronising torque are also foreseen (70% IBR share)

Source: Terna

Voltage stability - Ireland

- 2010 study 40% wind share, no major issues found
- 2020: Constraint of min. 8 large synchronous machines on-load at all times must be relaxed to reduce curtailing wind energy
- Dispersed location of wind farms (with different capability characteristics), combined with increasing installation of HV cables
- Voltage Trajectory Tool in control room for intra-day and day-ahead time horizons

Stability and weak grids

- US MISO: potential for dynamic stability issues due to weak grid increases sharply > 20% share, small-signal stability > 30% share of wind and solar
- Increased need for integrated planning and a blend of transmission solution types – including IBR capabilities
- Damping: tuned for HVDC import situations (Nordic); tuning for IBRs

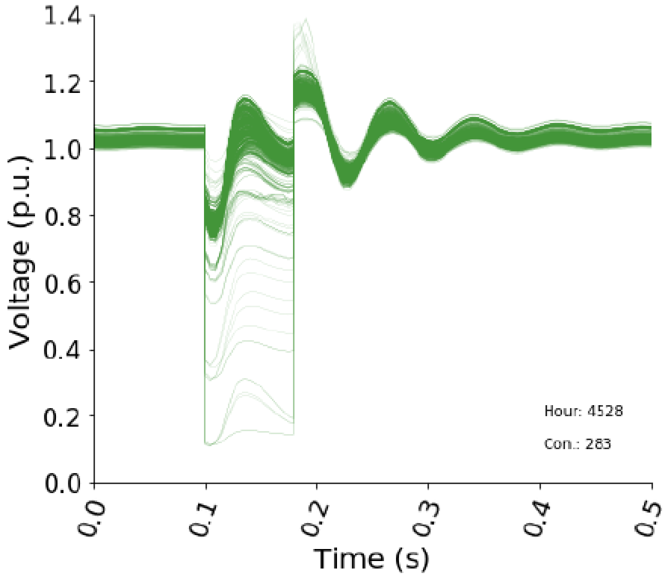


Fig. Transient voltage stability for 70% share of IBR for Ireland

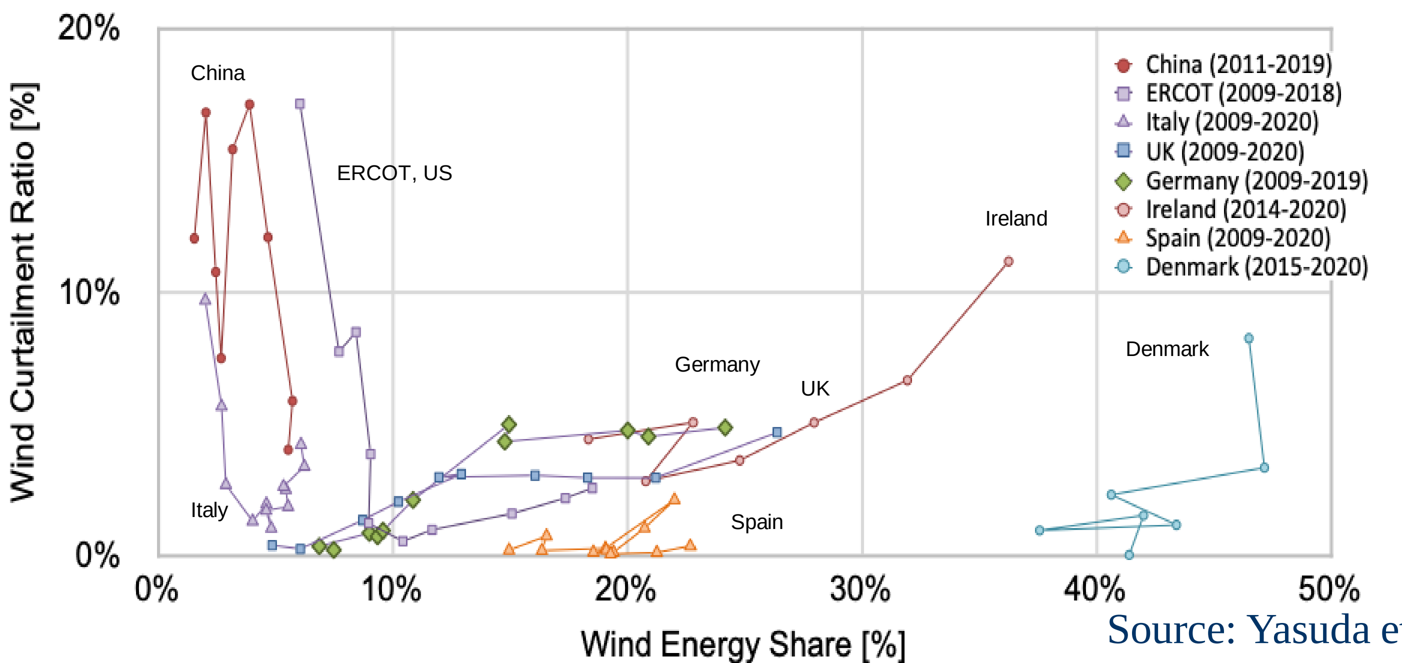
Source: EU-SysFlex project

6. Maximising wind energy value: Estimating wind's value

- Integration cost concept
  - Will be outdated when looking at net zero carbon systems of the future
  - Extracting and allocating a so-called integration cost cannot be achieved in a consistent manner
  - Adding different options to a system in a different order will change the costs incurred (!)
  - More relevant to look at different options/pathways and compare the cost of those scenarios
- Value of wind increasingly important to assess
  - Beyond LCOE
  - From transparent and cost reflective markets

6. Maximising wind energy value: Curtailment

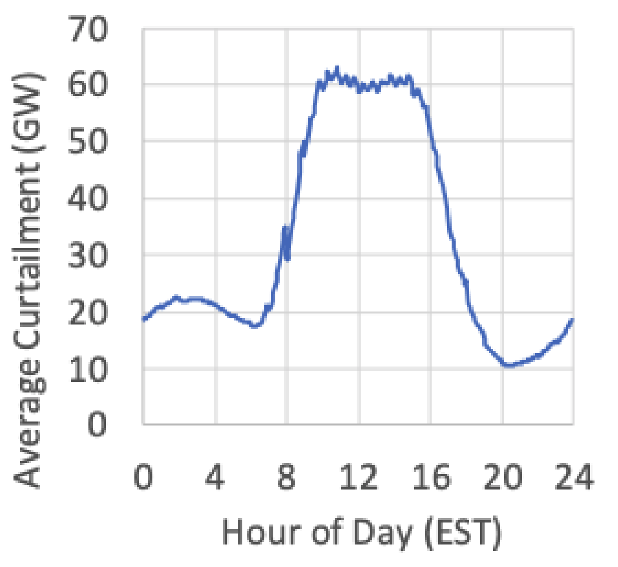
- up in Europe, down in China
- Reasons: grid inadequacy, inflexibility, system limits
- Solved by building grid (IT, CHI); increasing instantaneous penetration limits (SNSP in IE)
- market based curtailment, bidding down-reg (ES, DK)

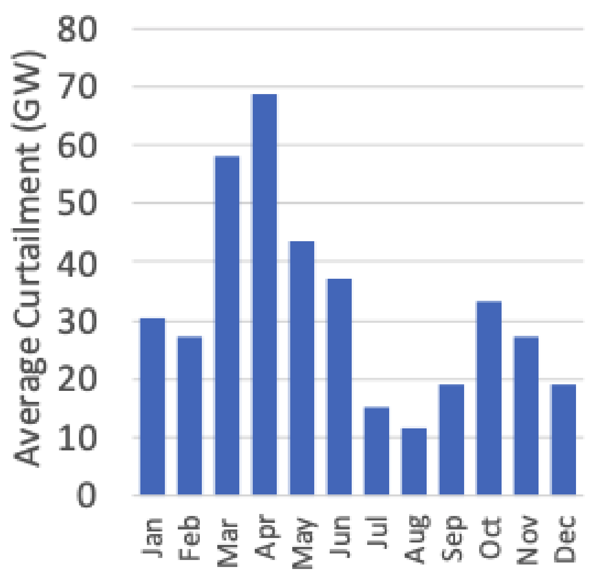


Source: Yasuda et al. 2022

Estimating curtailment for future wind scenarios

- Studies for 30-40% share of wind and solar – very little curtailment seen
  - Pan-Canadian wind integration study: 6.5% to 6.9% with 20% wind share
- US: 9.3% with >60% wind and solar share (NARIS LowCostVG)





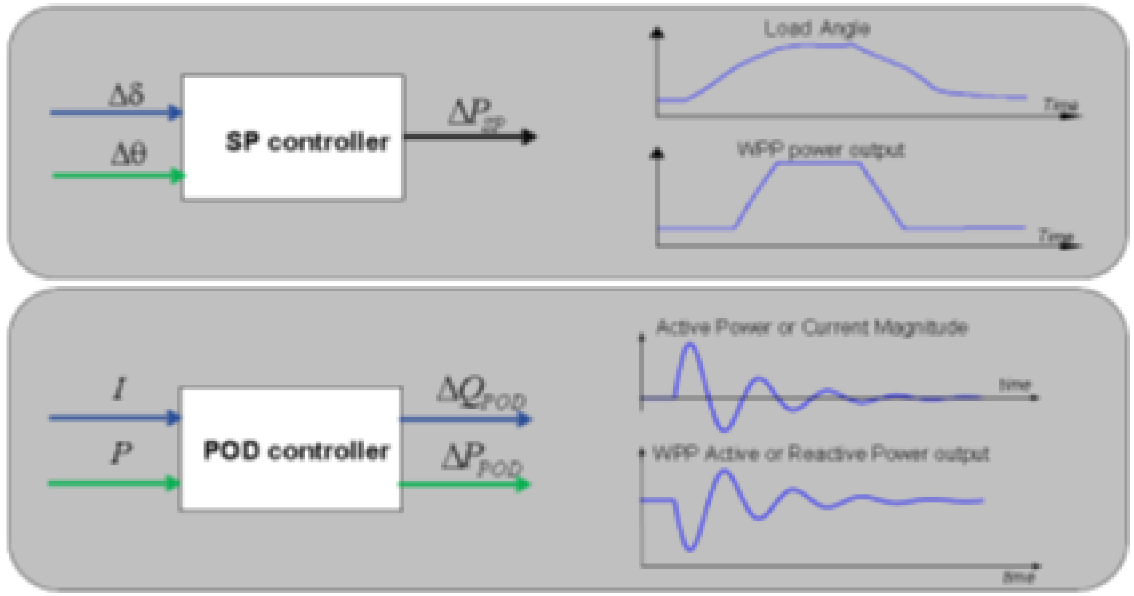
Bulk of curtailment occurs in a small percentage of the hours, but curtailment occurs somewhere in the United States in almost every hour. Source: NARIS study, Brinkman et al. 2021

6. Maximising wind energy value: Using wind power for AS

- With surplus wind and PV, important to provide AS, otherwise risk being curtailed to commit a synchronous generator to provide the same services
- Frequency control and balancing markets as well as voltage control from transmission connected power plants - experience already from several power systems
- **Spain:** 17 of 27 GW wind power complying for (mainly tertiary) freq control. Use of reserves from wind power is increasingly being used:
  - 14.4% of total downward reserves in 2018 and 14.8% in 2019
  - 4.8% of total upward reserves in 2018 and 7.5% in 2019
- Regulation /AGC and faster responses: good compliance and value for system shown (TX, CO, HQ)

New services + paying for them

- New: Power oscillation damping POD, Synchronising power SP, Restoration, Grid-forming inverters
- Start paying for Inertia, FFR, Ramping, Voltage
- Timing: introducing services when system actually needs them

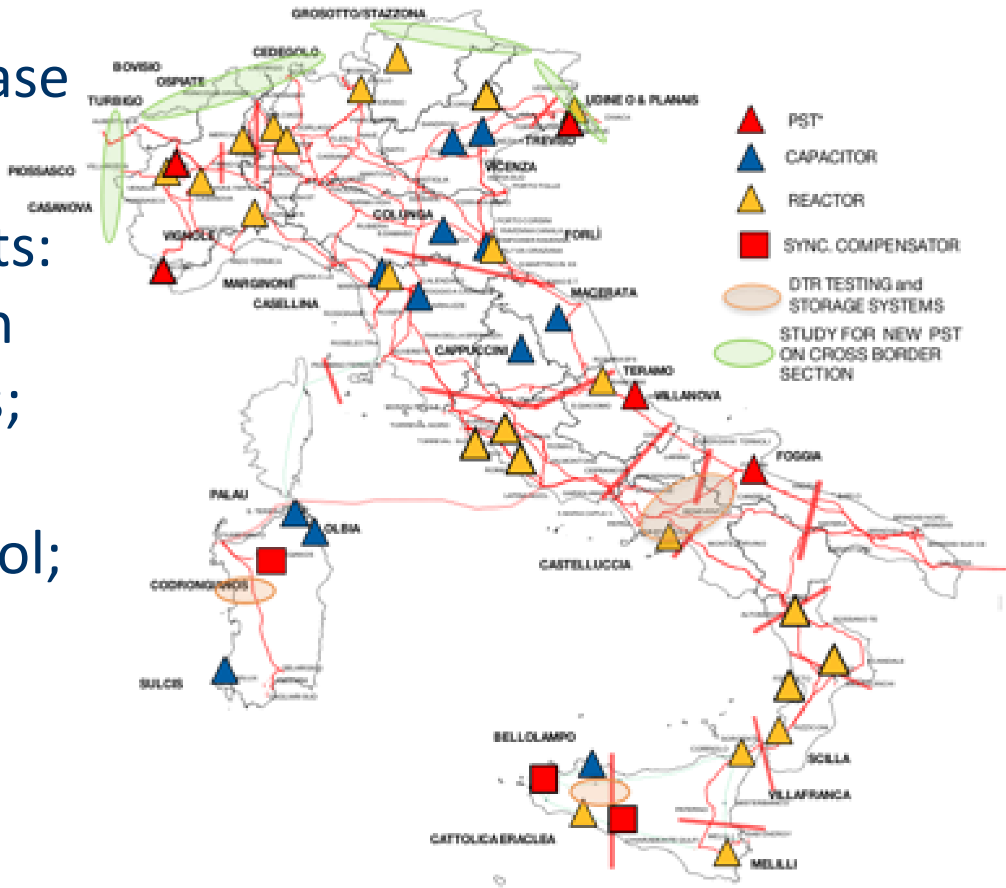


Source: DTU

Paying for all services – many now required in grid codes without compensation

6. Maximising wind energy value: Operational practices – grid

- Congestion management
  - Avoid curtailment and increase efficiency
  - Using existing grid to its limits: Setting security margins with stochastic weather forecasts; Dynamic Line Ratings (DLR); 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)

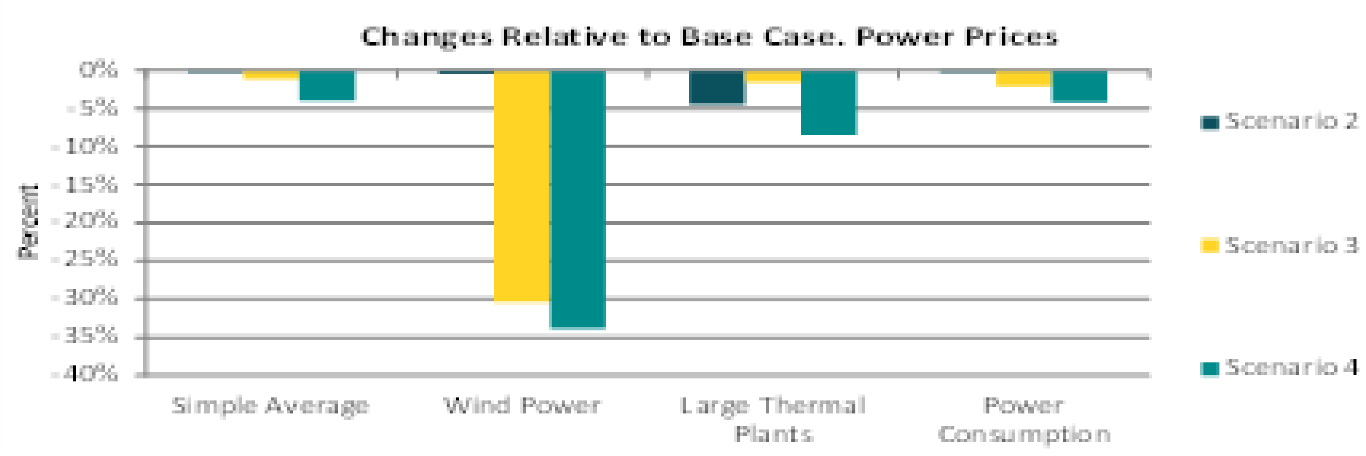
6. Maximising wind energy value: Flexibility

- Thermal power
  - Retrofits to lower minimum on-line power helps reduce curtailment
  - Combined heat and power (CHP) and heat pumps, with heat storage
- Increasing transmission has good cost benefit
- Hydro power
  - Pumped hydro useful for longer than few hours, hydro storage costs driven by the kW costs (cables + reversible pumps)
  - Larger reservoirs enable long term storage
- Storage
  - Batteries provide short-term balancing over one to some hours, reduce the need for peaker power plants
- Demand response
  - Short-term flexibility for existing loads and longer-term flexibility for Power2X loads – with hydrogen/derivative storage

Flexibility increases wind energy market value

“Profile losses” of wind and solar are lower when other generation and loads operate more flexibly, according to wind and solar availability – sharing balancing task with neighbouring systems, using the interconnectors, helps

ENERGINET



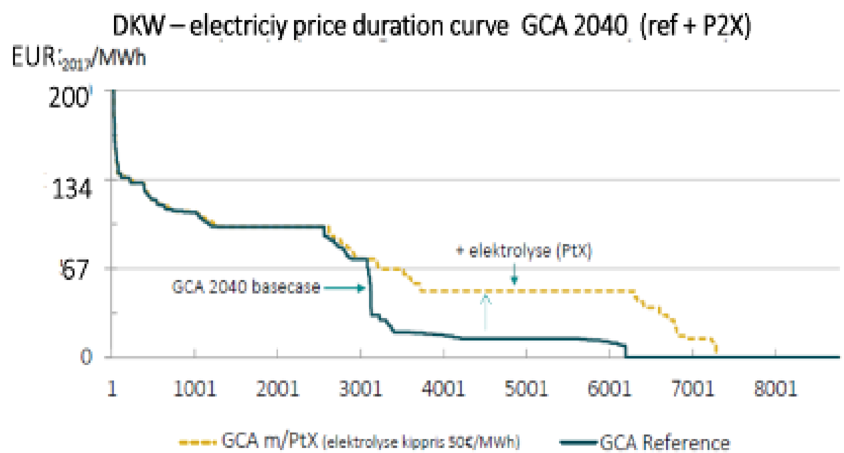
Changes in market prices in case of non-flexible system in Denmark

Flexibility increases wind energy market value

New demand from decarbonisation and power to X, can be utilised especially during times of surplus wind and solar and revive close-to-zero market prices

ENERGINET

P2X CAN INCREASE THE VALUE OF WIND/ PV



No P2X in the basecase.

In P2X scenario there is:

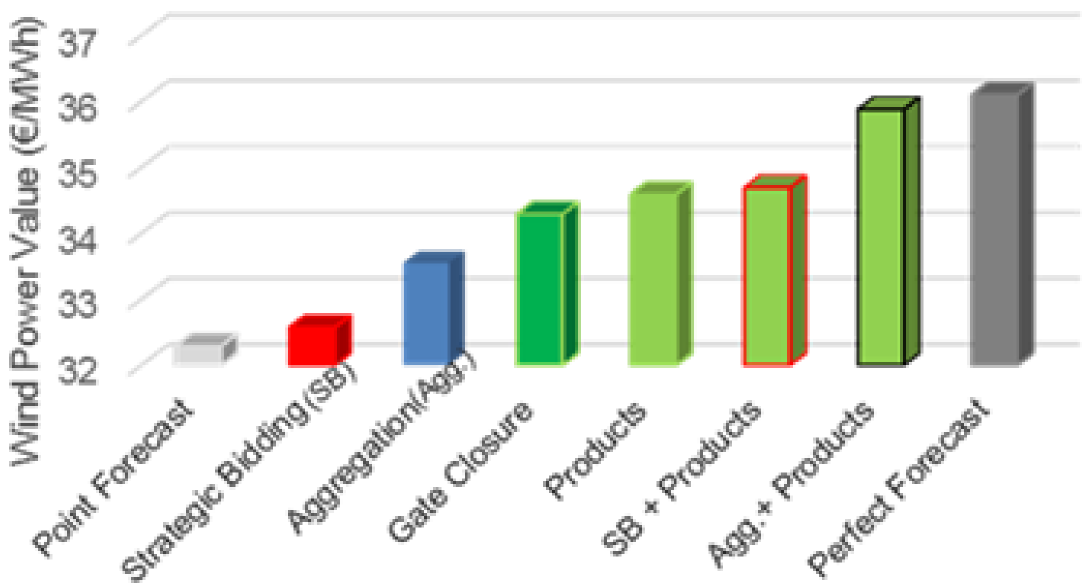
- 750 MW electrolysis in DK
- Ca 26 GW in DE, UK, NL and DK in total

The average annual settlement price for wind and PV in DKW increases from ~20 €/ MWh to 40 €/ MWh in the P2X scenario

Source Energinet

6. Maximising wind energy value: Market design

- Flexibility to avoid low price energy; also larger and faster markets
- Grid support from wind and solar
  - bidding close to delivery (for example, hour ahead)
  - bidding smaller amounts of MW and only down-reg

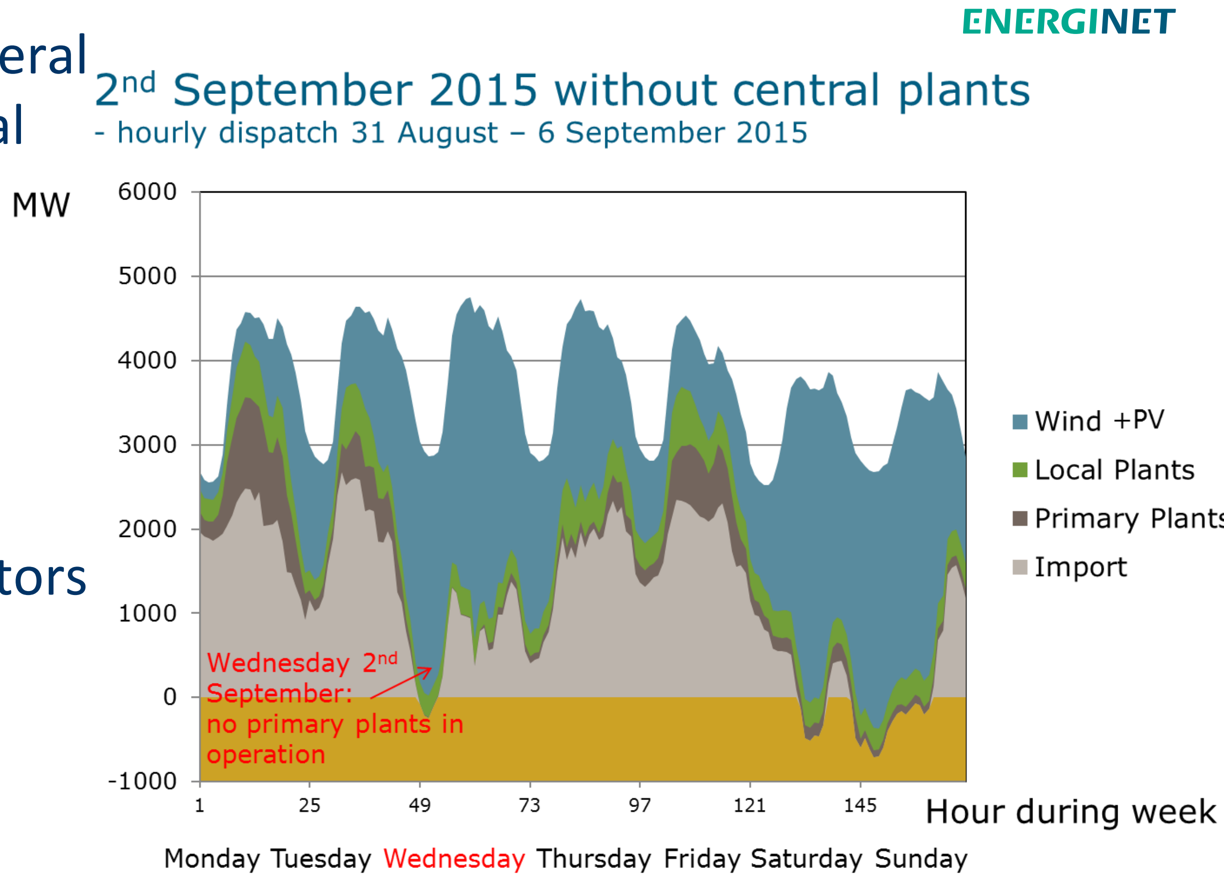


Increasing wind energy value to the market using different approaches: strategic bidding based on probabilistic forecast (SB), aggregation (Agg.), shorter gate closure and balancing products (Source: Algarvio & Knorr, 2017).

7. Pushing the limits
Denmark operating the system without central power plants

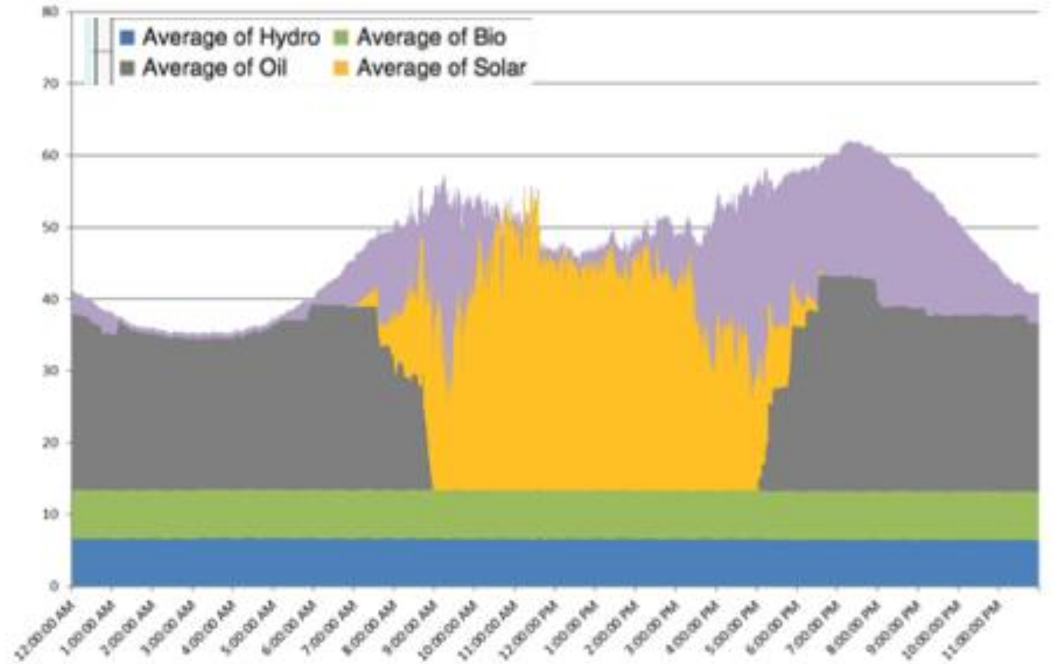
First time in 2015, and several times since then, all central power plants shut down. Necessary system support obtained from:

- HVDC link: 700 MW Denmark-Norway
- synchronous compensators 4 in DK-W and 2 in DK-E
- and small-scale power plants



Small island power system: Kauai in Hawaii

- Quick-start diesel reciprocating engines
  - Fast reserves (start up in minutes); one engine operating in synchronous condenser mode: inertia and system strength
- PV/battery hybrids for fast response
  - (Passing cloud events of order of seconds) hold 50% of real-time output as spinning contingency reserve



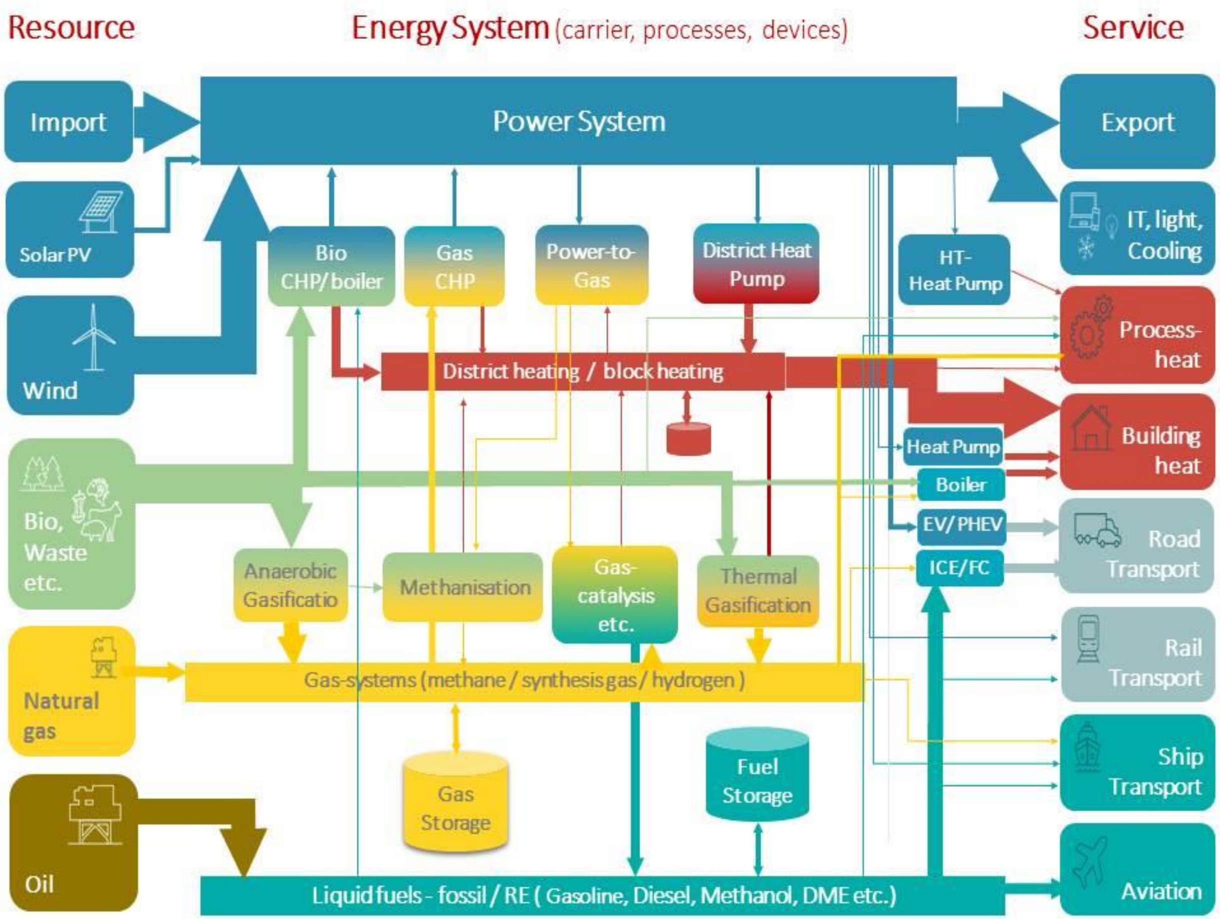
KIUC system dispatch on 3/14/20 with 8 hours of 100% renewables operations. Purple shows PV/battery hybrid output. (Source: Brad Rockwell, KIUC).

Pushing the limits: 100% renewable power system studies

- Most look at hourly energy balances, and some include the increased electricity demand due to **electrification**, e.g., EU Fit for 55 study:
  - Electricity will cover 57% of final energy uses directly, plus 18% indirectly through H_2 and its derivatives
  - Electricity demand grows from 3,000 TWh to 6,800 TWh
  - Wind comprises 50% of the EU's electricity mix (total renewables 81%)
- **Transmission expansion** is common theme, e.g., U.S. MIT study:
  - Interstate coordination and transmission expansion reduce system cost from 135 $/MWh to 73 $/MWh
  - Cost reductions in solar, wind, and batteries lead to lowest electricity costs for systems with transmission expansion
  - Cost reductions for nuclear power or long-duration storage leads to greater electricity cost reductions for isolated systems

Pushing the limits: carbon neutrality

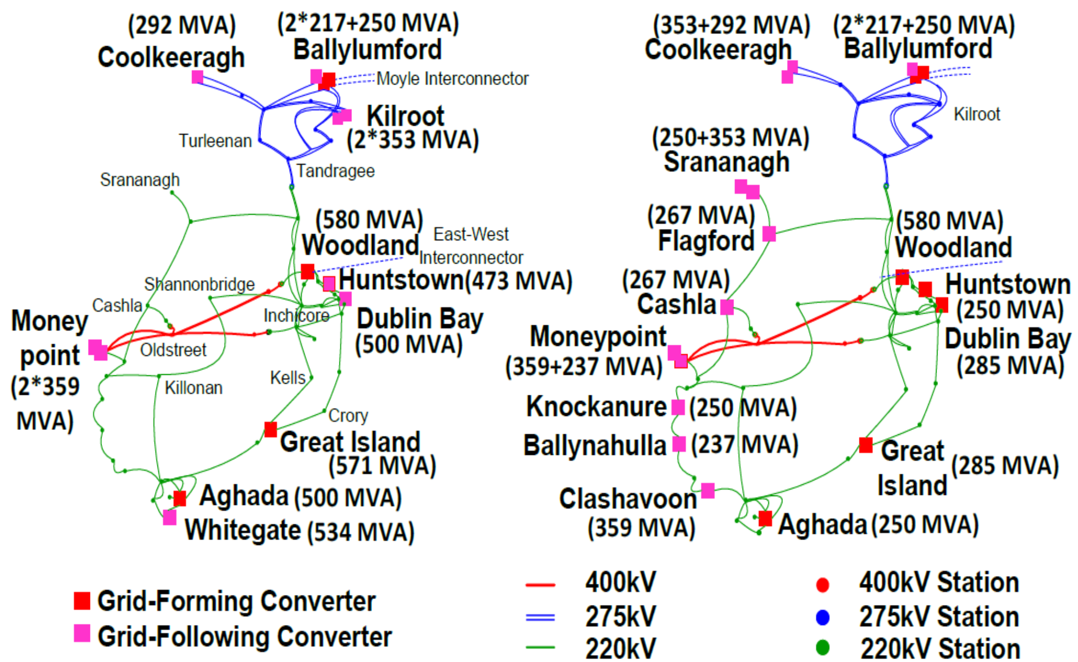
- Capturing all energy sectors and their coupling
- Looking at energy balances, no stability
- Some liquid fuels remain, from biomass or electricity, different pathways, such as ammonia



Source: Energinet

Stability of a 100% IBR grid

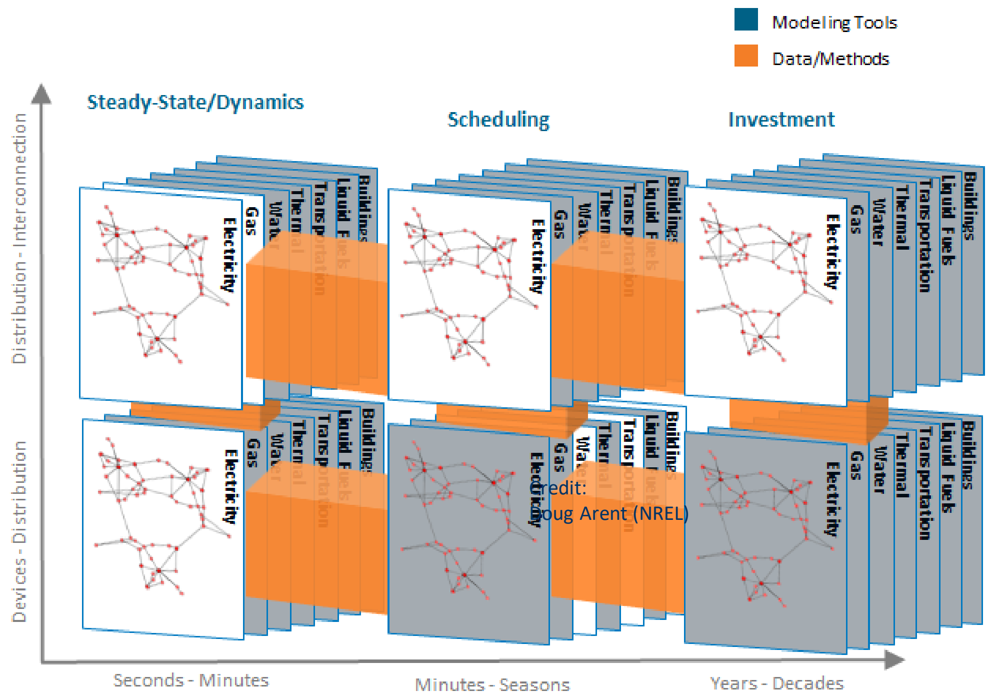
- GB system: 65% IBR share with modified grid-following control; combining grid-following and grid-forming controls to a theoretical 100% (MIGRATE D1.6, 2019)
- Ireland system: ~30% of grid-forming feasible



Source: UCD, MIGRATE project

Pushing the limits: Tools

- Modelling complexity
  - VIBRES (variable inverter-based renewable energy source)
  - Need for higher resolution (temporal and spatial)
- Larger areas
  - Entire synchronous systems
- Integrated planning, operational, stability tools
- Cost versus risk
  - Price responsive demand
  - Differentiated reliability



NREL's Scalable Integrated Infrastructure Planning (SIIP) modeling framework.

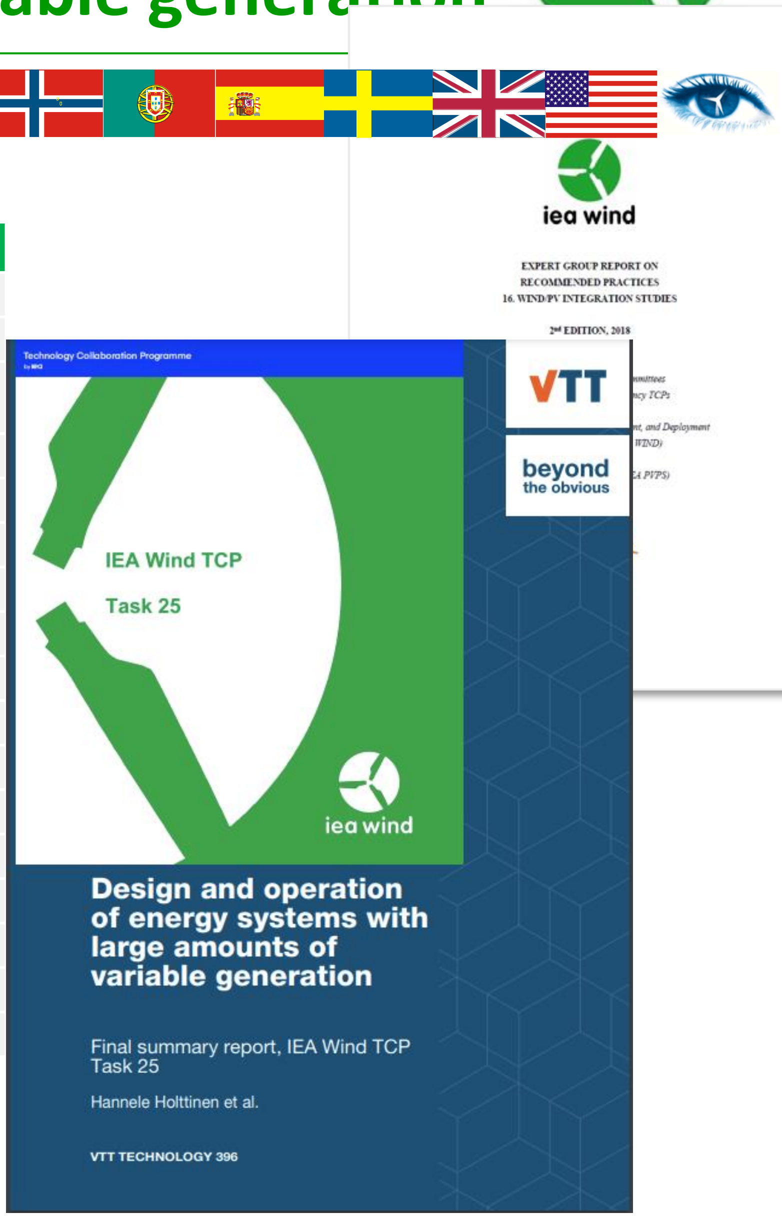
Source: Doug Arent (NREL)

8. Conclusion

- VIBRES (wind and solar) will make a large contribution to future decarbonised energy systems - potential to form the backbone of future power systems when full range of inverter capabilities are used
  – New paradigms of non-synchronous power system operation and long-term resource adequacy are being developed, with a suite of new tools and methods for system operators
- Experience of operating and planning systems with large amounts of VIBRES is accumulating
  – Research to tackle challenges, and opportunities of inverter-based, non-synchronous generation is on the way
  – Energy transition and digitalisation also bring new flexibility opportunities, both short and long term

IEA Wind Task 25: Design and operation of energy systems with large amounts of variable generation

Country	Institution
Canada	Hydro Quebec (Alain Forcione, Nickie Menemenlis); NRCan (Thomas Levy)
China	SGERI (Wang Yaohua, Liu Jun)
Denmark	DTU (Nicolaos Cutululis); Energinet.dk (Antje Orths); Ea analyse (Peter Börre Eriksen)
Finland (OA)	Recognis (Hannele Holttinen); VTT (Niina Helistö, Juha Kiviluoma)
France	EdF R&D (E. Neau); TSO RTE (J-Y Bourmaud); Mines (G. Kariniotakis)
Germany	Fraunhofer IEE (J. Dobschinski); FfE (S. von Roon)
Ireland	UCD (D. Flynn); SEAI (J. McCann); Energy Reform (J. Dillon);
Italy	TSO Terna Rete Italia (Enrico Maria Carlini)
Japan	Kyoto Uni (Y. Yasuda); CRIEPI (R. Tanabe)
Netherlands	TUDelft (Arjen van der Meer, Simon Watson); TNO (German Morales Sspana)
Norway	NTNU (Magnus Korpås); SINTEF (John Olav Tande, Til Kristian Vrana)
Portugal	LNEG (Ana Estanquiero); INESC-Porto (Bernando Silva)
Spain	University of Castilla La Mancha (Emilio Gomez Lazaro); Comillas (Adres Ramos)
Sweden	KTH (Lennart Söder)
UK	Imperial College (Goran Strbac, Danny Pudjianto);
USA	NREL (Bethany Frew, Bri-Mathias Hodge); UVIG (J.C. Smith); DoE (Jian Fu)
Wind Europe	European Wind Energy Association (Vasiliki Klonari, Daniel Fraile)



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

Thank You!!

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Q&A

Hannele Holttinen,

Operating Agent Task25

Bethany Frew

(NREL)

Damian Flynn

(UCD)

Based on IEA WIND Task 25 collaborative publications

- Summary report **"Design and operation of energy system with large amounts of variable generation"** https://doi.org/ 10.32040/2242-122X.2021.T396
- "**Towards 100% Variable Inverter-based Renewable Energy Power Systems**" by Bri-Mathias Hodge, C Brancucci, H Jain, G Seo, B Kroposki, J Kiviluoma, H Holttinen, J C Smith, A Estanqueiro, A Orths, L Söder, D Flynn, M Korpås, T K Vrana, Yoh Yasuda. WIREs Energy and Environment vol 9, iss. 5, e354 https://doi.org/10.1002/wene.376
- "**System impact studies for near 100% renewable energy systems dominated by inverter based variable generation**" by H Holttinen; J Kiviluoma; D Flynn; C Smith; A Orths; P B Eriksen; N Cutululis; L Söder; M Korpås, A Estanqueiro, J MacDowell, A Tuohy, T K Vrana, M O'Malley , IEEE TPWRS Oct 2020 open access https://ieeexplore.ieee.org/document/9246271
- https://www.researchgate.net/project/IEA-Task-25-Design-and-Operation-of-Power-Systems-with-Large-Amounts-of-wind-power