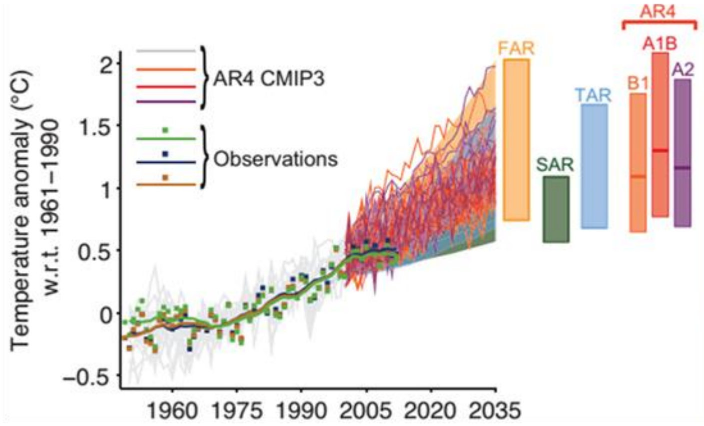
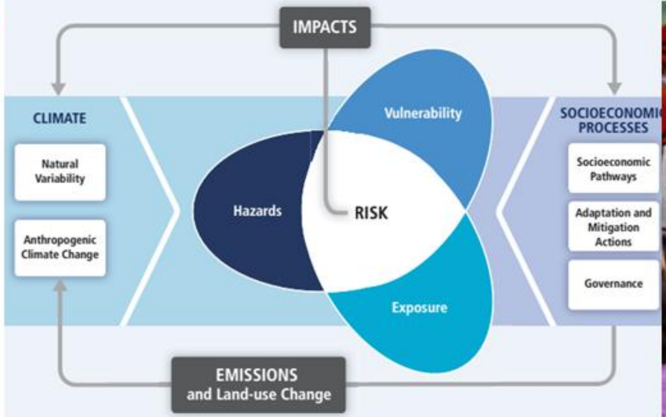




Energy Systems & Climate Change





Electricity from the wind

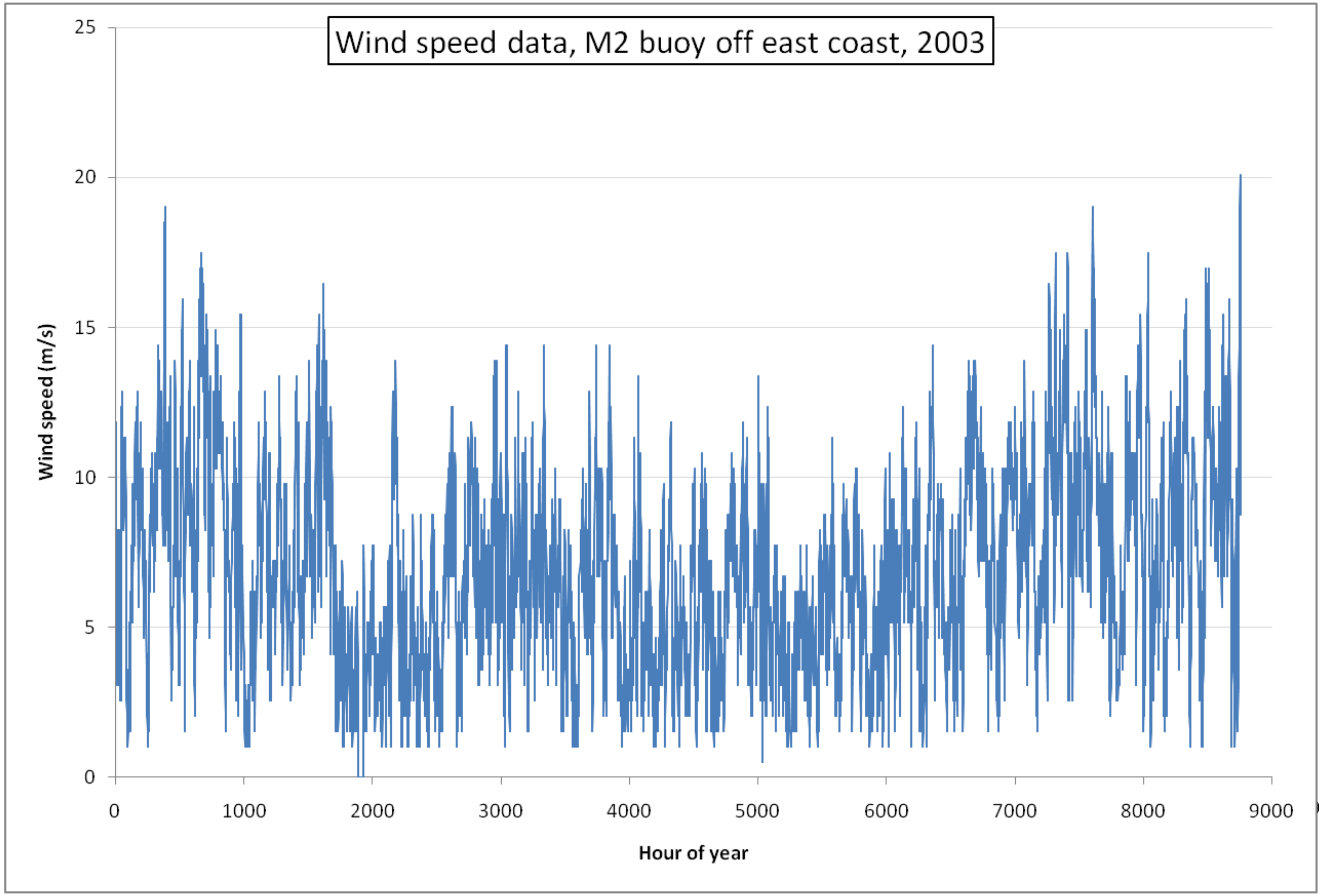


4c: Wind energy

- The wind resource
- Harvesting wind
- Moving offshore
- Grid integration
- The global and regional contexts

The wind resource

The wind resource

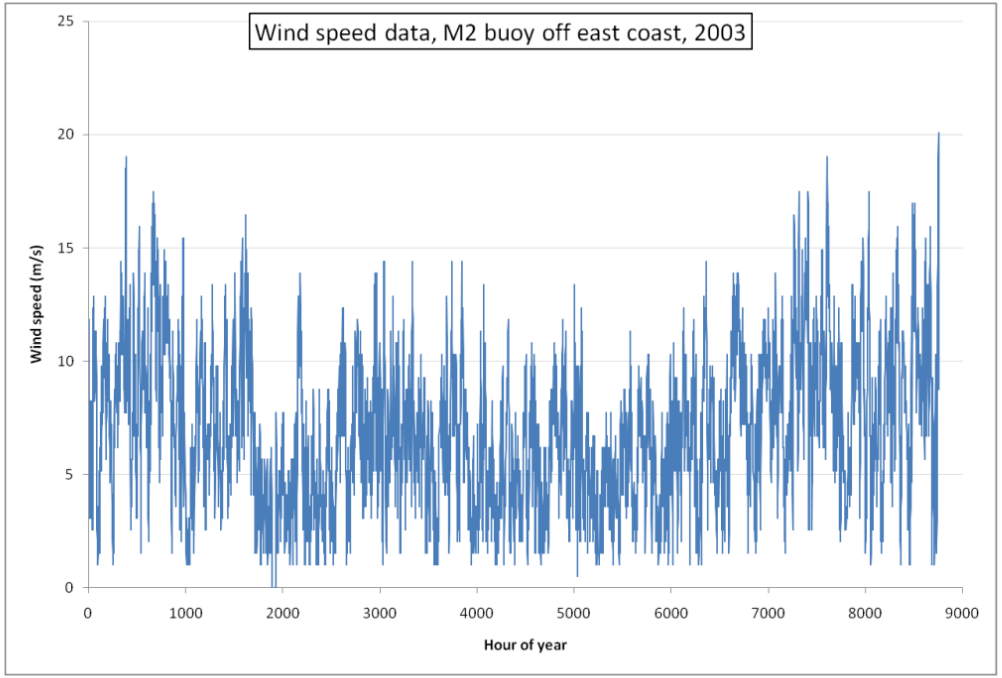


The wind resource

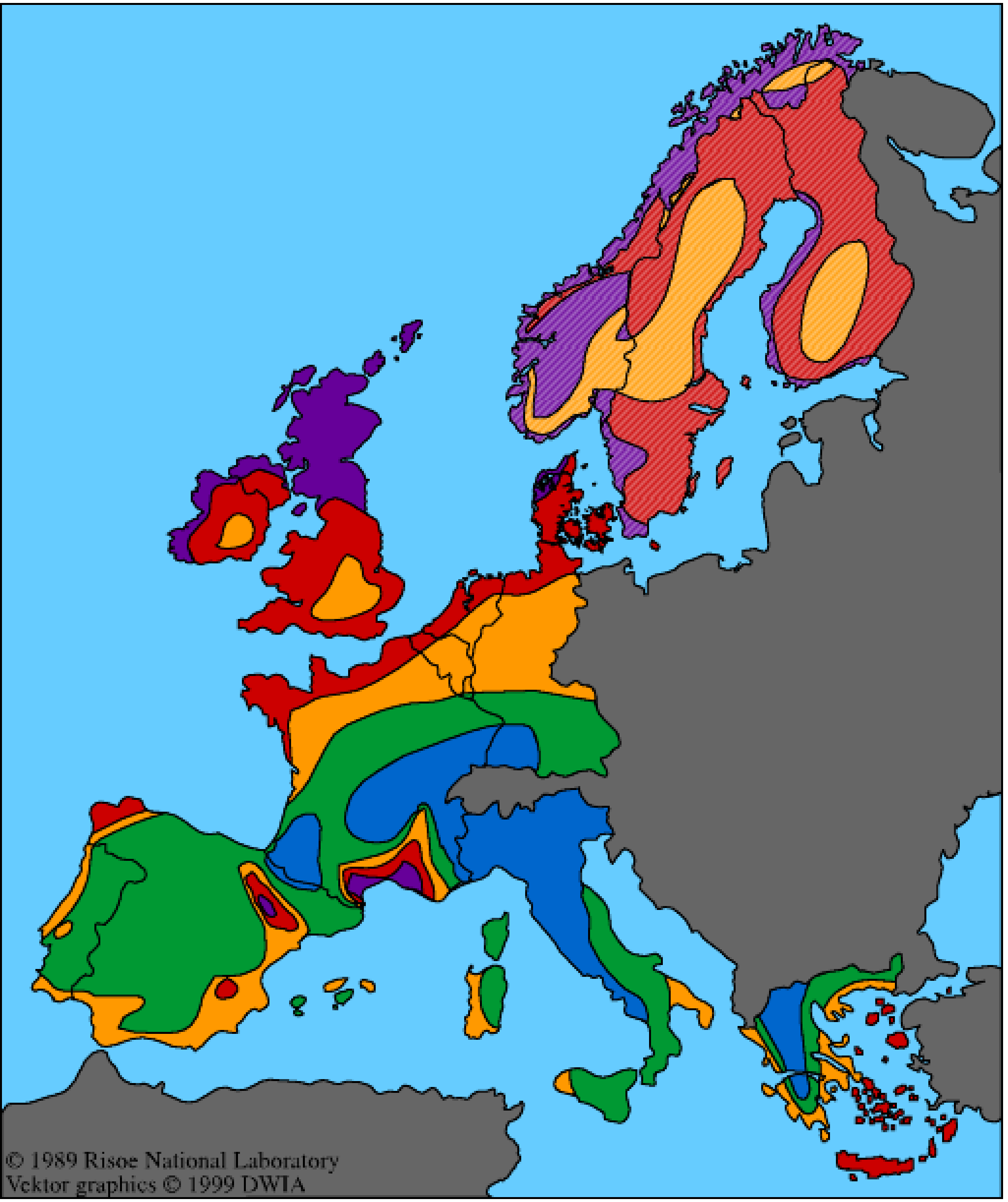
Wind speed is highly variable

Seasonal, diurnal, and shorter-term fluctuations

Data presented here is averaged over one-hour periods – turbulent fluctuations are filtered out.



The wind resource

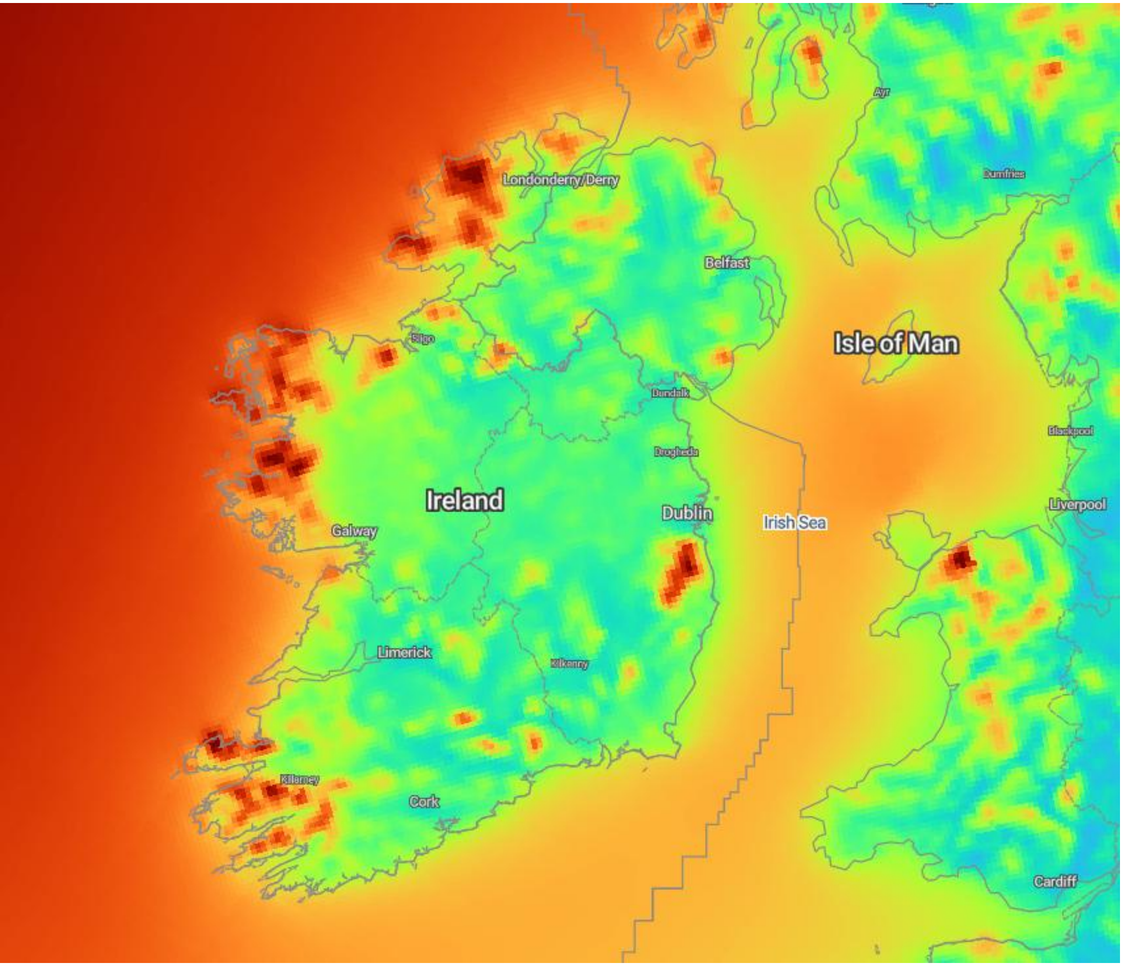


Wind Resources at 50 m above Ground Level

	Sheltered terrain		Open plain		Hills and ridges	
	$m.s^{-1}$	$W.m^{-2}$	$m.s^{-1}$	$W.m^{-2}$	$m.s^{-1}$	$W.m^{-2}$
Purple	> 6.0	> 250	> 7.5	> 500	> 8.5	> 800
Red	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	600-800
Yellow	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	400-600
Green	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	200-400
Blue	< 3.5	< 50	< 4.5	< 100	< 5.0	< 200

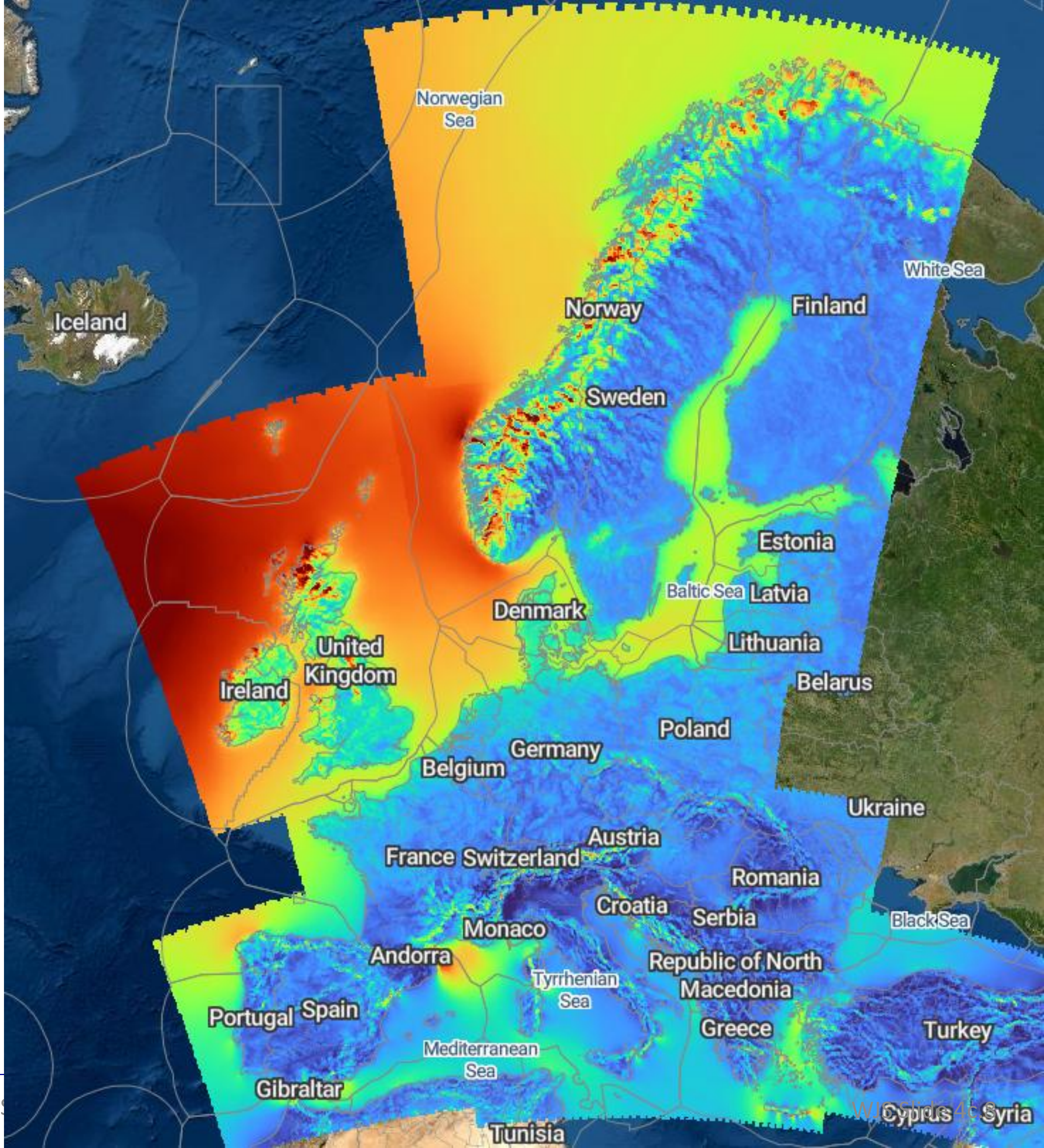
The wind resource

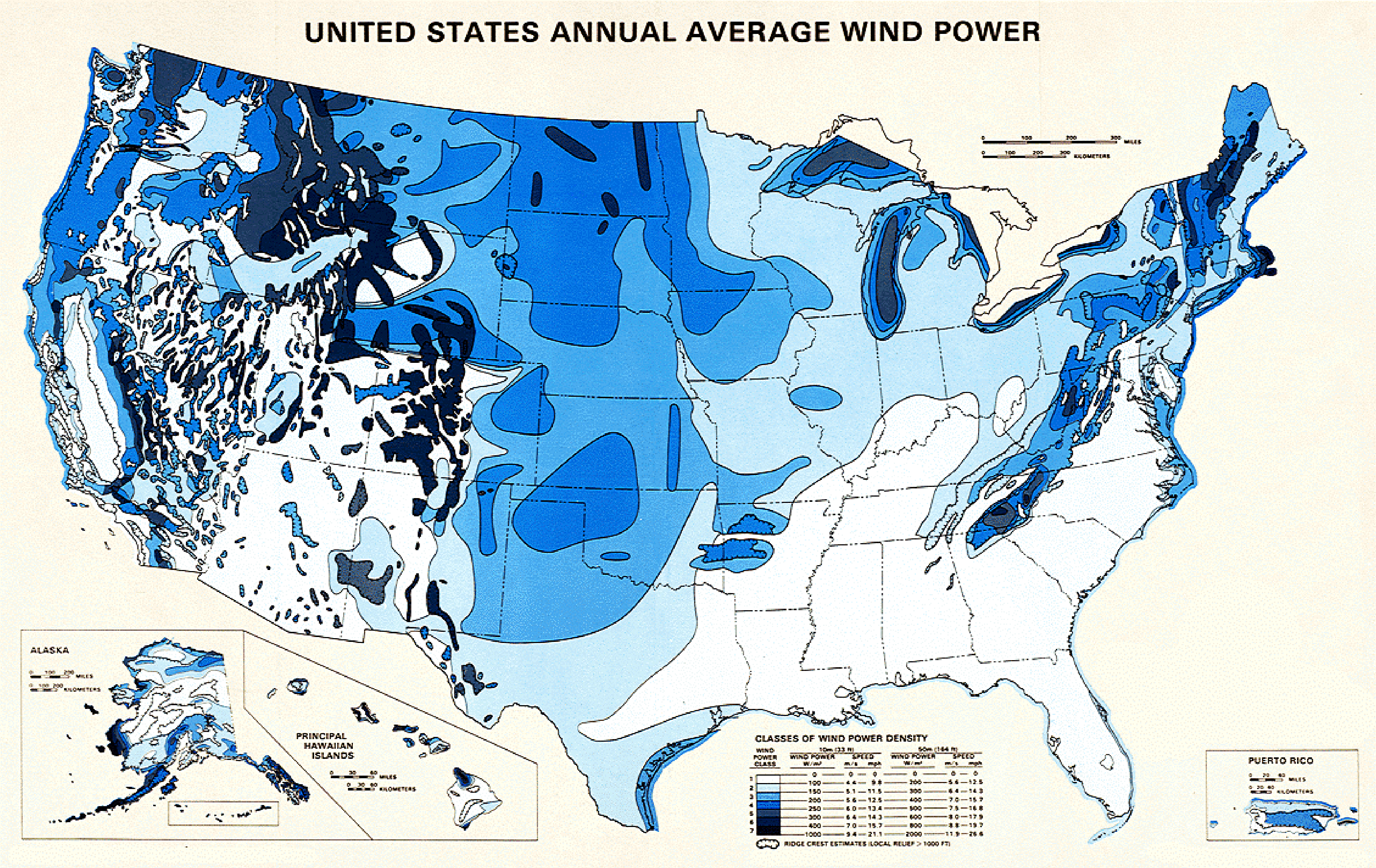
Mean wind power density ($W.m^{-2}$), at 150 m



See the New European Wind Atlas:

https://map.neweuropeanwindatlas.eu/

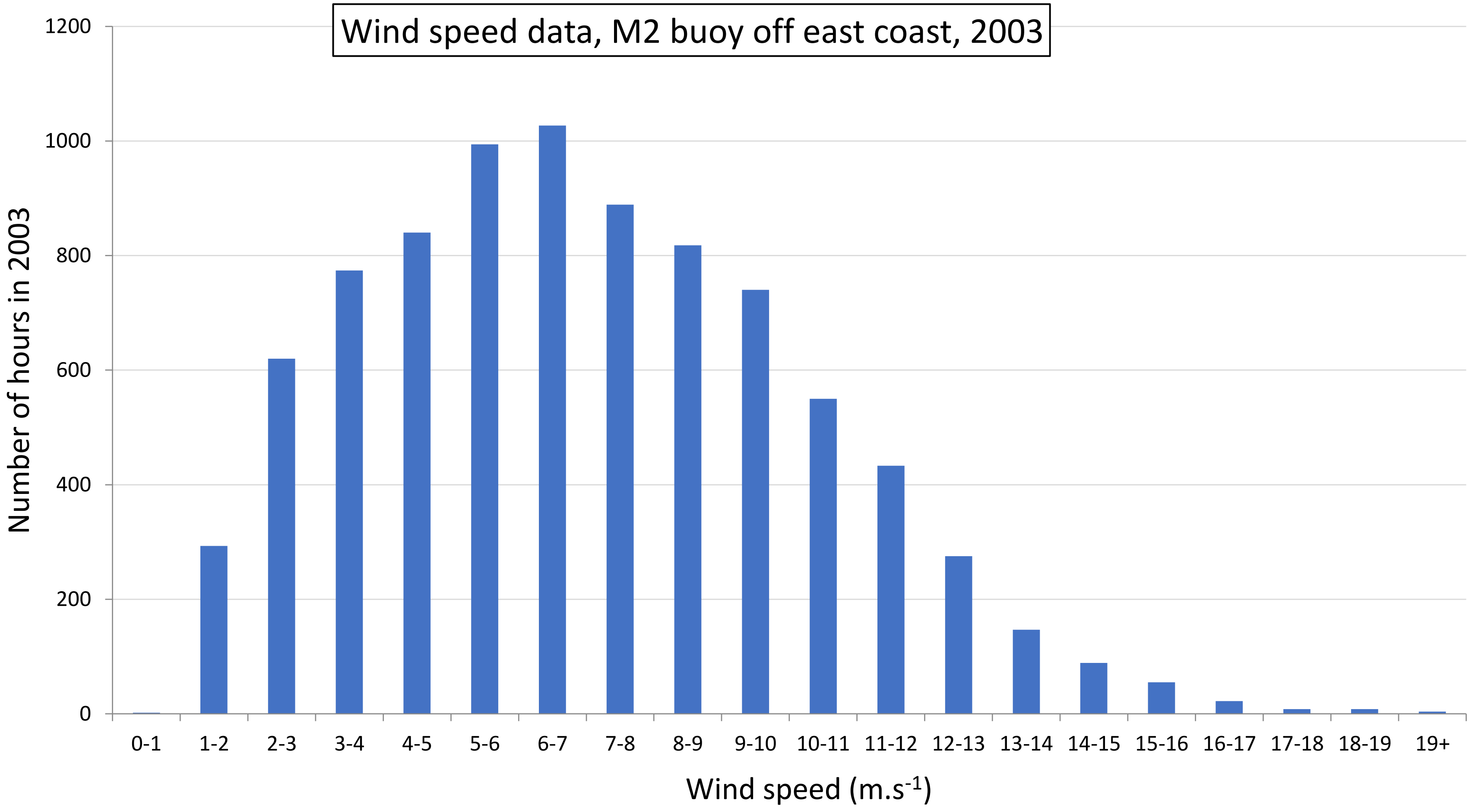



UNITED STATES ANNUAL AVERAGE WIND POWER
ALASKA
PRINCIPAL HAWAIIAN ISLANDS
PUERTO RICO
CLASSES OF WIND POWER DENSITY
WIND POWER CLASS
WIND POWER
SPEED
RIDGE CREST ESTIMATES (LOCAL RELIEF > 1000 FT)

The wind resource

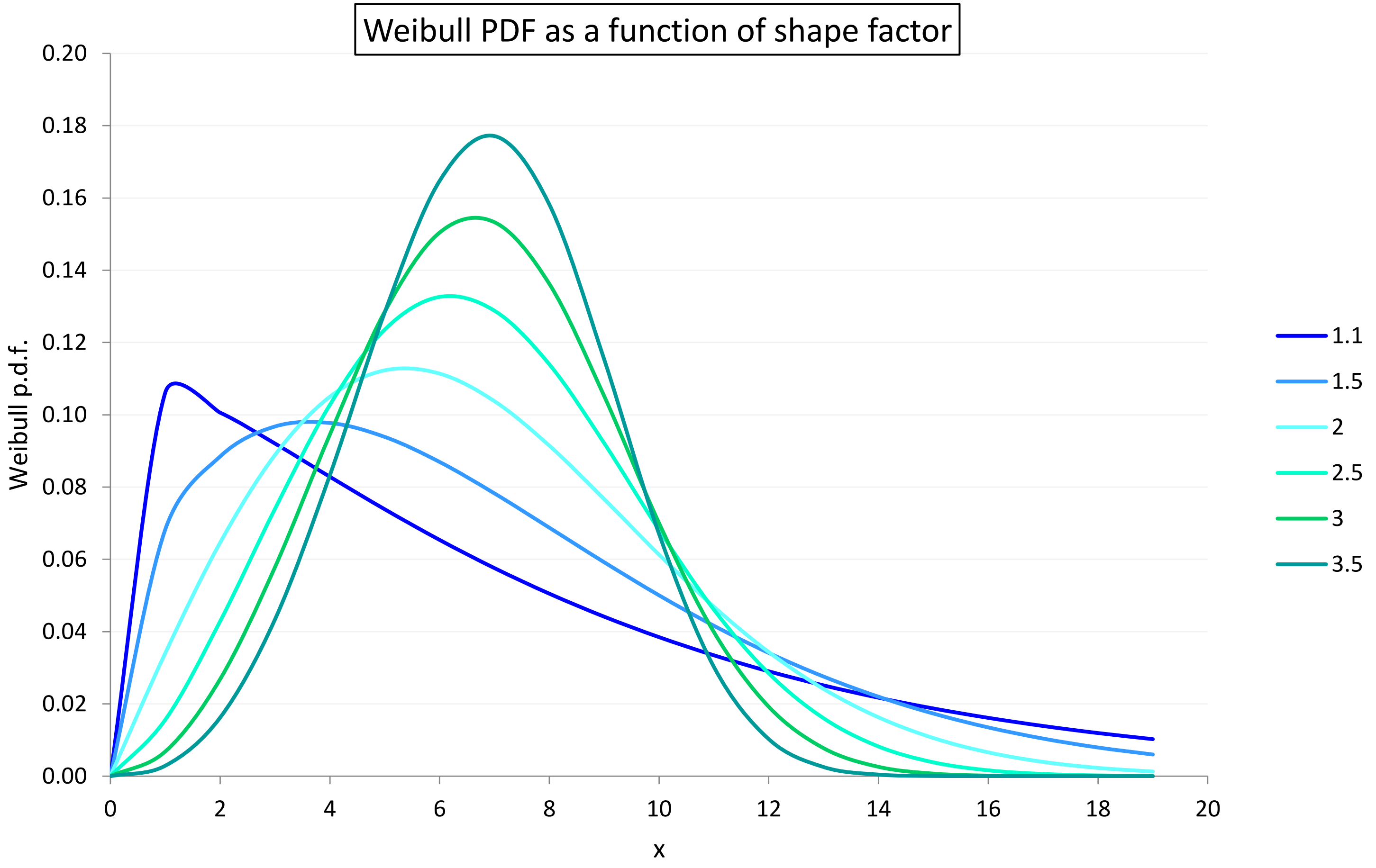
Distribution of wind speeds is non-Gaussian

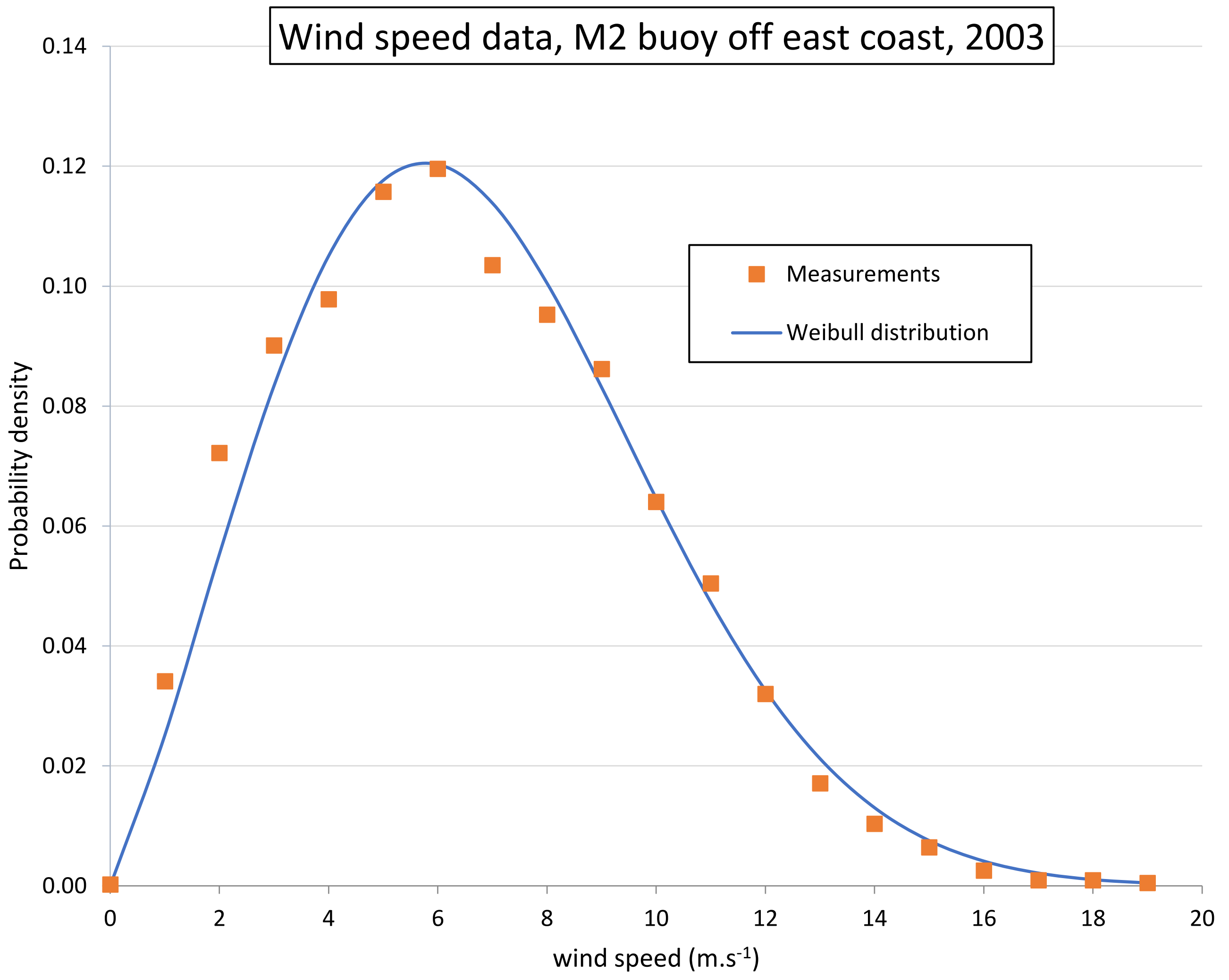
Usually assumed to follow a Weibull distribution



Weibull probability density function: $$P(x) = \alpha \times c^{-\alpha} \times x^{\alpha-1} \times e^{-\left(x/c\right)^{\alpha}}$$

Shape factor Scale factor





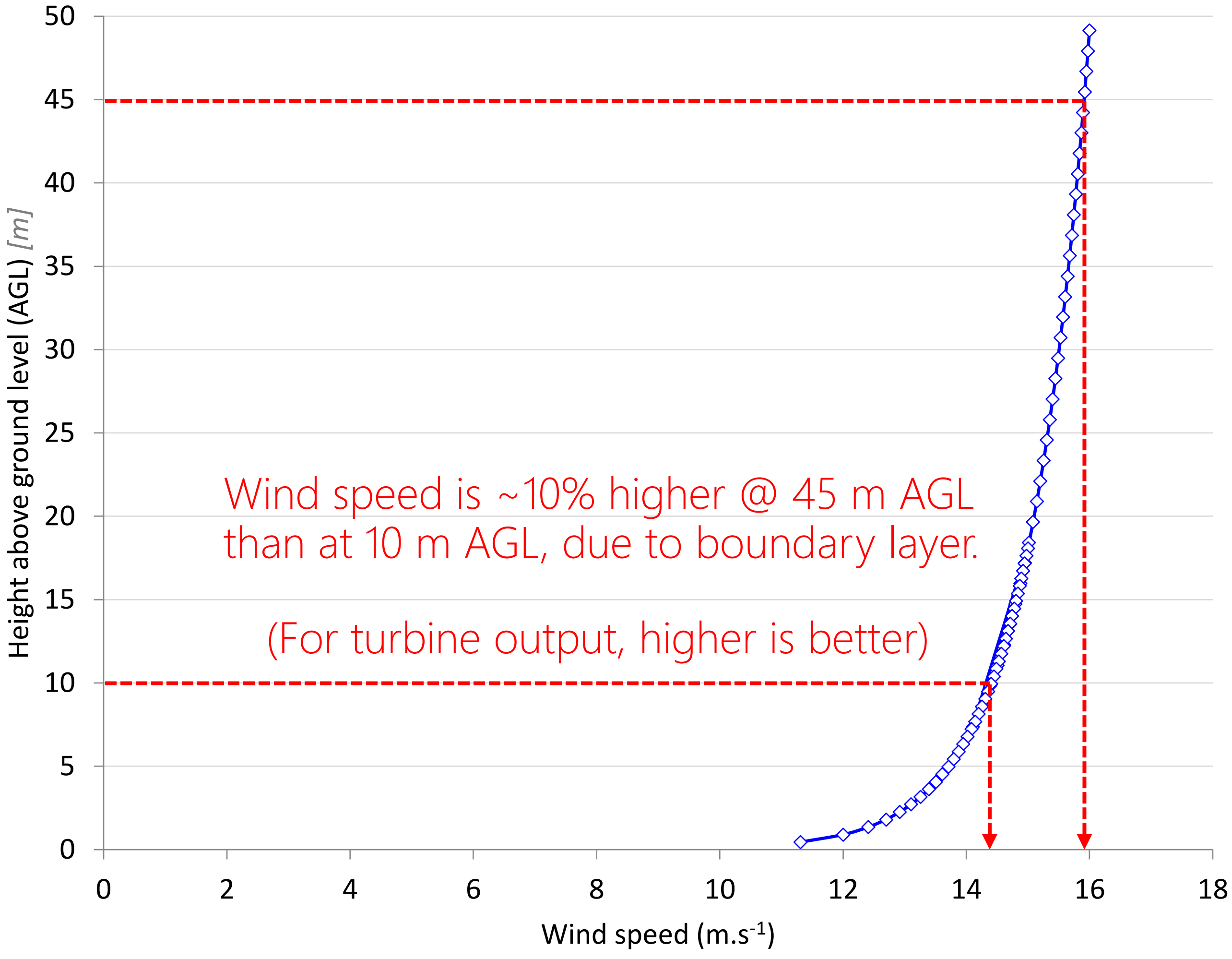
varies geographically
normally ~2

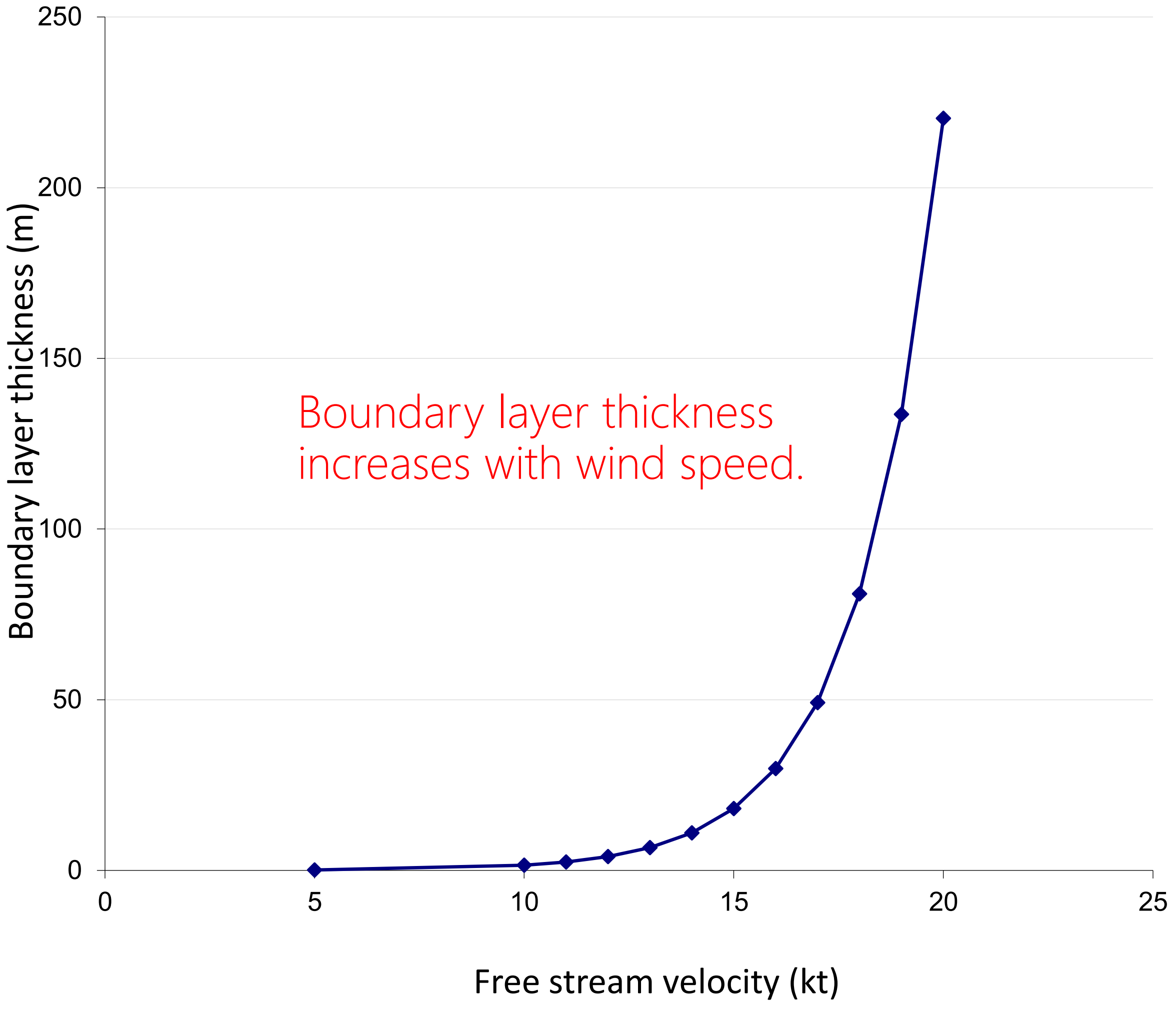
$$\alpha = 2.2$$

$$c = 7.6$$

normally slightly larger than
mean wind speed

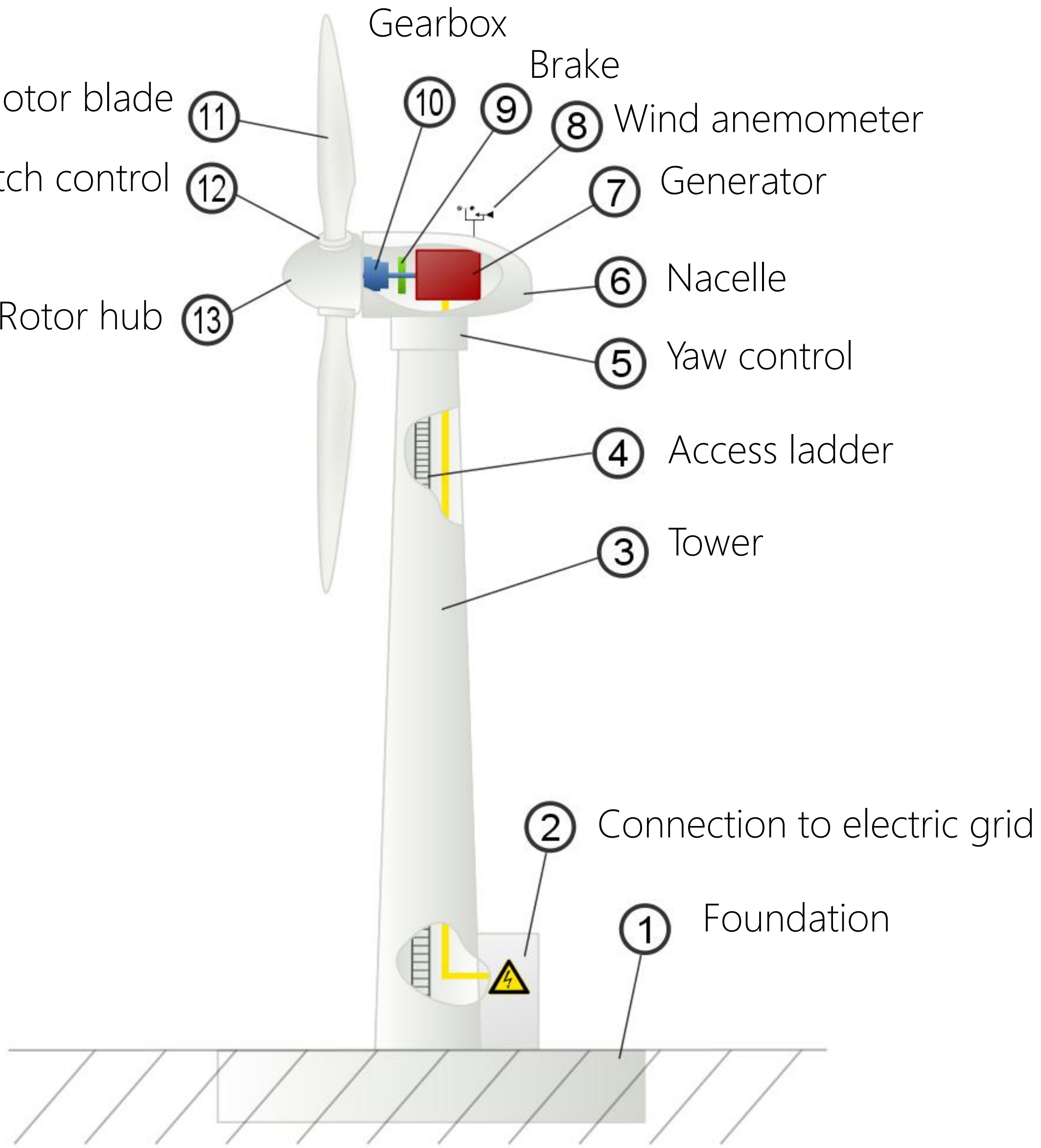
Near ground level, aerodynamic drag (due to buildings, trees, topography, etc.) causes a boundary layer to form.





Harvesting wind

Harvesting wind



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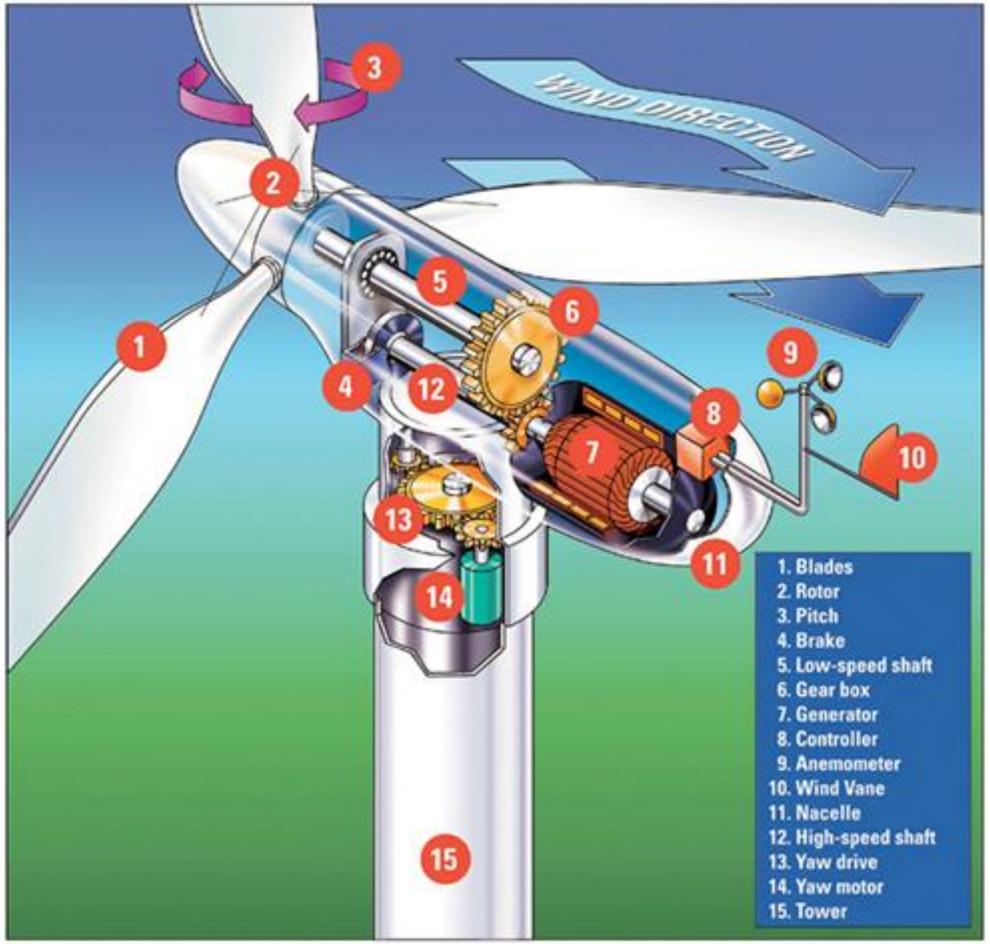


Harvesting wind

Sunderland UK 2005

Harvesting wind

Scotland, November 2007

Harvesting wind

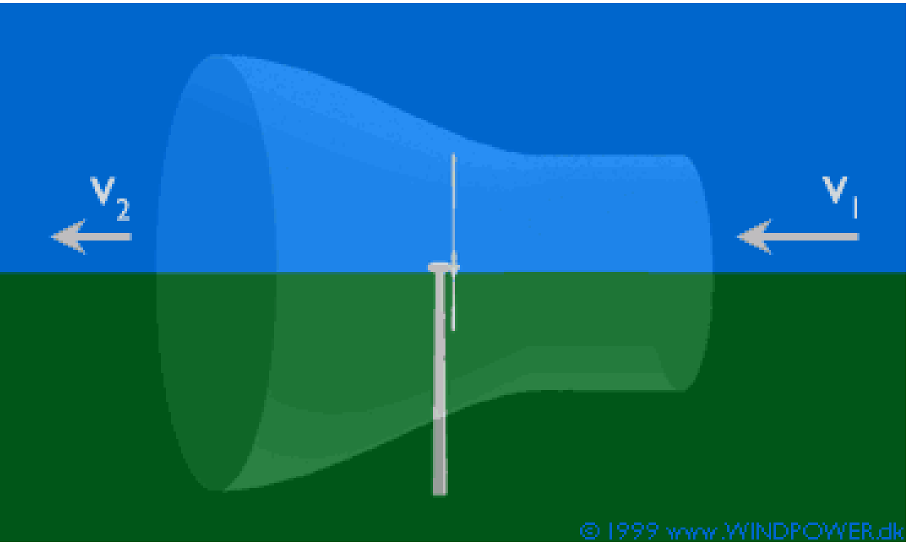
Oct 2008, Illinois

7 Feb 2009, Perkins, Ohio

Harvesting wind

Vertical-axis wind turbines

Harvesting wind



<u>1st Law (SSSF)</u>

$$\dot{E}_{in} - \dot{E}_{out} = \cancelto{0}{\dot{E}_{CV}}$$

$$\cancelto{0}{\dot{Q}_{in}} + \dot{m}\left(h_1 + \frac{v_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{v_2^2}{2} + gz_2\right)$$

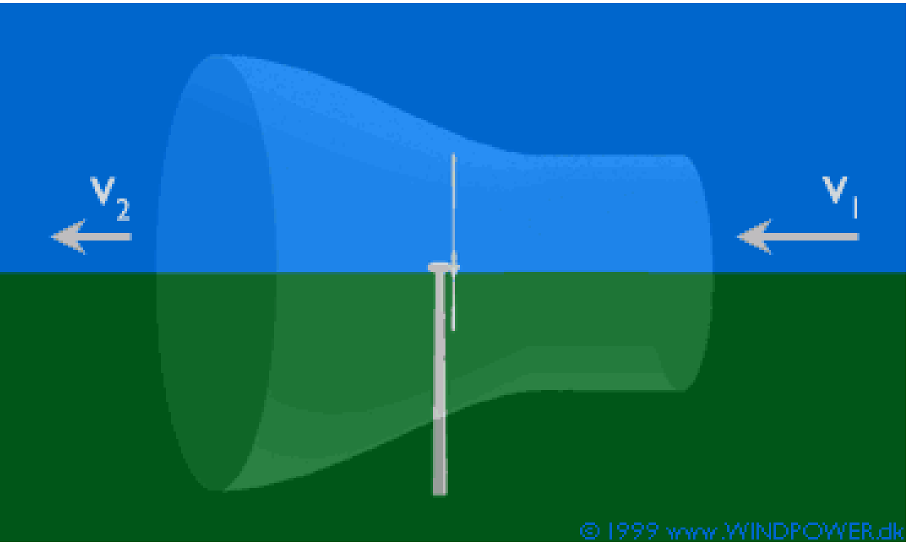
$$\therefore \dot{W}_{out} = \dot{m}\left(\frac{v_1^2 - v_2^2}{2}\right)$$

<u>Continuity equation</u> $\quad \dot{m} = \rho A v \approx \rho A\left(\frac{v_1 + v_2}{2}\right) \quad \Rightarrow \dot{W}_{out} = \rho A\left(\frac{v_1 + v_2}{2}\right)\left(\frac{v_1^2 - v_2^2}{2}\right)$

Substituting for v_2: $\quad v_2 = a v_1 \quad \Rightarrow \dot{W}_{out} = \rho A\left[\frac{v_1(1+a)}{2}\right]\left[\frac{v_1^2(1-a^2)}{2}\right] = \frac{\rho A v_1^3}{4}(1 + a - a^2 - a^3)$

Differentiating w.r.t. a: $\quad \frac{\partial \dot{W}_{out}}{\partial a} = 0 \quad = 1 - 2a - 3a^2 \quad \Rightarrow a = -1 \text{ or } a = \frac{1}{3}$

Harvesting wind



$$\dot{W}_{out,max} = \frac{\rho A}{4} v_1^3 \left(1 + \frac{1}{3} - \frac{1}{9} - \frac{1}{27}\right) = \frac{8}{27} \rho A v_1^3$$

Define *Power Coefficient, C_p*:

$$C_p = \frac{\dot{W}_{out}}{\dot{E}_{in}}$$

$$C_p = \frac{\dot{W}_{out}}{\frac{\rho A v_1^3}{2}} \quad \Rightarrow \quad C_{p,max} = \frac{16}{27} = 0.593$$

C_p has a max value of 0.593 when v_2 / v_1 = 1/3

Notes:

$\dot{W}_{out} \propto v_1^3$ ..... a 10% change in wind speed = 33% change in output

$\dot{W}_{out} \propto D_{rotor}^2$ ..... size matters, and bigger is better

$\dot{W}_{out} \propto 0.6\, \dot{KE}_{wind}$ ..... even under ideal conditions

Harvesting wind

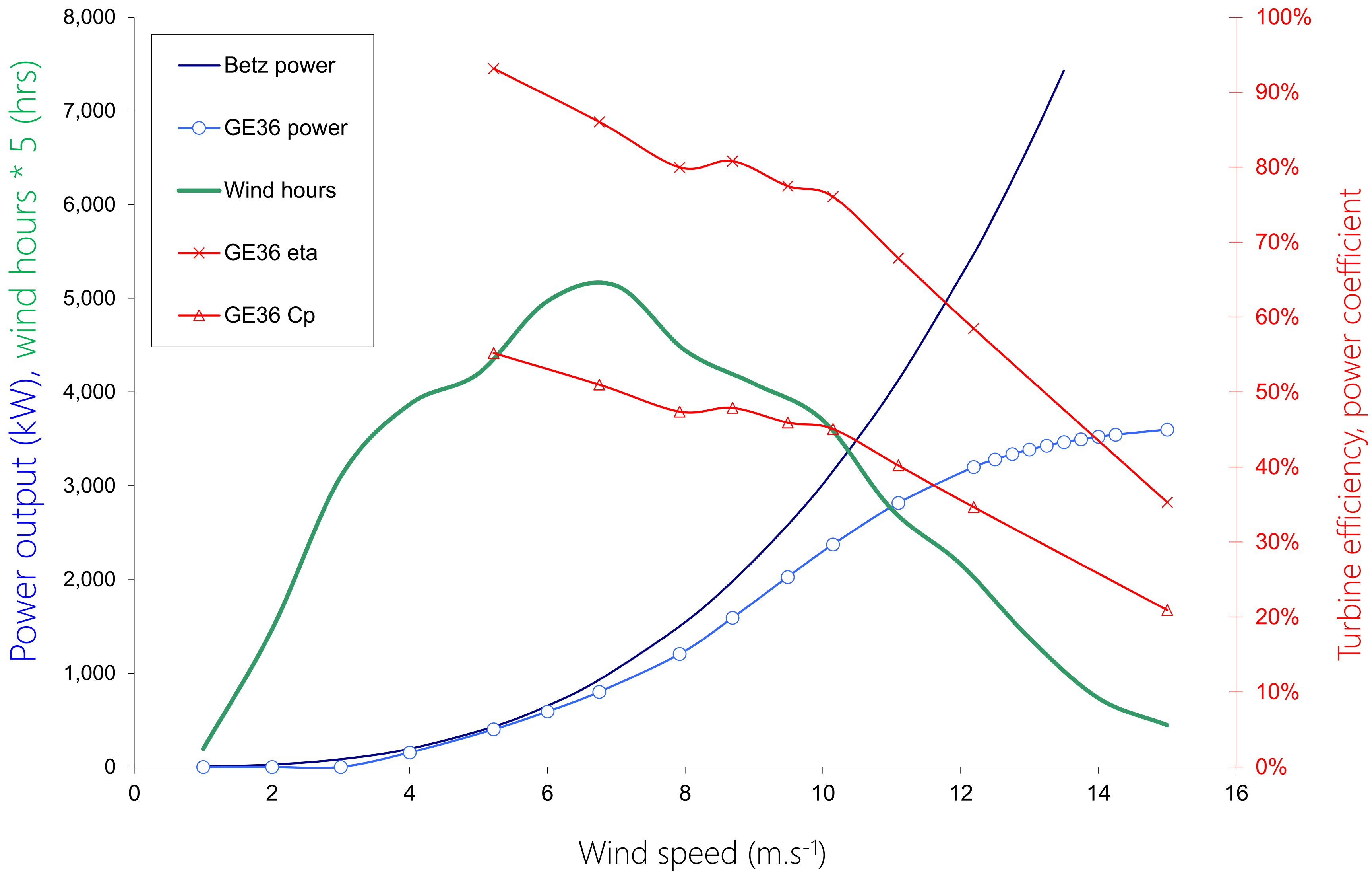
$\dot{W}_{max} < 0.6 \times K\dot{E}_{wind}$ ..... even under ideal conditions.........but...

The energy source is *free* – efficiency of capture is not *necessarily* very important.

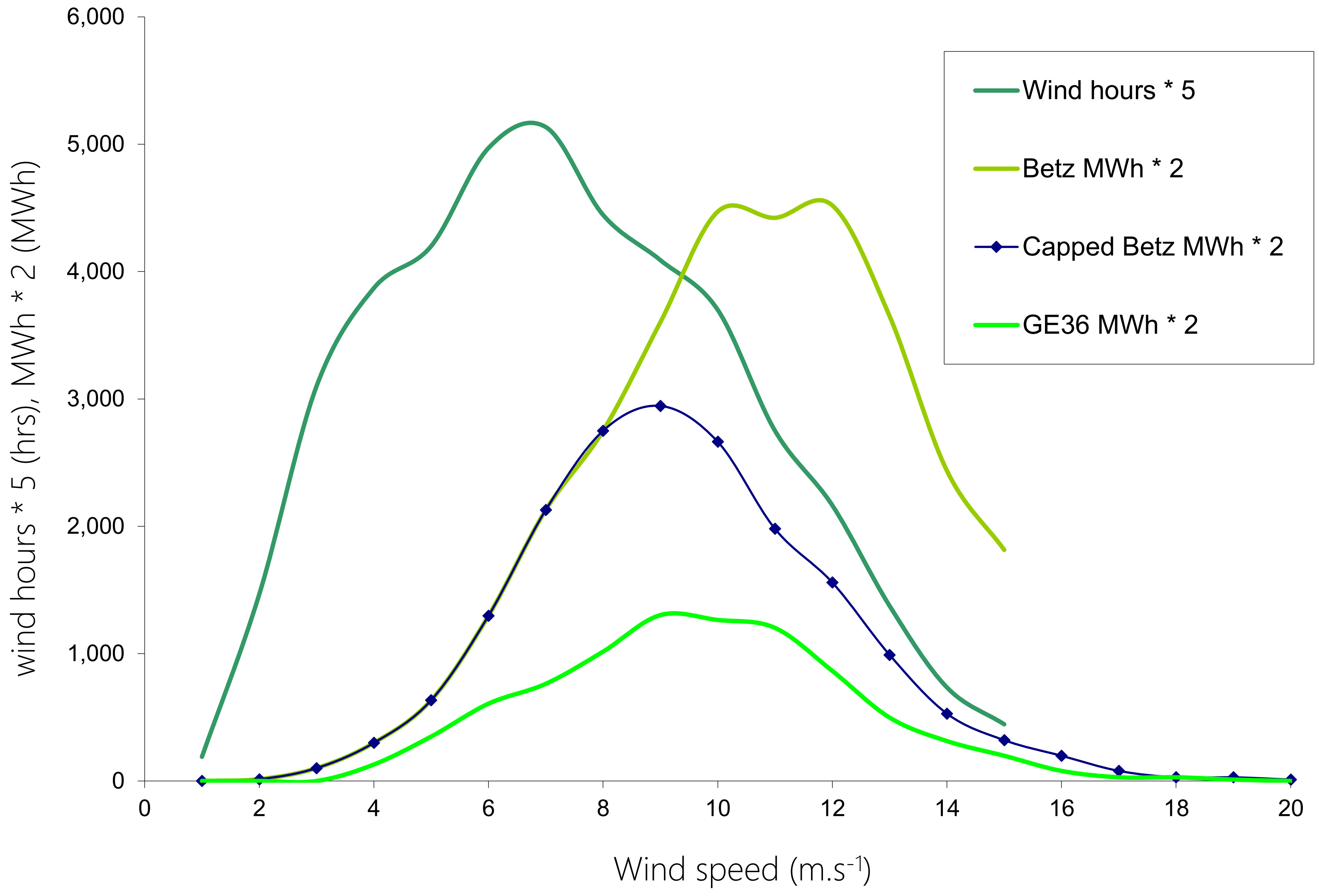
Objective is to maximise electrical production at minimum cost, so:

- a good wind resource is essential (to maximise production)
- a cheaper turbine *might* be better than a more efficient, more expensive design

Harvesting wind



Harvesting wind



Using the preceding analysis, it is easy to determine the electrical energy output to be expected from a GE36 under the 2003 wind regime: 9,800 MWh per year.

We can now determine a capacity factor for the wind turbine:

MWh per year

$$\text{Capacity factor} = \frac{W_{out}}{\dot{W}_{rated} \times 8{,}760} = \frac{9{,}800}{3.6 \times 8{,}760} = 31\%$$

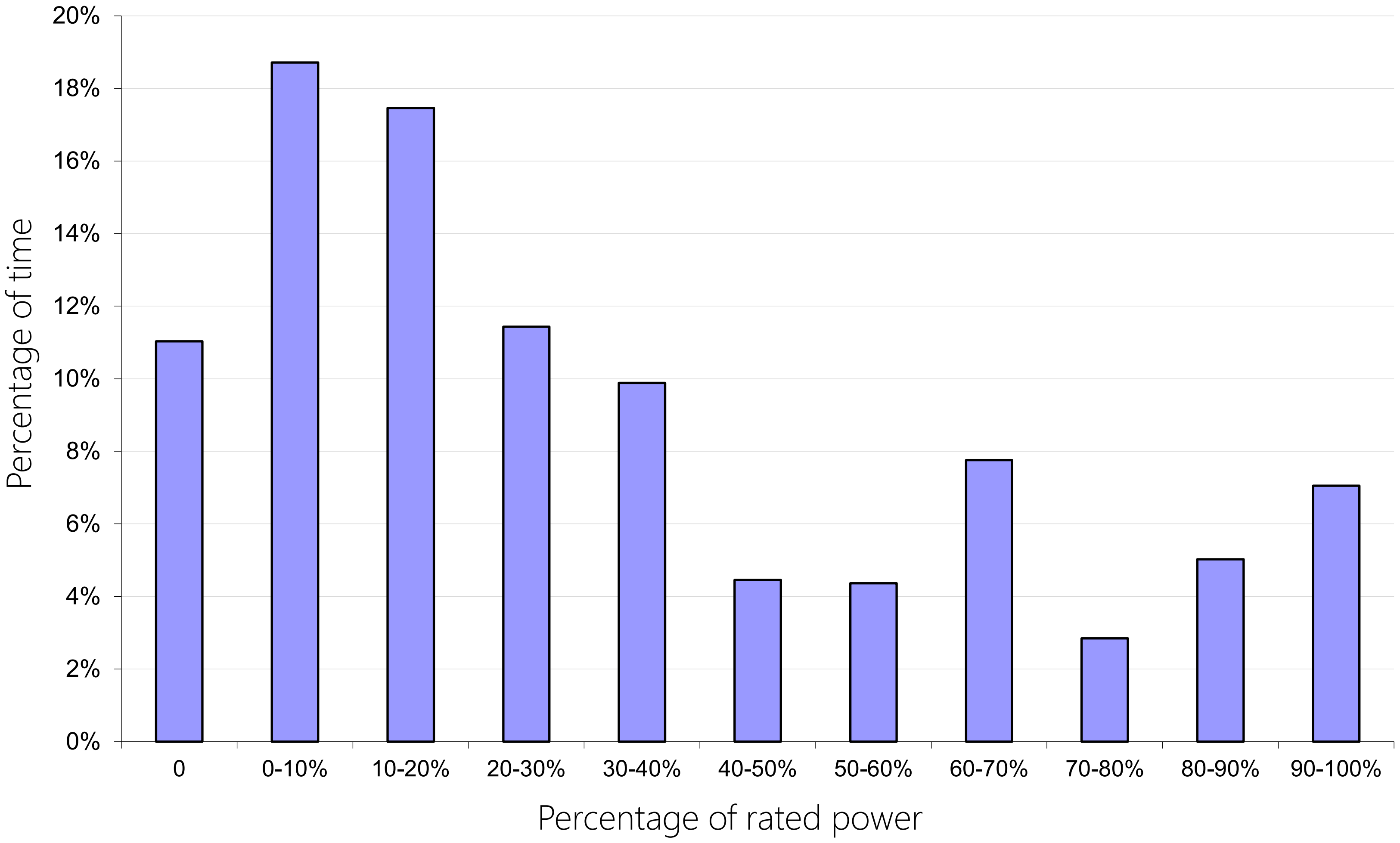
hours per year

Rated power (MW)

A capacity factor of ~30% is representative of what might be expected from a good, onshore, wind site.

Note that we have assumed that the transmissions system operator (TSO) will *always* accept power from wind-driven plant. As wind penetration increases, that ceases to be the case…

It is also easy to see that a wind turbine would spend very little time at rated power.



Harvesting wind

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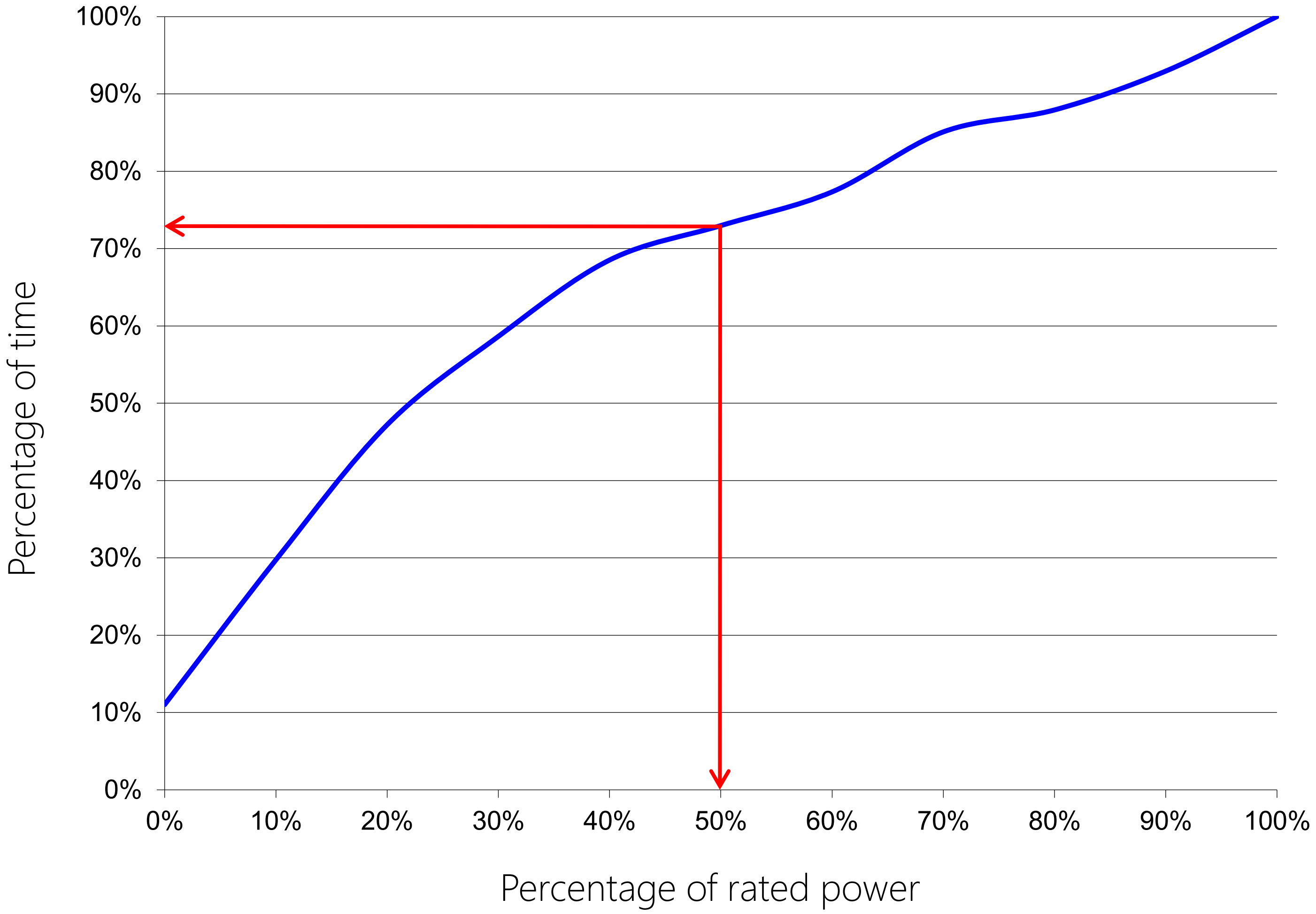
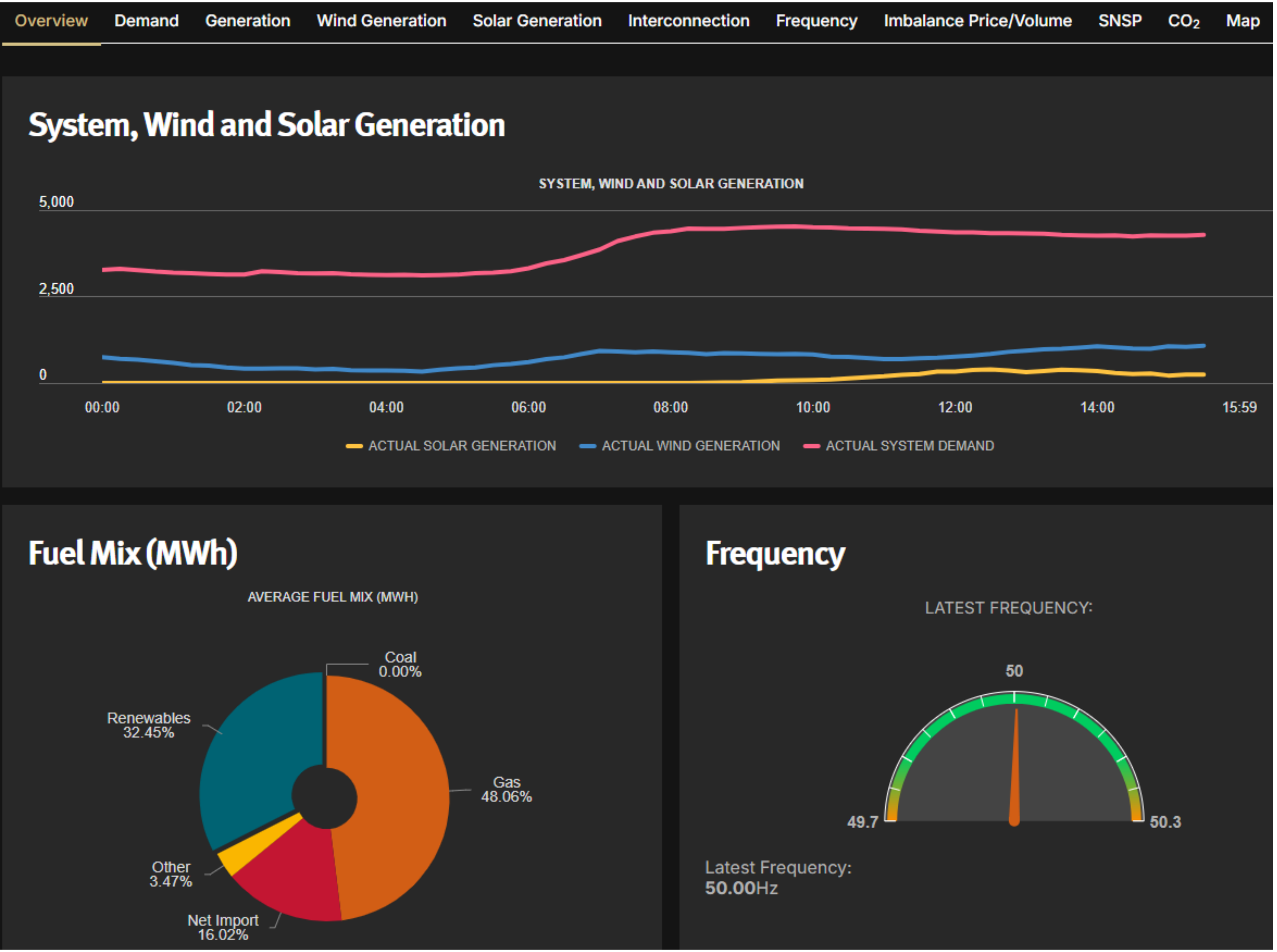


Energy from renewables:

Wind

Harvesting wind



http://smartgriddashboard.eirgrid.com/roi

Harvesting w

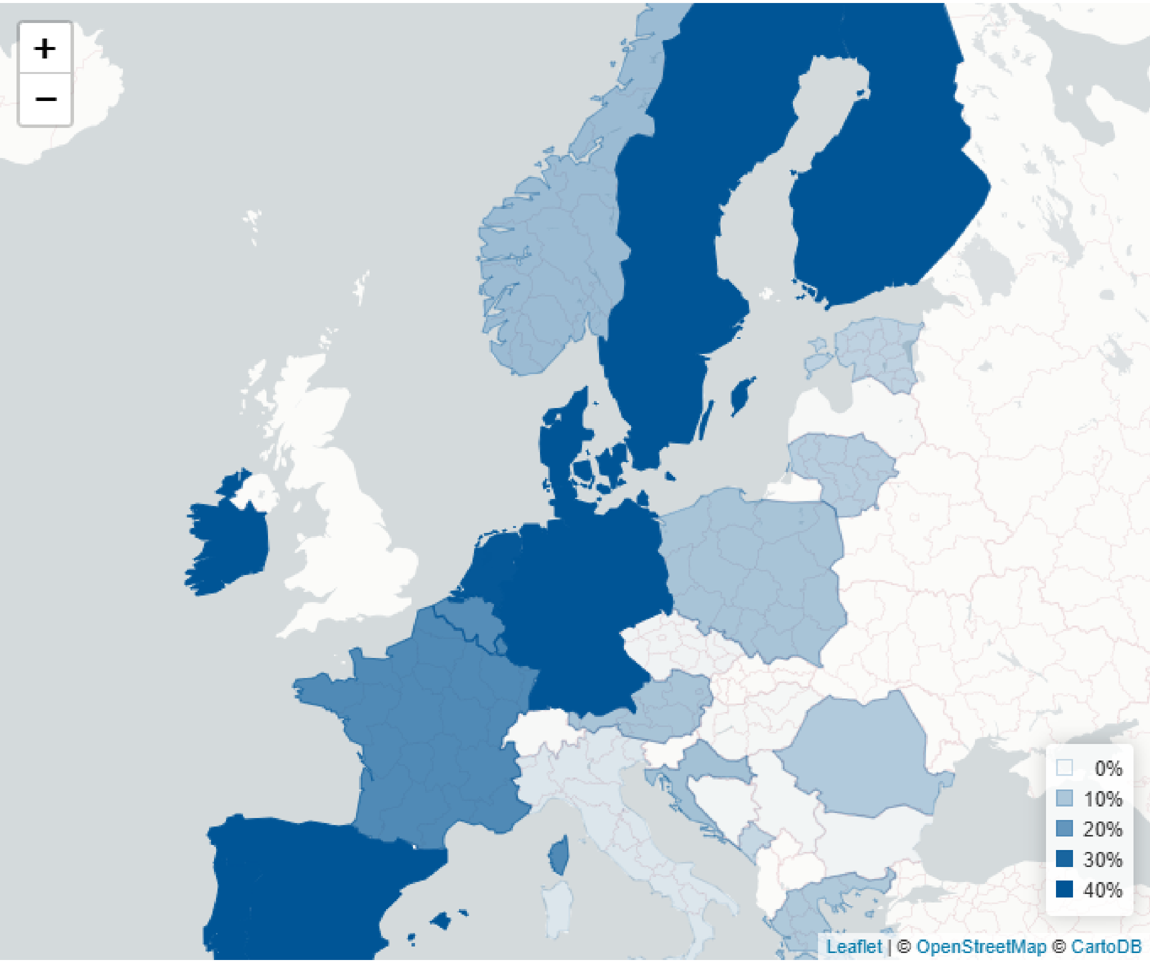
Wind EUROPE — WIND POWER NUMBERS DAILY

Currently displaying data from 19 October 2025

Looking for archive data?

How much wind was in Europe's electricity yesterday?

- DAILY WIND ENERGY
- YESTERDAY'S TOP 20 COUNTRIES
- HOURLY ELECTRICITY MIX
- HOURLY WIND ENERGY GENERATION
- CAPACITY FACTORS



Share of wind energy in electricity demand

25.5%

21.3%
1,376 GWh
onshore wind

4.1%
267 GWh
offshore wind

Would you like to receive **Daily Wind Power Numbers** every morning in your inbox?

Subscribe here

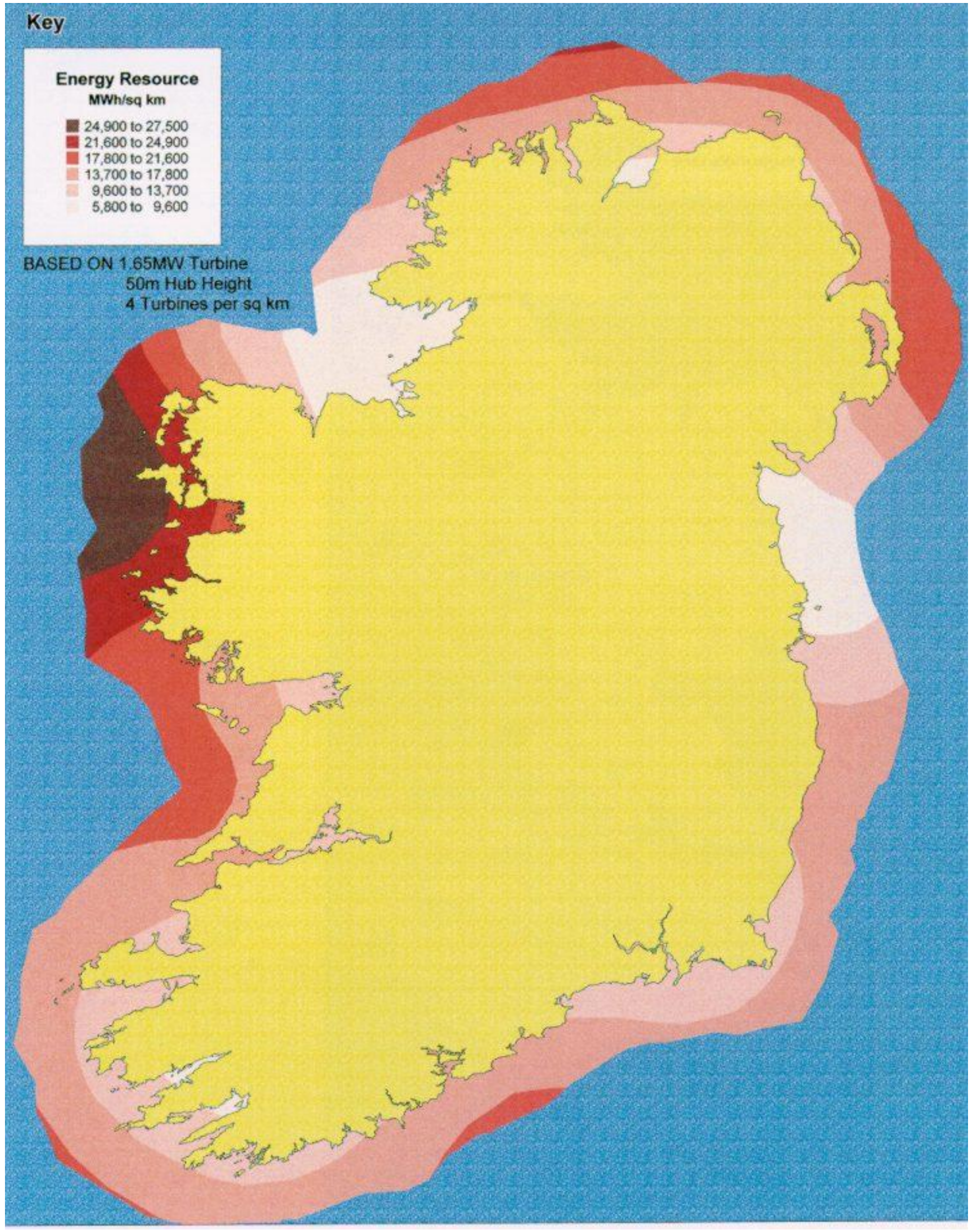
New to wind power numbers?

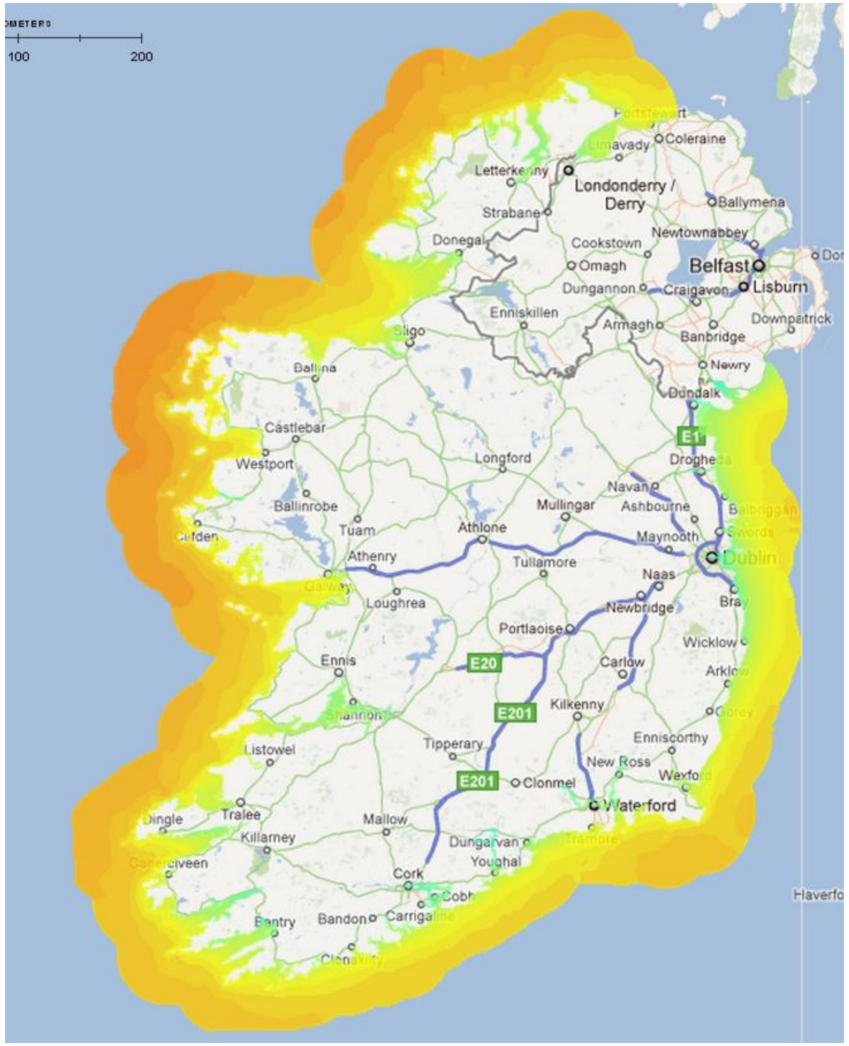
See the explanation

https://windeurope.org/about-wind/daily-wind/

Moving offshore

Moving offshore



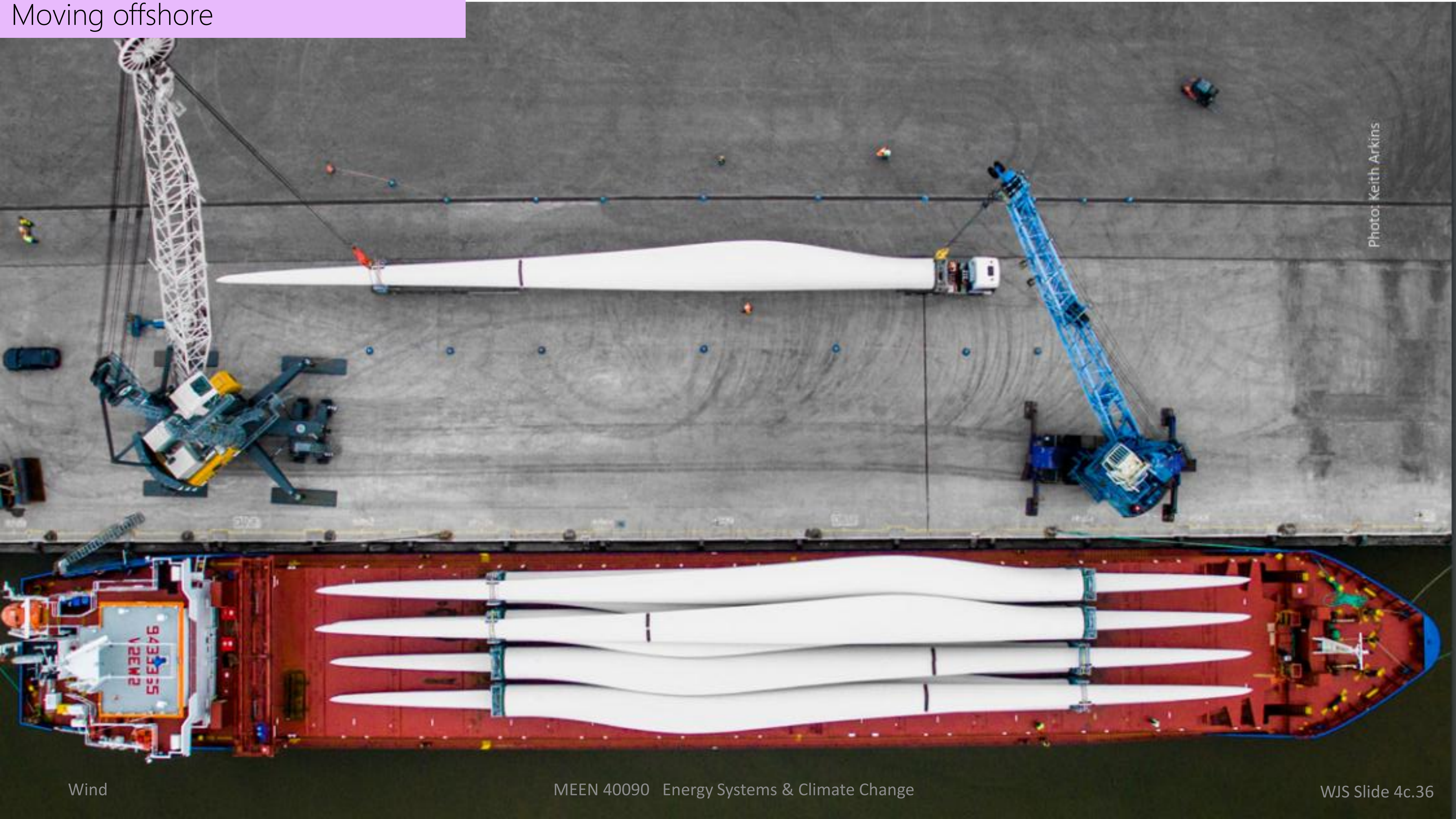


Source: SEAI Wind Atlas, maps.seai.ie/wind

Moving offshore

Moving offshore

Moving offshore



Moving offshore

Incentives

- Superior wind resource;
- Large economies of scale;
- Reduction in perceived impact on visual amenity;
- Less difficulty in securing planning approval.

Higher Reward

Challenges

- Technology less well developed;
- Harsh environment;
- Difficulty in accessing plant in foul weather;
- Higher investment and O&M costs.

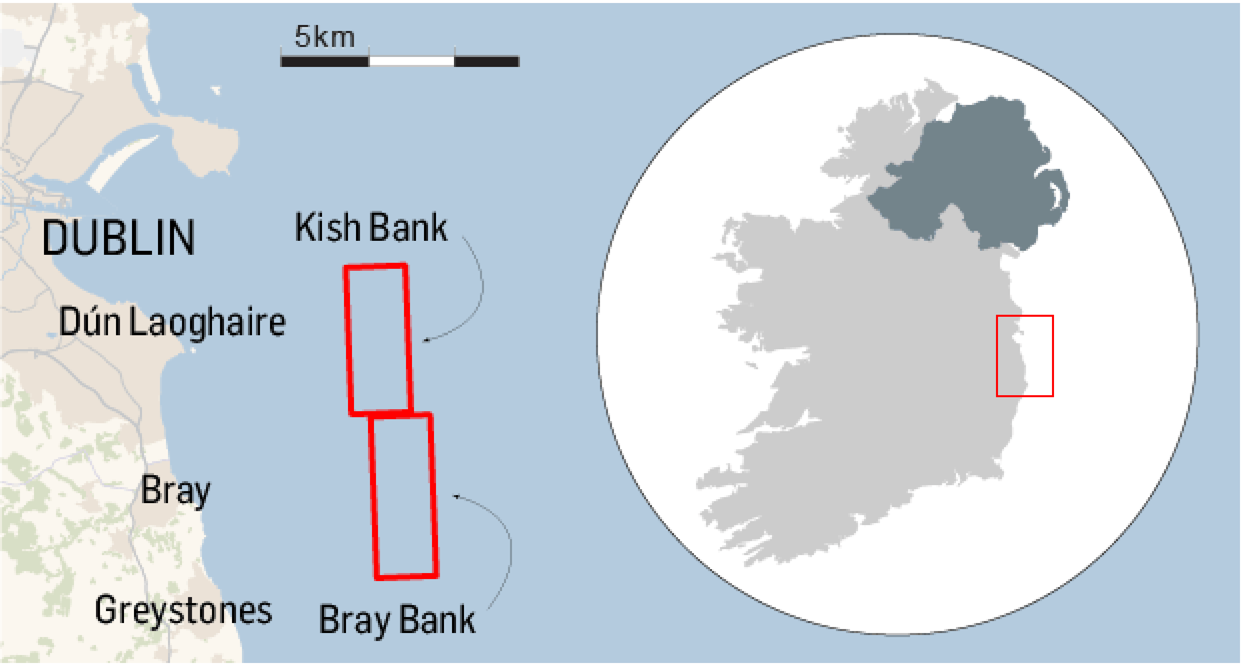
Higher Risk

Moving offshore

- Large farms – 100 – 1,500 MW
- Higher wind speeds ⇒ superior energy yield
- Superior wind regime (fewer obstructions and lower temperature gradients) ⇒ longer operational lives (20 to 25 years?)
- Very large machines to deliver economies of scale: 15 MW now, 20+ MW in final testing
- Towers up to 180 m
- Blades up to 150 m long
- Fixed foundation: shallow(ish) water, up to ~55 m deep; either monopile or jacket type
- Floating: still under development, depths of 50 – 1,000 m, potential to unleash enormous resource
- Must be minimum distance from shore to minimise impact on visual amenity (IRL > 5 km)
- Offshore substation and at least one grid connection to the shore – expensive.

Moving offshore

Ireland's Climate Action Plan includes at least 3.5 GW of offshore wind by 2030



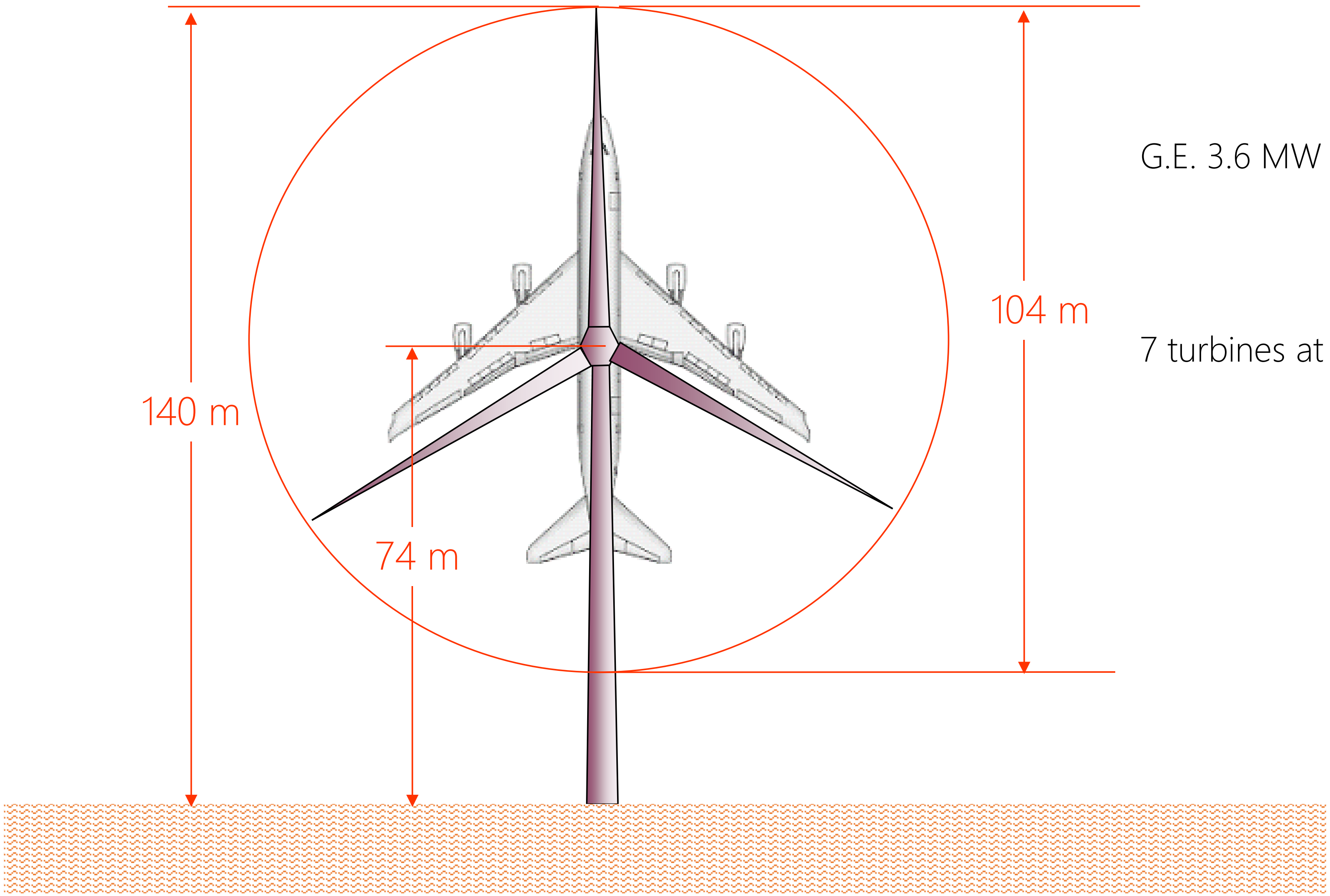
www.dublinarray.com

Moving offshore

Moving offshore

Arklow Bank (Ireland)

Arklow Bank (Ireland)



G.E. 3.6 MW wind turbine

7 turbines at 600 m apart

Moving offshore

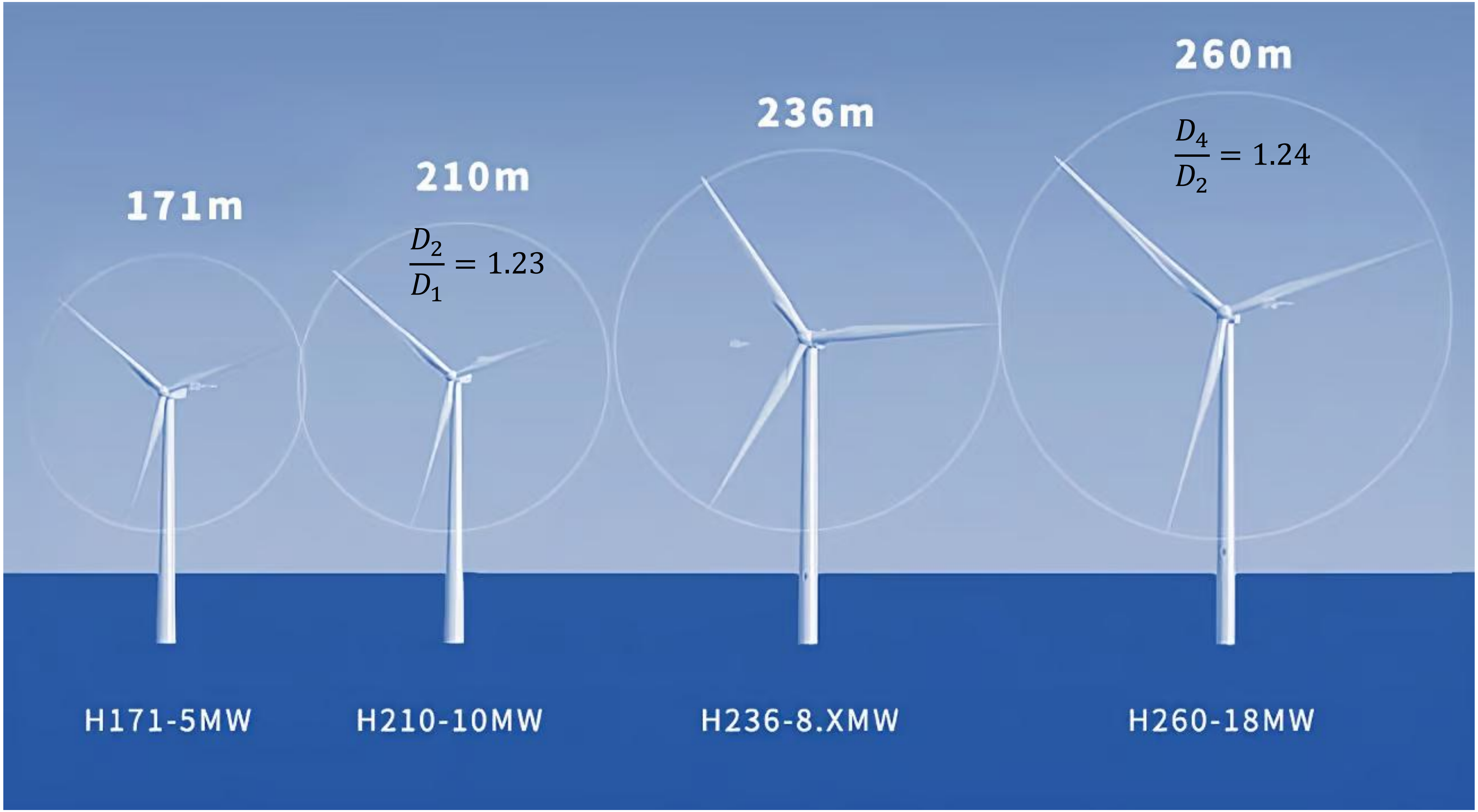
World's most powerful – 18 MW – wind turbine (Oct 2024)

https://www.rivieramm.com/news-content-hub/news-content-hub/chinas-cssc-haizhuang-unveils-18-mw-mega-turbine-74459

CSSC H260-18

https://maritime-executive.com/article/dongfang-unveils-record-smashing-26-mw-offshore-wind-turbine

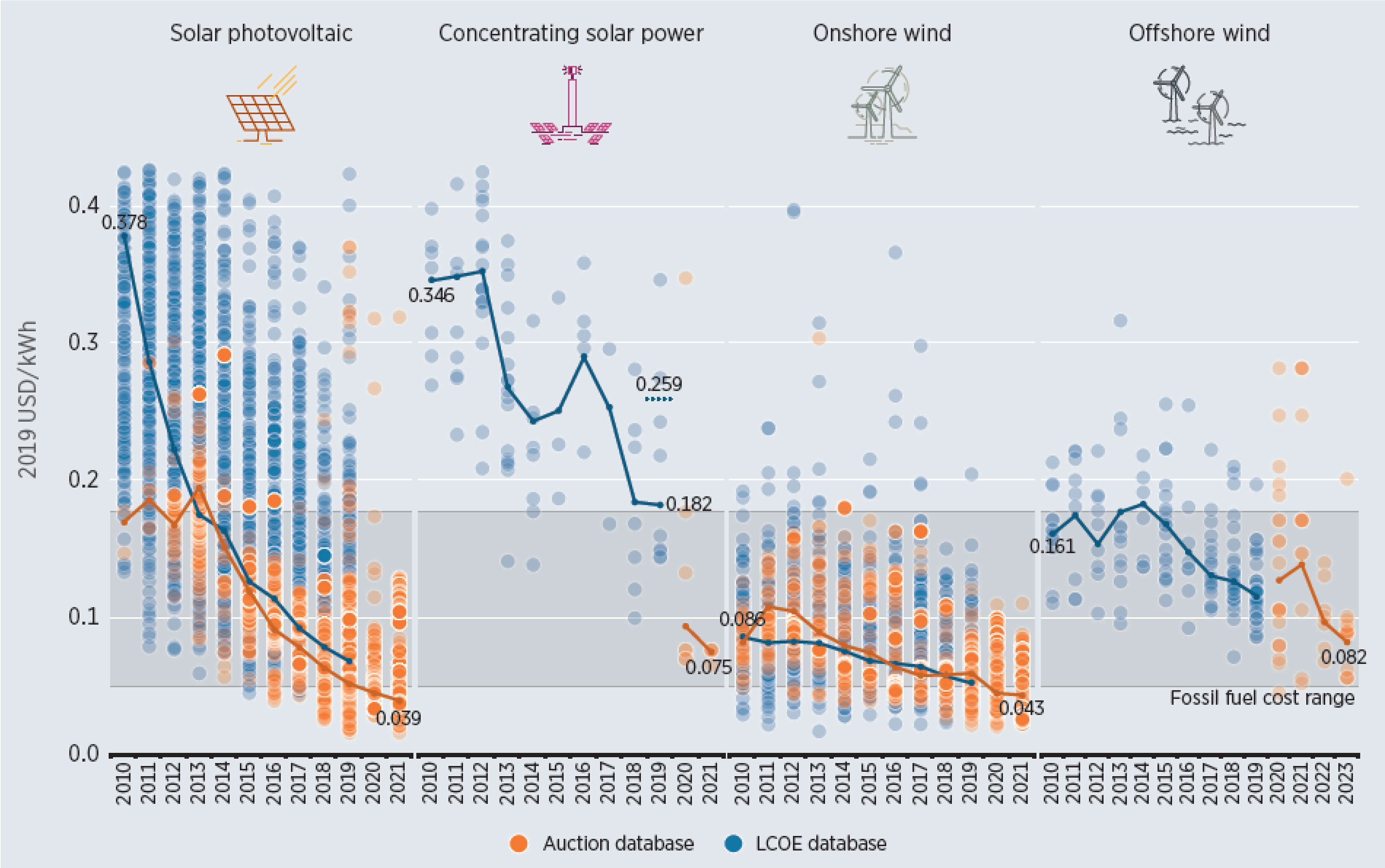
Moving offshore



$$\frac{D_2}{D_1} = 1.23$$

$$\frac{D_4}{D_2} = 1.24$$

Moving offshore



Source: IRENA (2020), "Renewable Power generation Costs in 2019". www.irena.org

Moving offshore

€1bn ESB offshore wind project being paused 'due to uncertainty over government policy'

Foreshore licence for 500MW Clogherhead wind farm off Co Louth expired in summer

Project among those aimed at helping state meet green energy targets. Stock image

John Mulligan
Thu 17 Oct 2024 at 02:30

Residents raise concern as Ireland's six new offshore wind farms move closer to reality

Developers are seeking planning permission for large-turbine wind farms as people from Louth to Wexford say they are worried about more than visual intrusion

European Investment Bank to support offshore wind port investment

Updated / Wednesday, 11 Sep 2024 12:00

The development of Offshore Renewable Energy port infrastructure is vital to help Ireland meet its renewable energy targets

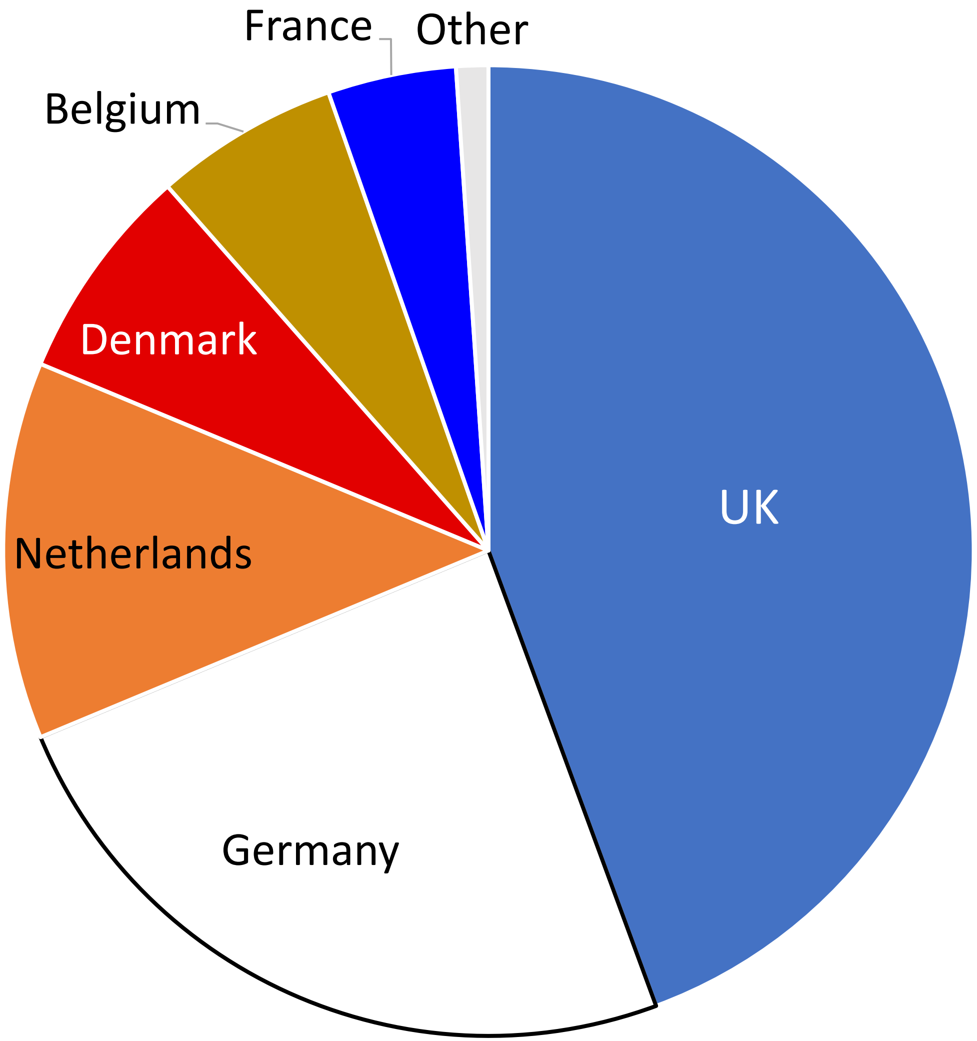
Planning application submitted for Ireland's largest offshore wind park

August 29, 2024 3001 Views

Codling Wind Park, Ireland's largest Phase 1[1] offshore renewable energy project will submit its planning application to An Bord Pleanála early next week. A planning notice for the project is being published in local papers in Wicklow and Dublin and will be included in a national newspapers.

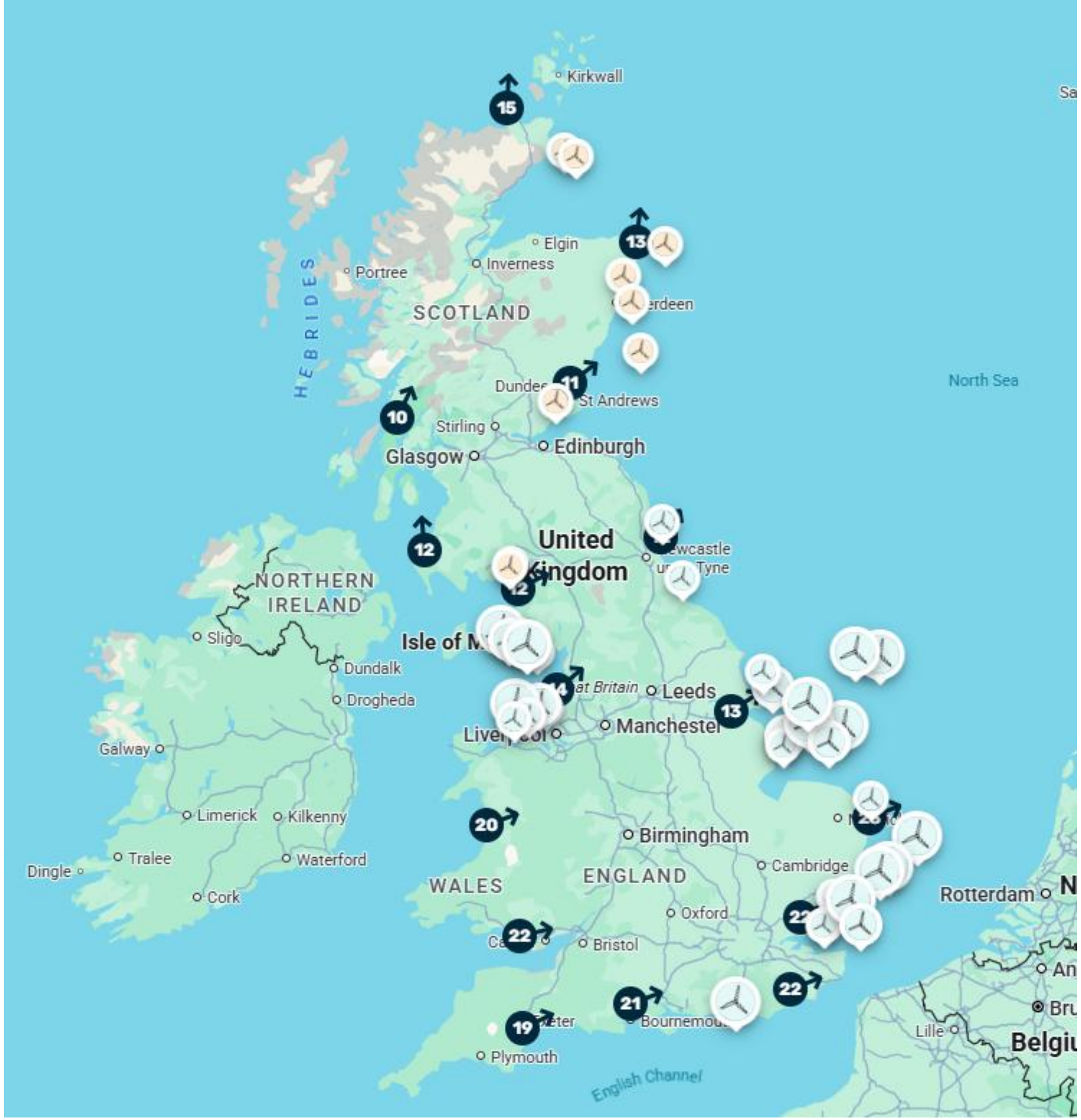
Offshore wind: EU+UK installed capacity at mid 2025

37 GW



Source: Wind Europe (2025), ""Offshore wind energy: 2025 mid-year statistics". www.windeurope.org

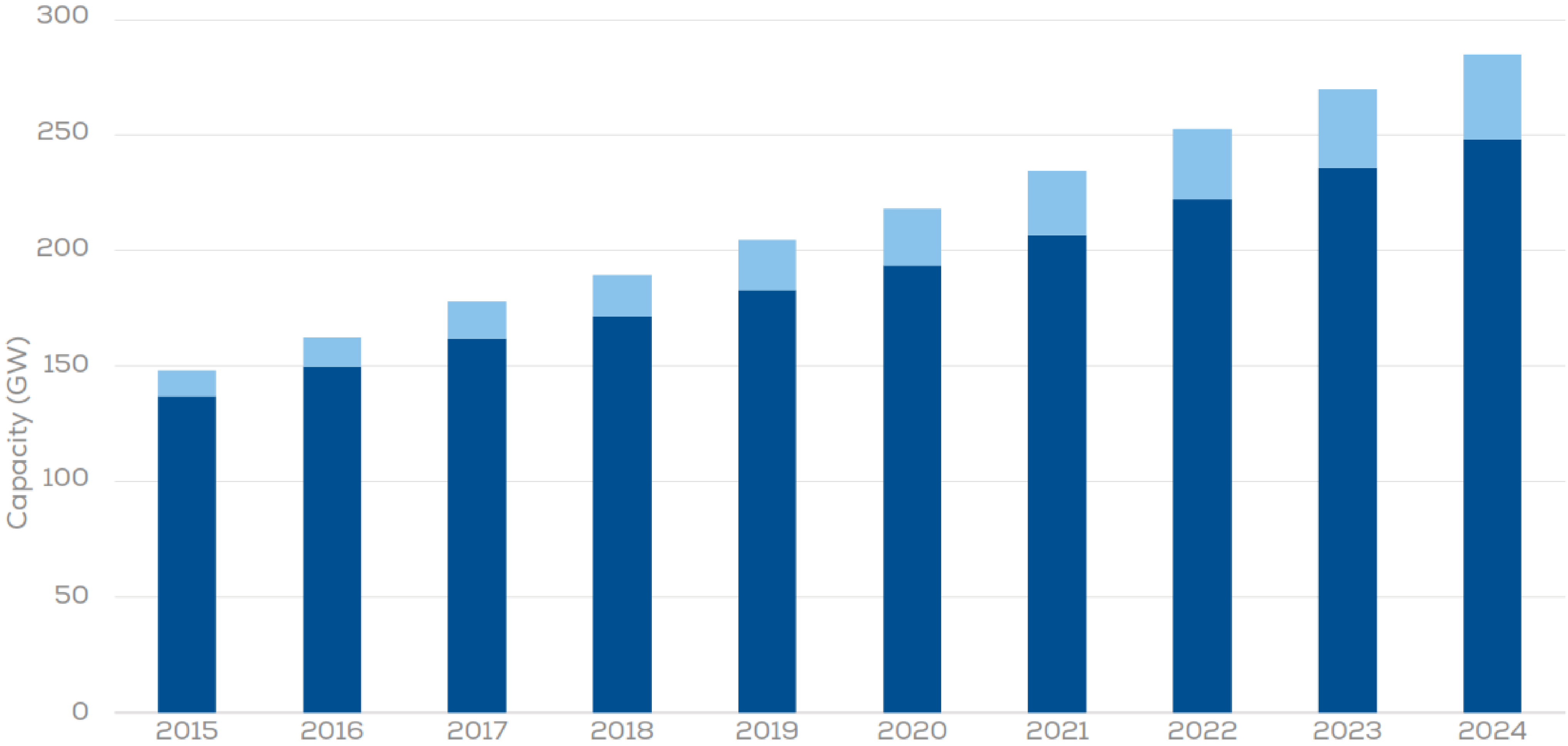
Moving offshore



For a current map, see:
https://www.thecrownestate.co.uk/our-business/marine/offshore-wind/offshore-wind-map

Moving offshore

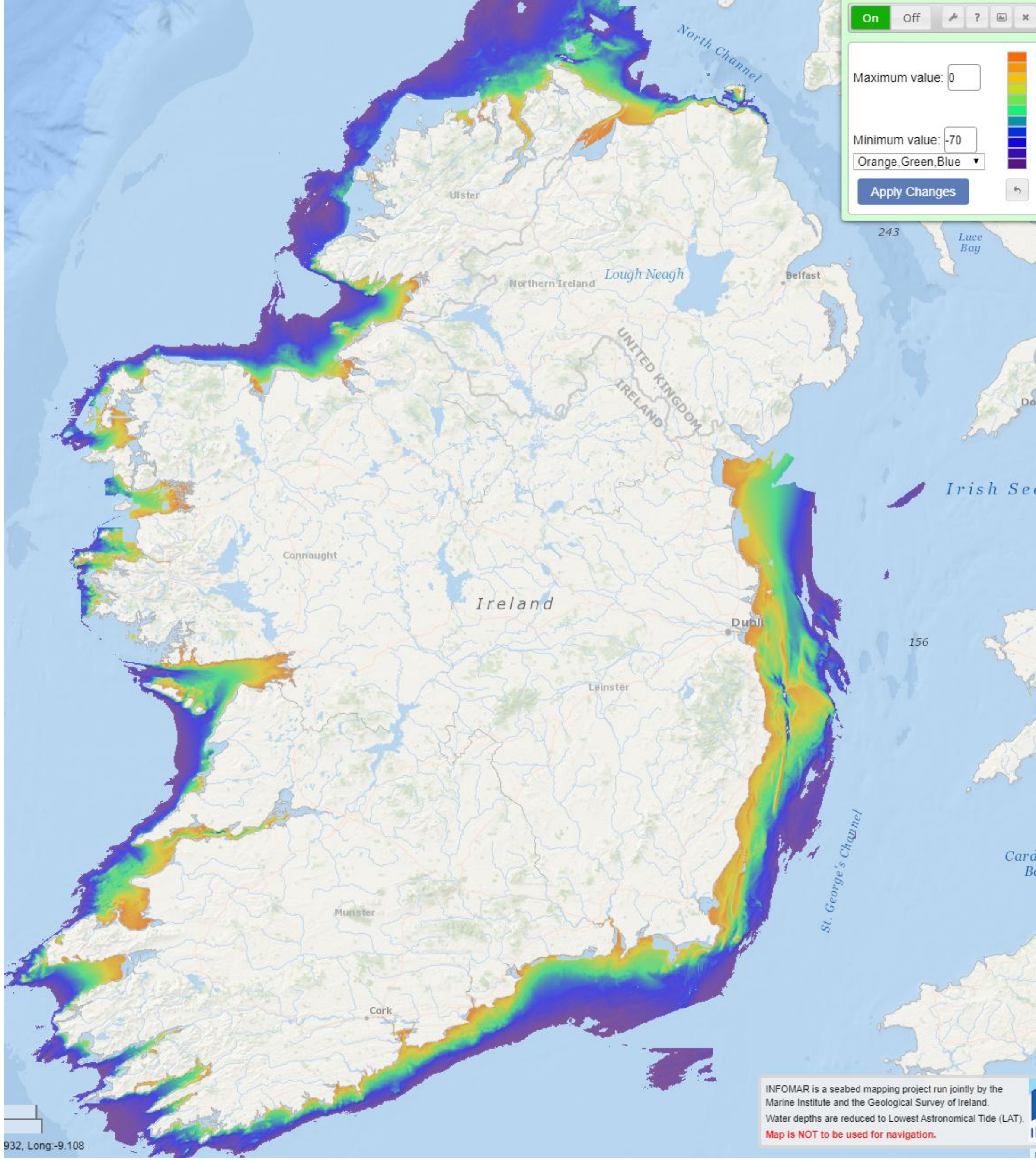
Historical onshore and offshore wind capacity installations, Europe



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Onshore	137	150	162	171	183	193	207	222	236	248
Offshore	11	12	16	18	22	25	28	30	34	37

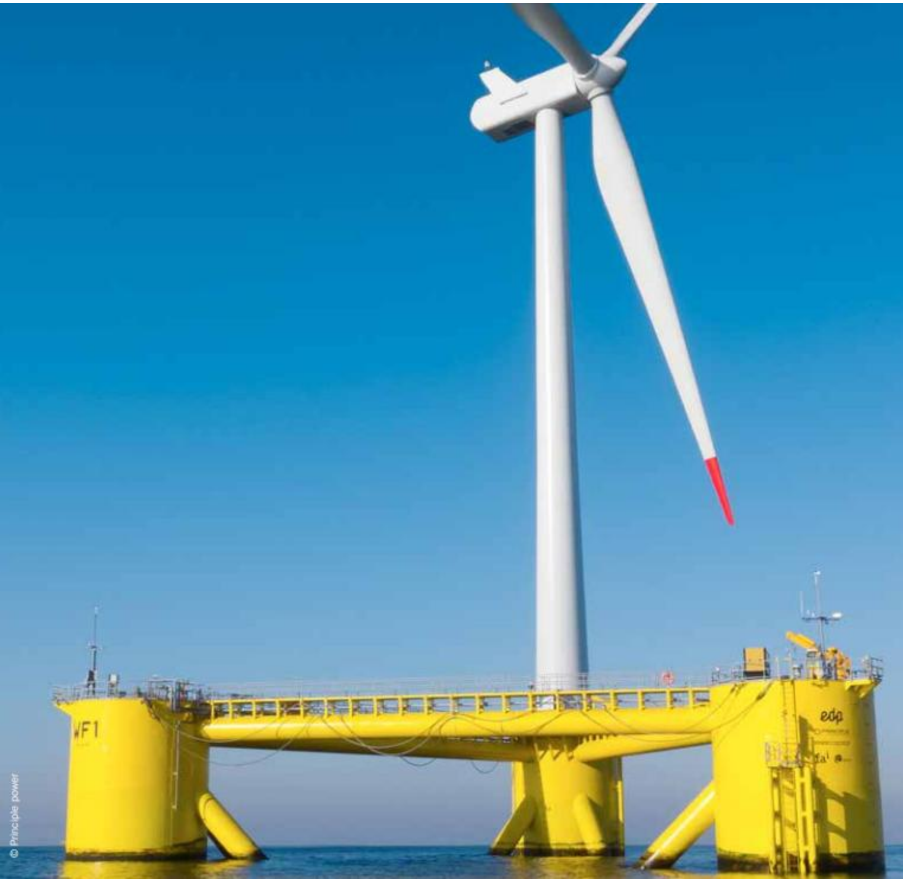
Source: Wind Europe (2025), "Wind energy in Europe: 2024". www.windeurope.org

Moving offshore: floating wind



Moving offshore: floating wind

The next step: floating wind turbine platforms



Moving offshore: floating wind

Hywind video links:

- https://www.youtube.com/watch?v=PUlfvXaISvc (9 minutes, v.good)
- https://www.youtube.com/watch?v=sgCA5e7K7r8 (2 minutes, not bad)
- https://www.youtube.com/watch?v=PpMOP5ogWWA (1 minute, CGI, ok)

First floating wind farm, built by offshore oil company, delivers electricity

Anchored, floating turbines allow offshore wind installations in deep waters.

MEGAN GEUSS - 10/18/2017, 7:13 PM

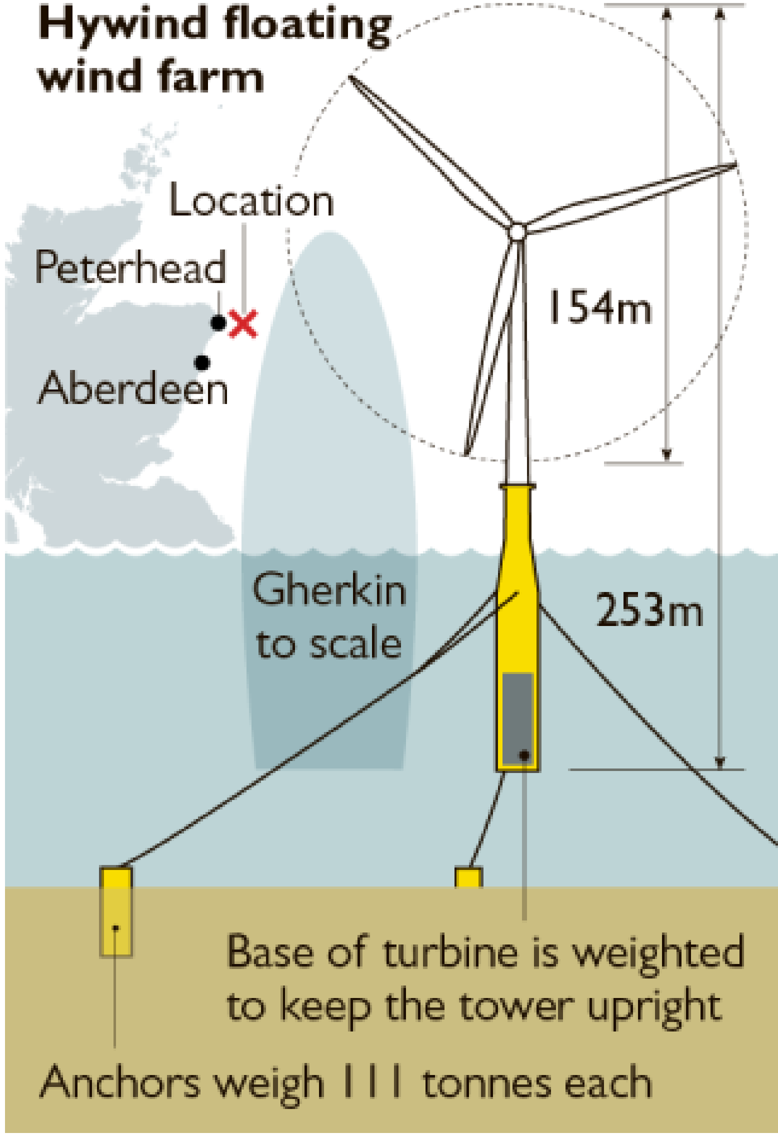
World's first floating wind farm starts generating electricity

18 October 2017 | Scotland

Hywind floating project starts production

18 October 2017 by Craig Richard, Be the first to comment

UK: The world's first floating wind farm has started to deliver electricity to the Scottish grid.



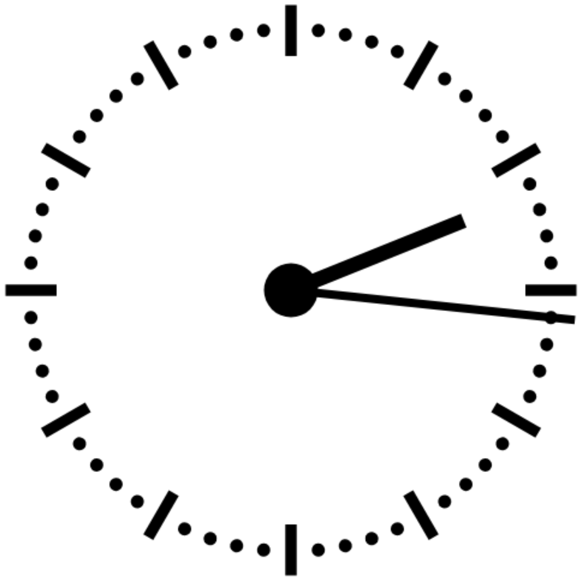
Grid integration

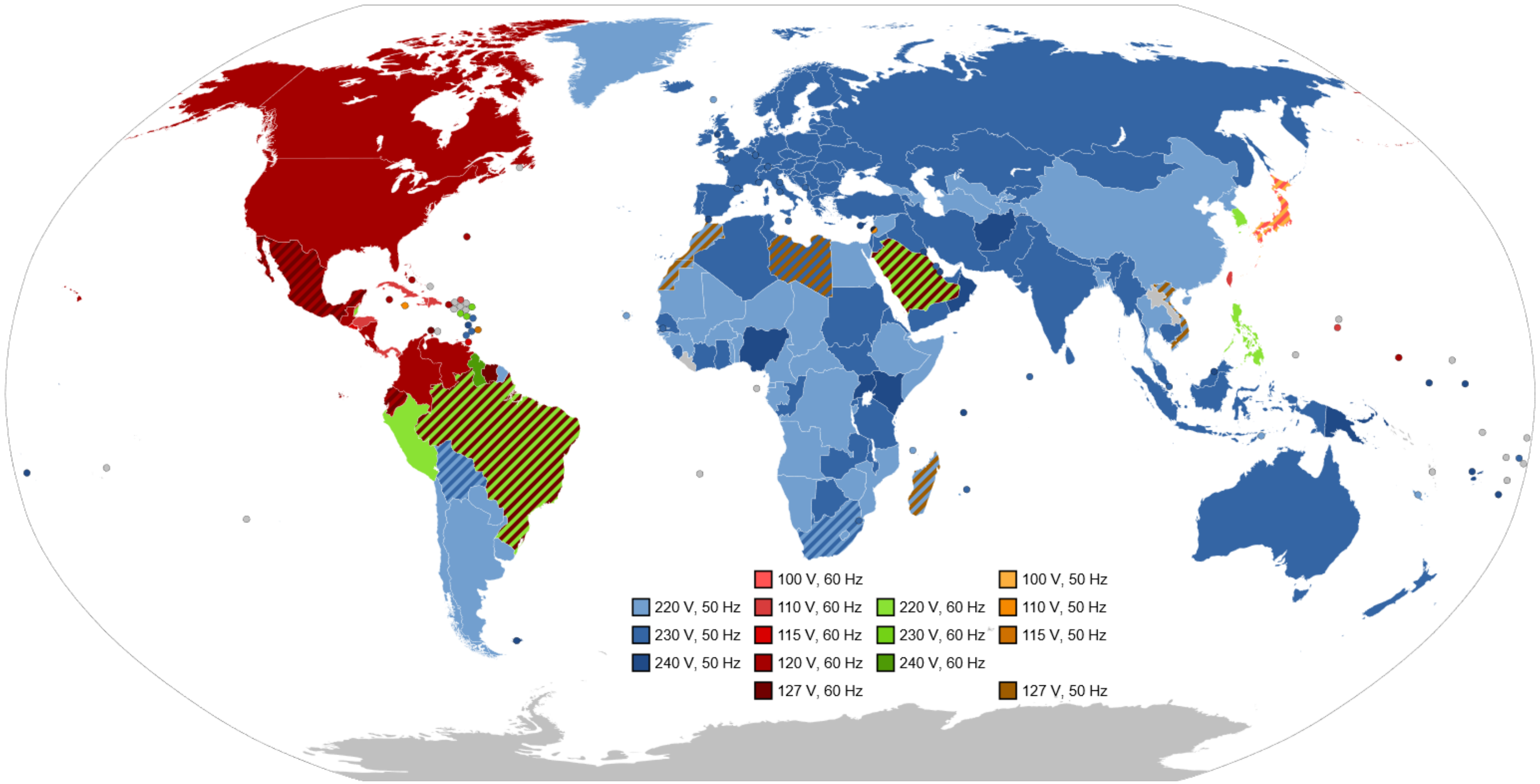
Grid integration

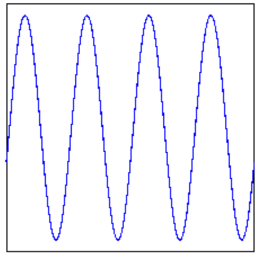
Maintaining a steady system frequency is the number one priority for the grid operator.

In Europe, the system frequency is 50 Hz.

In North America, the system frequency is 60 Hz.

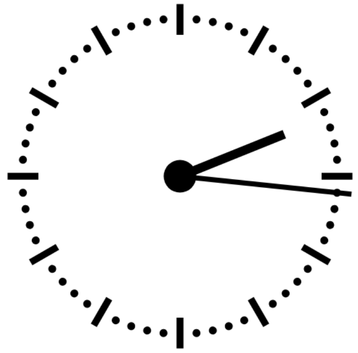






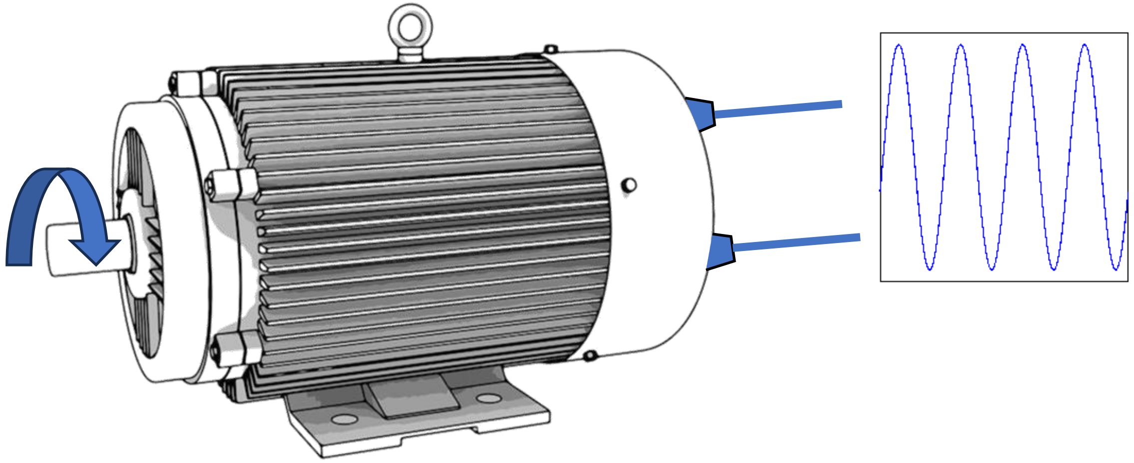
Grid integration

Maintaining a steady system frequency is the **number one priority** for the grid operator.



System frequency is determined by the rotational speed of the synchronous generators operating on the system.

If the rotational speed of a generator changes, the frequency of its electrical output will also change.



Grid integration

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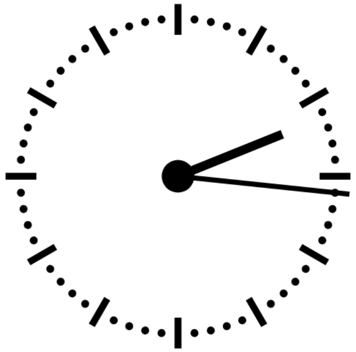
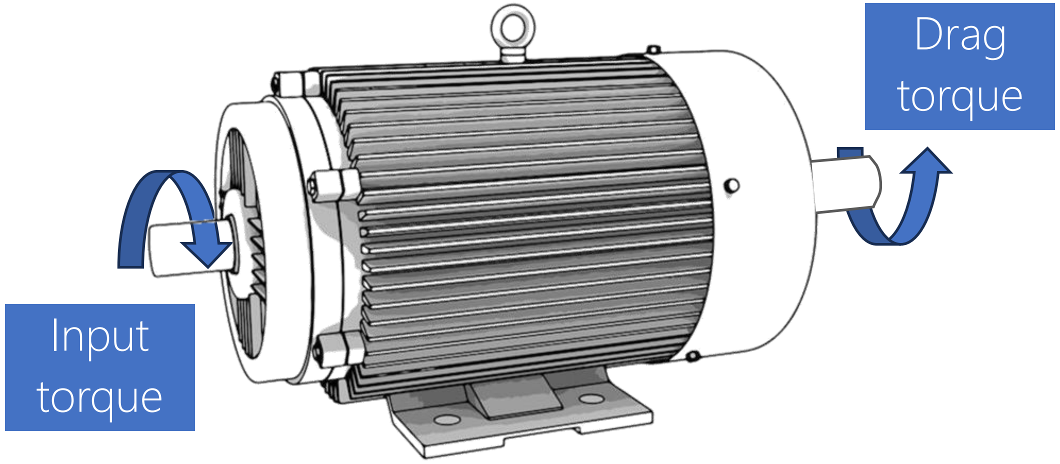


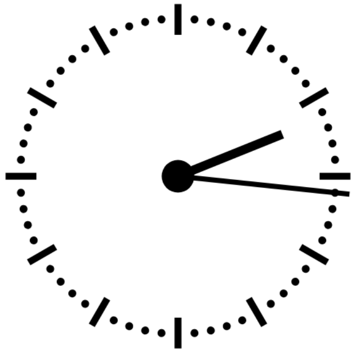
System frequency is determined by the rotational speed of the synchronous generators operating on the system.

To maintain a steady rotational speed, the torque being supplied to the generator must match the drag torque exerted by the load on the generator.

- If drag torque increases, system frequency will tend to fall.
- If drag torque decreases, system frequency will tend to rise.

The tolerance on system frequency control is typically ±1%, with a normal range of ± 0.2%.





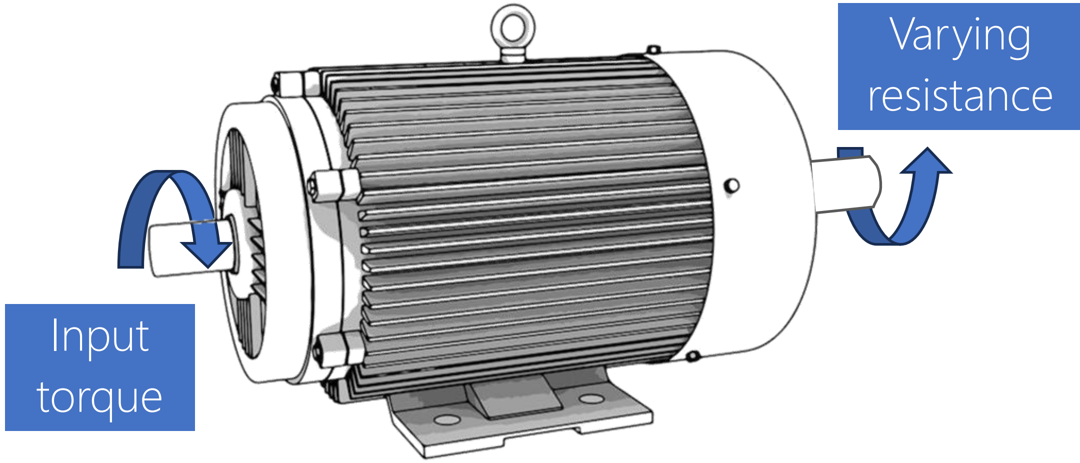
Maintaining a steady system frequency is the <u>number one priority</u> for the grid operator.

System frequency is determined by the rotational speed of the synchronous generators operating on the system.

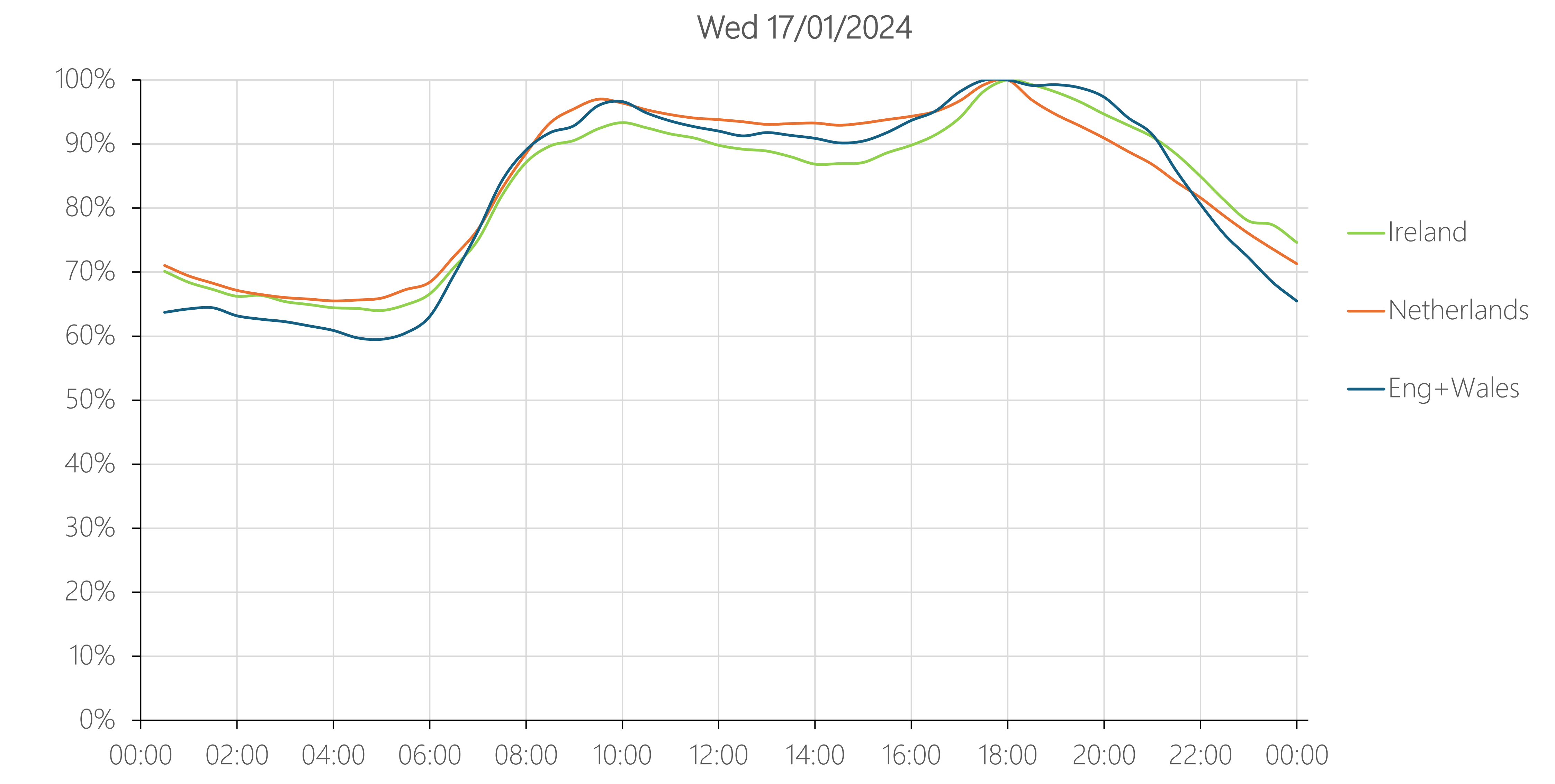
To maintain a steady rotational speed, the torque being supplied to the generator must match the drag torque exerted by the load on the generator.

The drag torque is proportional to the electrical power being drawn from the generator.

The electrical power demand varies, as consumers plug in, switch on, or turn off appliances.



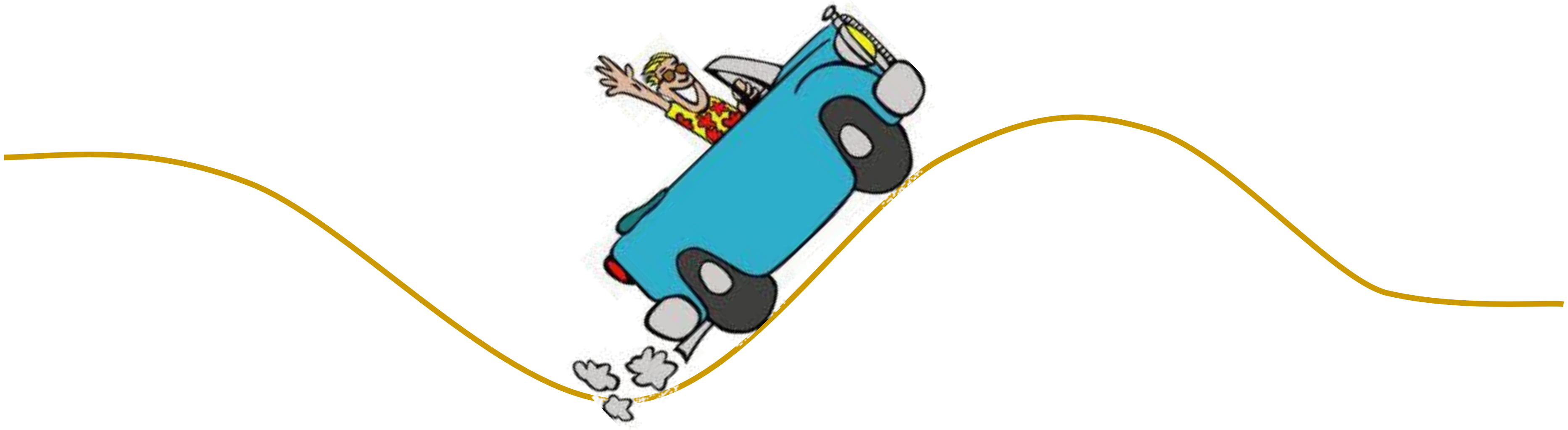
Grid integration

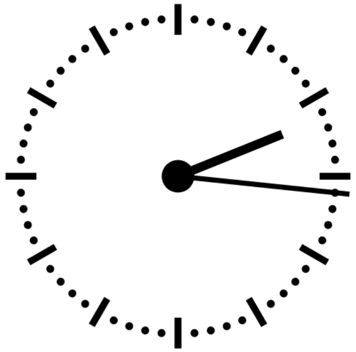


Raw data: Eirgrid, UK National Grid

Maintaining a steady system frequency is the <u>number one priority</u> for the grid operator.

As system demand changes, the grid operator's job is akin to driving a car along a hilly road at a fixed speed: tricky.



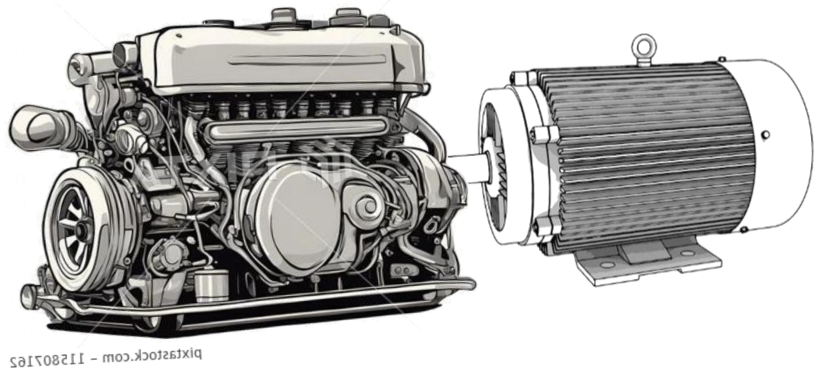


Maintaining a steady system frequency is the <u>number one priority</u> for the grid operator.

System frequency is determined by the rotational speed of the synchronous generators operating on the system.

The grid operator has 3 main tools to help maintain a steady system frequency:

Fuelling rate to the prime mover

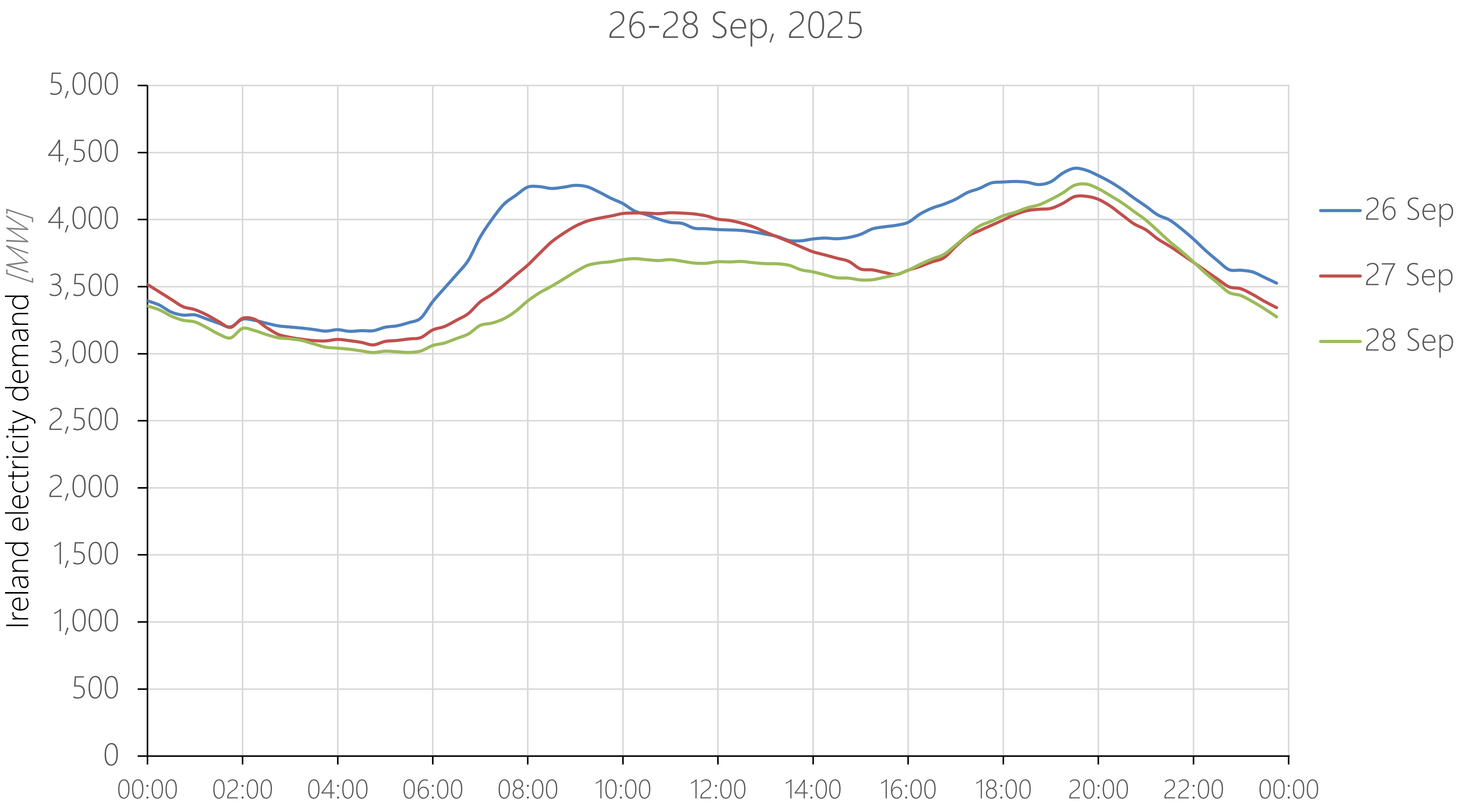


Rotational inertia

Predictability of human behaviour

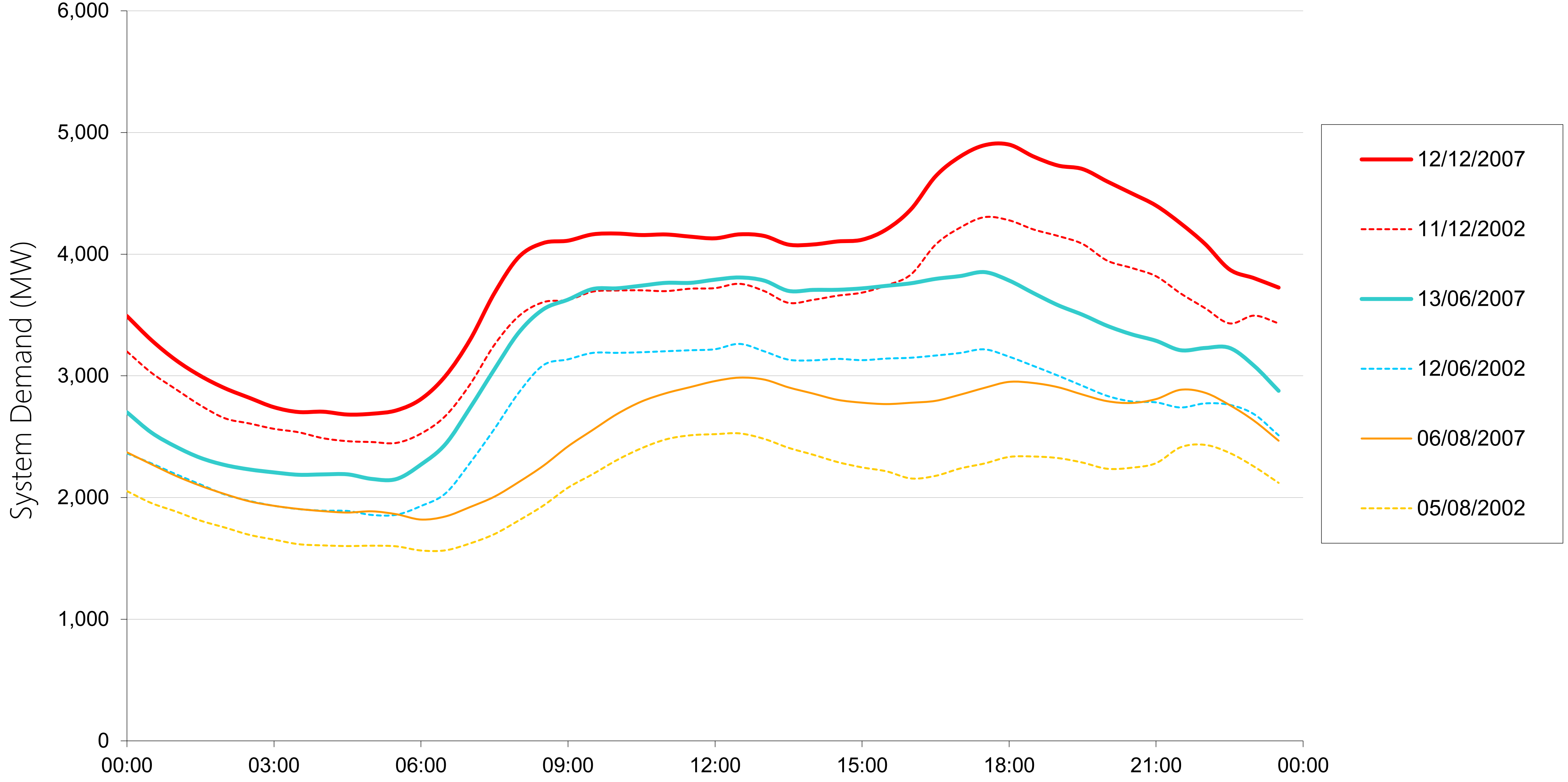
Grid integration

The demand profile changes from day to day…



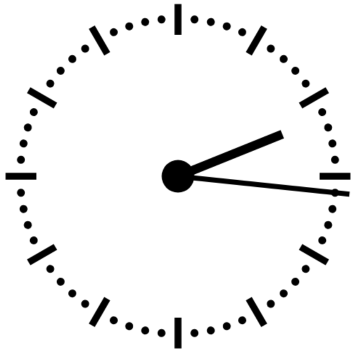
Raw data: EirGrid, www.eirgrid.com

…but certain patterns are discernible.



Raw data: EirGrid, www.eirgrid.com

Grid integration



Maintaining a steady system frequency is the <u>number one priority</u> for the grid operator.

System frequency is determined by the rotational speed of the synchronous generators operating on the system.

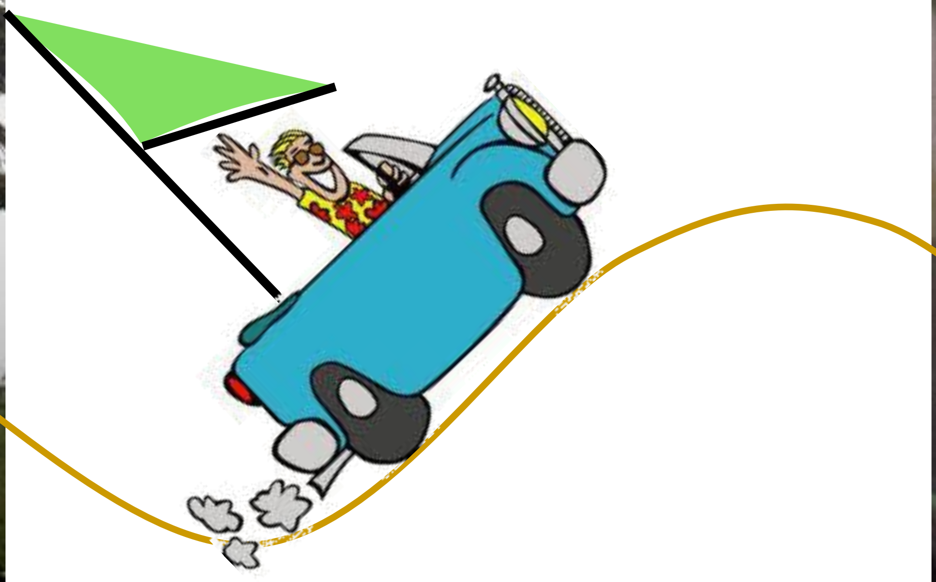
Variable renewable-energy source (VRE) – such as wind and solar PV – present 3 challenges, in this context.

VRE provide:

- Zero rotational inertia (these are non-synchronous generators).
- Zero capacity to command increased energy input.
- Rapid fluctuations in electrical output.

The presence of wind-powered generation (WPG) on the system can make it more difficult to maintain system frequency.

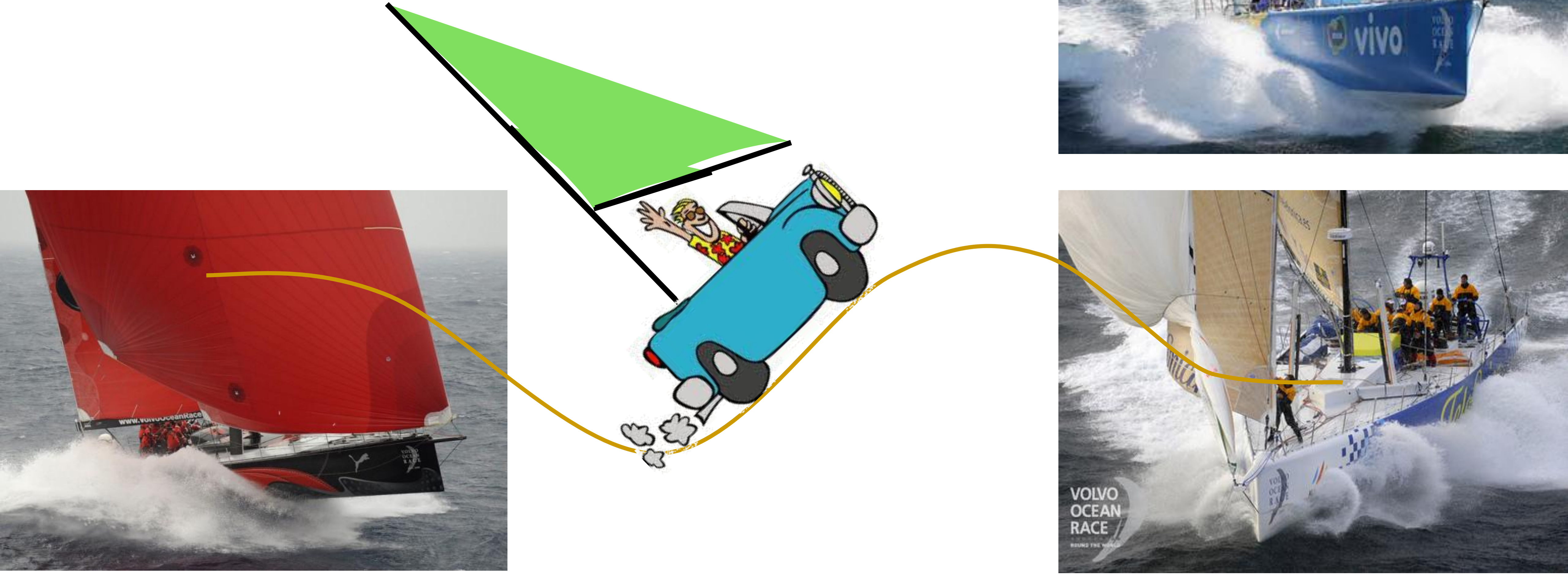
Imagine trying to maintain a fixed speed on the road, but with a sail attached to the car.

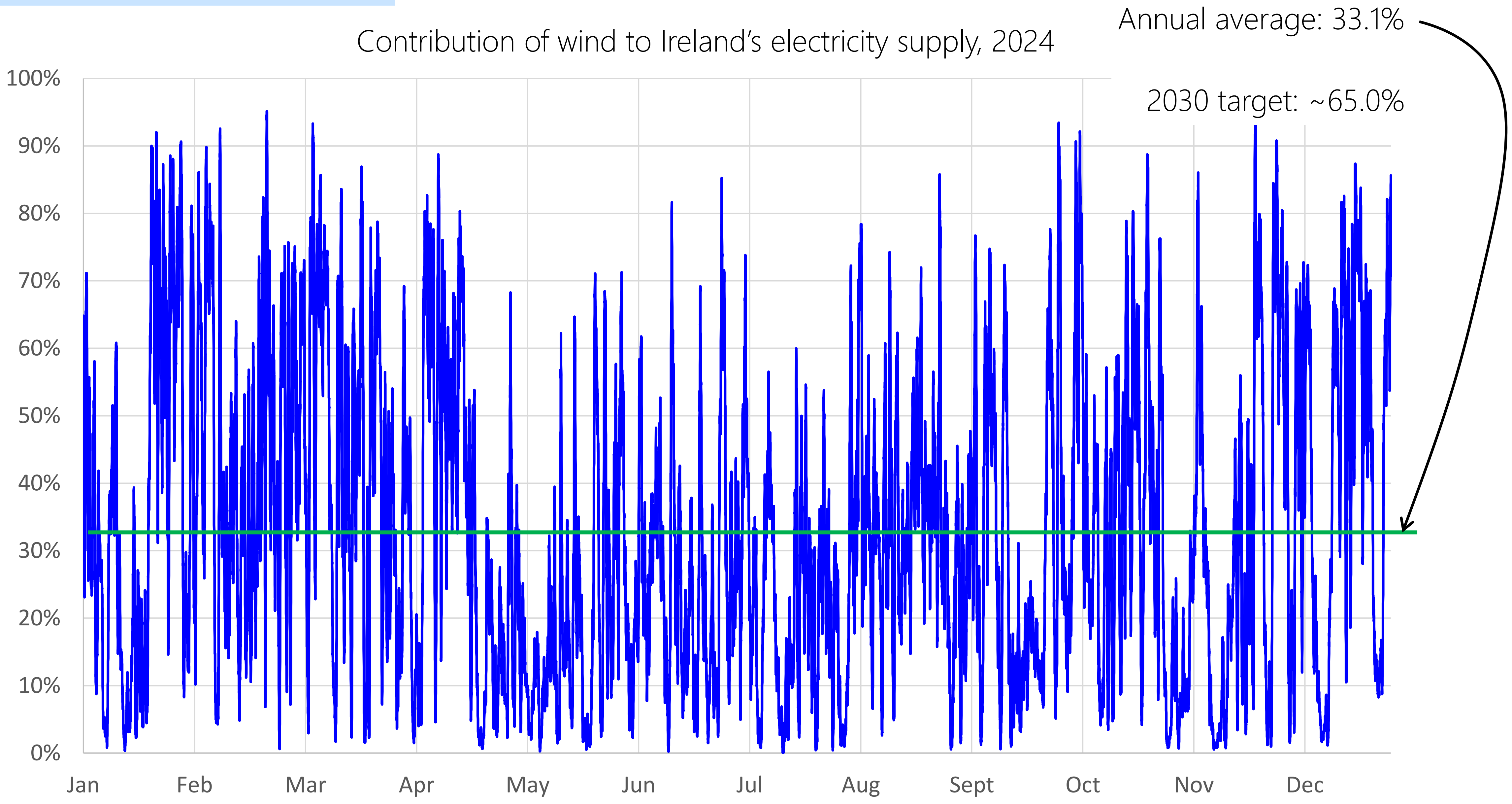


On a blustery day...

Grid integration

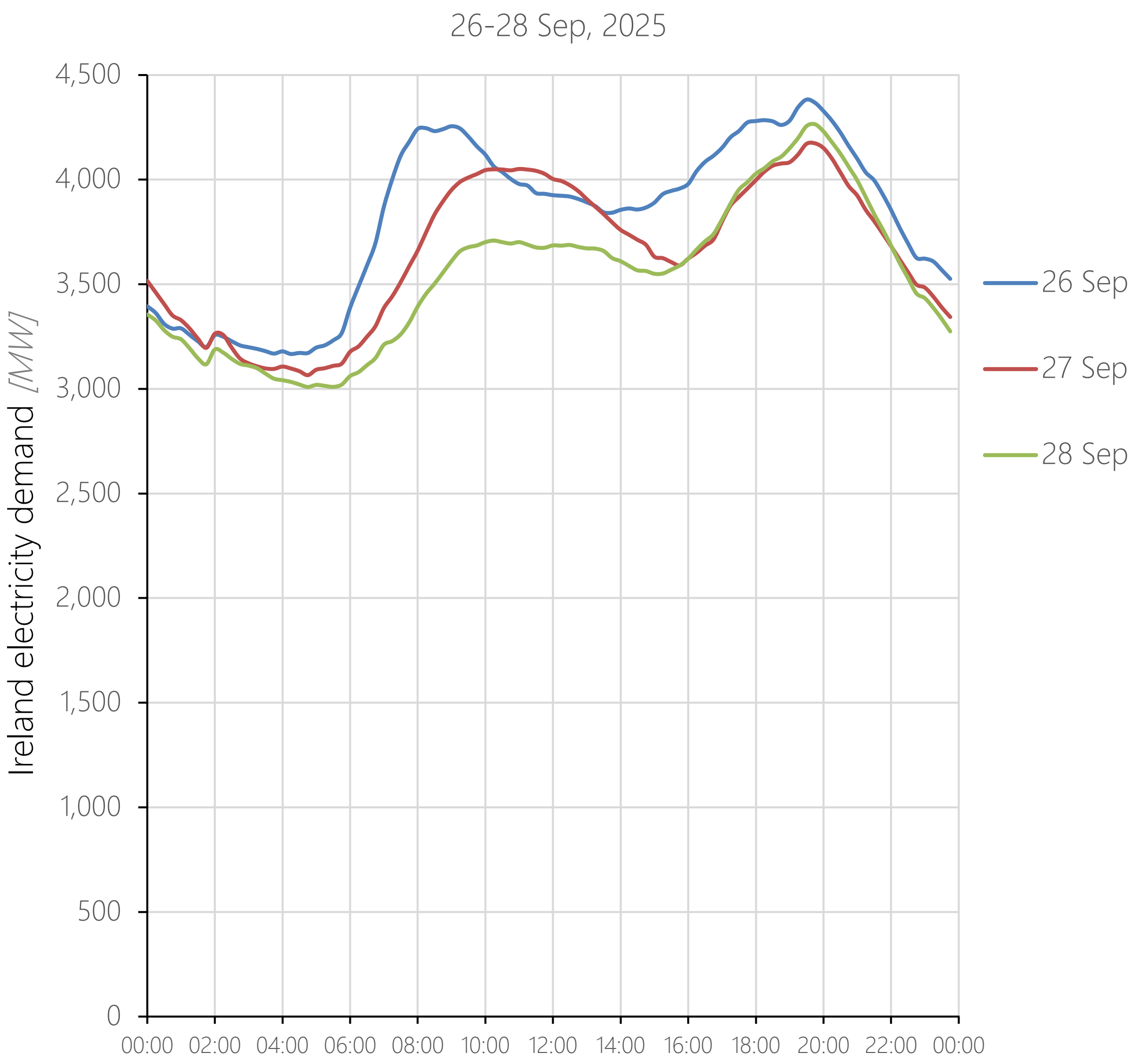
Now make the sail really big…

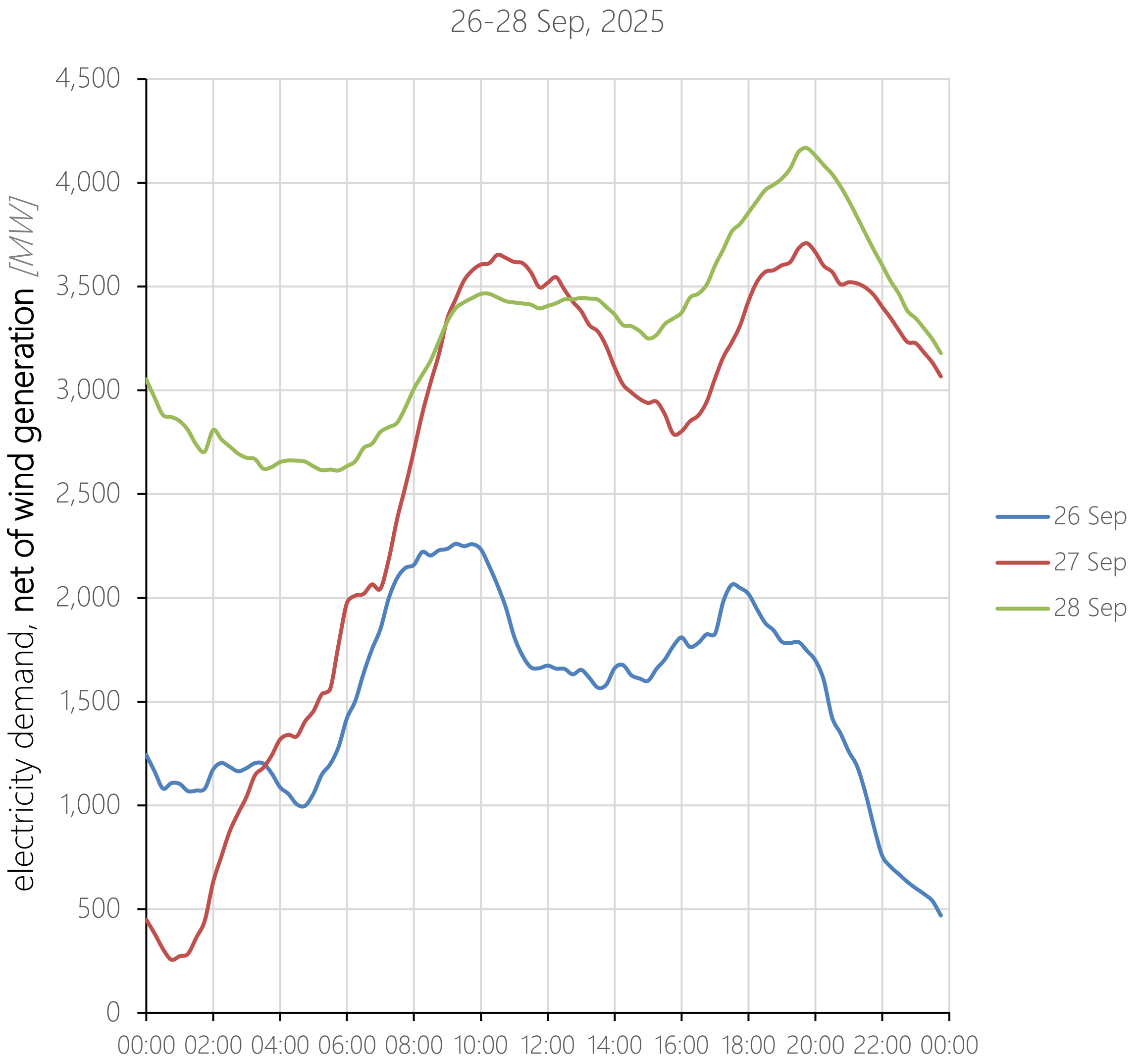




Raw data: EirGrid, www.eirgrid.com

The impact of wind on demand for thermal generation





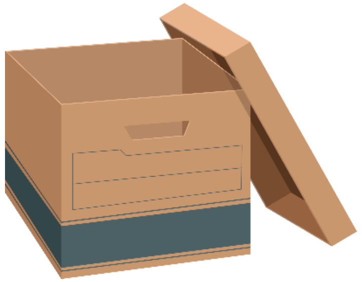
Raw data: EirGrid, www.eirgrid.com

MAIN solutions for integrating variable renewables (VRE) into the electricity grid:

- Curtailment

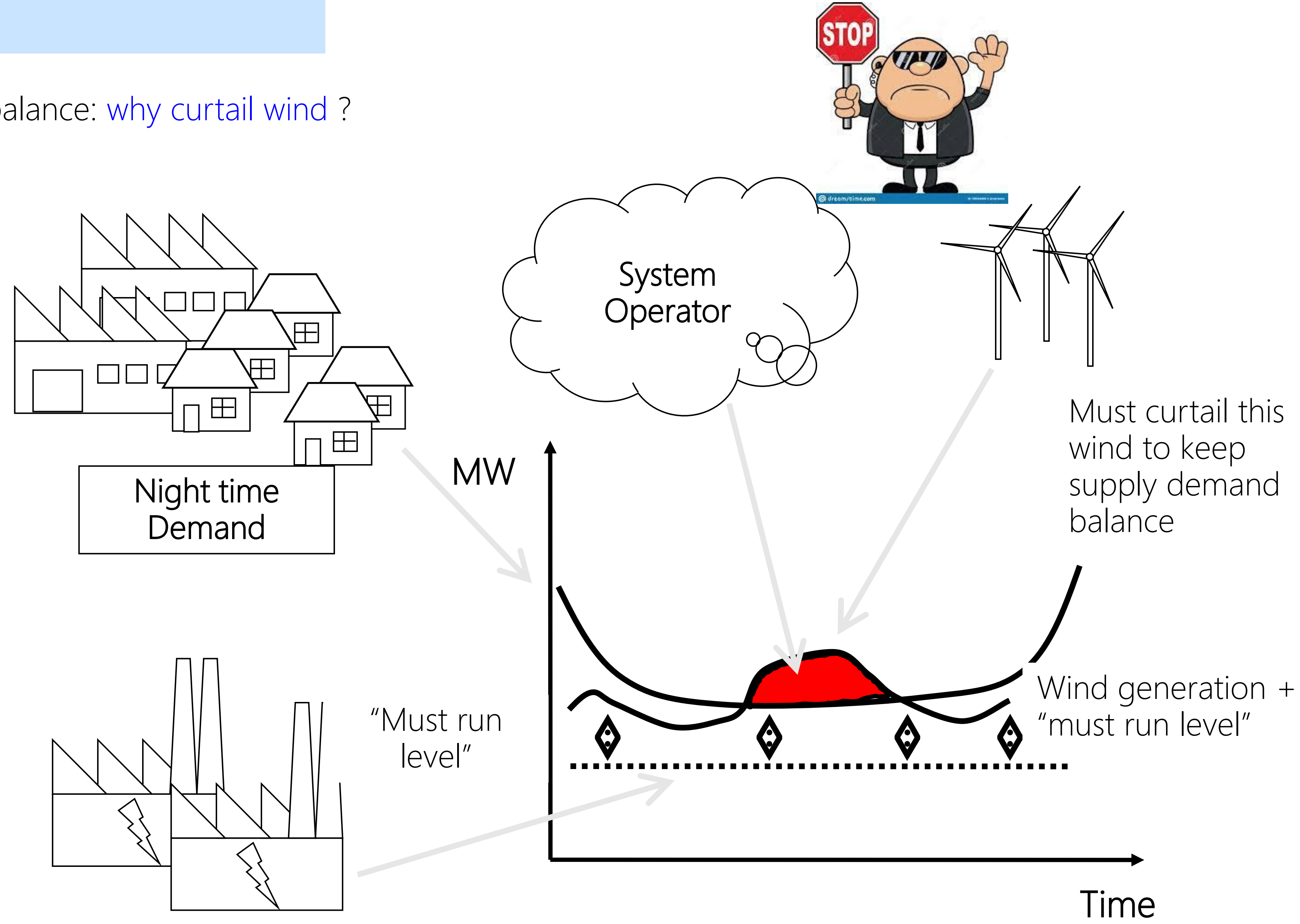
- Interconnection (to another grid)

- Storage (hours, days, weeks)



Grid integration

Supply demand balance: why curtail wind ?



Grid integration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UK spends over $1.3 billion on forced shutdown of wind farms

British regulators have paid more than £1 billion ($1.3 billion) to wind farm operators for forced downtime since the beginning of this year. Companies are receiving orders to stop generating electricity at wind farms due to a capacity shortage with regard to transmission lines, the modernization of which lags behind the introduction of generating capacities. Another factor is the dependence of renewable energy sources (RES) on weather conditions: favorable wind conditions do not always coincide with peaks in power demand.

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Offaly scheme to heat domestic water cylinders for free

Updated / Tuesday, 10 Dec 2024 07:47

By Sinéad Hussey
Midlands Correspondent

Hundreds of homes in Co Offaly are set to benefit from surplus renewable electricity to heat their water cylinders for free.

Figure 8.7 Dispatched-down wind and solar PV generation (left)

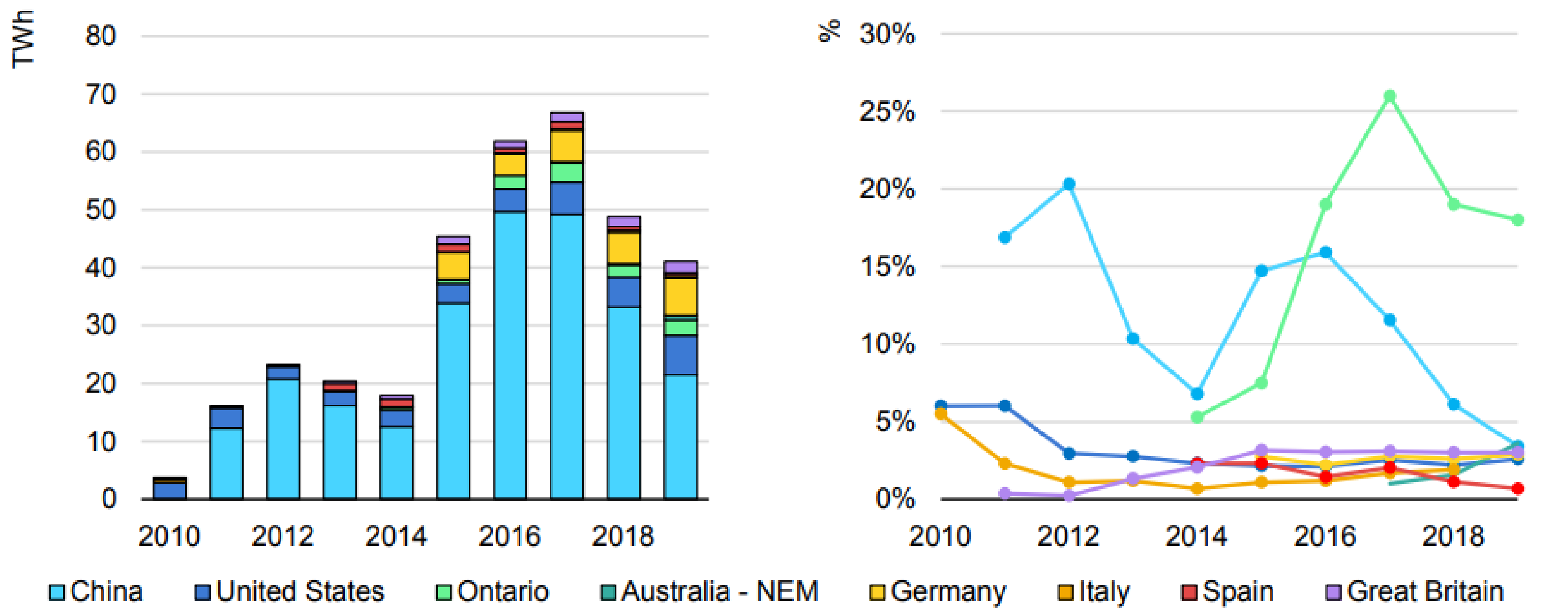


Figure 8.7 taken from Renewables 2020, International Energy Agency (2020)

Technical curtailment vs VRE share

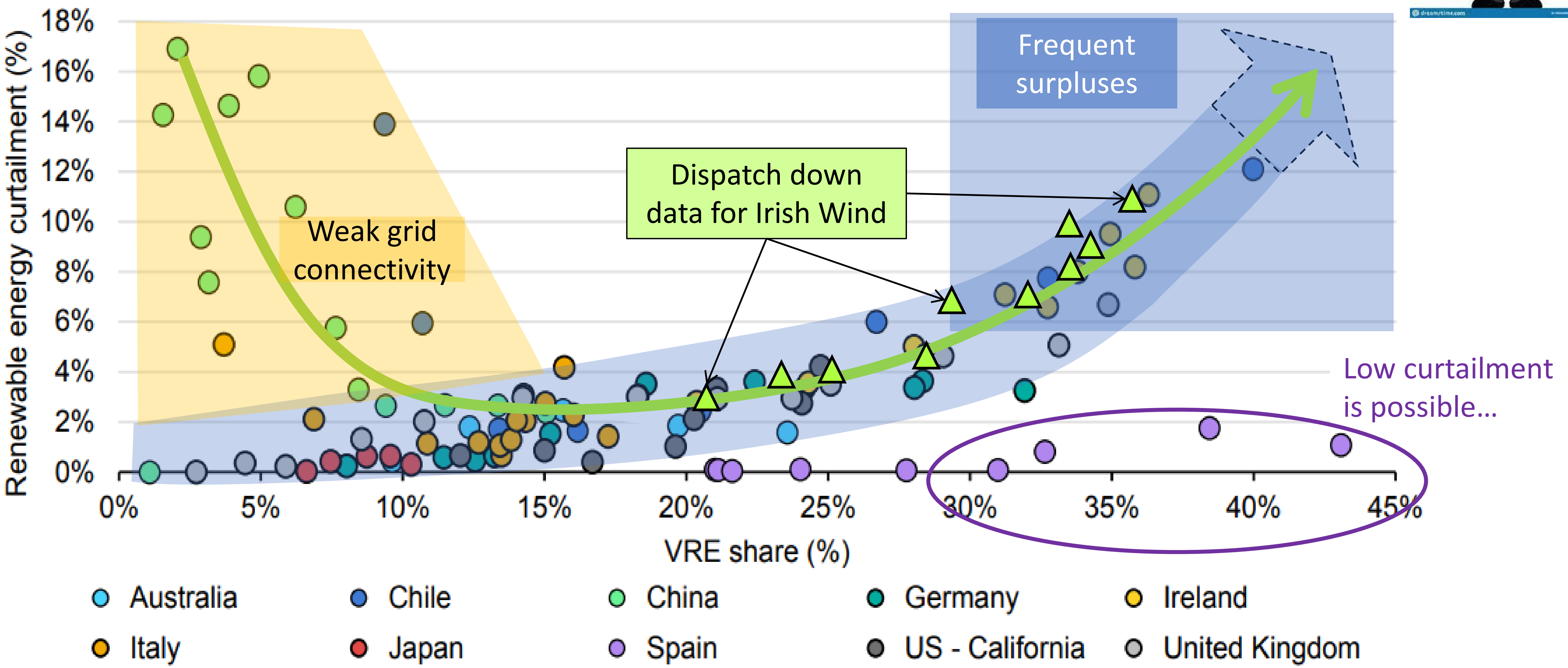
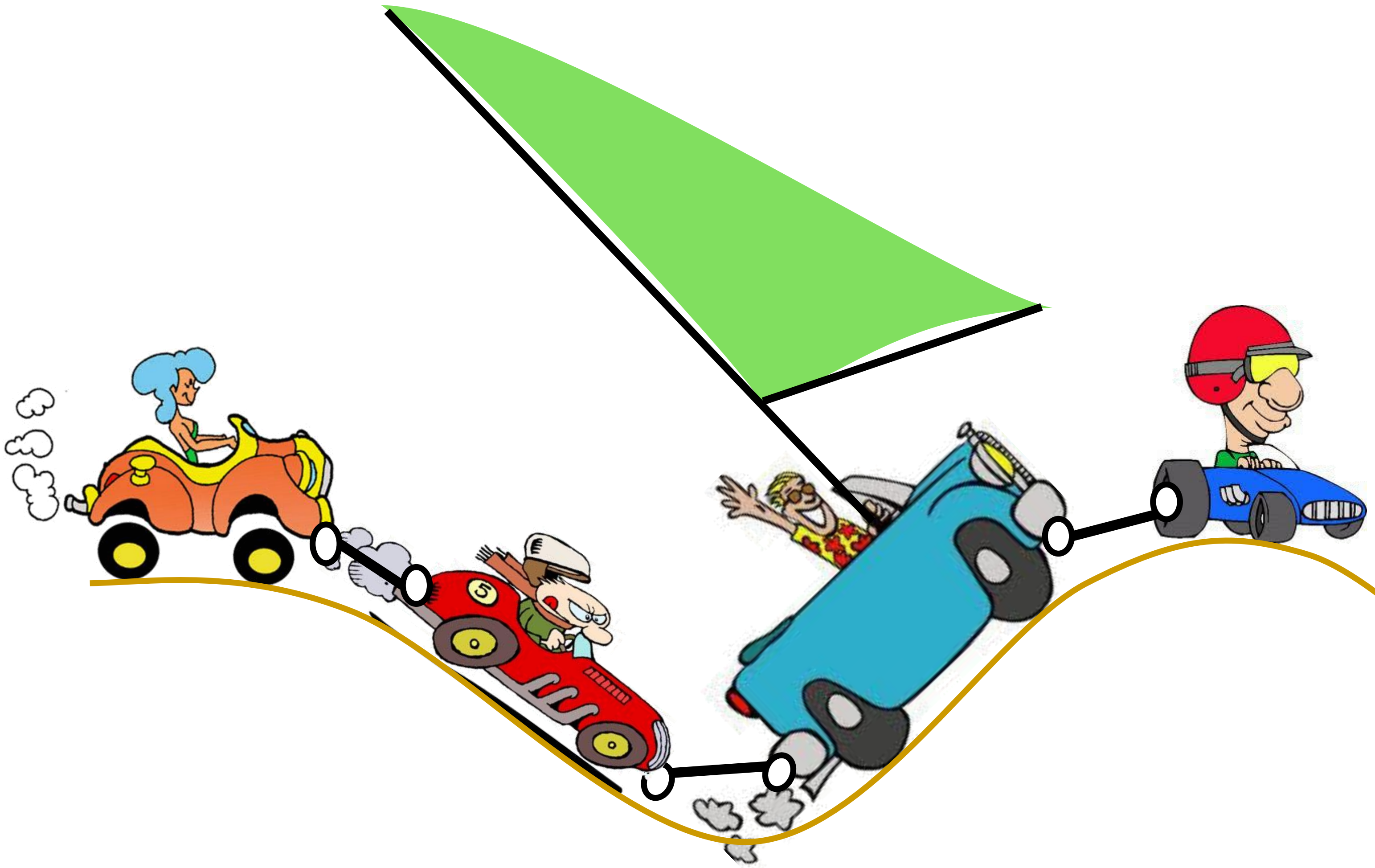


Figure source: IEA (2024). Renewables 2024, *p115*

Interconnection

Grid integration

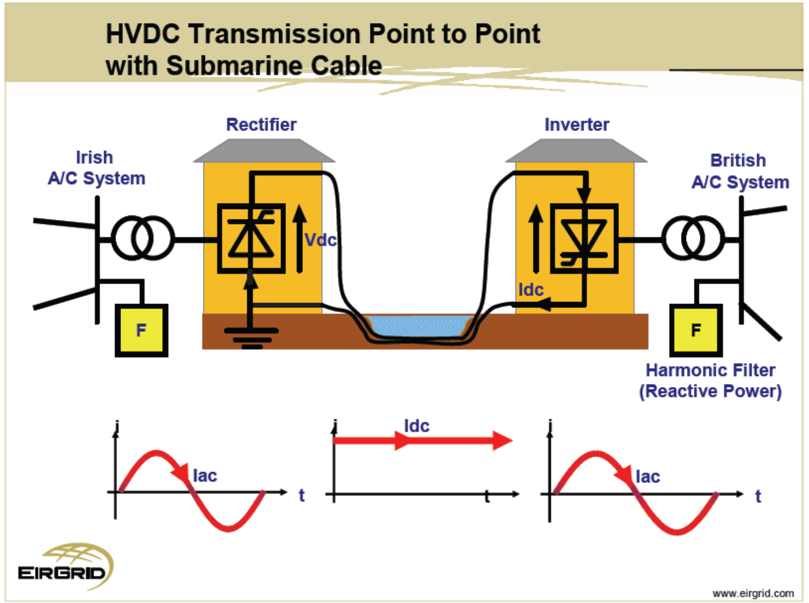
Interconnection – joining your car to others moving at the same speed – should help, by sharing the surpluses and deficits.



Grid integration

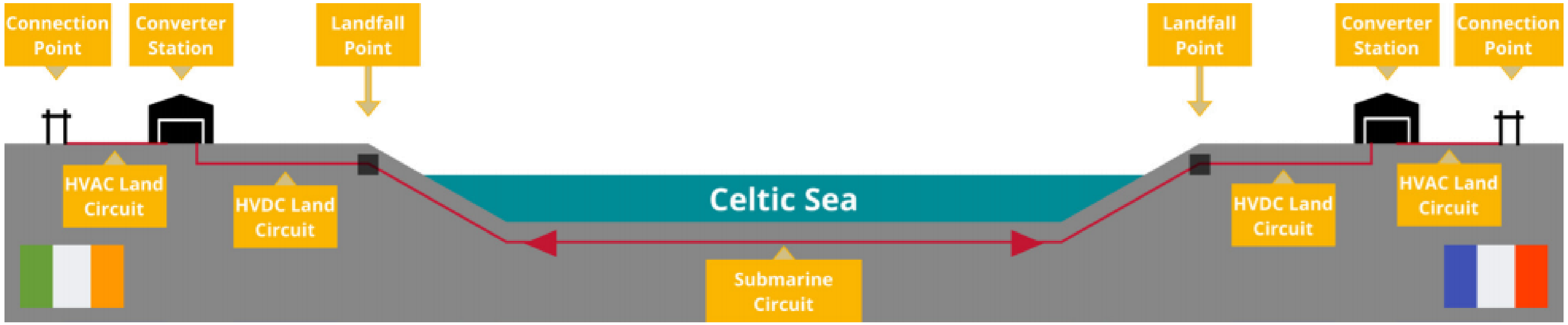
Ireland has 3 HVDC interconnectors to UK and France.

- HVDC used to reduce transmissions losses.

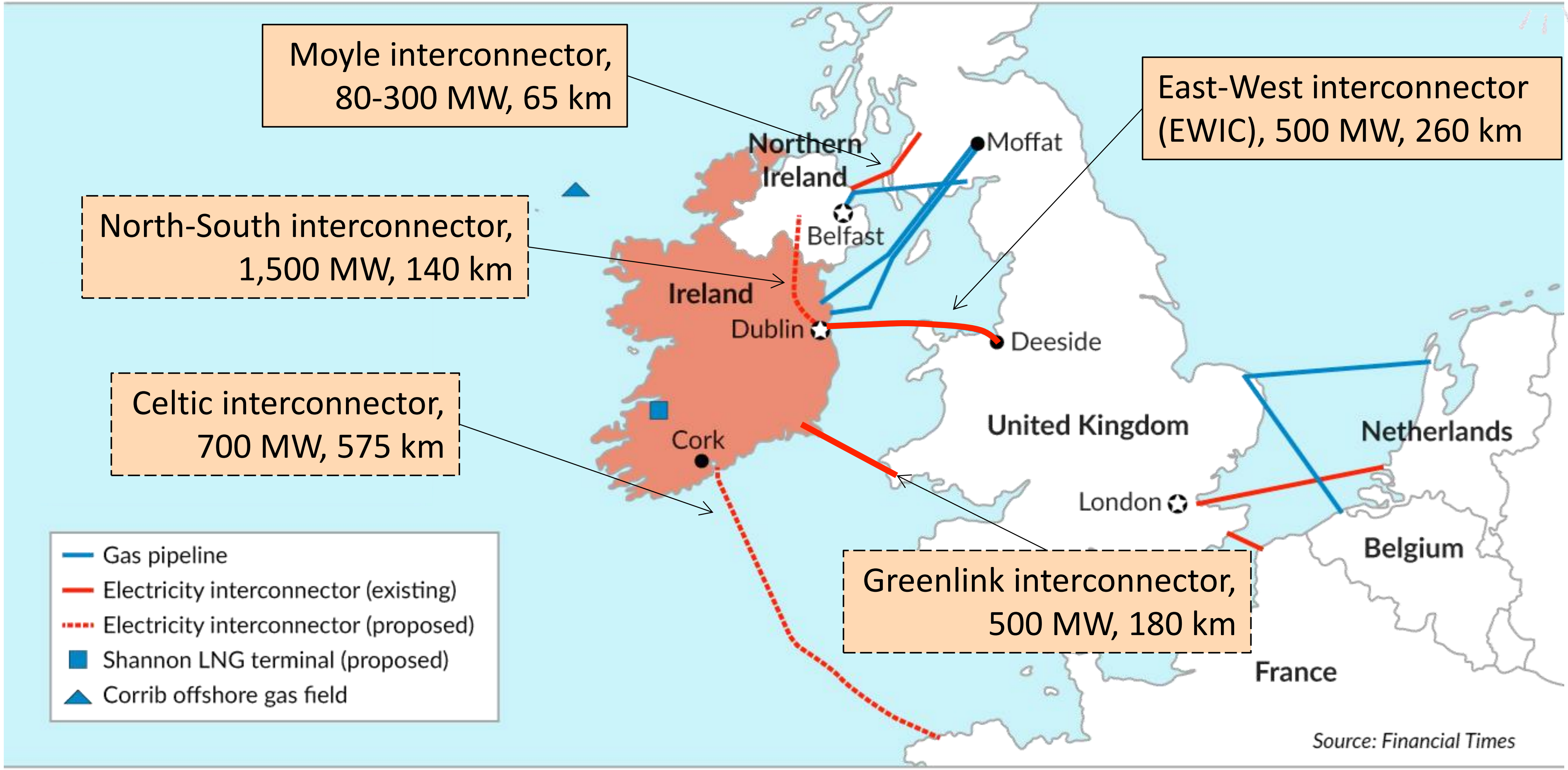


Each HVDC interconnector requires:

- a rectifier (AC to DC) and an inverter (DC to AC) at each end.
- a DC circuit between landfall point and converter station.
- an AC circuit between converter station and grid connection point.



Ireland's energy interconnectors



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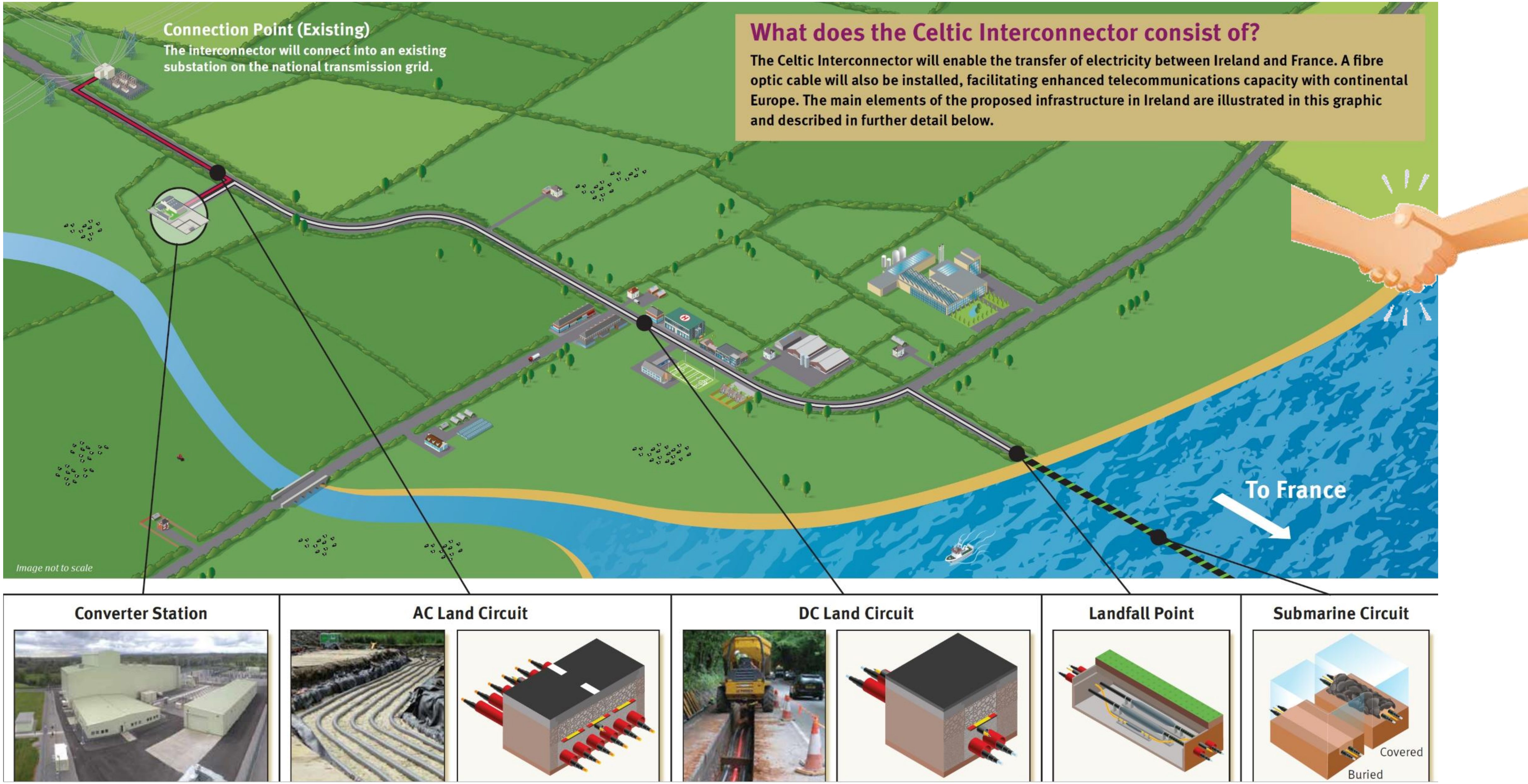
Grid integration



Storage

Storage

<= 1 hour

flywheels

capacitors

batteries

demand management

> 1 hour, <= 1 day

batteries

pumped hydro

CAES

demand management

> 1 day

CAES

hydrogen

demand management

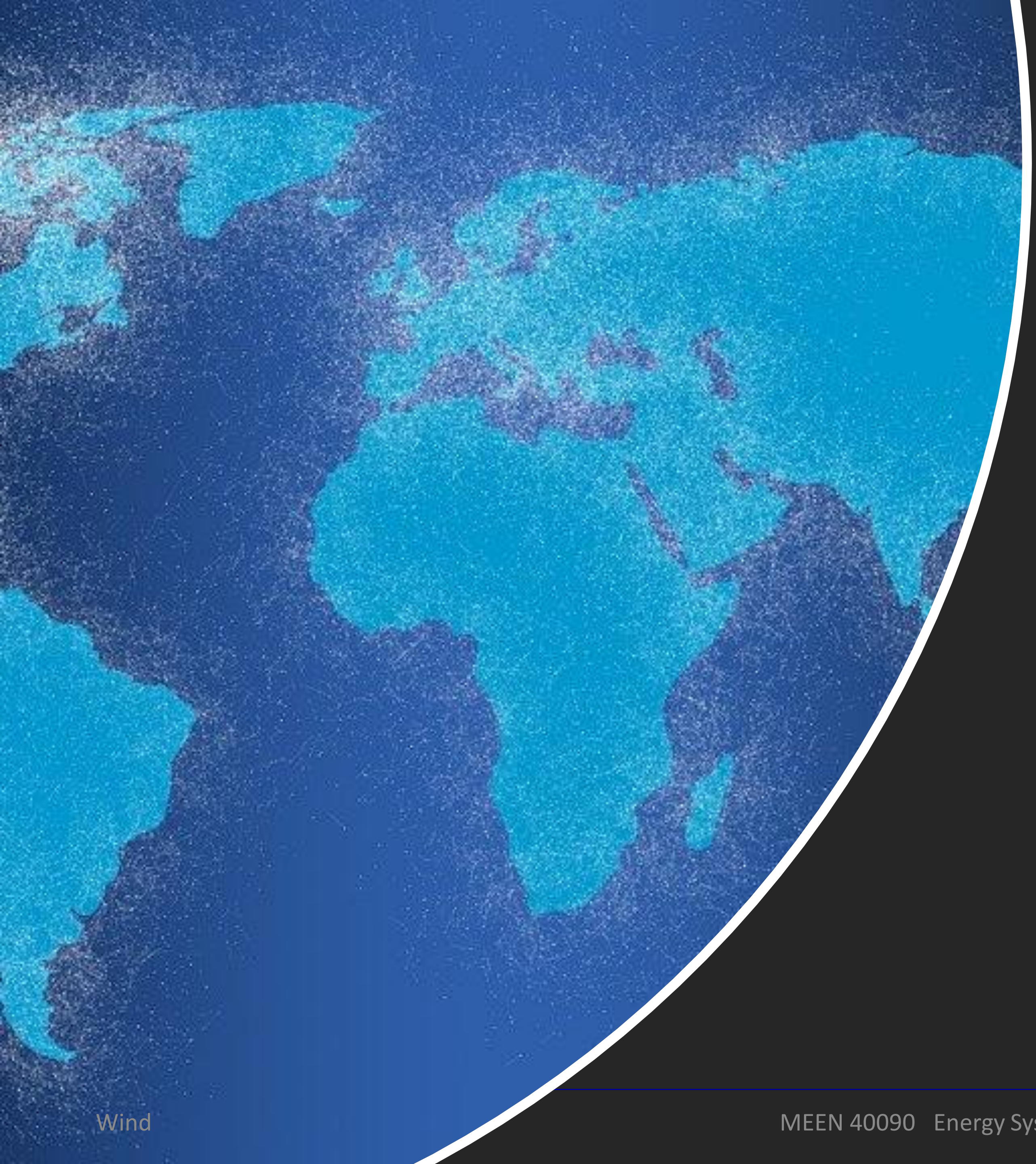
Grid integration

Wind, and Solar PV, are CO_2 free, but they…

- …are non-dispatchable
- …make frequency control more difficult
- …require additional supports, *e.g.* interconnection and storage.

High penetration of VRE such as wind, and solar PV, also:

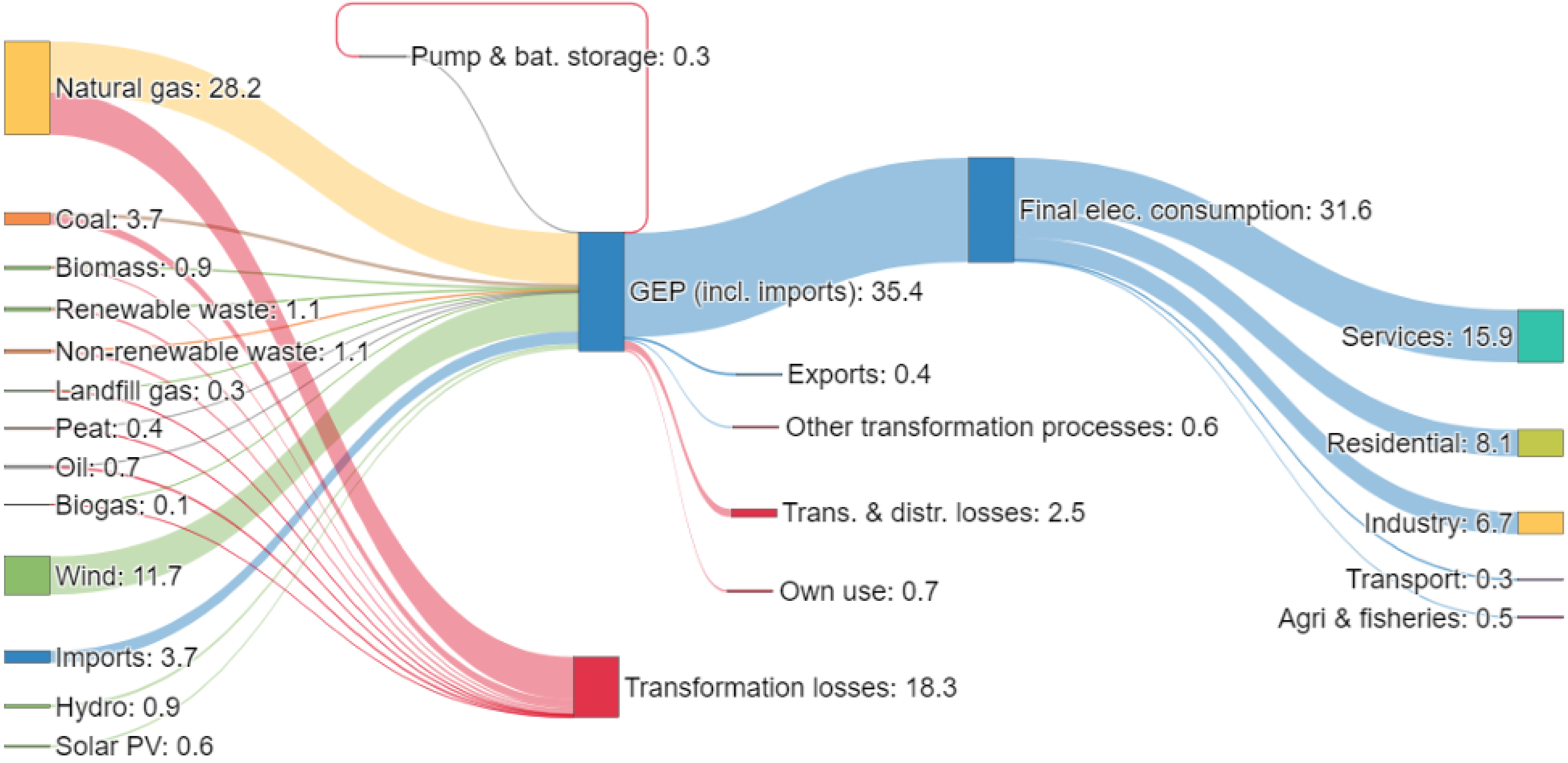
- requires additional spinning reserve
- leads to increased part-load operation of fossil plant (reduced efficiency)
- leads to increased cycling of fossil plant (more wear and tear)



The global and regional contexts

Electricity generation, by primary energy source, in Ireland

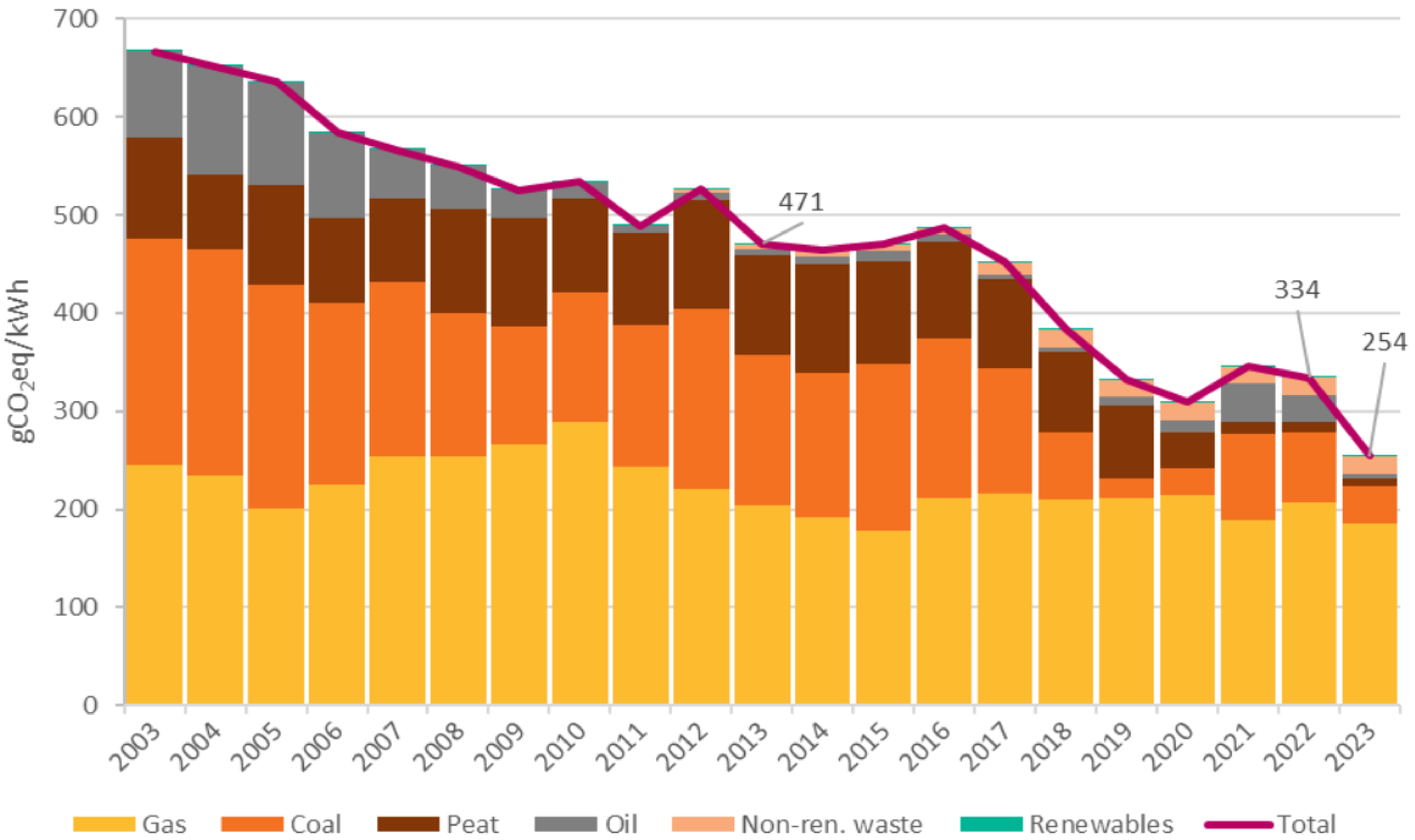
Figure 4.2: Flow of energy in electricity generation and consumption (TWh)[7]



Source: SEAI (2024),"Energy in Ireland, 2024 Report" www.seai.ie

Electricity GHG intensity, in Ireland

Figure 7.1: GHG emissions per kWh of electricity consumption, with contribution by energy type



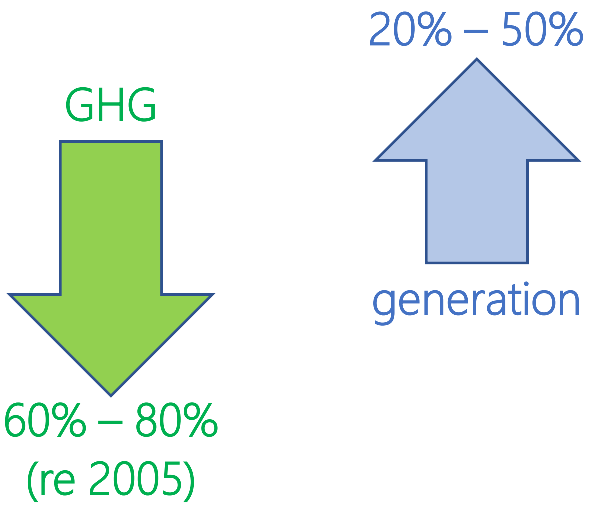
Source: SEAI (2024),"Energy in Ireland, 2024 report". www.seai.ie

Now:

- 15,063[1] MW installed electricity generation capacity (incl. interconnectors), 5,425 MW[1] of which is wind.
- Winter peak 6,024[2] MW; summer night valley 2,781 MW; max wind 3,884 MW[2] (13-02-2025).

Looking forward:

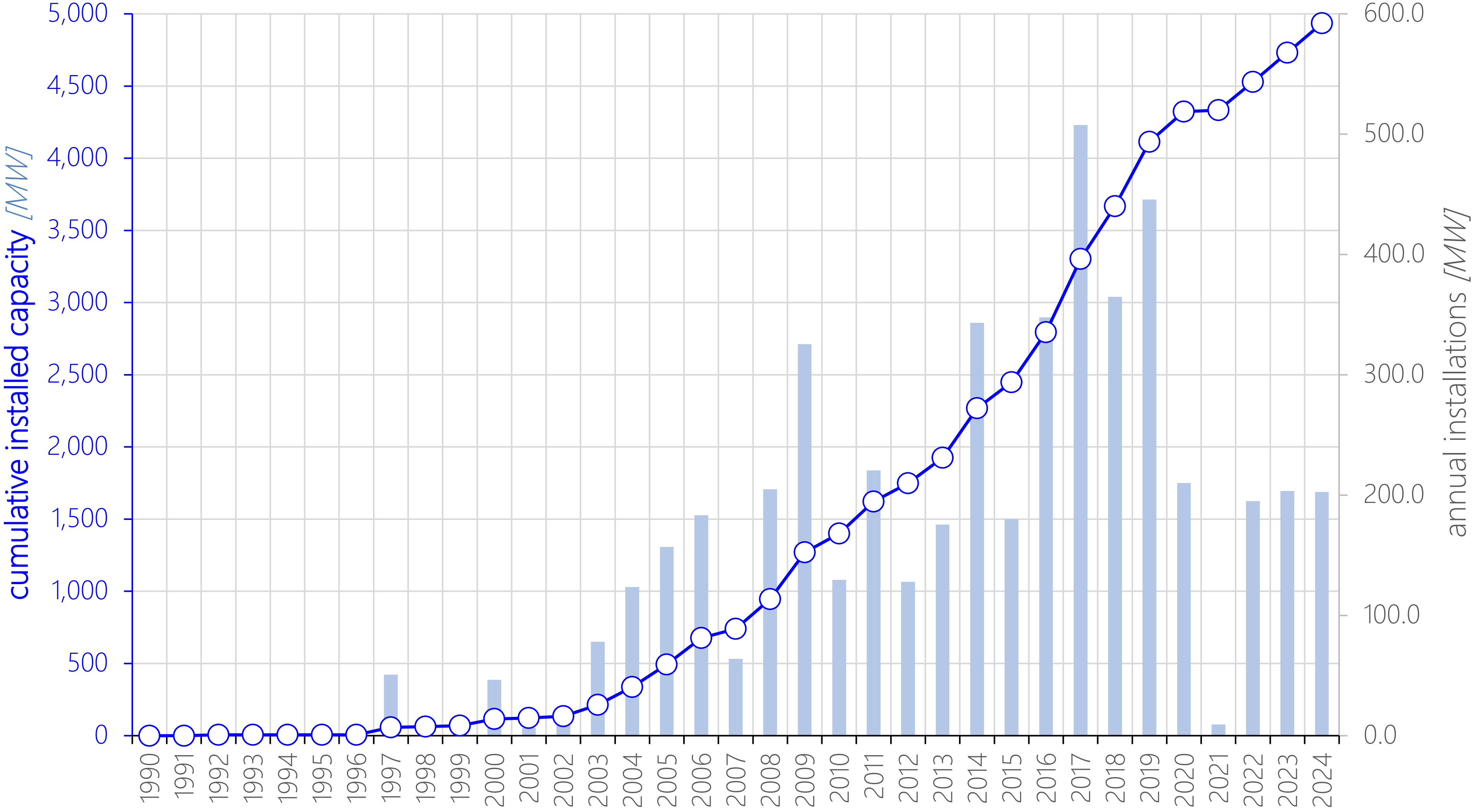
- Greenhouse gas (GHG) emissions targets 2030



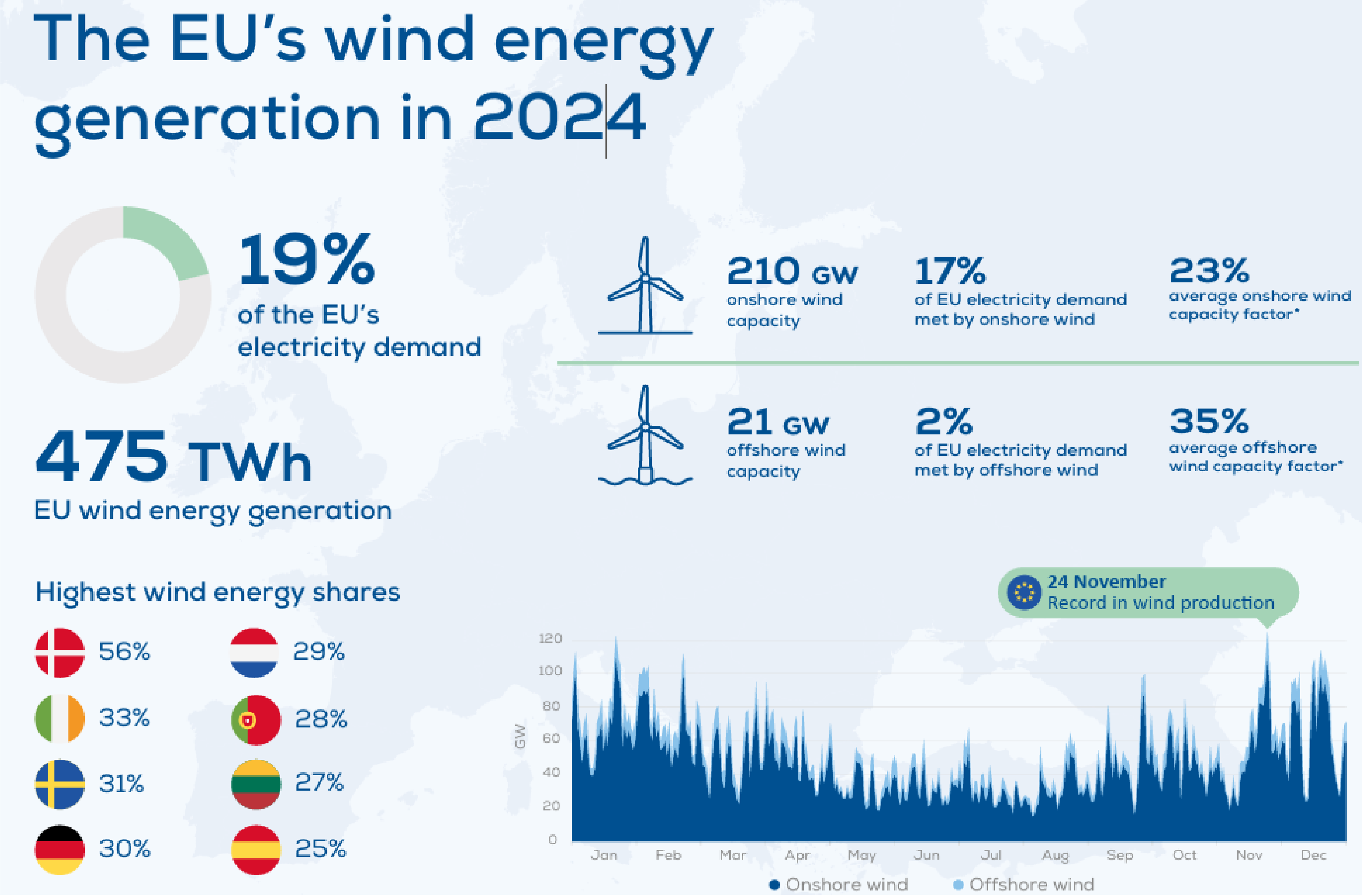
- Government & EU targets for renewable energy by 2030 ⟷ "up to" 80% of generated electricity (CAP24)
- Very limited opportunities for additional Hydro in Ireland.

[1] Source: Ireland Capacity Outlook 2022-2031, Tables A3-1 and A3-2, https://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid_SONI_Ireland_Capacity_Outlook_2022-2031.pdf
[2] Source: smartgriddashboard.eirgrid.com/#roi/wind

Wind-powered generation capacity in Ireland

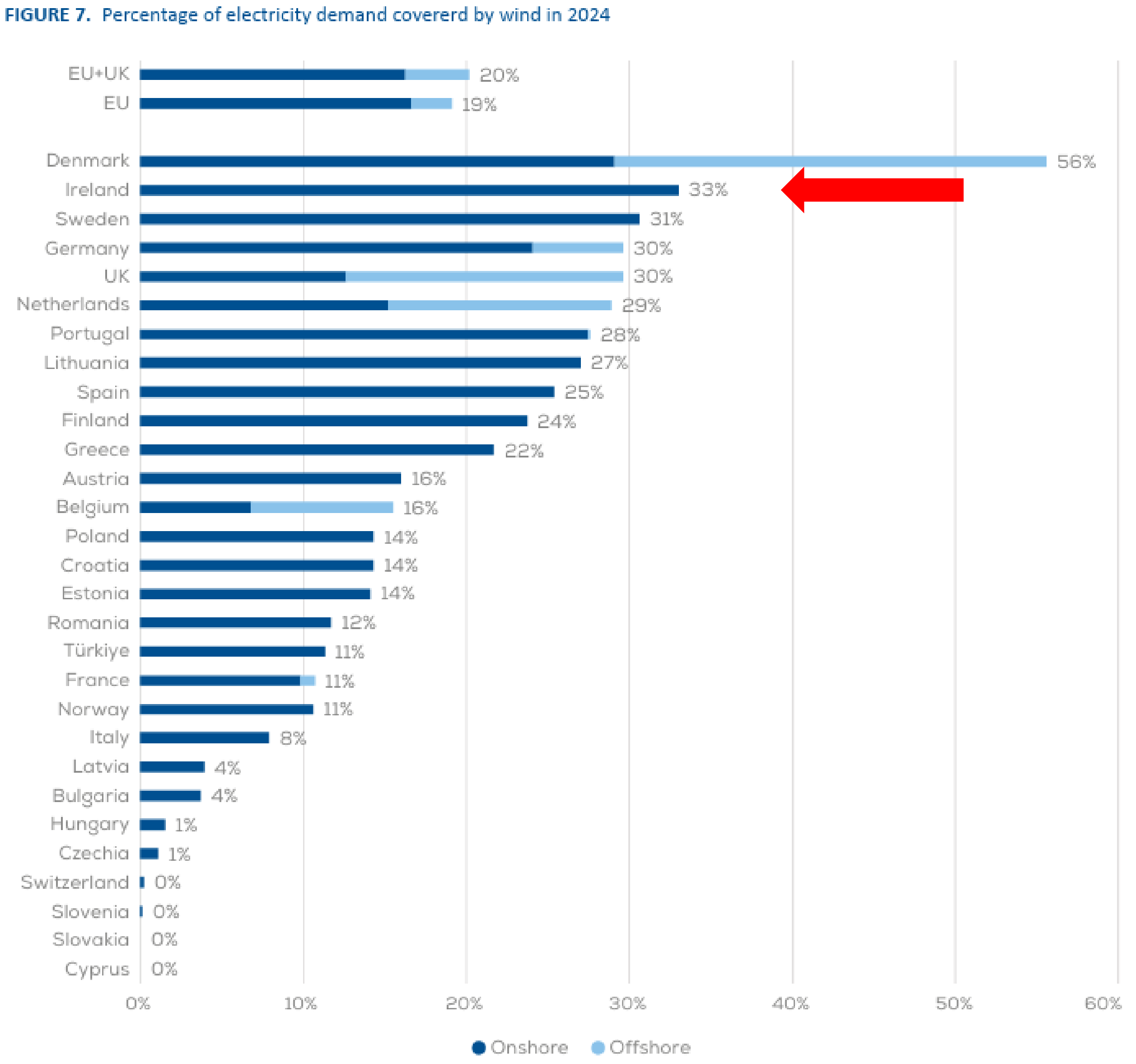


Source: SEAI (2020), "Renewable Energy in Ireland: 2020 Update". www.seai.ie

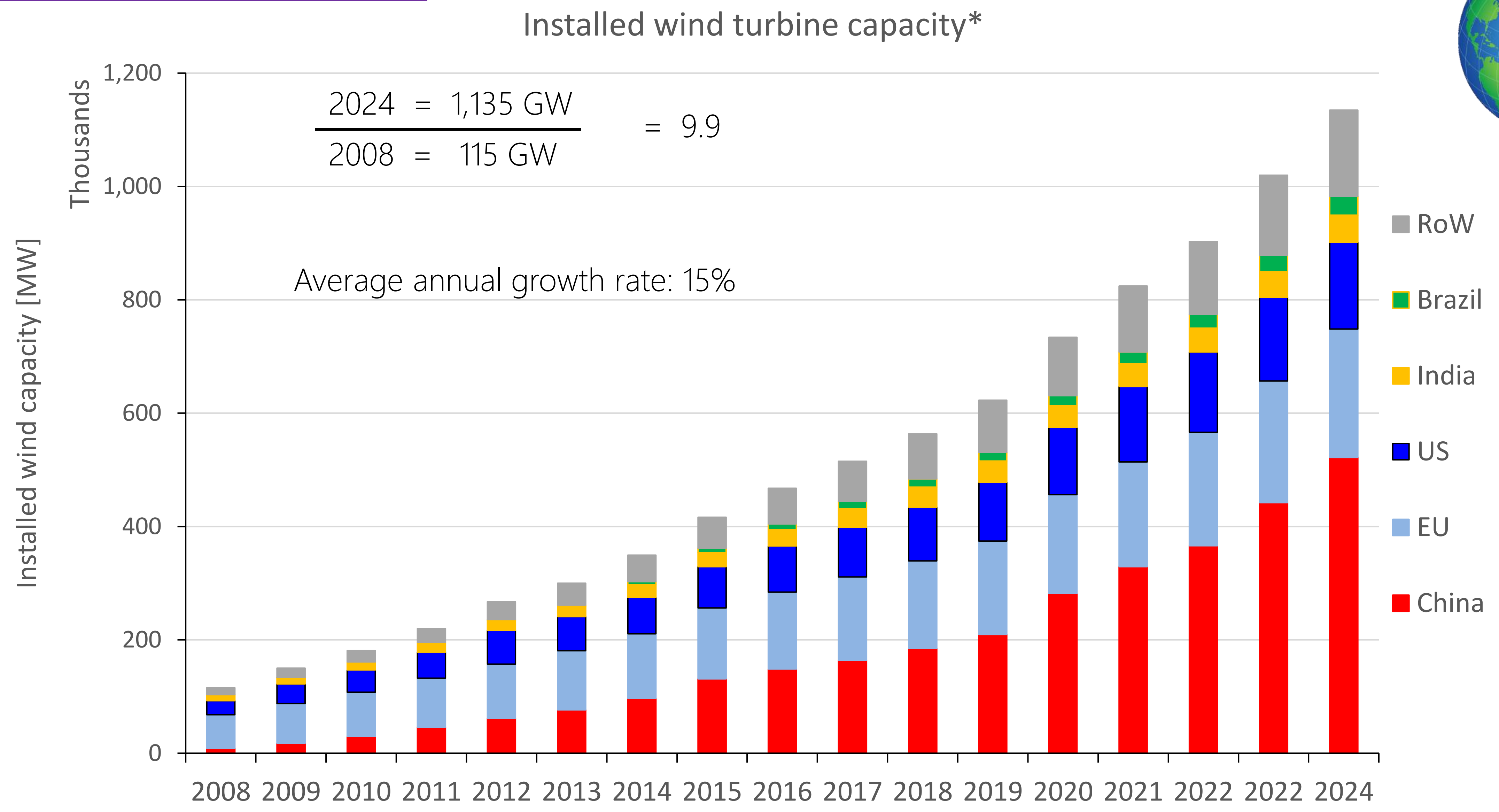


Source: Wind Europe (2022), "Wind energy in Europe: 2021 Statistics". www.windeurope.org

Percentage of annual electricity generation provided by wind, 2024

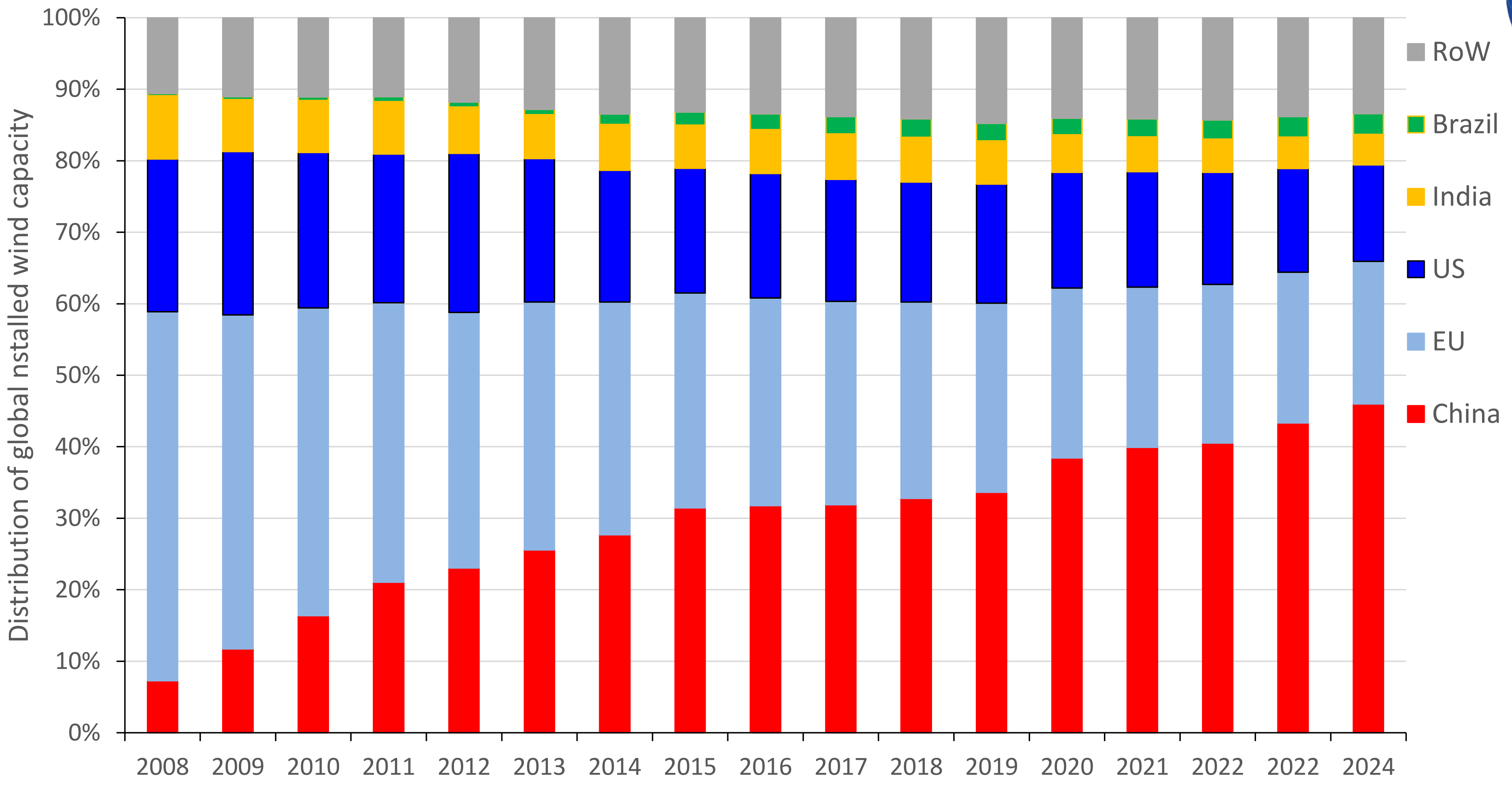


Source: Wind Europe (2025), "Wind energy in Europe: 2024". www.windeurope.org



Raw data: Statistical Review of World Energy , https://www.energyinst.org/statistical-review

The global and regional contexts



Raw data: Statistical Review of World Energy , https://www.energyinst.org/statistical-review





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