Cities & renewable energy, part 1 (wind)
MIT 11.165/477, 11.286J

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Urban Studies & Planning
MIT

October 25, 2022

Materials for today

- Mackay's short chapters on renewables: chapters 4,6,8,10,16,18,B, and D from withouthotair.com
- U.S. Department of Energy. Computing Americas Offshore Wind Energy Potential, September 2016. URL.
- U.S. Department of Energy. Simple Levelized Cost of Energy (LCOE) Calculator Documentation — Energy Analysis — NREL. URL.
- Lazard. Lazards Levelized Cost of Energy Analysis, Version 15.0. October 2021. URL.
- William H. Schlesinger. Are wood pellets a green fuel? Science, 359(6382):13281329, March 2018. ISSN 0036-8075, 1095-9203. doi. URL.

Williams et al 2021 decarbonization pathways

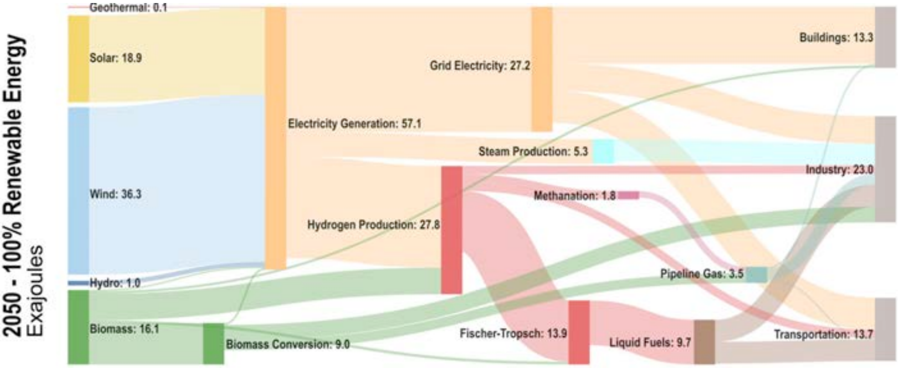

Figure courtesy of John Wiley & Sons. License: CC BY.

Your renewable toolbox

Mackay, sustainable energy:

In the right-hand sustainable-production stack, our main categories will be:

- wind
- solar
  - photovoltaics, thermal, biomass
- hydroelectric
- wave
- tide
- geothermal
- nuclear? (with a question-mark, because it's not clear whether nuclear power counts as "sustainable")

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- clean, net-zero, or carbon-free?
- energy efficiency: technologies, products, and services that reduce the energy required for processes or tasks

Your renewable toolbox

Key limitations:

1. total potential
2. intermittency
3. land use / take

Wind:

http://hint.fm/wind/
http://earth.nullschool.net/

Your renewable toolbox

Deploying these at scale requires building a new energy system:

Building blocks:

- solar

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To do list:

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- reliability
- resilience
- siting

Agenda for the next few classes

- wind basics: capacity factors

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- wind basics: capacity factors
- solar basics: adoption costs, learning curves, siting issues
- storage and geothermal: developing new niches

Renewable energy potential – what is it?

Potential amount of this renewable resource that can be generated.

International Renewable Energy Agency (IRENA)

- founded 2009
- specifically focused on renewables
- http://www.irena.org/potential_studies/
- over 10,000 studies on five major categories

Our World in Data, updated 2021

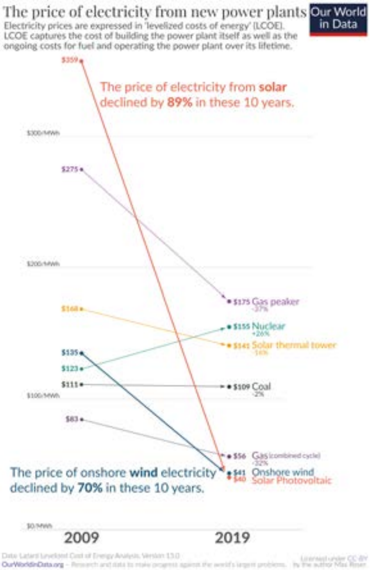

Figure by Max Roser, courtesy of Our World in Data. License: CC BY.

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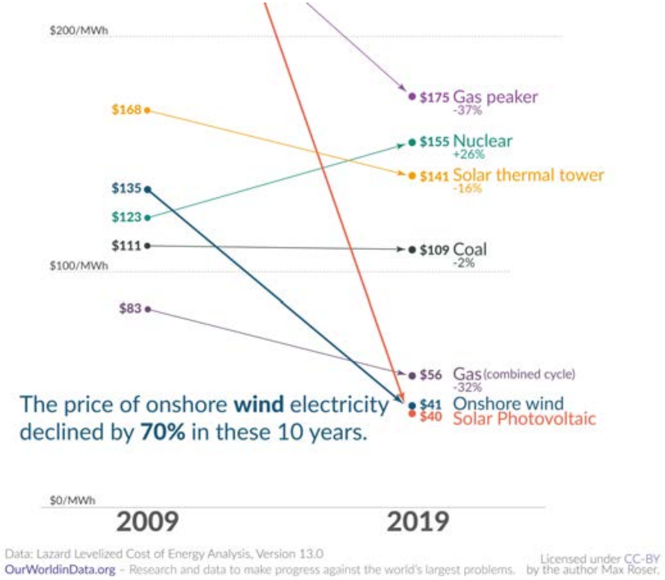
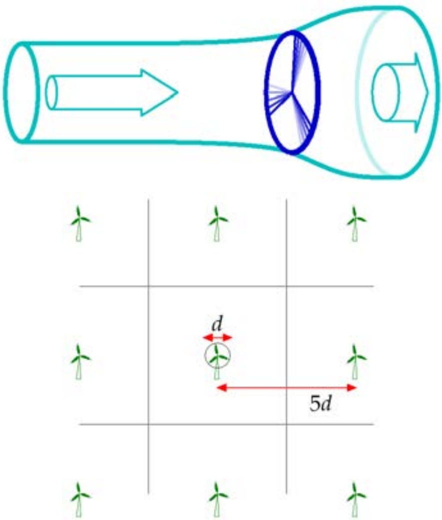


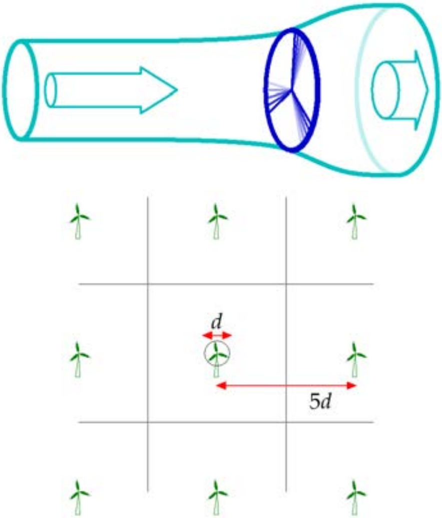
From Our World in Data

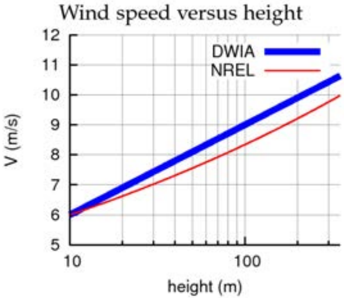
Wind II in Mackay

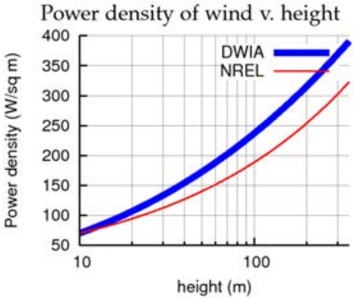


Courtesy of David MacKay.

Wind II in Mackay

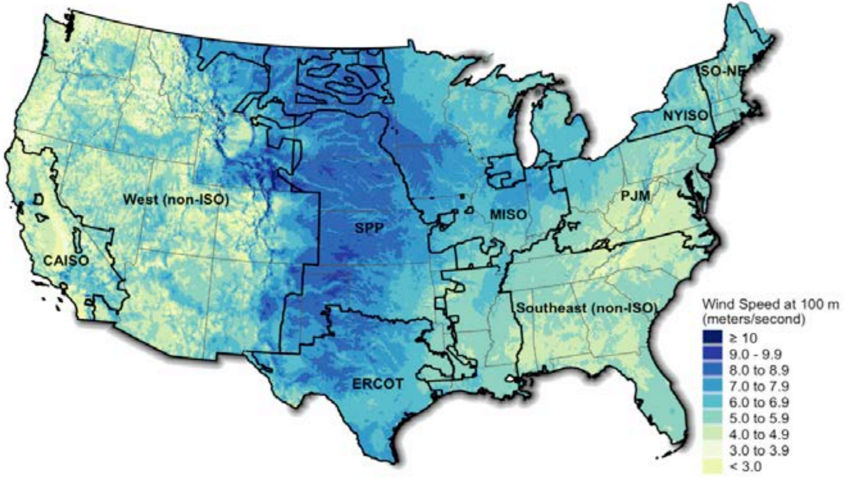






Courtesy of David MacKay.

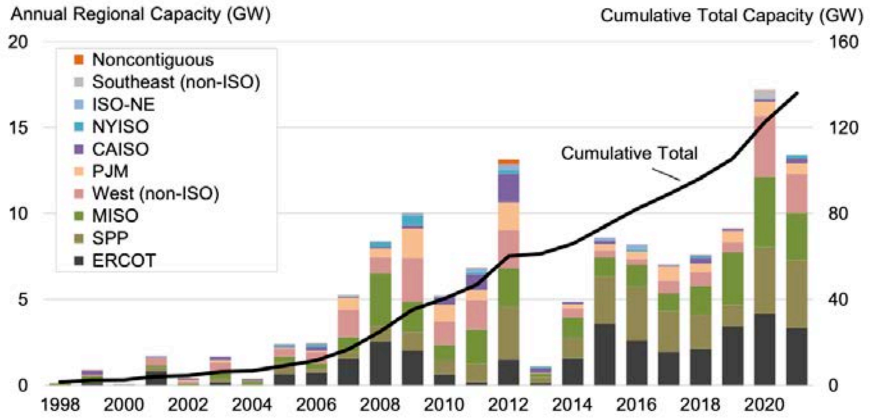
DOE Land-Based Wind Market Report 2022



Sources: AWS Truepower, National Renewable Energy Laboratory (NREL)

Figure 1. Regional boundaries overlaid on a map of average annual wind speed at 100 meters

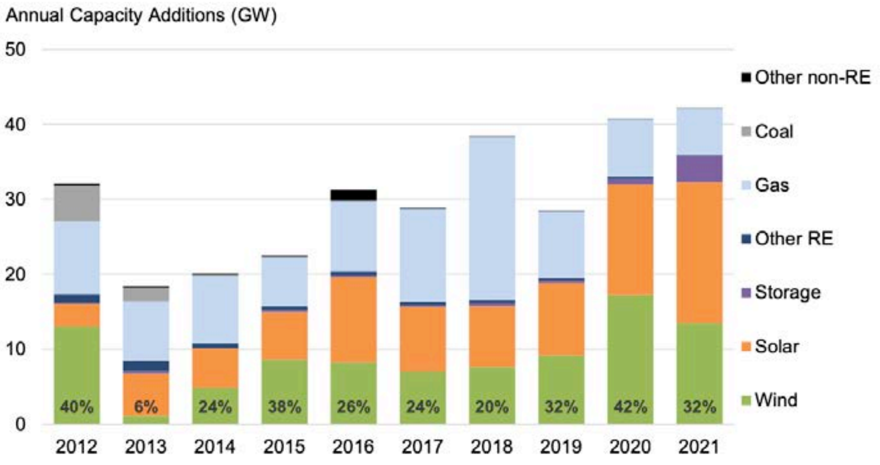
DOE Land-Based Wind Market Report 2022



Source: ACP

Figure 2. Annual and cumulative growth in U.S. wind power capacity

DOE Land-Based Wind Market Report 2022



Sources: Hitachi, ACP, EIA, Berkeley Lab

Figure 3. Relative contribution of generation types and storage to U.S. annual capacity additions

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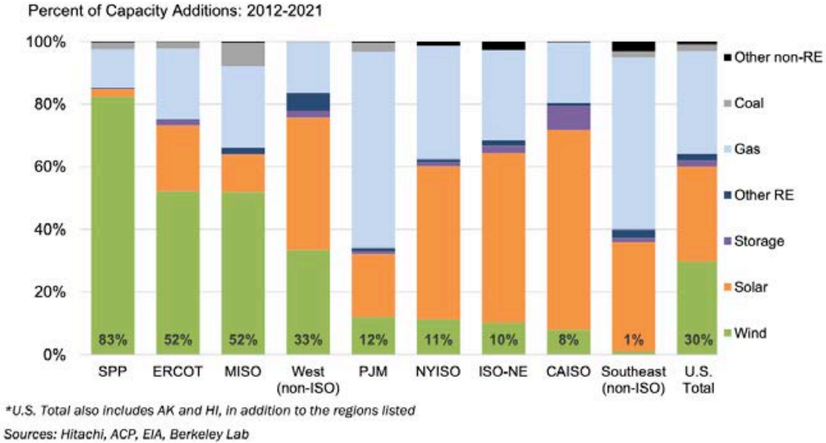

Figure 4. Generation and storage capacity additions by region over last ten years

Public domain content courtesy of US Department of Energy.


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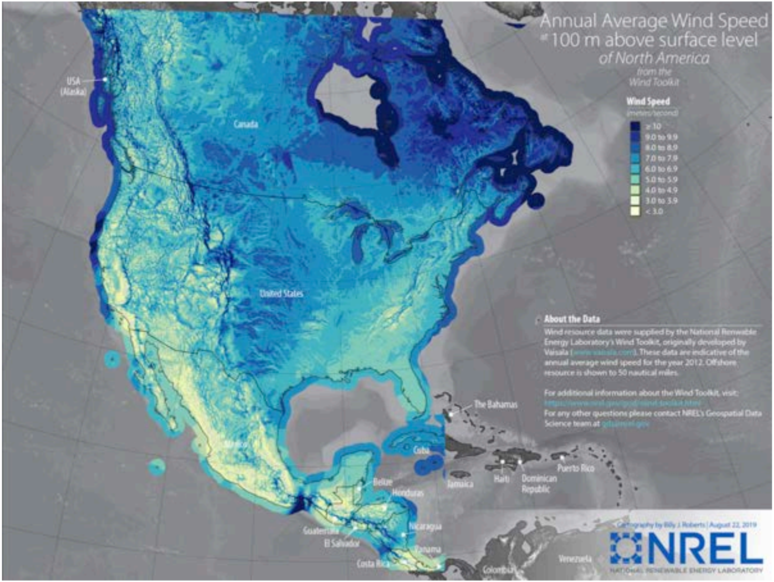
Public domain image courtesy of NREL / US Department of Energy.



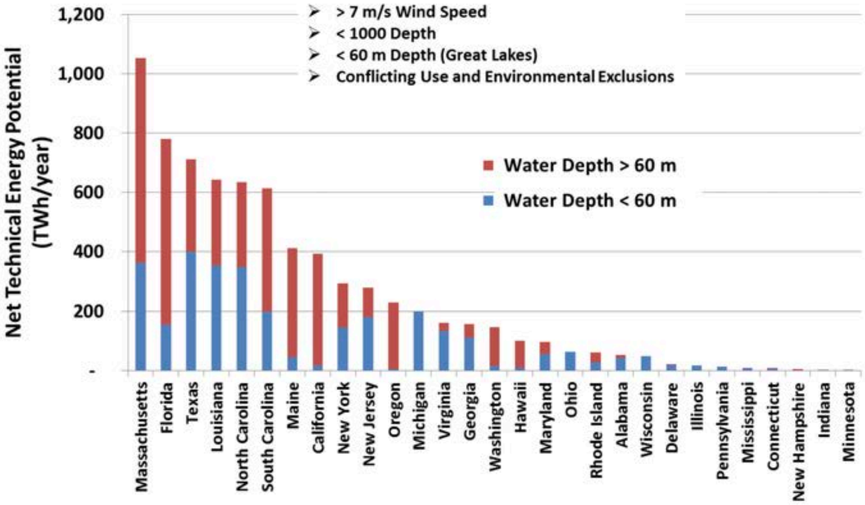
NREL Wind Atlas

Public domain image courtesy of Josh Bauer, NREL.

Floating wind turbines

Joshua Bauer, NREL

NREL Technical Potential



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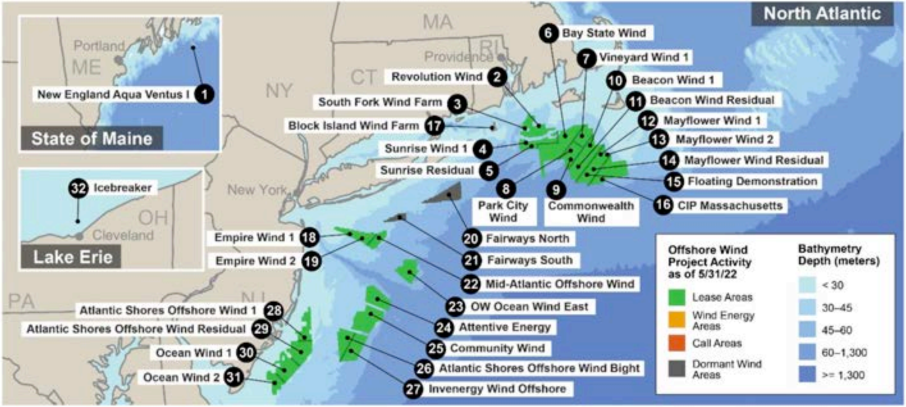

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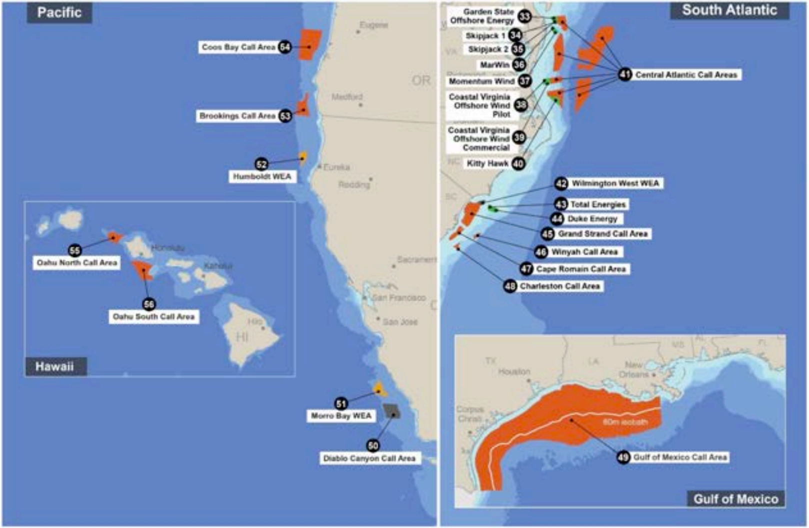


Figure ES-1. Locations of U.S. offshore wind pipeline activity and Call Areas as of May 31, 2022. ***Map created by NREL***

DOE Offshore Wind Market Report 2022

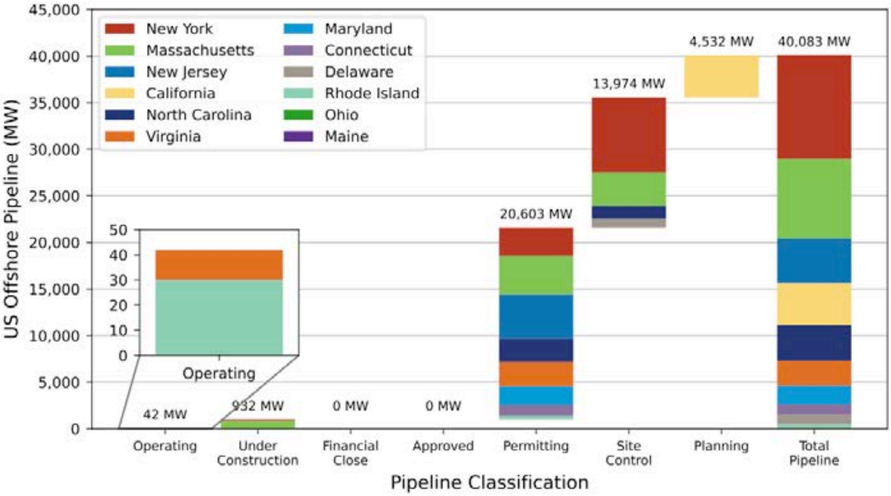


Figure 1. U.S. project pipeline classification by status

DOE Offshore Wind Market Report 2022

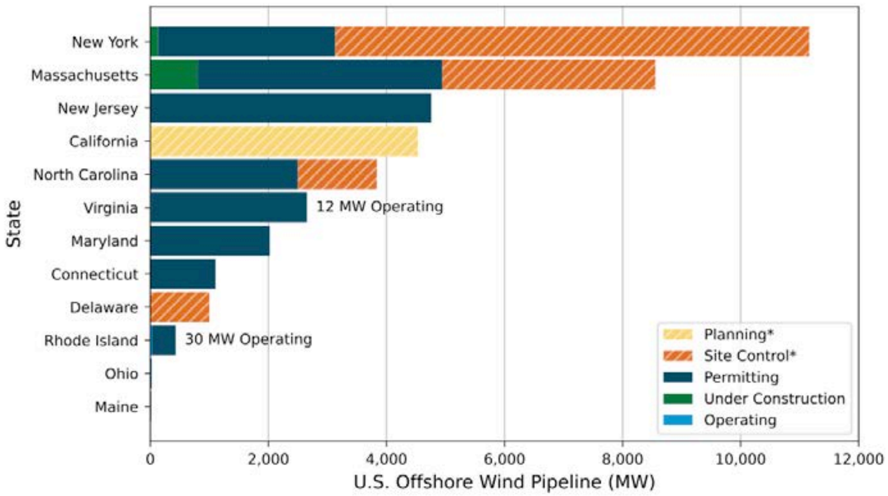
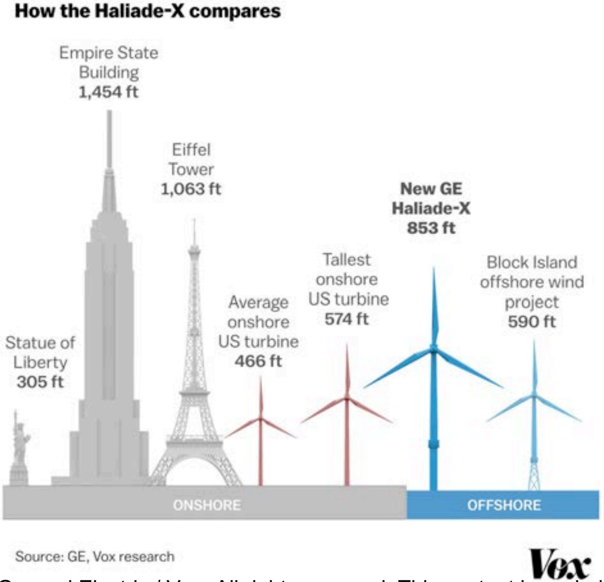
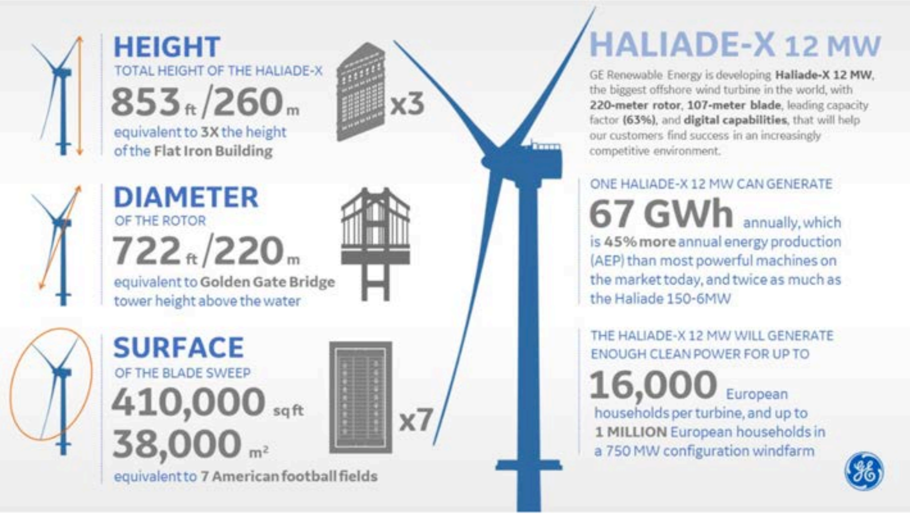


Figure 2. U.S. project pipeline by state

How big are wind turbine blades, really?




HEIGHT
TOTAL HEIGHT OF THE HALIADE-X
853 ft /260 m
equivalent to 3X the height of the Flat Iron Building
x3
DIAMETER
OF THE ROTOR
722 ft /220 m
equivalent to Golden Gate Bridge tower height above the water
SURFACE
OF THE BLADE SWEEP
410,000 sq ft
38,000 m²
equivalent to 7 American football fields
x7
HALIADE-X 12 MW
GE Renewable Energy is developing Haliade-X 12 MW, the biggest offshore wind turbine in the world, with 220-meter rotor, 107-meter blade, leading capacity factor (63%), and digital capabilities, that will help our customers find success in an increasingly competitive environment.
ONE HALIADE-X 12 MW CAN GENERATE
67 GWh annually, which is 45% more annual energy production (AEP) than most powerful machines on the market today, and twice as much as the Haliade 150-6MW
THE HALIADE-X 12 MW WILL GENERATE ENOUGH CLEAN POWER FOR UP TO
16,000 European households per turbine, and up to 1 MILLION European households in a 750 MW configuration windfarm

12 MW capacity
220-meter rotor
107-meter long blades
260 meters high
67 GWh gross AEP
63% capacity factor
38,000 m² swept area
Wind Class IEC: IB
Generates double the energy as previous GE Haliade model
Generates almost 45% more energy than most powerful wind turbine available on the market today
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1063 ft
324 m
853 ft
260 m
1046 ft
319 m
Eiffel Tower
Haliade-X 12 MW
Chrysler Building

Really* fun wind stuff to look at

GE Haliade-X, 12 MW turbine
Vox article on wind turbine blades, 5/20/19
DOE segmented blades
Boeing wing test
Columbia Energy Exchange podcast on offshore wind

Intermittency / capacity factor

Capacity factor: ratio of actual power produced / maximum possible power over a period of time.

- unit-less (%)
- empirically determined in real life operation
- changes seasonally

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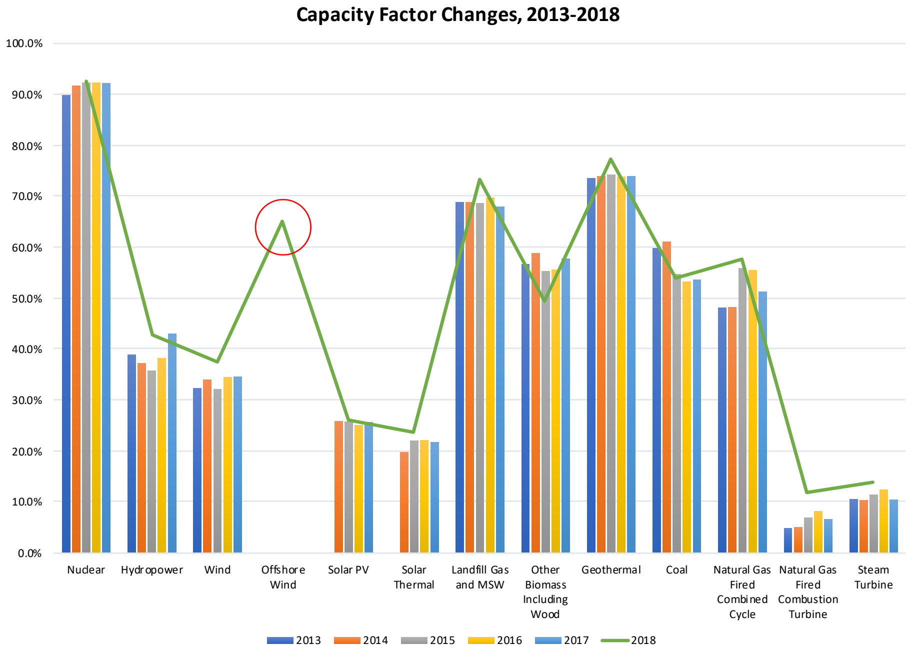
Nameplate generation capacity: determined by manufacturer

- coal-fired power plant
- natural gas turbine
- 200 W solar panel
- 12 MW wind turbine

EIA Electric Power Monthly: Tables 6.07A for fossil, 6.07B for non-fossil


Capacity Factor Changes, 2013-2018
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Nuclear
Hydropower
Wind
Offshore Wind
Solar PV
Solar Thermal
Landfill Gas and MSW
Other Biomass Including Wood
Geothermal
Coal
Natural Gas Fired Combined Cycle
Natural Gas Fired Combustion Turbine
Steam Turbine
2013
2014
2015
2016
2017
2018

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sLCOE = fixed costs + fuel costs + variable operations & maintenace

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$$\text{sLCOE} = \frac{\text{capital cost} \times \text{recovery factor} + \text{fixed O\&M}}{8760 \times \text{capacity factor}}$$

Levelized Cost of Energy (LCOE)

sLCOE = fixed costs + fuel costs + variable operations & maintenace

$$\begin{aligned} \text{sLCOE} &= \frac{\text{capital cost} \times \text{recovery factor} + \text{fixed O\&M}}{8760 \times \text{capacity factor}} \\ &+ \text{fuel cost} \times \text{heat rate} \end{aligned}$$

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&+ \text{fuel cost} \times \text{heat rate} \\
&+ \text{variable O\&M costs}
\end{aligned}
$$

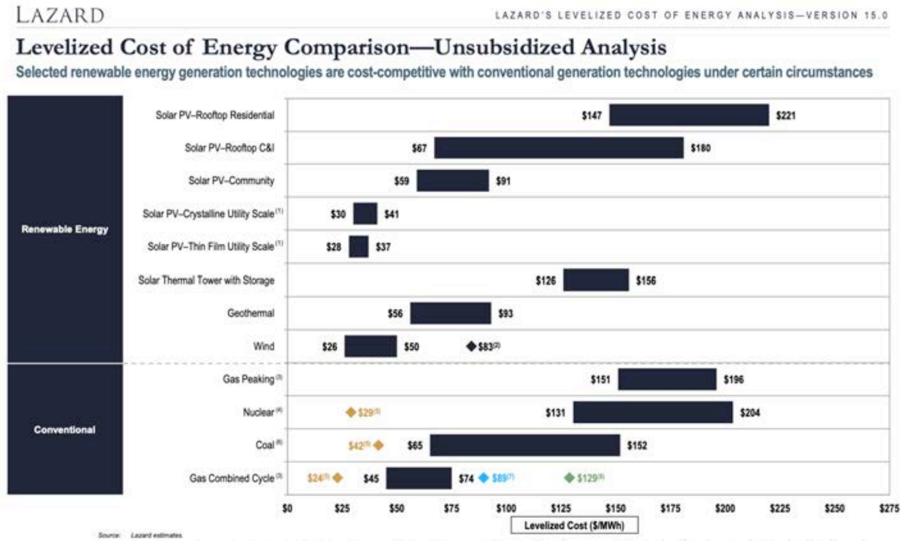
Wikipedia: "Levelized cost of energy"

The levelized cost of electricity (LCOE) is given by:

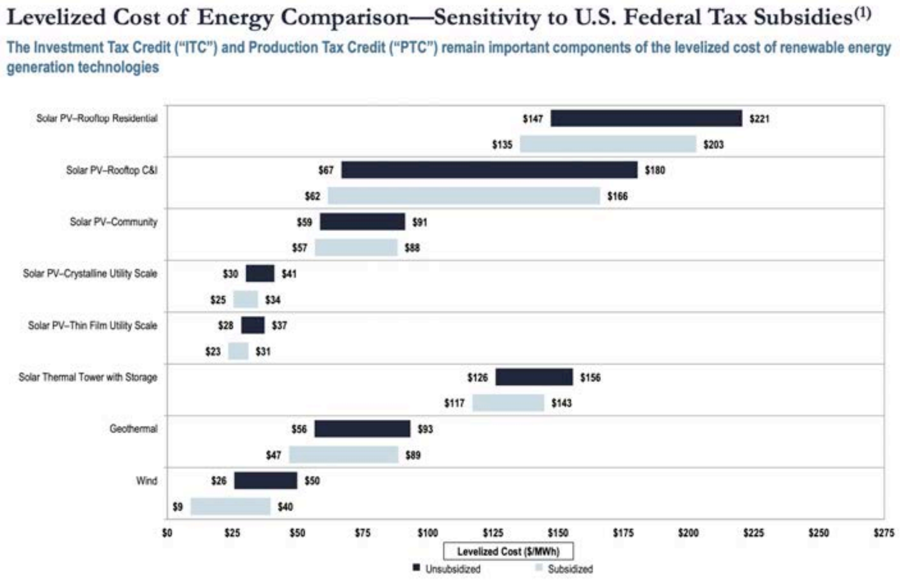
$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

- I_t : investment expenditures in the year t
- M_t : operations and maintenance expenditures in the year t
- F_t : fuel expenditures in the year t
- E_t : electrical energy generated in the year t
- r : discount rate
- n : expected lifetime of system or power station

Note: Some caution must be taken when using formulas for the levelized cost, as they often embody unseen assumptions, neglect effects like taxes, and may be specified in real or nominal levelized cost. For example, other versions of the above formula do not discount the electricity stream.[citation needed]



Lazard's Levelized Cost of Energy Analysis, v15, 2021



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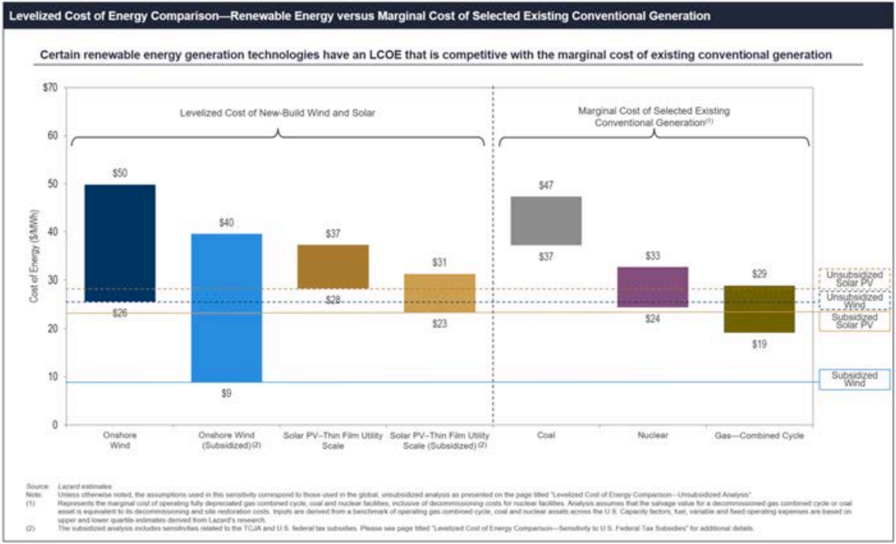

Lazard's Levelized Cost of Energy Analysis, v15, 2021

Thank you!