Offshore wind farm operations and power system economics

Remco Verzijlbergh

13-2-2026

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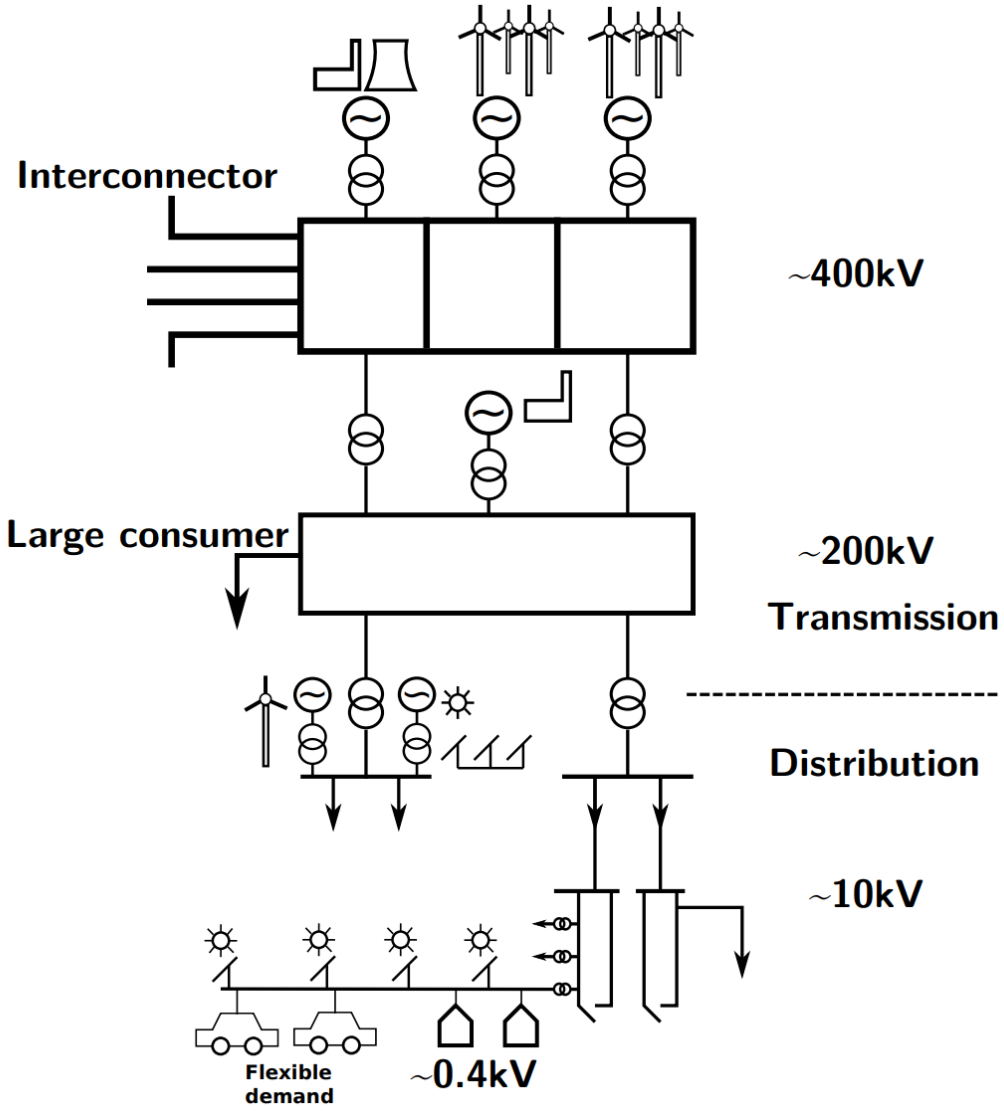
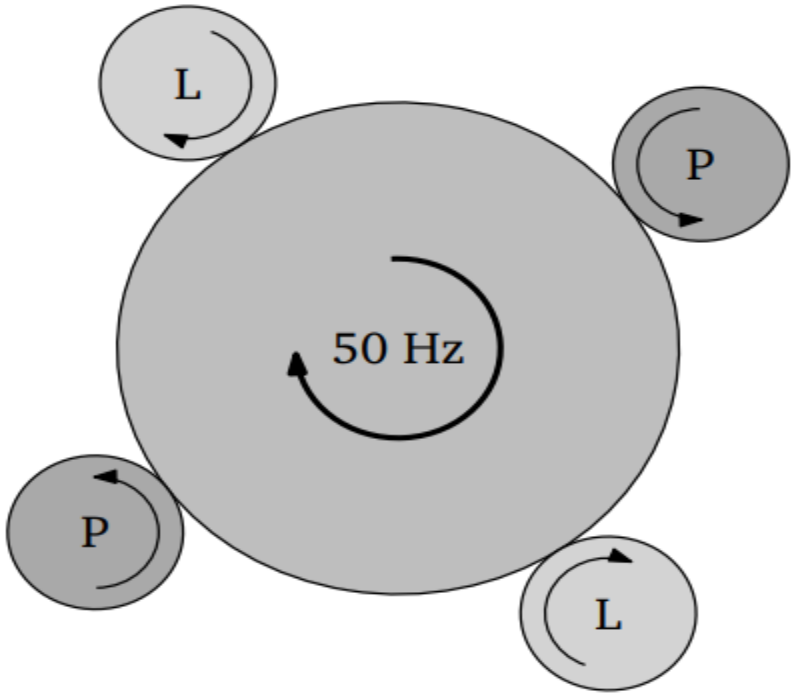
Technical overview of the system

- Generation: production of electricity with traditional power plants and renewable energy sources
- Transmission: transport of electricity over large distances and at a high voltage using overhead lines (hoogspanningskabels)
- Distribution: transport of electricity to the end-users at medium and low voltages. Almost always with underground cables.
- Consumption: where electricity from the ‘socket’ is turned into another form of energy (motion, light, heat, etc.)



Power system balance and frequency

- Why does supply need to match demand in a power system?
- Answer: to maintain the frequency at 50 Hz.



Mechanical torque of the turbine ('dynamo')

Change in frequency

Electrical torque of the alternator

A synchronous generator is driven by a prime mover. The equation governing the rotor motion is given by:[1]

$$J\frac{d^2\theta_{\mathrm{m}}}{dt^2} = T_a = T_{\mathrm{m}} - T_{\mathrm{e}},$$

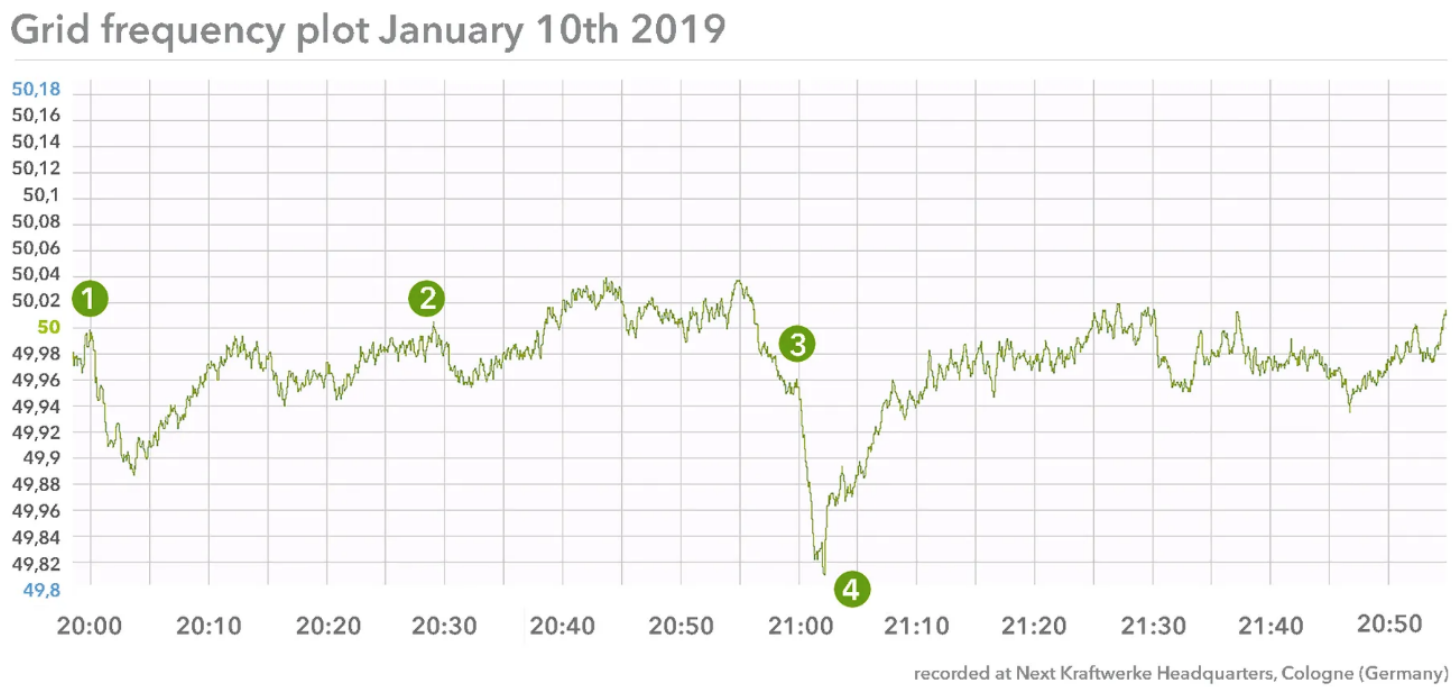
where:

- J is the total moment of inertia of the rotor mass in kg-m^2
- θ_{m} is the angular position of the rotor with respect to a stationary axis in radians (rad)
- t is time in seconds (s)
- T_a is the net accelerating torque, in **N**-m
- T_{m} is the mechanical torque supplied by the prime mover in **N**-m
- T_{e} is the electrical torque output of the alternator in **N**-m

Swing equation - Wikipedia

Frunt 2011. Analysis of Balancing Requirements in Future Sustainable and Reliable Power Systems. PhD Thesis

Frequency can be measured in any socket

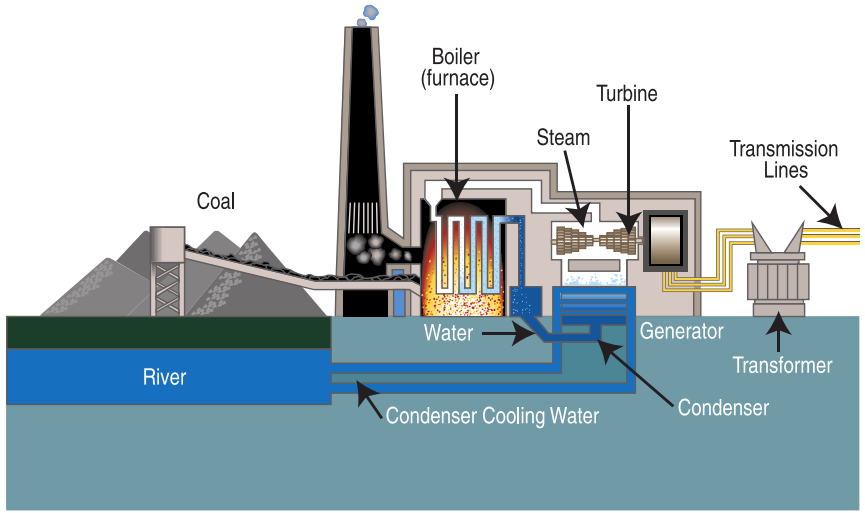


20:00 CET	According to ENTSO-E, 140 MW of available power dropped off the grid at 20:00 from boiler 1 of Spain's Litoral coal-fired power plant near Almeria. It is not certain, if this had an impact on the utility frequency collapse that occurred about an hour later.
20:26 CET	At the French nuclear power plant Penly near Dieppe, ENTSO-E states that reactor 2 went offline at 20:26, taking 850 MW available capacity out of 1,330 MW installed capacity off the grid.
21:00 CET	Energy sector news service montelnews.com quoted TenneT press spokesperson Matthias Fischer, who said there was "a short but significant peak of power consumption" when pumps were activated at pumped-storage hydro plants, including the 1.1 GW Goldisthal facility in Thuringia (Germany)

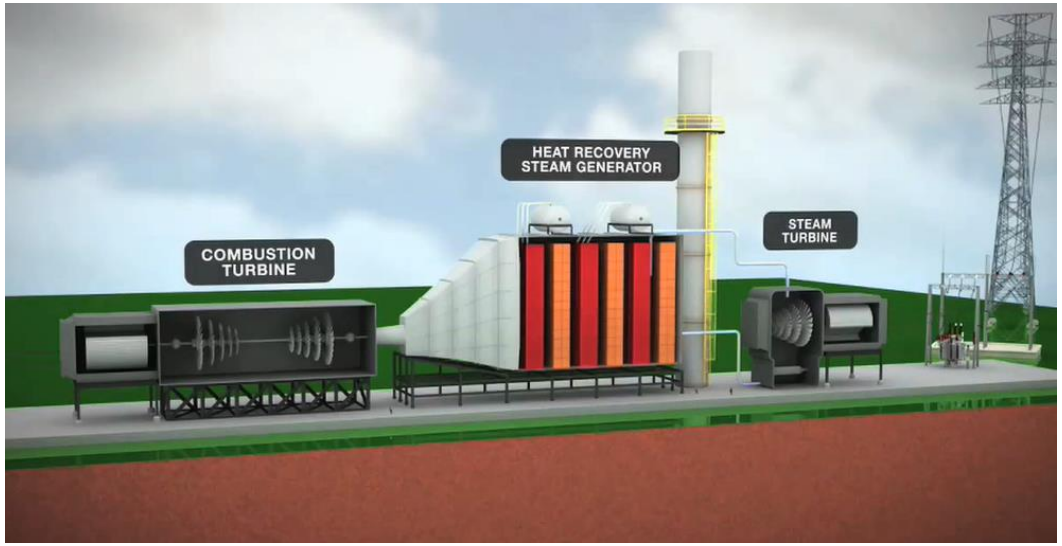
Grid frequency dip of 10 January 2019: Causes and Theories

Different types of power plants

Coal plant



Gas plant



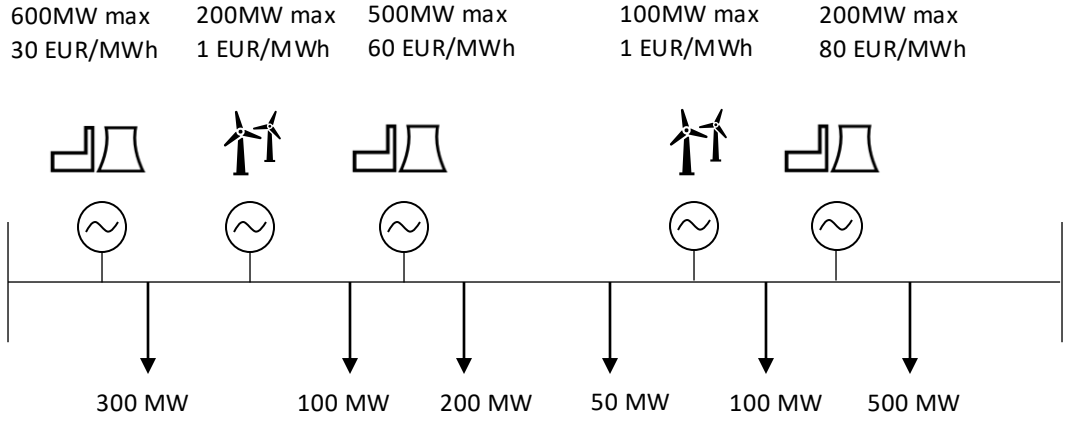
[Coal-fired power station - Wikipedia]

- Capital costs: 1.6 M EUR/MW
- Fuel costs: 30 EUR/MWh
- Typical size: 1000 MW
- Typical efficiency: 40%
- Typical CO2 emission 0.9 t CO2/MWh
- Minimum load of 50%
- Slow response

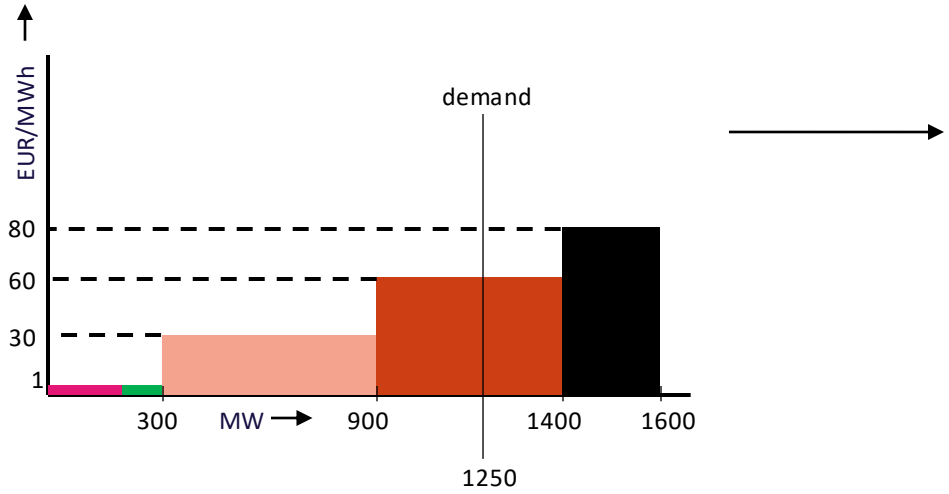
[Combined cycle power plant - Wikipedia]

- Capital costs: 0.8M EUR/MW
- Fuel costs: 60 EUR/MWh
- Typical size: 500 MW
- Typical efficiency: 60%
- Typical CO2 emission 0.45 t CO2/MWh
- Minimum load of 25%
- Fast response

How can electricity be supplied against the lowest cost?

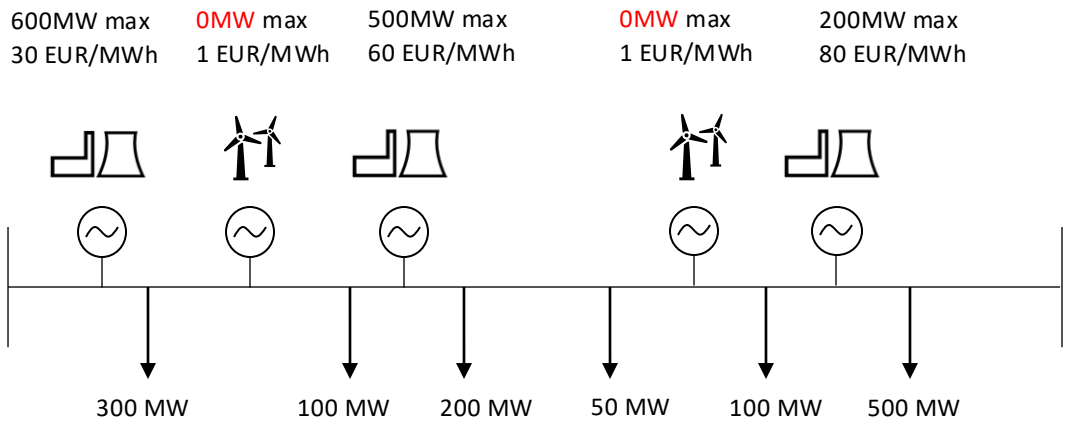


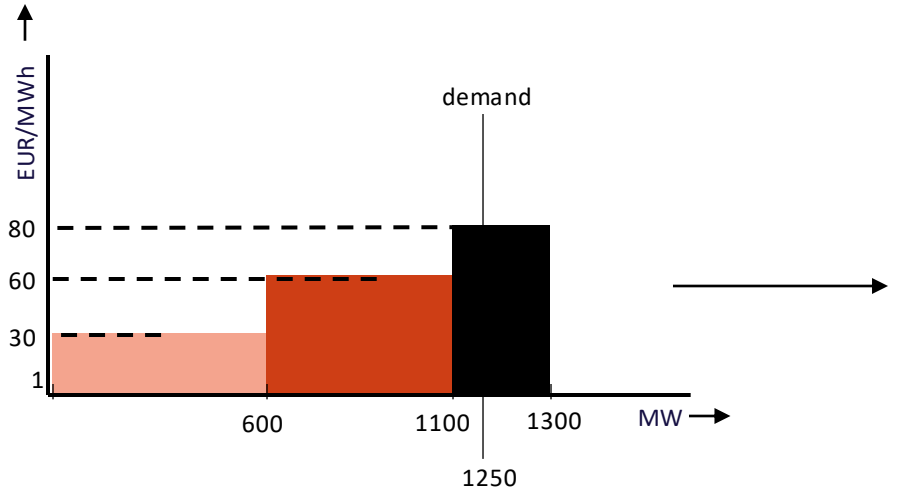
Answer: the cheapest plants go first.



All the power plants in an electricity system, order according to their marginal cost. This is called **'the merit order'**

What is the solution in case of no wind?

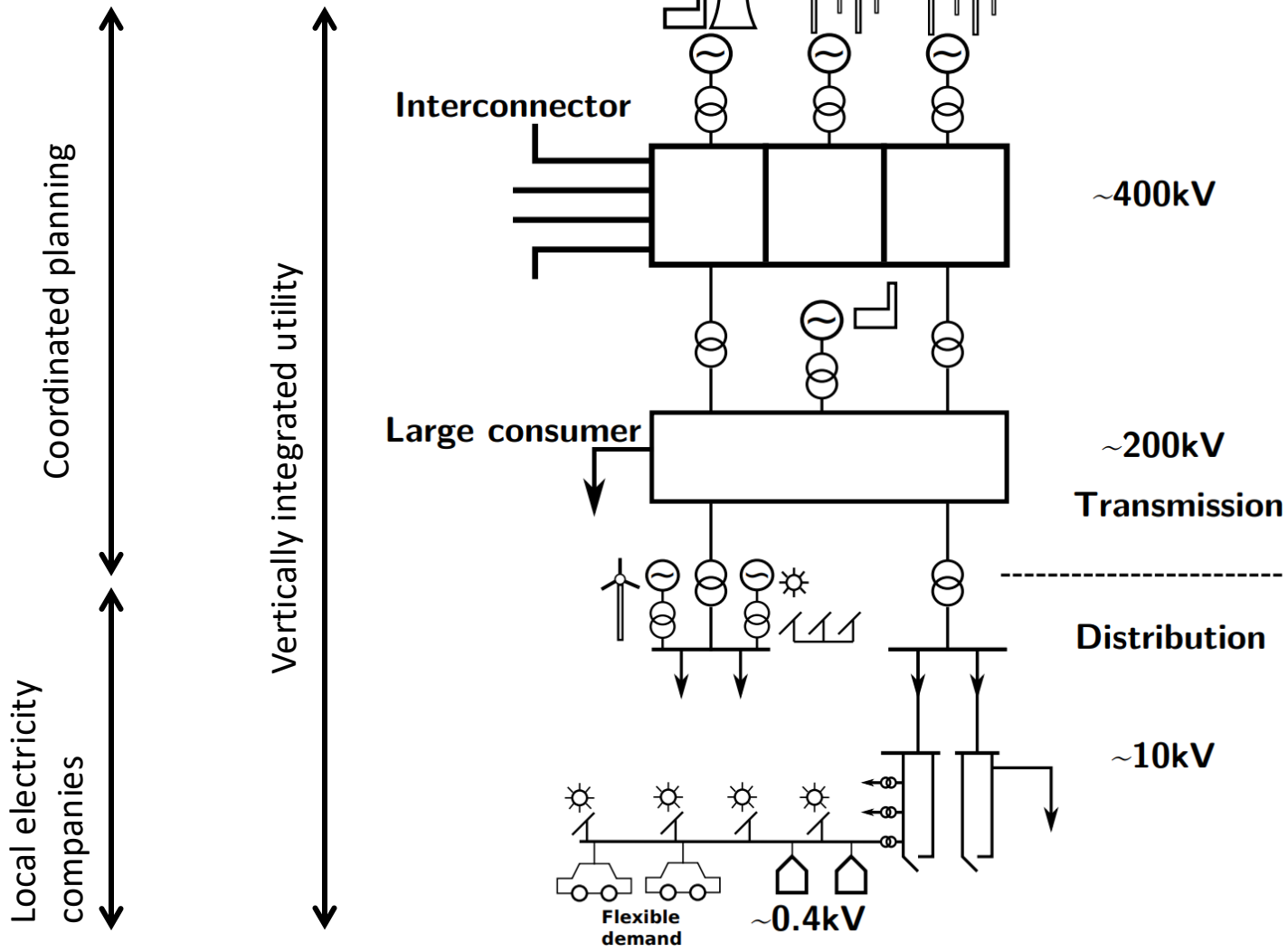




In case of no wind, a more expensive power plant is needed

Before liberalization and unbundling

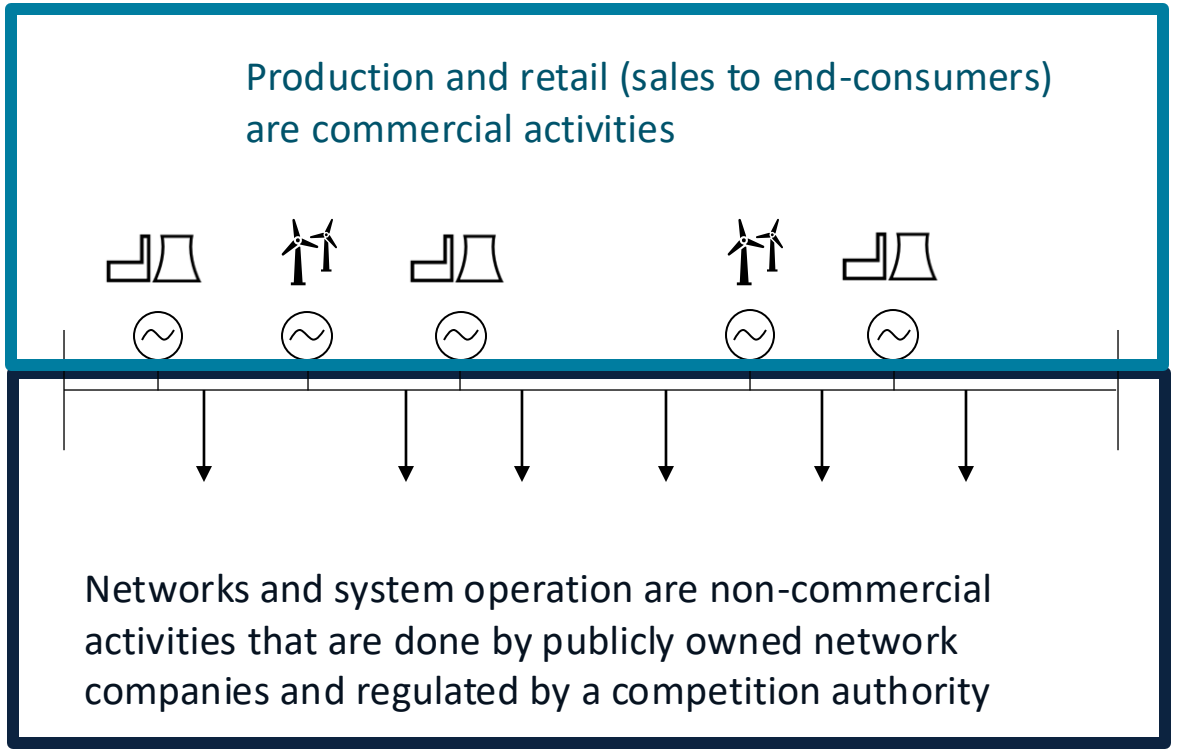
- The distribution (and originally also production) of electricity was often organized per municipality or province. (Gemeentelijk Energiebedrijf GEB).
- Later, there was more coordination and the technical functions related to production and transmission were done by a single entity. In the Netherlands this was called SEP Samenwerkende Elektriciteitsproducenten)
- In some countries or US states all technical functions were done by a single entity: a so-called vertically integrated utility



The main idea about liberalization and unbundling

- Before the 1980's: "ministry of electricity" who did everything
- In the 1980's and 1990's, the idea of electricity markets became popular
- The electricity networks are considered as a *natural monopoly* and as such are not intended to be part of the market.

Unbundling means that commercial activities are separated from network management



The theory behind an electricity market

- Comes from a group of MIT scientists, developed in the early 1980's.
- The concept of an electricity market is centered around the 'spot price', or real-time price (see also Spot market – Wikipedia)
- Essentially, the 'spot price' reflects the extra costs the electricity system would make to serve one extra unit of electricity demand.

3234 IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 9 September 1982

OPTIMAL SPOT PRICING: PRACTICE AND THEORY

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Member, IEEE

R.E. Bohn

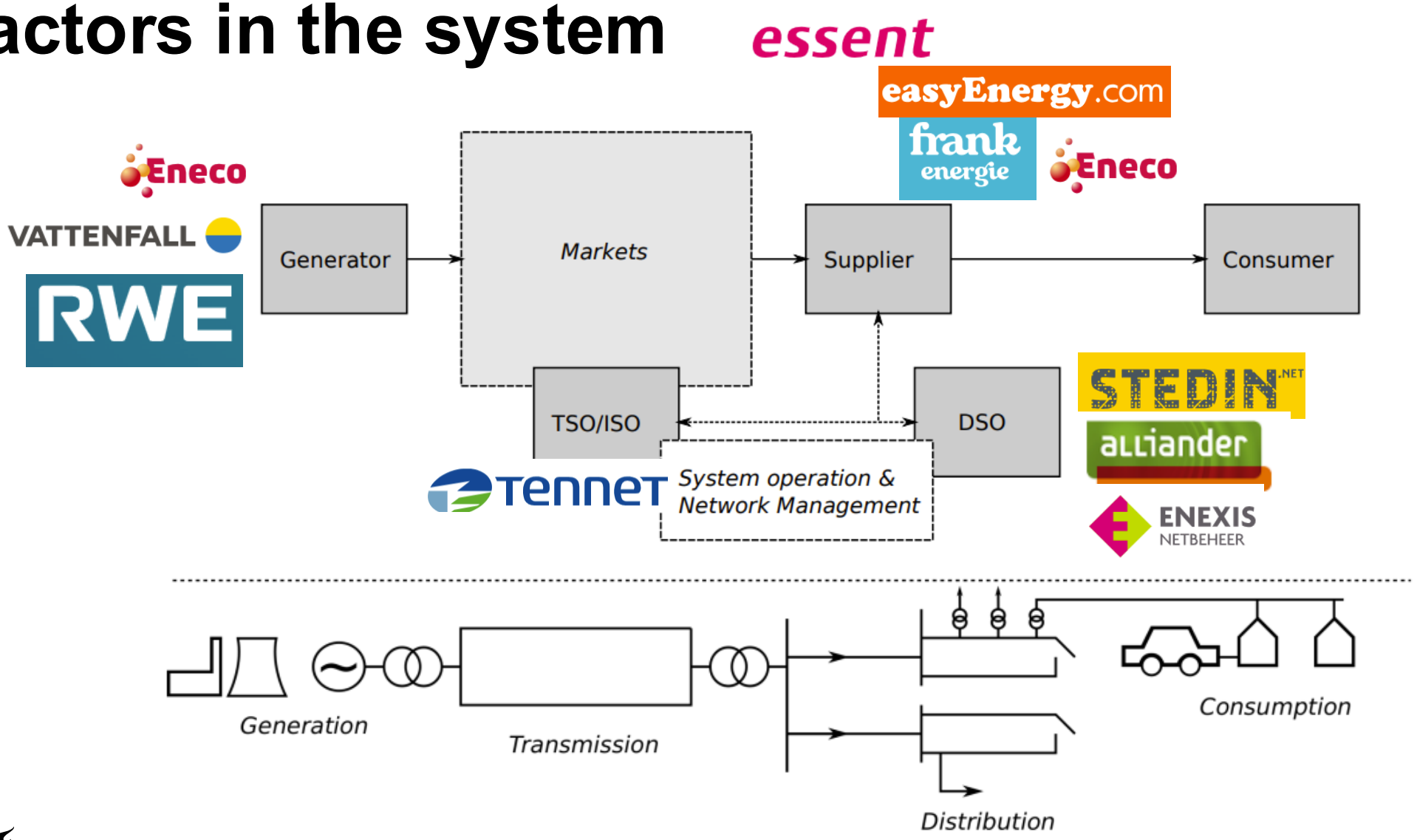
F.C. Schweppe
Fellow, IEEE

Energy Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

Abstract. A new concept of electricity pricing referred to as "spot pricing" is presented. Spot pricing is

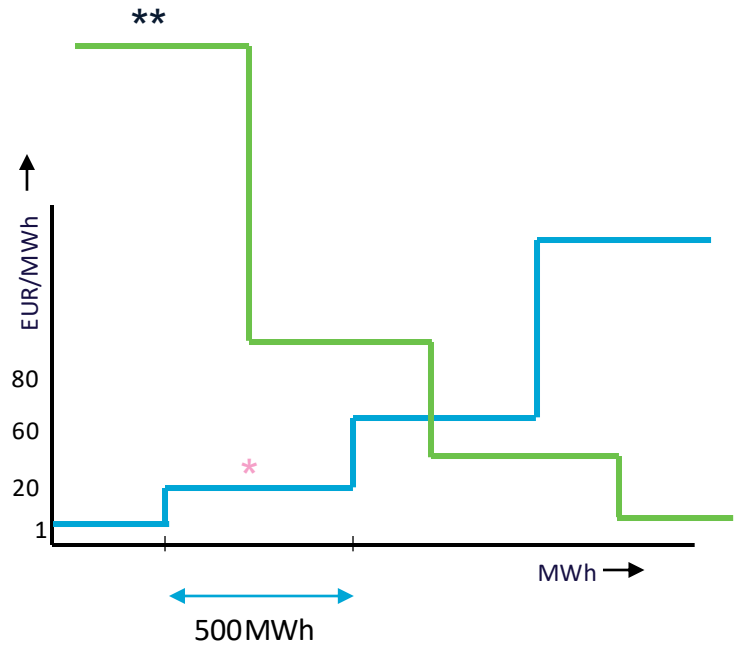
The concept of spot pricing is part of a much larger framework called Homeostatic Control [13]. Homeostatic Control also includes other concepts which deal with

How technical functions related to different actors in the system



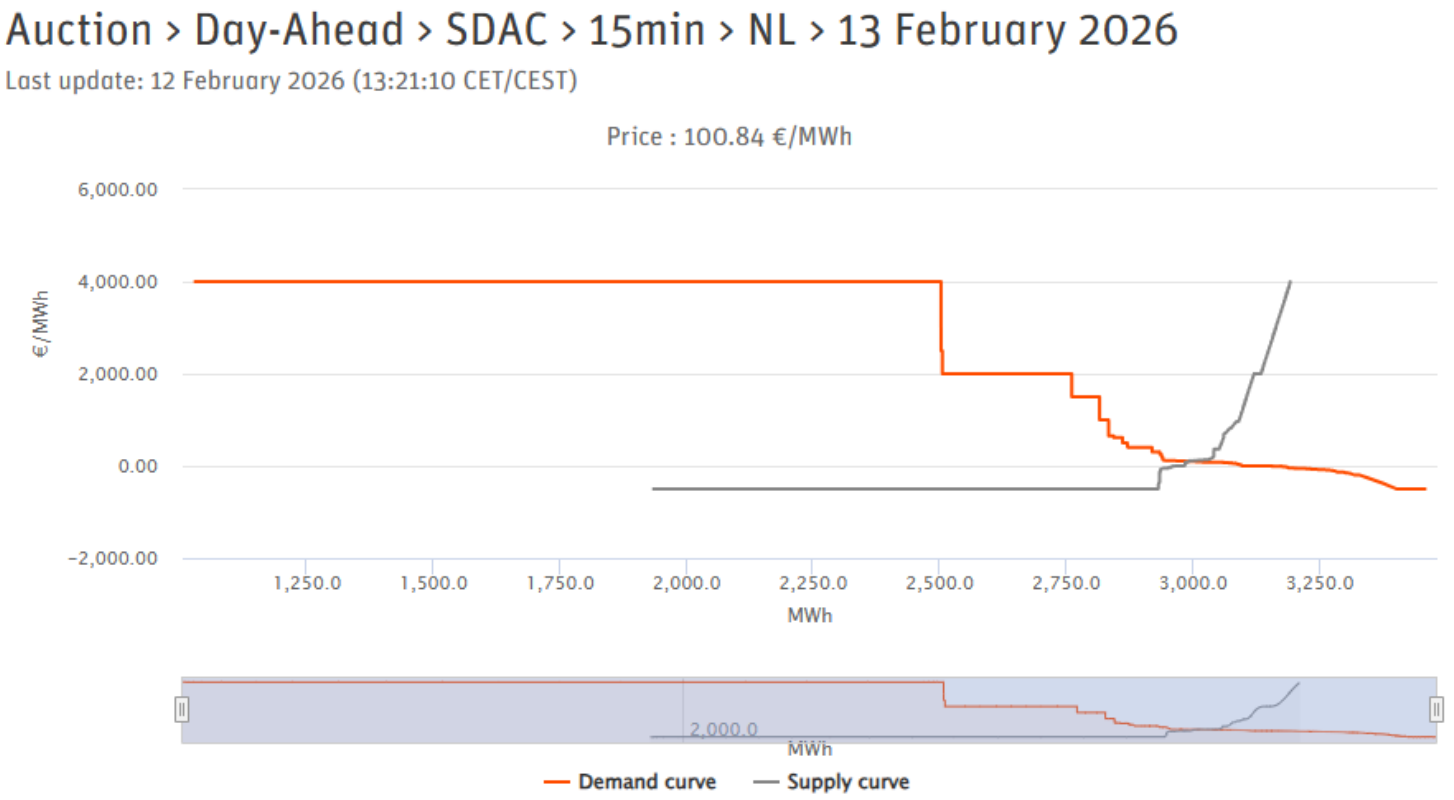
The day-ahead market in practice

- Each market party submits price-volume pairs per hour of the day. For example:
  - I have for sale between 1500h and 1600h, 500MWh of energy (volume) at a price of 20 EUR/MWh. *
  - I want to buy between 1500h and 1600h, 100MWh of energy at a price of 200 EUR/MWh. **
- All bids are collected by the market operator (EPEX spot)
- All supply bids are ordered from low to high
- All demand bids are ordered from high to low
- The intersection point is the market price for that hour.
- Everyone (!) pays or receives that **'clearing price'**, regardless of your bid.



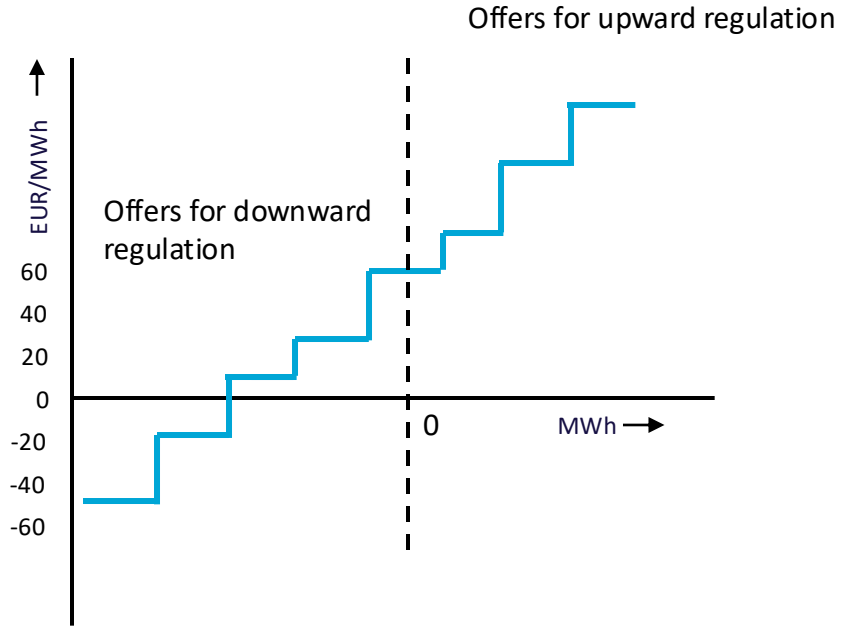
Market results from the EPEX spot market

00 - 01	01 - 02	02 - 03	03 - 04	04 - 05	05 - 06	06 - 07	07 - 08	08 - 09	09 - 10	10 - 11	10:00 - 10:30	10:30 - 11:00	10:30 - 10:45	10:45 - 11:00	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	20 - 21	21 - 22	22 - 23	23 - 24



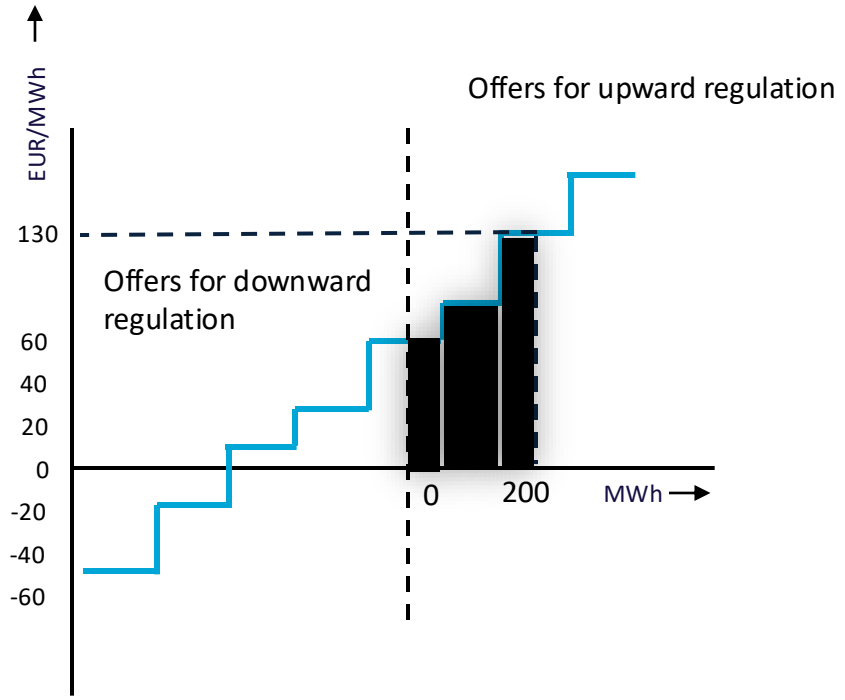
Balancing market and imbalance settlement

- This is a so-called ‘single buyer market’: the TSO (i.e. TenneT in the Netherlands) buys all the power that is offered there. Market parties offer their power to the TSO.
- Like on the day-ahead market, all the bids are ordered from high to low. There two sorts of bids: for ‘up-regulation’ and ‘down-regulation’ (opregelen/afregelen)
- The idea is that even after all day-ahead and intra-day trades, there are still unforeseen deviations from all the intended production schedules.
- The TSO uses the power offered on the balancing market to ‘match’ the deviations from the intended production schedules
- The cost it pays to remunerate the balancing power providers is passed on to the entity creating the deviation (i.e. the imbalance). So, the TSO does not make any money with this.
- This process is done every 15 minutes, the so-called Program Time Unit (PTU)



Balancing market and imbalance settlement

- An example of how the balancing price is set: suppose that in a given program time unit (PTU), the entire Dutch system has a shortage of 200 MWh. This is called the *system imbalance*
- The system needs 200MWh of ‘up-regulation’ and the TSO activates all the bids up to 200 MWh to provide this. These plants will get an automatic signal to provide the power they offered.
- The most expensive plant (in jargon: *the marginal plant)* that is needed to cover the 200MWh sets the price, this is called the *balancing price*
- A party that has created an imbalance of, say 50 MWh, pays this price to the TSO.
- When the system has a surplus, parties are required to down-regulate.



The value of forecasting for a producer

- Suppose Eneco has sold 100 MWh at the day-ahead market at a price of 60 EUR/MWh. They earned 100 x 60 = 6000 EUR
- Now suppose it is less windy than expected and they only generate 80 MWh. Suppose that the balancing price during that time is 120 EUR/MWh. Eneco has an imbalance of 100-80=20 MWh and is forced to buy this from TenneT at 120 EUR/MWh. So, they lose 20 MWh*120 EUR/MWh = 2400 EUR.
- The total earnings in that time are 6000 EUR – 2400 EUR = 3600 EUR. You could also say that for the 100 MWh ‘generated’, they paid a balancing costs of 24 EUR/MWh.

- If you calculate with realistic electricity prices, you find that a wind power producer loses roughly 5-8 EUR/MWh per generated

The value of forecast for producers (formula and real data)

Total revenue = day-income plus/minus balancing income/costs

$$R = \sum_{t=1}^{T} \hat{P}_t \lambda_t + \Delta_t^+ \lambda_t^+ - \Delta_t^- \lambda_t^-$$

Day-ahead income

Surplus sold on balancing market

Shortage bought on balancing market

Forecast errors = **exposure** on balancing market

$$\Delta_t = P_t - \hat{P}_t$$

Error = actual - forecast

Year-round average imbalance costs:

Wind ~ 5-8 EUR/MWh. Solar ~14-26 EUR/MWh

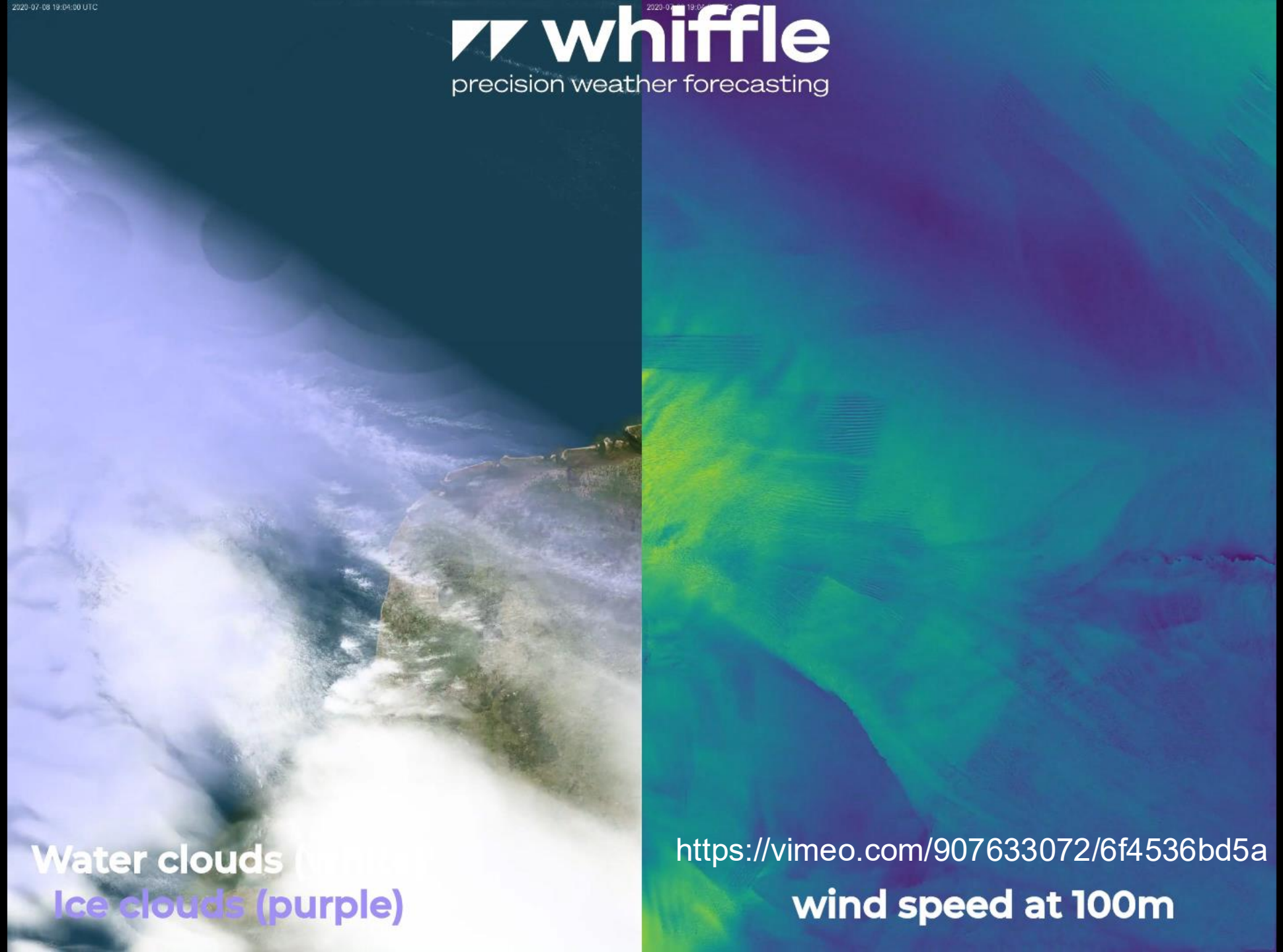
Tabel 71
Overzicht van absolute profiel- en onbalanskosten in 2021 en 2022 (in euro/kWh)

	PO-kosten* 2022	Profiel-kosten 2022	Onbalans-kosten 2022	PO-kosten 2021	Profiel-kosten 2021	Onbalans-kosten 2021
Wind op land	0,0620	0,0583	0,0049	0,0181	0,0108	0,0072
Wind op zee	0,0511	0,0438	0,0073	0,0083	0,000	0,0083
Zon-pv	0,0401	0,0146	0,0267	0,0346	0,0201	0,0144

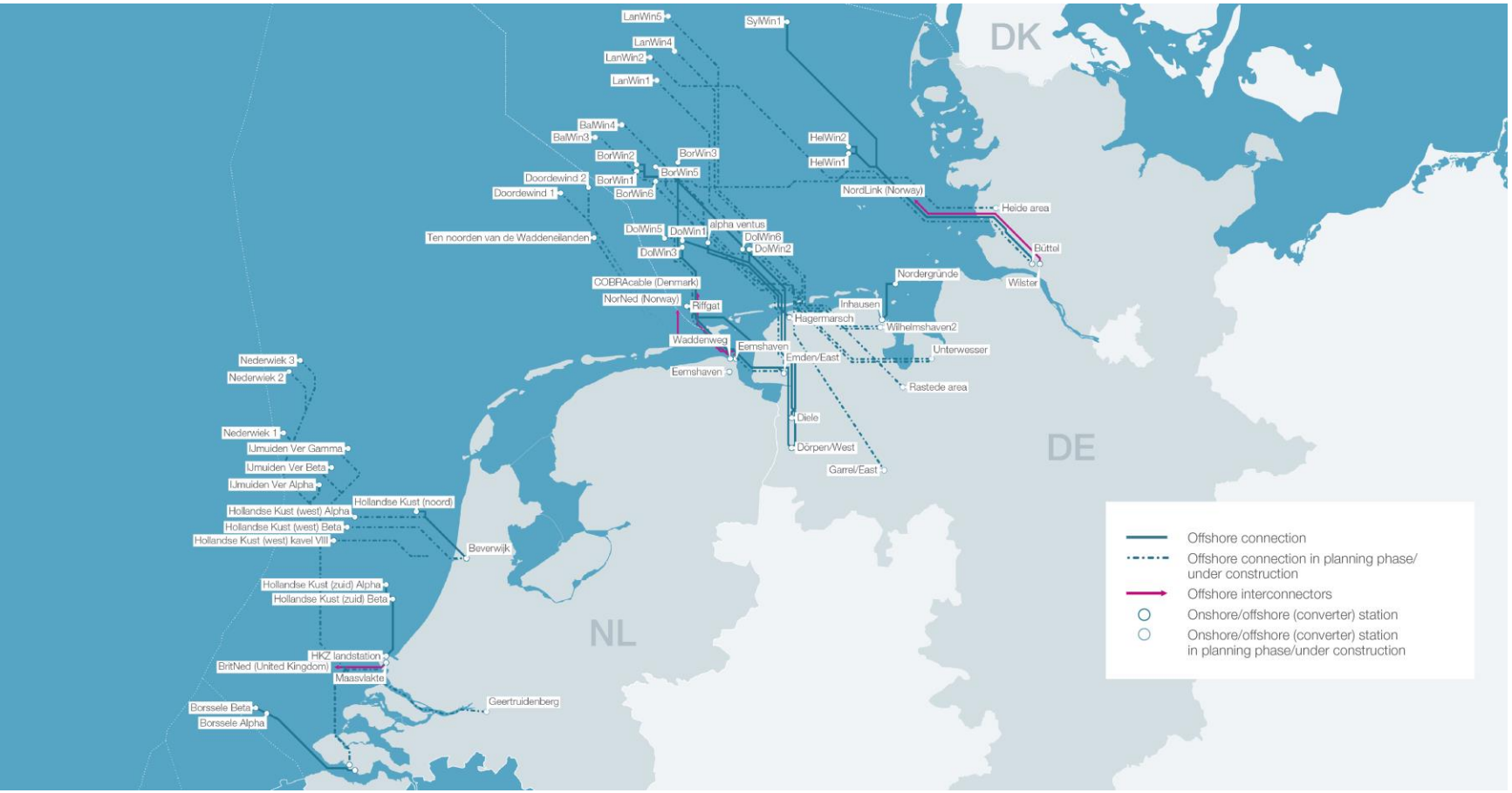
* Vanwege afrondingsverschillen tellen de profiel- en onbalanskosten soms niet op tot de totale PO-kosten.

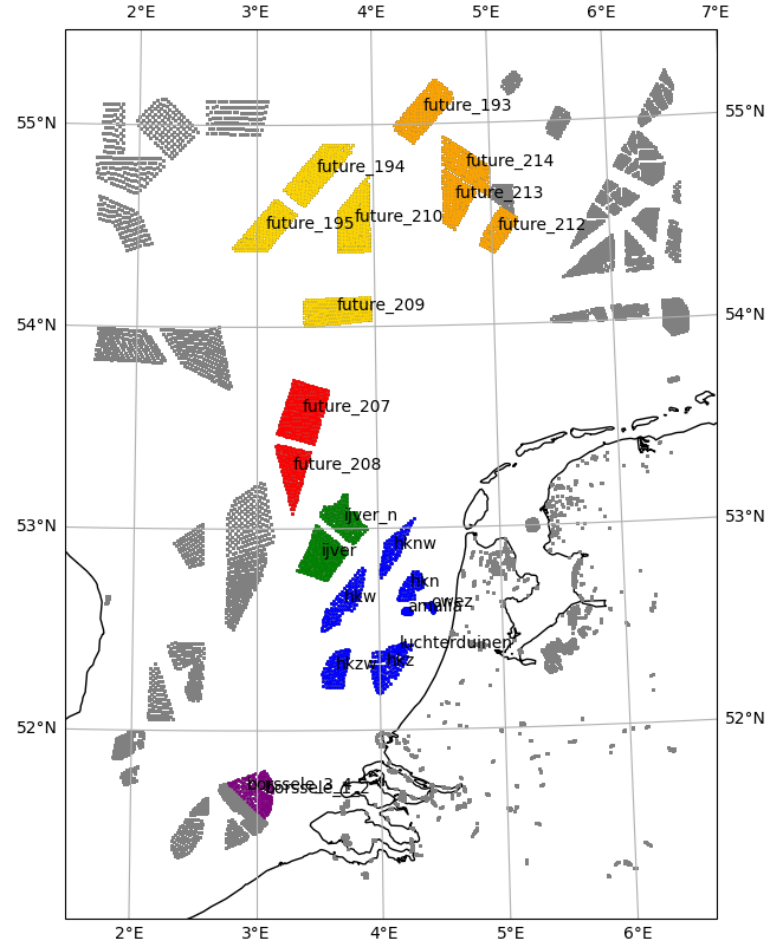
Definitieve correctiebedragen 2022 – Herziene versie – in het kader van de SDE++- en SCE-regelingen (pbl.nl)

The case of an offshore wind farm


2020-07-08 19:04:00 UTC
whiffle
precision weather forecasting
Water clouds
Ice clouds (purple)
https://vimeo.com/907633072/6f4536bd5a
wind speed at 100m

Power production patterns on the HV network





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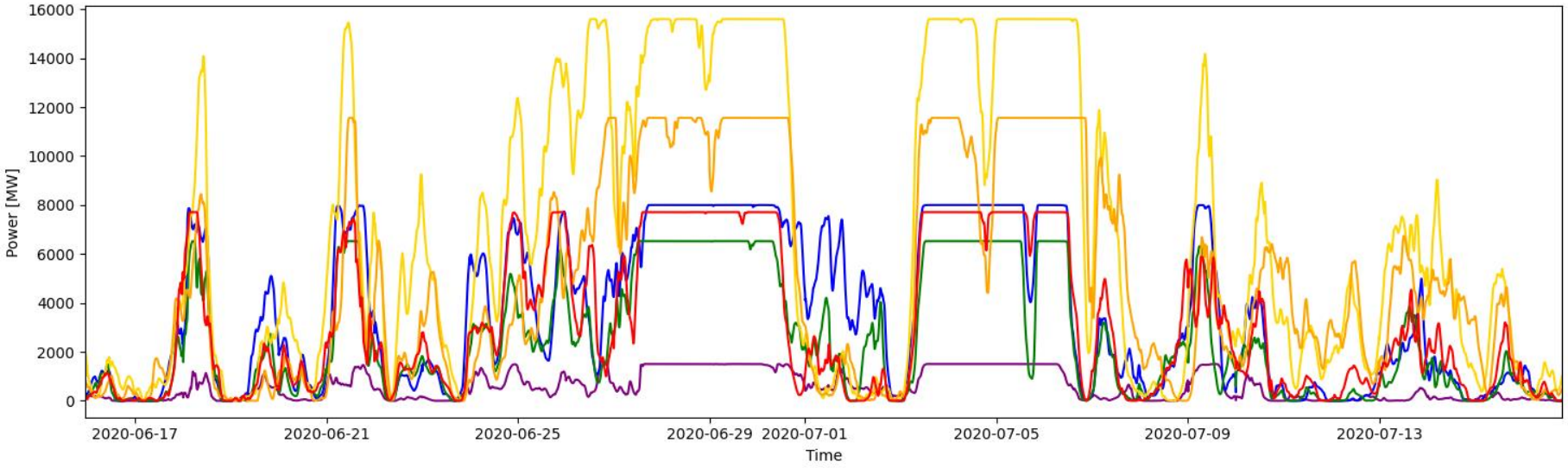
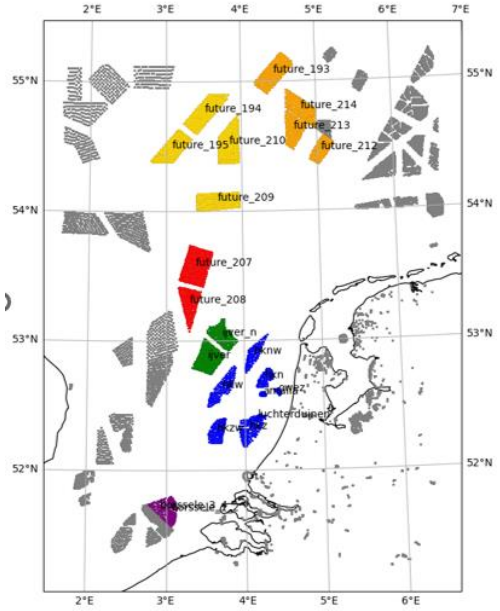
Timeseries of aggregated production

Imagine the effects of forced and unforeseen shutdowns

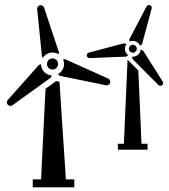




What it boils down to

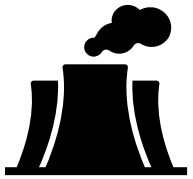
Bird approaches wind turbine

Turbine shuts down

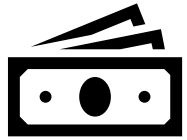


System is out-of-balance

Other power plant needs to generate more



Financial consequences are for wind farm operator



Insights

- Electricity systems are complicated socio-technical systems

- Creating power imbalances comes with huge financial penalties

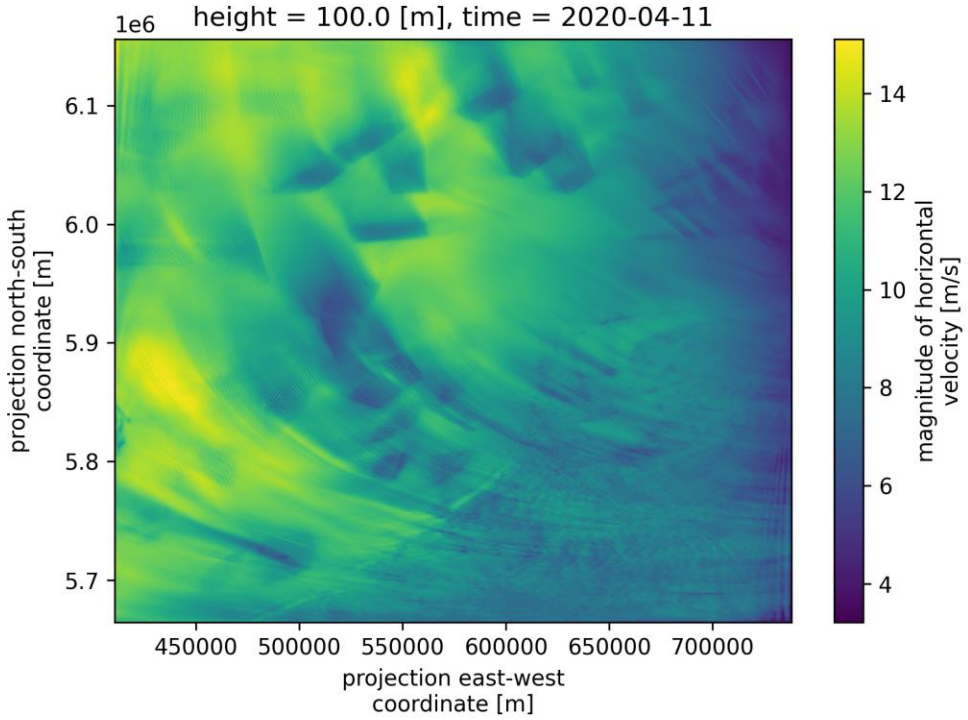
- **We need smart ways to avoid unnecessary shutdowns**

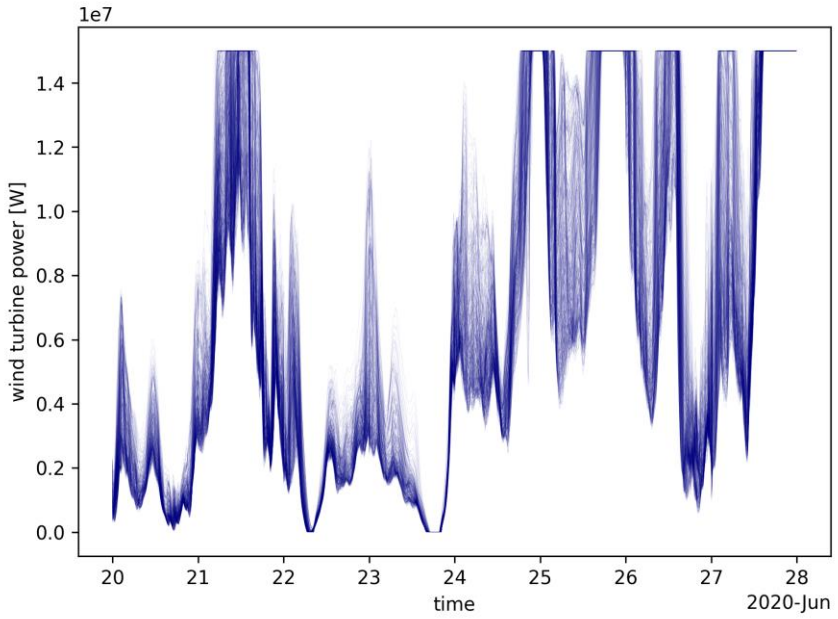
Dissemination

- Publicly available through AWS Open Data Registry
- [Whiffle-public / whiffle-open-data · GitLab]
- [Whiffle WINS50 Open Data on AWS - Registry of Open Data on AWS]
- Cloud native data storage and user-friendly

```python
def plot_fields():
    ds = xr.open_dataset(
        "s3://whiffle-wins50/arco/whiffle_wins50_2050_scenario_fields.zarr",
        engine="zarr",
    ).sel(time="2020/04/11/00", height=100)

    ds["wind_speed"].plot.pcolormesh()

    plt.tight_layout()
    plt.savefig('./figs/windspeed-2020-04-11-00.png', dpi=300)
```

```python
def plot_farm_timeseries():
    ds = xr.open_dataset(
        "s3://whiffle-wins50/arco/whiffle_wins50_2050_scenario_turbines.zarr",
        engine="zarr",
    )

    ds = ds.sel(time=slice("2020/06/20", "2020/06/27"))

    select_farm = np.where(ds["windfarm_identifier"] == "future_207")[0]
    ds["power"][:, select_farm].plot.line(x='time', color='navy',
                                          alpha=0.2, linewidth=0.1, add_legend=False)

    plt.tight_layout()
    plt.savefig('./figs/farm-timeseries-future_207.png', dpi=300)
```





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Good luck!

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