Task 25 webinar

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

Technical report presentation to ExCo, 16 Sep, 2021 -recorded-

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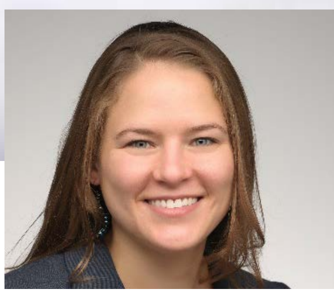

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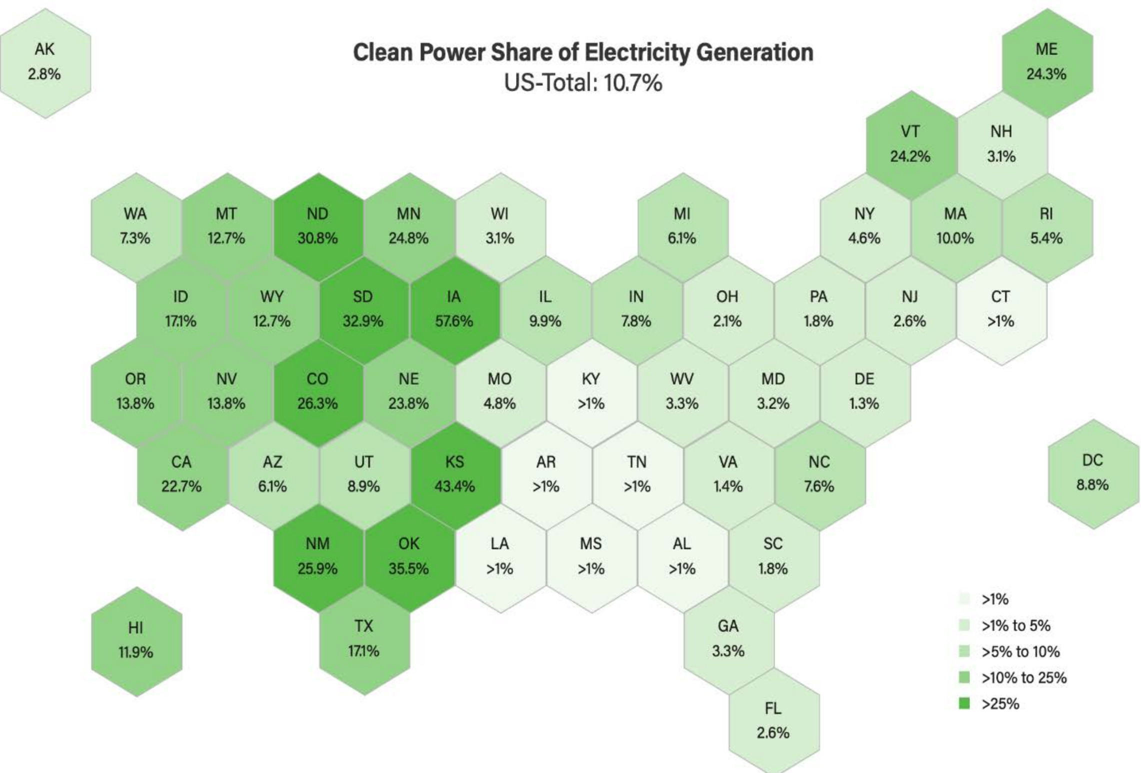
iea wind

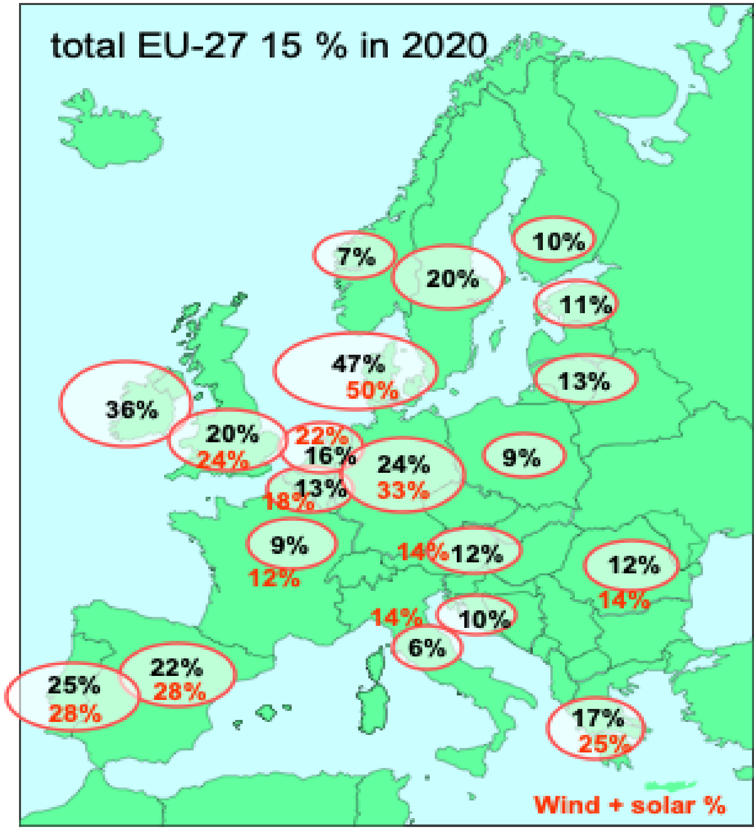
Agenda

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

Increasing shares of wind (and solar)…

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

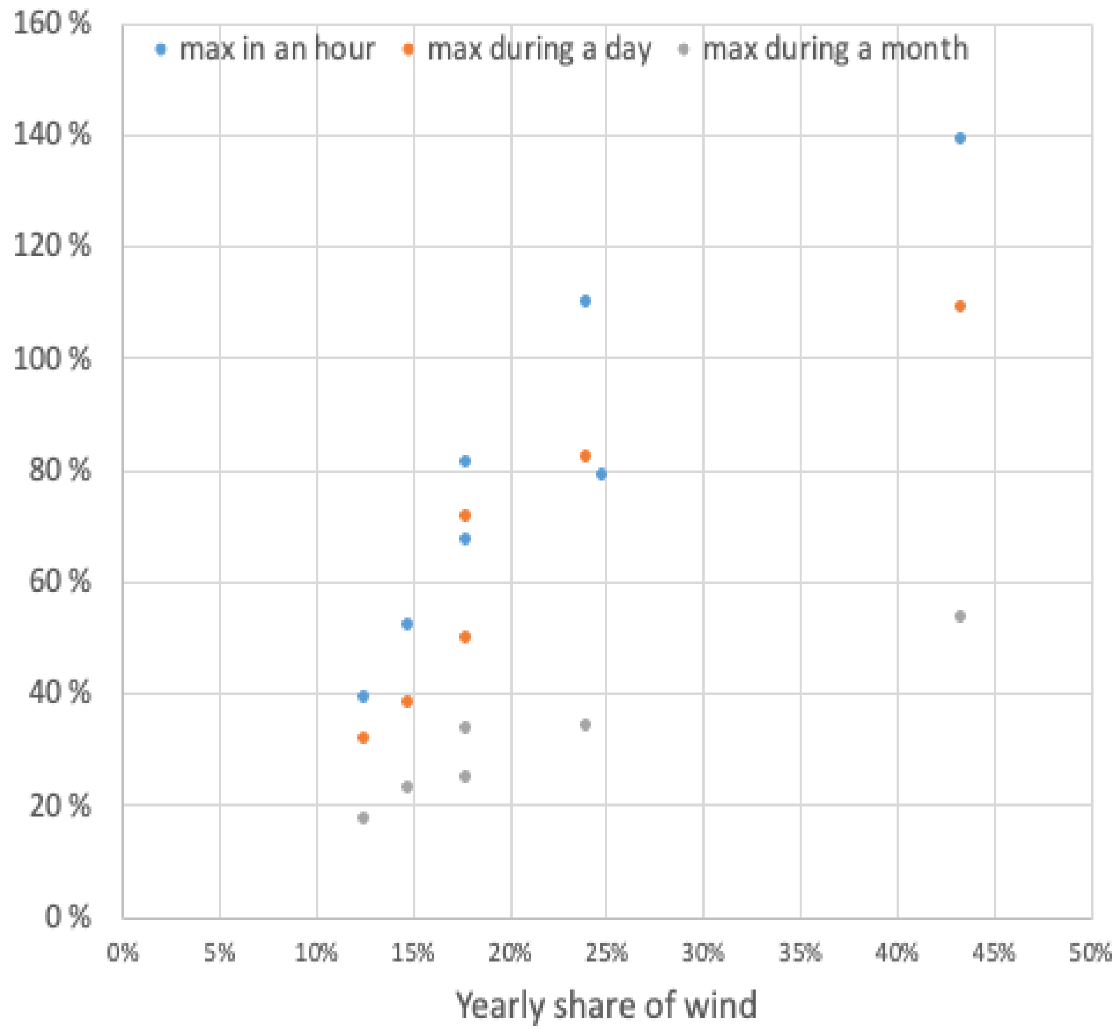




Source: ACP

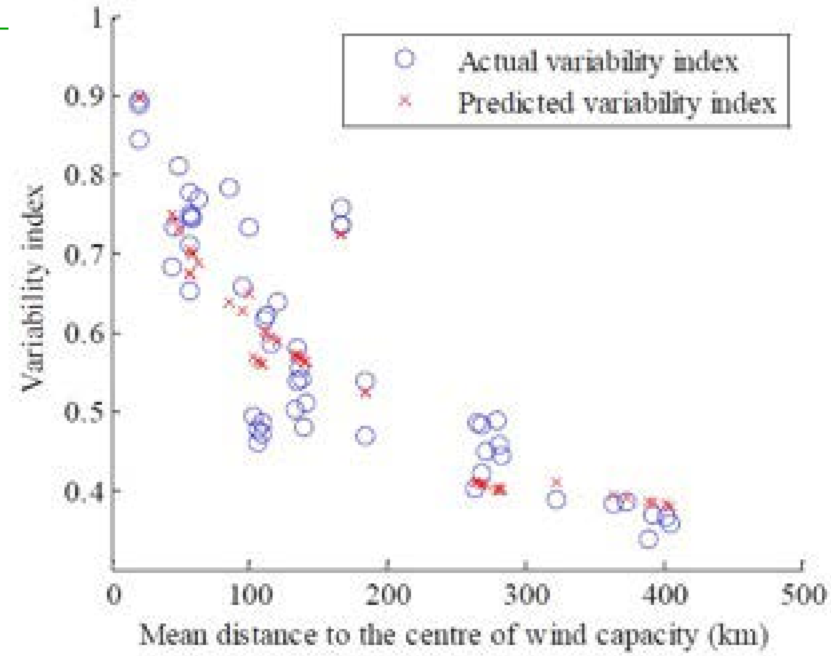
..mean increasing instant shares

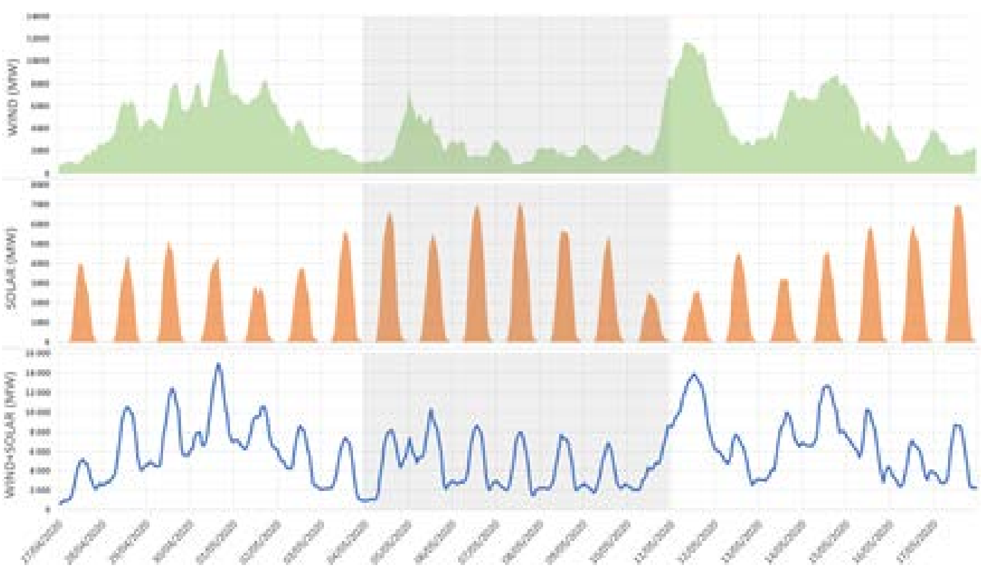
- challenges when >50% in synchronous power system (Island of Ireland, Texas, GB)
- larger power systems still 10-15% share of wind&solar



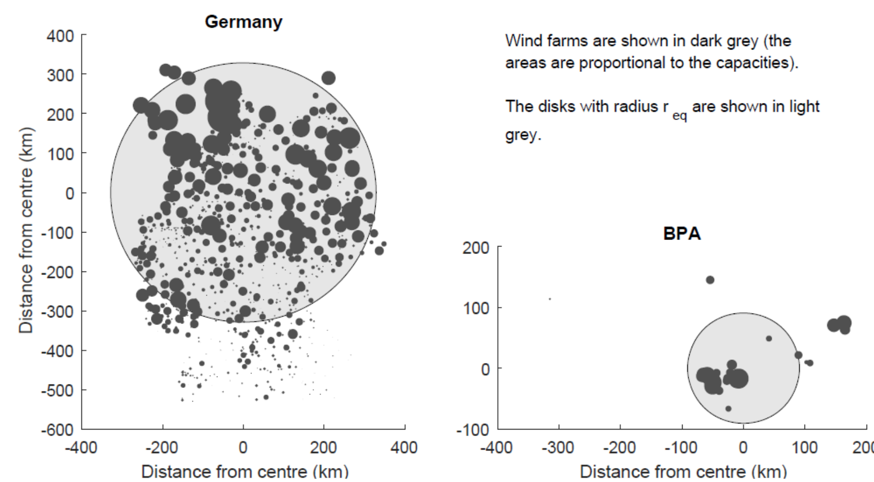
For assessing impacts of variability and uncertainty :

- wind smoothing impact (size of area, dispersion)
- aggregation benefits to power system models
- also wind and solar:



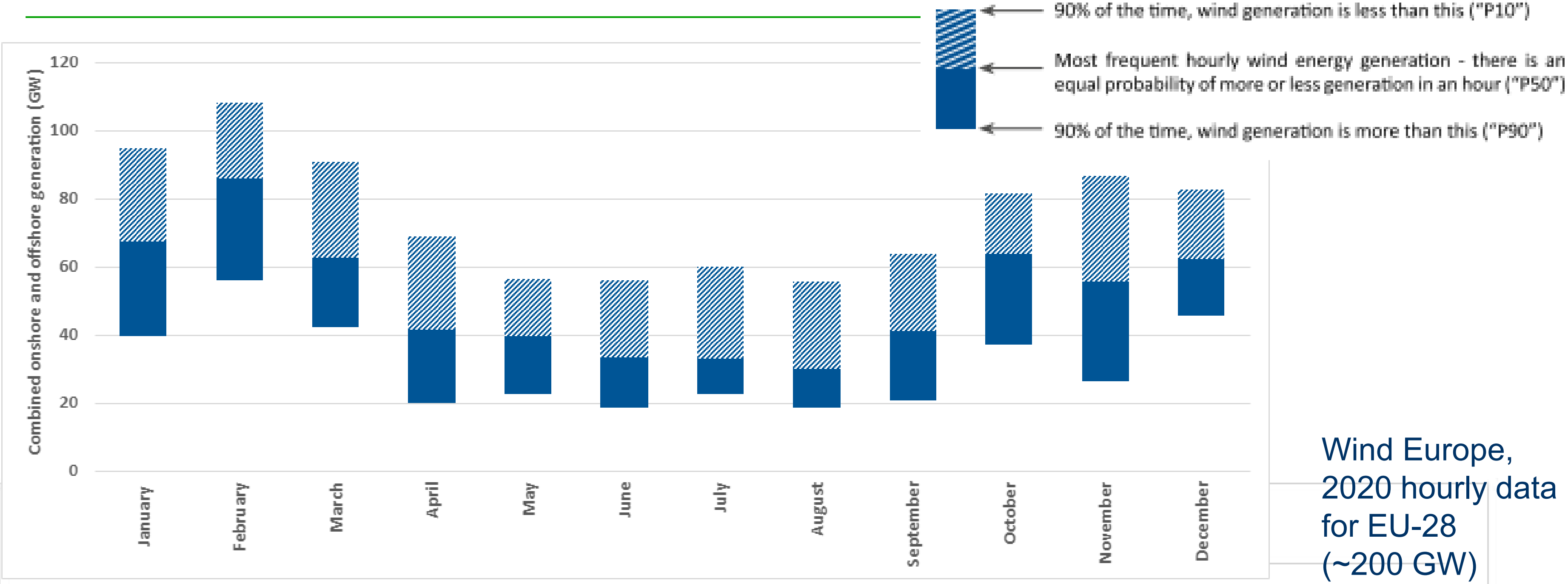


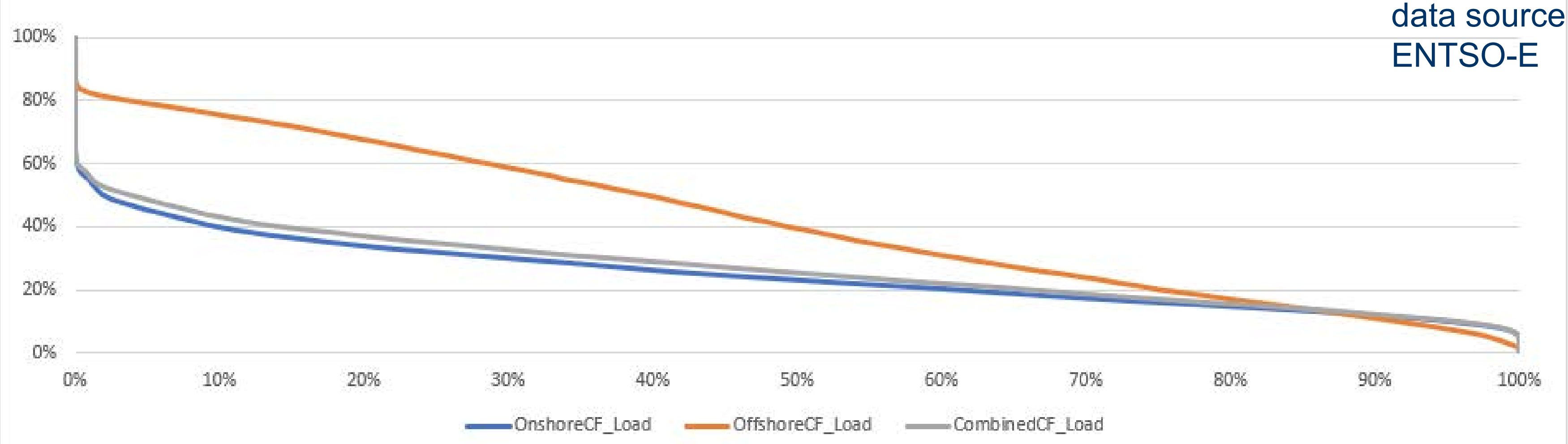
3 weeks in France, from ENTSO-E data



Equivalent system radius, Olauson et al. 2016

Smoothing impact: Europe



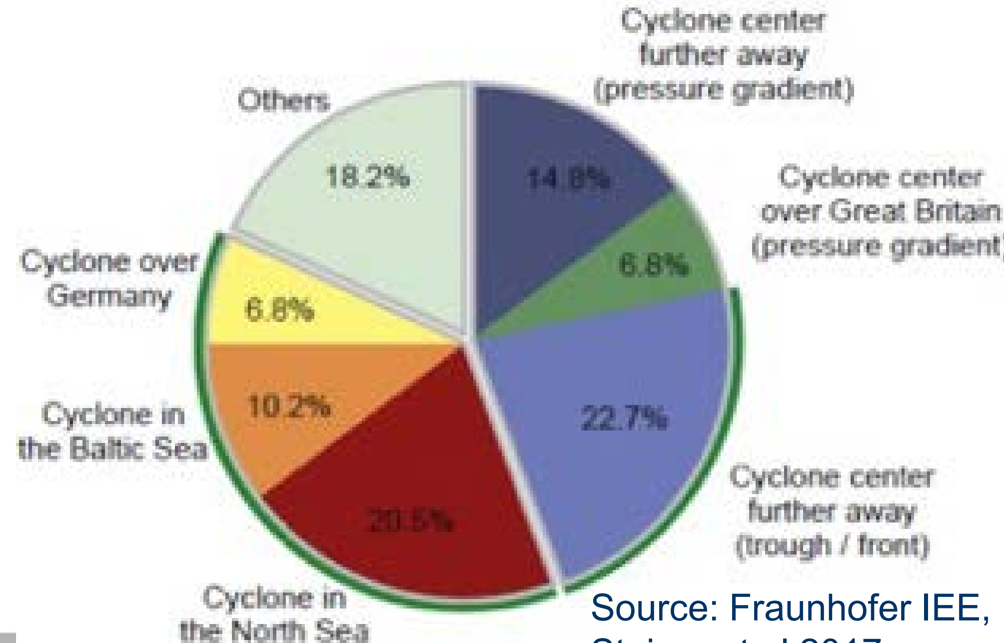


Wind Europe, 2020 hourly data for EU-28 (~200 GW) data source ENTSO-E

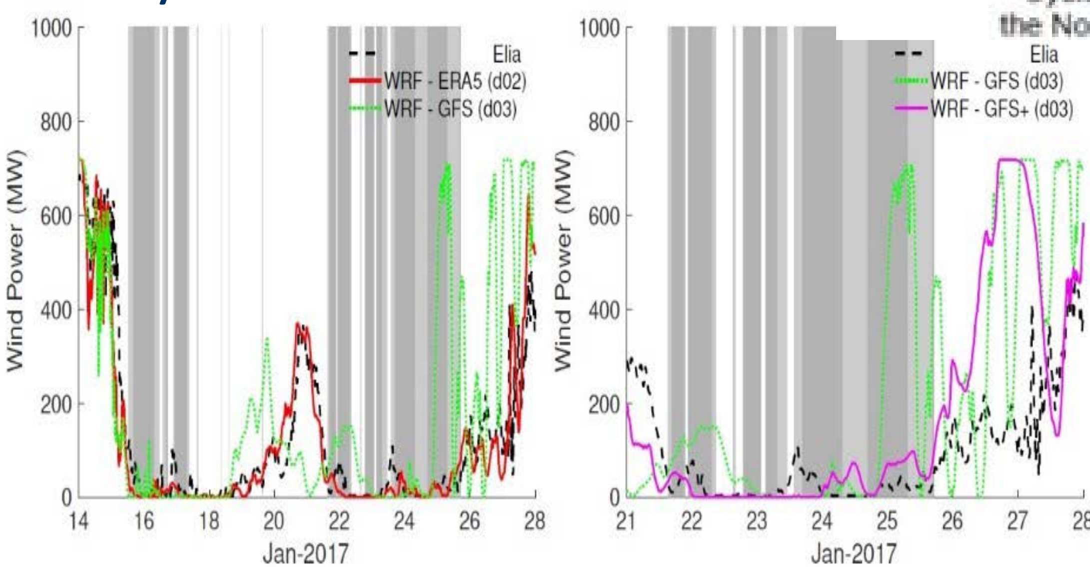
Extreme events important to capture

Ramp forecasting

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



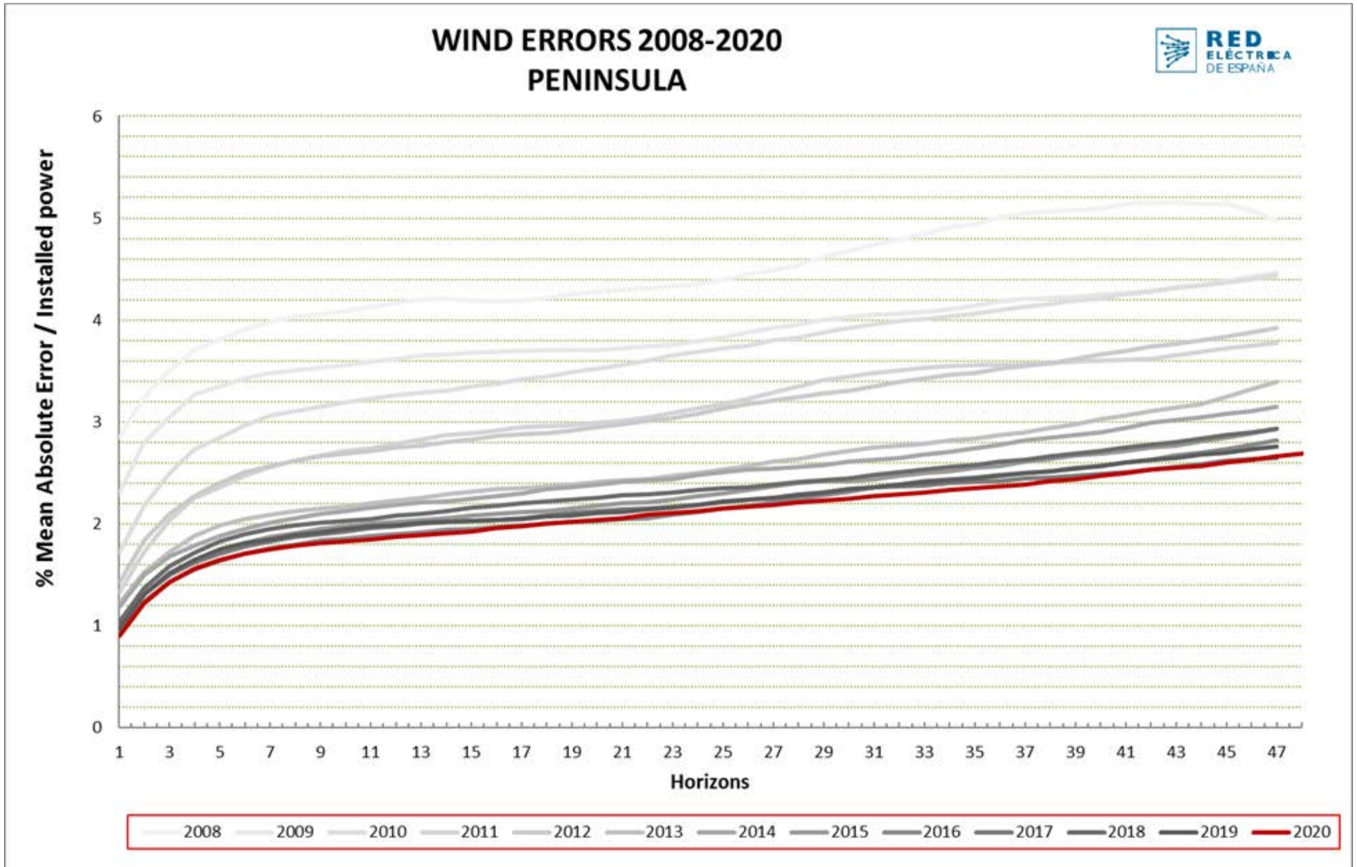
Source: Fraunhofer IEE, Steiner et al 2017



Source: TUDelft, Li et al 2021

Data and models improving

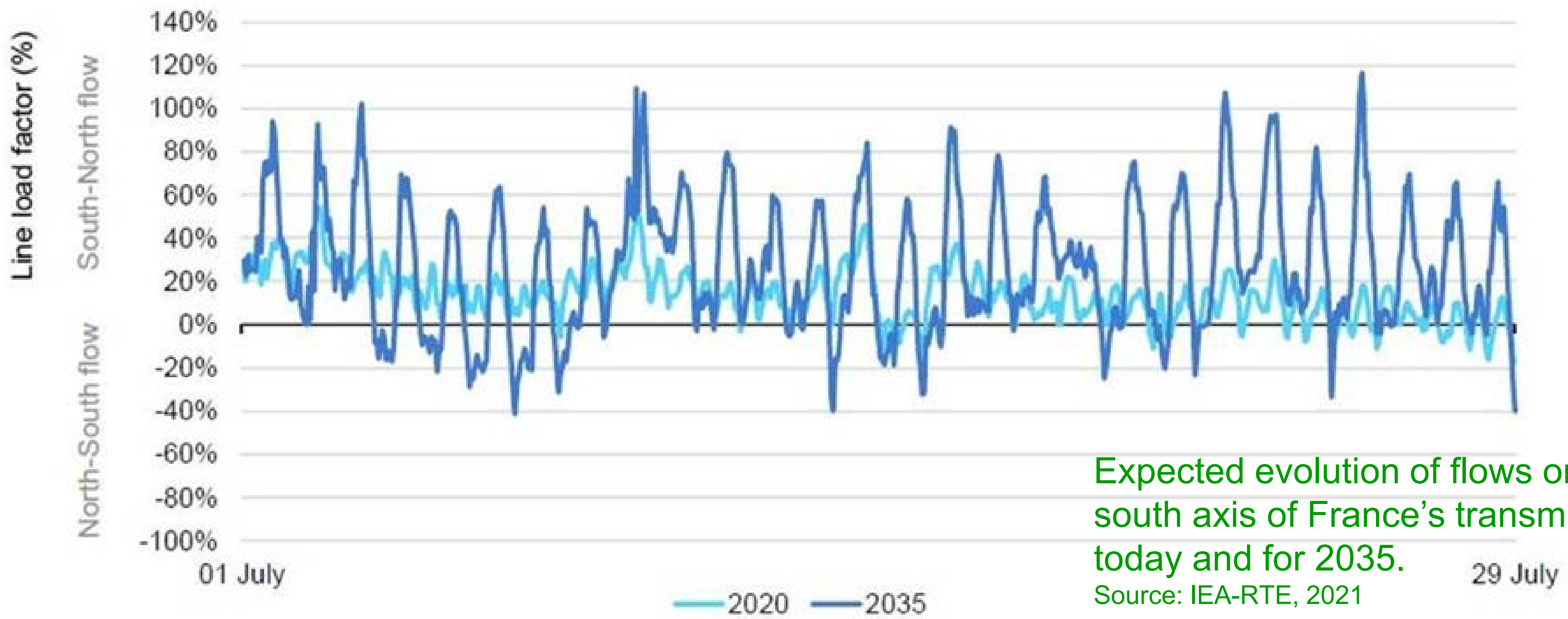
- simulated weather data has improved: future wind scenario output time series for models
- forecasts continue improving



Source: REE, Spain

Transmission planning

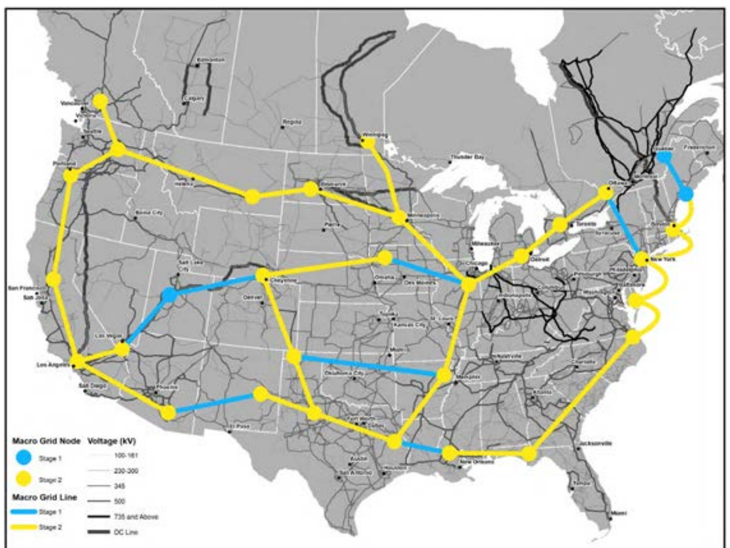
- Greater deployment of wind (and solar) yields higher line utilization, indicating greater benefit and additional need for transmission
- Public engagement with citizens is key for social acceptance
  - In Ireland and Germany, a stepwise process has been developed to increase transparency
  - Investments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



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

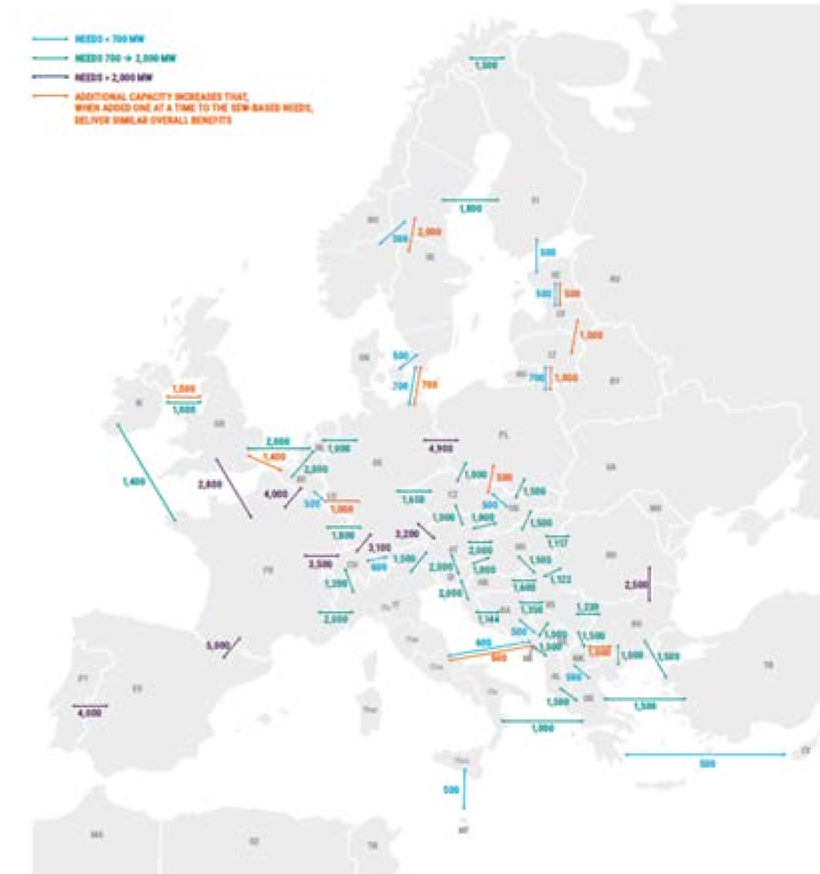
Transmission planning

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



Conceptual macro-grid to unite the US power systems.

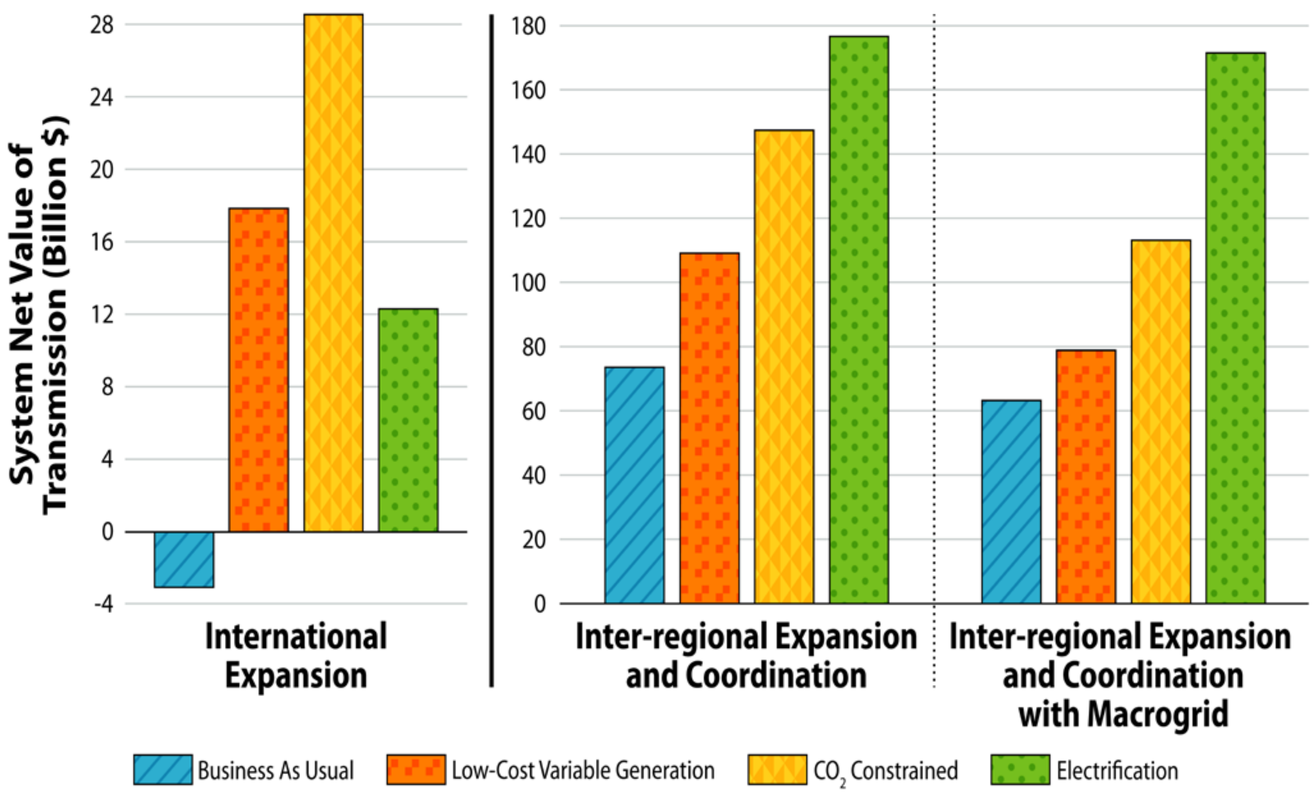
Source: ESIG. 2021. Transmission Planning for 100% Clean Electricity. https://www.esig.energy/wp-content/uploads/2021/02/Transmission-Planning-White-Paper.pdf



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; ENTSO-E, Nov 2020).

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

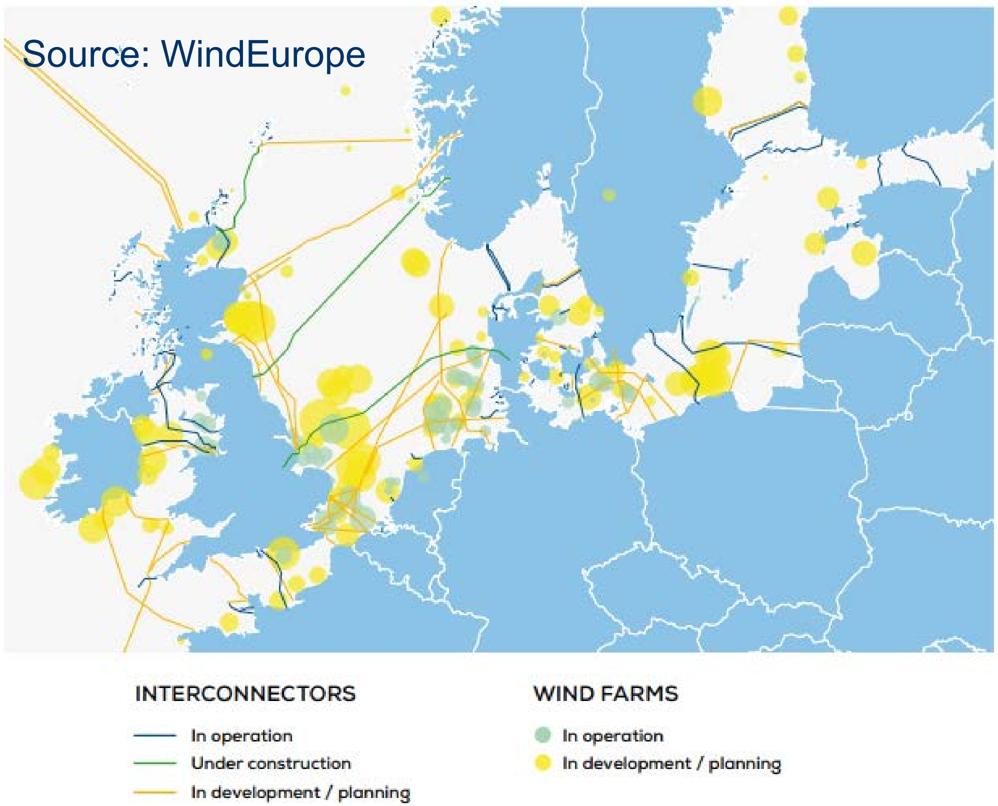


Continent-wide net value of transmission expansion for the four scenarios in the NARIS study.

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.

Offshore grids

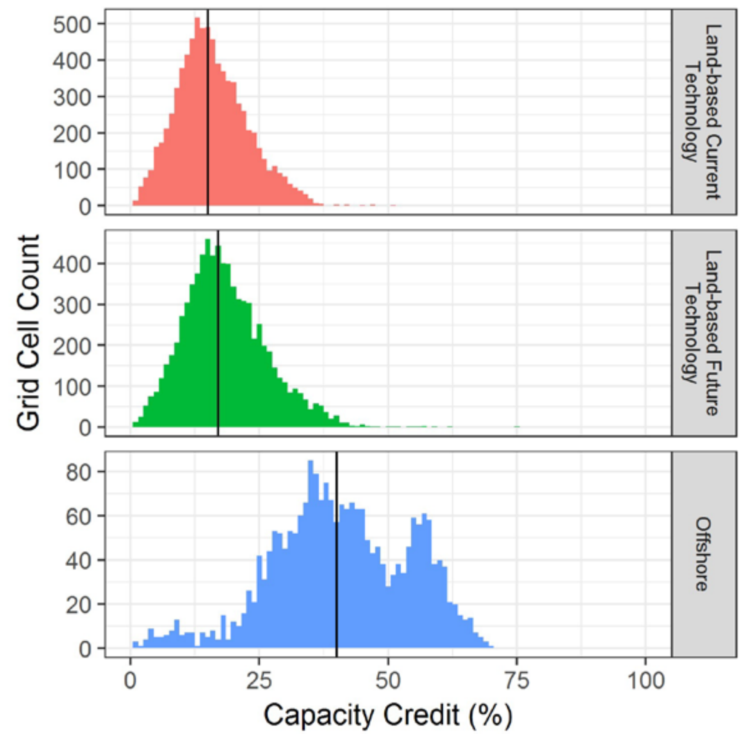
- TSOs are planning offshore grids as well
  - Meshed grids, hubs, and energy islands
  - HVDC technology improvements to increase cost effectiveness, reliability, and land-based grid support



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).

Ensuring long term reliability and security of supply

- Capacity value (capacity credit) of wind
  - Generally decreases with increasing share of wind, but this trend is less pronounced across larger geographic areas
  - More years of data are needed for robust results
- Necessary (but potentially not sufficient) for resource adequacy

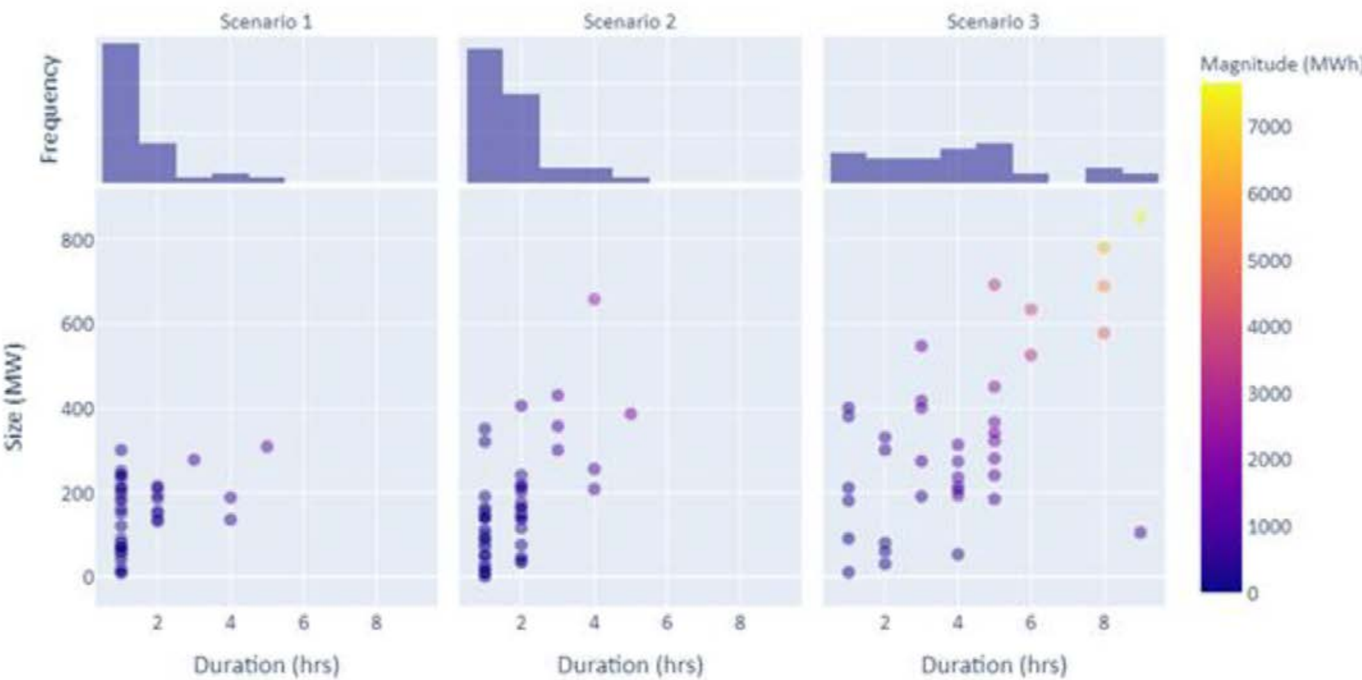


Capacity credit of wind in the Western United States. The average capacity credit is16% for land-based turbines and 41 % for offshore turbines.

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).

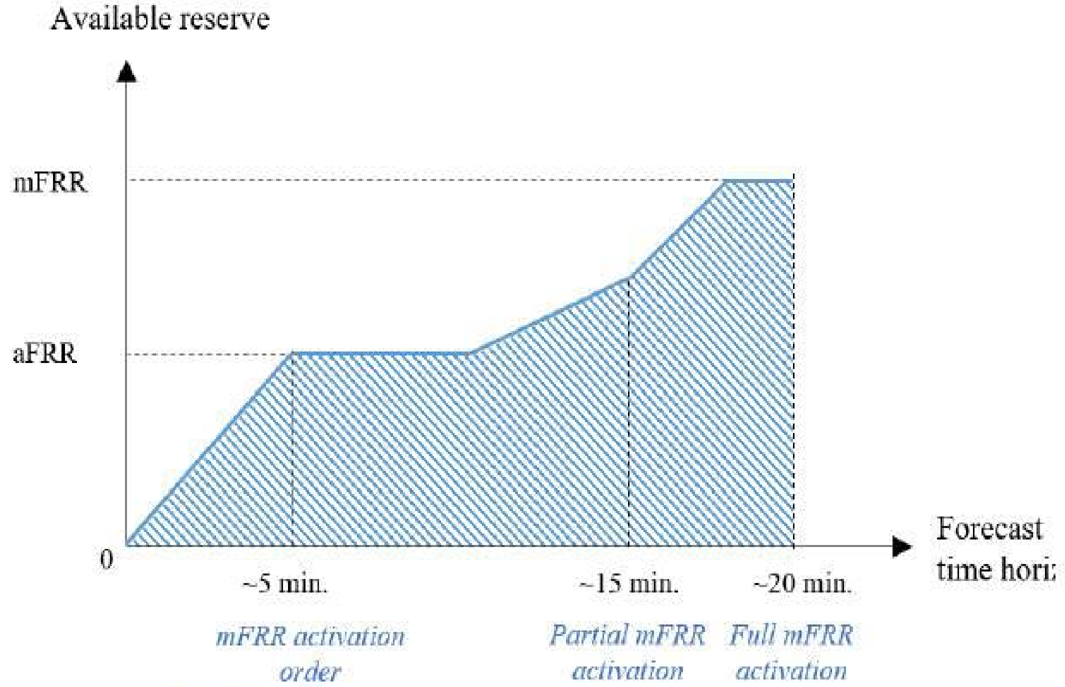
Source: ESIG. 2021. Redefining Resource Adequacy. https://www.esig.energy/resource-adequacy-for-modern-power-systems/

Ensuring short term reliability

- Operating reserves
- Stability

BALANCING CHALLENGE

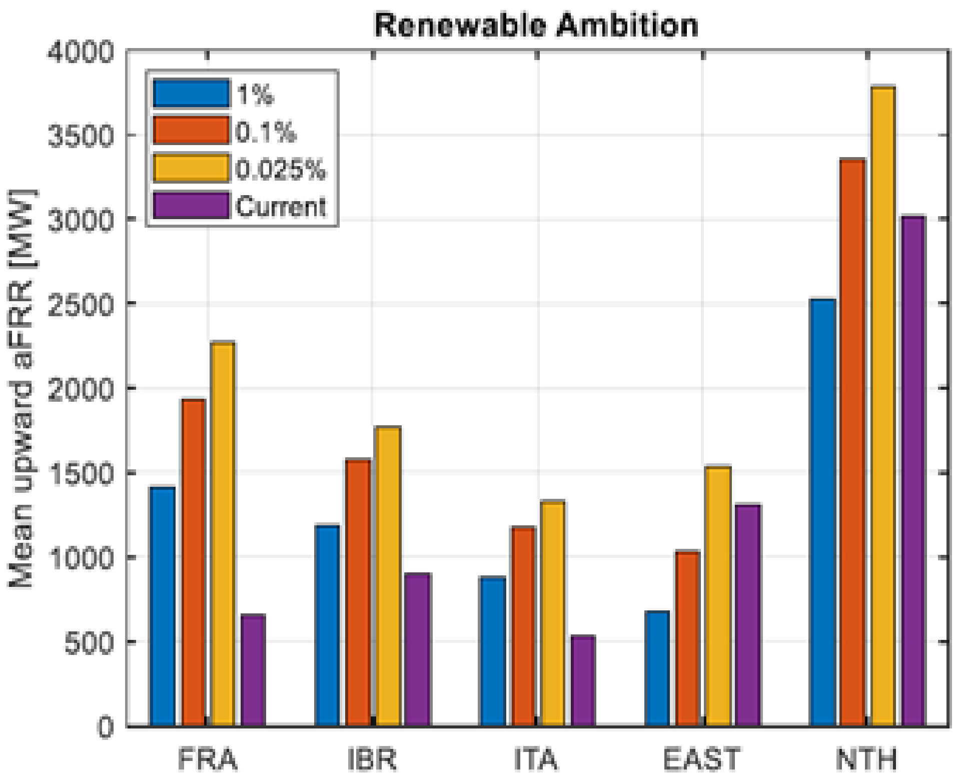
STABILITY CHALLENGE



Source: EdF

Operating reserve - simulations

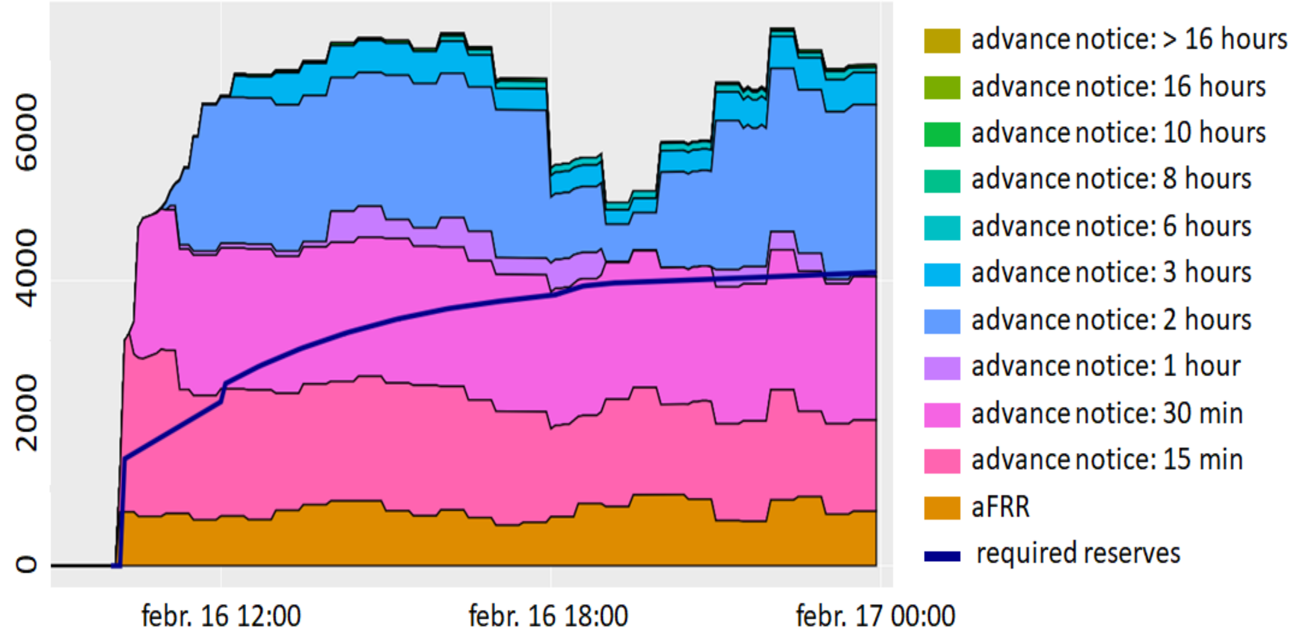
- Adding wind and solar uncertainty will require more short-term reserves
- How much?
  - Reliability level has an impact



Source: EU-SysFlex project

Reserve margins example

- General trend towards dynamic reserve setting – closer to real time, and probabilistic methods
- RTE: required reserve and available margin on a rolling horizon
  - considers minimum advance notice, dynamic constraints of each generation unit



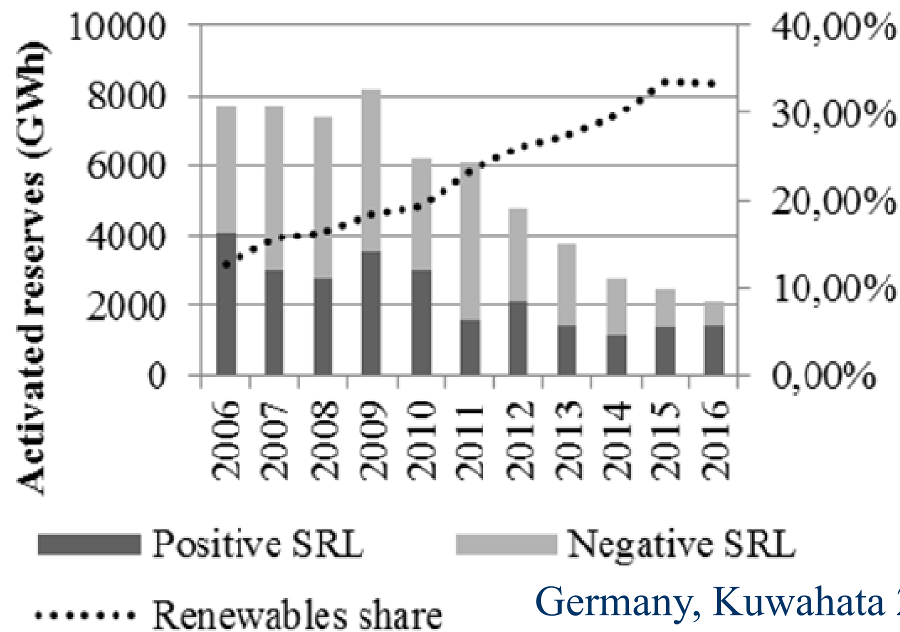
Source: RTE

Operating reserve - experience

Changing operational practices

– sharing reserves with neighbours, faster operation

– reduces need for short-term reserve more than added wind



Germany, Kuwahata 2017

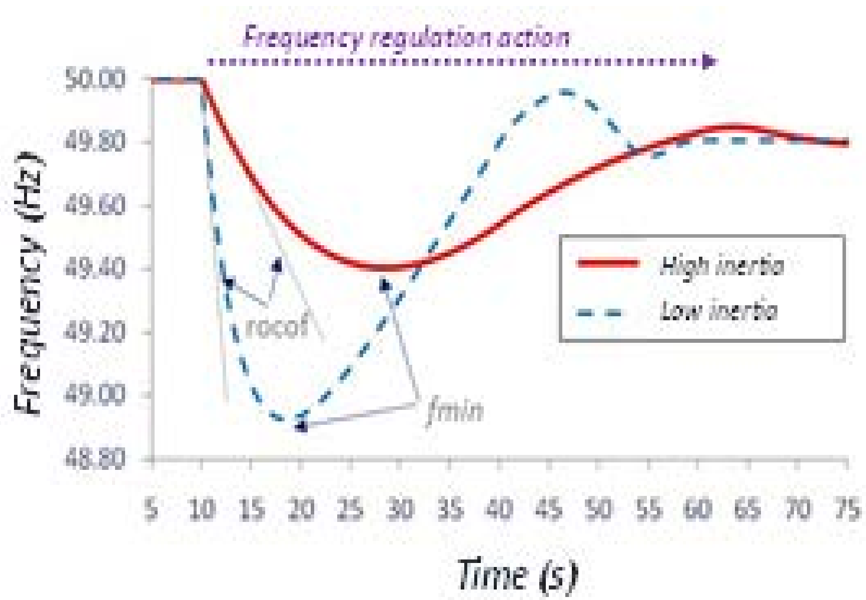
Source: ERCOT

Stability concerns so far

- Responses to fault situations – grid code settings:
  - FRT; South Australia 2016 consecutive storms
  - 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 oscillations modes
  - so far local incidents, in future need to assess

Frequency stability

- challenges depend on system size, share of wind power, and applied control strategies

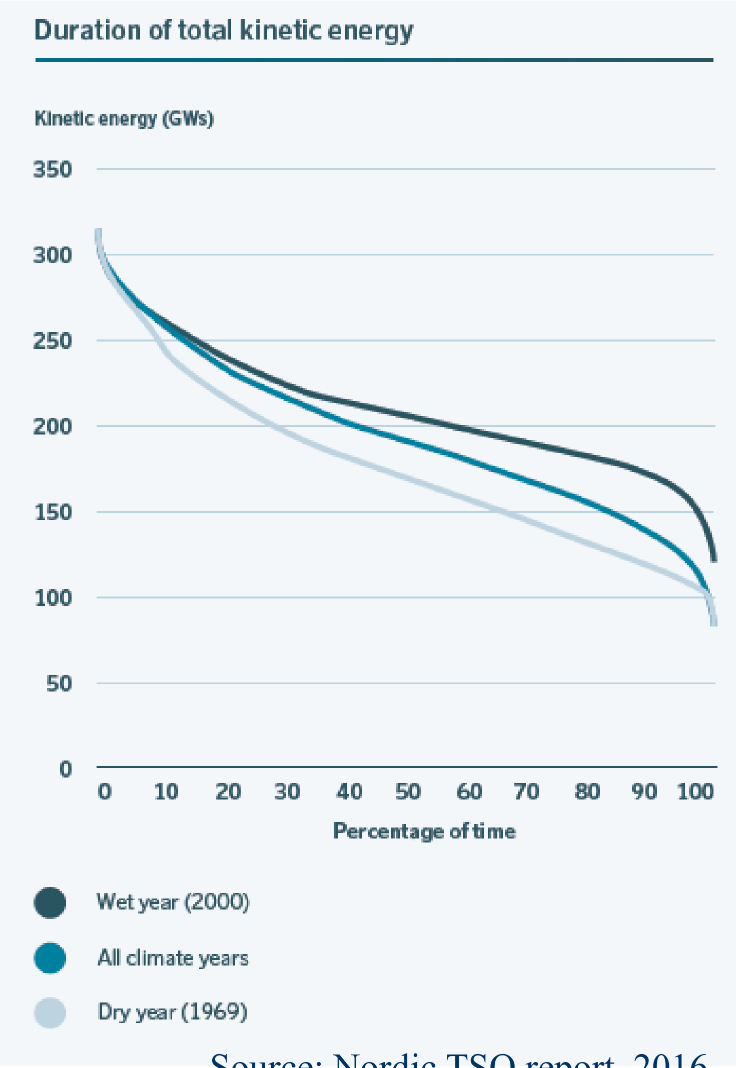


Case 1: rocof= 0.2 Hz/s, nadir= 49.4 Hz

Case 2: rocof= 1 Hz/s, nadir = 48.9Hz

Frequency stability

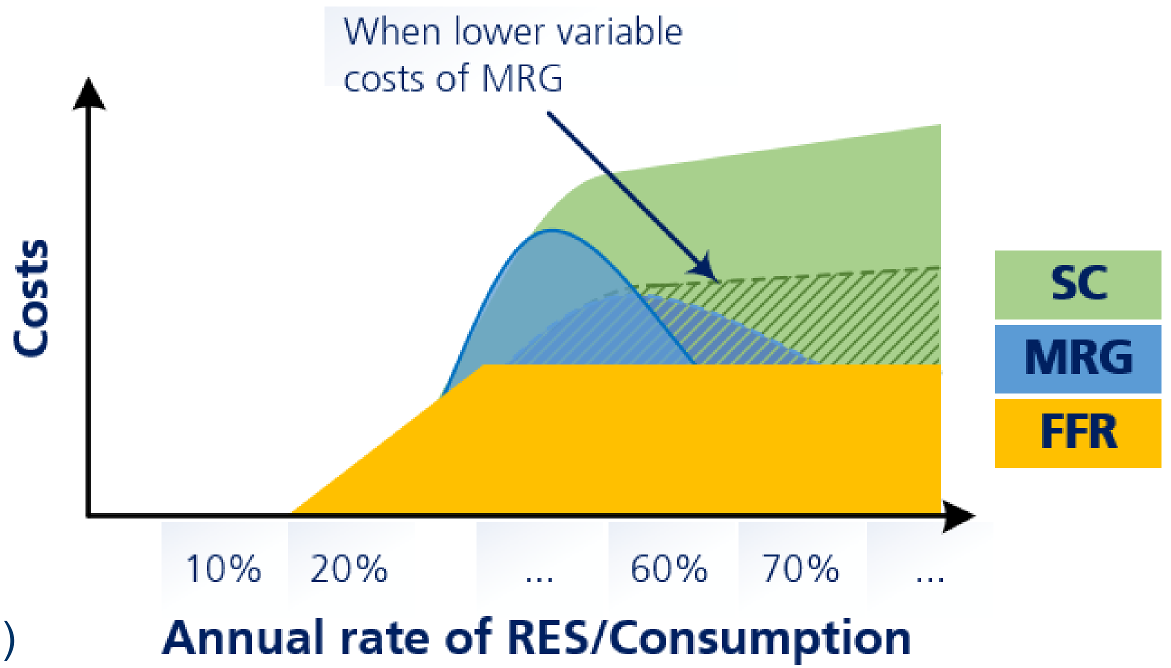
- Small system: Ireland case: limiting wind, SNSP
- Medium size systems: Nordic, Texas, GB new tools to monitor inertia real-time/day-ahead
- US MISO case, not seen as an issue at <60% average share of wind and solar
- European system: system splits could happen (Iberia)
  Mitigation: cross-border flow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



Source: Nordic TSO report, 2016

Supporting frequency stability

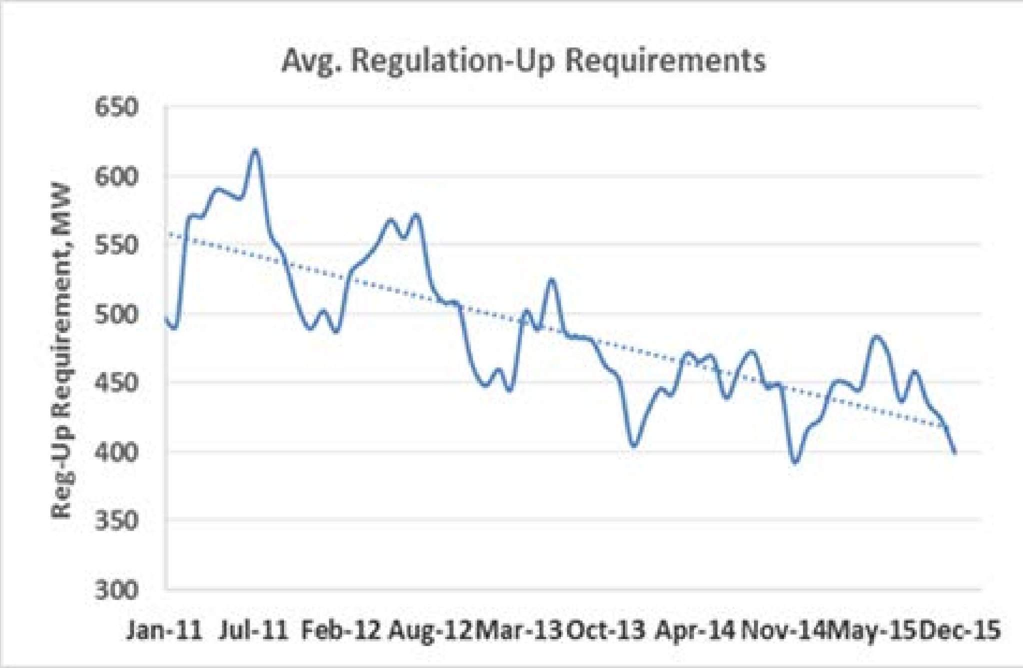
- Maintain online inertia by keeping synchronous machines running (MRG) or other sources of synchronous inertia (SC, synchronous condensers)
- Speed up frequency response, Faster primary frequency response (on sync machines), Fast frequency response (FFR)



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 fast frequency support after wind power plants provide good response (Source: Julia Matevosjana, ERCOT)

Voltage stability

- replacement of rotating, sync generators with IBRs decreases short-circuit currents and widens area of voltage disturbance
- Ireland 2020: voltage control tool to control room, when minimum sync generator constraint will be released.
- 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 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 for 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

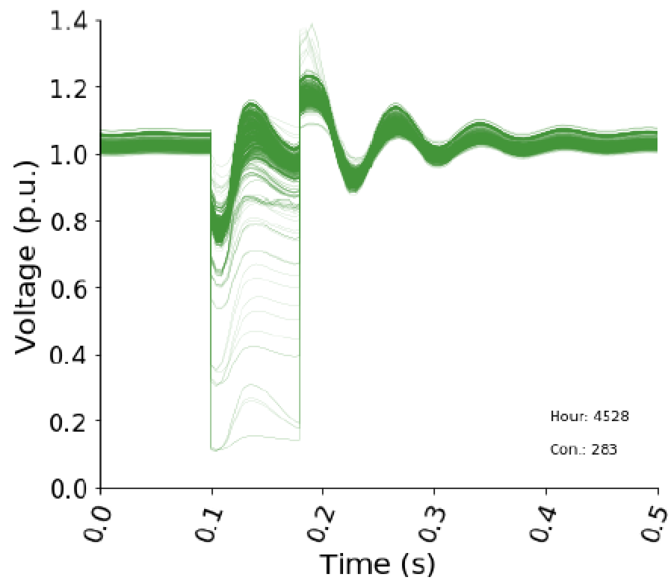


Fig. Transient voltage stability for 70% share of IBR for Ireland

Source: EU-SysFlex project

Maximising value of wind energy

- Minimising curtailment BALANCING CHALLENGE
- Using wind power for system services
  STABILITY CHALLENGE
- Operational practices
  BALANCING CHALLENGE
  - grid
  - market design MARKET CHALLENGE
- Using existing and new flexibilities BALANCING CHALLENGE

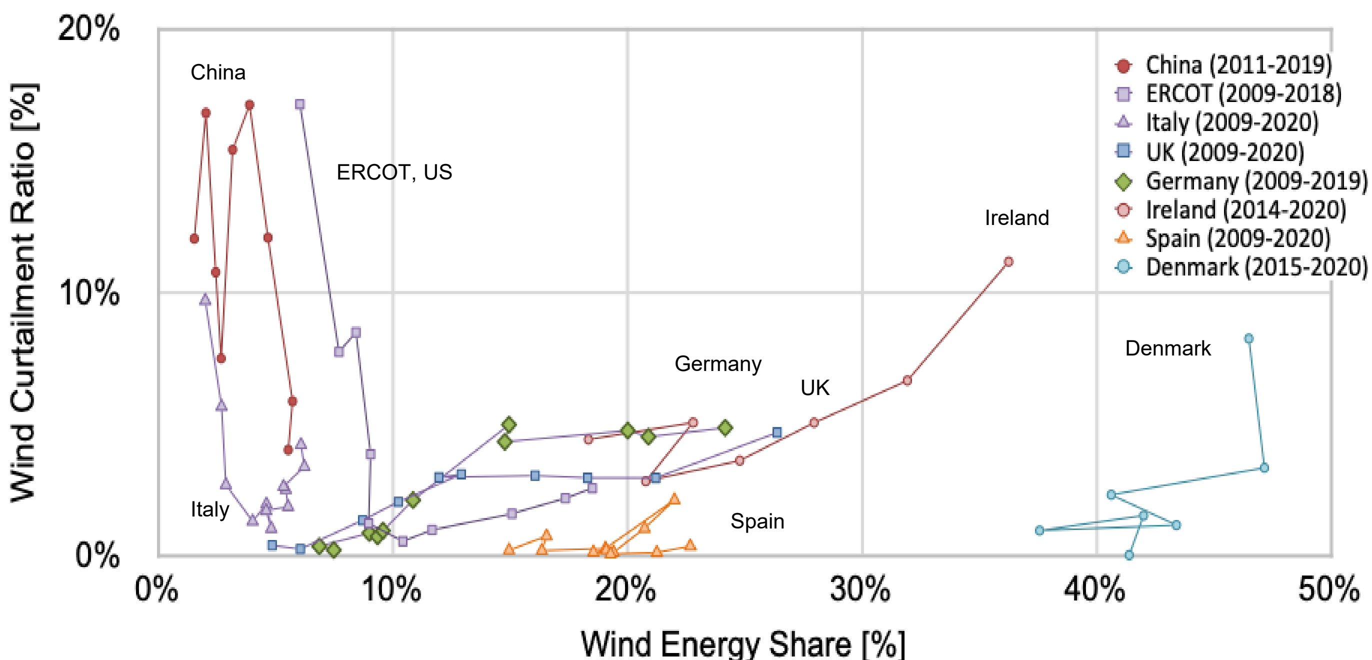
ENERGINET

Estimating the value of wind

- 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 made in a consistent way
  - 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 costs of scenarios
- Value of wind increasingly important to assess
  - Beyond LCOE
  - from transparent and cost reflective markets

Curtailment

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

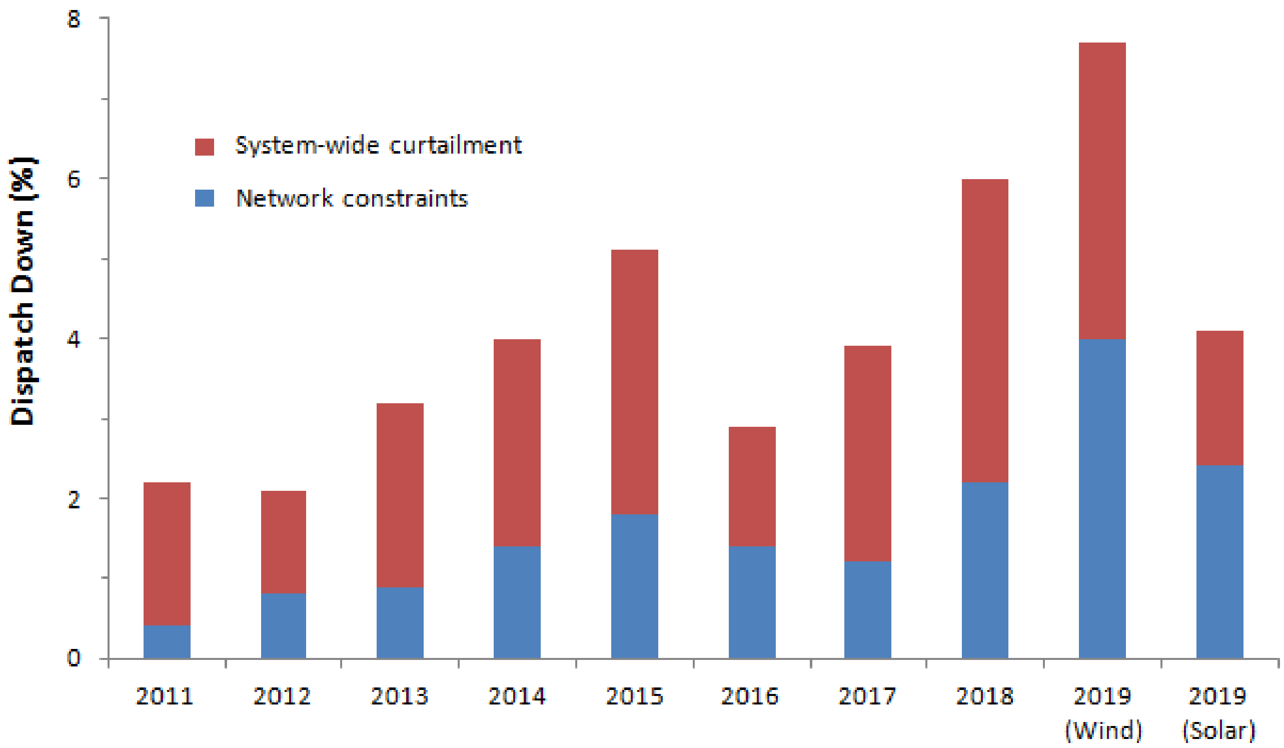


BALANCING CHALLENGE

Ireland - system curtailment

- Network constraints are more local
- System wide: SNSP limit
  - increased to 75% instant share of non-sync generation

STABILITY CHALLENGE

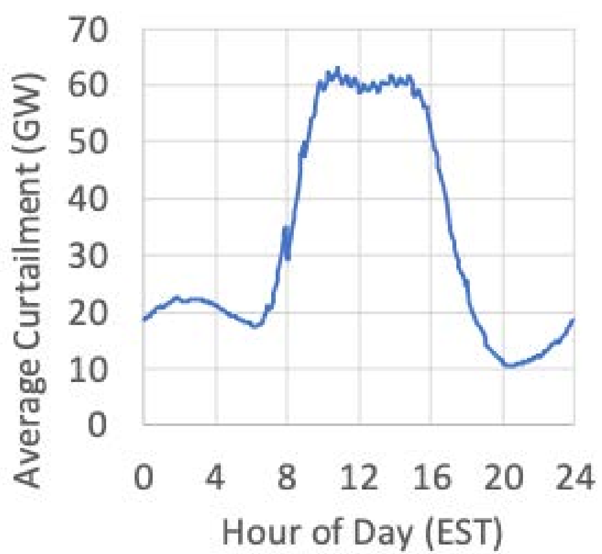


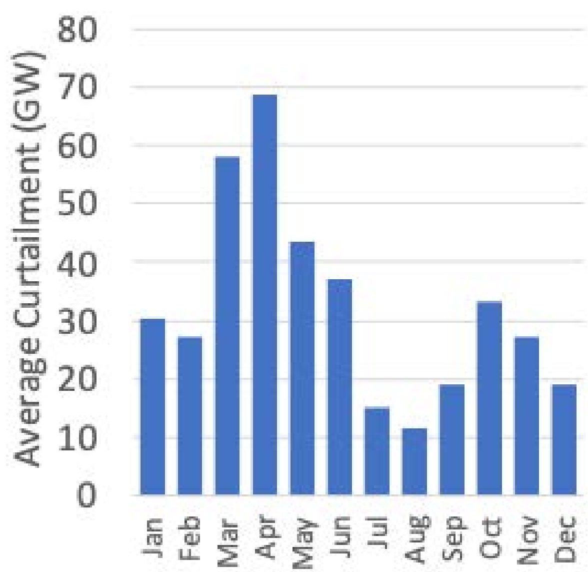
Source: UCD

2020: 5.3% system wide, 6 % network = 11%, record high wind share 36%

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)

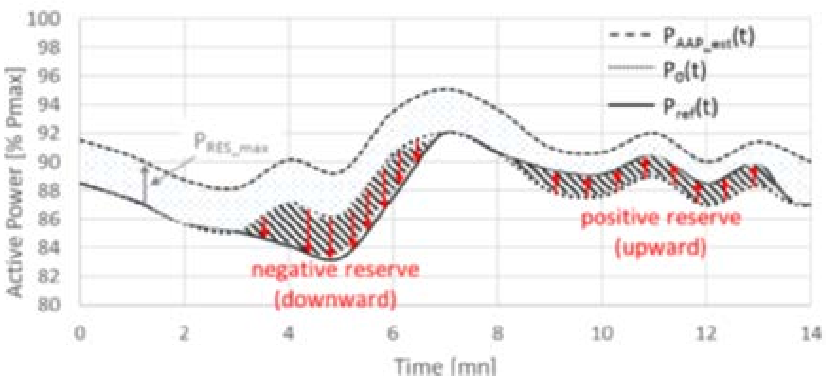




The bulk of the curtailment occurs in a small percentage of the hours, but curtailment occurs somewhere in the United States in almost every hour. Source: NARIS study, Brinkman et al. 2021

Using wind power for AS

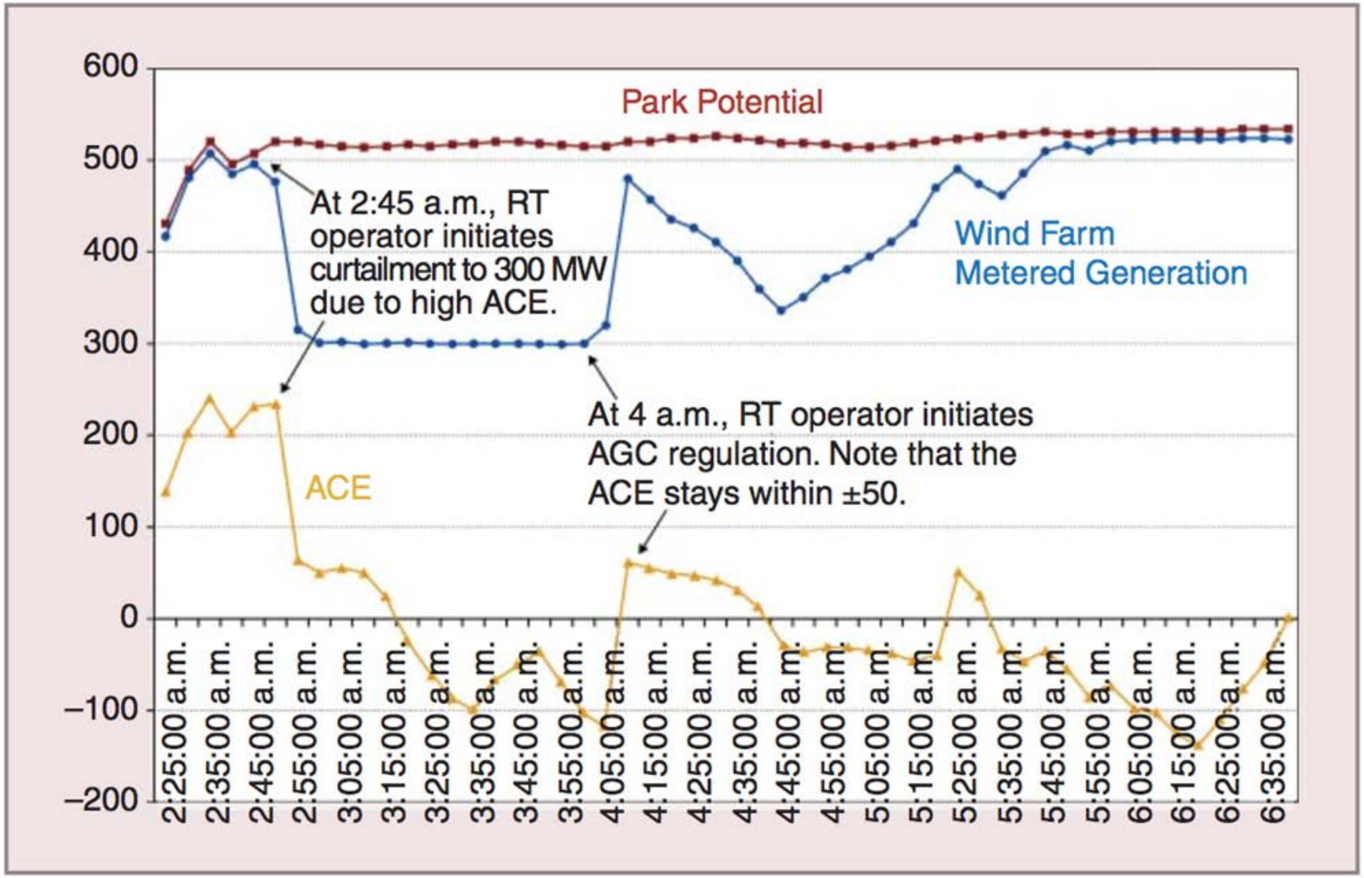
- When wind and PV surplus, important to provide AS, otherwise risk being curtailed to commit a synchronous generator for providing the services
- Frequency control, and balancing markets already have experience from several power systems
  - **Spain:** 17 of 27 GW wind power participate in the ancillary services, increasingly being used:
    - of total downward reserves 14.4% in 2018 and 14.8% in 2019
    - of total upward reserves, 4.8% in 2018 and 7.5% in 2019



Source: EU Sysflex project

Regulation / AGC

- Experience Colorado Xcel
- Curtailed wind & solar can also provide up-regulation

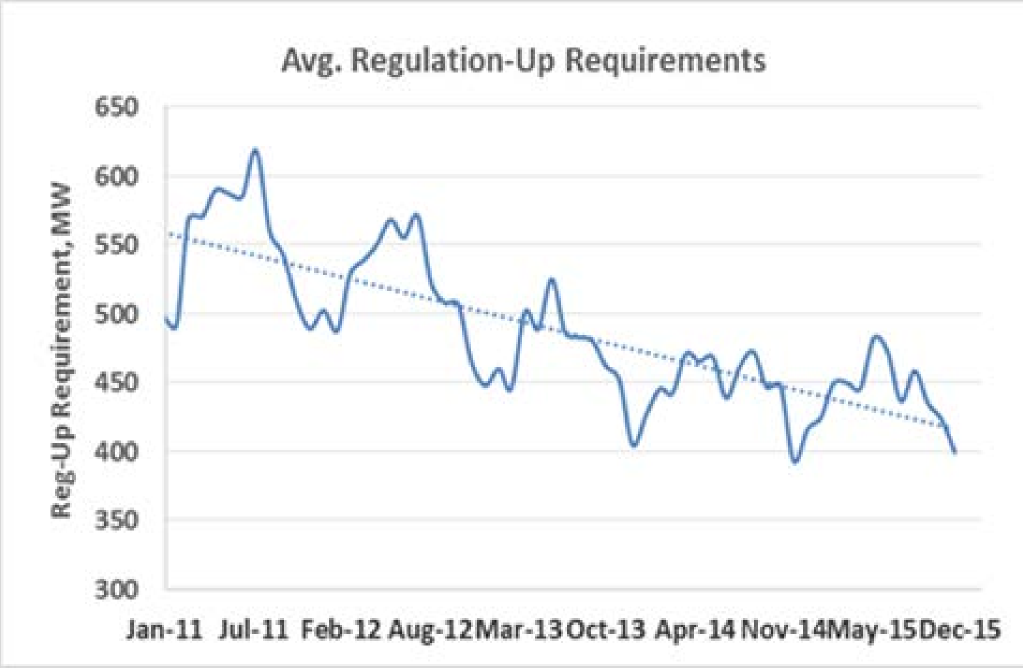


Source: Drake Bartlett, Xcel

Primary / Fast frequency response

- ERCOT, Texas: FFR (0.5s) 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

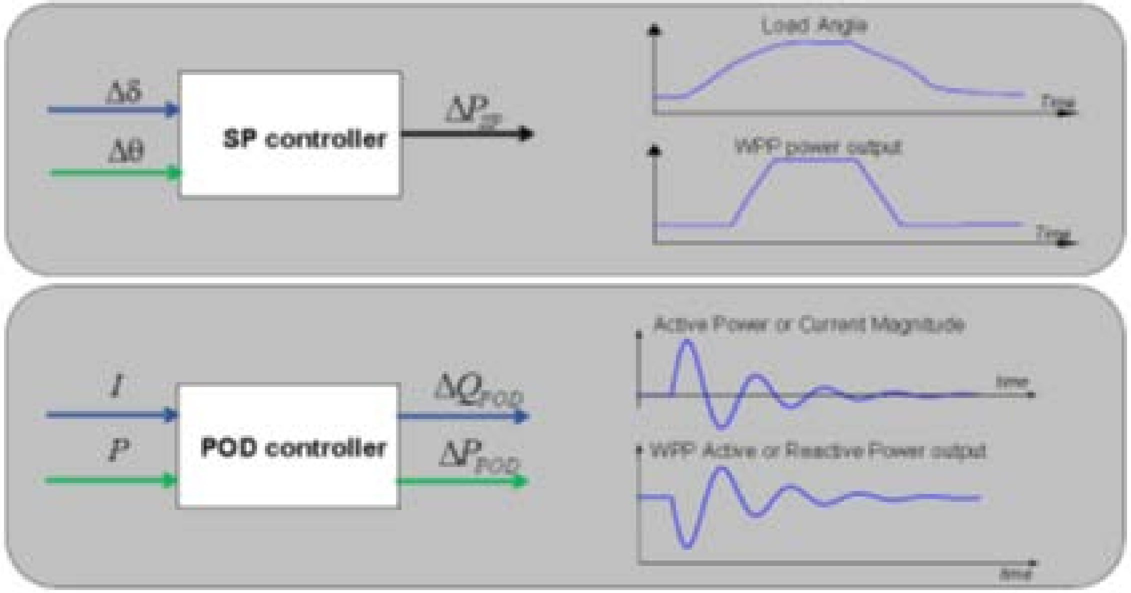
Faster response is more valuable



Texas experience, less need for fast frequency support after wind power plants provide good response (Source: Julia Matevosjana, ERCOT)

New services + paying for them

- New: Power oscillation damping POD, Synchronising power SP, Restoration, Grid-forming inverters
- Start paying for Inertia, Ramping, Voltage
- introducing services when system benefits and need

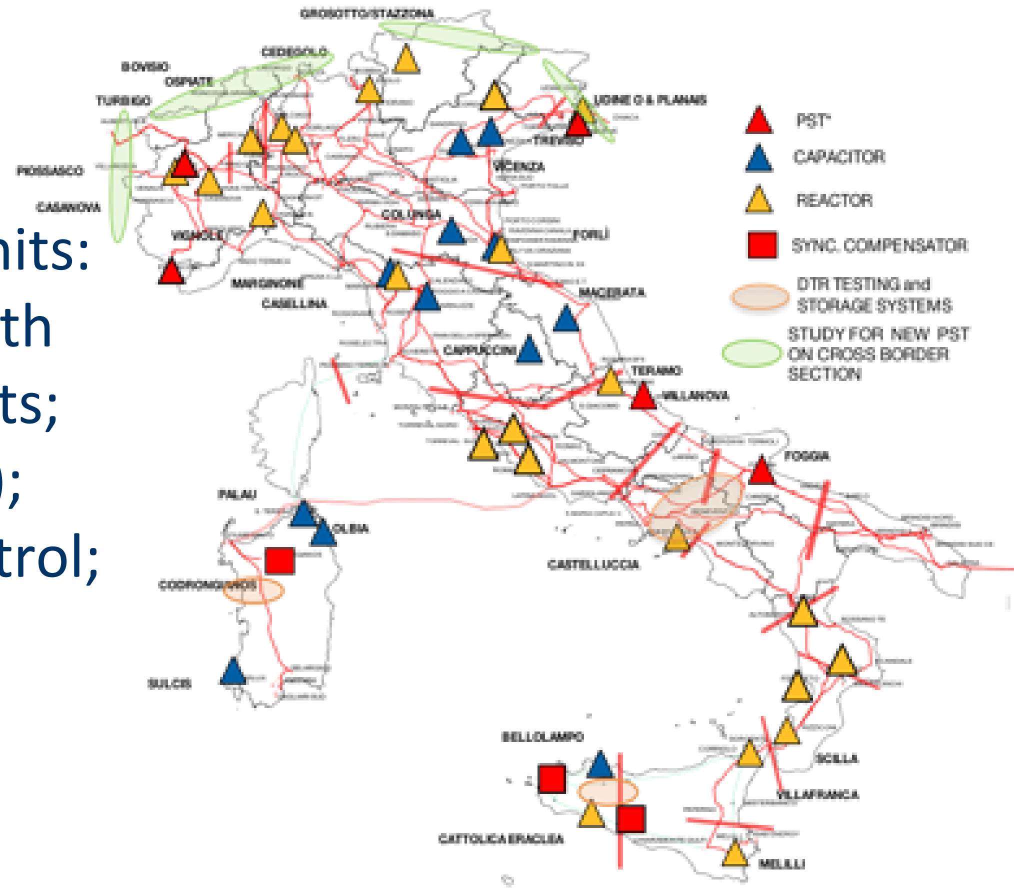


Source: DTU

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

Operational practices – grid

- Congestion management
  - to 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



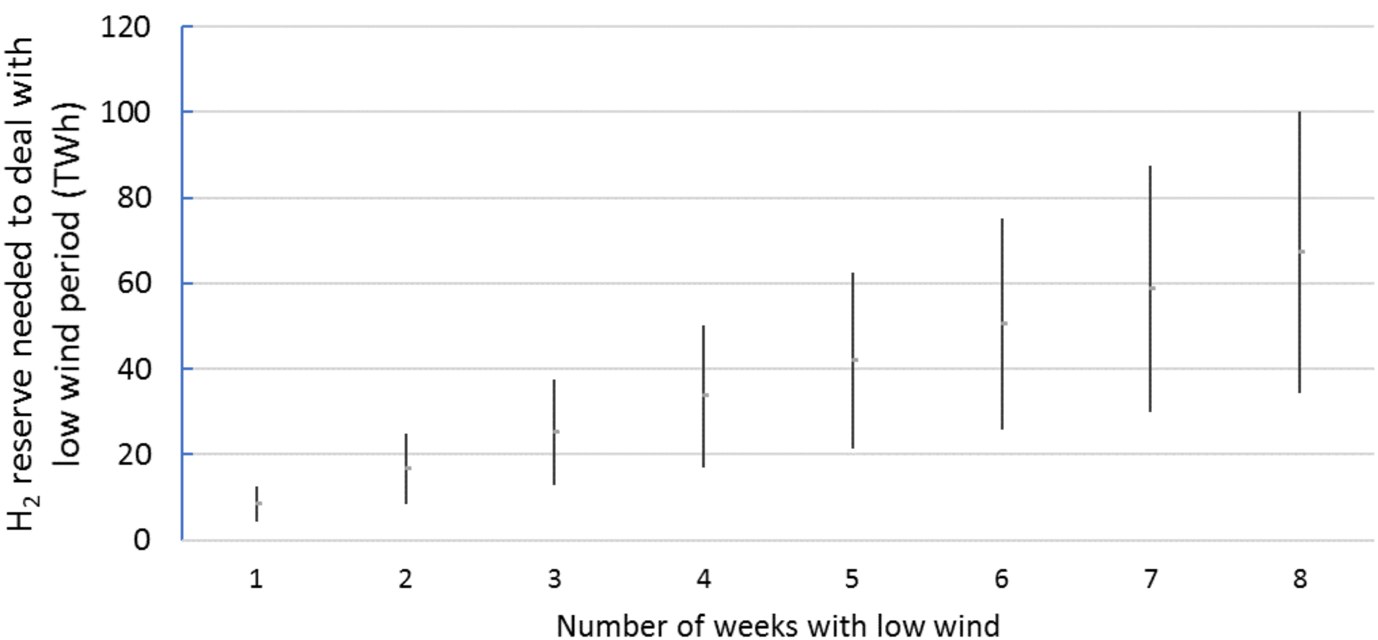
Example of grid investments to active and reactive power management in Italy (DTR = dynamic transmission rating). (Terna)

Flexibility sources

- Hydro power
  - pumped hydro useful for longer than few hours, hydro storage costs driven by the kW costs (cables + reversible pumps), reduces the need for CCGT (Askeland et al., 2016).
- Thermal power
  - retrofits to lower minimum on-line power helps reduce curtailment
  - Combined heat and power (CHP) and heat pumps, with heat storage
- Storage
  - Batteries provide short-term balancing over one to some hours, reduce the need for peaker power plants
- Increasing transmission has good cost benefit
- Demand response
  - short-term flexibility for existing loads and longer-term flexibility for Power2X loads

Long term flexibility crucial for decarbonised energy systems

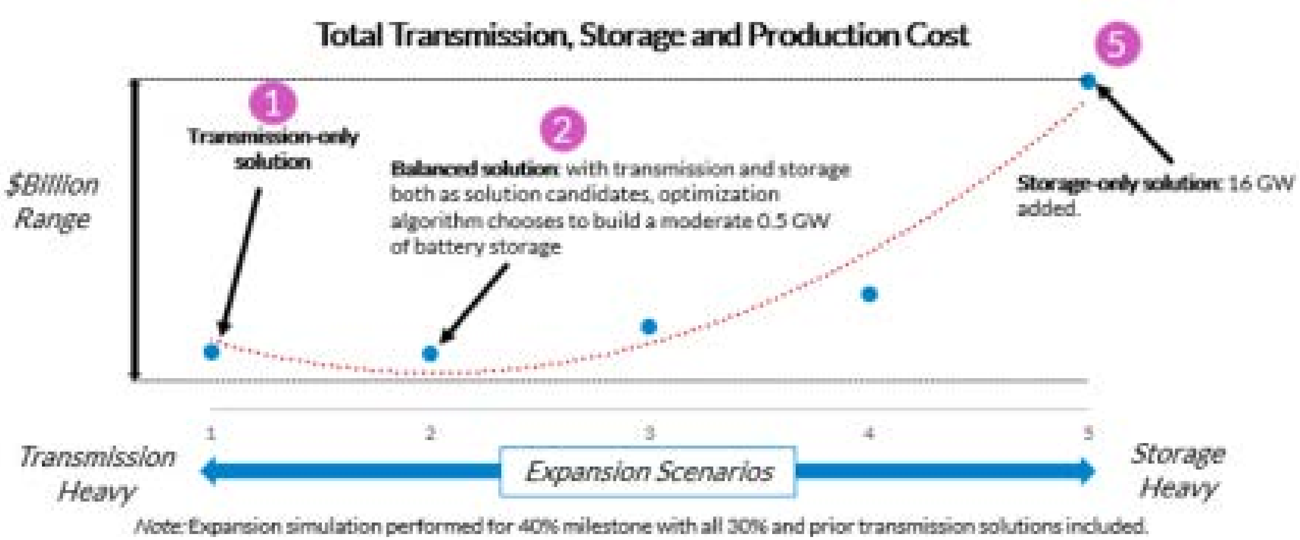
- Hydropower with reservoirs or pumped hydro are used as longer-term storage.
- Hydrogen storage could also be an alternative
  - Amount of hydrogen that needs to be stored, as a function of number of weeks, with low wind output for the Great Britain system (range, min–max, of wind energy that needs to be compensated)



GB zero emissions study, 241 TWh wind. Illustration of storage for longer low wind cases (time series analysis) Source: Imperial College

Comparing cost benefit of flexibility options

- Curtailment - indication of inflexibility, estimating future curtailment in integration studies – and adequacy of flexibility
- Flexibility options for different time scales, and may compete - cannibalising each others' benefits



Compare transmission-only, storage-only, and combined transmission / storage solutions for 40% wind and solar in Eastern Interconnect of the US (MISO RIIA)

Market challenges

Source: Strbac et al, IEEE PES, TradeRes US priorities include very similar issues

- merit order effect and missing money problem;

Resource adequacy and system resilience
Energy price formation

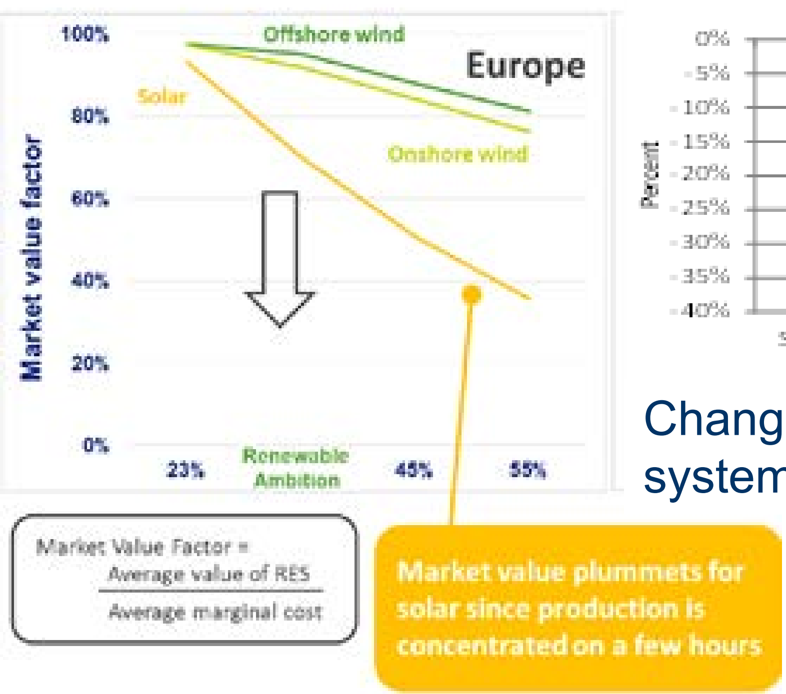
- integration of new smaller and variable assets to energy and ancillary services markets;
- design of an effective carbon emissions market;
- capturing of full value of (distributed) flexibility resources;

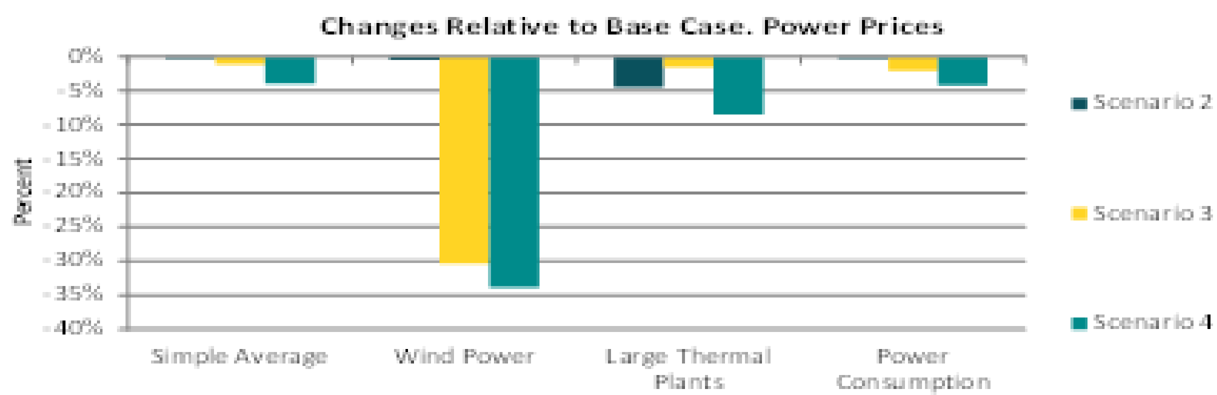
Incentivising reliability services and operational flexibility

- geographic integration of different market segments, including harmonisation of pan-European markets and co-ordination of emerging local energy markets

Flexibility will increase value of wind energy in markets

"Profile losses" of wind and solar are lower when other generation and loads operate more flexibly, according to wind and solar availability





Changes in market prices in case of non-flexible system in Denmark (Source: Energinet)

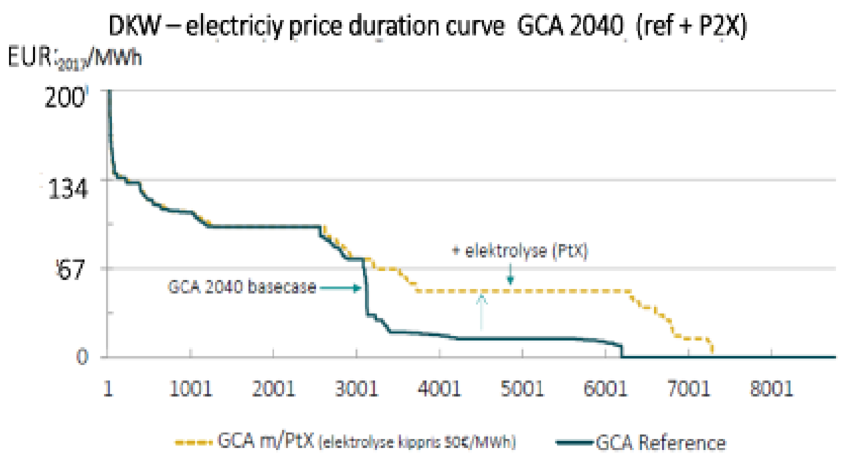
Source: EU-SYSFLEX D2.5

Flexibility will increase value of wind energy in markets

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

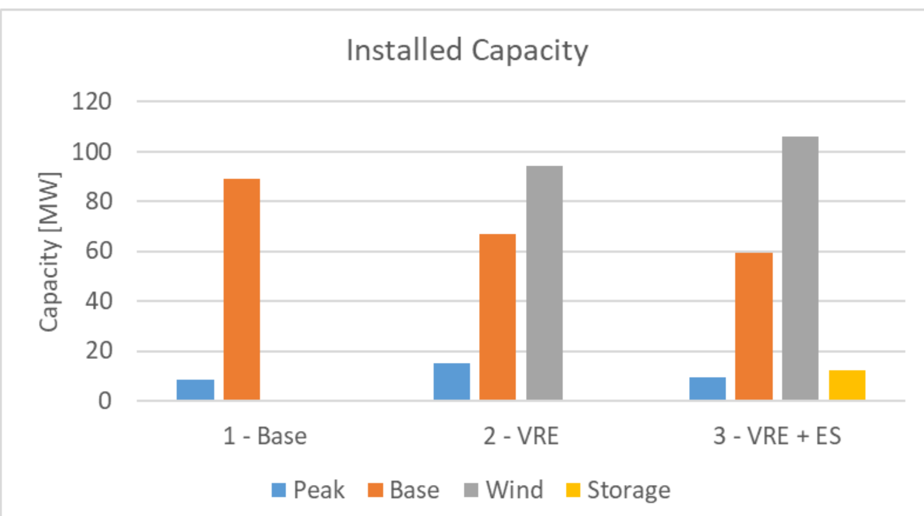
The average annual settlement price for wind and PV in DKW increases from ~20 €/ MWh to 40 €/ MWh in the P2X scenario

Source Energinet

Flexibility will increase value of wind energy in markets

Storage and flexible demand creates new price segments which increases profitablity of wind energy

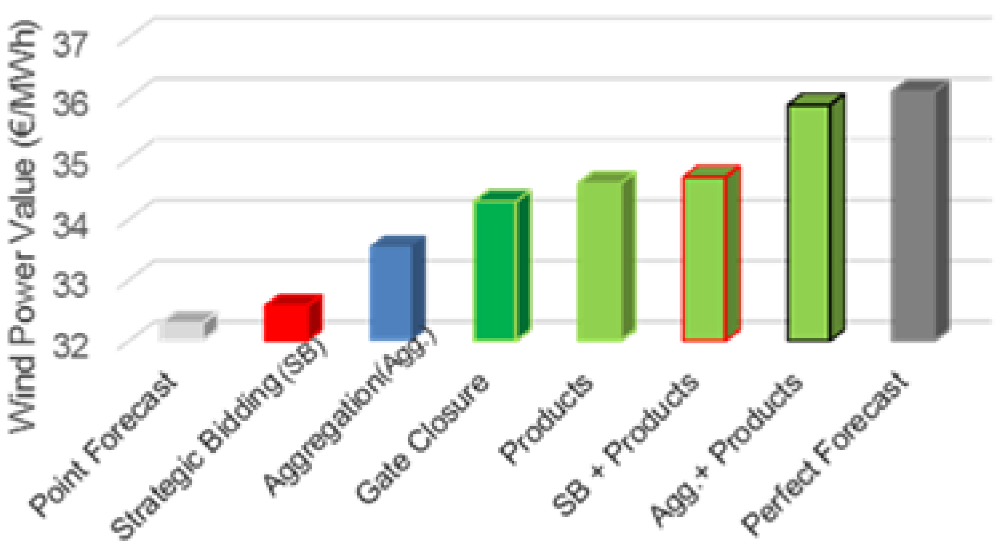
→ Lead to more installed wind power in competitive markets



Source Korpås, Botterud, 2020

Market design to enable grid support services income to wind

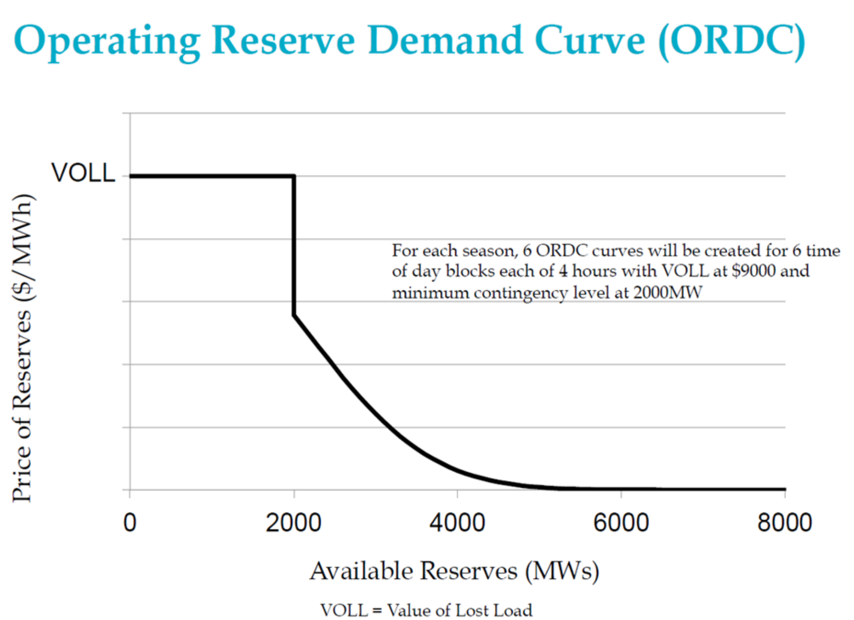
- Possibility to bid close to delivery (for example, hour ahead); smaller amounts of MW; only down-reg
- Local flexibility markets – DSO/TSO coordination

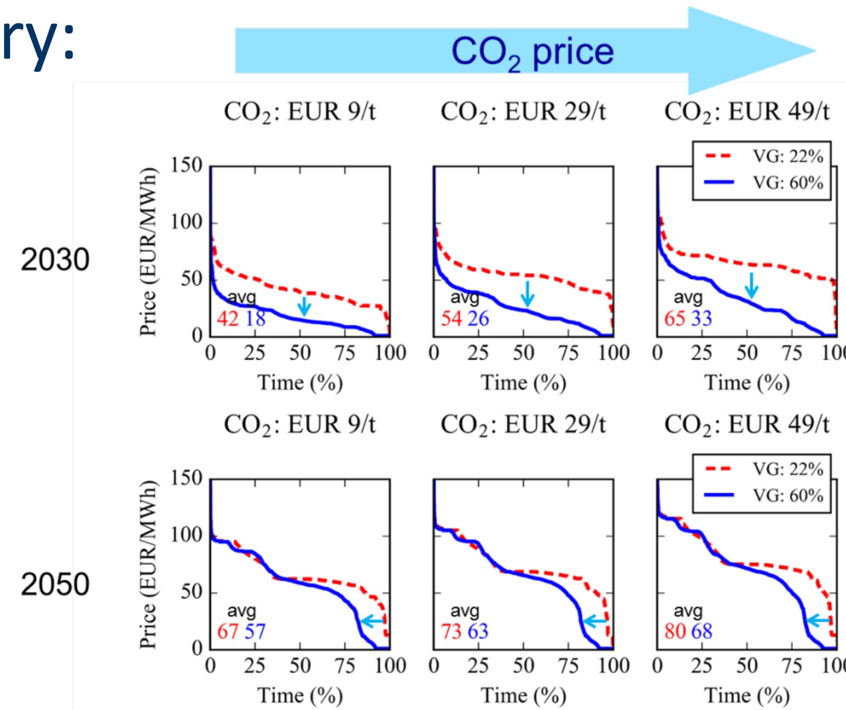


Increasing wind energy value to the market using different approaches: strategic bidding based on probabilistic forecast (SB), aggregation (Agg.), shorter gate closure and balancing products (Source: Algarvio & Knorr, 2017).

Revenue sufficiency

- Ideal energy-only markets can recover costs
  - Also valid for systems with thermal generation, energy storage and VRE (Source: Korpås, Botterud 2020)
- Ways to improve cost recovery:
  - CO_2 pricing





Source: VTT

Summary of maximising value of wind

- Larger market area – keeping prices up
  - less correlated wind power production
- Faster markets – balancing costs down
  - Improved load/net load following dispatch
- Flexibility to avoid low price energy
  - New loads to take cheap electricity -> new price segments
- Grid support from wind and solar
  - Becomes cost effective at larger (>20%) shares of wind /PV
  - At surplus energy /very low prices, wind/PV can operate part load and offer fast response up/down, and other services
  - System needs – what exactly is needed in different operational situations, and how much?

Pushing the limits – towards 100% VIBRES operation

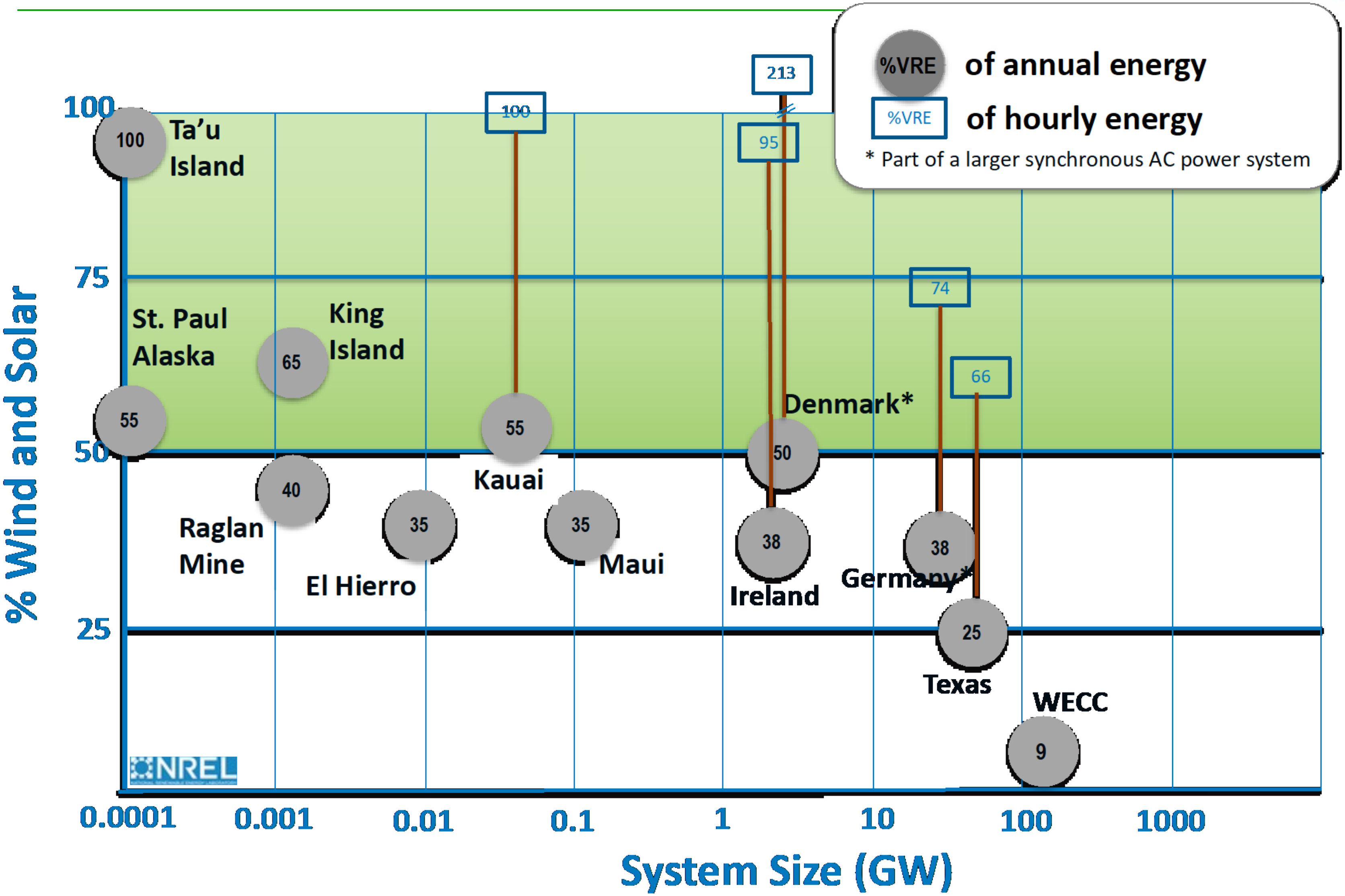
- Studies for 100% renewable power system, hourly energy balances
- Studies for net zero carbon energy systems
- Stability of 100% VIBRES power system

no stability considerations

…with new tools and methods developing

ENERGINET

Experience is growing

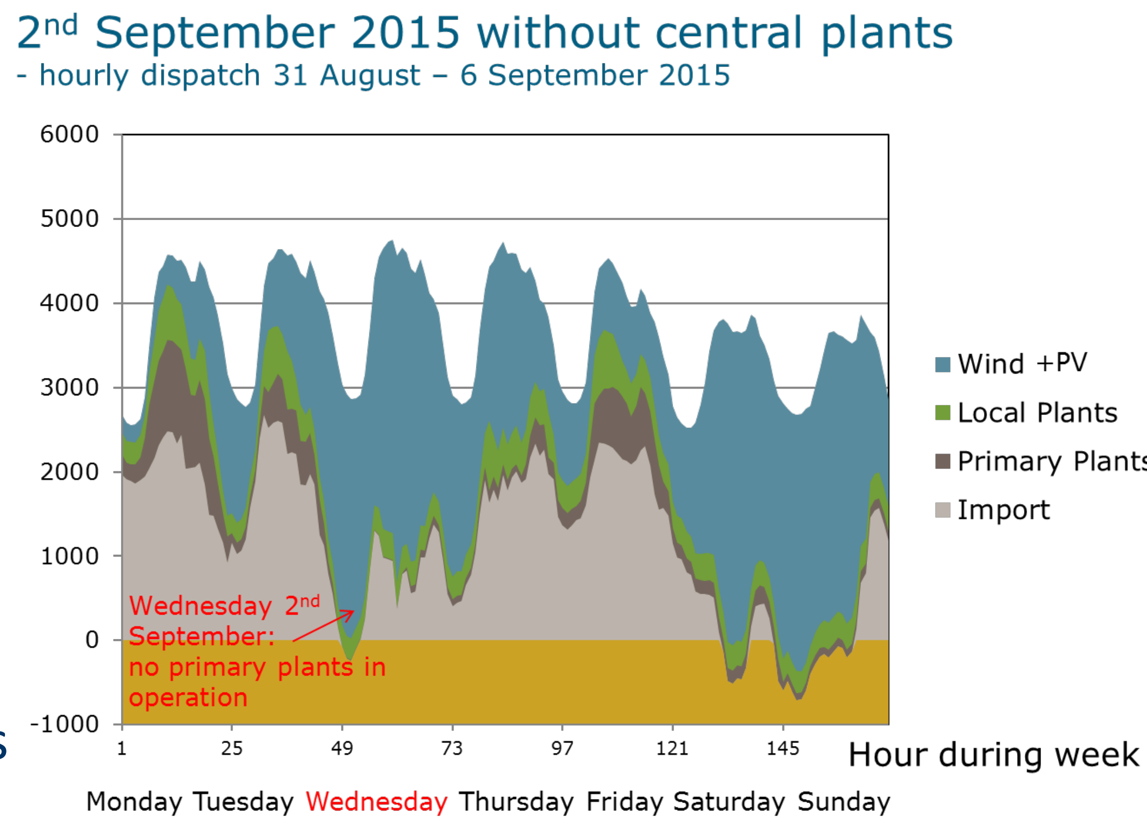


Transition to a (nearly) 100% annual VIBRES system gradually during the next decades

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:

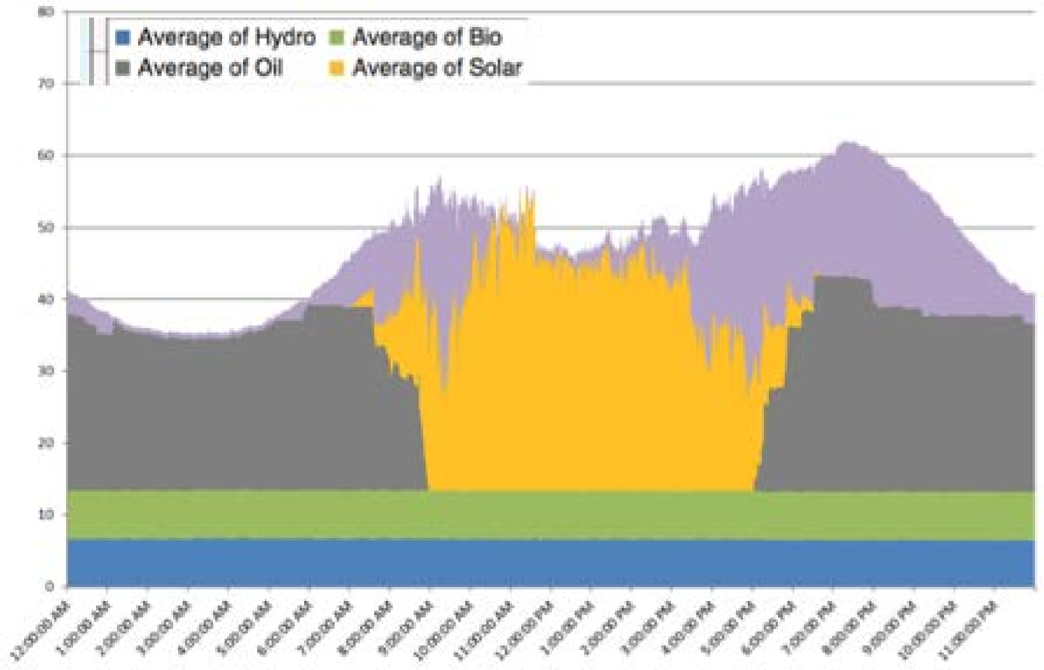
- HVDC link: 700 MW Denmark-Norway
- synchronous compensators 4 in DK-W and 2 in DK-E
- and small-scale power plants



ENERGINET

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
  - (cloud events of order of seconds) hold 50% of real-time output as spinning contingency reserve



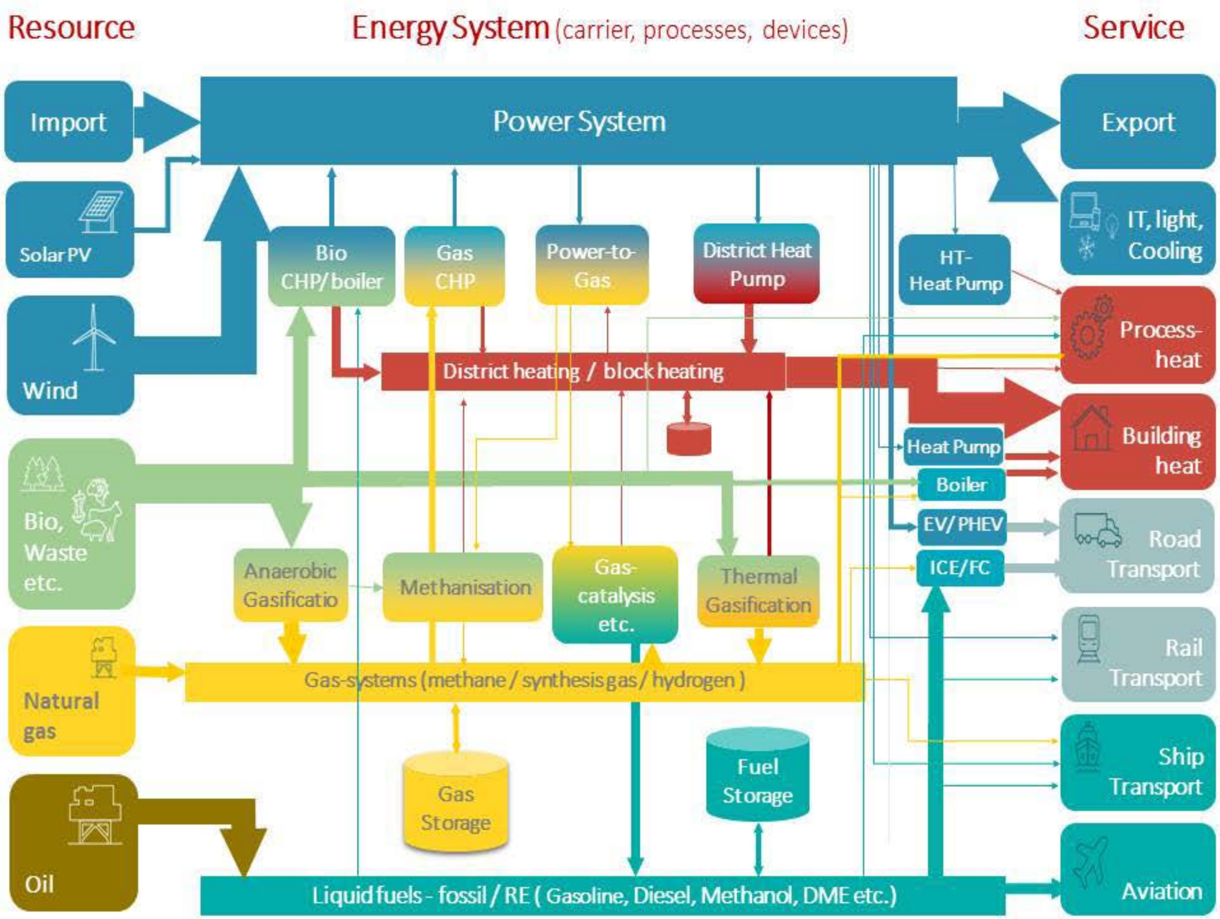
KIUC system dispatch on 3/14/20 with 8 hours of 100% renewables operations. Purple shows PV/battery hybrid output. (Source: Brad Rockwell, KIUC).

Pushing the limits: 100% renewable power systems

- Looking at hourly energy balances. Some include the increased electricity demand due to electrification
  - EU Fit for 55: Electricity will cover 57% of final energy uses directly, plus 18% indirectly through H_2 and its derivatives, electricity demand growing from 3,000 TWh to 6,800 TWh. Wind 50% of the EU's electricity mix (renewables 81%)
- Transmission build out one common result
  - US 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 lead 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

Pushing the limits: challenges

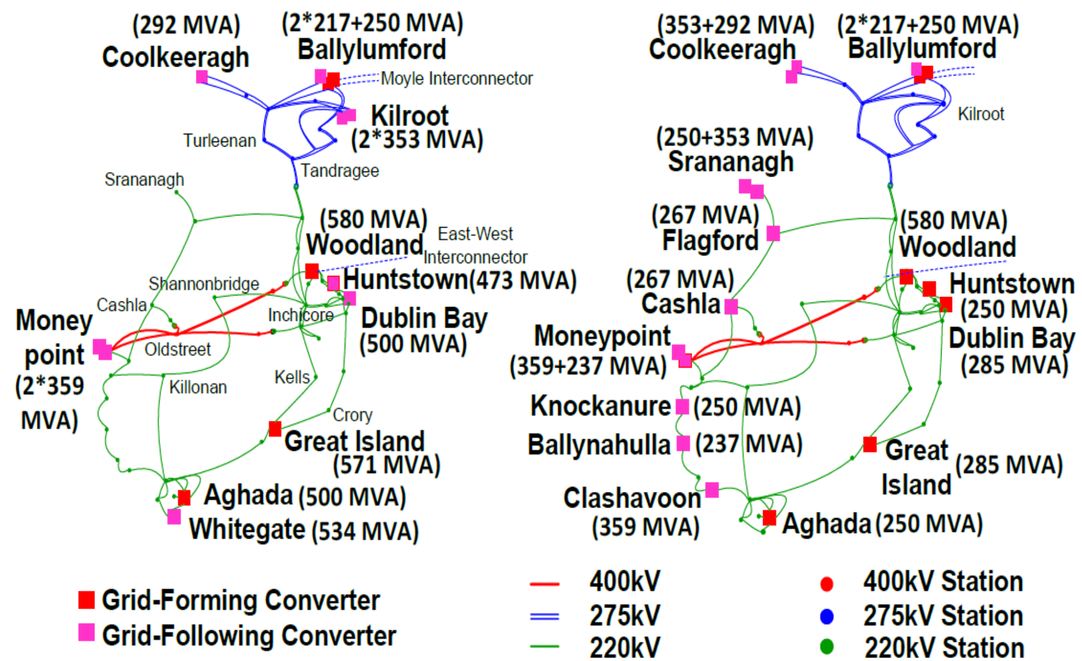
- Planning for resource adequacy
  - cost effective demand response, storage, peakers
- Operation / stability
  - vast difference between 75% IBR share, supported by synchronous generators and synchronous compensators, and a 100% all-IBR system: a fundamental rethinking of power systems
  - definition of needed system services will change; the provision of those services must come from a broad spectrum of resources
- Substantial grid development efforts

Pushing the limits: Tools

- Modelling complexity – VIBRES and higher resolution
- Larger areas – entire synchronous systems
- Integrated planning, operational, stability tools
- Cost versus risk – price responsive demand
- Paradigm change to non-synchronous systems pose limits to applicability of existing tools and methods
  - new tools and methods to ensure the reliability, security, and stability of the power system
  - capture interactions and impact of IBR control algorithms which can be detrimental or beneficial to power system stability and performance

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

Summary

- 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 asynchronous power system operation and long-term resource adequacy developing, 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

Task 25 future work – planned journal article topics

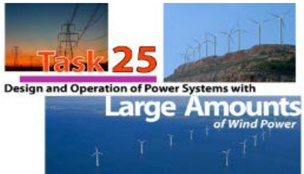
- Planning:
  - Energy system coupling versus transmission
  - Dynamic Line Rating impacts on transmission planning
- Balancing:
  - Electrification; Sector coupling; Curtailment
  - What do we need (balancing) models to do?
- Stability: Wind power plant capabilities
- Markets: Market design; Cost recovery

In addition: Grand challenges Grid (NAWEA webinar 13 Oct)

Based on IEA WIND Task 25 collaborative publications

- Summary report **”Design and operation of energy system with large amounts of variable generation”** to be published September 2021
- ”**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



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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