Wind power impacts on power systems

PHYS-E6572 Advanced Wind Power Technology

Hannele Holttinen

30.11.2022

Contents

- Wind power impacts on power systems – the issues
- Balancing power systems
- Grid and generation capacity adequacy
- Stability

- Electricity market operation
- Wind power operator in electricity markets
- Wind power impacts on market prices

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Wind power impacts on power systems – the issues

- Balancing power systems
- Capturing the impacts of wind on power systems

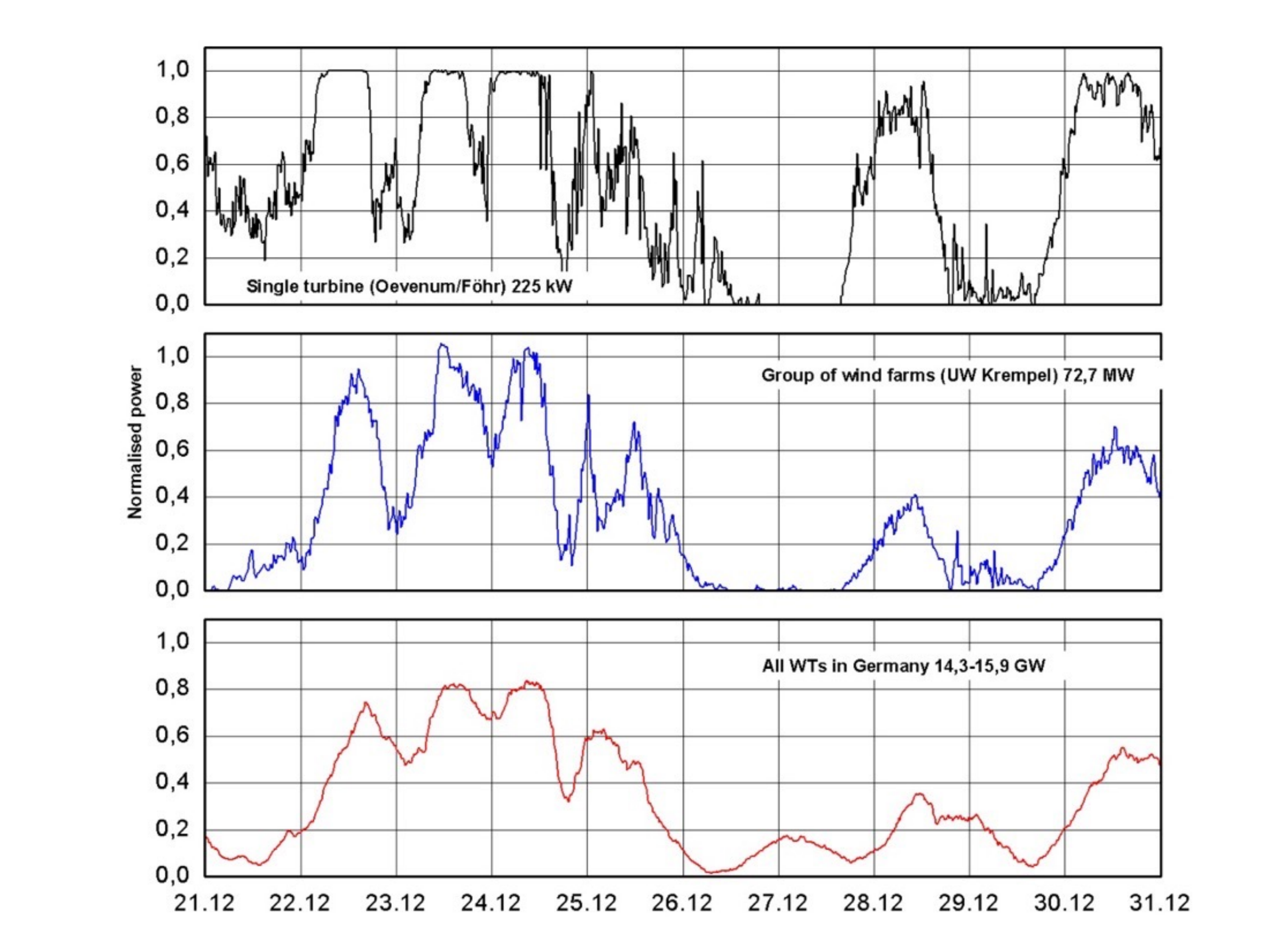
- Electricity market operation
- Wind power operator in electricity markets
- Wind power impacts on market prices

All generation power plants need to be connected to the grid and managed as part of power system operation

VRE integration issues:

- **How is wind /solar different from other generation?** Special concerns:

1. Variability: second/minute/hour variations will smooth out in power system area to a large extent. Daily variability is still large (low/high wind days)

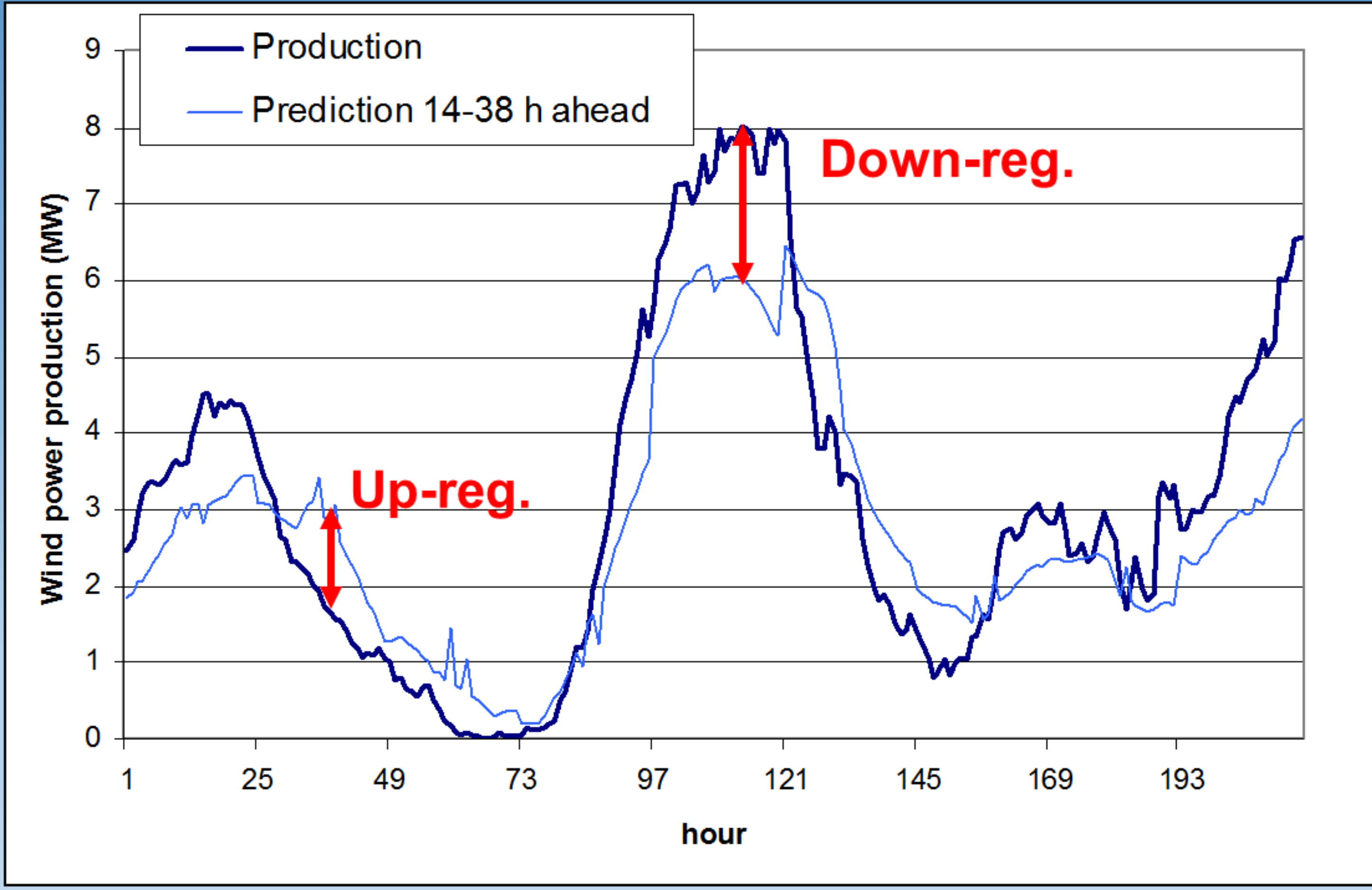


Source: Fraunhofer IWES

Wind/solar integration issues

- **How is wind /solar different from other generation?** Special concerns:

1. Variability
2. Uncertainty: undispatchable, prediction errors. Better accuracy for 1-3 hours ahead than day-ahead. Aggregation benefits from large areas.

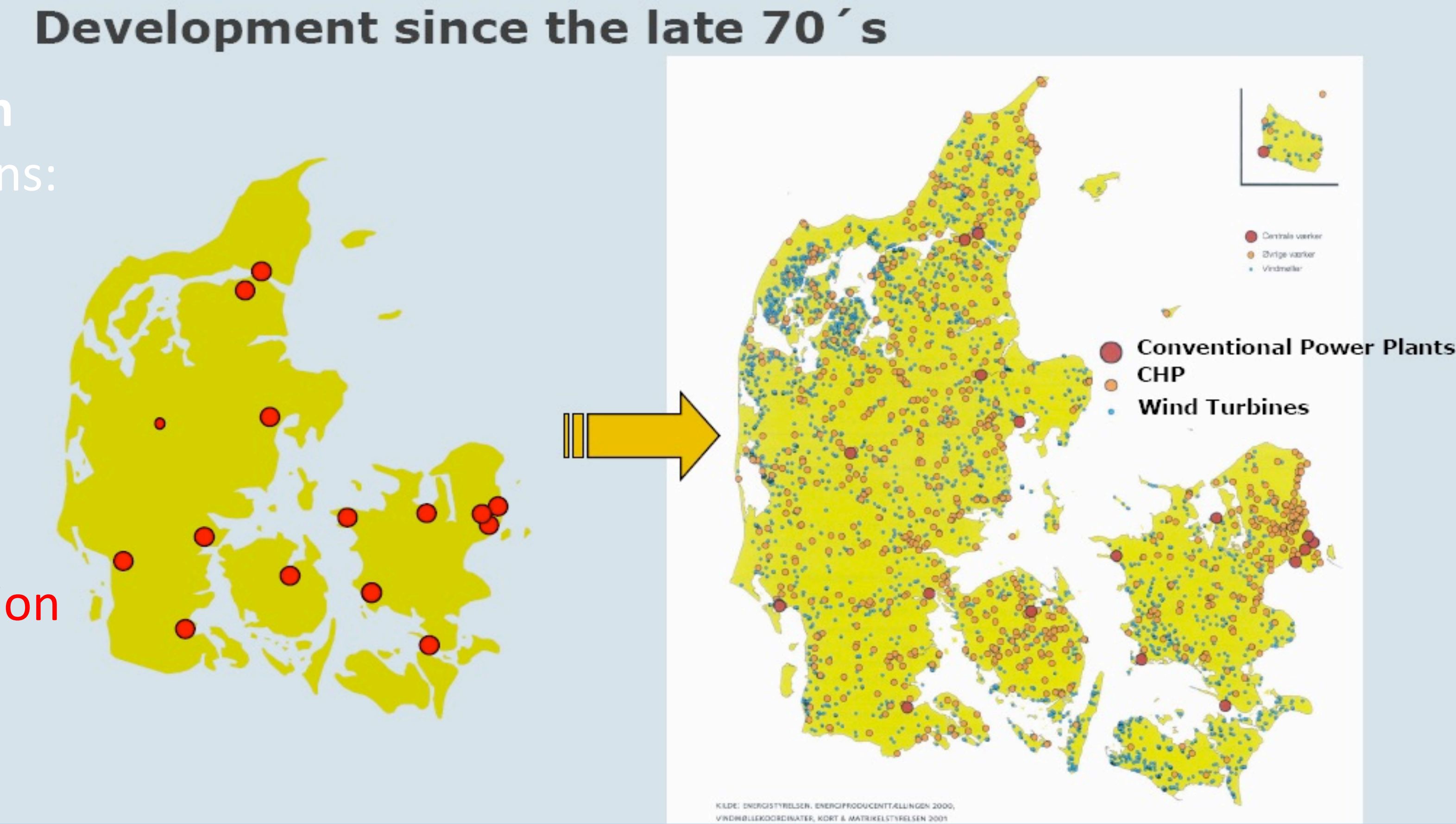


Example for a wind power operator at markets recognis

Wind/solar integration issues

- **How is wind /solar different from other generation?** Special concerns:

1. Variability
2. Uncertainty
3. Location/ Distributed: often connected in medium voltage levels, not in transmission network (large WPPs transmission connected)

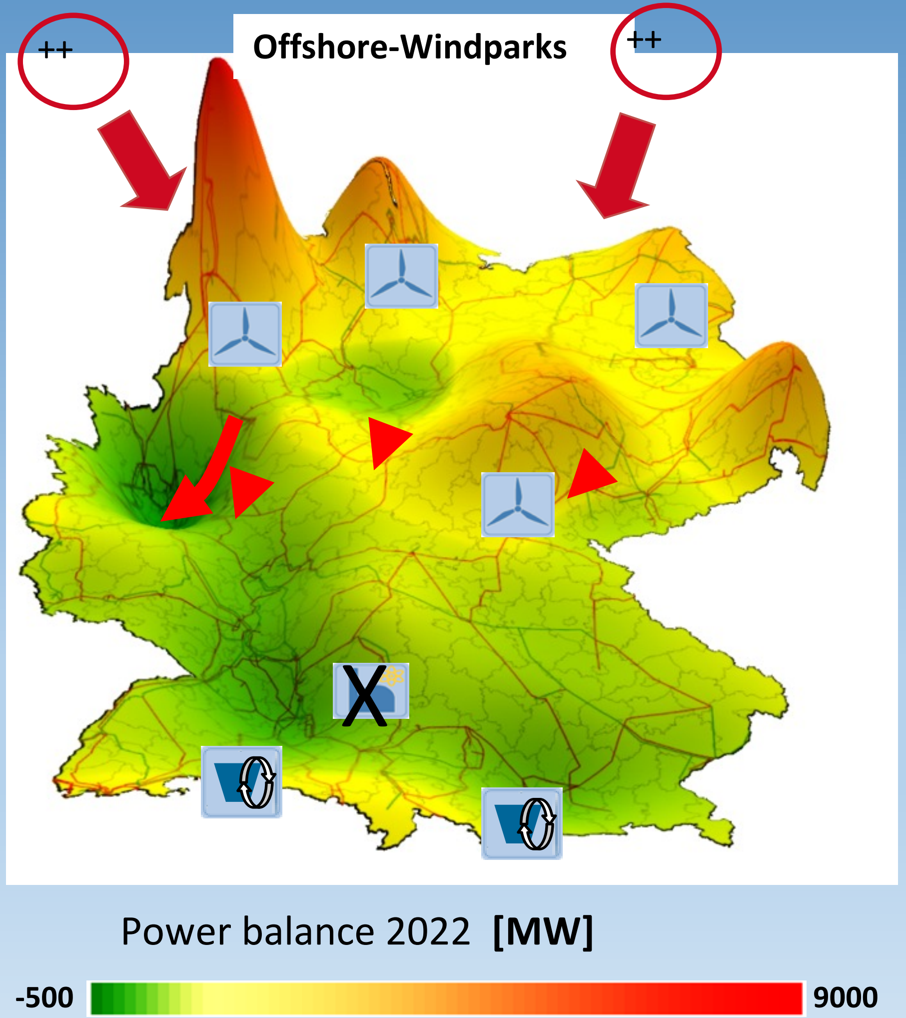


ENERGINET

Wind/solar integration issues

- **How is wind /solar different from other generation?** Special concerns:

1. Variability
2. Uncertainty
3. Location/Distibuted
4. Location: in some countries far from load centres. Grid extension and reinforcement needs depend also on how robust is existing grid infrastructure

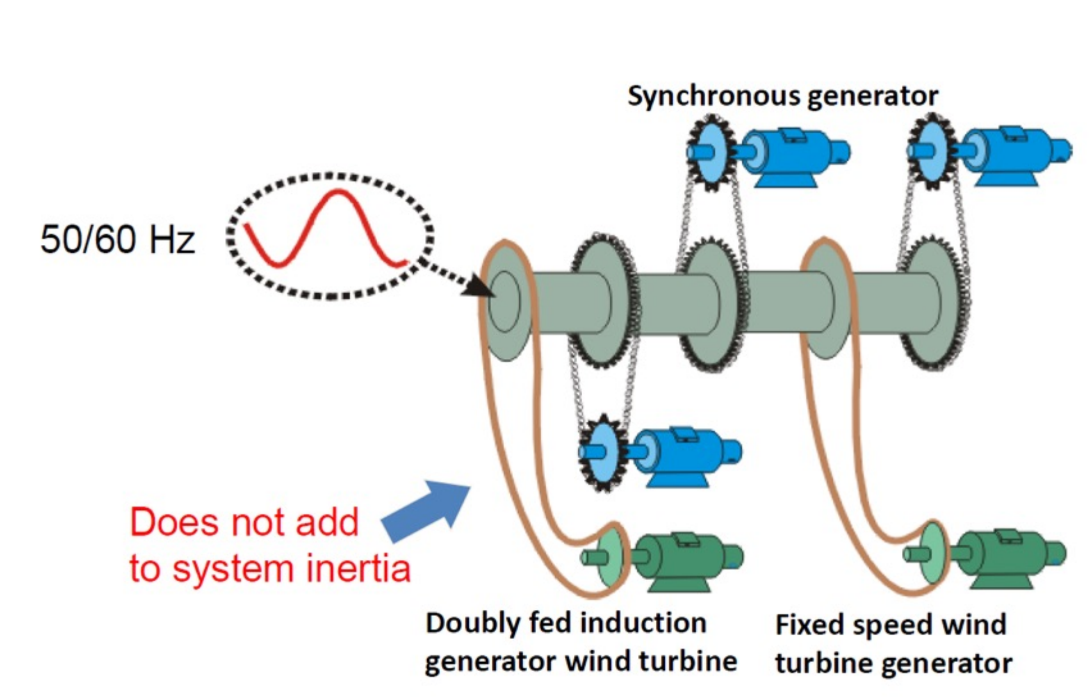


Wind/solar integration issues

- How is wind power different from other generation? Special concerns :
  1. Variability
  2. Uncertainty: prediction errors
  3. Location/ distributed
  4. Location can be far from load centres

  At larger shares of wind power also:

  5. Technology: non-synchronous (no inertia support to power systems)

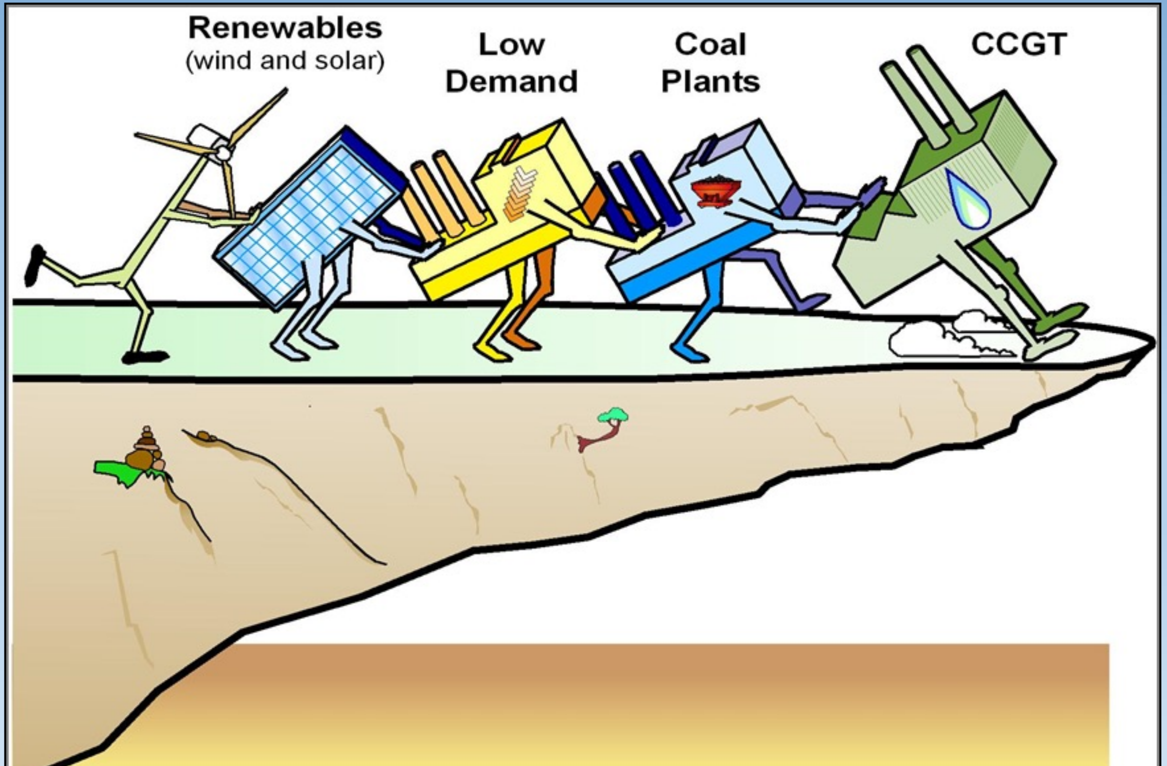


Wind/solar integration issues

- How is wind power different from other generation? Special concerns :
  1. Variability
  2. Uncertainty: prediction errors
  3. Location/ distributed
  4. Location can be far from load centres

  At larger shares of wind power also:

  5. Technology: non-synchronous (no inertia support to power systems)
  6. Capacity value lower than for conventional power plants (some wind generation is usually available at peak load events). Total operating time reduces, but capacity still needed



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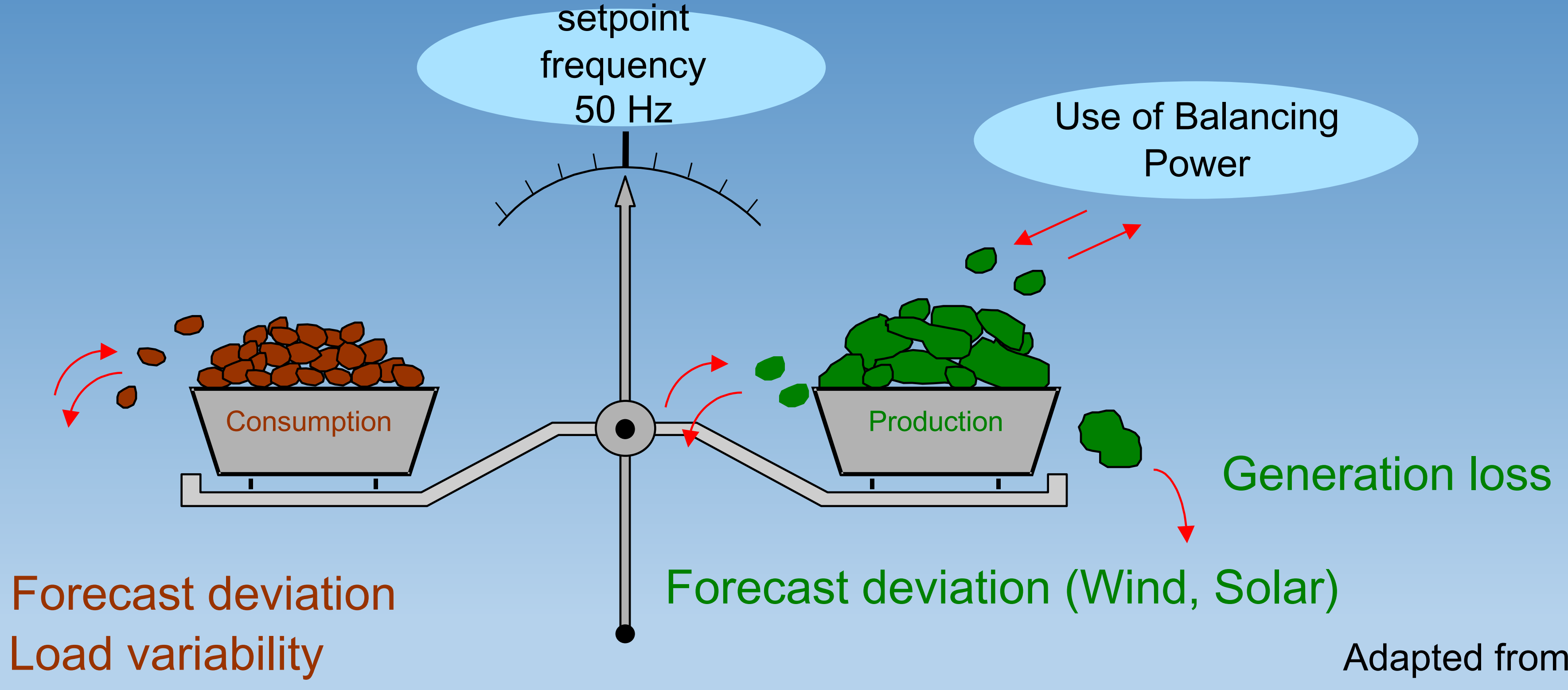
Power system balancing – coordinated at system level

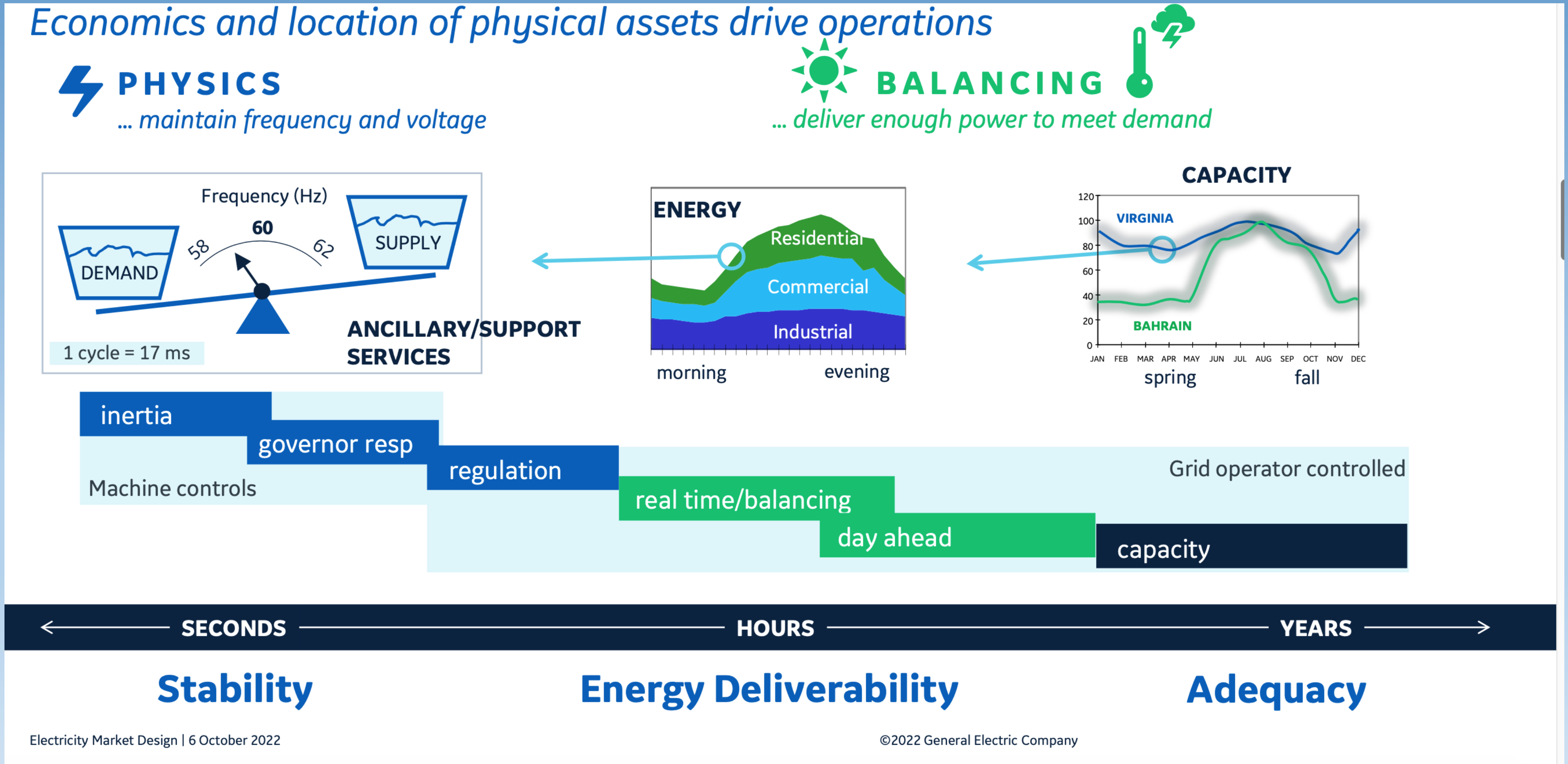


Adapted from © Amprion

No balancing for wind alone – for system net imbalances

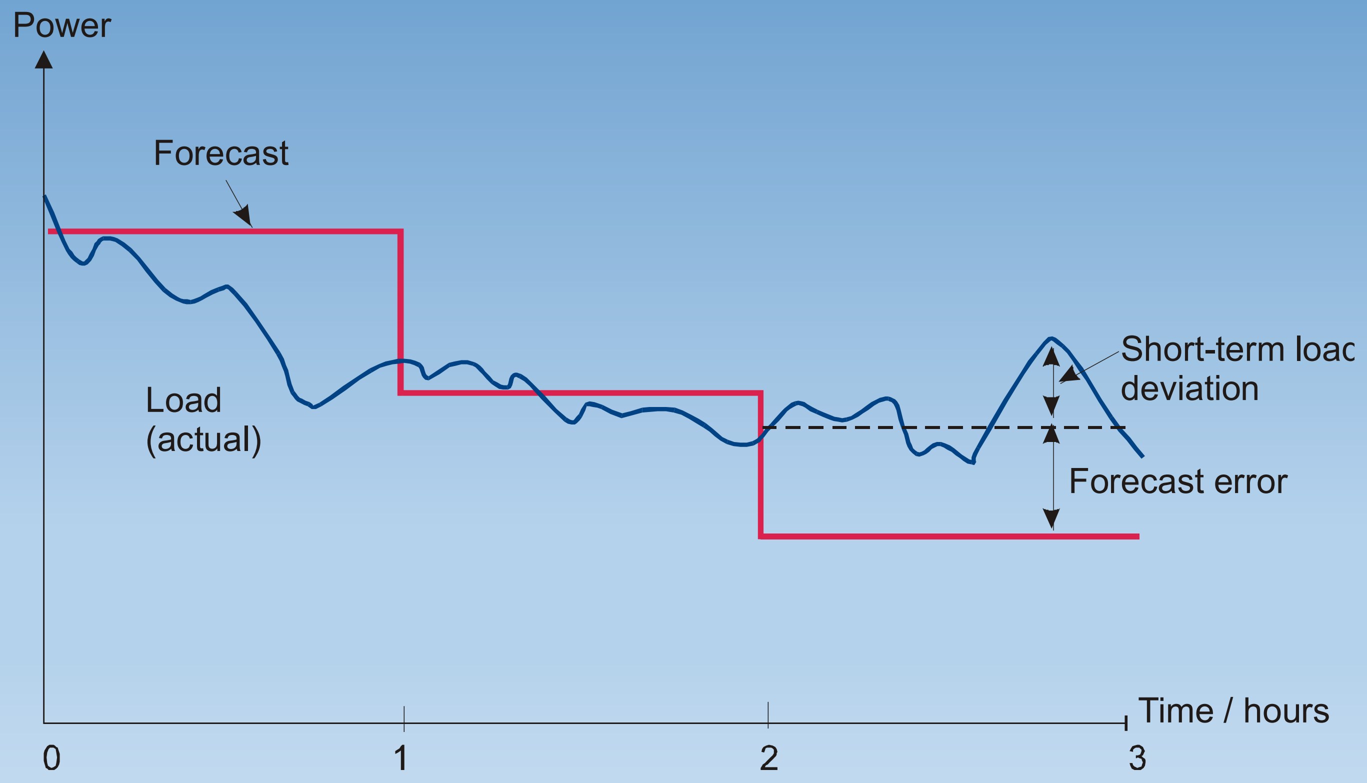
Power system balancing –time scales

- Uncertainty and short-term variability: short term operating reserves (from balancing/real-time markets)
- Variability: Unit commitment and dispatch (day-ahead and intra-day markets)



Operating reserves

- Example: electricity demand - varies also within hour, and is partially predictable.



TSO balancing task (Nordic) – from schedules of the producers/main actors in the market

NOTE
The scale:
Balancing
~ 1-3 %
of volume

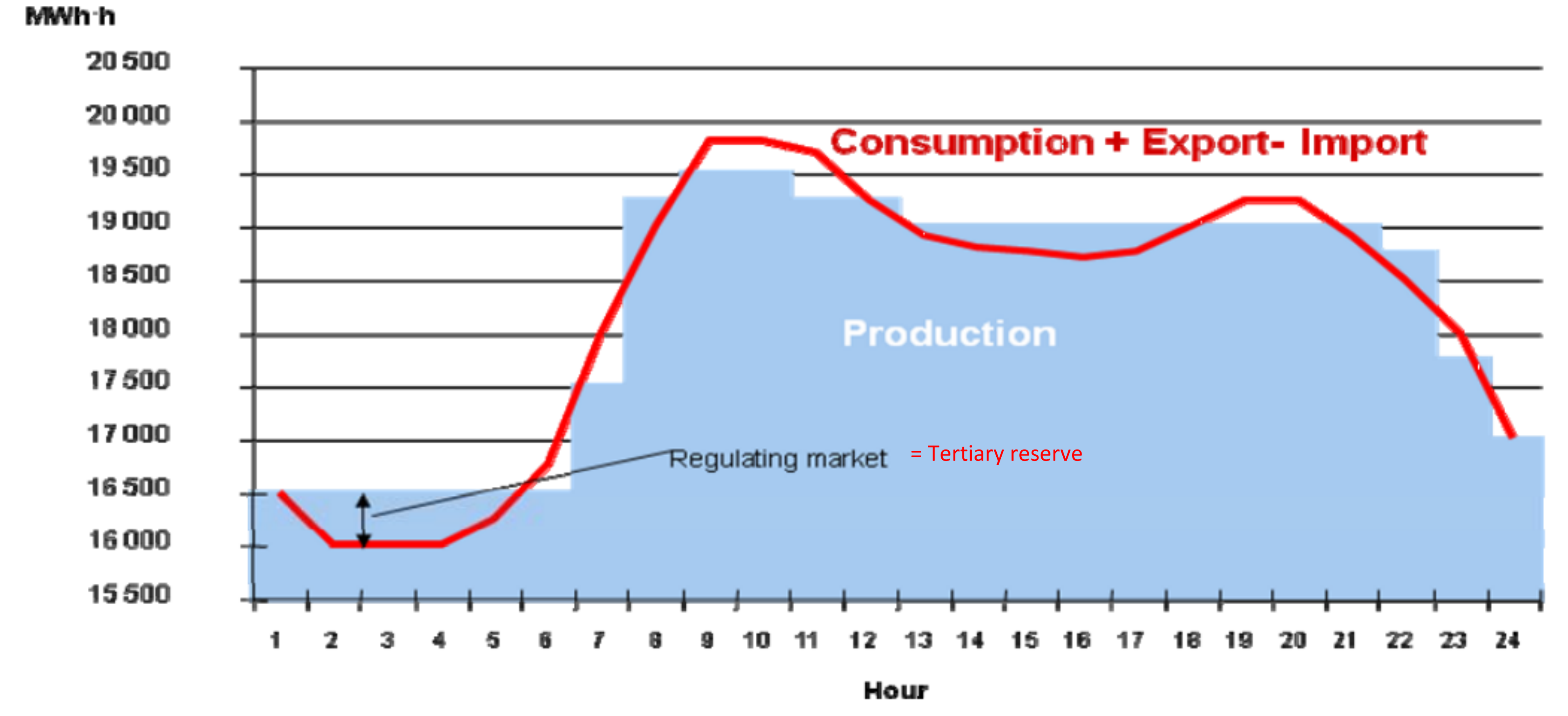
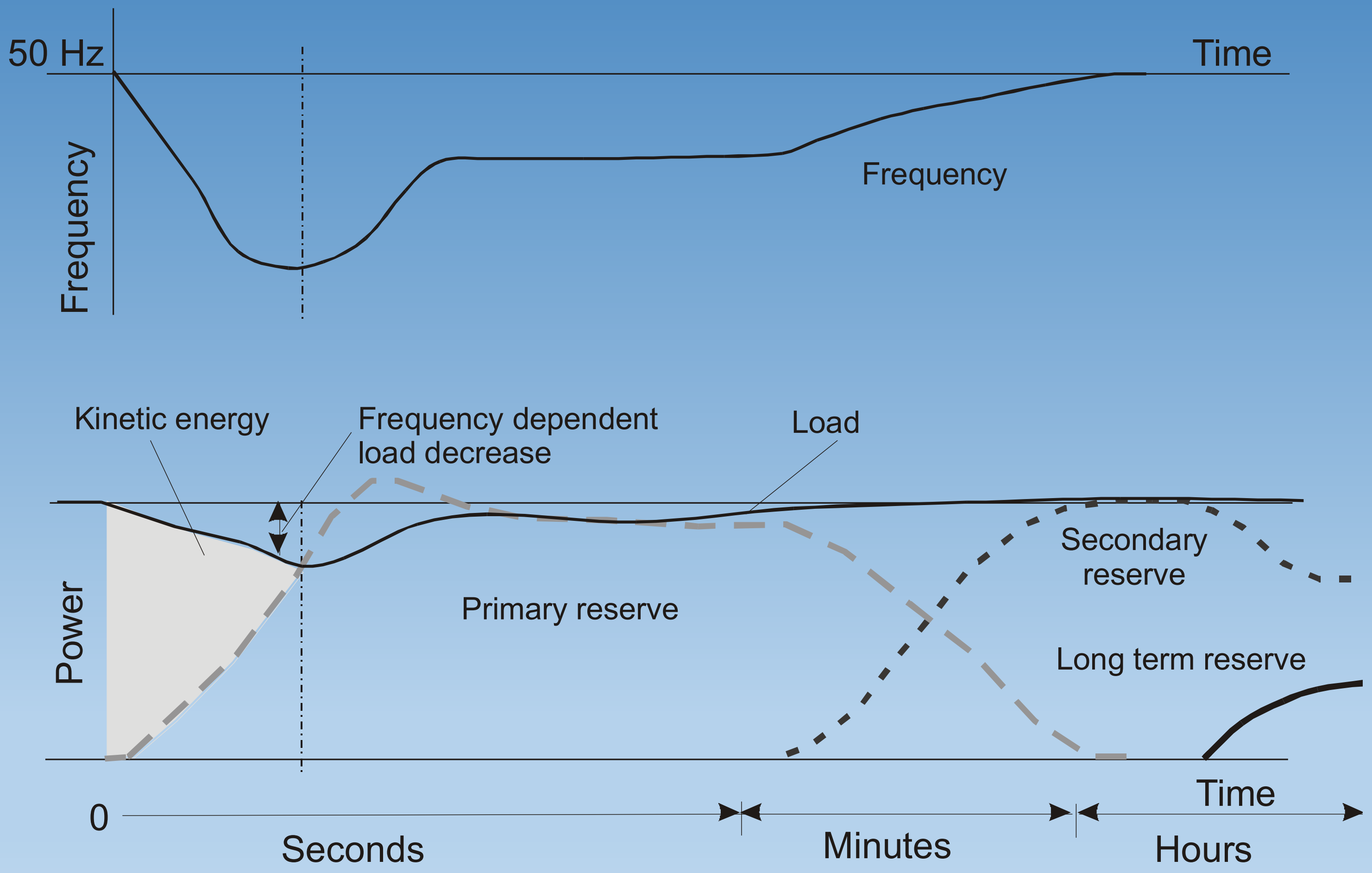


FIGURE 1 THE BLUE PRODUCTION GRAPH REPRESENTS THE HOURLY NOTIFICATIONS PLAN. THE TSO MUST MAINTAIN THE MOMENTARY BALANCE BETWEEN PRODUCTION, CONSUMPTION AND EXCHANGE IN THE OPERATIONAL HOUR. THE REGULATING MARKET (TERTIARY RESERVE) IS THE TOOL TO ADJUST THE PRODUCTION TO THE ACTUAL CONSUMPTION (NORDIC MODEL).

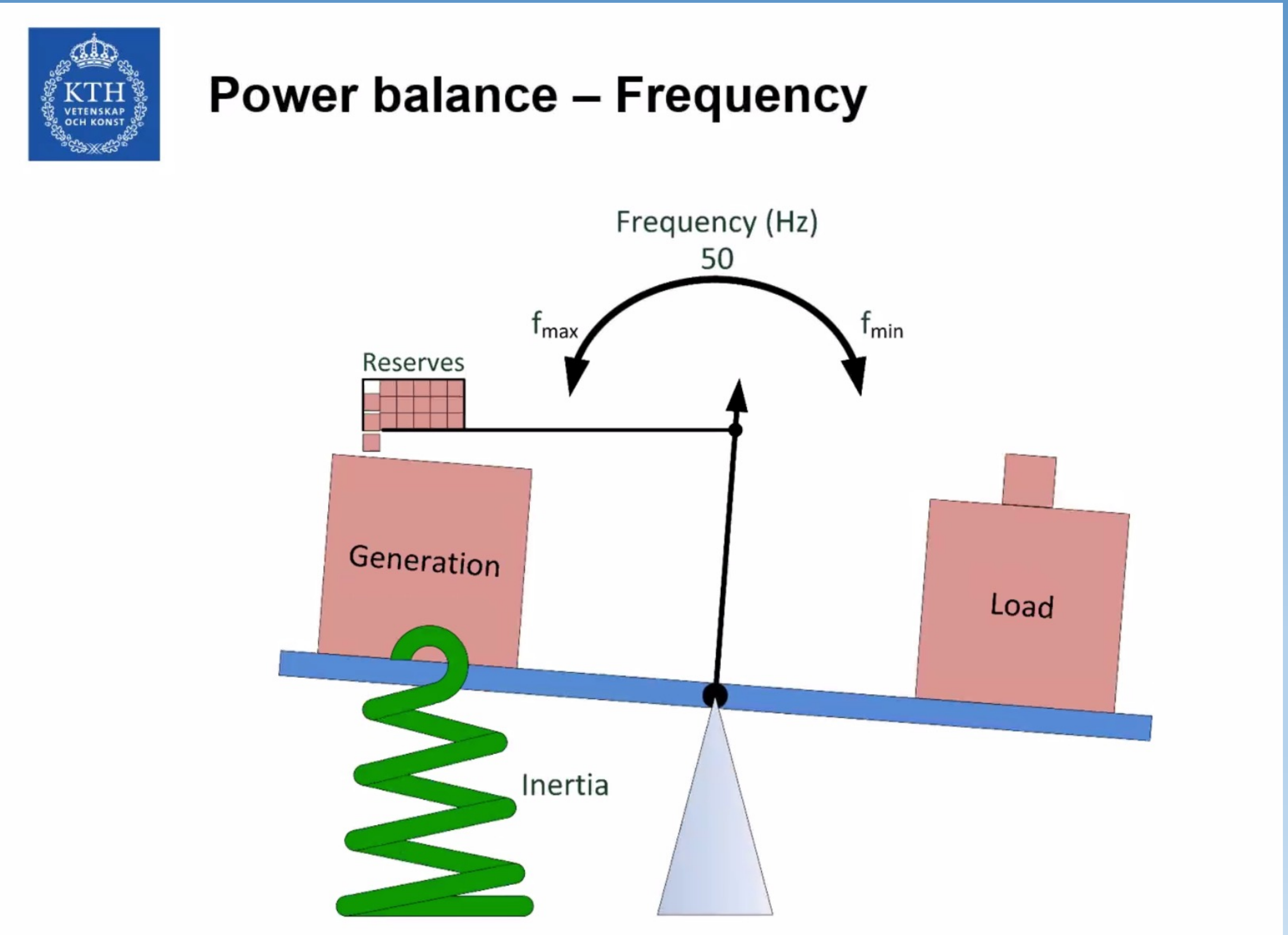
Reserve activation time scales – example of a power plant trip-off

Frequency deviation is large when a large power plant trips

Inertia and frequency control reserves kick in to restore frequency



Power system balancing – role of inertia



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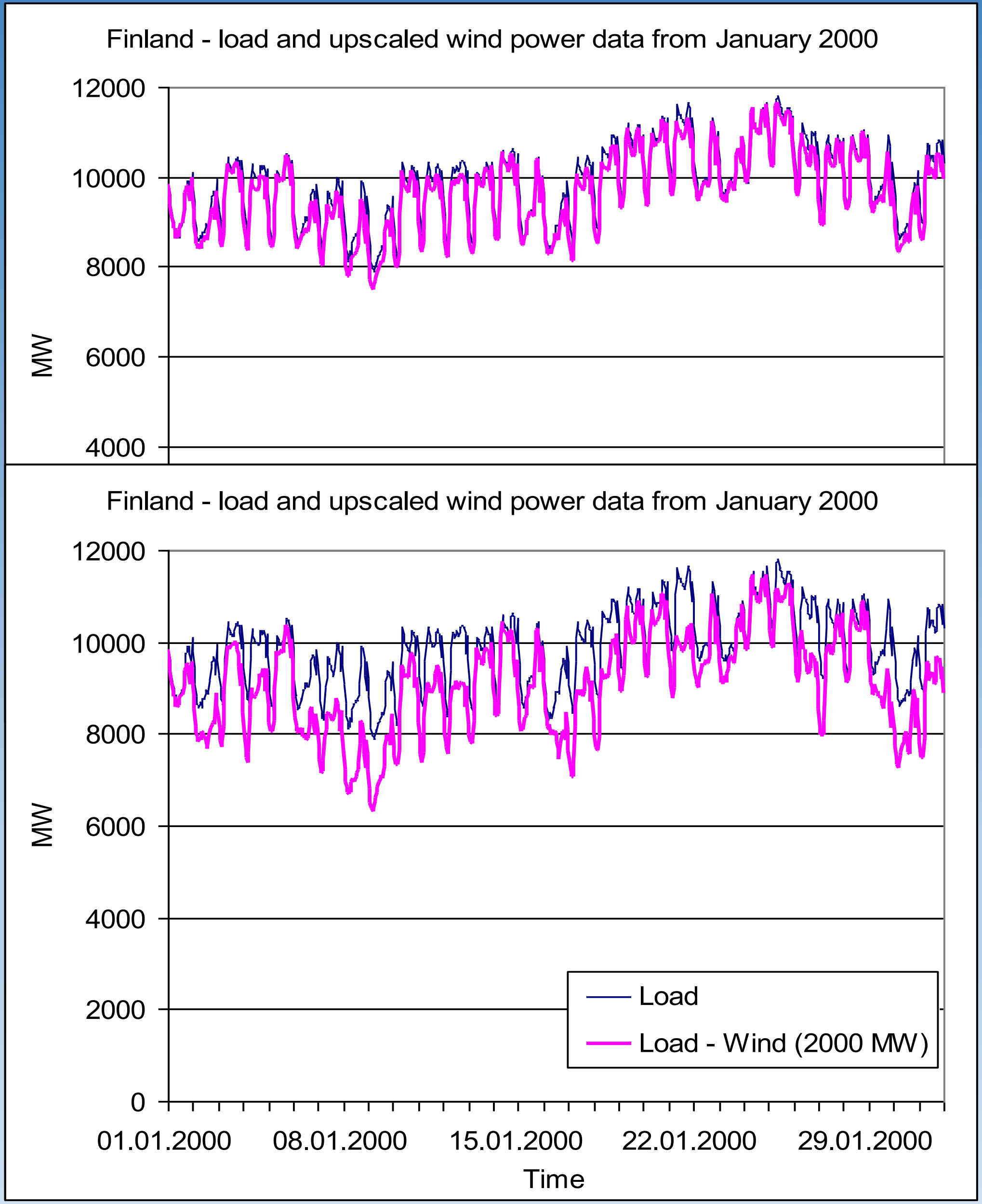
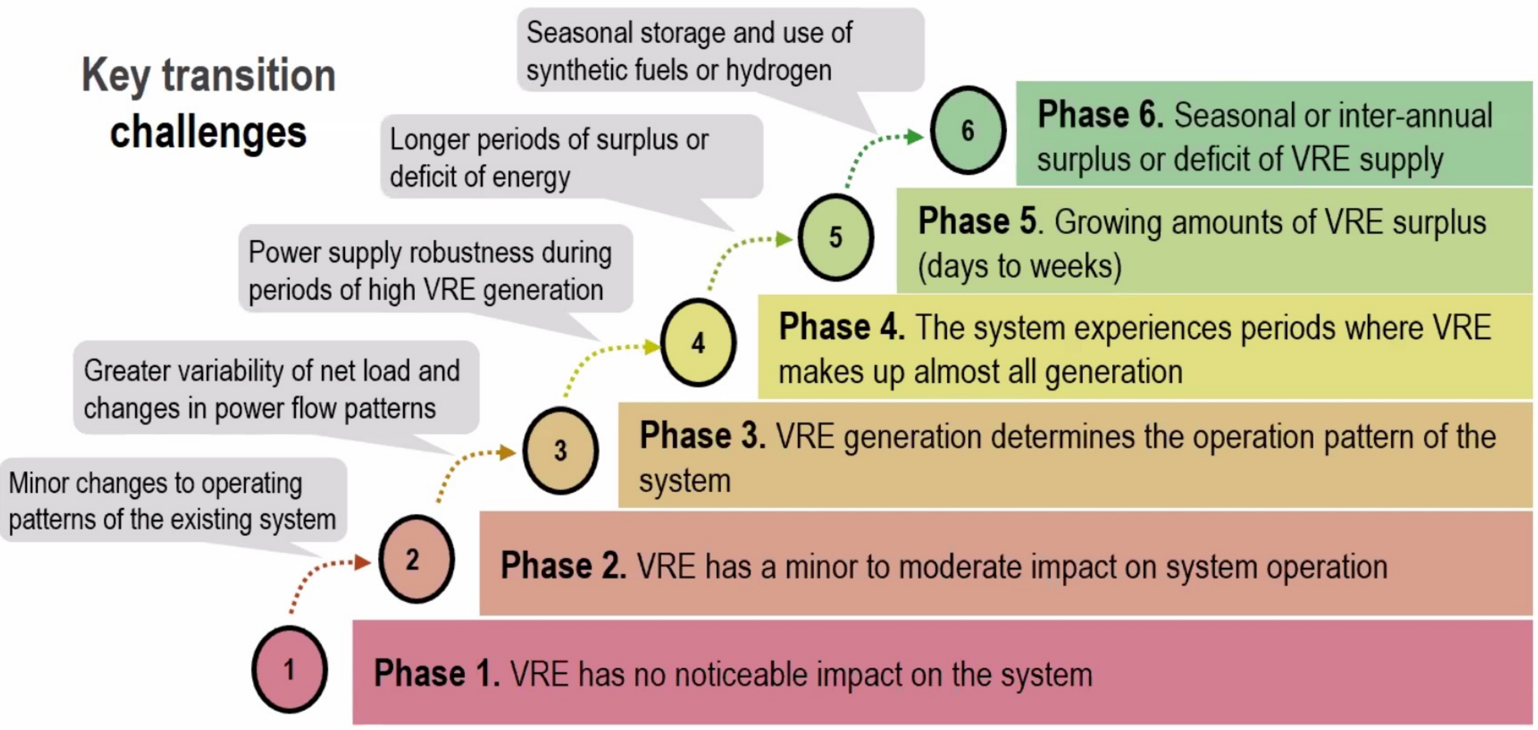
Impacts on power systems from variability and uncertainty - from load to net load

- Impacts will depend on the share of wind power
- Impacts will depend on the power system:
  - The variability of load
  - The flexibility of power generation fleet and possibilities to increase flexible production and consumption



Phases of wind and solar (VRE) integration

Characteristics in different phases of system integration of VRE

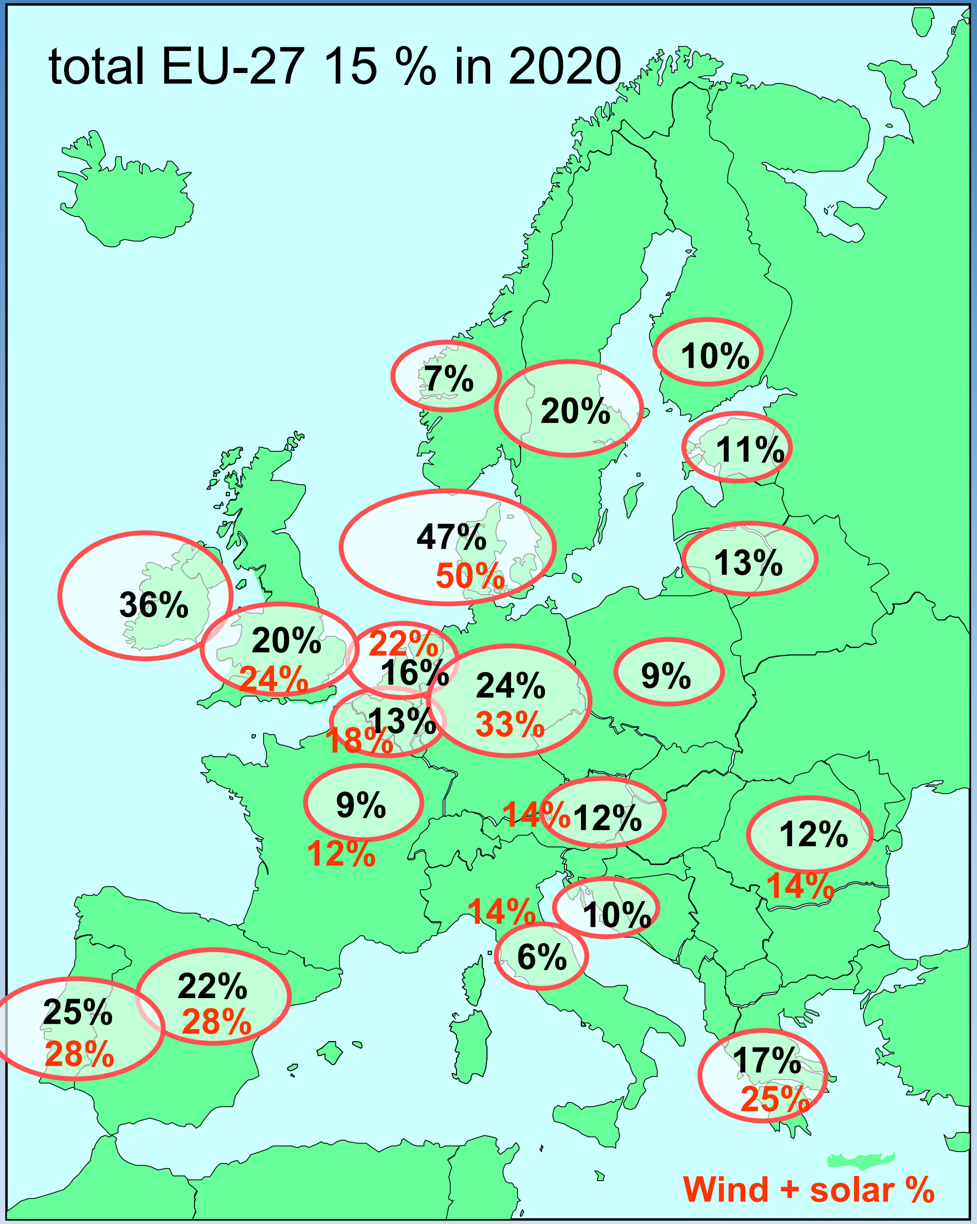


Key challenges in each phase that should be addressed for moving up to higher phases of VRE integration

Source: World Energy Outlook 2018

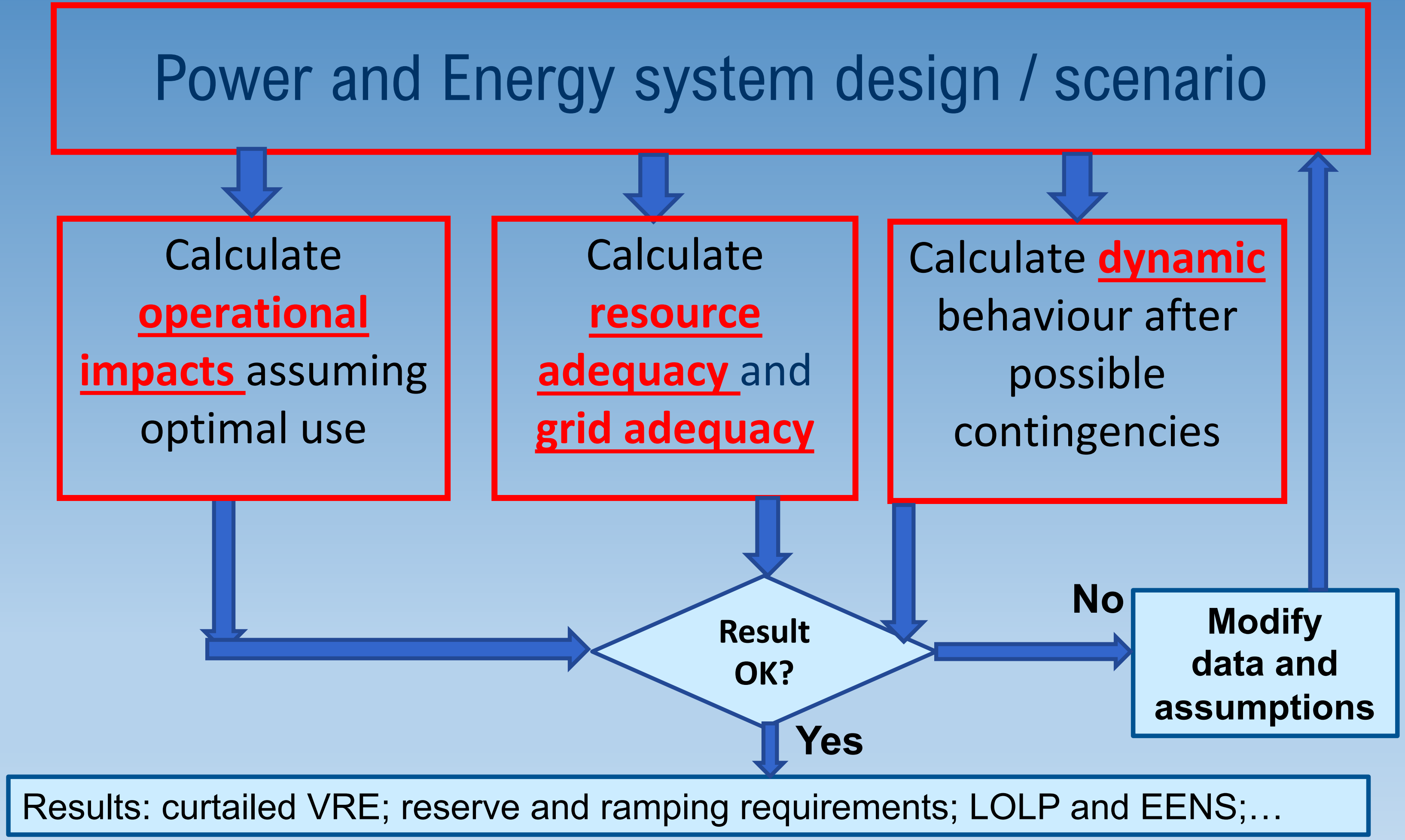
Increasing experience of wind integration

- First 10-20 % share of wind:
  - Updated information from on-line production and forecasts and possibility to curtail in critical situations.
  - Grid connection codes
  - Transmission/trade with neighbouring areas recognized as a key enabler. Regional planning efforts (Europe: ENTSO-E)
- Higher shares of wind:
  - Technical capabilities of wind power plants used in grid support, also stability
  - Generation and demand flexibility and adequacy
  - Market design and value of wind



Recommended Practices for wind/PV integration studies

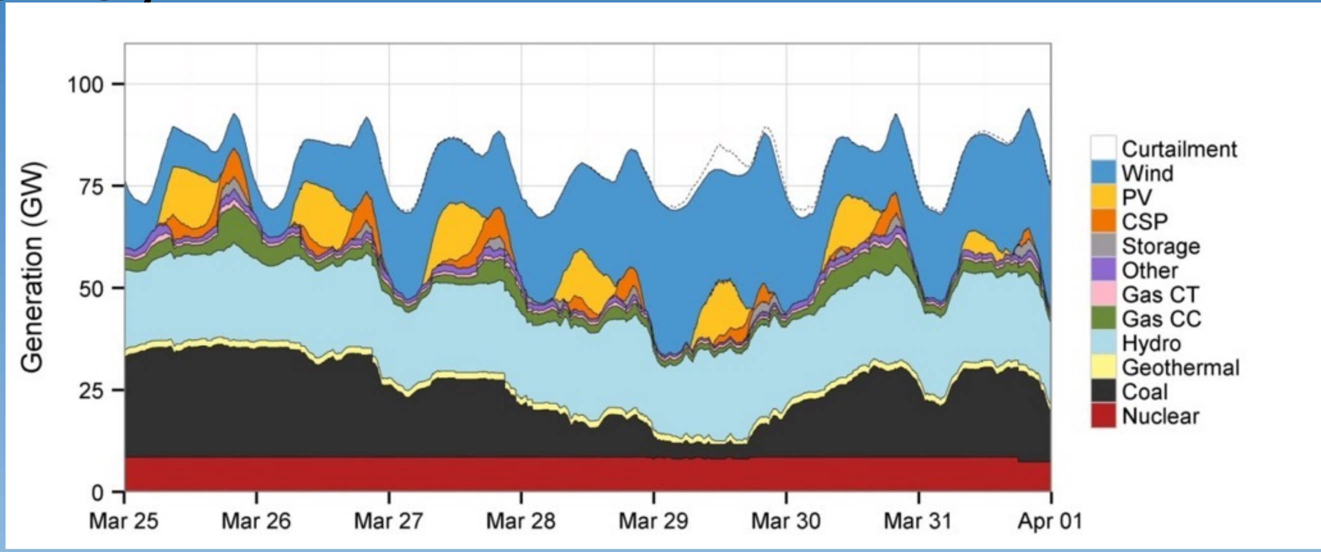
- Most studies analyse part of the impacts – goals and approaches differ

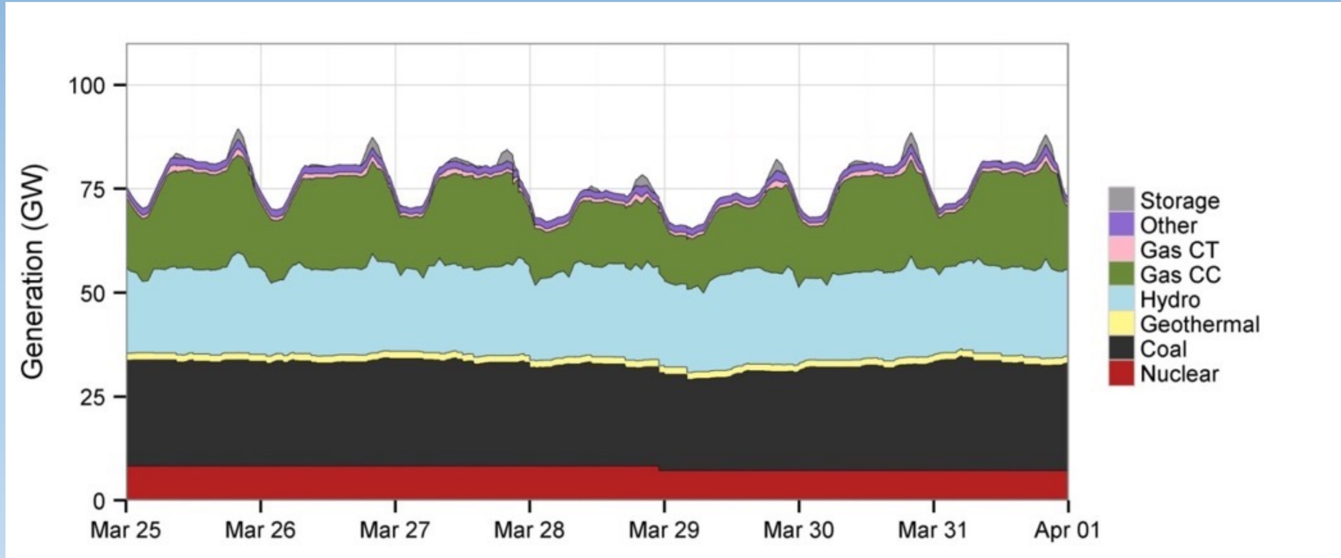


https://iea-wind.org/iea-publications/

Capturing impacts of wind power on balancing, dispatch efficiency

- Comparing simulations without and with wind: what happens when wind power is added
- Main impact is that operational / fuel costs are reduced
- Small increase in balancing related costs





Example dispatch simulation : WWSIS study in USA, high RES case (8% solar, 25% wind) compared with no RES

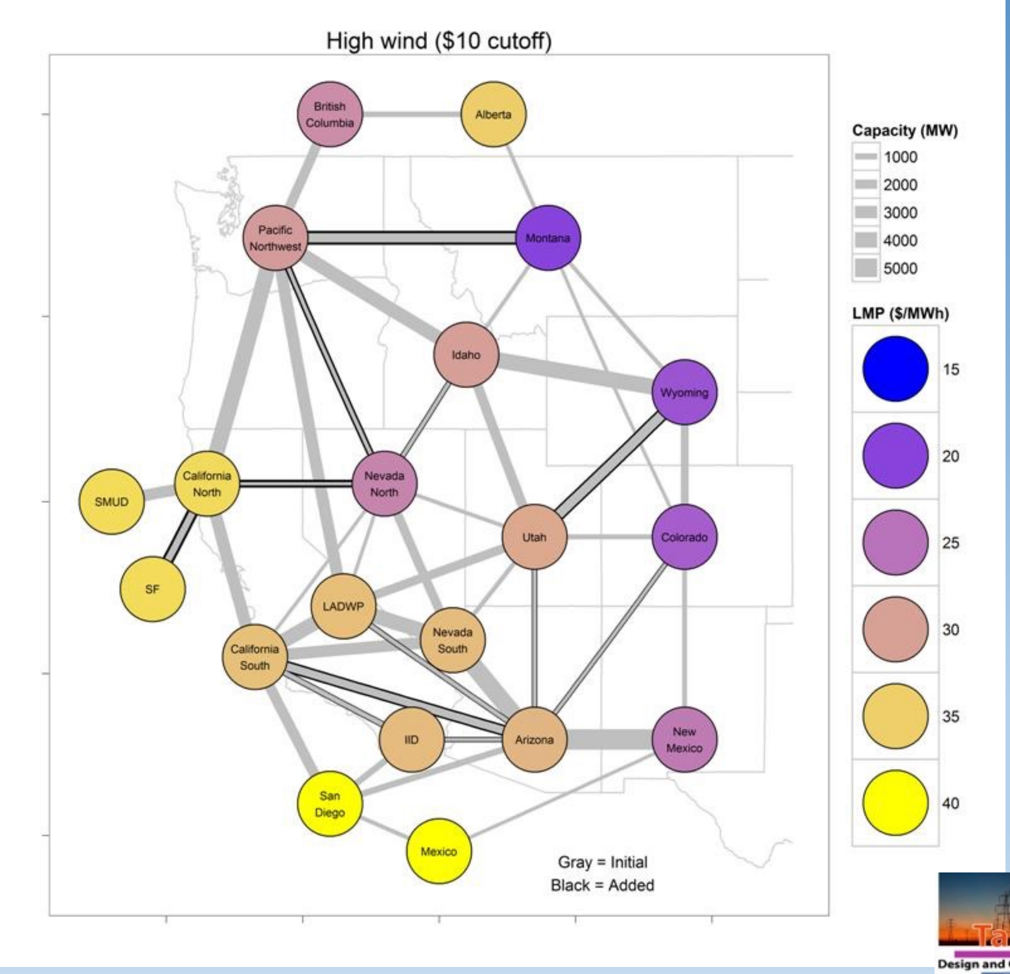
Task 25 Design and Operation of Power Systems with Large Amounts of Wind Power

iea wind

NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

What is important to take into account: flexibility potential and limits

- **Existing flexibility**: power plant ramping and cycling capabilities; interconnection and possibilities to share balancing with neighbouring areas; demand side flexibility; storages
- **Limitations of flexibility**: minimum on-line generation level of power plants, efficiency losses, cycling costs, hydro power river couplings, transmission limits



UCED= Unit commitment and Economic Dispatch

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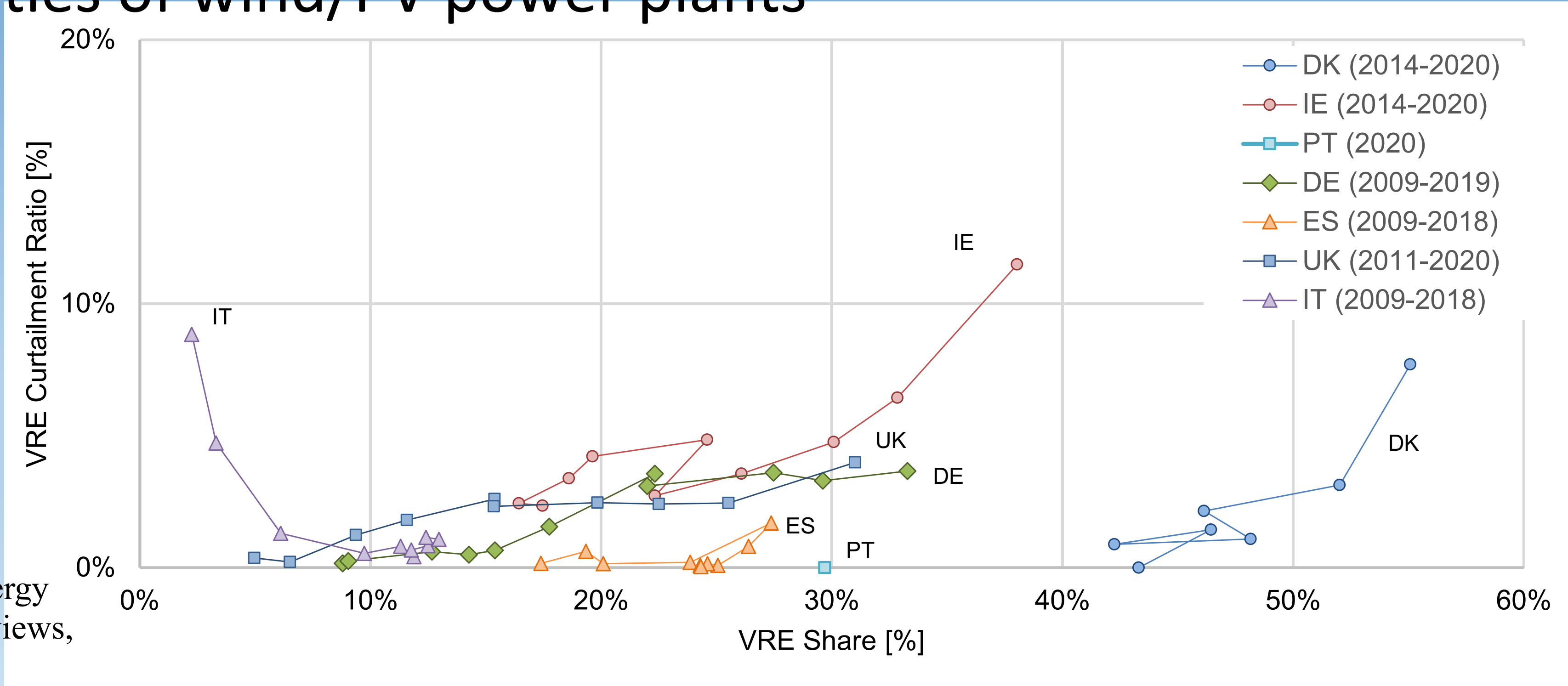
Wind/PV in the simulations

- **variability:** representative power system area with smoothing effect
- **forecast accuracy:** more accurate for 1-3 hours ahead than day-ahead (rolling planning horizons for the model)
- **grid support**: capabilities of wind/PV power plants

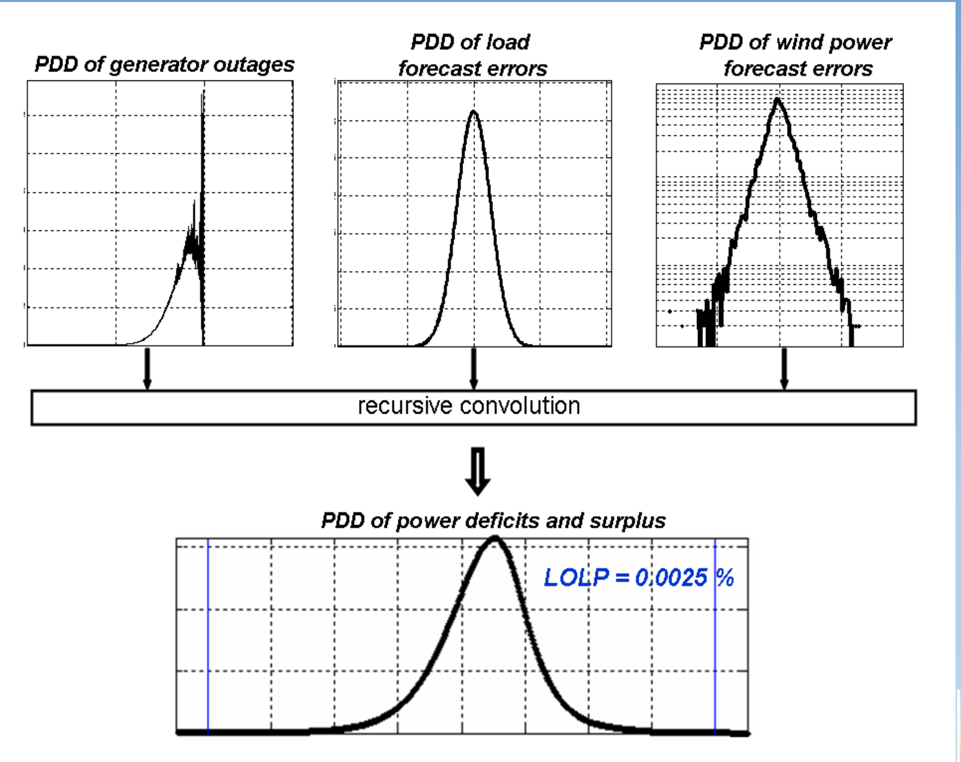
Flexibility from wind: curtailing surplus generation. Providing balancing up/down while curtailed.



Source: Y Yasuda et al (2022) C-E (curtailment – Energy share) map... Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2022.112212

Analysing impacts of wind power on short term (operating) reserves

- Wind power added to system that already copes with variability and uncertainty of loads – and sudden failures of large thermal power plants
  - Combining variability and uncertainty of all sources: Analysing with proper data the probabilities of each event and combining them.
  - Increase in reserve requirements can be estimated from non-wind to wind case keeping the risk level the same
  - Dynamic reserve setting: building on information on how variablity and forecast uncertainties vary over time (like: lower uncertainty during a low wind day)



Source: IEA Wind Recommended Practices for wind integration studies www.ieawind.org

Trade with neighbouring areas will help balancing

- Denmark integration of close to 50% wind share is based on using Nordic power system flexibility
- Sharing balancing task with neighbouring system operators in Germany has resulted in reduction of use of frequency control, while wind and solar have increased

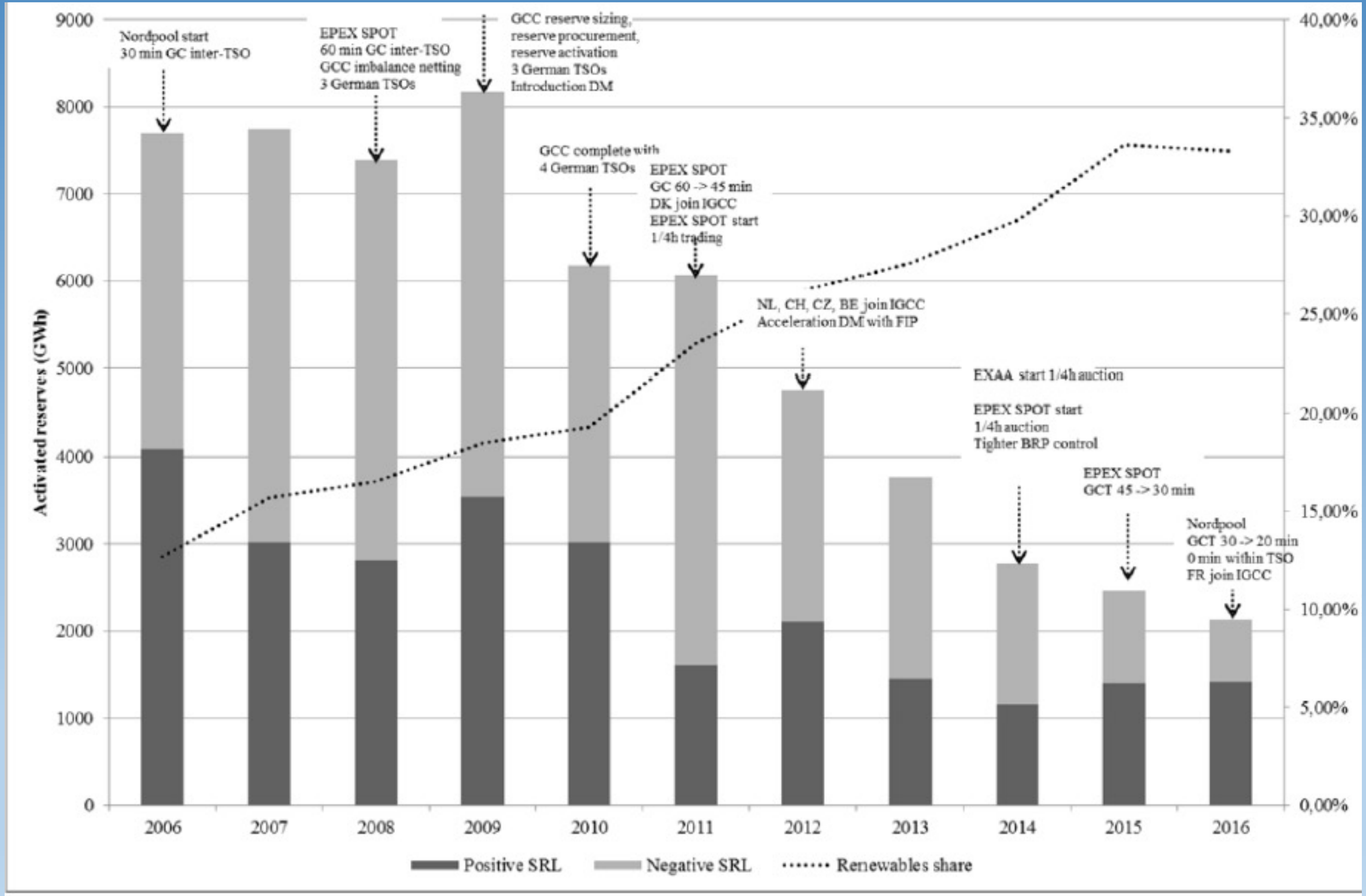
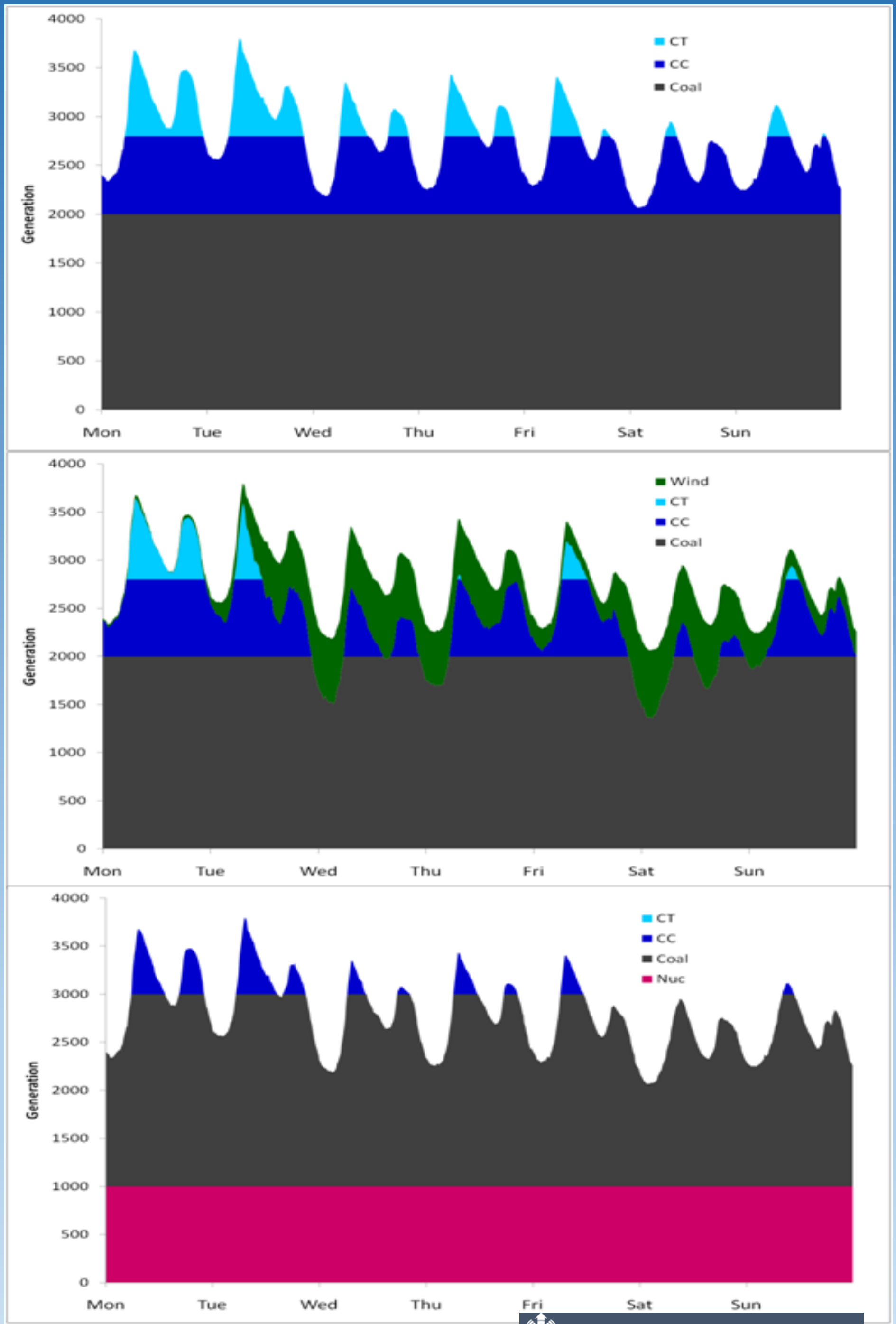


Figure 13: Total activated German Secondary Reserves (or aFRR) per year marked with events considered in this paper.

Rena Kuwahata, Peter Merk, WIW17

Integration cost?

- Not unique to wind or solar
- Little agreement on methods, how to calculate accurately
    - benefits and costs for the system are difficult to extract for single technology
- Total operational cost can be compared for wind and non-wind case
    - Benchmark case difficult to form.
- Recommendation
    - compare total costs for different scenarios, not extracting balancing/grid costs
    - Note that as wind power in markets, will bear the costs of balancing, grid, and loss of value
- From integration costs to cost of inflexibility



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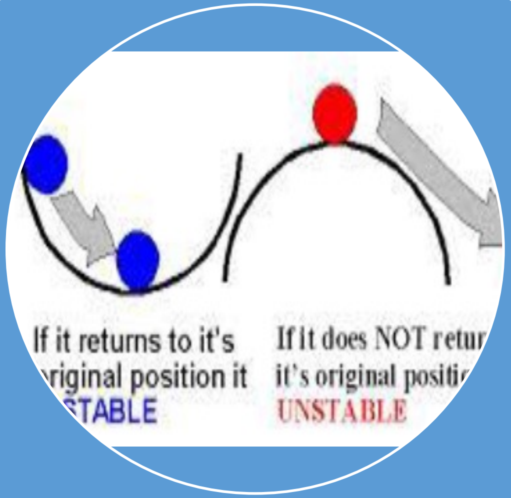
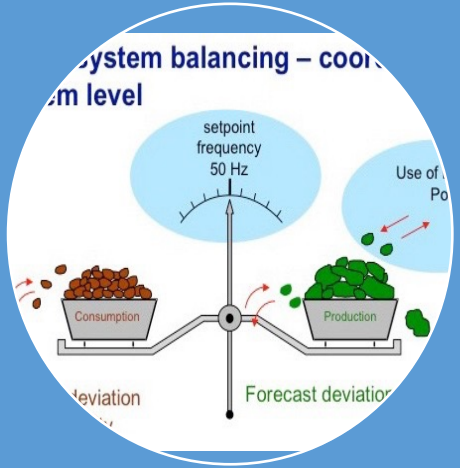
Future power system challenges



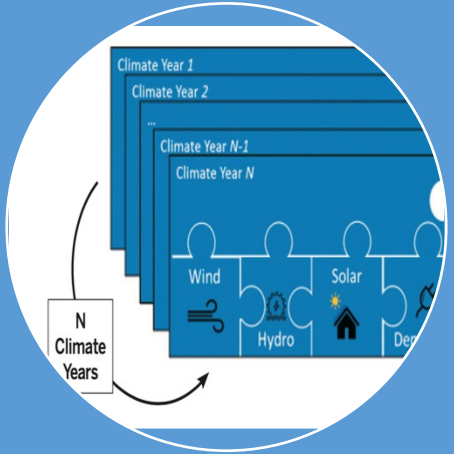
Stability

keep the power system resilient to disturbances and external events; control interactions



Short term balancing

demand and supply in balance – weather impacts like storms



Long term balancing

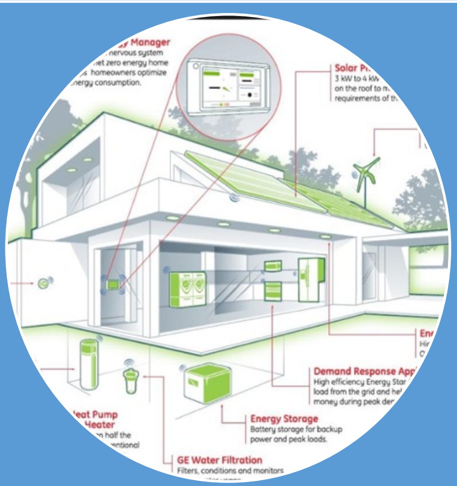
Increased weather dependency, extreme rare events of low wind, solar, hydro resource

seconds, minutes, hours, seasons/years

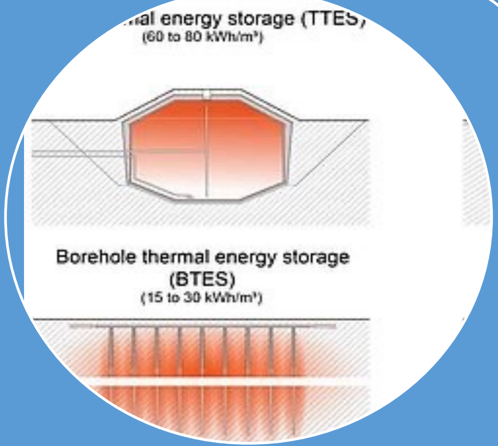
Flexibility and resilience solutions

Stability: How to operate non synchronous system?

How to get resilience from wind, solar, batteries? exploit wider flexibility of inverters, not just replicating synchronous machine features



Short term balancing: technology solutions are there (use demand, wind and solar and storage) - how to incentivise?



Long term balancing:

no more fixed load paradigm, optimise a combination of peakers, storage and demand side. How to incentivise smart sector coupling with all power2X storage options?

no mass
all brains

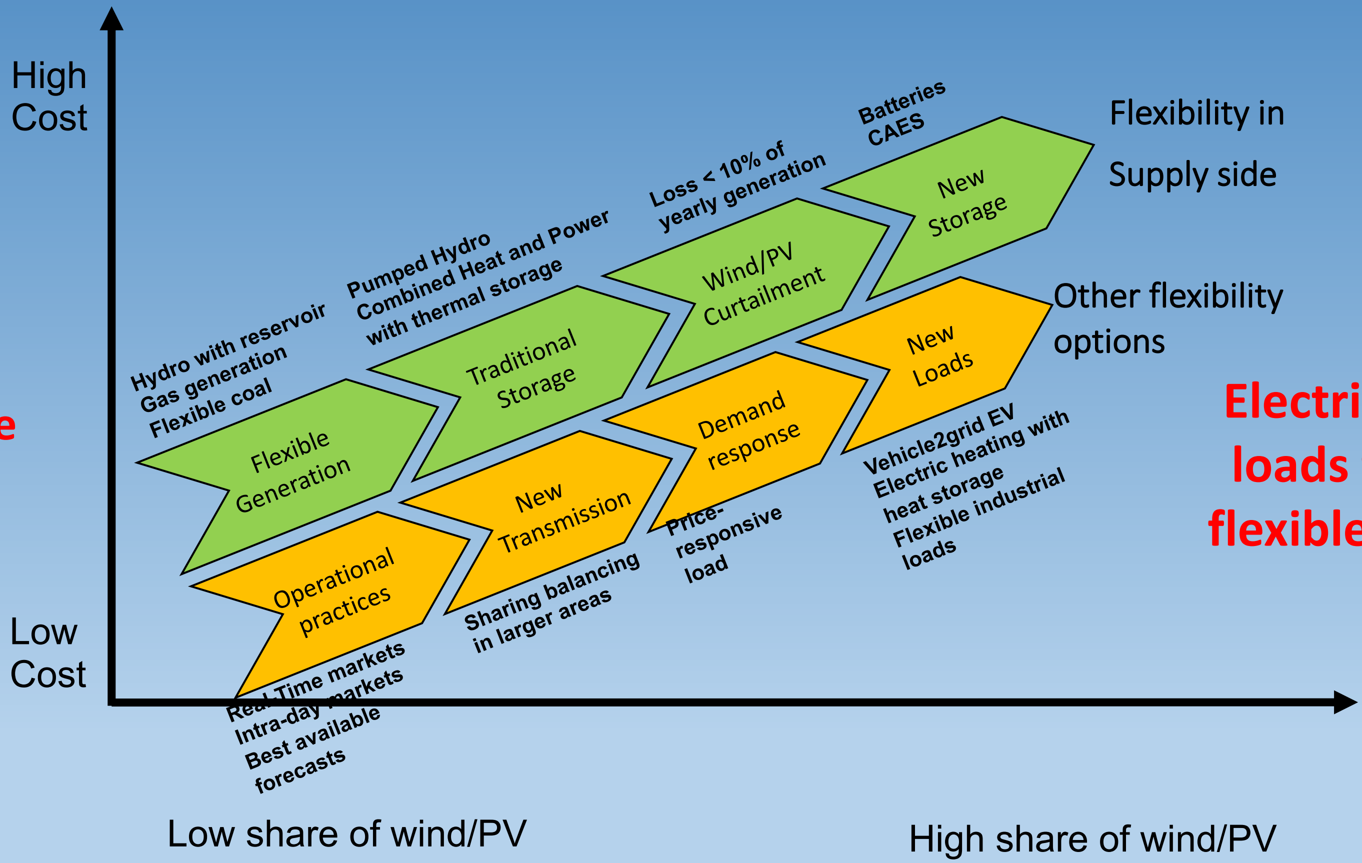
large and
fast markets

huge energy systems
power, heat, gas,…

More complexity and amount of data is exploding - digitalisation

Balancing challenge is all about flexibility – we can get far by using all options

Operational practices – and tools – key to enable high shares of VIBRES



Electrification – new loads that are more flexible that the loads today

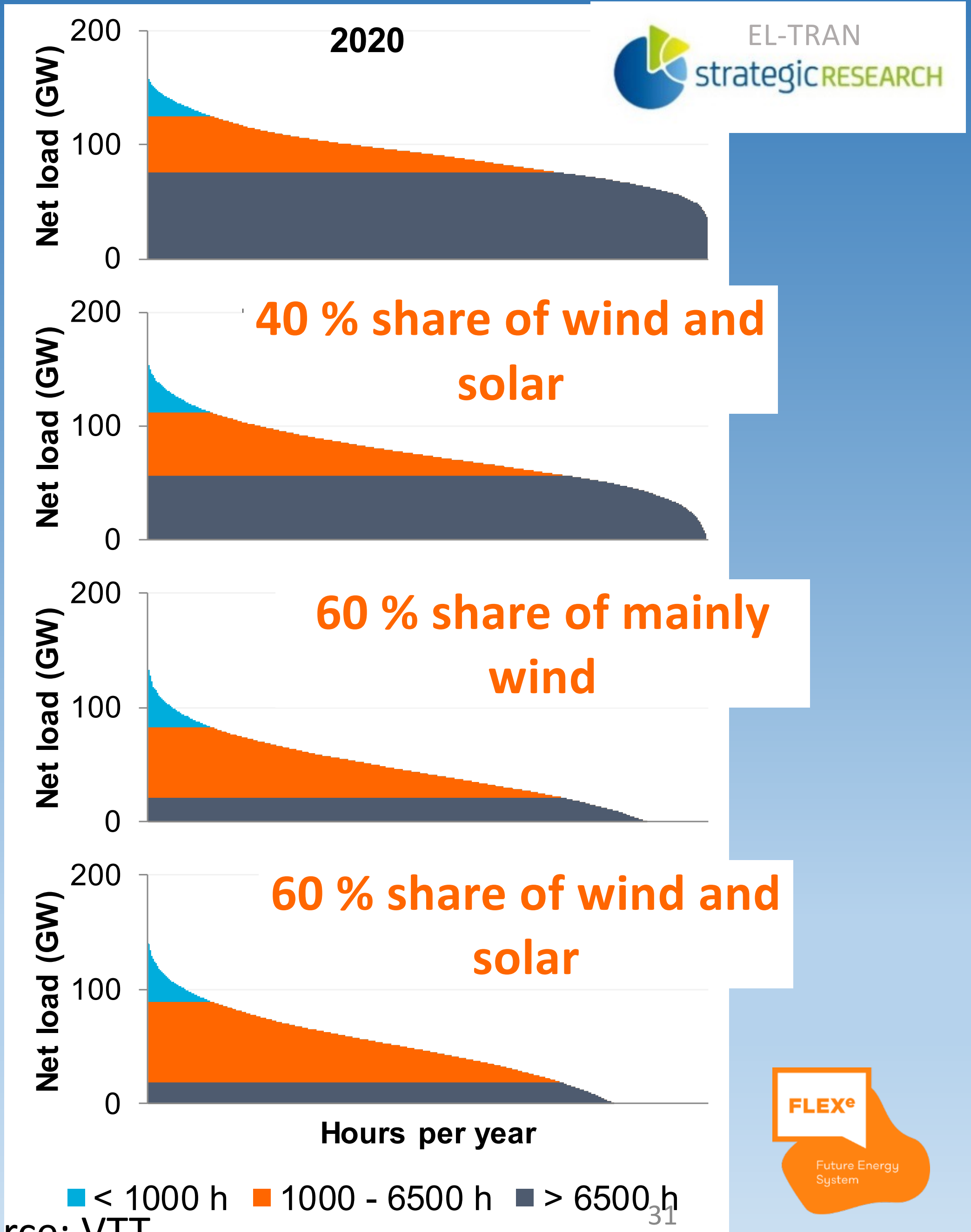
VIBREs – and loads and electrical storage can provide the system support services provided by generators today

VIBRES= Variable Inverter based Renewable Energy sources

Towards higher shares of wind and solar energy

- The time of base load power plants is over
  - Less and less time operating (full load hours), resulting in costs/MWh getting high
- The time of flexible power plants is here
  - producing less than 5000 hours per year, much of that time at part load operation

Case North Europe 20 → 60 % share of wind and solar



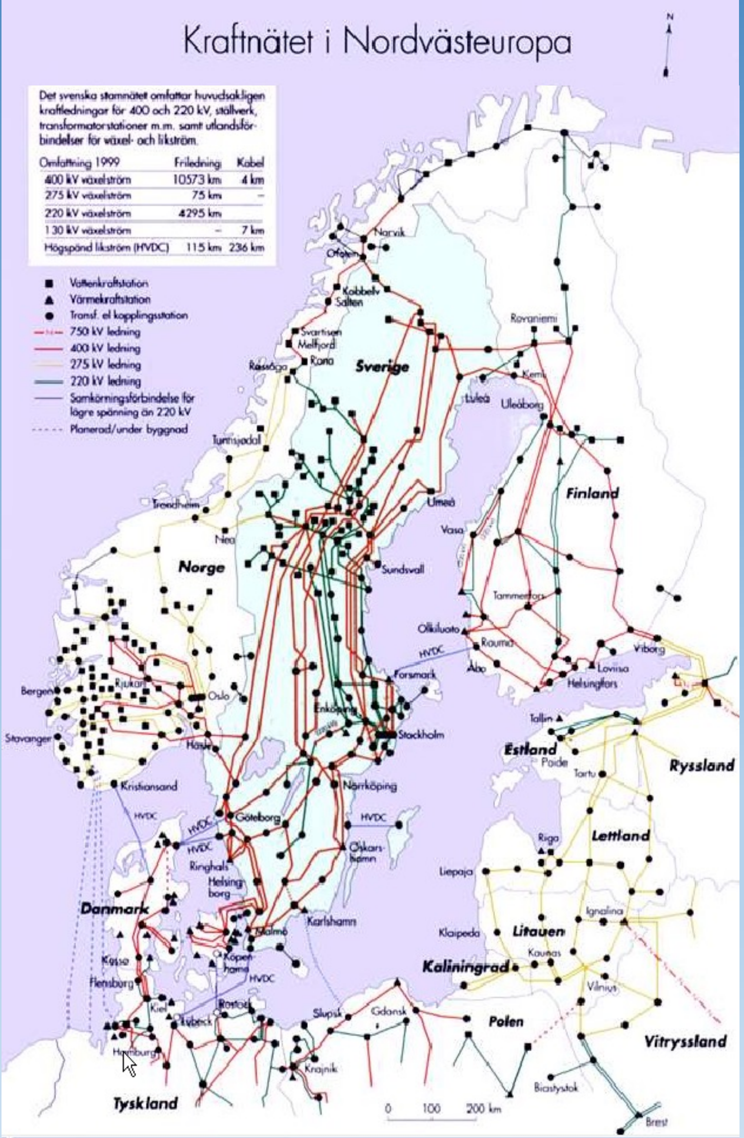
Source: VTT

Long term flexibility challenge – adequacy of generation capacity?

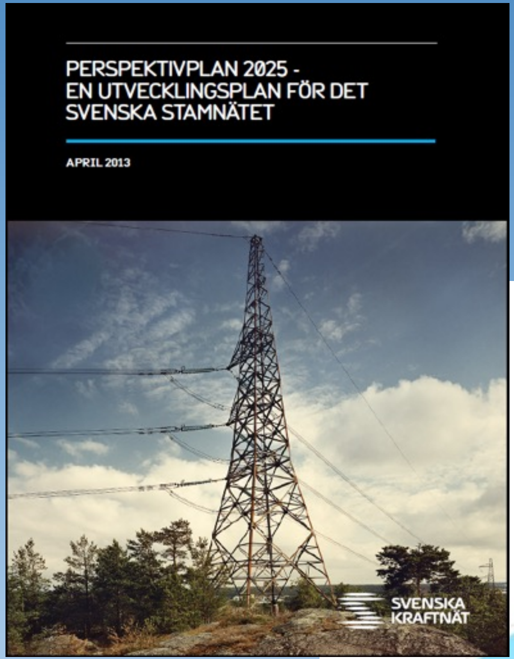
- Traditionally build gas turbines for back up – expensive use as peakers <1000h/a
- With wind/solar dominating, this will be expensive. Two other pathways possible:
  - Load becomes flexible – also in weeks time scale, electrolysers for power2X, thermal storages for heat etc
  - Electric storage becomes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

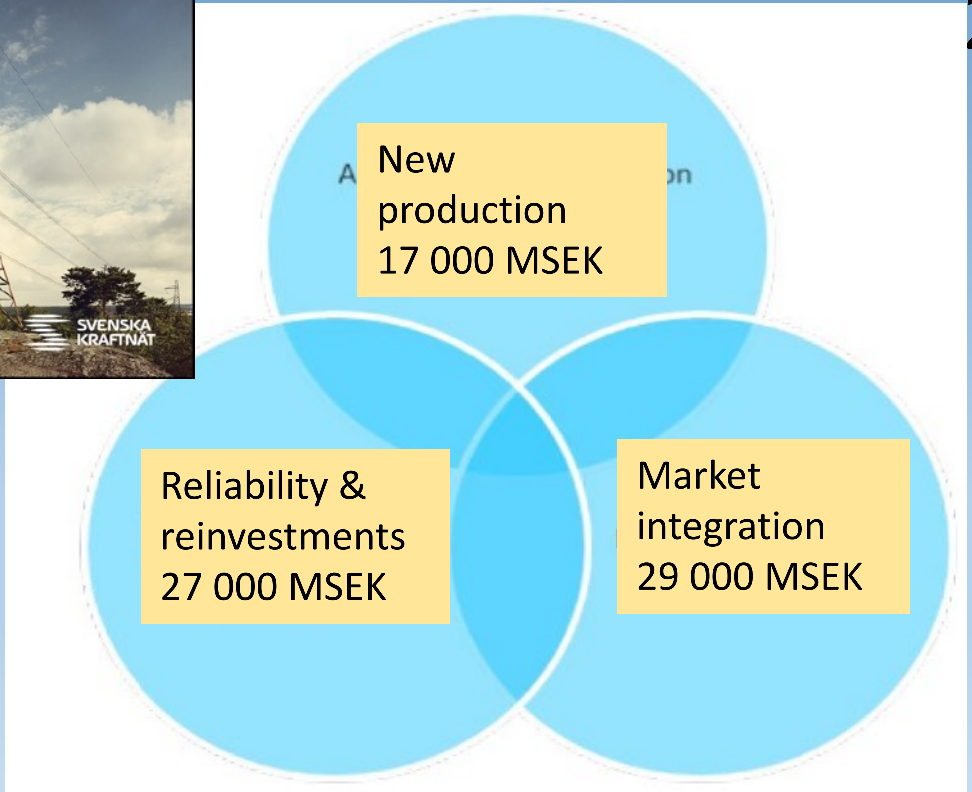
Grid impacts

- Grid to connect and transfer the power
  - Currently the grid transferring power from existing units
- Power flows will change
  - Sometimes more, sometimes less losses
  - In some cases, grid bottlenecks will increase and result in part of the generation being lost (curtailed)
  - Grid reinforcement needs may become large if wind power is built far from load centres – usually cost effective to build more interconnectors btw countries and transmission
- Usually transmission grid costs are not allocated to single cause of reinforcement – once the grid is there it will be used by everyone and will increase the security of supply



Transmission planning - costs





Example Sweden:

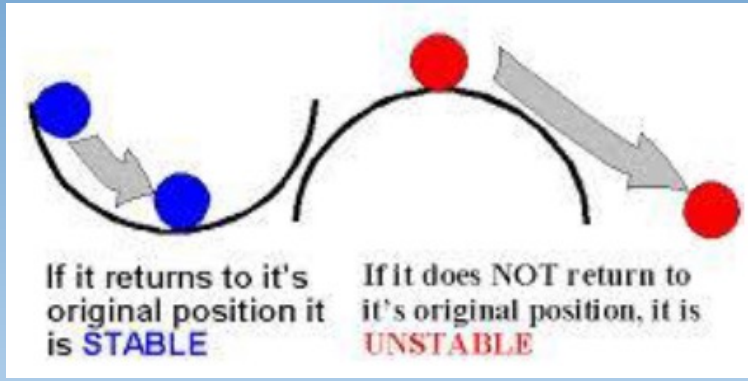
- Caused by new production ≈ 20% of total cost
  - Caused by new production = 50% caused by new wind, 50% by upgraded nuclear ➔ wind ≈ 10%
  - Wind power caused cost 0,3 öre/kWh ≈ 0,03 Eurocent/kWh

Transmission congestion - bottlenecks

- Thermal
  - Where the amount of energy that would flow naturally from one region to another exceeds the capacity of the circuits connecting the two regions.
- Voltage
  - Where generation is needed in a particular area to support the local voltage.
- Stability
  - Where particular circuit configurations have to be avoided because of the risk of oscillations in voltage or current.

For larger shares of wind: impacts on stability

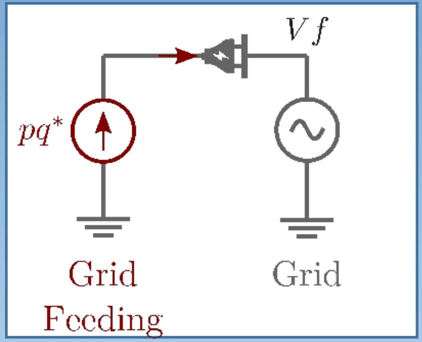
- Dynamics of power systems need to be studied at higher shares of wind power
- Wind power plant supporting the grid to help stability issues – from grid following to grid forming



Brown-out
Black-out

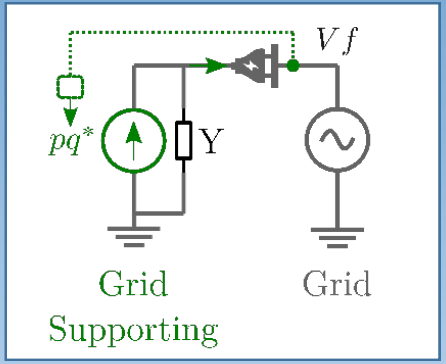
Power systems need to have a 'glue-like' capablity to keep the system up and running

First generation



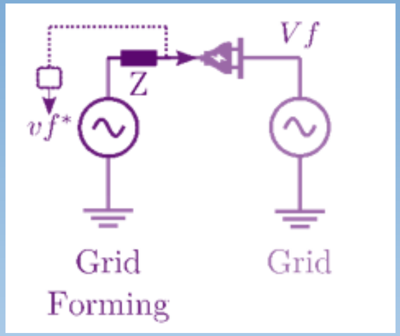
- Focus on MPPT
- Ability of controlling P & Q
- Needs energized and strong grid
- Minor contribution to system stability

Second generation



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

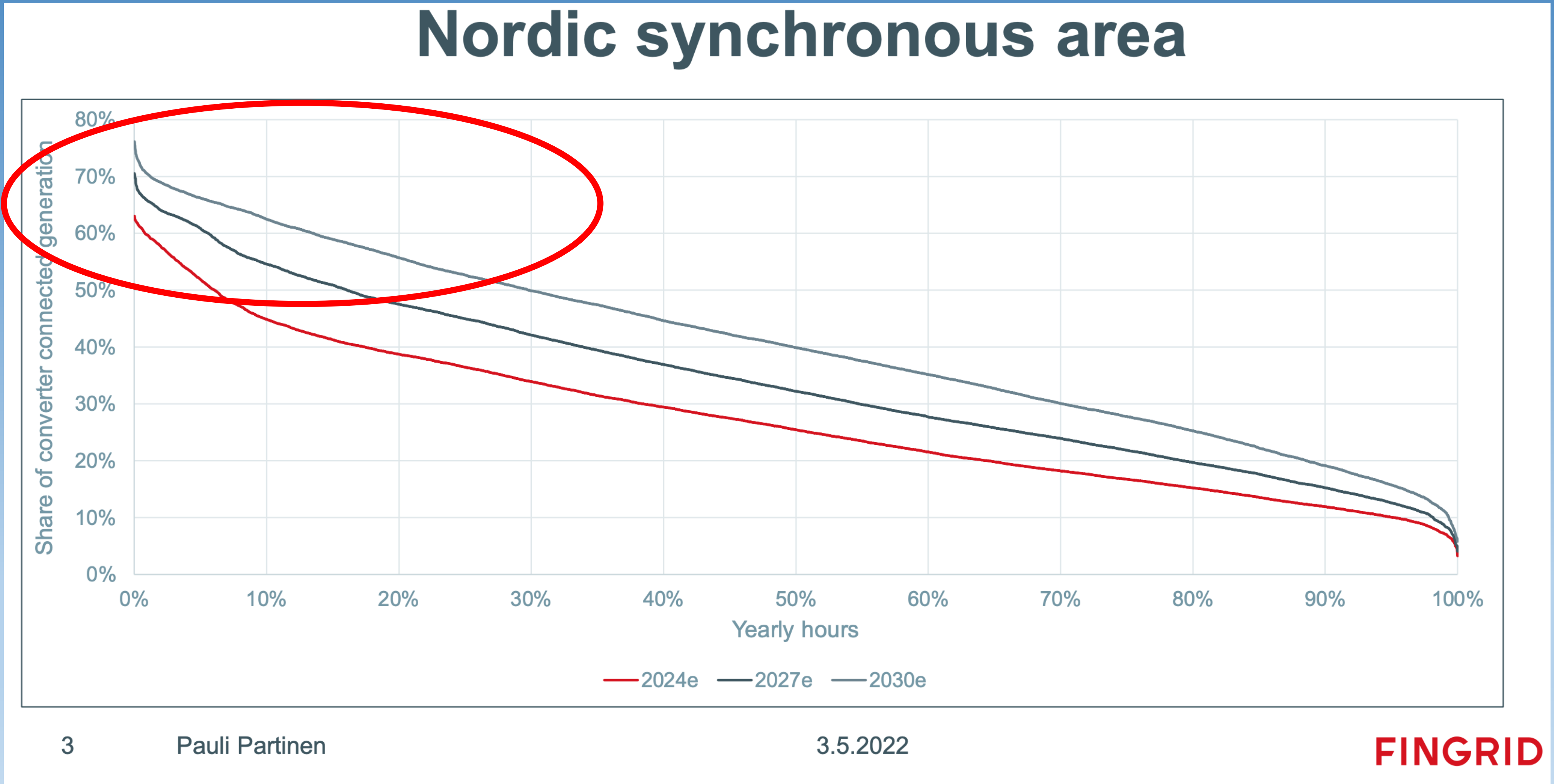
Next generation



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

MPPT: maximum power point tracking. F&V Frequency and Voltage.

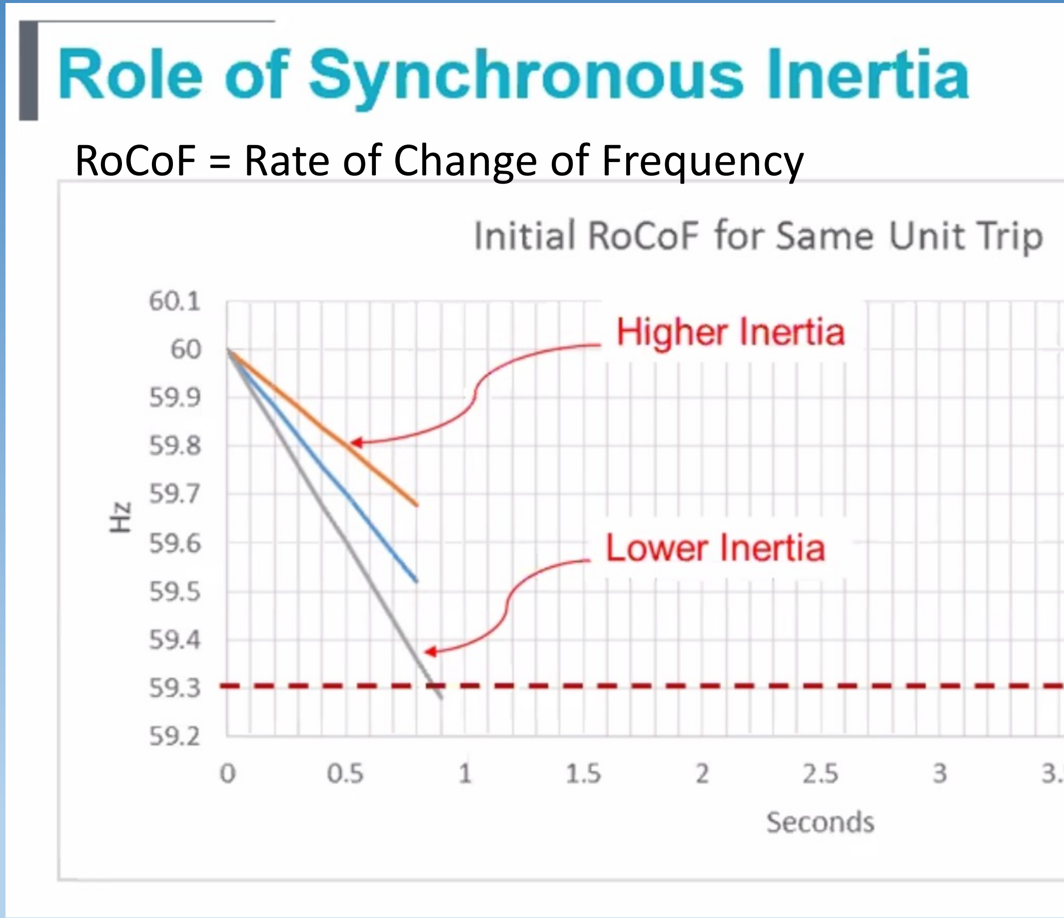
Low inertia operation



Ireland island system (size ~7GW versus Nordic ~70GW) limit non synchronus share to 50% to start with, then 65%, in 2022 75% and target 90%

Frequency stability

- Maintain inertia
  - Keep synchronous machines running that would otherwise not run
  - Find other sources of synchronous inertia (i.e. synchronous condensers)
- Speed up frequency response
  - Faster primary frequency response (on synchronous machines)
  - Fast frequenncy response and other clever frequency controls, especially on inverters
- Make inverter behavior "better"
  - Grid forming inverters and Virtual synchronous machines



Other stability issues

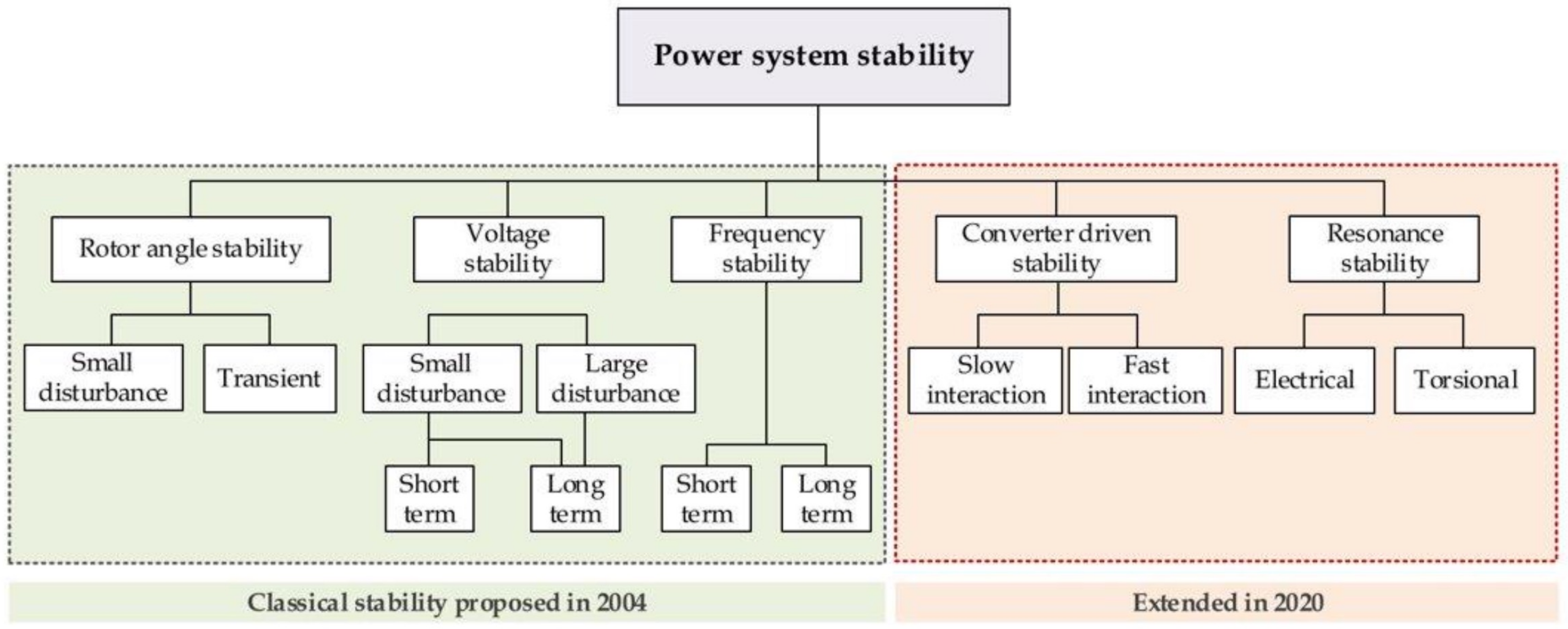


Fig. 1. IEEE classifications of power system stability (Year: 2004 and 2020).

Ancillary services (Grid support services):

- Frequency Control
- Voltage Control
- Black start /restoration

Grid code requirements:

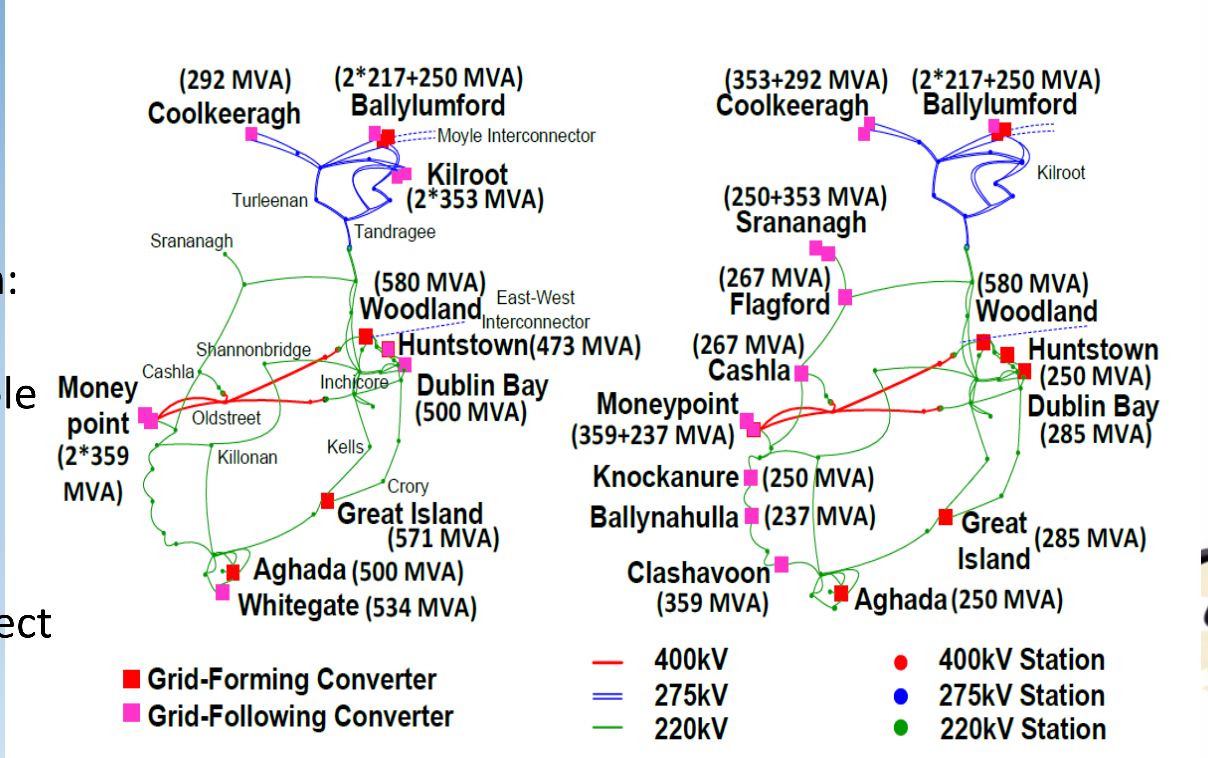
- Fault ride through
- Protection
- Damping

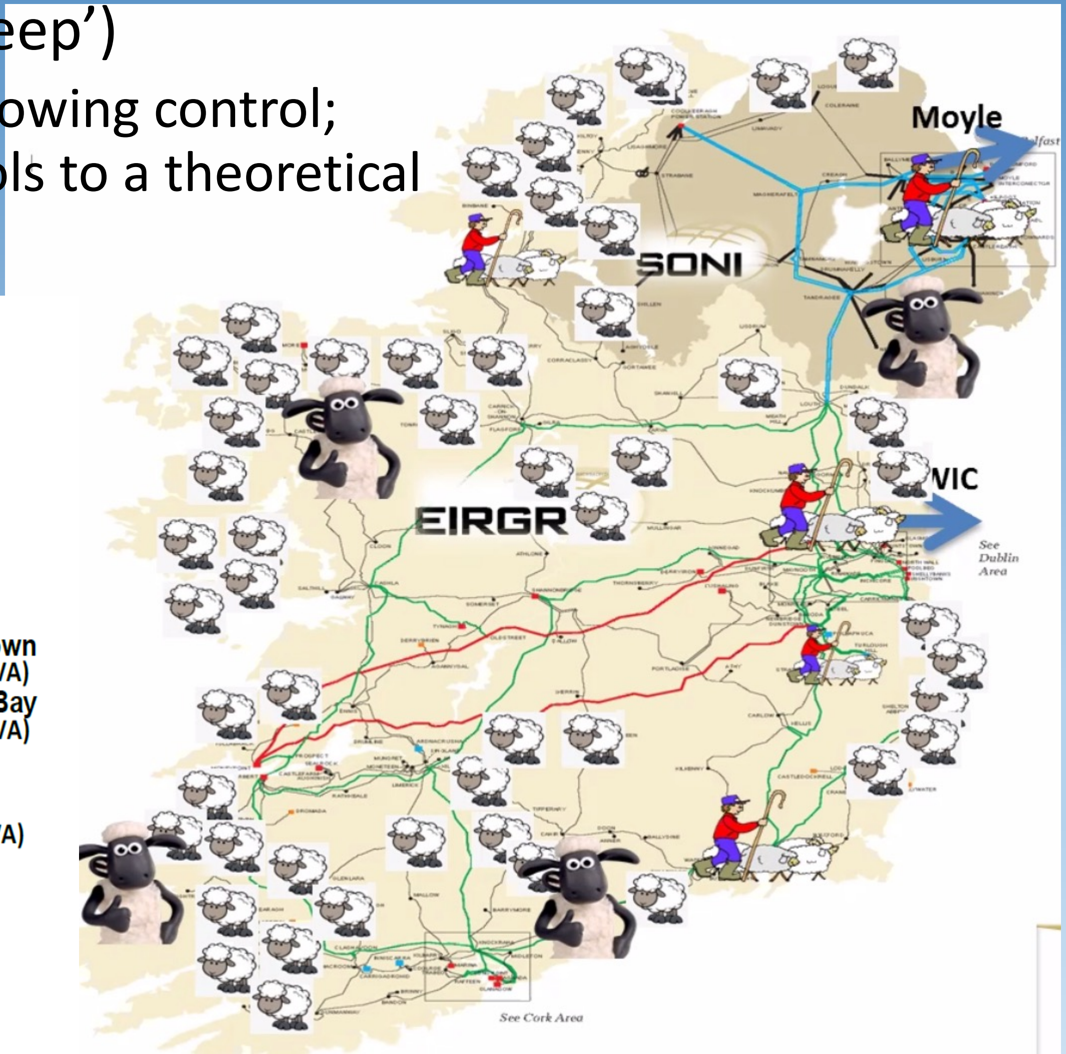
- Interoperability: Synchronous Machines and Inverter based resources (IBR, Grid Following and Grid Forming) should work harmoniously with each other (oscillations – and damping)

Stability of 100% IBR grid – first grid forming studies emerging

- Grid forming inverters to replace synchronous machines ('shepherds') for the grid following inverters ('sheep')
  - 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 for 100% IBR simulation
Source: UCD, MIGRATE project





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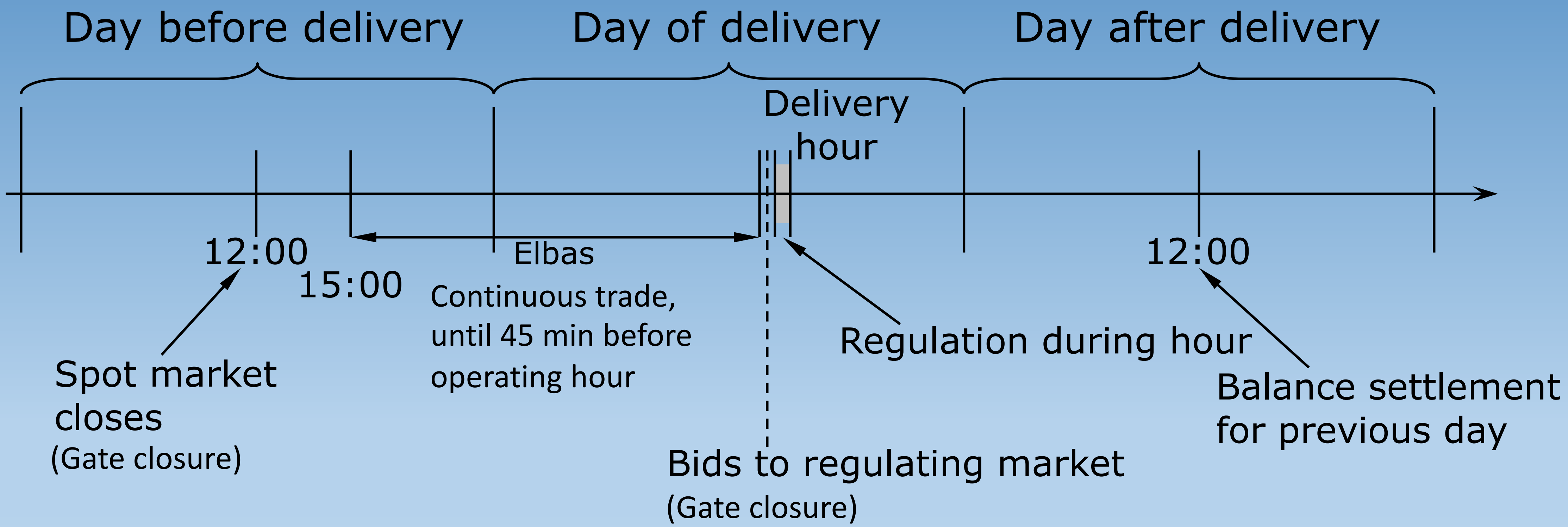
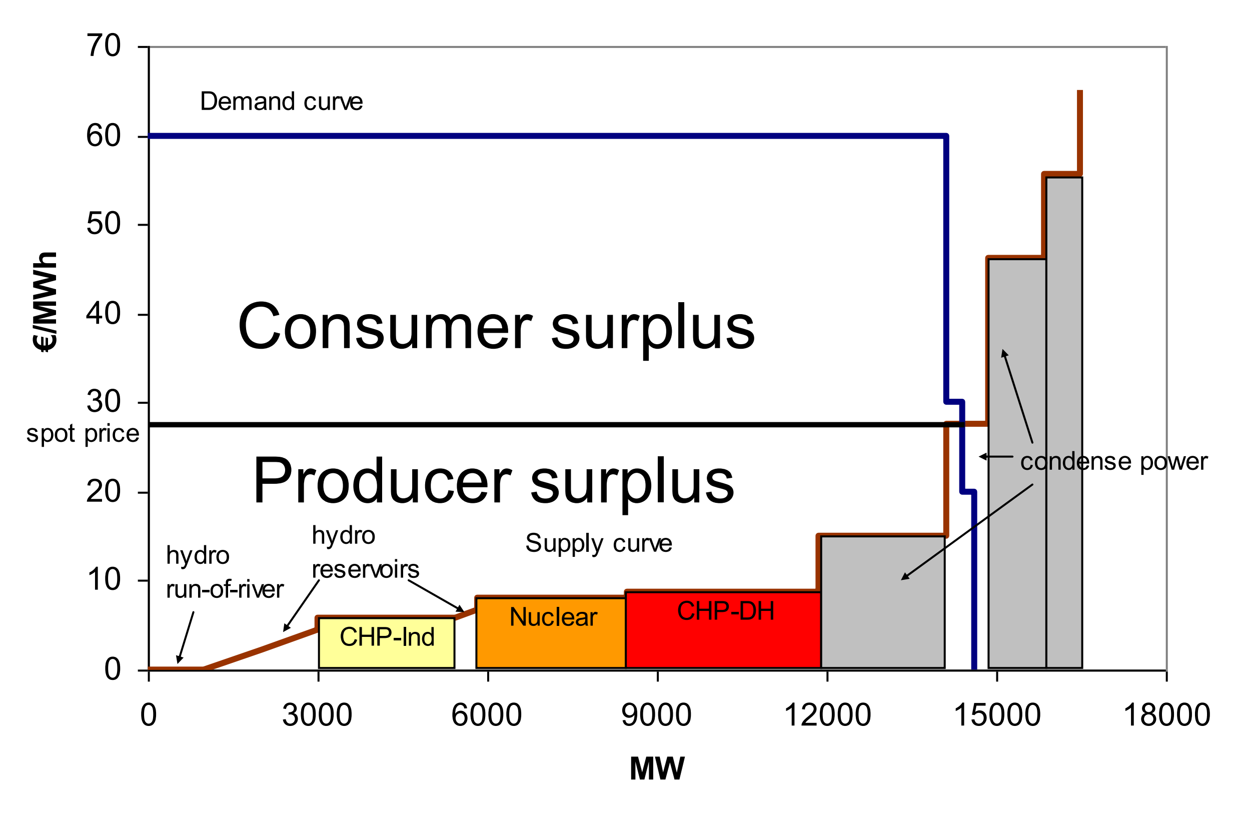
Example of electricity markets: Nordic/European target model



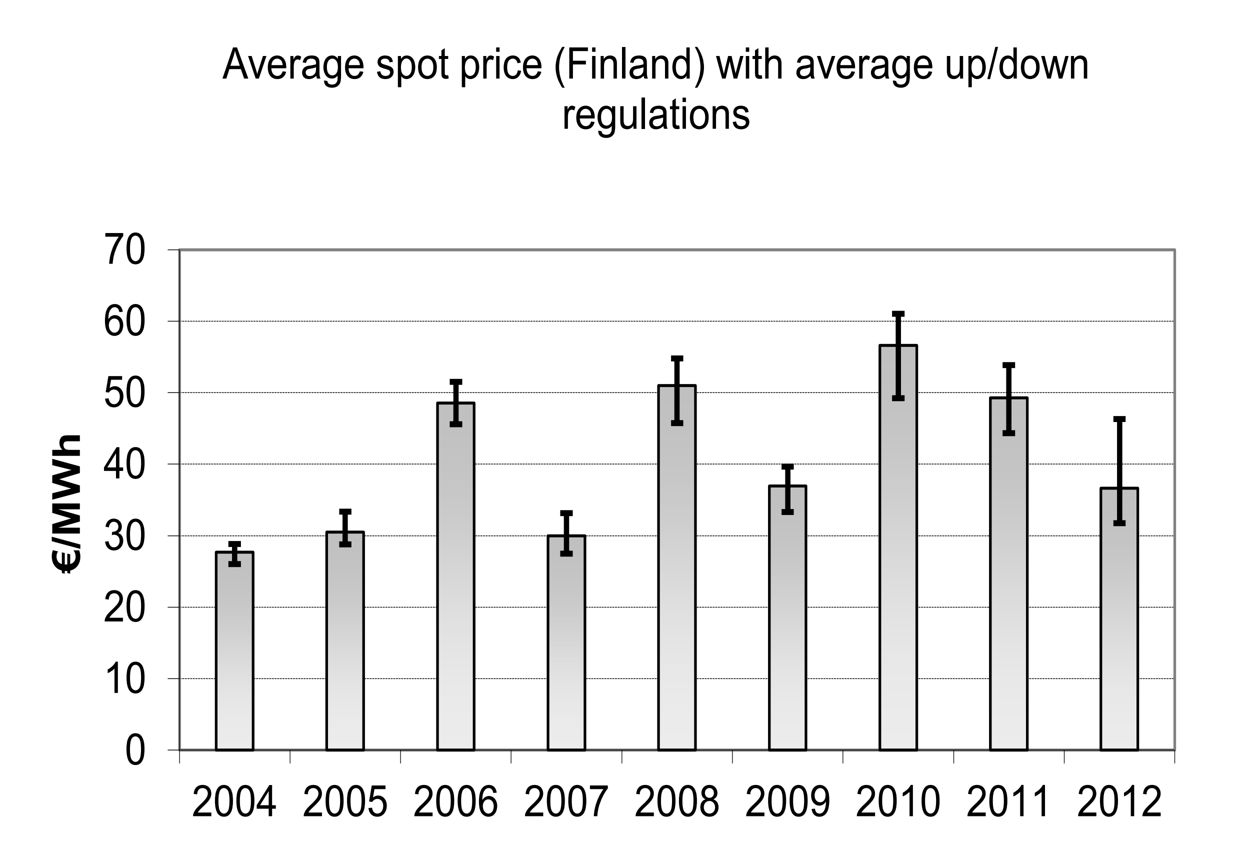
Price formation in the energy only market spot market auction

- Producers make bids based on their marginal costs (in theory).
  - The price of reservoir hydro power is based on the generation costs it expects to replace now or in the future
- Last bid determines the price for all. Producer surplus will cover for the fixed costs of investments and maintenance



Balancing markets to pool all available short term flexibility

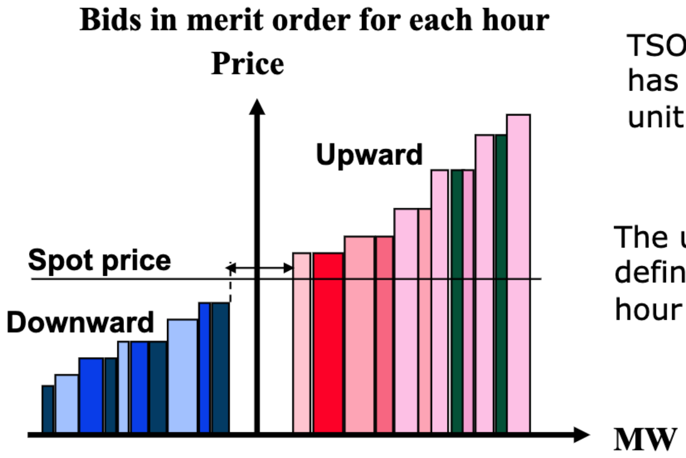
- It is cost effective to bid all available flexibility to balancing market
- If you have flexibility to bid, it is better to bid than to start balancing your own portfolio.
  - If the balancing is needed, you will get paid – no loss
  - If the balancing is not needed, the balancing will be cheaper that your cost (or to the opposite direction



Day-ahead and Regulating Power (=balancing) market prices in Finland. Average day-ahead price varies substantially from year to year. Black error bars depict average unit regulation costs for up and down regulation

Price signal from markets for imbalances

- Handling of imbalances in real time



TSO select the cheapest unit if generation has to be increased and the most expensive unit if generation has to be decreased.

The unit last called upon in each hour defines the real time price for the specific hour

By the end of each hour of operation a price is determined.
This price is also the price of imbalances

 13

- Cost reflective and transparent
- Penalty of imbalance is the same as getting paid for balancing
- You will pay for imbalances more if your imbalance has been causing the use of balancing (if opposite side, then no penalty)

The size of balancing market is only some % of the size of Spot market

Contents

- Wind power impacts on power systems – the issues
- Balancing power systems
- Capturing the impacts of wind on power systems

- Electricity market operation

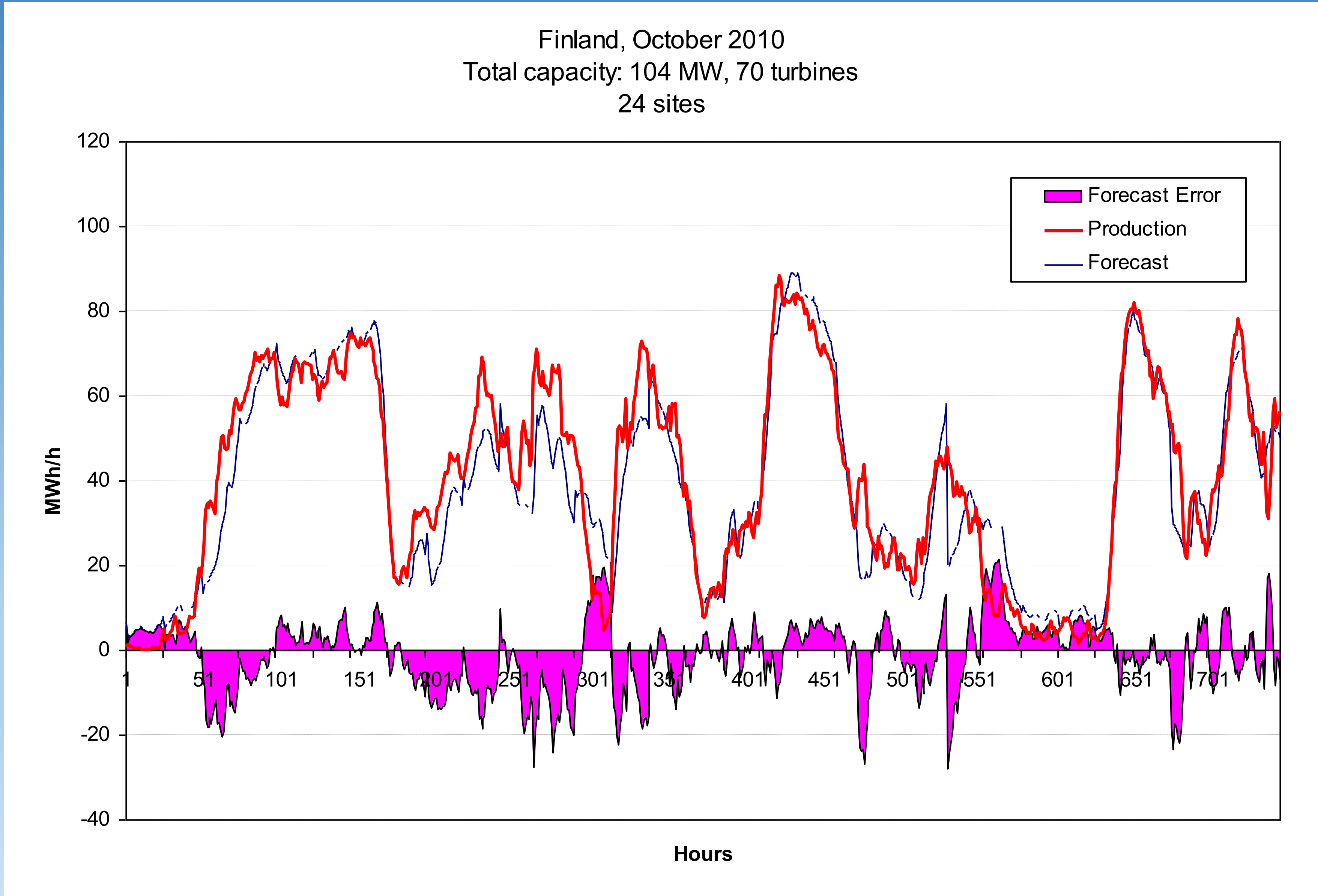
Wind power operator in electricity markets

- Wind power impacts on market prices

Using forecasting at markets

Day-ahead for spot price, to get paid for the energy produced.

Upward or downward regulation needed every hour – paying for imbalances



Wind-power forecasting error - key performance indicators

$$MAE = \frac{1}{N_h}\sum_{N_h}\frac{|error(h)|}{P_{installed}(h)} = 6.0\%$$

$$RMSE = \frac{1}{N_h}\sum_{N_h}\sqrt{\left(\frac{error(h)}{P_{installed}(h)}\right)^2} = 8.9\%$$

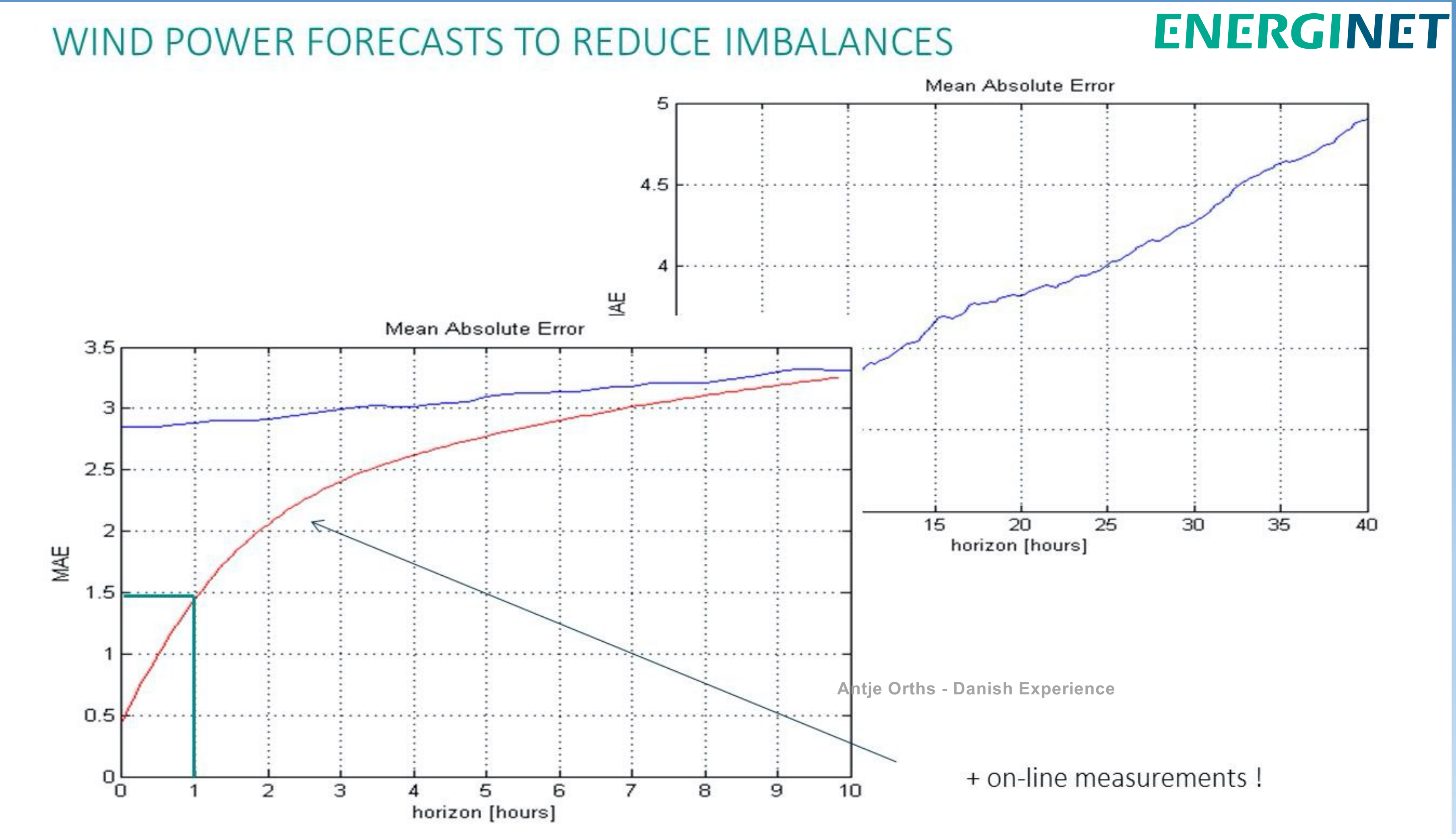
$$MAPE = \frac{\sum_{N_h}|error(h)|}{\sum_{N_h}production(h)} = 23.8\%$$

MAE= Mean Absolute Error
RMSE= Root-mean-square error
MAPE=Mean Absolute Production error

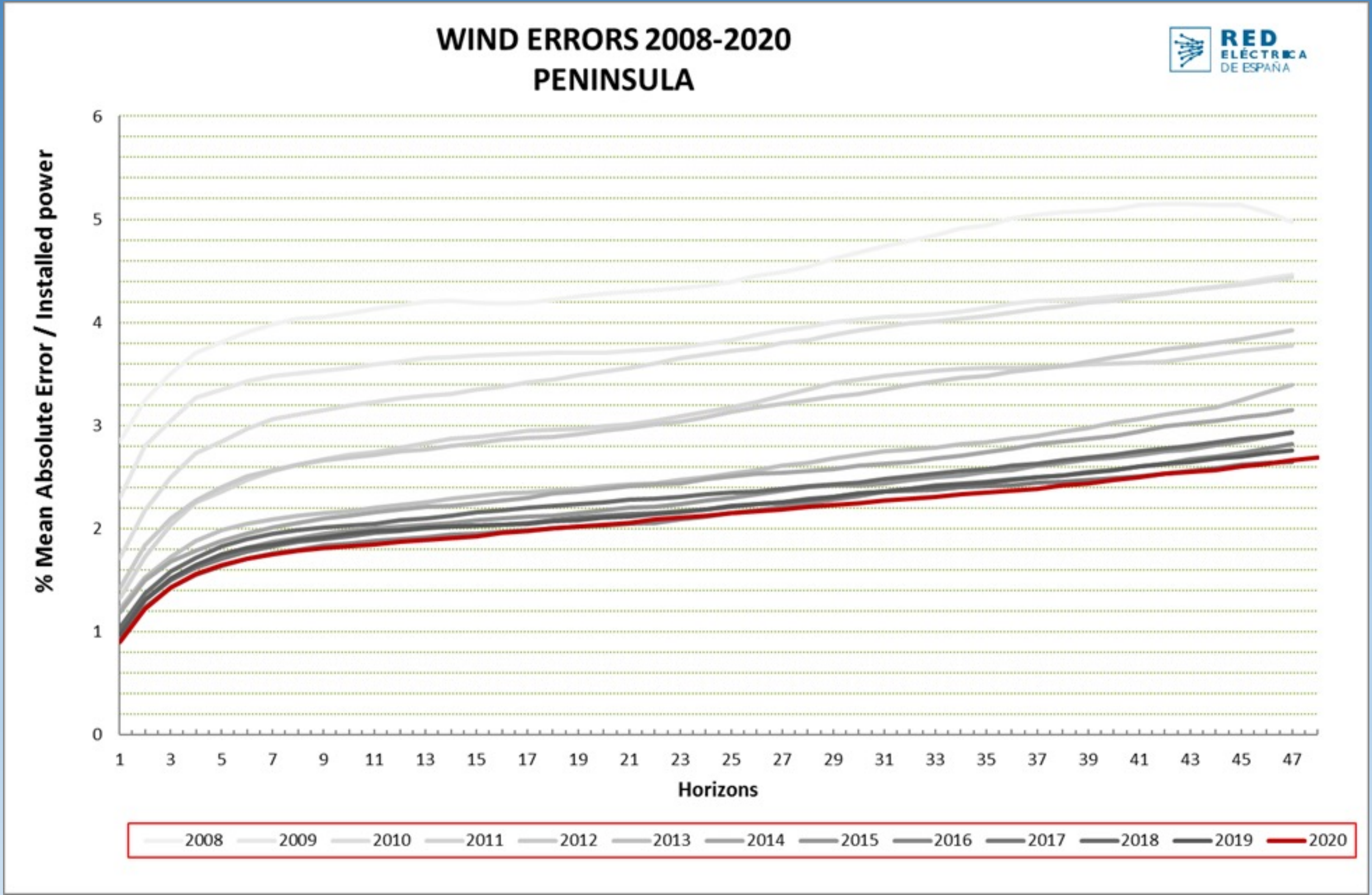
- case Western part of Denmark, Based on 1512 MW of wind power 2007 (see next slides for more state-of-the art MAE values):
  - Forecast at 11 am for the next day (t+13 to t+37 hours)

System wide forecasting

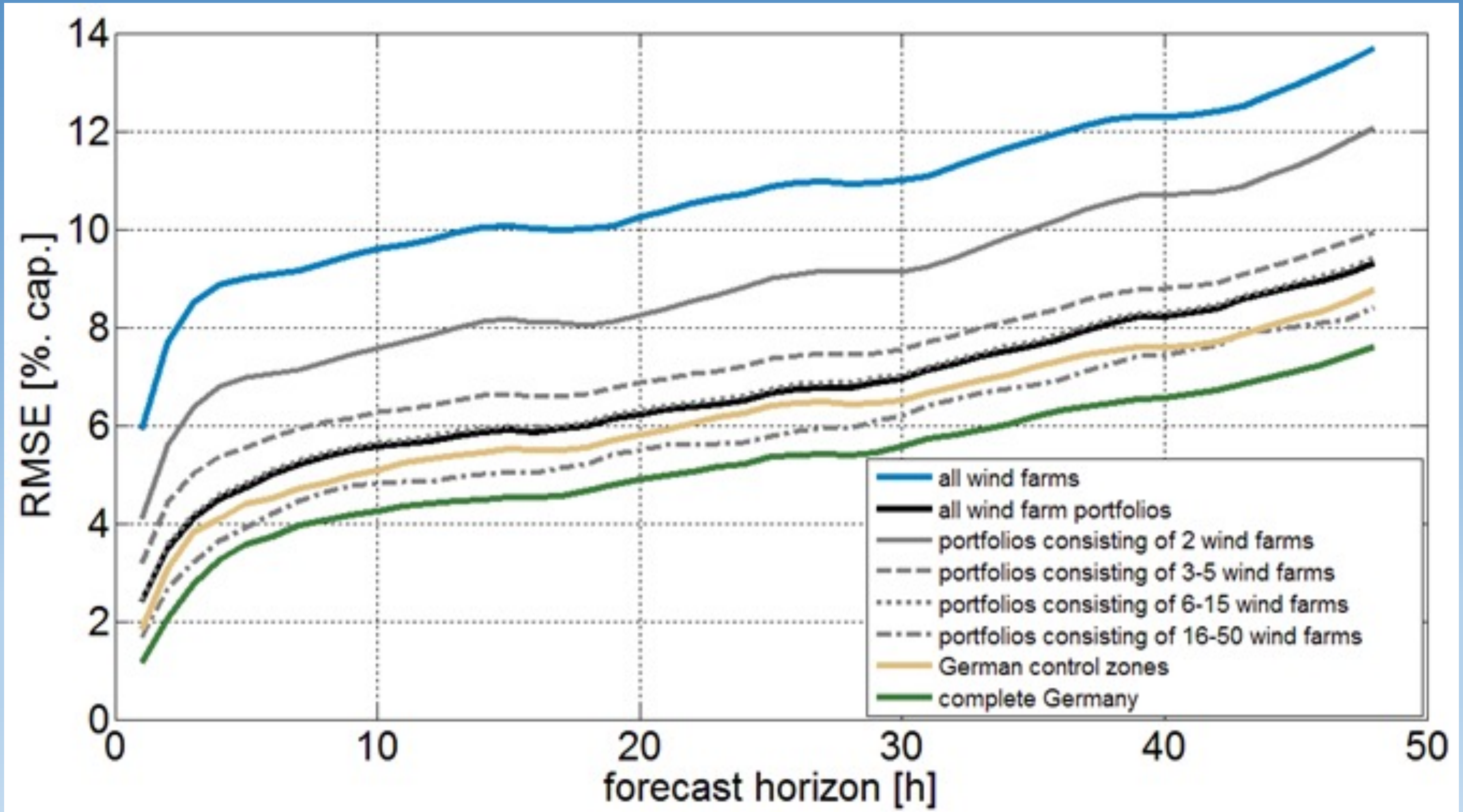
- System operator forecasts for the balancing area
- Combined forecasts from market parties / Balance responsible players



Forecasts are improving over time (example wind in Spain)

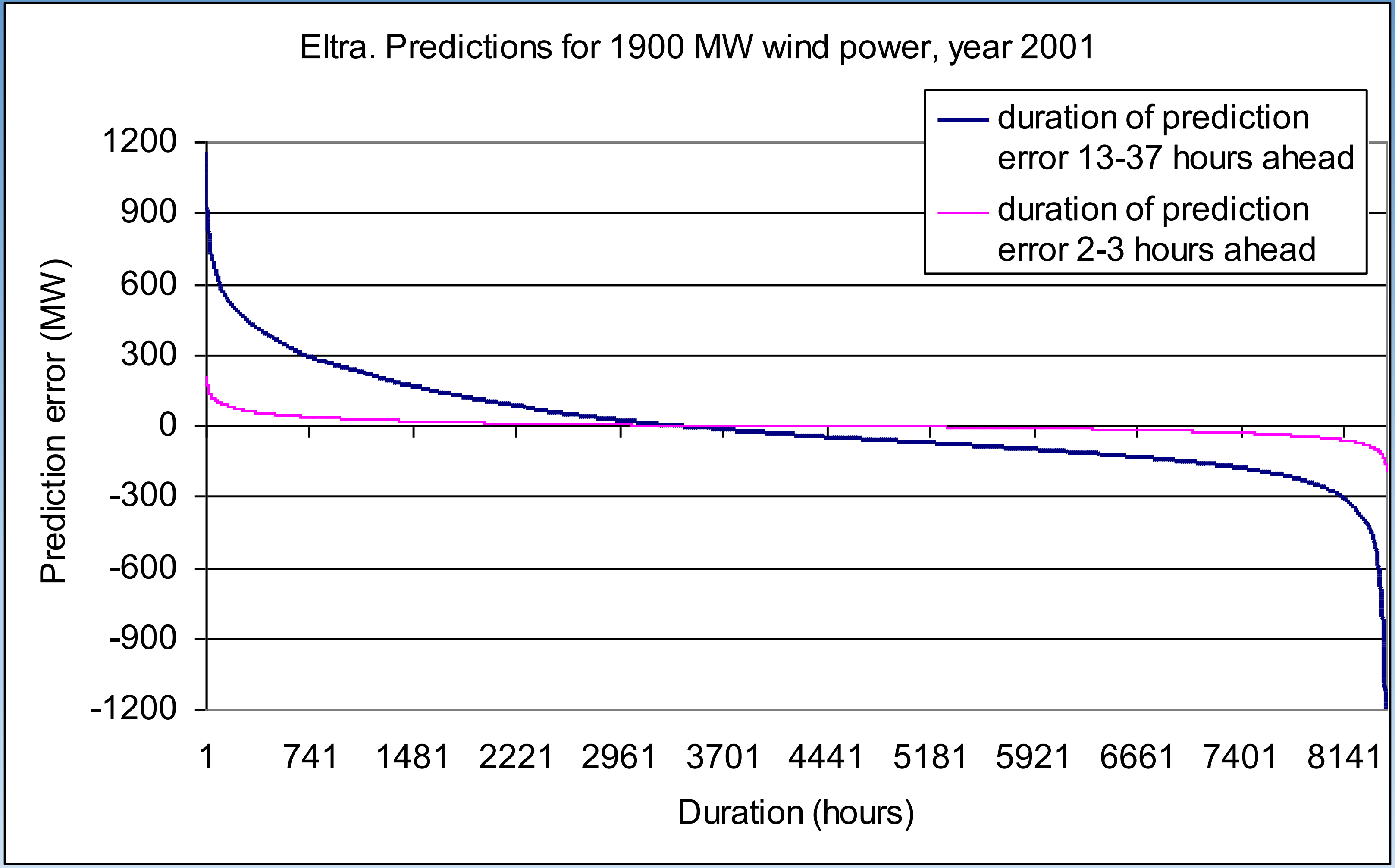


Forecasts better for aggregated wind



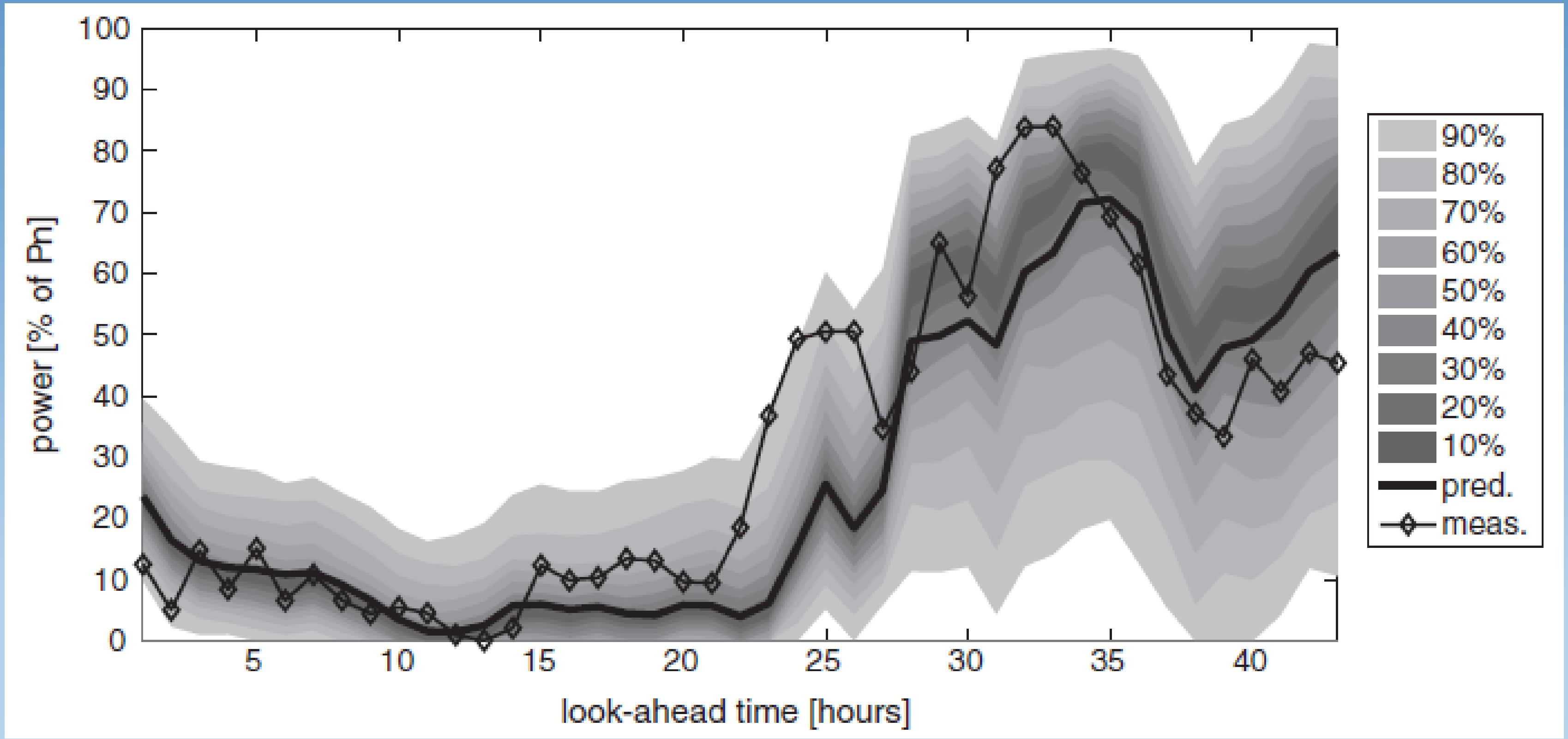
Source: Jan Dobschiski, Fraunhofer IEE

Forecast errors improve a lot from day ahead to some hours ahead– intra-day trade may be used for correcting day-ahead bids



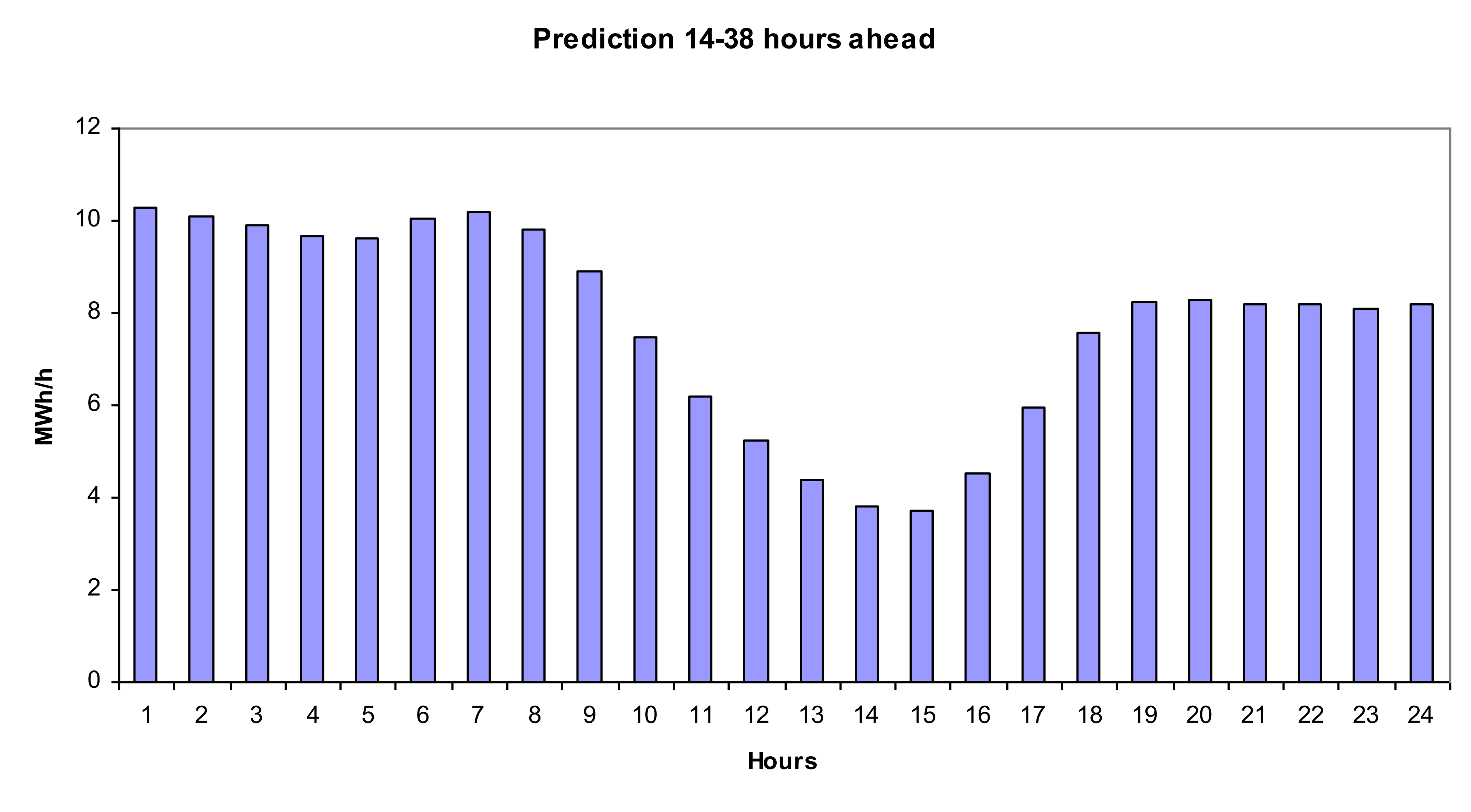
The data for the figure is from 1997 state-of-the-art forecast model, nowadays much smaller

Information about uncertainty can be used when making the bids - ensembles

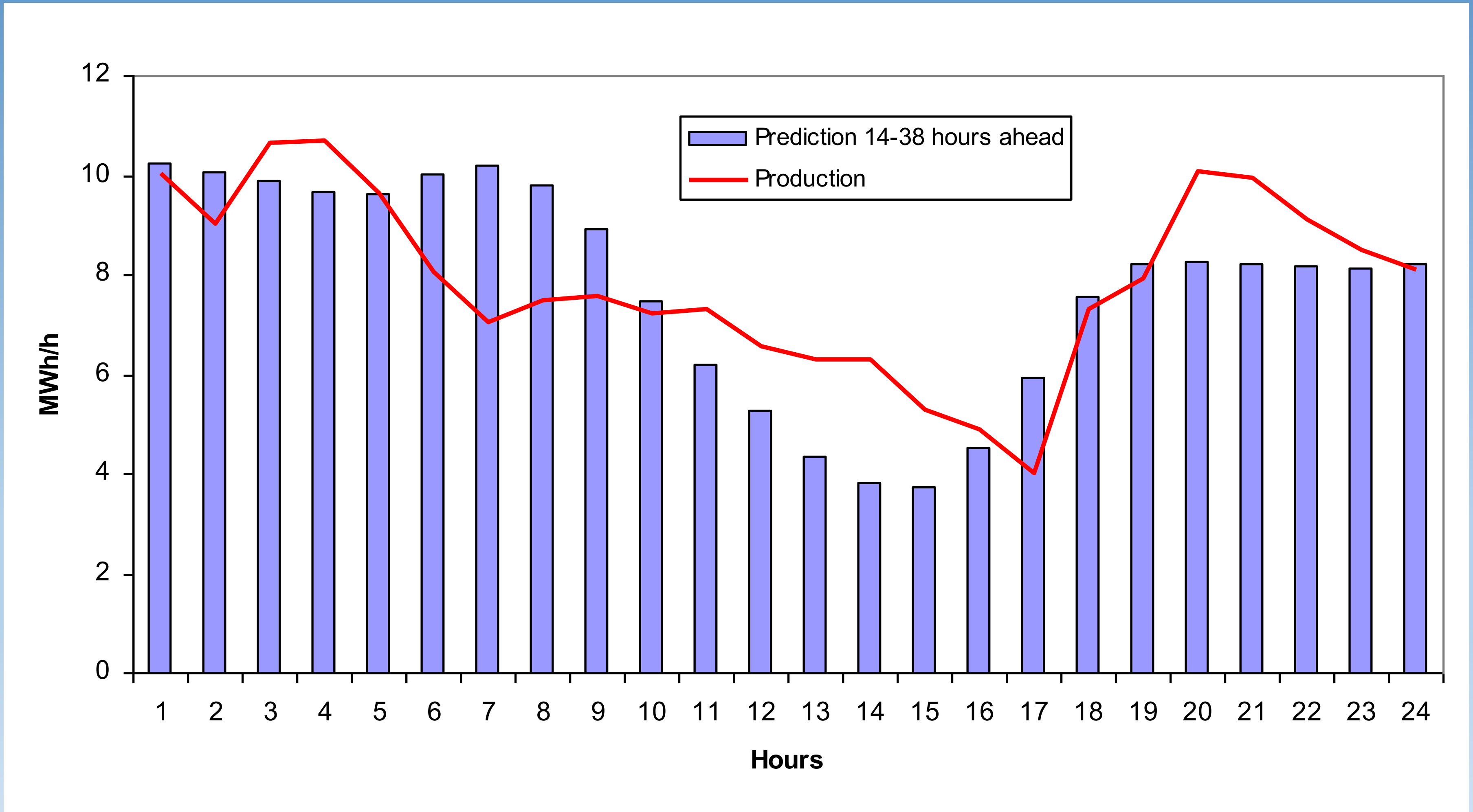


Source: Pinsen P, Madsen H, Nielsen HA, Papaefthymiou G, Klöckl B. From Probabilistic Forecasts to Statistical Scenarios of Short-term Wind Power Production. Wind Energy 2009; 12:51–62

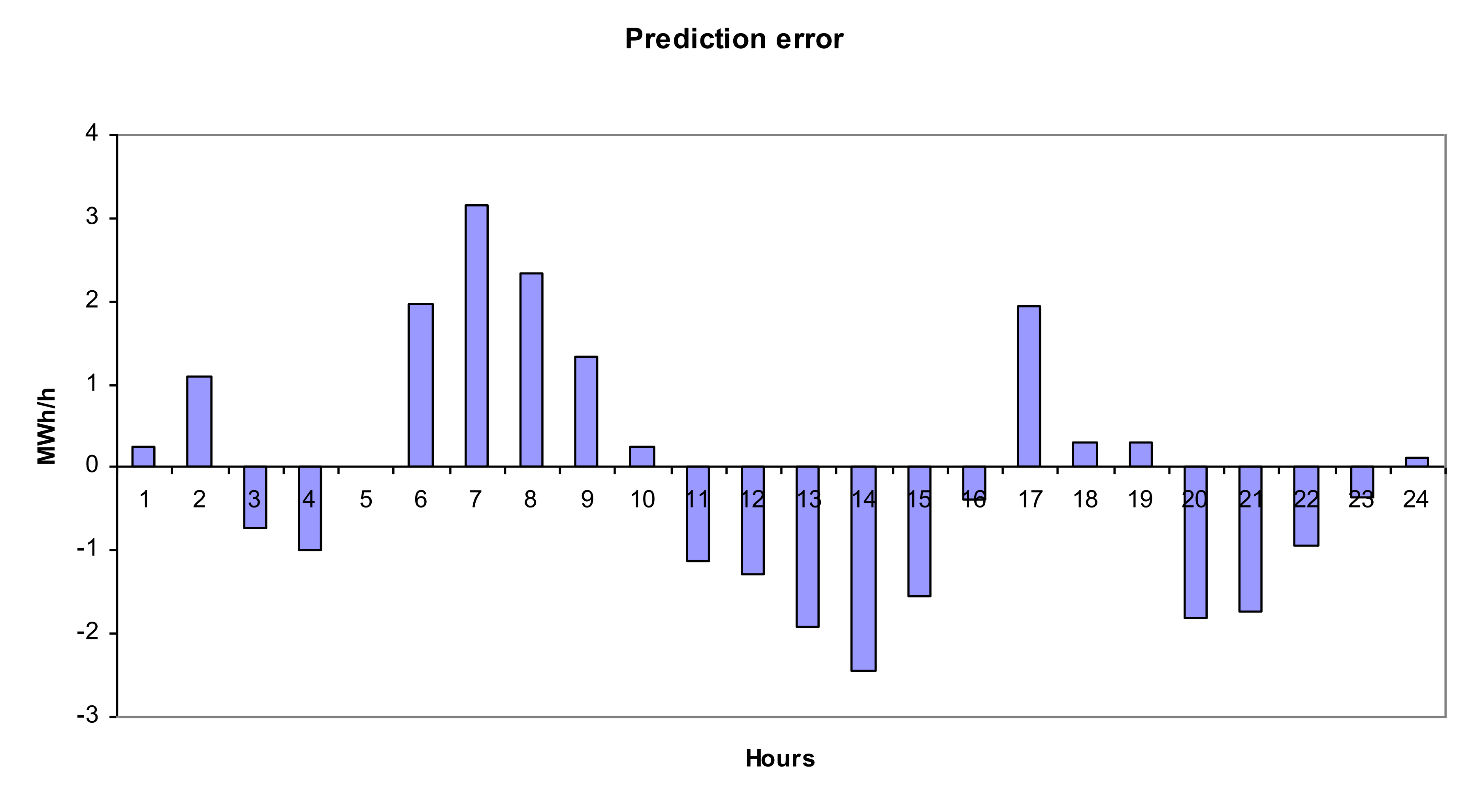
Example of market operation of wind power plant for one day: Forecast to the markets 12-36 hours ahead



Forecast and realised generation



Forecast errors

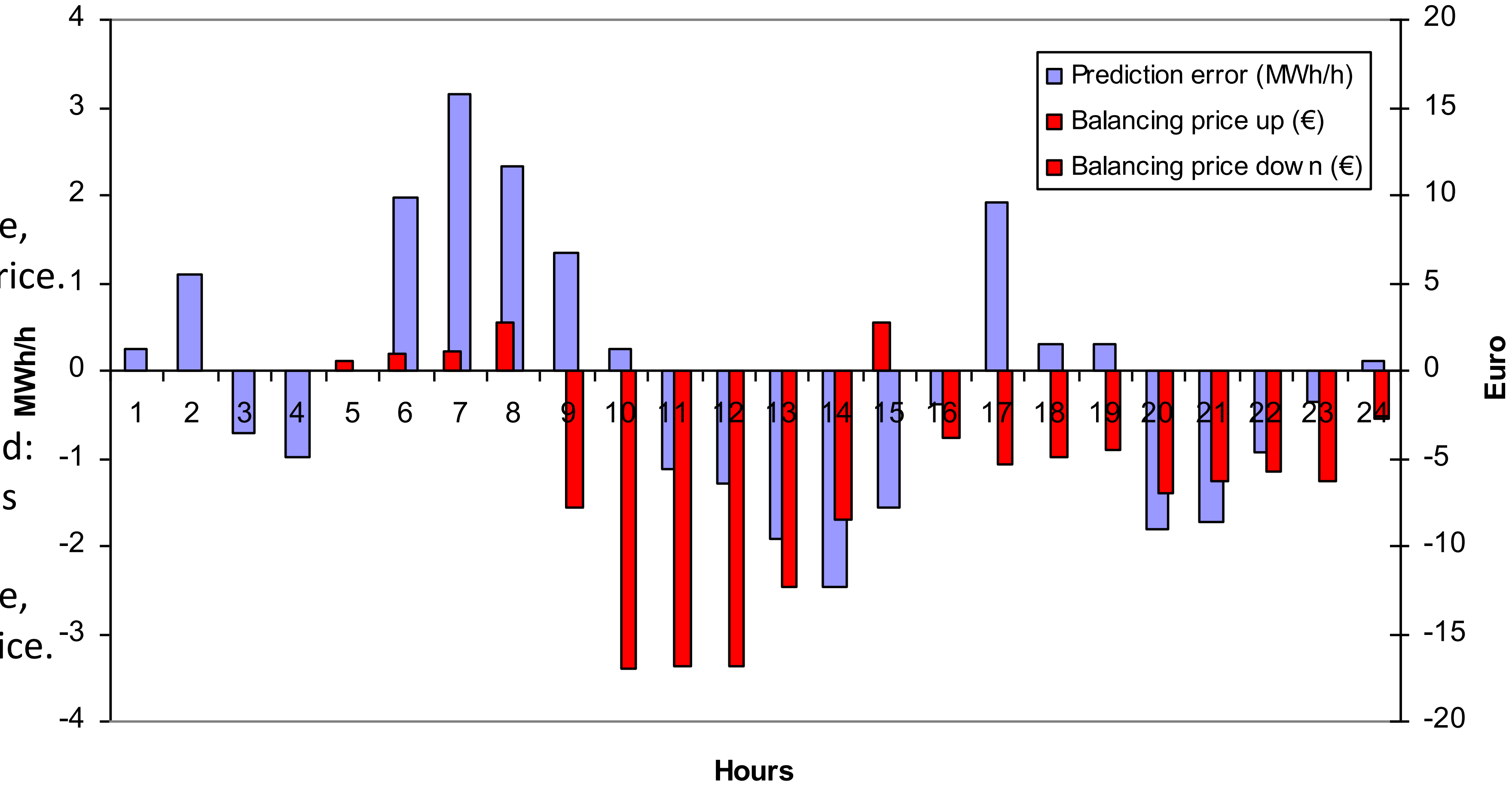


Forecast errors and balancing costs (cost from egulating power market to correct the system net deviation for that hour)

Balancing price: difference of spot price and Regulating power market price, €/MWh

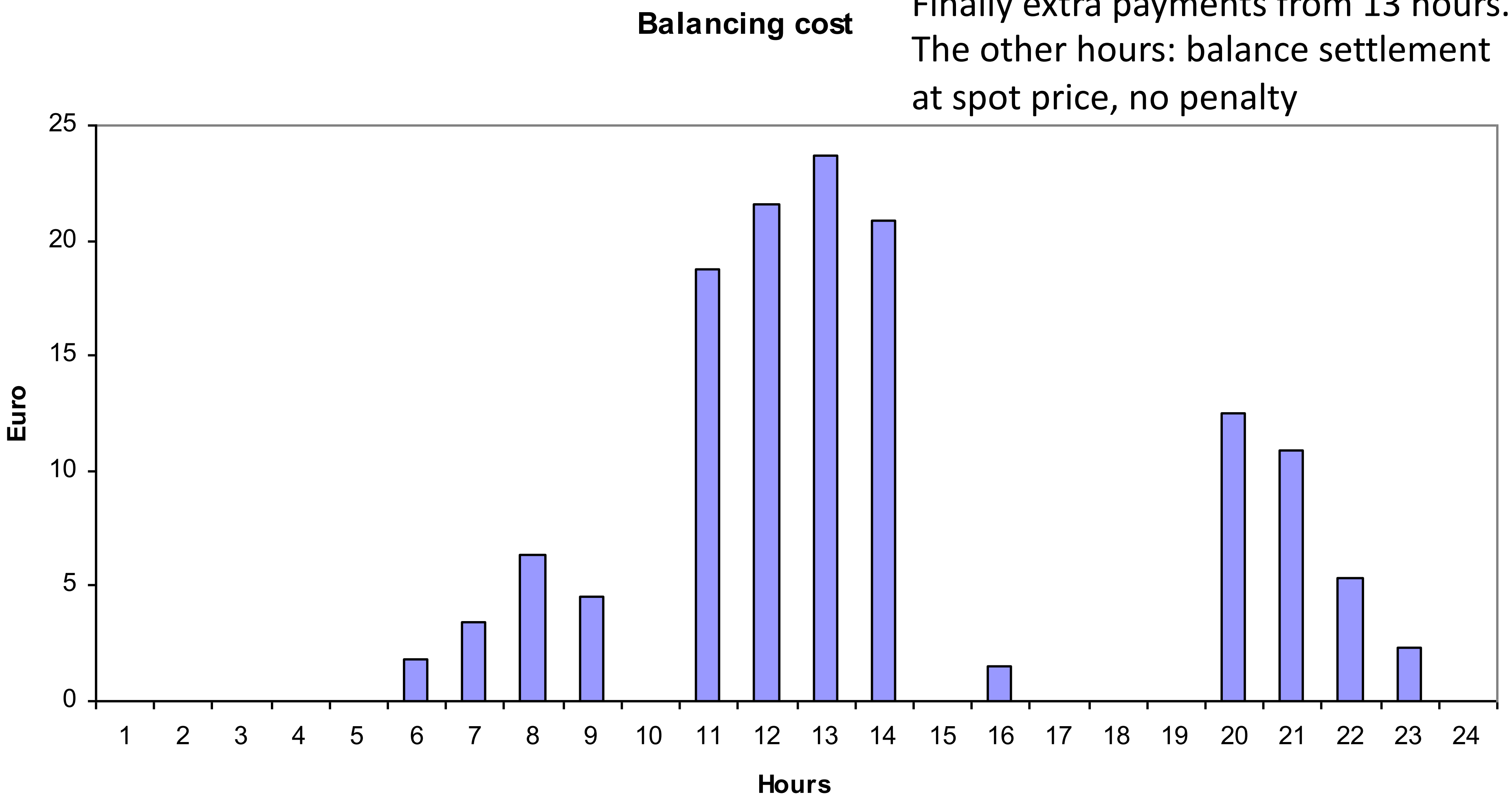
Balancing cost for upregulation needed: buying the missing generation at a Regulating market price, higher than the spot price.

Balancing cost for downregulation needed: selling the extra surplus generation at a Regulating market price, lower than the spot price.



Costs only from hours where system error is increased due to wind power error

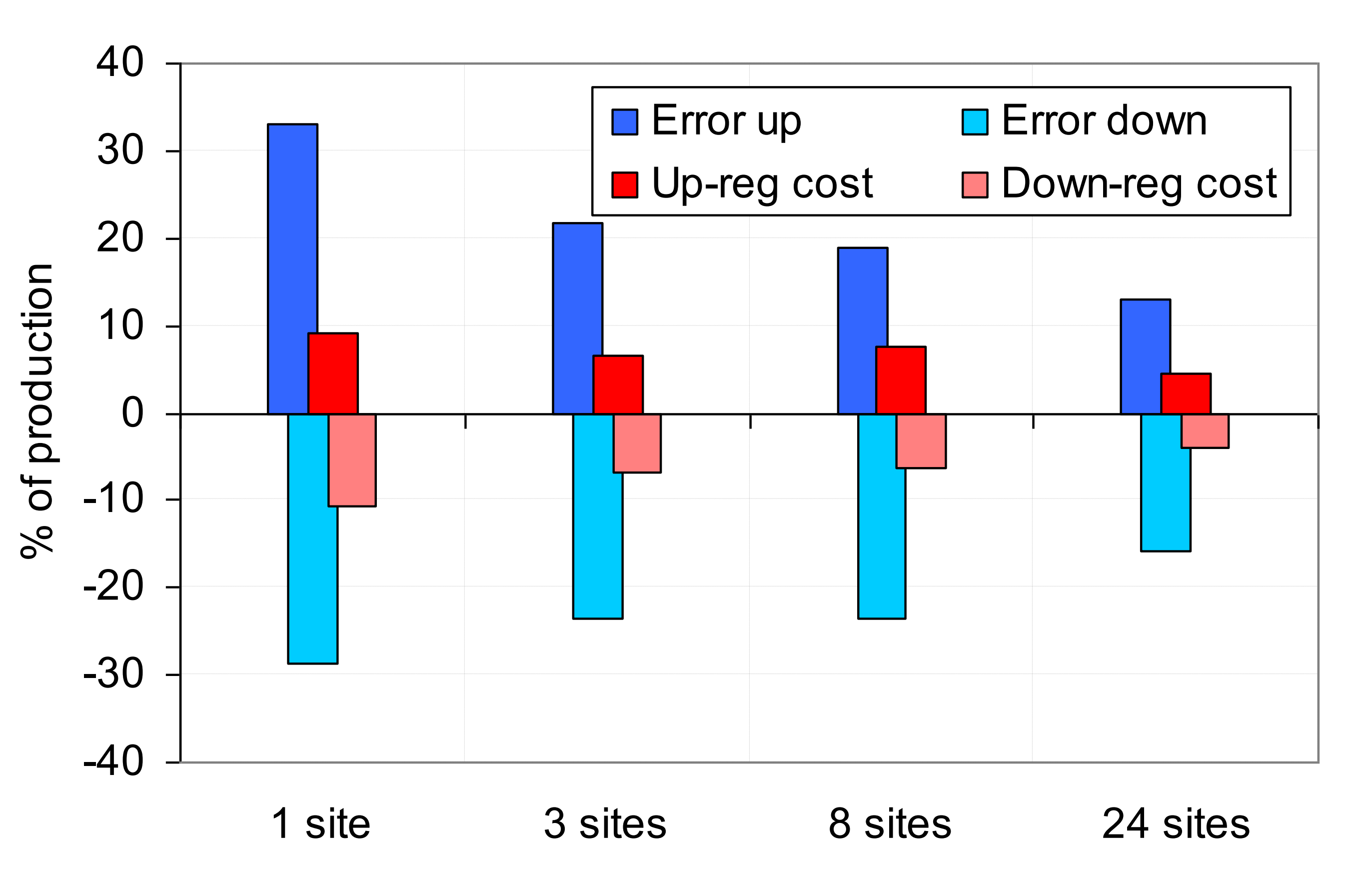
Balancing costs: difference of spot market income and balance settlement



Finally extra payments from 13 hours. The other hours: balance settlement at spot price, no penalty

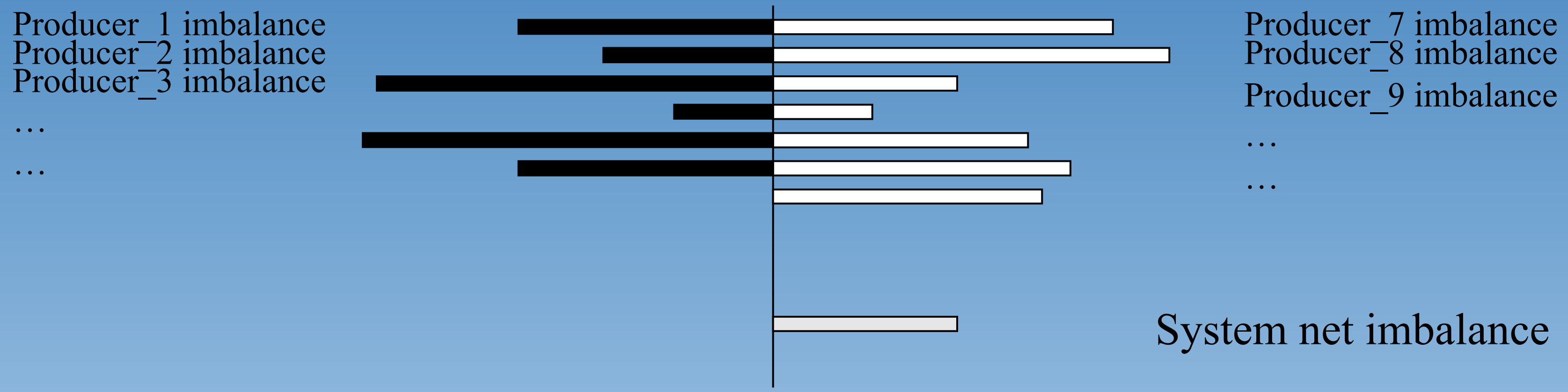
Forecast errors resulting to balancing costs example for aggregated sites, one year

- Blue bars – sum of prediction errors up/down, as % of the total production
- Red bars – sum of prediction errors up/down that result in extra payments



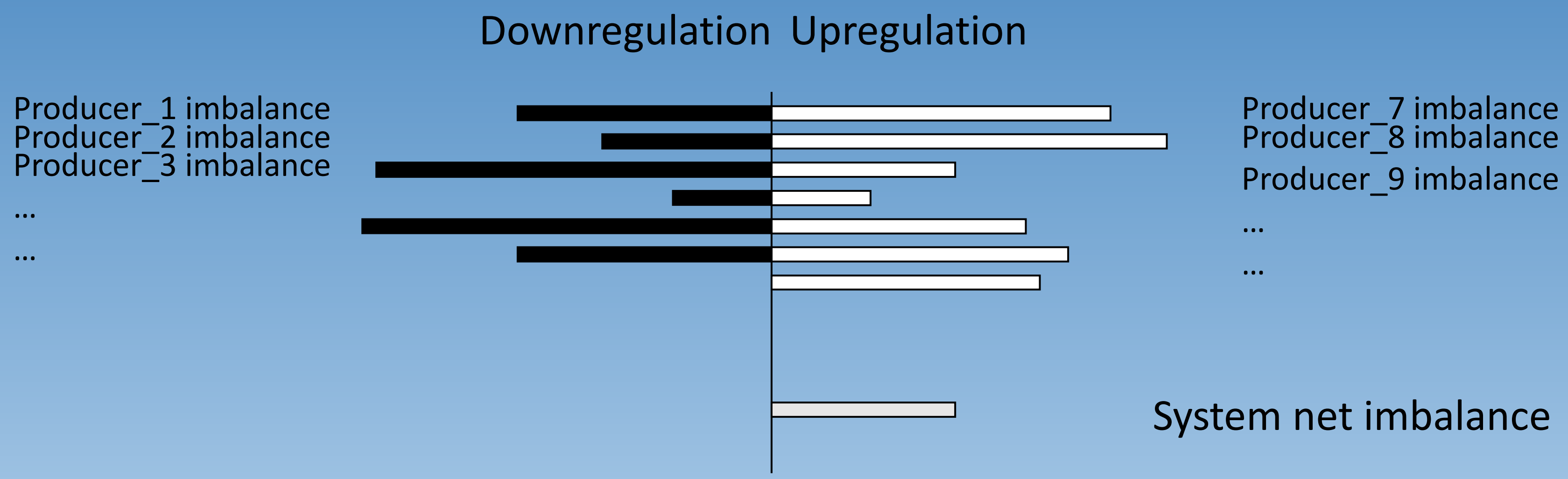
Cost reflective market rules for imbalances help a lot
Fixed penalties would result in high imbalance costs

Imbalances are penalised



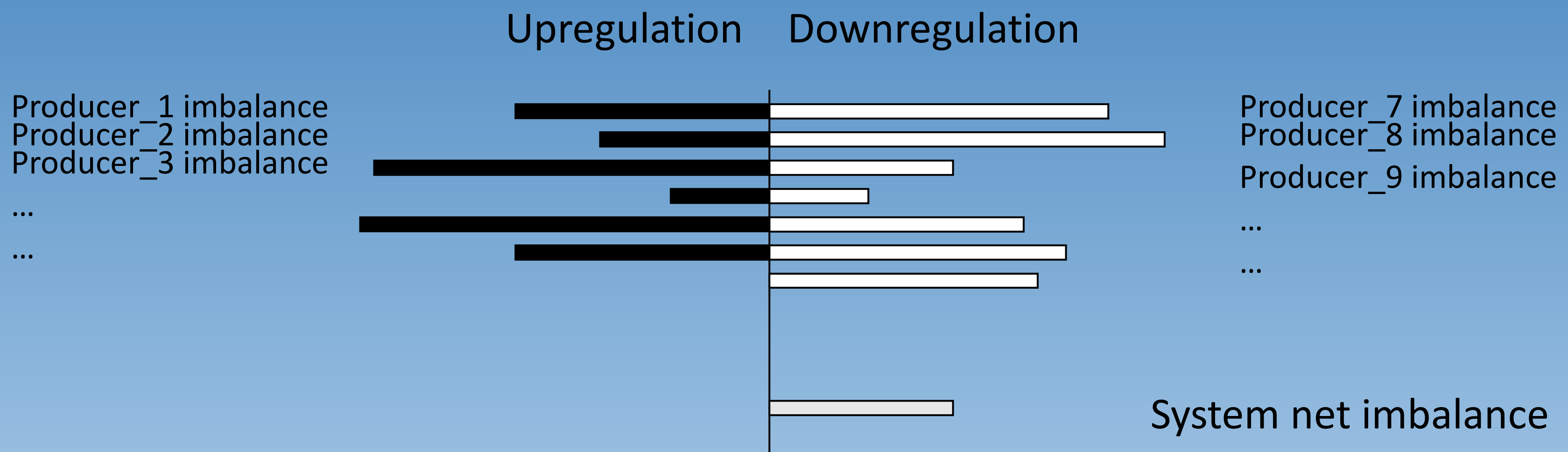
- Transparent and cost reflecting pricing of imbalances:
  - Balancing market to cover the system net imbalance → price for imbalances of that hour
- System operator charges regulating power price for imbalances from all producers that have had their imbalance in the same direction as the system need
- The producers that have had their imbalance in the opposite direction: What about if your imbalance has actually helped the system (the black ones)?
  - pay/receive the spot market price for the imbalance (two-price model) – no penalty
  - pay/receive the balancing market price (balancing fees are circulated; one-price model) – you make money even just accidentally helping the system

Balance settlement rules – example case upregulation



- Upregulation price higher than spot price
- The producers that have produced less than predicted have to pay more than spot price for the missing energy
- The producers that have produced more than predicted get the spot market price for extra production (two-price model) or get the regulating market price (extra gain; one-price model)

Balance settlement rules – example case downregulation



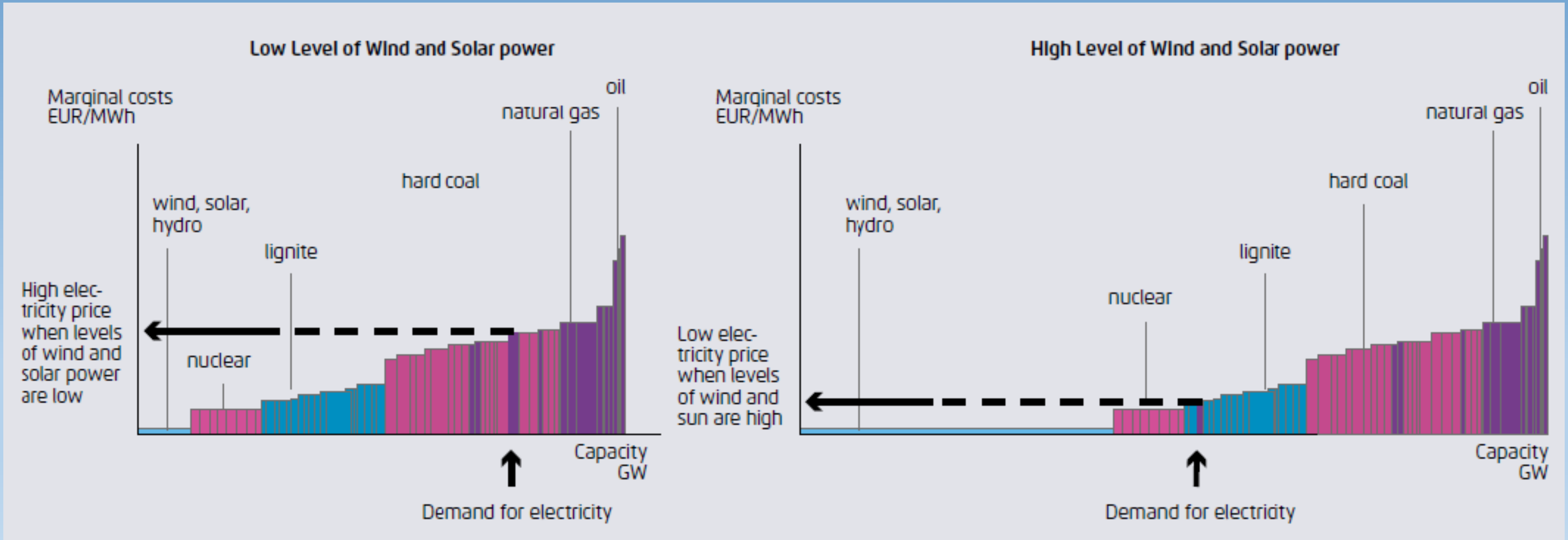
- Downregulation price lower than spot price
- The producers that have produced more than predicted get less than spot price for the extra energy
- The producers that have produced less than predicted pay the spot market price for missing production (two-price model) or pay less than spot price for the missing quantity (extra gain; one-price model)

Contents

Wind power impacts on market prices

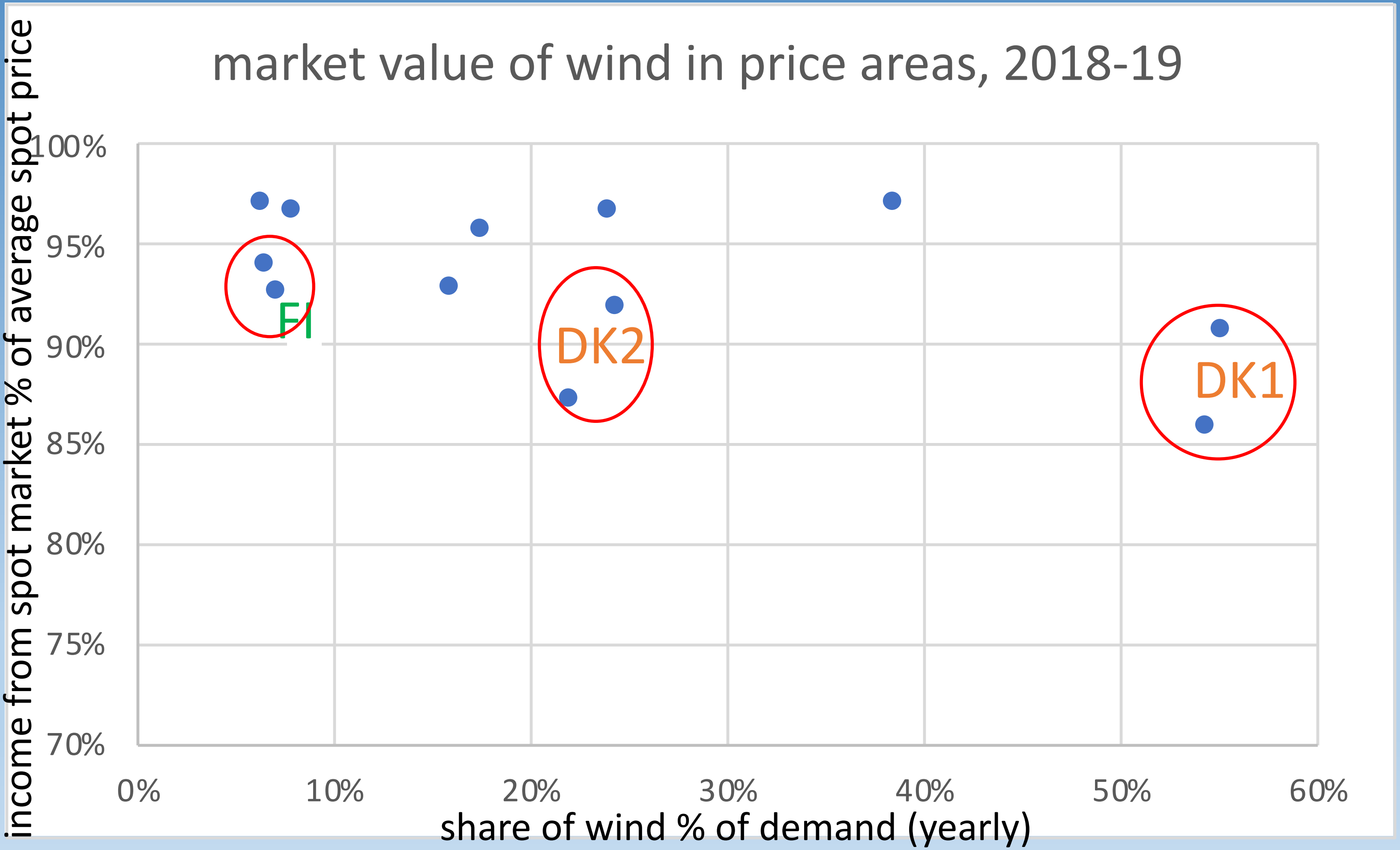
Merit order effect: lower market prices due to wind and solar

Wind power production bids according to forecasts. Wind, solar and run-of-river hydro power have almost no marginal costs → Supply curve moves to the right. → Lowers market price when a lot of wind available → more volatility to prices, low wind / high wind days

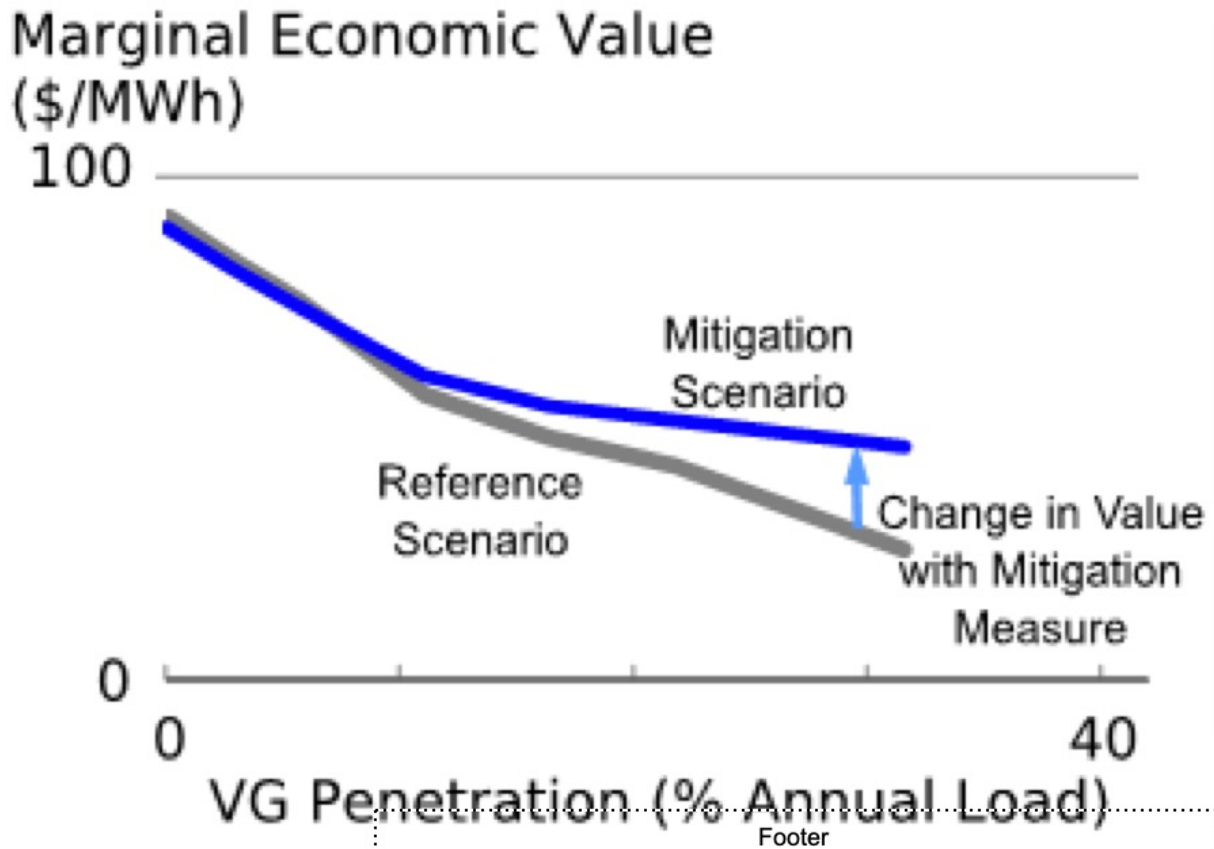


Source Agora Energie wende, “12 Insights on Germany’s Energiewende”

Example of merit order / cannibalism effect, Nordic market price areas



Ways to mitigate the cannibalism effect



The mitigation measures considered include:

- increased geographic diversity
- technological diversity
- lower-cost bulk power storage
- price elastic demand subject to RTP

Large market area.
Distribute wind power
Build wind and solar

Add flexibility

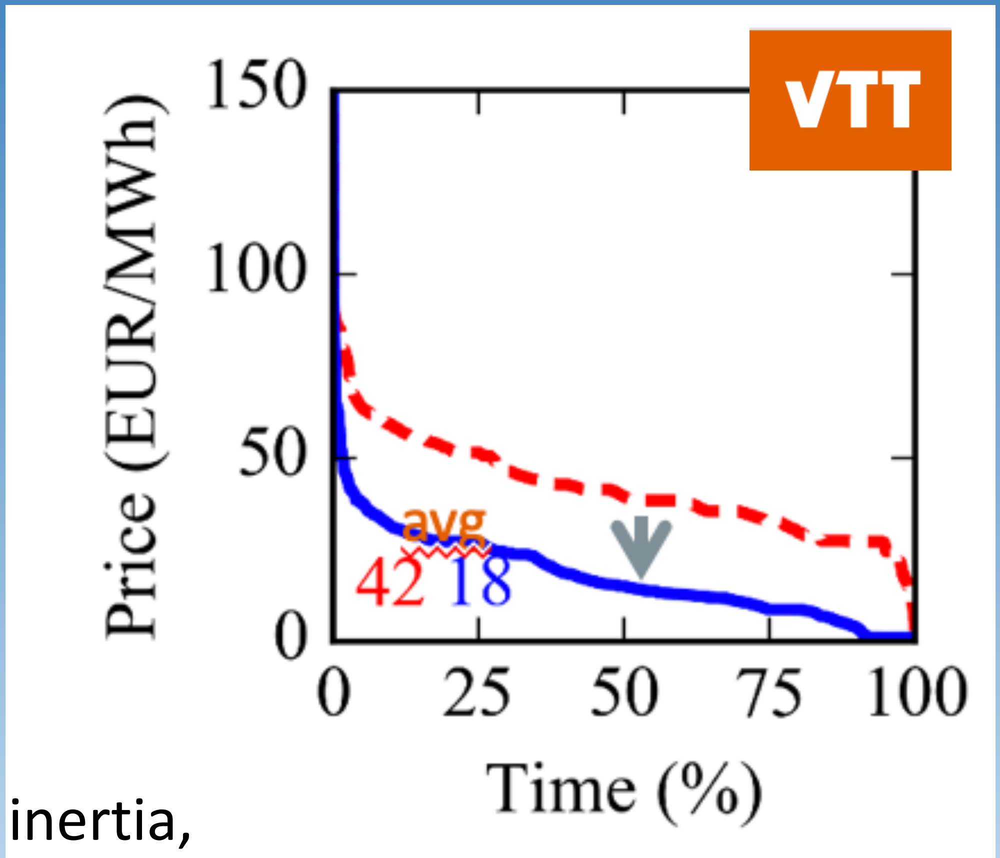
Footer

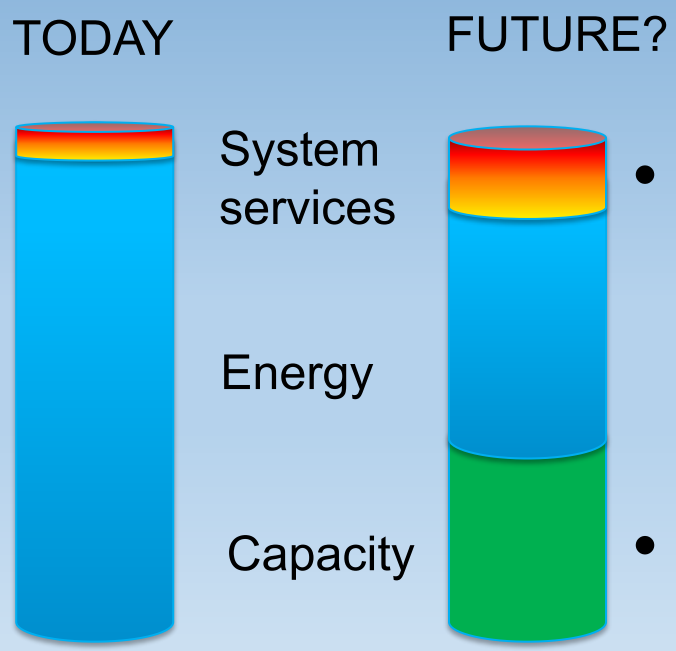
Environmental Energy Technologies Division 8

Source: Ryan Wiser, Berkeley lab LBNL

Market challenge: revenue sufficiency also for other than wind

- Due to 0 marginal cost renewables
- New power-to-X loads can change the picture if timing when wind/PV available
- Storage may be an option

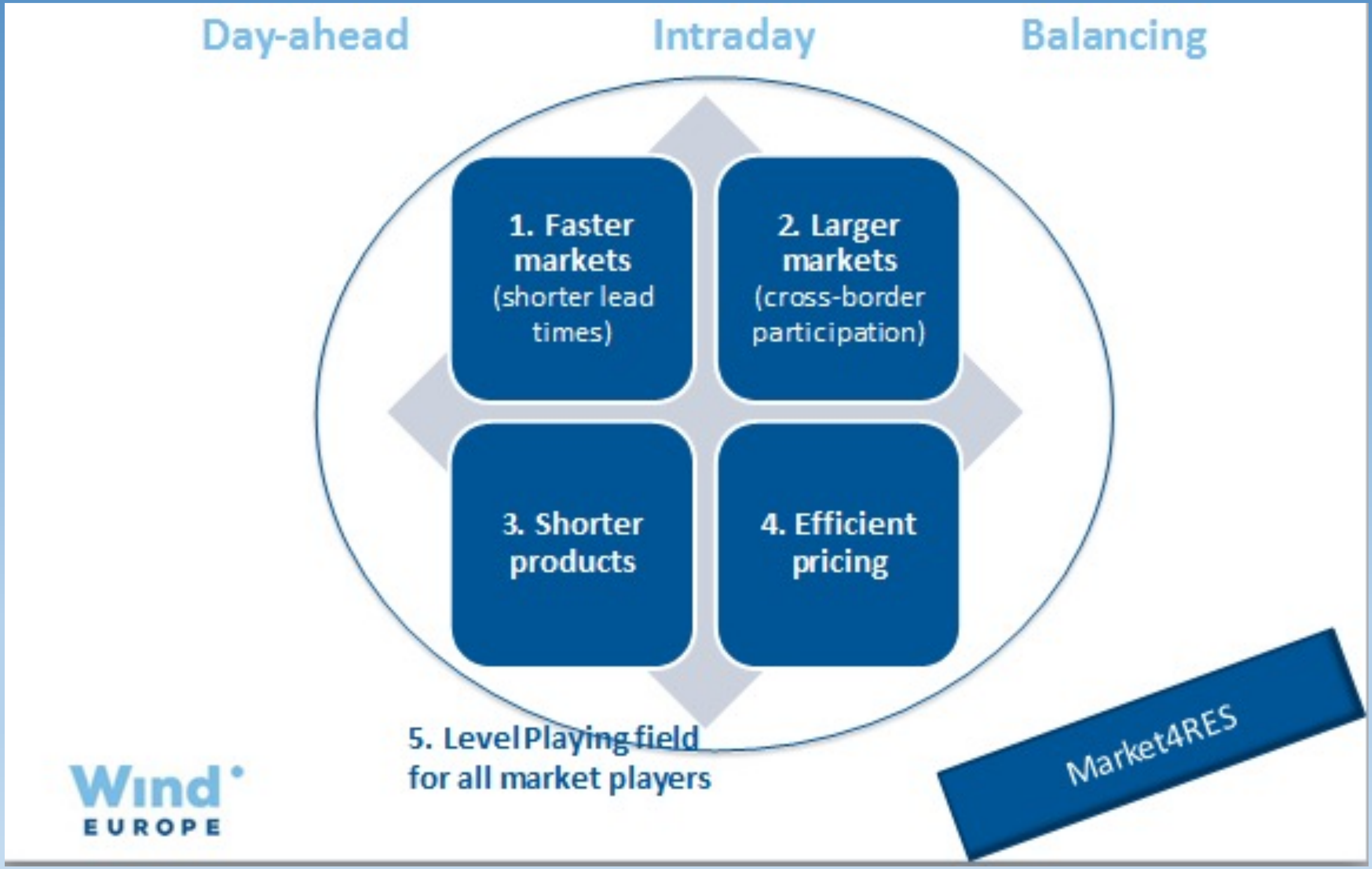




- Paying for new services
  - More grid support services: inertia, ramping, voltage,..
  - Remunerating for capabilities in grid code requirement
- Scarcity pricing or capacity payment

Market design changes to enable wind/solar to participate

Gate closure time – can you bid some hours ahead, when you know your generation level?



Summary of today

- What are the main impacts of wind on power and energy systems
  - Balancing needs – flexibility, different time scales
    - minutes – operating reserves (impact from uncertainty)
    - hours – ramping
    - days and weeks – turning down other generation – or more demand- to make wind fit
    - years – events of low wind and high demand, adequacy of generation (or flexibility of load)
  - Transmission and larger areas and faster system operation as enablers
  - Future: also stability impacts, wind offering more support (grid forming)

- Wind power operators acting in markets
  - forecasts, imbalance settlement for forecast errors
- Wind power impact on market prices and ways to mitigate

For further reading

- Fact sheets: https://community.ieawind.org/task25/home (scroll down for Integration Fact Sheets)
  - Also good: https://greeningthegrid.org/resources/factsheets

- For further reading on how to study power systems with wind and solar: Recommended Practices for wind and solar integration studies https://community.ieawind.org/rp

Thank you for your attention

Recognis Consulting

www.recognis.fi

hannele.holttinen@recognis.fi