DTU

DTU Wind and Energy Systems

- The worlds premier wind energy institute
- 500 people
- From 40+ countries
- More than 40 years experience

Wind Energy Technology for people and planet

Education

Innovation

Scientific advice

Research

PCiC.Energy, Copenhagen, 2 June 2026

Wind Energy For People and Planet

100% Renewables – is it possible?

The Sun

Nearly all energy comes from the sun

Geothermal, tidal and finite resources are extra

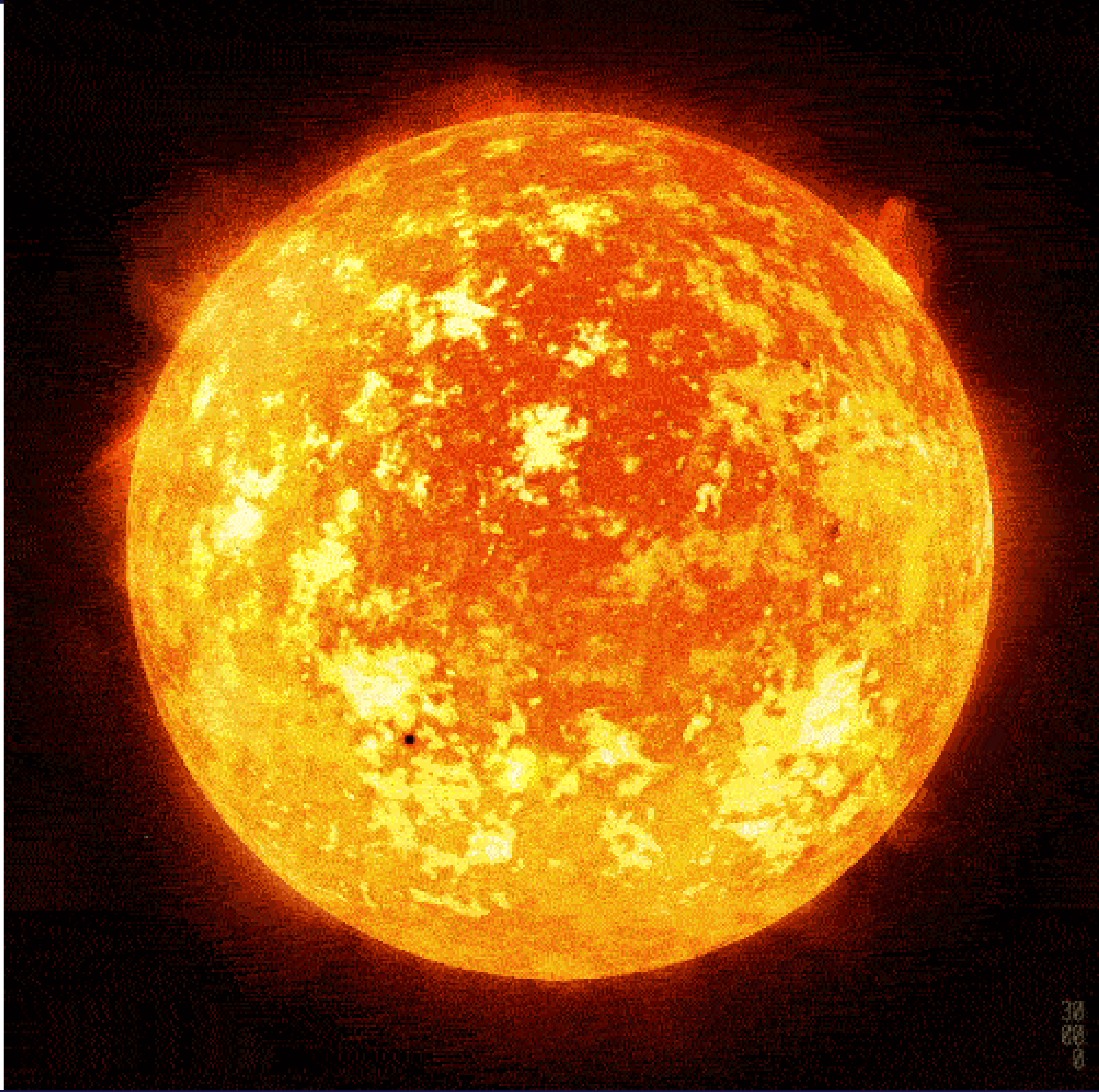


Image: NASA.gov

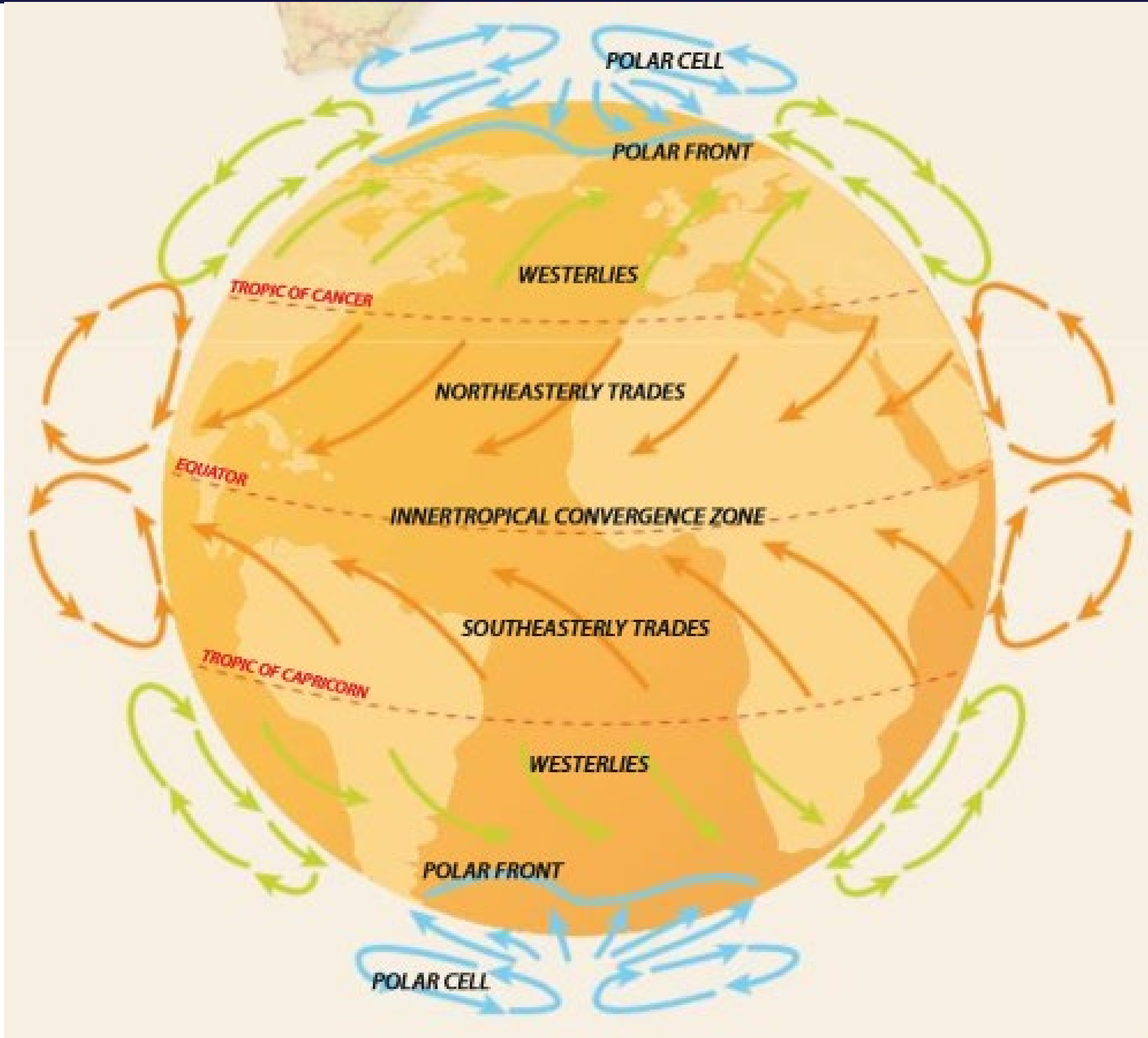
Wind Energy

Solar radiation warms the planet differently

Also gives rise to pressure gradients

Wind systems try to equalise the difference

Wind energy exploitation only close to the ground

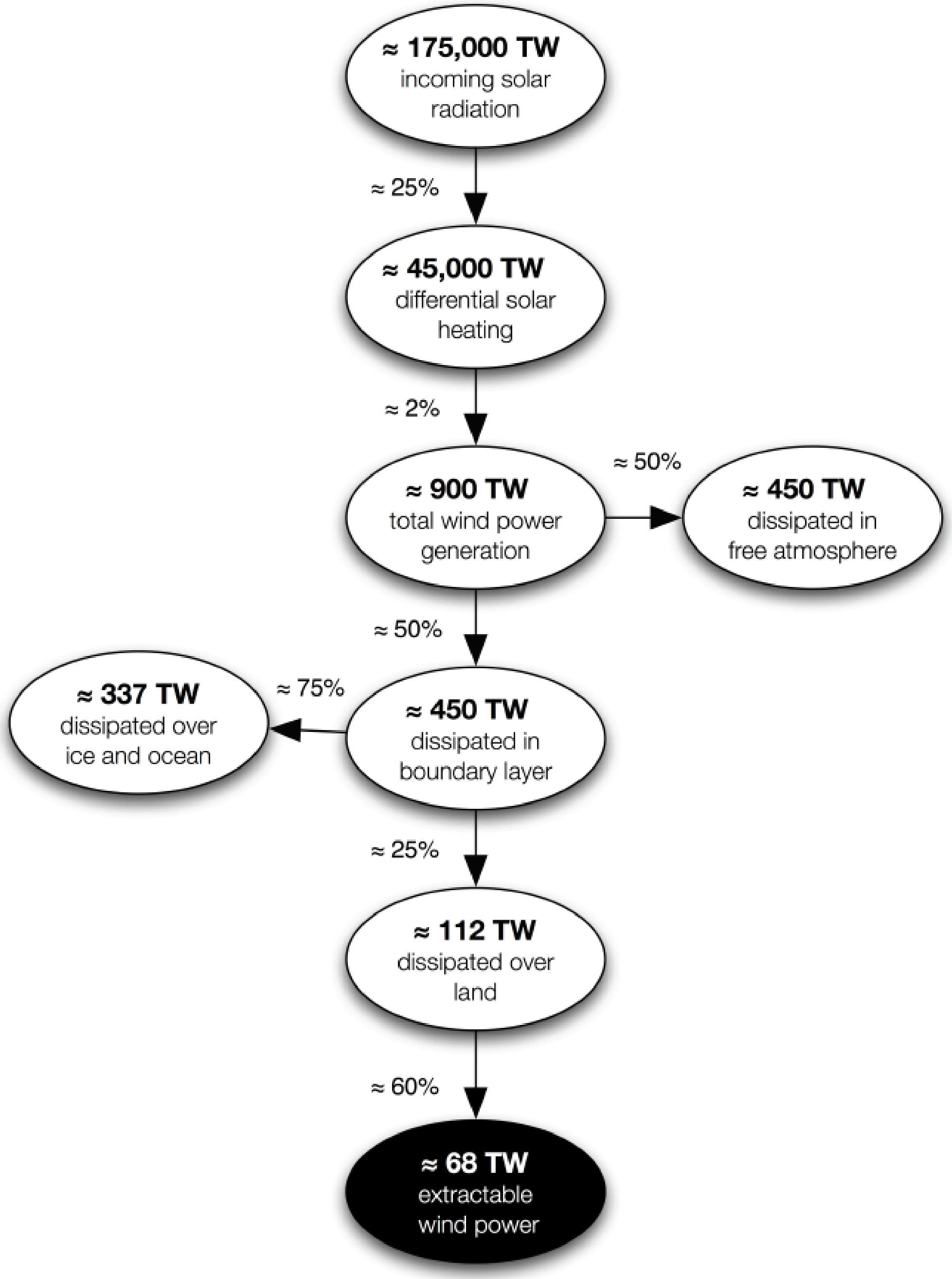


Source: Desertec Atlas Global Energiewende

Global wind resource

Miller, Gans, Kleidon 2011:

The conversion processes between incoming solar radiation and extractable wind power over the land in the Earth system is shown. In this simplified framework, assuming a 100% conversion efficiency from mechanical power to electrical power, a maximum of 68TW of electricity can be produced from wind power extraction from the atmospheric boundary layer over all non-glaciated land surfaces.



~3,4 TW
global electricity demand

L. M. Miller, F. Gans, and A. Kleidon: *Estimating maximum global land surface wind power extractability and associated climatic consequences*. Earth System Dynamics, 2011

Potential for Electricity production from offshore wind power plants

The North Sea alone would do just about half of the world's present need.

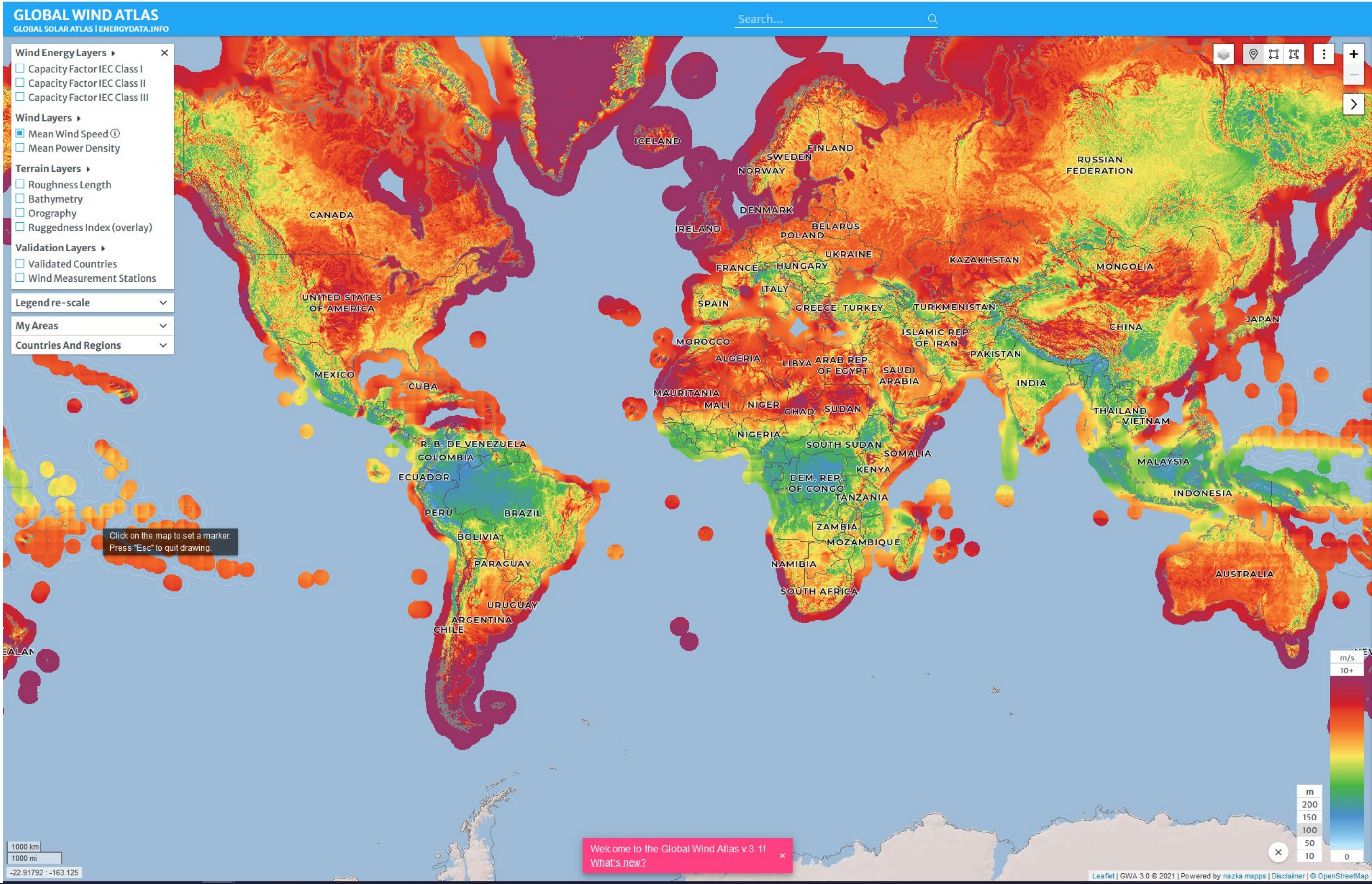
Source: Niels-Erik Clausen, DTU Wind Energy

Global Wind Atlas – the entire world modelled with 50m resolution.

Online map and API.

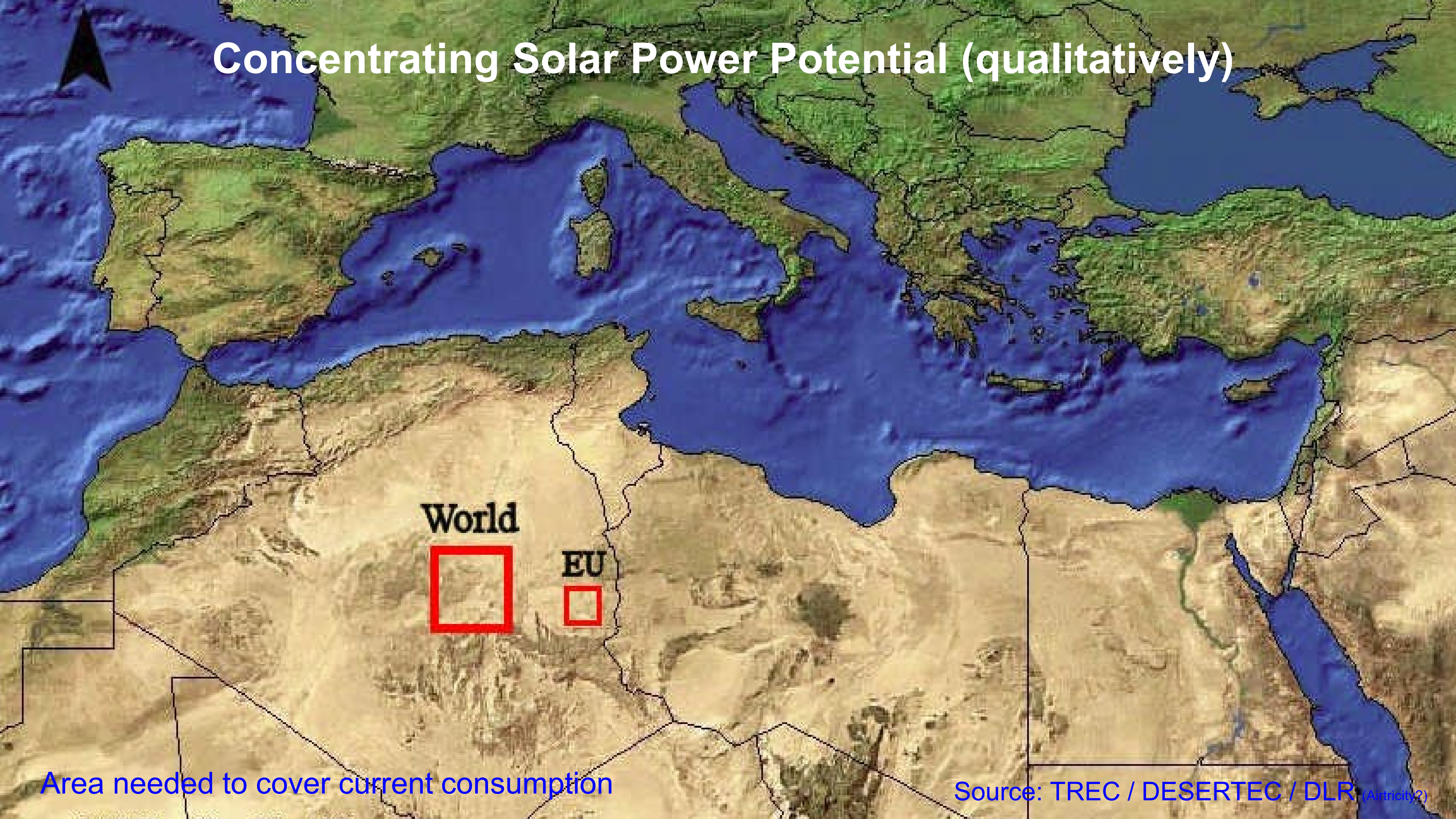
v3.1 April 2021.

Also available: Global Solar Atlas.



GlobalWindAtlas.info

Concentrating Solar Power Potential (qualitatively)



Area needed to cover current consumption

Source: TREC / DESERTEC / DLR (Airtricity?)

100% Renewables – is it possible?

100% Renewables – it is possible!

Narrative

- The climate pressure
- Which technology do we need?
- Wind technology
- The example of Denmark

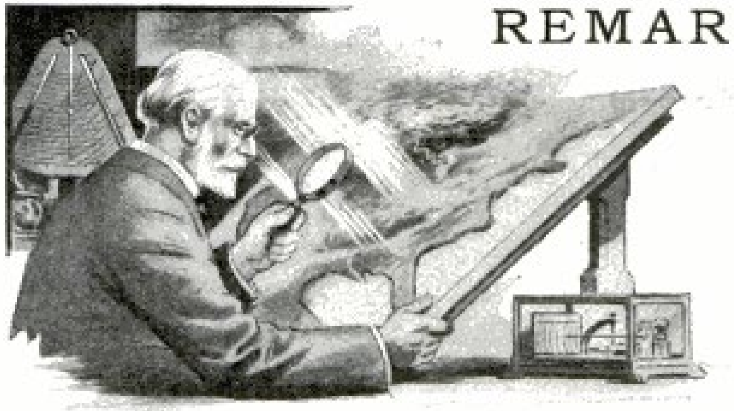
Early warning

Newspaper clip from **1912**

Read: the physics has been well known for a while

First article by Svante Arrhenius 1896 discussed ”greenhouse gases”.

Source: National Library of New Zealand, reproduced from an article in The Braidwood Dispatch and Mining Journal July 17, 1912 (via National Library of Australia. Both links and Popular Mechanics clip found on snopes.com.

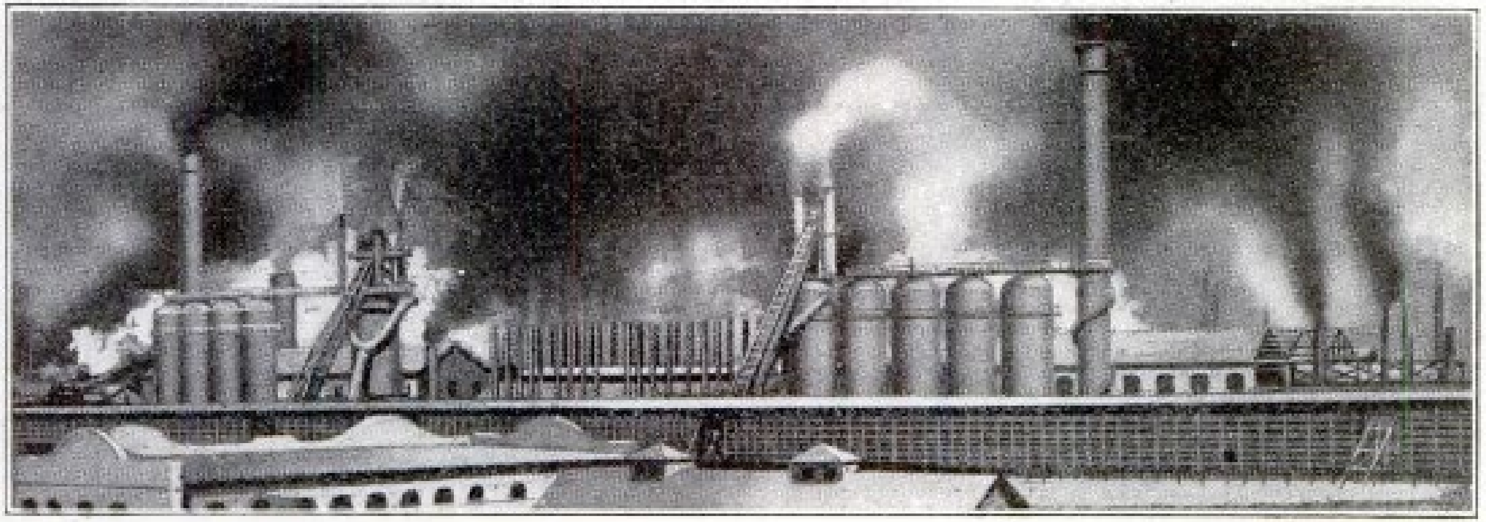


REMARKABLE WEATHER OF 1911

The Effect of the Combustion of Coal on the Climate — What Scientists Predict for the Future

By FRANCIS MOLENA

POPULAR MECHANICS 341

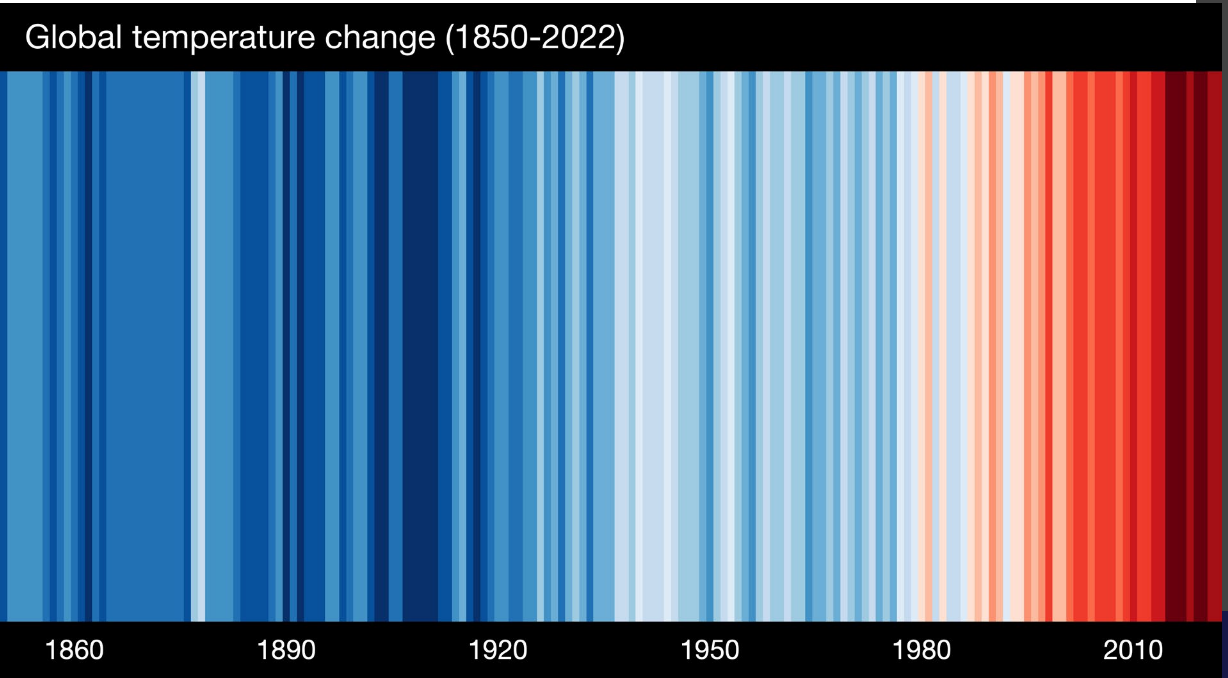


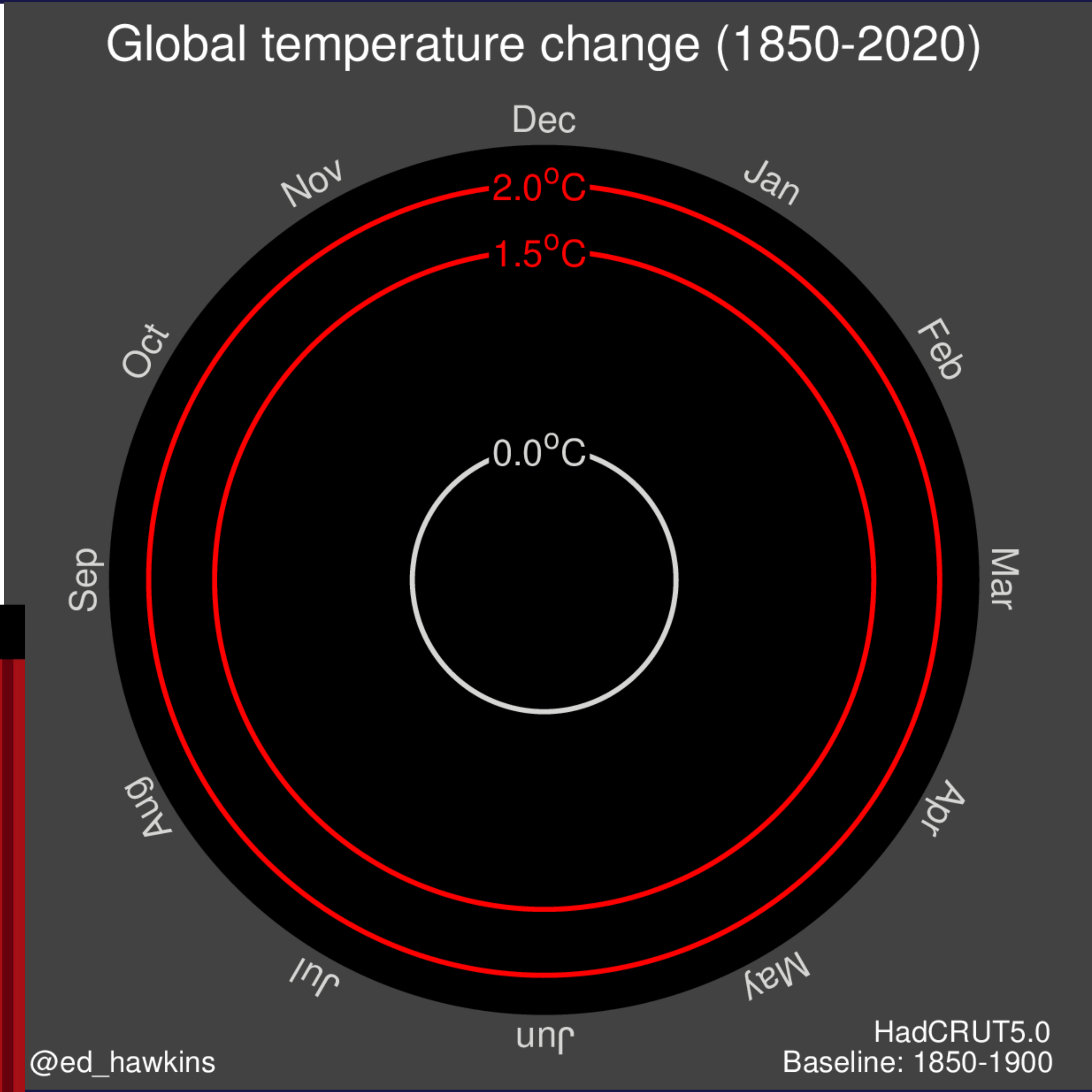
The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

Climate spiral

- Shows mean global monthly temperature relative to baseline 1850-1900.

Source: ShowYourStripes.info, Climate-Lab-Book.ac.uk
See also https://openclimatedata.net/climate-spirals/

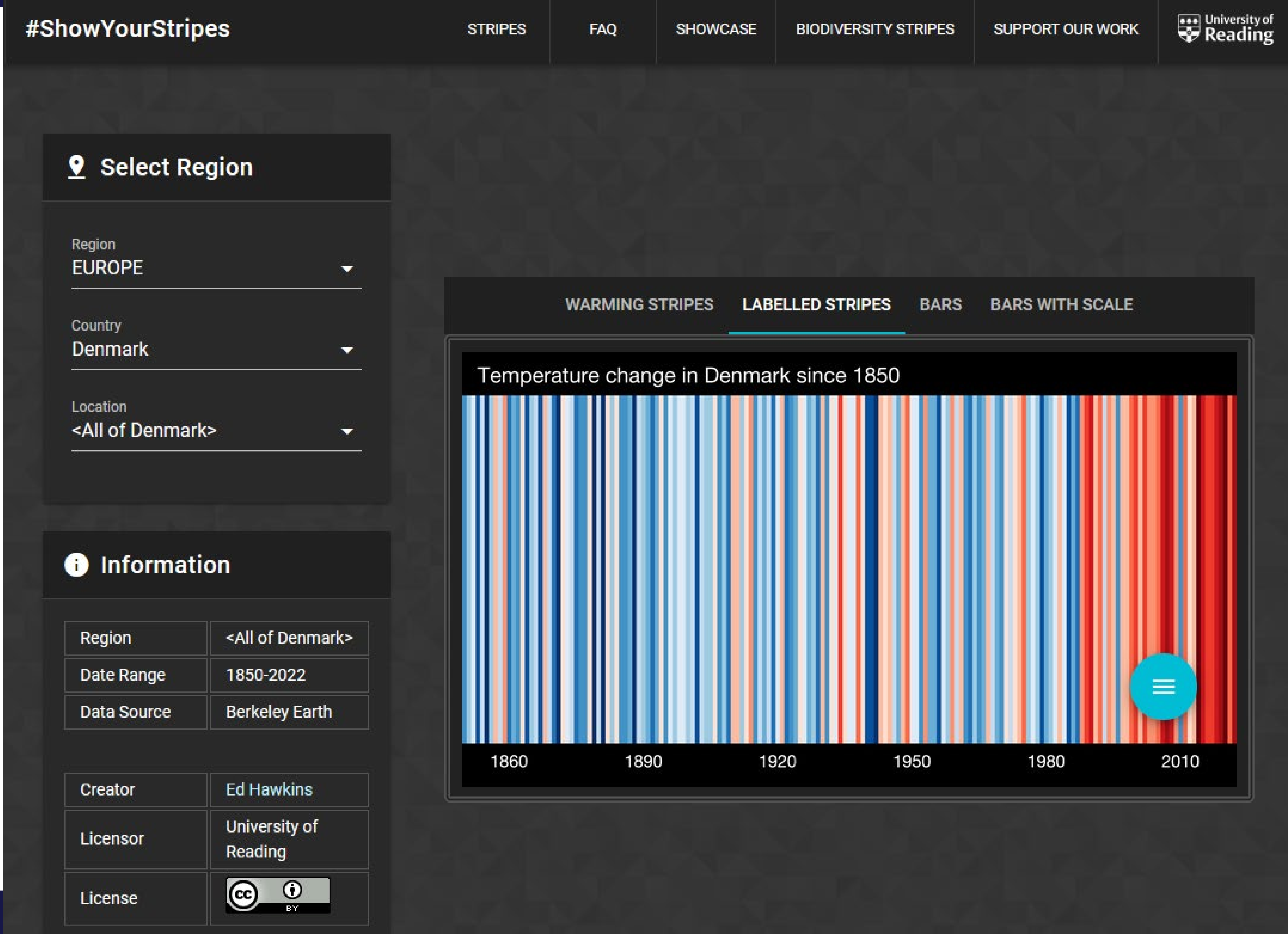


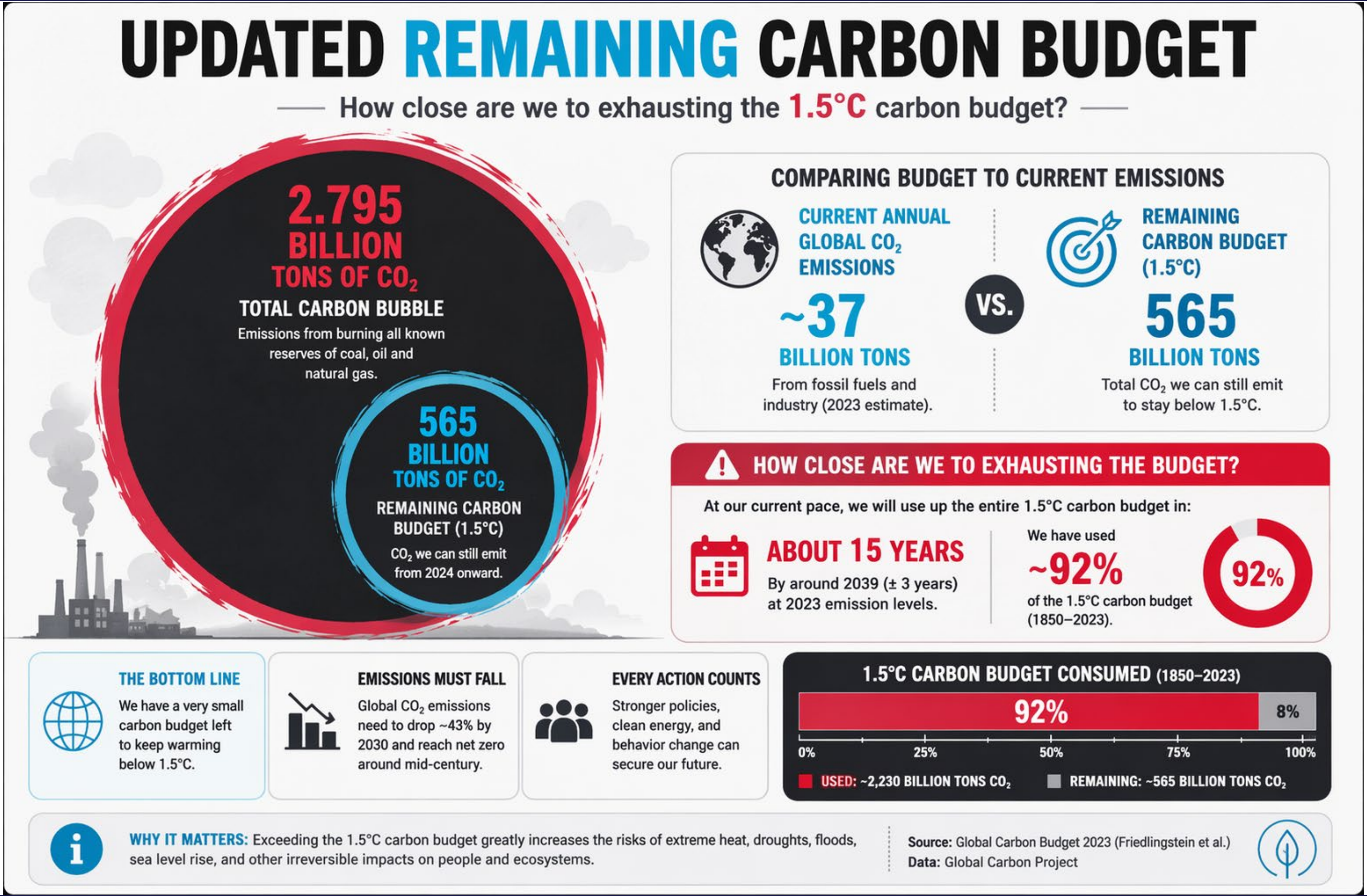


ShowYourStripes.info

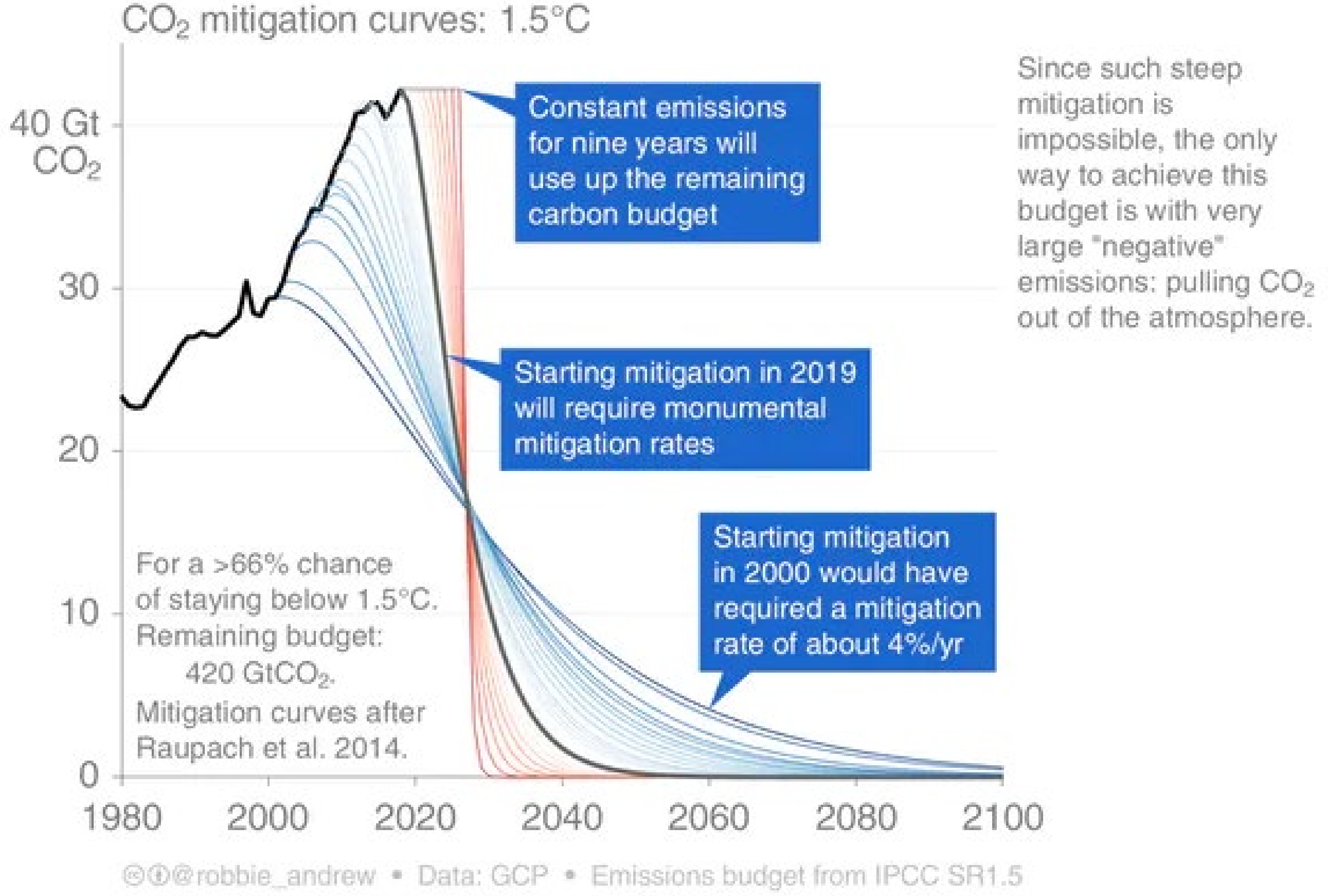
Down on country level

Also biodiversitystripes.info.





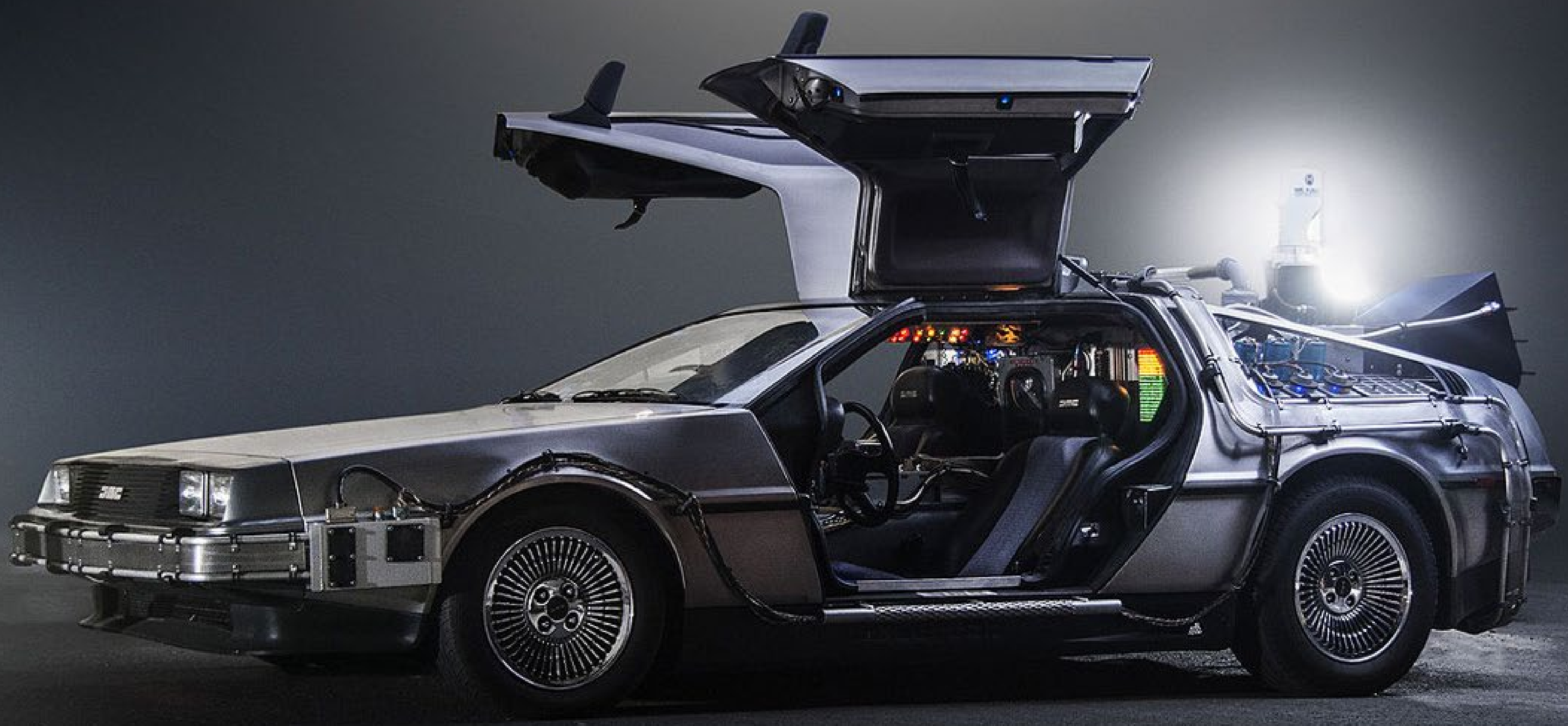
Source: Global Carbon Budget 2024 / Indicators of Global Climate Change, updated 2025



Graph demonstrating how fast mitigation has to happen to keep to 1.5°C. © Robbie Andrew, CC BY

Source: James Dyke, Robert Watson, Wolfgang Knorr: *Climate scientists: concept of net zero is a dangerous trap*. The Conversation, 2021

The necessary future tech…



No new miracle tech needed

Marc Jacobson, Stanford:

- ” The worldwide upfront capital cost of such a 2050 WWS [wind, water and sun] system is around $62tn. However, due to the $11tn annual energy cost savings, the payback time is less than six years. The new system may also create over 28m more long-term, full-time jobs than lost worldwide”
- ”we have 95% of the technologies we need to solve the problem. The ones we don’t have include long-distance aircraft and ships and some industrial technologies, but we know how to transition those technologies.”

https://www.theguardian.com/commentisfree/2023/feb/07/climate-crisis-miracle-technology-wind-water-solar (also as book)

Opinion Climate crisis

We don’t need ‘miracle’ technologies to fix the climate. We have the tools now

Mark Z Jacobson

Wind, water and solar energy is cheap, effective and green. We don’t need experimental or risky energy sources to save our planet

Tue 7 Feb 2023 11.22 GMT

270

‘The new system may also create over 28m more long-term, full-time jobs than lost worldwide and require only about 0.53% of the world’s land for new energy - less than the land required for the current energy system.’ Photograph: Phil Noble/Reuters

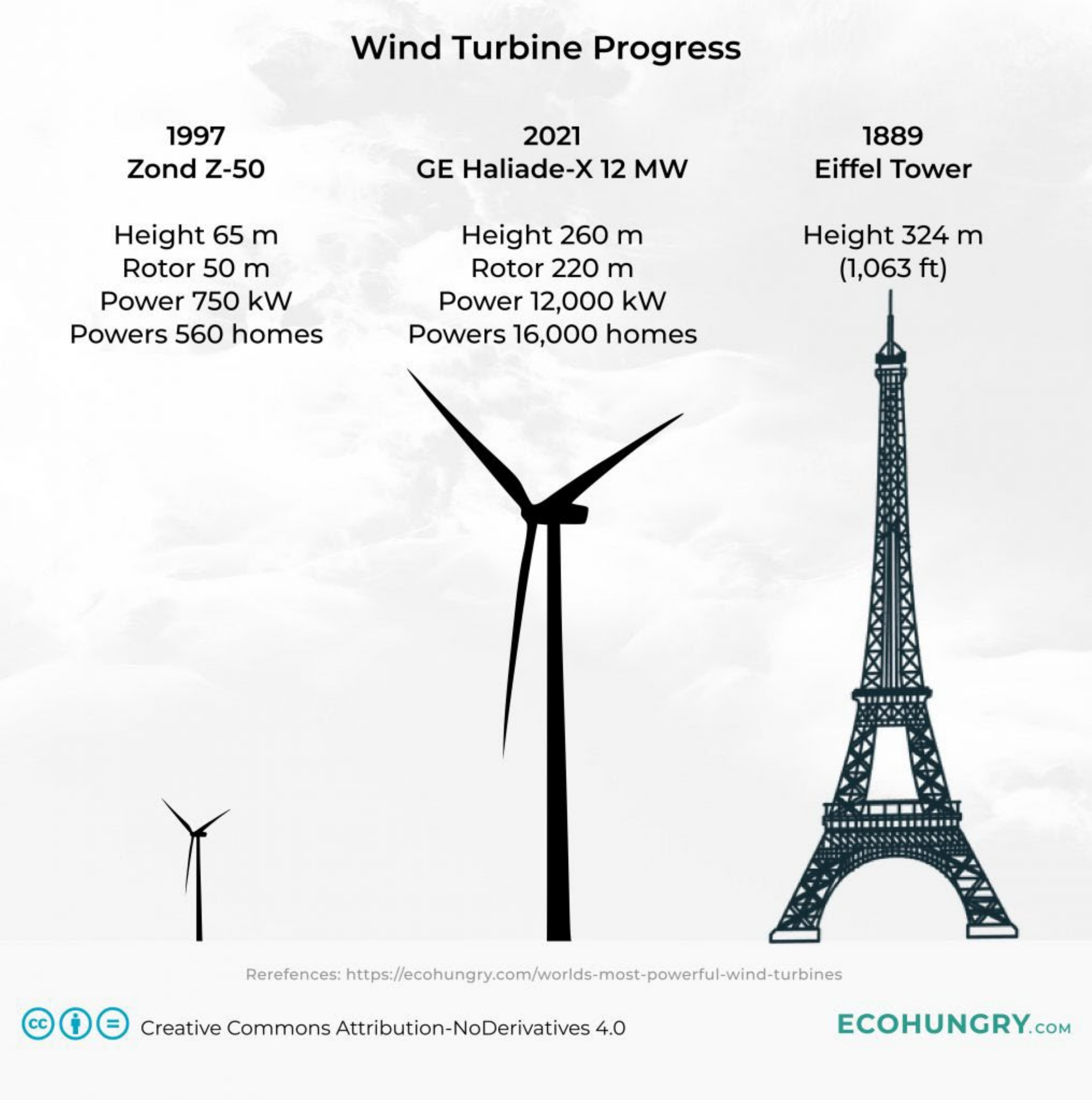
Tvind turbine 1978

- MW class turbine well before its time
- Probably longest running turbine world-wide

- Otherwise started out with small turbines, successively scaling up

Turbine size

- Significant progress over last 25 years
- …and no end in sight

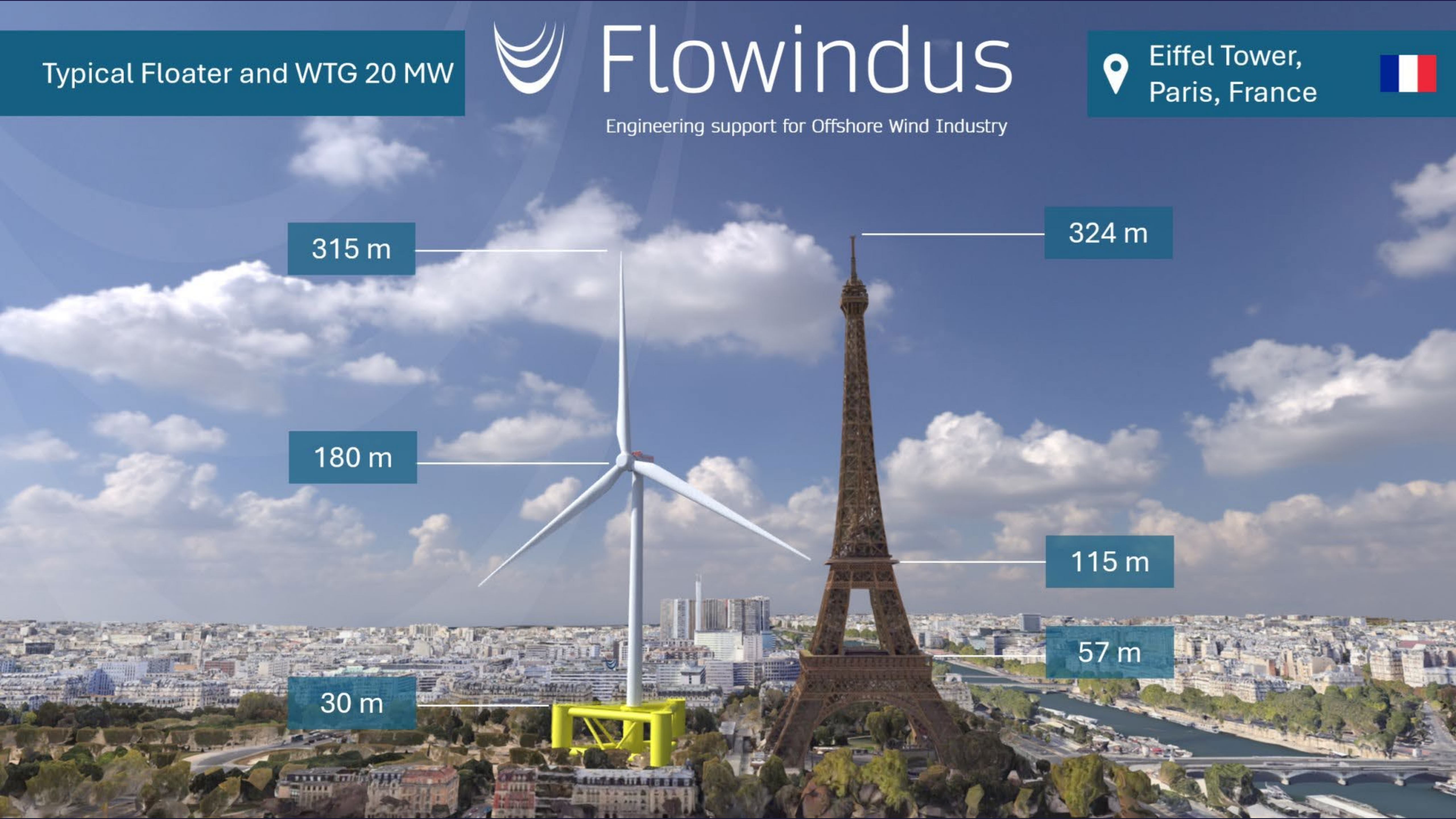


Vestas’ new nacelle is big

Image copied from: [Riviera, 17 Nov 2022]

Original image source: [Vestas]

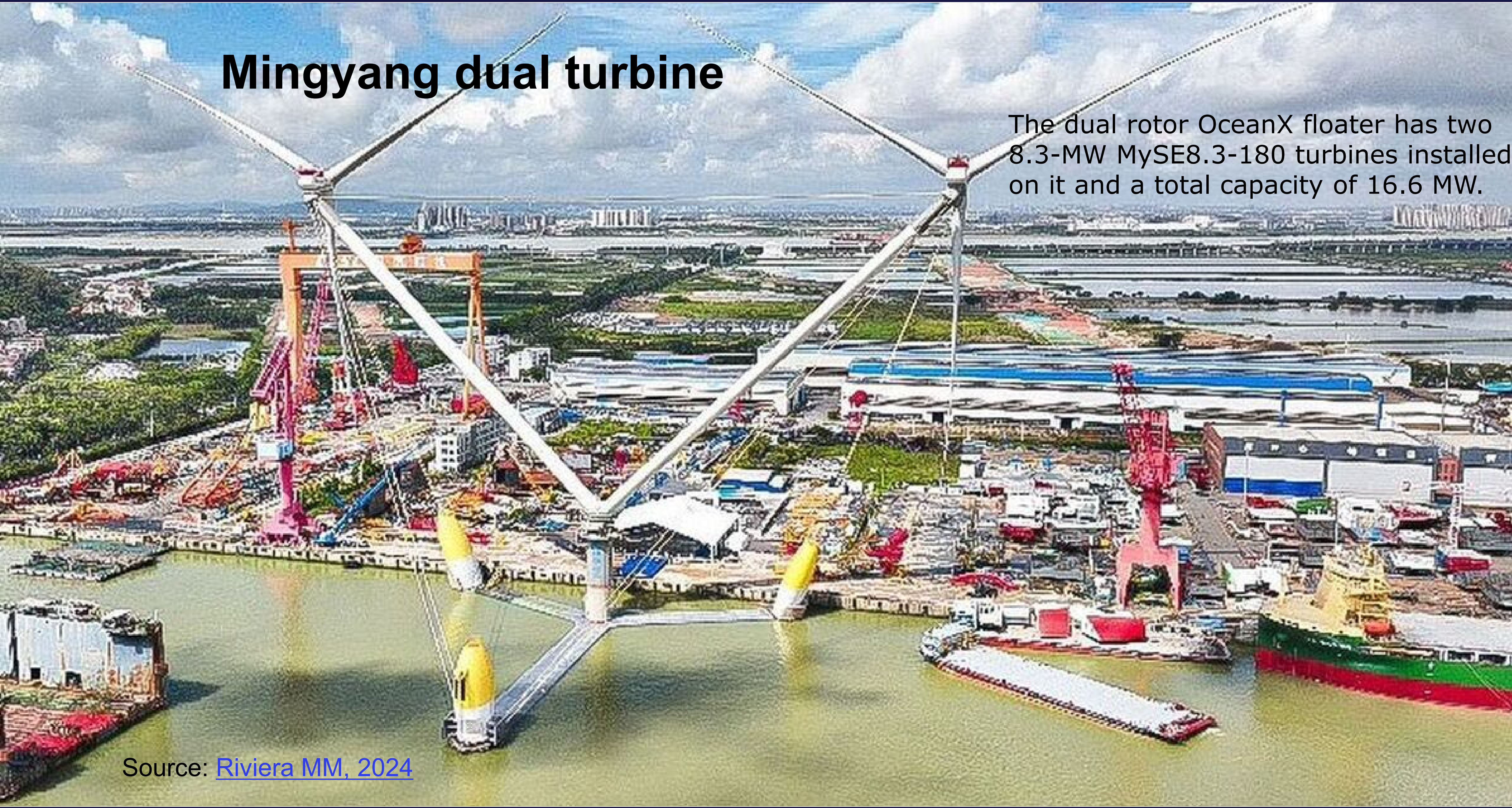
Image from: The Maritime Economy, Dec 2023


Typical Floater and WTG 20 MW
Flowindus
Engineering support for Offshore Wind Industry
Eiffel Tower,
Paris, France
315 m
180 m
30 m
324 m
115 m
57 m

Aerodyn SCDnezzy2 concept

2x 7,5MW
Downwind floating
90deg difference in rotor position

Mingyang dual turbine



The dual rotor OceanX floater has two 8.3-MW MySE8.3-180 turbines installed on it and a total capacity of 16.6 MW.

Source: [Riviera MM, 2024]

Energy payback time

At 10 m/s wind speed:

- 80 tons/sec: Mass of air through a rotor disc ø 92 m
- Generates in ?? electricity corresponding to the energy spent in manufacturing and erection (energy pay-back time)
- 90% can be recycled

Slide source Niels Erik Clausen, DTU

Energy payback time

At 10 m/s wind speed:

- 80 tons/sec: Mass of air through a rotor disc ø 92 m
- Generates in 6-7 months electricity corresponding to the energy spent in manufacturing and erection (energy pay-back time)
- 90% can be recycled
- 25 year lifetime: 50 times the energy invested

Slide source Niels Erik Clausen, DTU

Vestas provides LCAs

- Vestas provides full Life Cycle Assessments for their turbines
- Example: V236-15MW has a payback time of 13 months

Source: https://www.vestas.com/en/sustainability/environment/lifecycle-assessments

Wind plant key figures

Wind plant carbon footprint (Global Warming Potential)

7.0

gCO_2e/kWh

Wind plant return on energy

13

months

Wind plant return on energy

27

times

Life Cycle Assessment

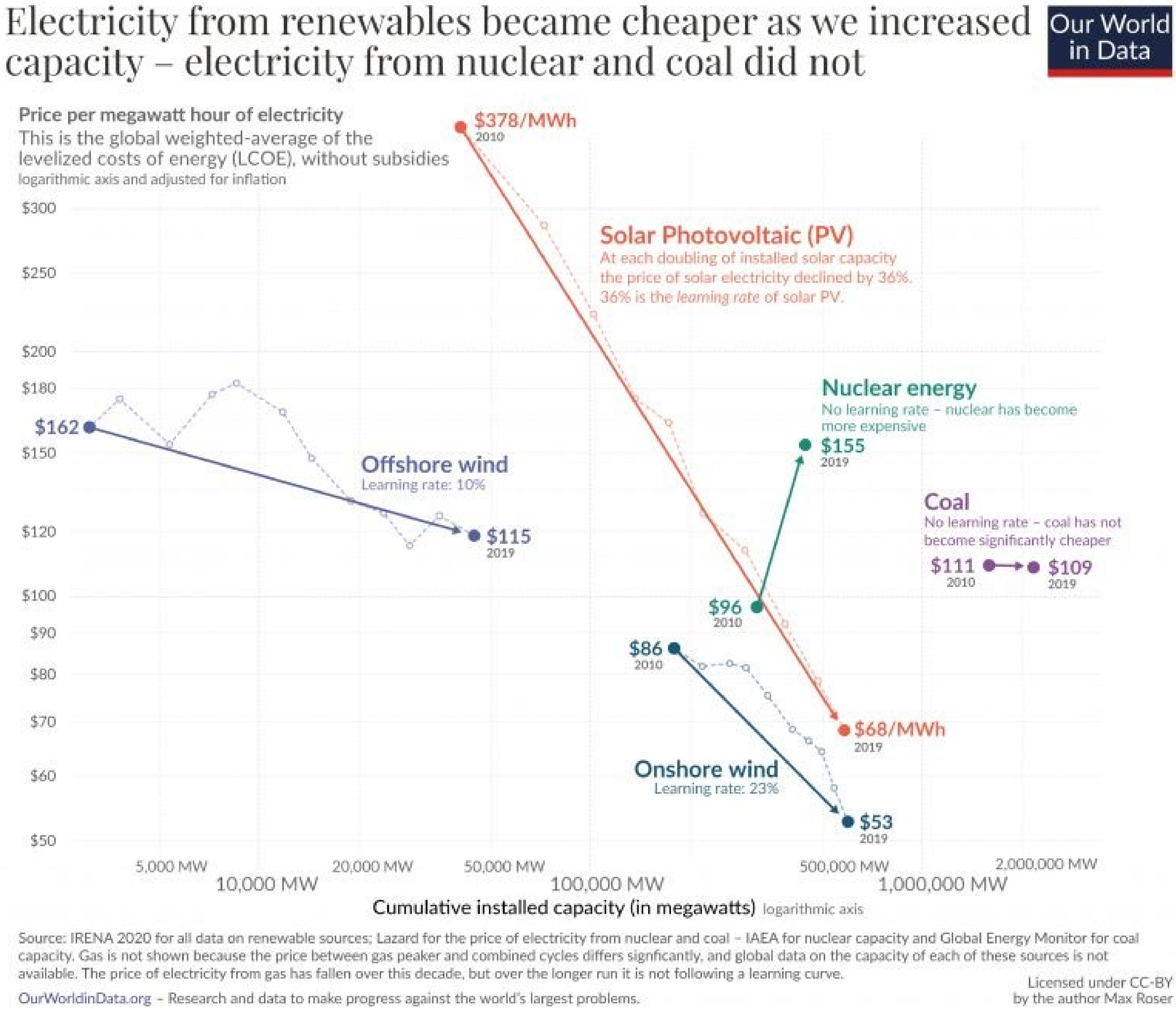
of electricity production from an offshore V236-15 MW™ wind plant

Learning curve

Every time the total installed capacity of a given technology doubles, the price falls by XX %.

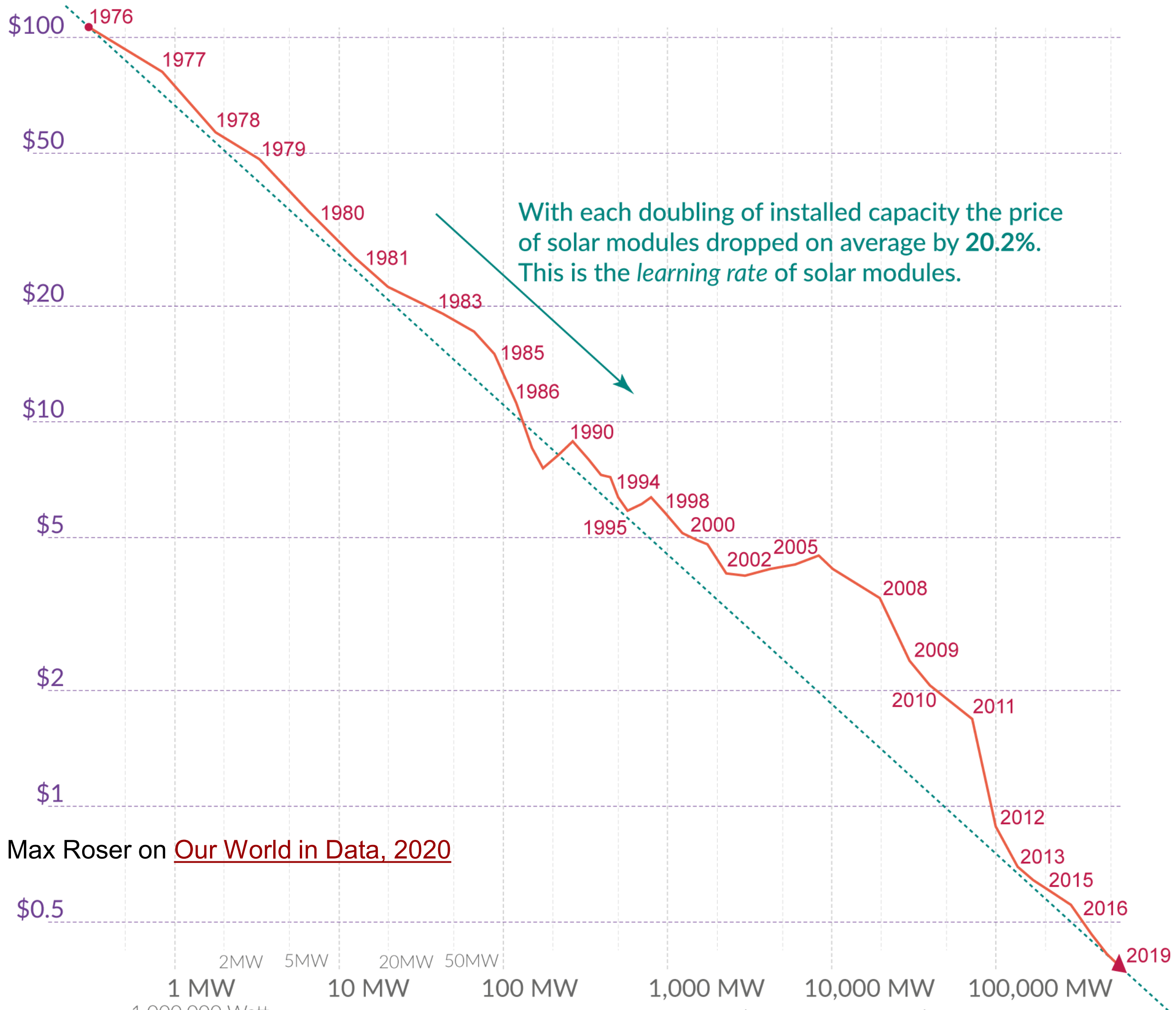
Nuclear is an exception.

Source: Max Roser on [Our World in Data, 2020]



The price of solar modules declined by 99.6% since 1976

Price per Watt of solar photovoltaics (PV) modules (logarithmic axis)
The prices are adjusted for inflation and presented in 2019 US-$.

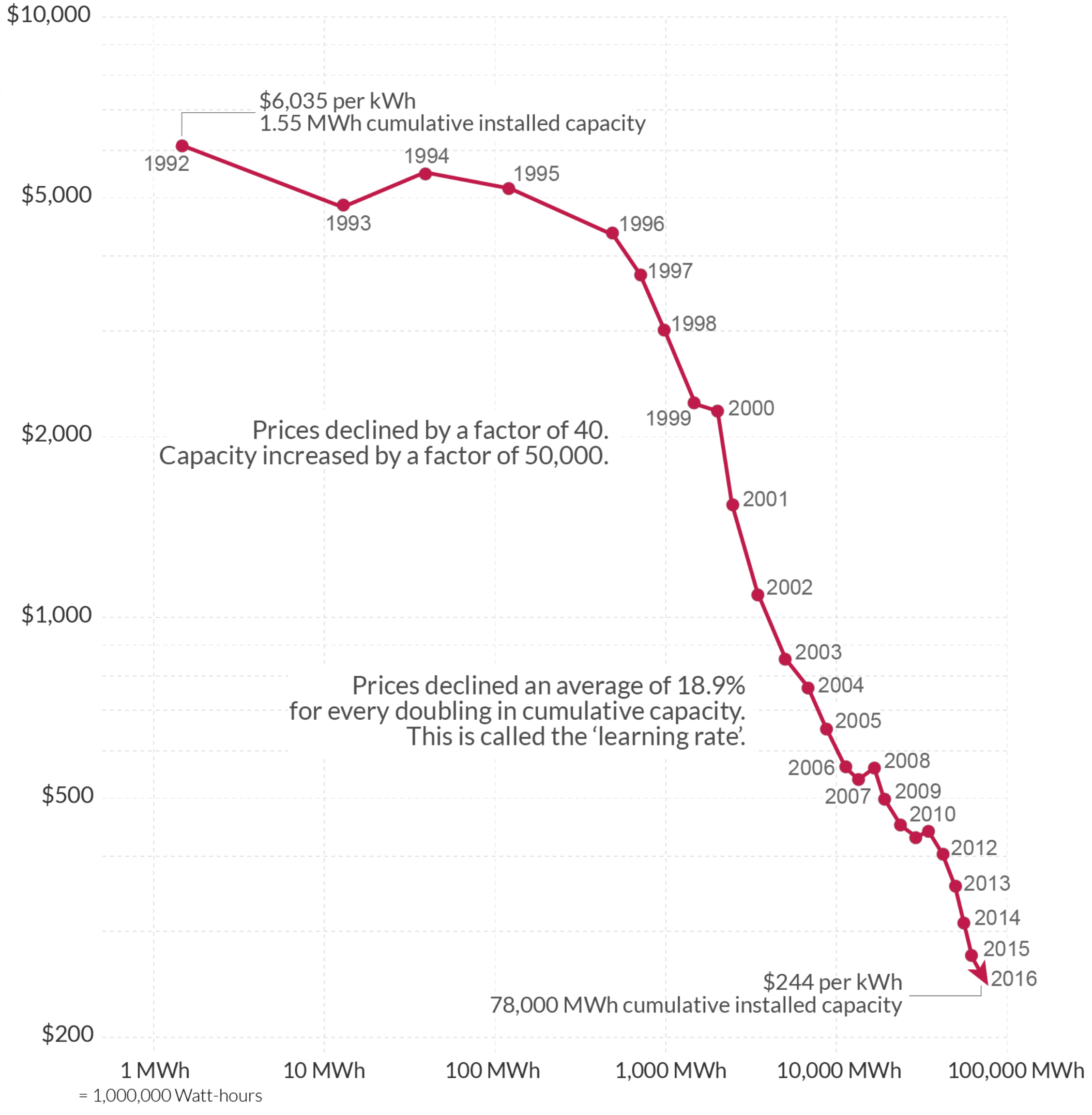


Source: Max Roser on Our World in Data, 2020

Data: Lafond et al. (2017) and IRENA Database; the reported learning rate is an average over several studies reported by de La Tour et al (2013) in Energy. The rate has remained very similar since then.
OurWorldinData.org – Research and data to make progress against the world's largest problems.

Price and market size of lithium-ion batteries since 1992

Price per kilowatt-hour; kWh (logarithmic axis)

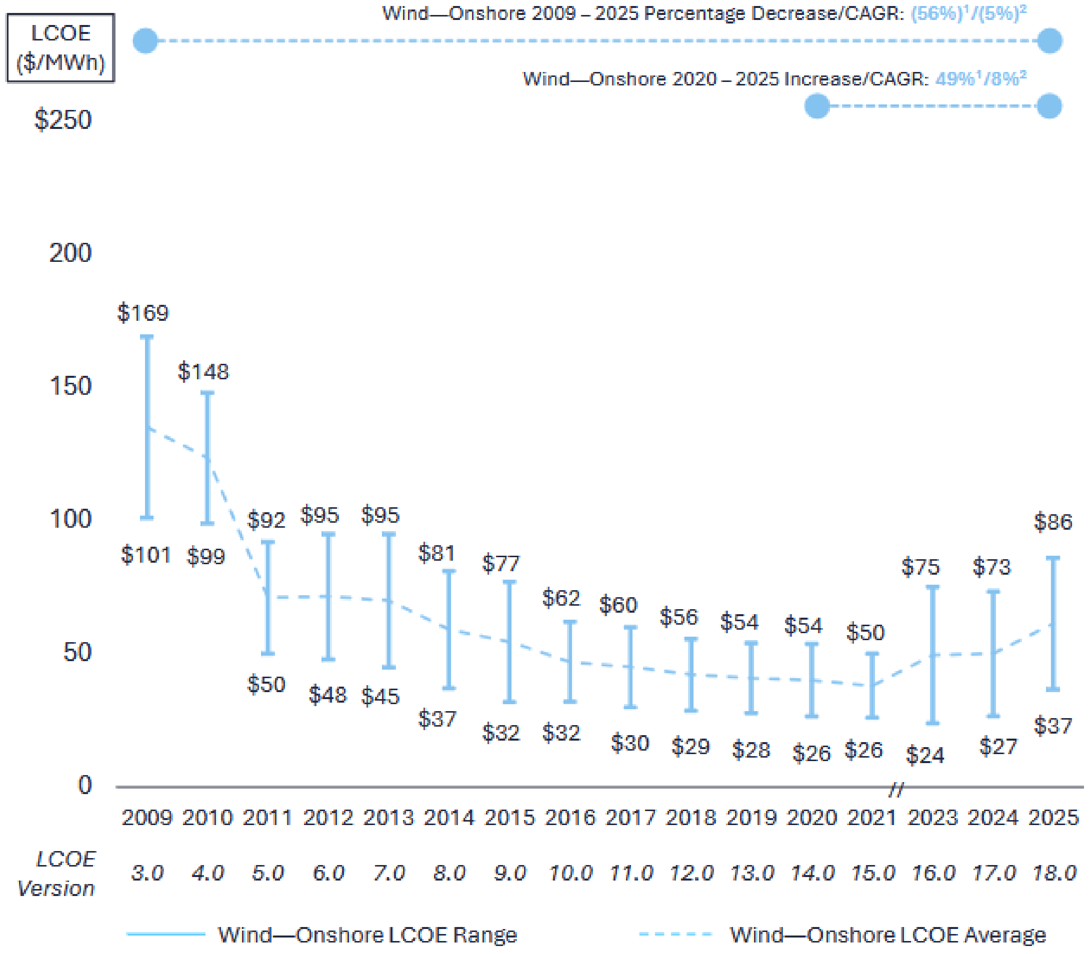


Prices are adjusted for inflation and given in 2018 US-$ per kilowatt-hour (kWh).
Source: Micah Ziegler and Jessika Trancik (2021). Re-examining rates of lithium-ion battery technology improvement and cost decline.
OurWorldinData.org – Research and data to make progress against the world's largest problems.

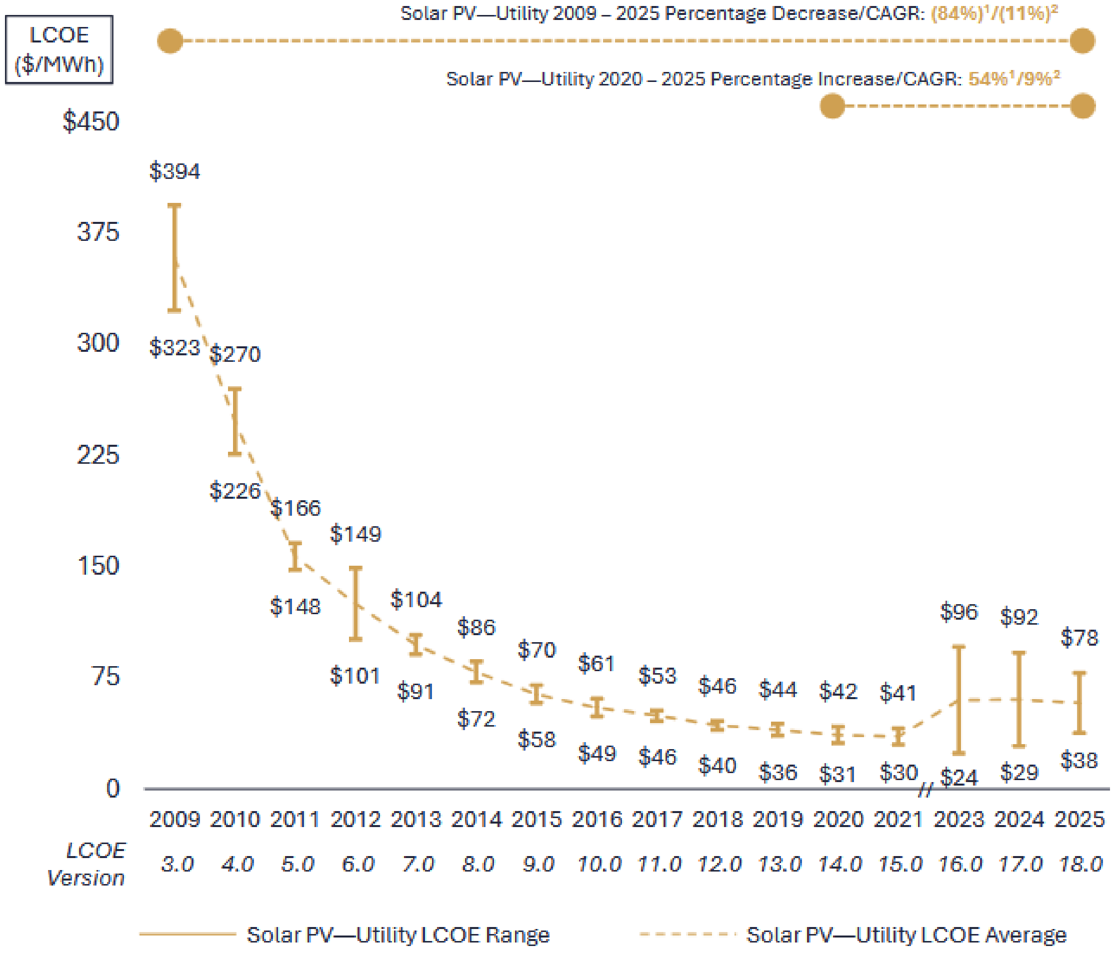
Levelized Cost of Energy Comparison—Historical Renewable Energy LCOE

This year's analysis shows a divergence in trends between wind and solar with solar costs declining slightly and wind costs increasing, likely reflecting the difference in supply chain conditions across each technology

Wind—Onshore

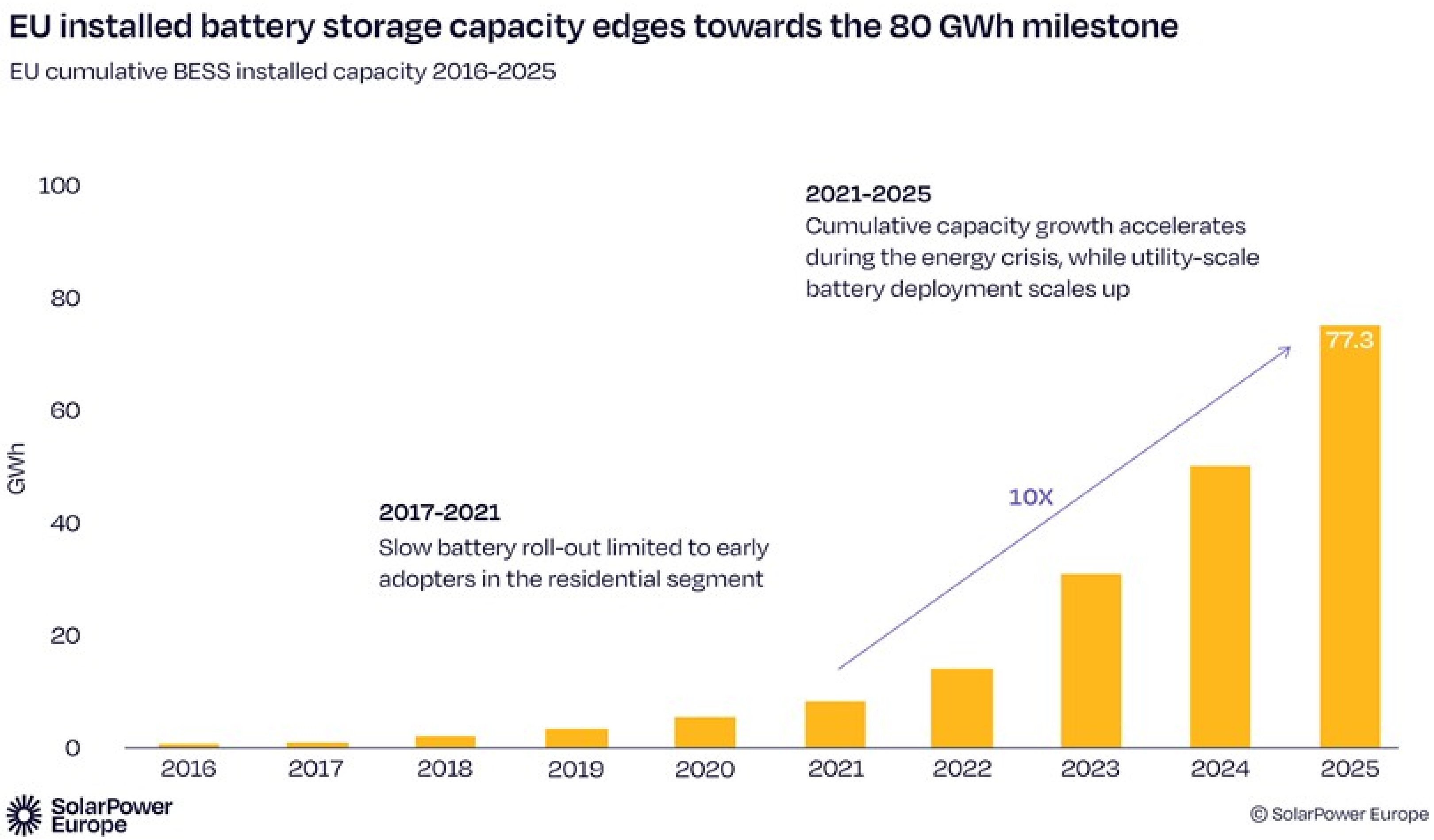


Solar PV—Utility



- https://www.lazard.com/research-insights/levelized-cost-of-energyplus-lcoeplus/

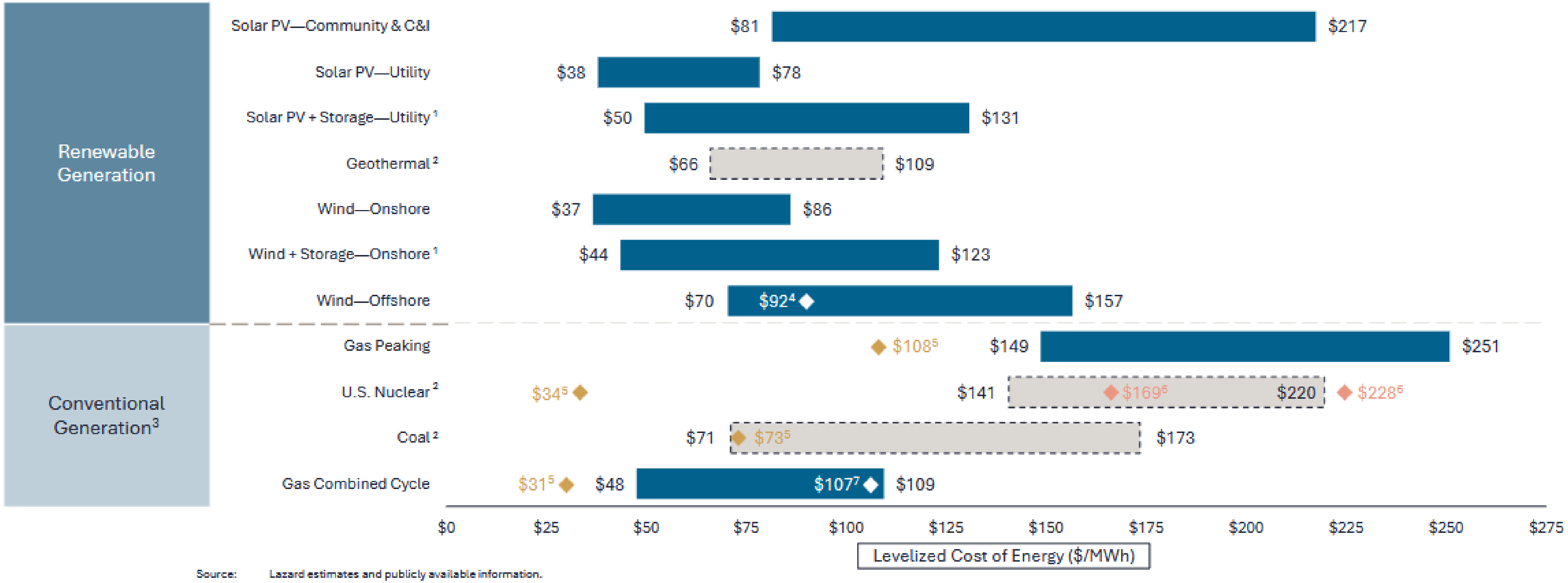
Source: Lazard estimates and publicly available information.
1 Reflects the average percentage increase/(decrease) of the high end and low end of the LCOE range.
2 Reflects the average compounded annual growth rate of the high end and low end of the LCOE range.


EU installed battery storage capacity edges towards the 80 GWh milestone
EU cumulative BESS installed capacity 2016-2025
100
80
60
40
20
0
GWh
2021-2025
Cumulative capacity growth accelerates during the energy crisis, while utility-scale battery deployment scales up
77.3
10X
2017-2021
Slow battery roll-out limited to early adopters in the residential segment
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
SolarPower Europe
© SolarPower Europe

DTU

Levelized Cost of Energy Comparison—Version 18.0

Selected renewable energy generation technologies remain cost-competitive with conventional generation technologies under certain circumstances



Source: Lazard estimates and publicly available information.

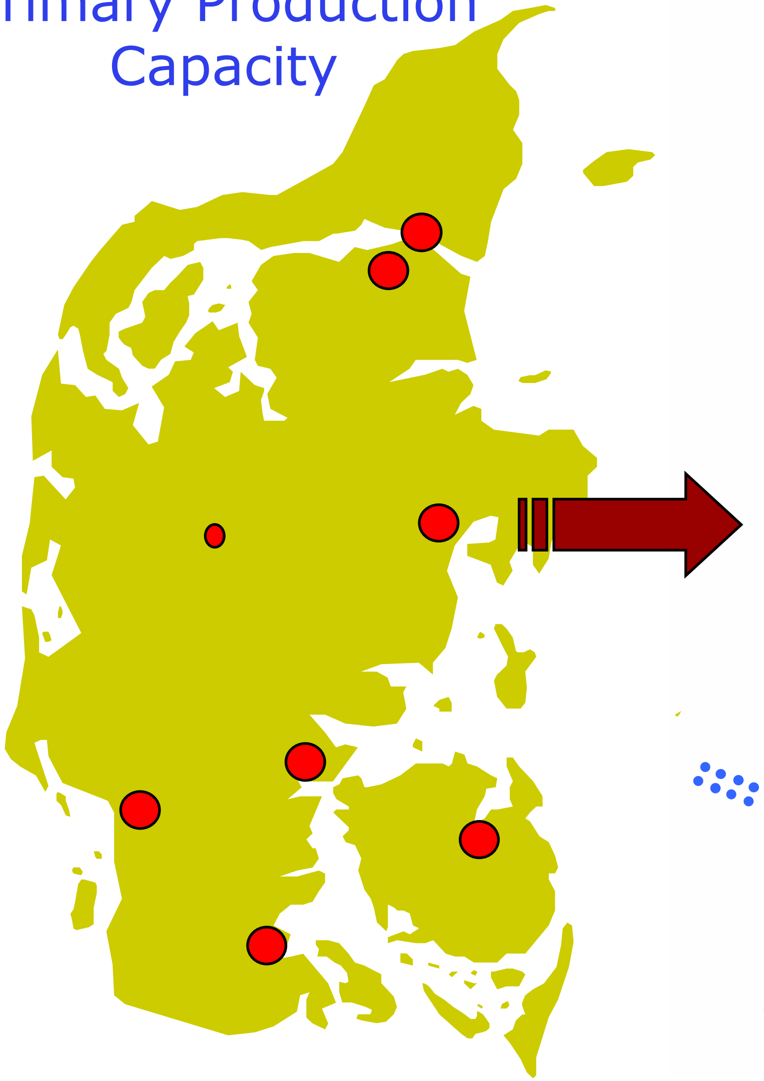
Note: Here and throughout this analysis, unless otherwise indicated, the analysis assumes 60% debt at an 8% interest rate and 40% equity at a 12% cost. See page titled "Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital" for cost of capital sensitivities.

1. Reflects the LCOE for a system composed of standalone generation plus standalone storage less the combined system-level synergies (assumed to be 10% of storage capital costs and 25% of inverter costs). The synergies capture potential cost reductions or efficiency gains from integrating generation and storage, such as shared interconnection infrastructure, improved energy dispatch, enhanced capacity utilization and operational efficiencies.
2. Given the limited public and/or observable data available for new-build geothermal, coal and nuclear projects, the LCOE presented herein reflects Lazard's LCOE v14.0 results adjusted for inflation and, for nuclear, are based on then-estimated costs of the Vogtle Plant. Coal LCOE does not include cost of transportation and storage.
3. The fuel cost assumptions for Lazard's LCOE analysis of gas-fired generation, coal-fired generation and nuclear generation resources are $3.45/MMBTU, $1.47/MMBTU and $0.85/MMBTU, respectively, for year-over-year comparison purposes. See page titled "Levelized Cost of Energy Comparison—Sensitivity to Fuel Prices" for fuel price sensitivities.
4. Represents the illustrative midpoint LCOE for Dominion's Coastal Virginia Offshore Wind ("CVOW") project, based on the publicly disclosed capital cost of ~$8.7 billion (excluding onshore transmission costs) and offshore wind estimates from Lazard. Dominion's projected LCOE for CVOW as of February 2025 is $91/MWh in 2027 dollars, with an expected COD in 4Q 2026.
5. Reflects the average of the high and low LCOE marginal cost of operating fully depreciated gas peaking, gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper- and lower-quartile estimates derived from Lazard's research. See page titled "Levelized Cost of Energy Comparison—New Build Renewable Generation vs. Marginal Cost of Conventional Generation" for additional details.
6. Represents illustrative LCOE values for Vogtle nuclear plant's units 3 and 4. The analysis is based on publicly available estimates and suggestions from selected industry experts, indicating a cost "learning curve" of ~30% between Vogtle units 3 and 4. Analysis assumes total operating capacity of ~2.2 GW, total capital cost of ~$32.3 billion, capacity factor of ~97%, operating life of 70 years and other operating parameters estimated by Lazard's LCOE v14.0 results, adjusted for inflation.
7. Illustrative high case reflects elevated capital costs ($2,400/kW – $2,600/kW) based on recently observed market quotes for CCGT projects in early stages of development (post-2028 COD)

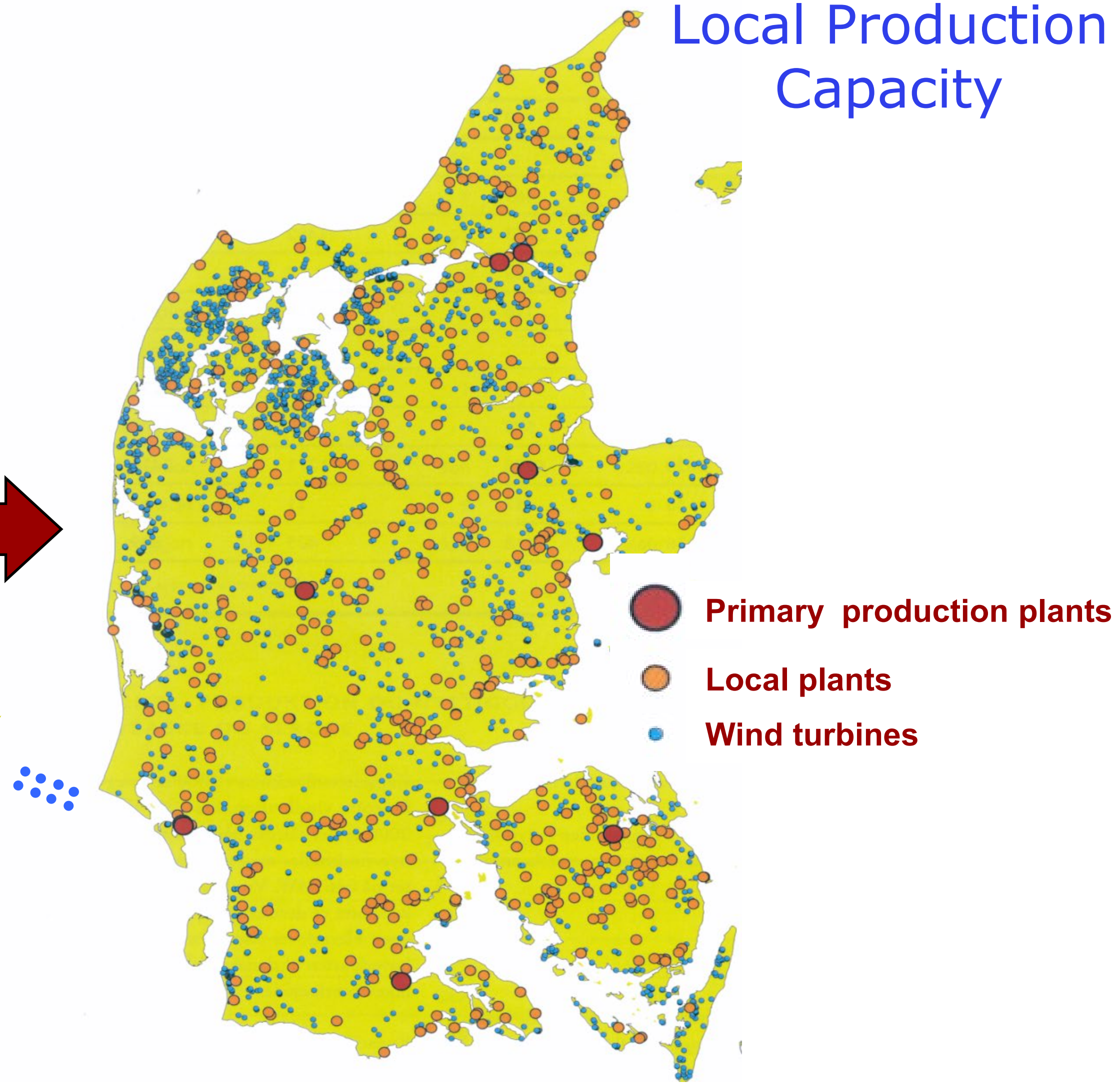
- https://www.lazard.com/research-insights/levelized-cost-of-energy-plus-lcoeplus/

Development from the 1980s

Primary Production Capacity



Local Production Capacity

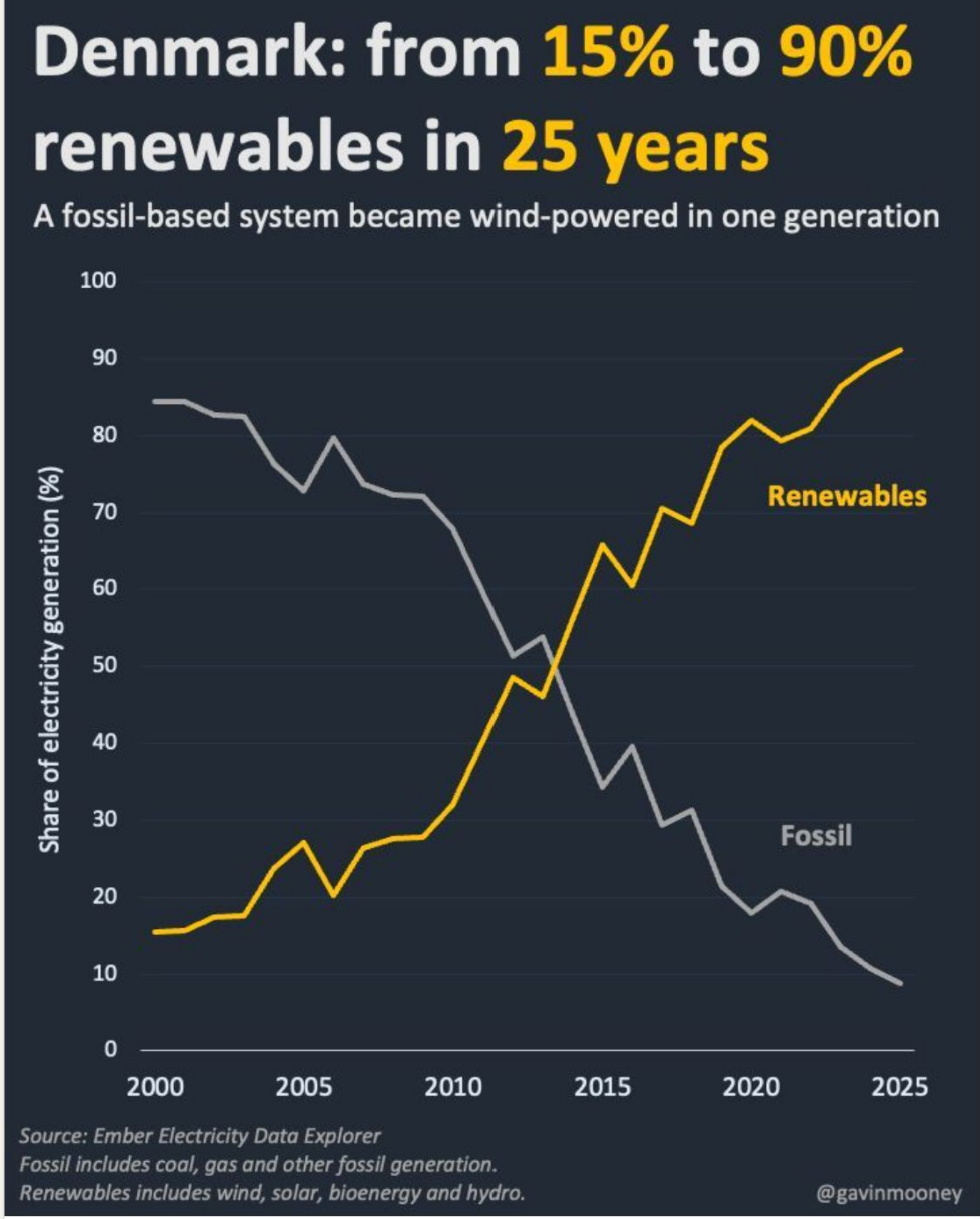


Source: Energinet.dk

Source: EcoGrid.dk (Energinet.dk)

DK trend since the 1970ies

- Shown here since 2000
- Includes biomass (debatable)



VRE in Denmark 2025

Source: Energinet.dk

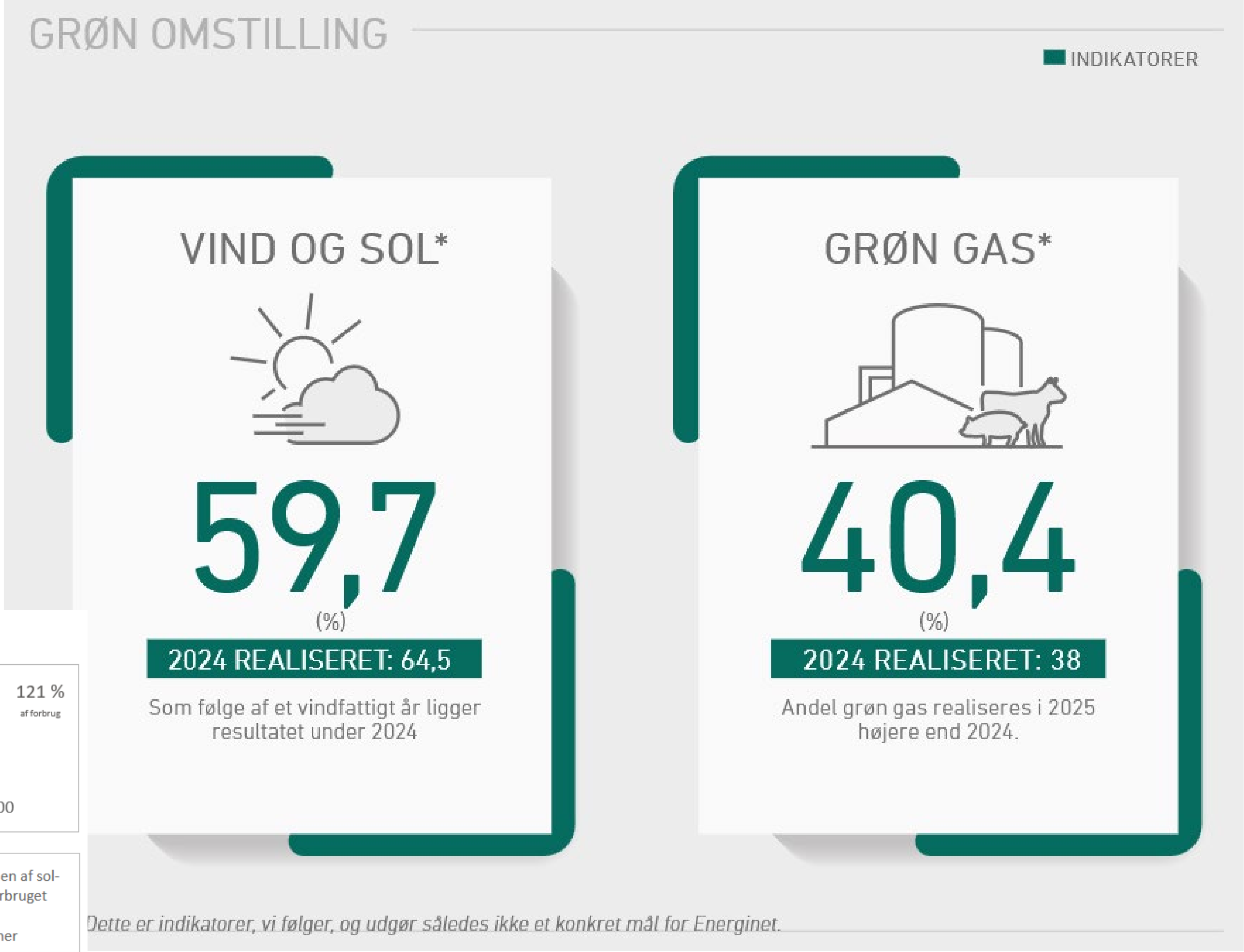
Udvalgte rekorder for sol- og vindenergi

Rekorder inkl. prognoser | Endelige rekorder

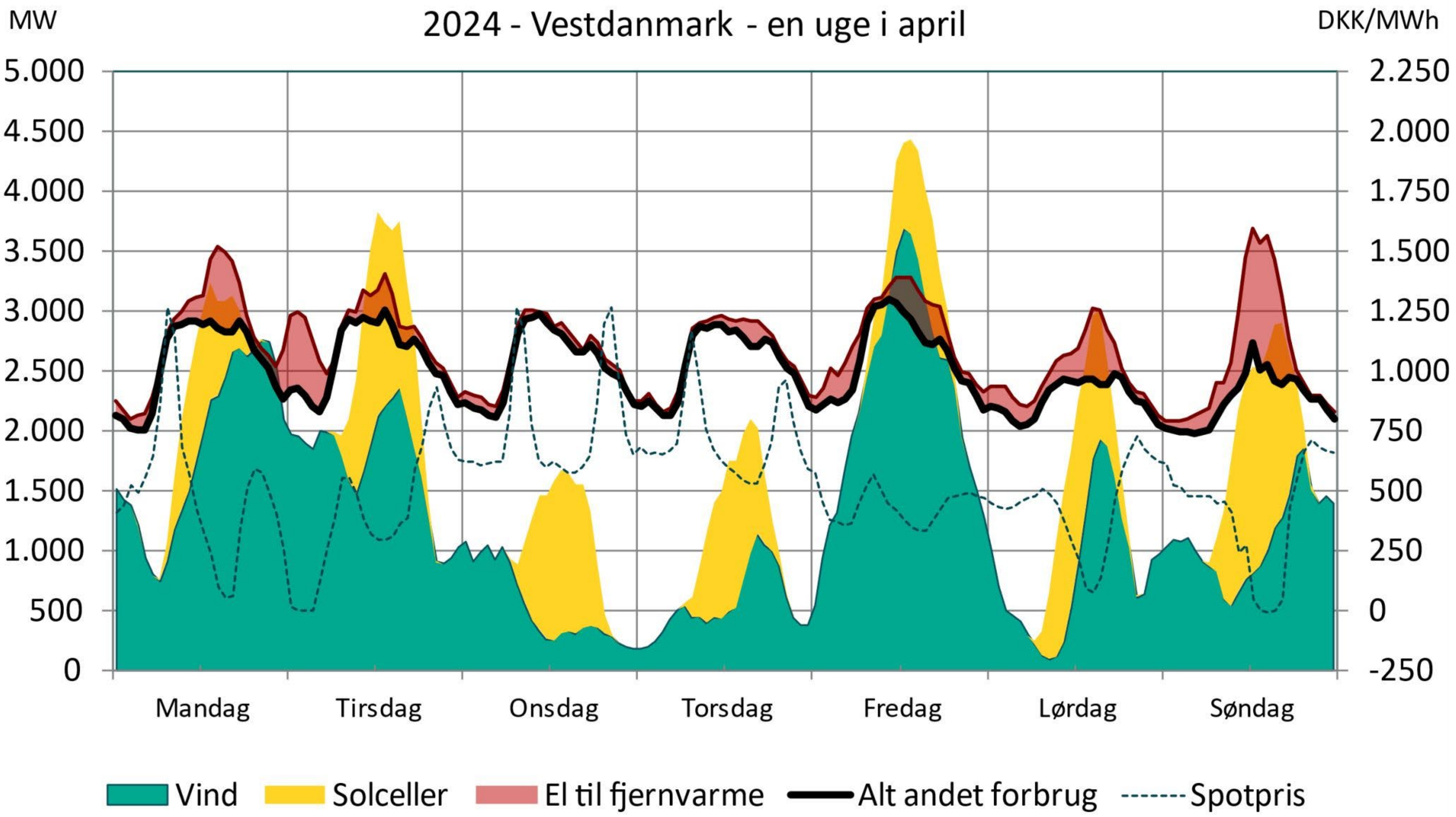
Sol — 80 % af forbrug — 4,017 MWh — 07-05-2026 11:00:00	Vind — 102 % af forbrug — 6,496 MWh — 24-01-2025 17:00:00	Sol & vind — 121 % af forbrug — 8,256 MWh — 26-03-2026 11:00:00
Forbrug — 7,468 MWh — 02-02-2026 10:00:00	Største andel af forbruget produceret af sol og vind — 182 % — 03-07-2023 01:00:00	Timer i træk hvor produktionen af sol- og vindenergi overstiger forbruget — 67 timer — I perioden fra: 02-02-2024 10:00:00 til: 05-02-2024 04:00:00

Årsrekorder | Månedsrekorder | Dagsrekorder | Timerekorder

Periode: 1/1/2010 – 6/2/2026



District heating with electricity adds flexibility



WindEurope DailyWind

Daily newsletter in inbox

More info on website

Valid for 24 April 2022 (Sunday)

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

WIND POWER NUMBERS DAILY

25 April 2022

How much wind was in Europe's electricity yesterday?

21.1%
Share of wind energy in electricity demand

16.2% (1,096 GWh) onshore wind

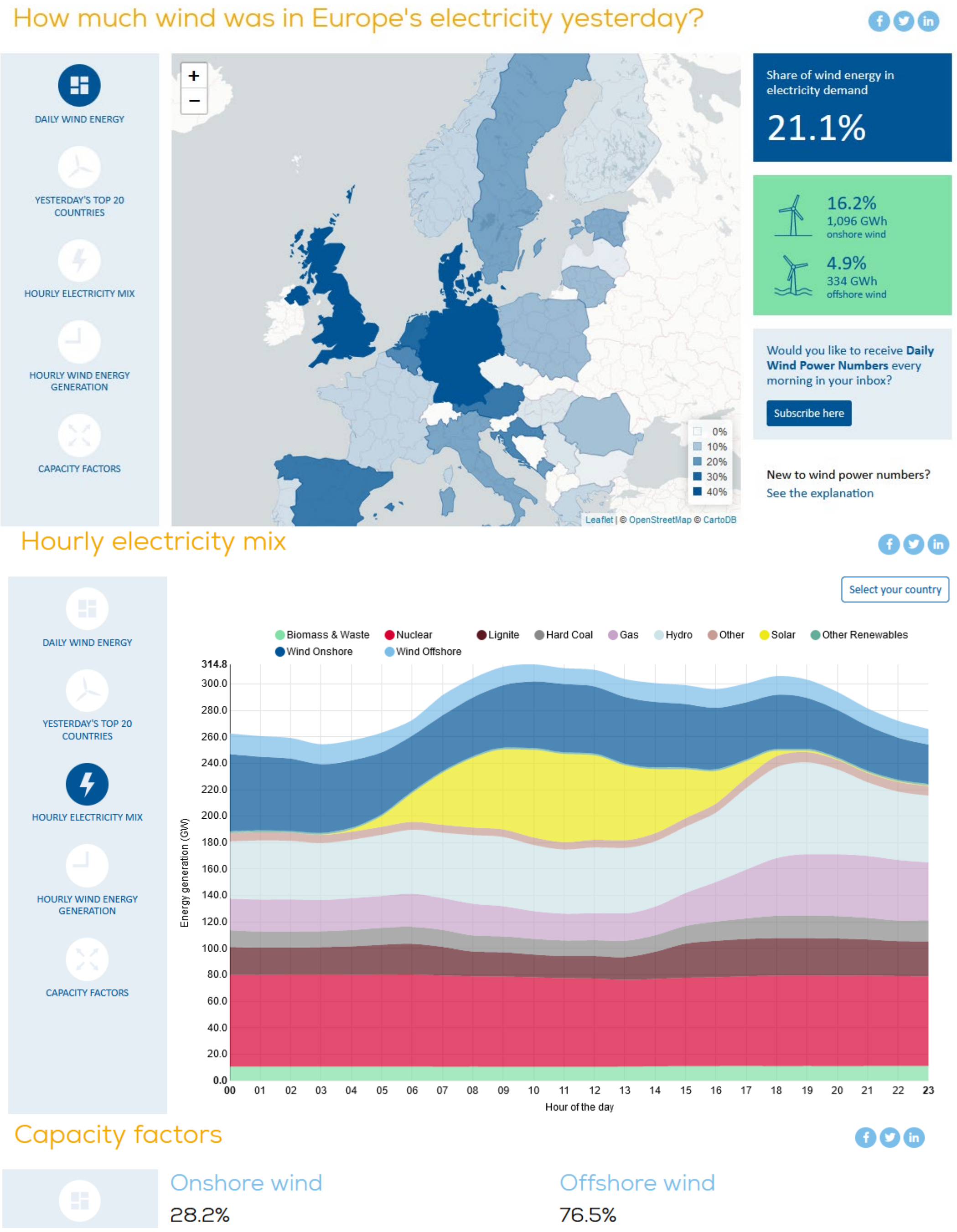
4.9% (334 GWh) offshore wind

Share these figures on:

Find out more

TOP 10 COUNTRIES

BY SHARE OF WIND ENERGY	BY WIND ENERGY GENERATION
1. Denmark: 88%	1. Germany: 479 GWh
2. Germany: 43%	2. United Kingdom: 211 GWh
3. United Kingdom: 33%	3. Spain: 138 GWh
4. Netherlands: 29%	4. Italy: 100 GWh
5. Austria: 26%	5. Denmark: 74 GWh
6. Spain: 26%	6. France: 73 GWh
7. Croatia: 23%	7. Sweden: 59 GWh
8. Belgium: 23%	8. Netherlands: 53 GWh
9. Montenegro: 19%	9. Poland: 52 GWh
10. Sweden: 18%	10. Belgium: 45 GWh



WindEurope DailyWind

Daily newsletter in inbox
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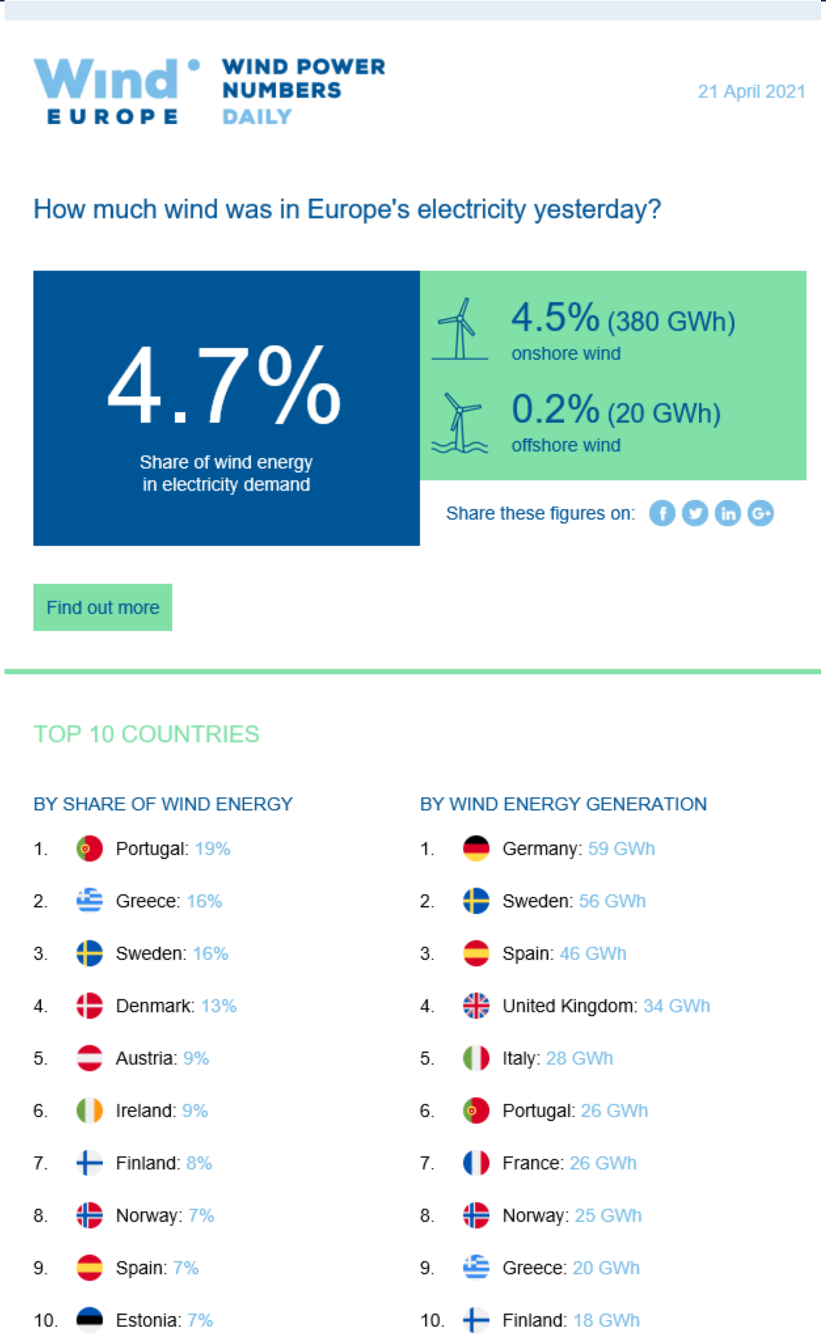
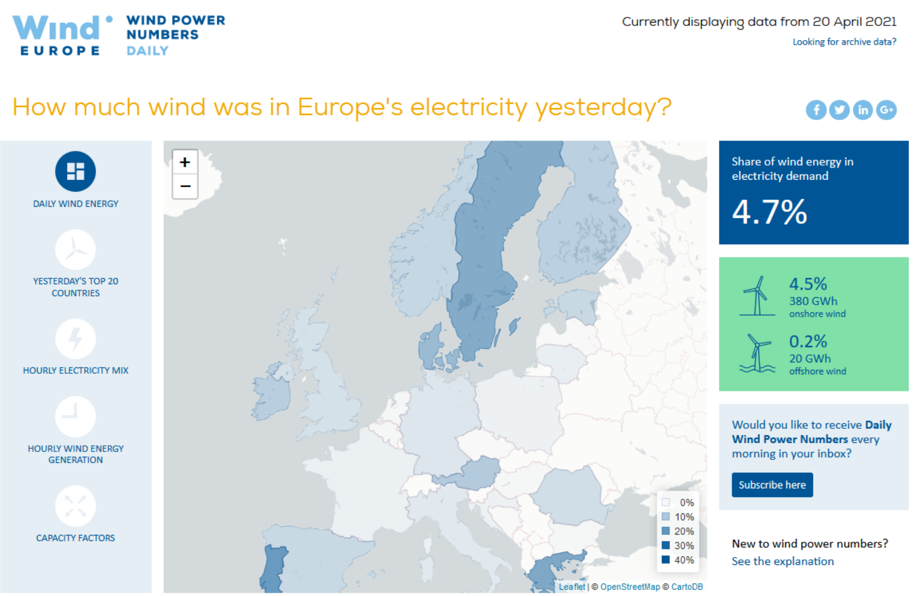
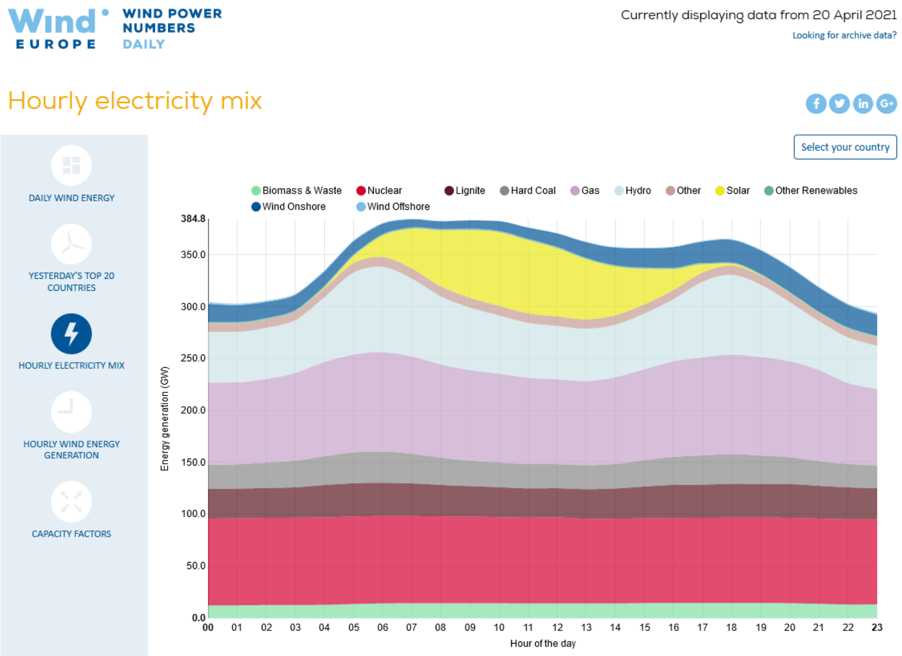
Valid for 20 April 2021 (Tuesday)







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

WindEurope DailyWind

Daily newsletter in inbox
More info on website

Record on 24 Nov 2024 (Sunday)

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

Wind EUROPE — WIND POWER NUMBERS DAILY

25 November 2024

How much wind was in Europe's electricity yesterday?

39.8%
Share of wind energy in electricity demand

35.0% (2,443 GWh) onshore wind

4.7% (331 GWh) offshore wind

Share these figures on:

Find out more

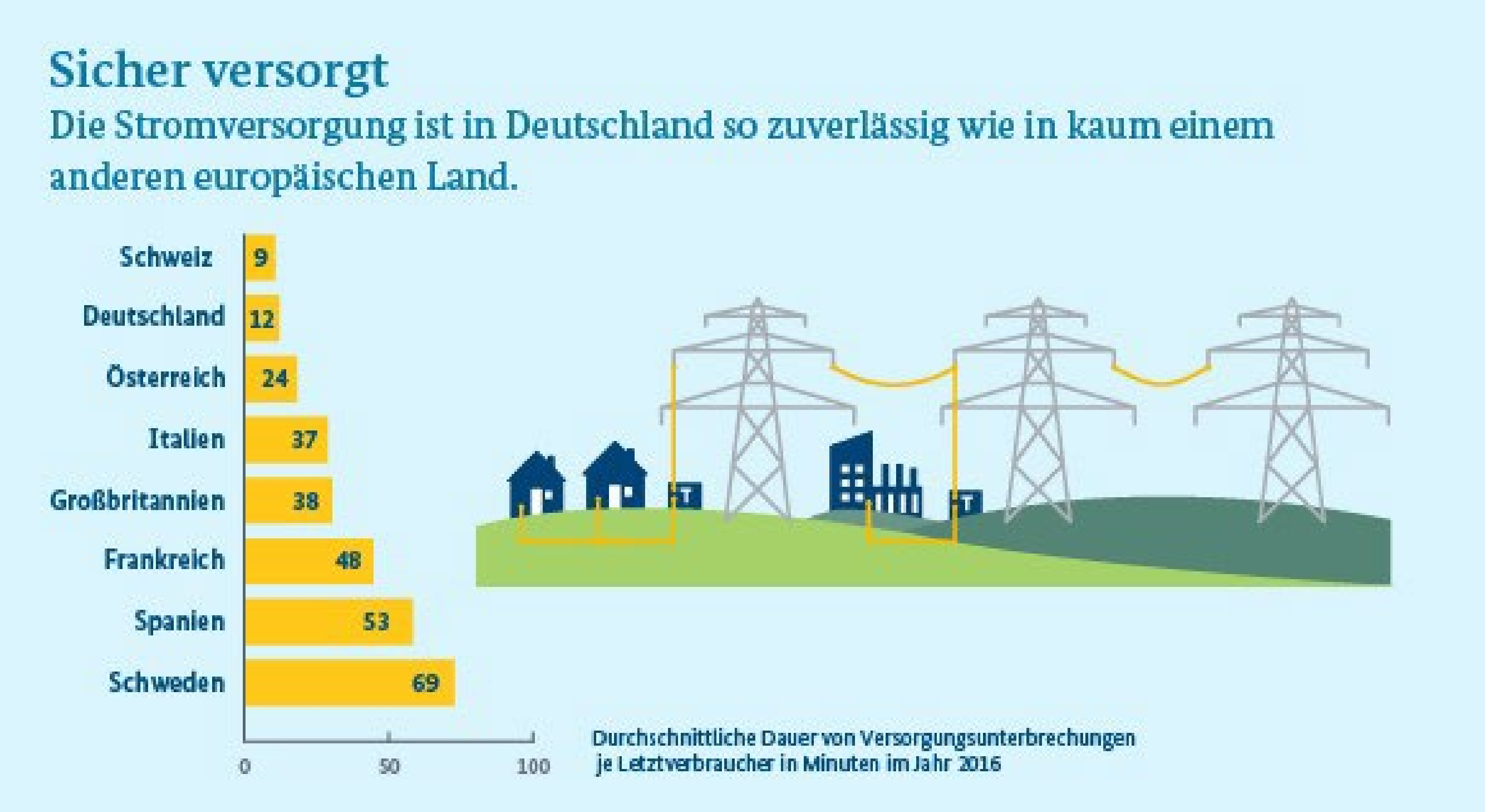
TOP 10 COUNTRIES

BY SHARE OF WIND ENERGY	BY WIND ENERGY GENERATION
1. Denmark: 107%	1. Germany: 1001 GWh
2. Portugal: 89%	2. France: 441 GWh
3. Germany: 81%	3. Spain: 329 GWh
4. Spain: 59%	4. Sweden: 218 GWh
5. Sweden: 53%	5. Poland: 135 GWh
6. Lithuania: 52%	6. Denmark: 125 GWh
7. Netherlands: 48%	7. Portugal: 111 GWh
8. Belgium: 47%	8. Netherlands: 109 GWh
9. France: 37%	9. Belgium: 99 GWh
10. Estonia: 35%	10. Norway: 71 GWh

No bad effects on power system security

Despite increase in renewable power due to the ”Energiewende”, Germany still is ahead in security of supply

Peter Franke, vice president of Bundesnetzagentur: ”The Energiwende and the rising share of decentralised generation have no negative impact on the quality of the supply.”

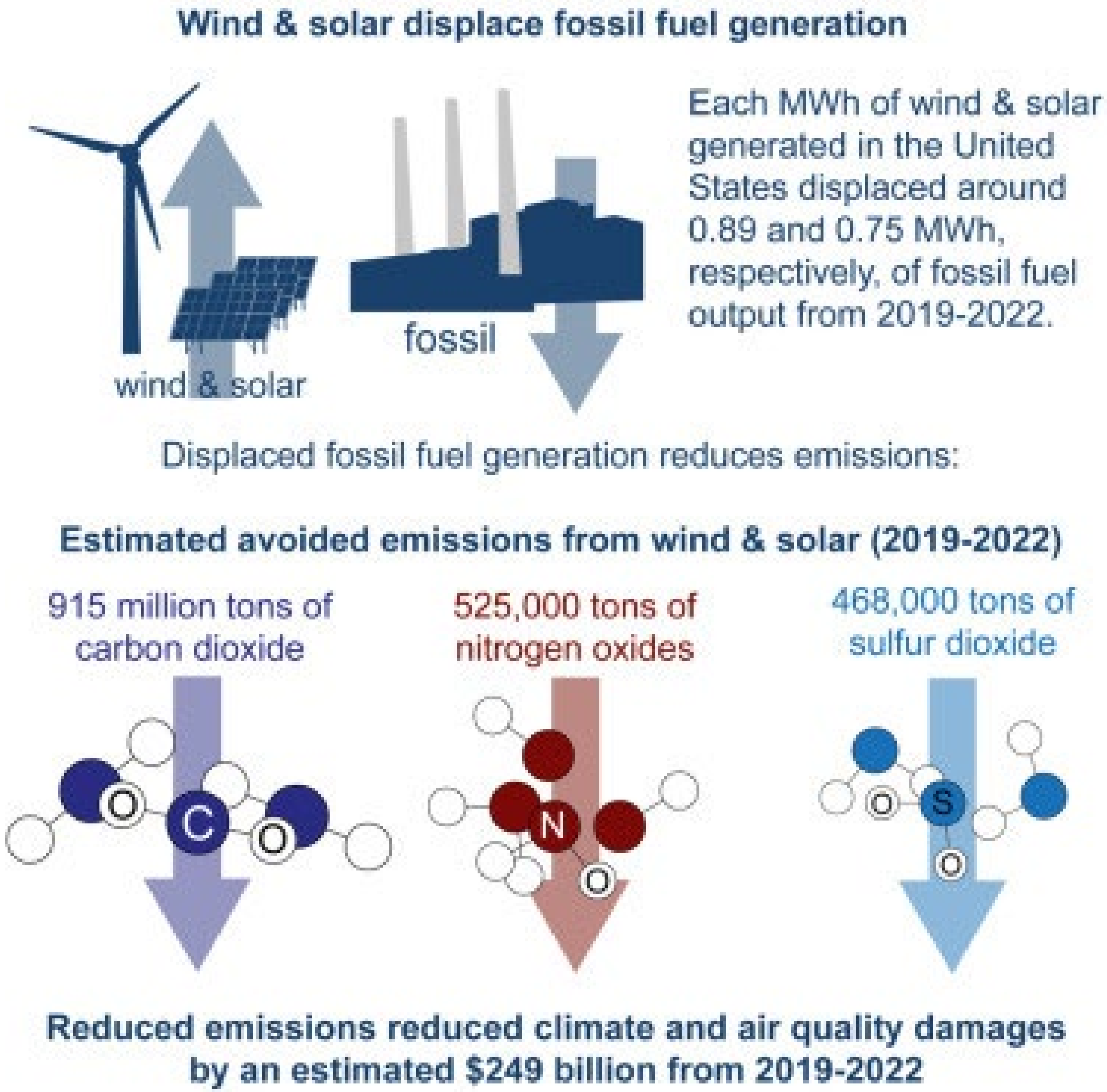


Data source: CEER Benchmarking Report, July 2018

Source: https://www.bmwi-energiewende.de/EWD/Redaktion/Newsletter/2019/05/Meldung/direkt-erfasst_infografik.html

Climate and air quality benefits of wind and solar

- United States wind and solar power cut CO2 emissions by 900 million metric tons from 2019–2022
- This wind and solar power cut SO2 and NOx emissions by 1 million metric tons
- These emission reductions provided $249 billion of climate and health benefits
- The average 2022 climate and health benefits were $143/MWh (wind) and $100/MWh (solar)

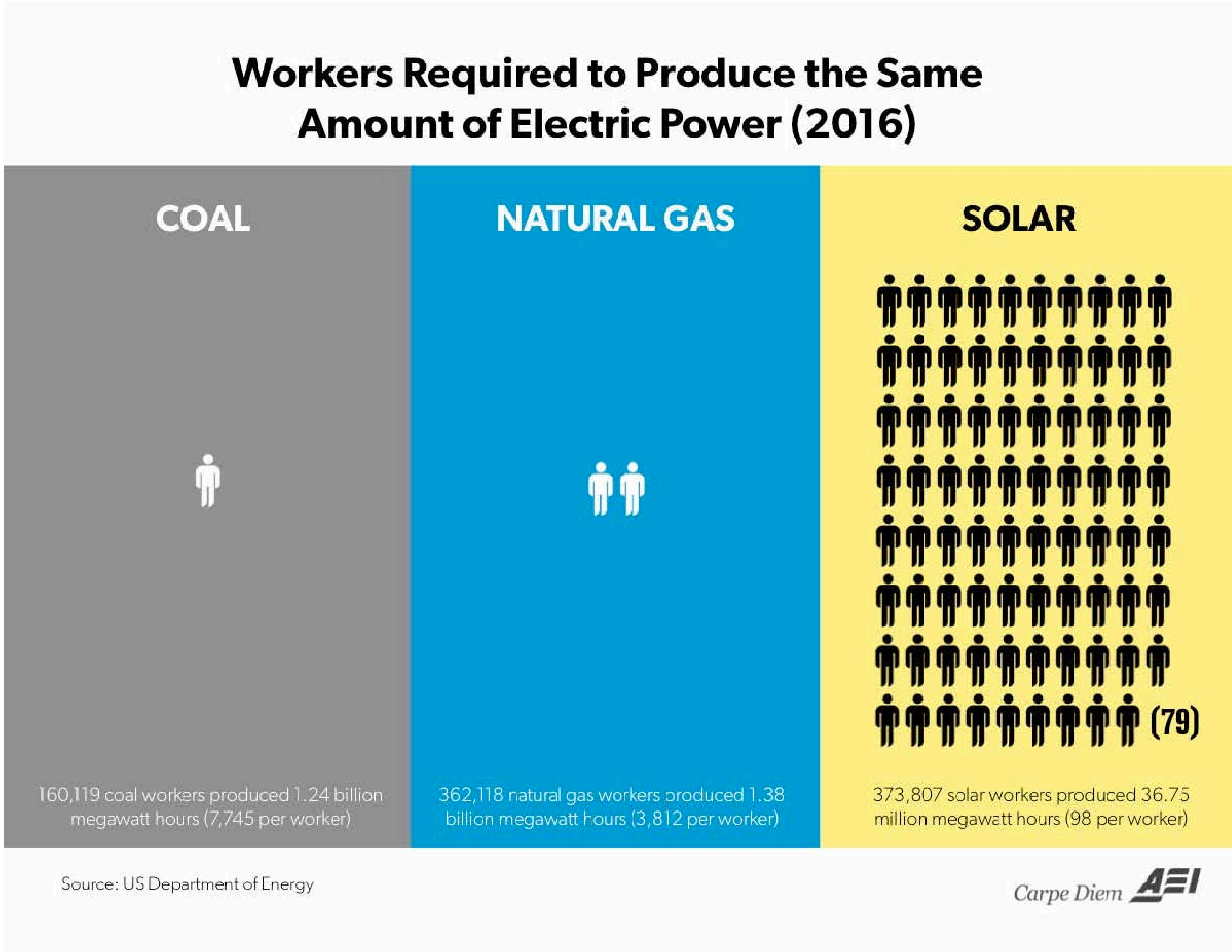


Source: Dev Millstein, Eric O'Shaughnessy, Ryan Wiser: Climate and air quality benefits of wind and solar generation in the United States from 2019 to 2022. Cell Reports Sustainability 2024. DOI:https://doi.org/10.1016/j.crsus.2024.100105

Jobs in Solar

Solar and wind create many more jobs per kWh

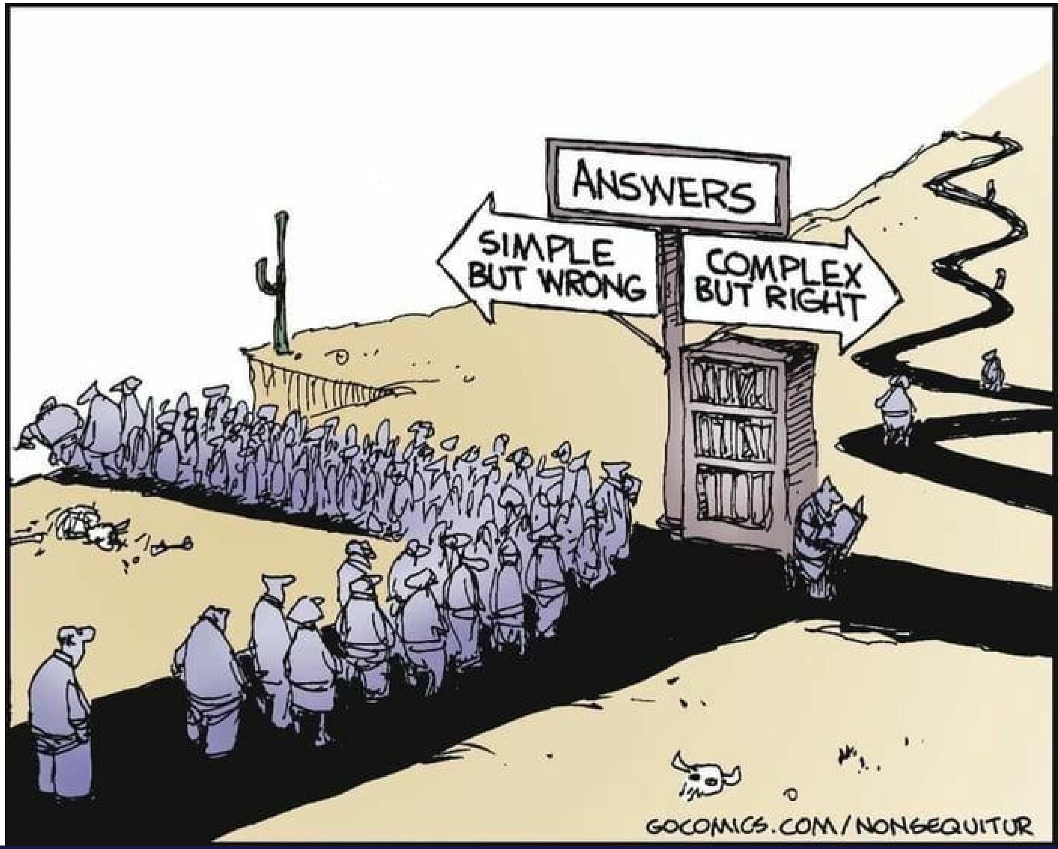
Solar creates more in construction, about same per kWh in operation, wind is less than half (Jacobsen et al 2017)



Data source: US DoE. Graphics from American Enterprise Institute.

Conclusions

- 100% renewables is possible!
- Wind energy is quite impressive engineering
- The coordination of variable generation with demand and storage (and a bit of dispatchable power) is paramount
- We can still get to 2 degC warming



Further resources

Photography encouraged

- Gregor Giebel, grgi@dtu.dk

Tak for opmærksomheden!

- ElectricityMap.org
- IEAWind.org / IEA.org
- IRENA.org
- Energinet.dk
- Ens.dk
- WindEurope.org
- EIA.gov/outlooks/ieo/
- GlobalWindAtlas.info

- Vindenergi.dtu.dk

- sustainabledevelopment.un.org

- www.coursera.org/learn/wind-energy