Fundamentals of Wind Energy

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Background

This slide deck was developed for and presented at an Energy Fundamentals Course hosted by the Bangladesh University of Engineering and Technology (BUET) in October 2022. The National Renewable Energy Laboratory (NREL) helped organize this course in partnership with the United States Agency for International Development (USAID). The students in this four-day course were postgraduates and working professionals in the energy sector or related industries in Bangladesh. While some of the content in the slide deck is tailored to Bangladesh specifically, this presentation is intended to be a general primer on wind energy that can be utilized for similar purposes by other universities or organizations throughout the world. The content of this slide deck is not intended to be fully comprehensive of all wind energy concepts.

Outline

1. Wind Energy Trends

a. Installations
b. Costs
c. Technology

2. Wind Technology Basics

a. Attributes & components
b. Utility-scale & distributed
c. Onshore & offshore

3. Wind Siting

a. Resource data
b. Land considerations
c. Interconnections

Image: Joshua Bauer (NREL)

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Installation Trends

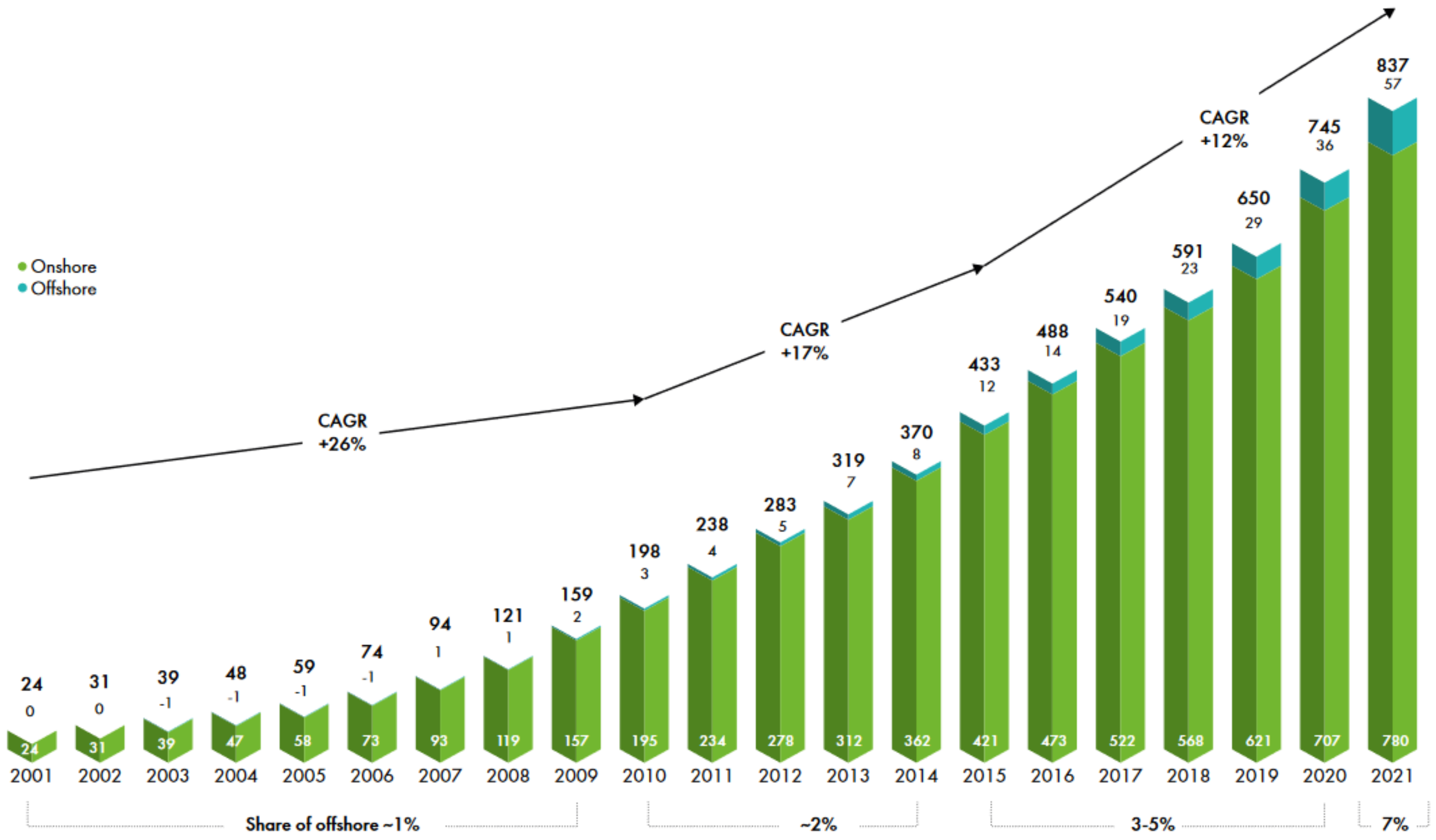
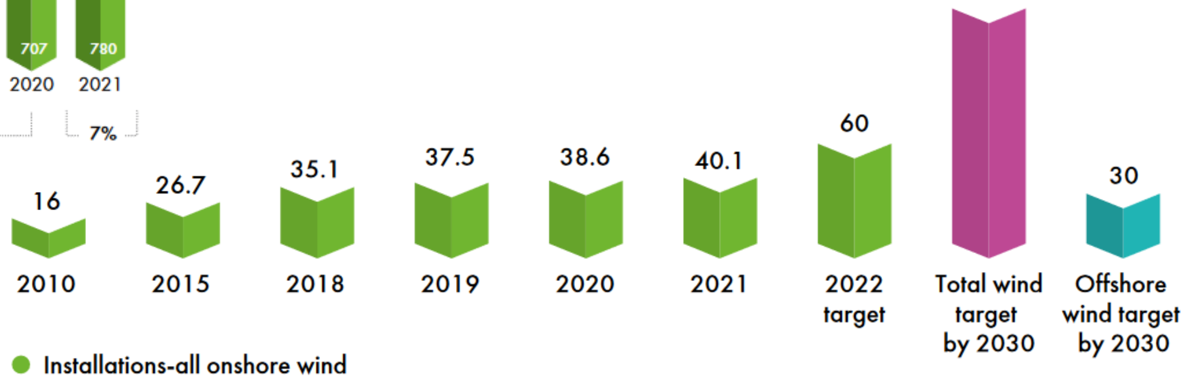


Figure. Global installed capacity of wind (GW), 2001-2021

Source: Global Wind Energy Council (2022)

Figure. India installed capacity of wind (GW) and targets, 2010-2030



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Market Share by Region

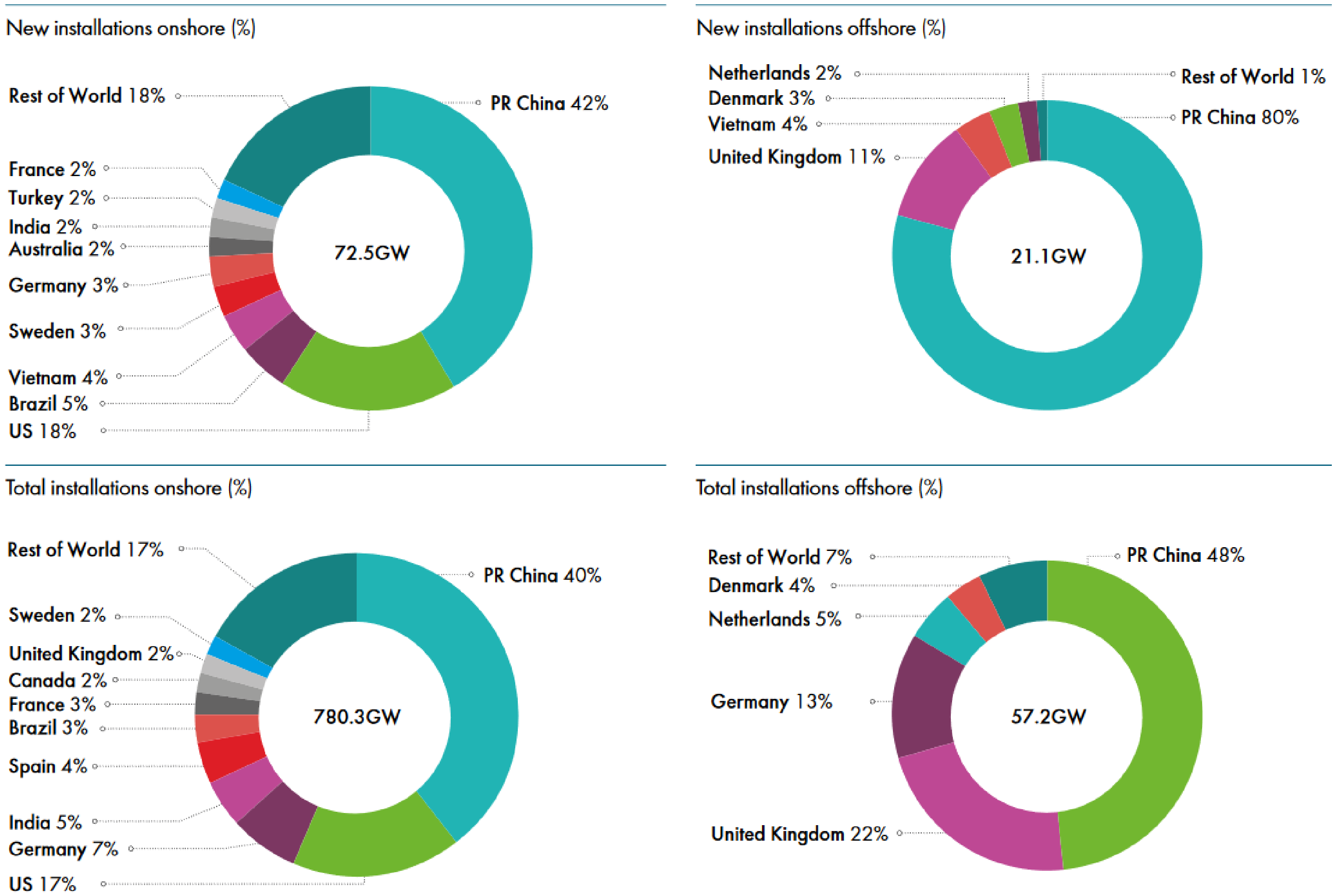

Figure. Percentage of new and total onshore and offshore wind installations by country (2021)

Source: Global Wind Energy Council (2022)

Levelized Cost of Electricity (LCOE) Comparison

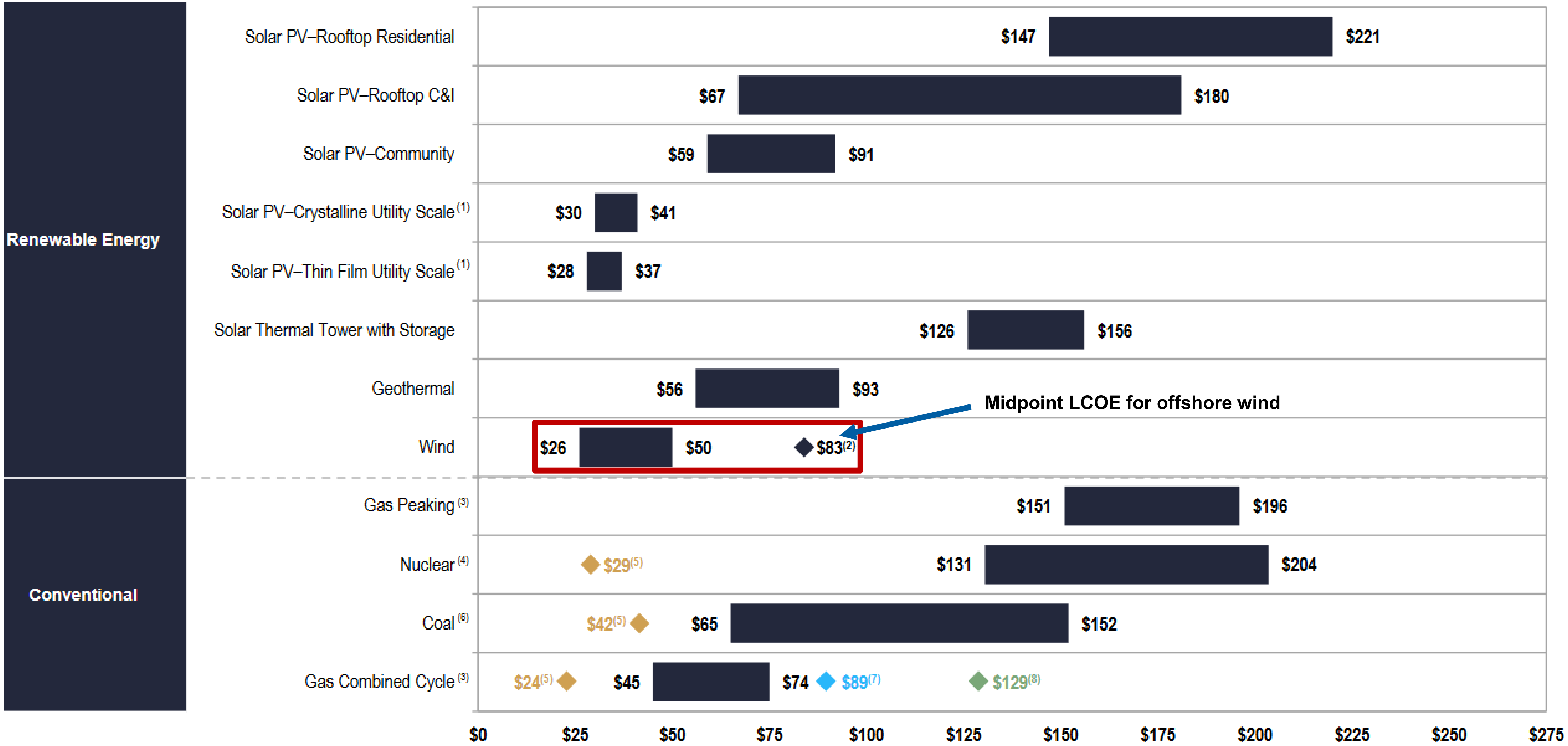

Figure. Unsubsidized levelized cost of electricity (LCOE) in $/MWh, 2021

Source: Lazard (2021)

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Cost Trends and Projections

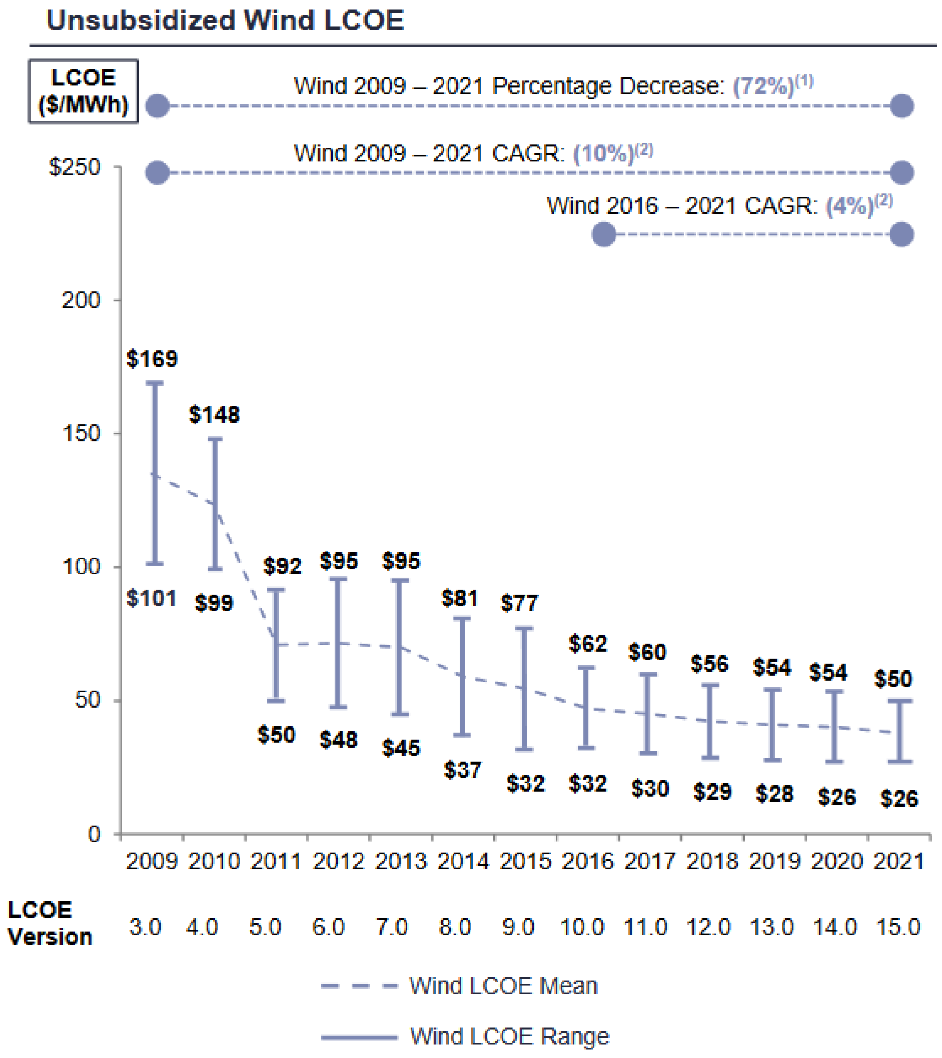

Figure. Unsubsidized wind LCOE ($/MWh), 2009-2021

Source: Lazard (2021)

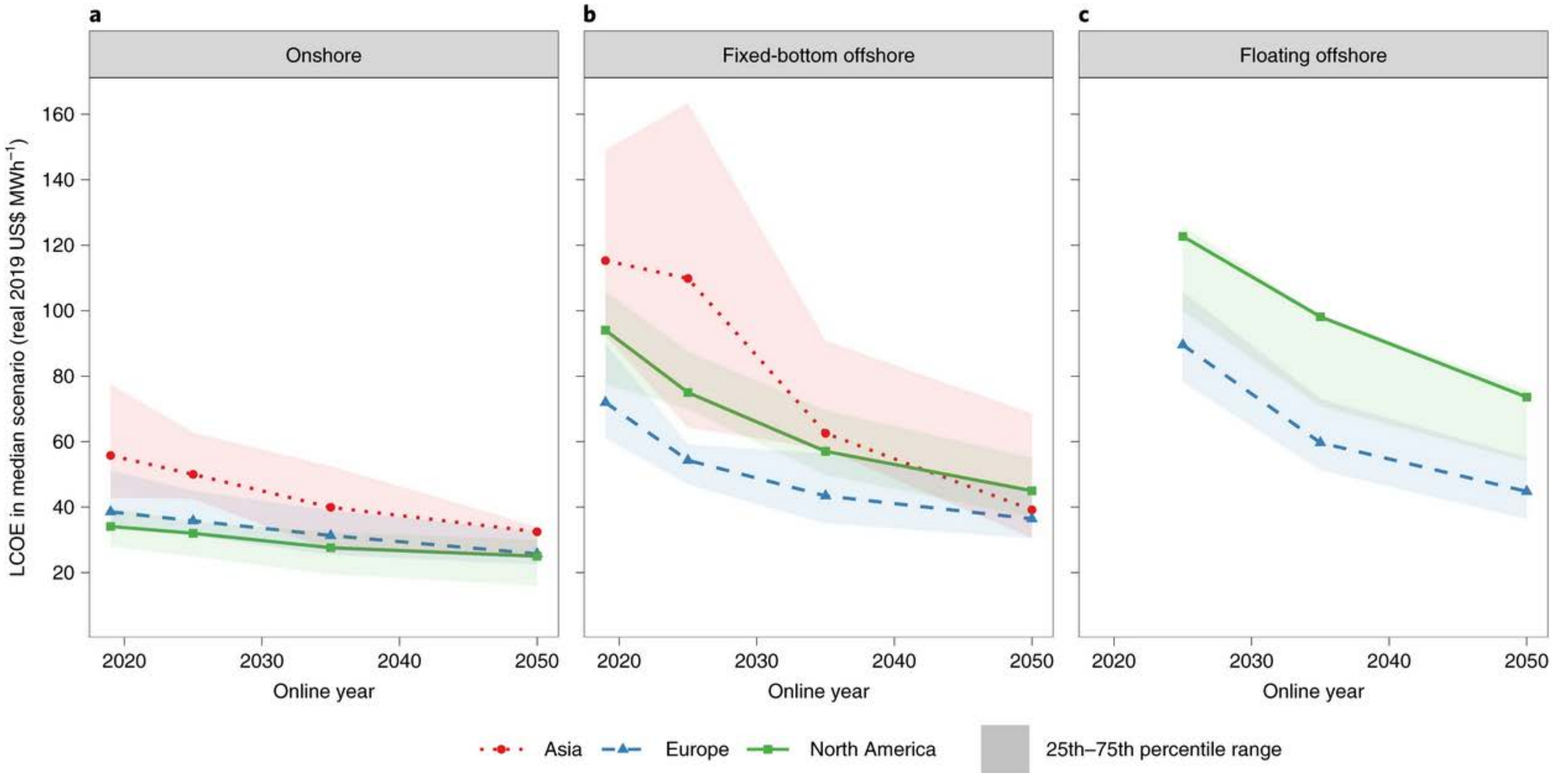

Figure. Median-scenario wind LCOE projections from 2020 survey of experts, 2021-2050

Source: Wiser et al. (2021)

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Technology Trends

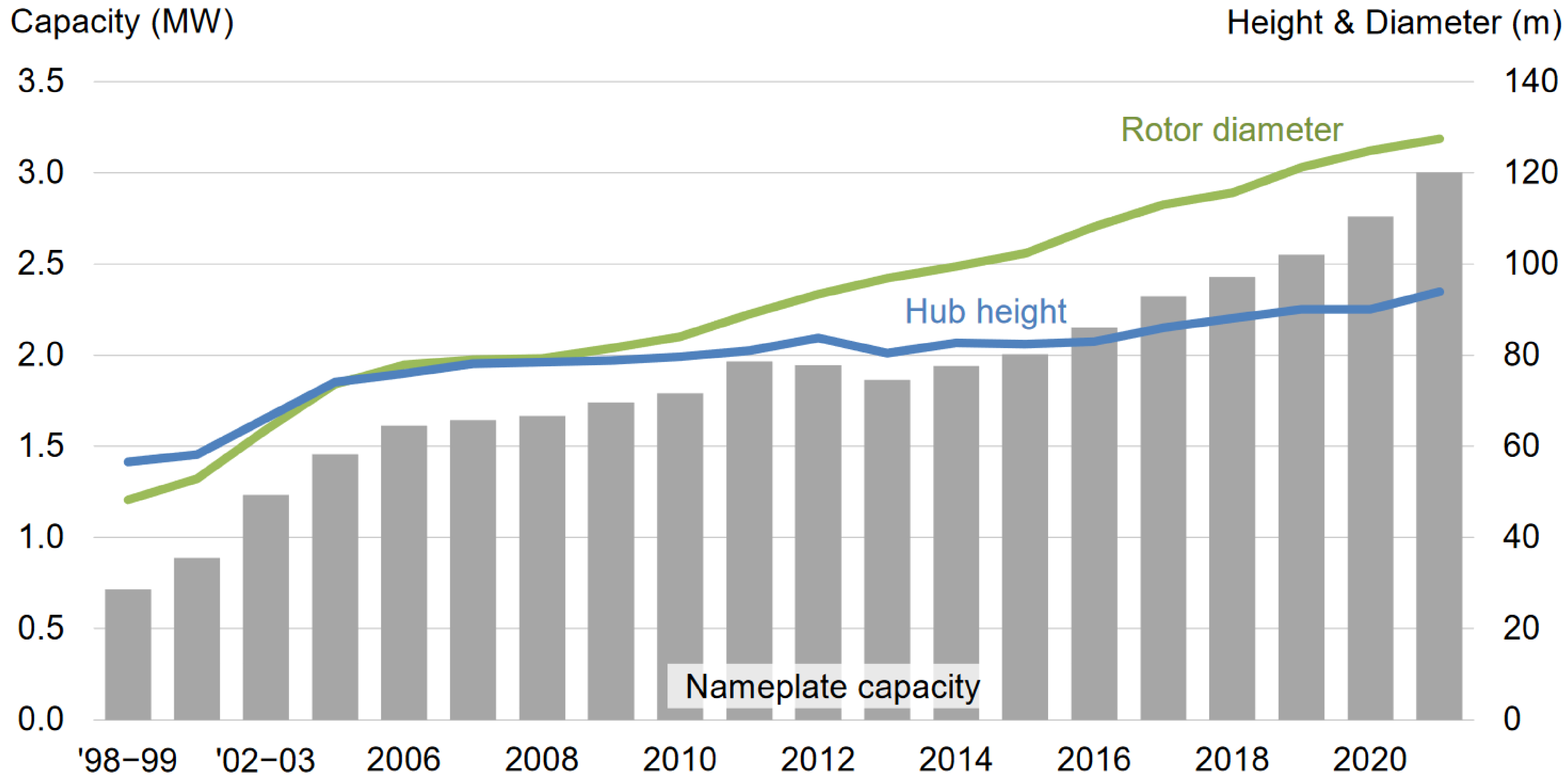

Figure. Trends in wind turbine technology for onshore utility-scale projects, 1998-2021

Source: U.S. Department of Energy (2022)

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Power from Wind

$$P_{wind} = E\frac{1}{2}\rho A v^3$$

P_{wind} = power extracted from wind
E = efficiency of the turbine
ρ = density of the air
A = swept area of the turbine = πr^2
r = radius of the rotor
v = wind speed

Greater power extraction:

Increase in rotor radius (r) results in larger swept area (A)

Increase in turbine height allows access to lower density air (ρ) and higher wind speeds (v)

Turbine Power Curves

Cut-In Speed: Speed below which power is not generated

Rated Wind Speed: Speed at which power is 100% of rated power

Cut-Out Speed: Speed at which turbine shuts down to protect rotor and drive train from damage

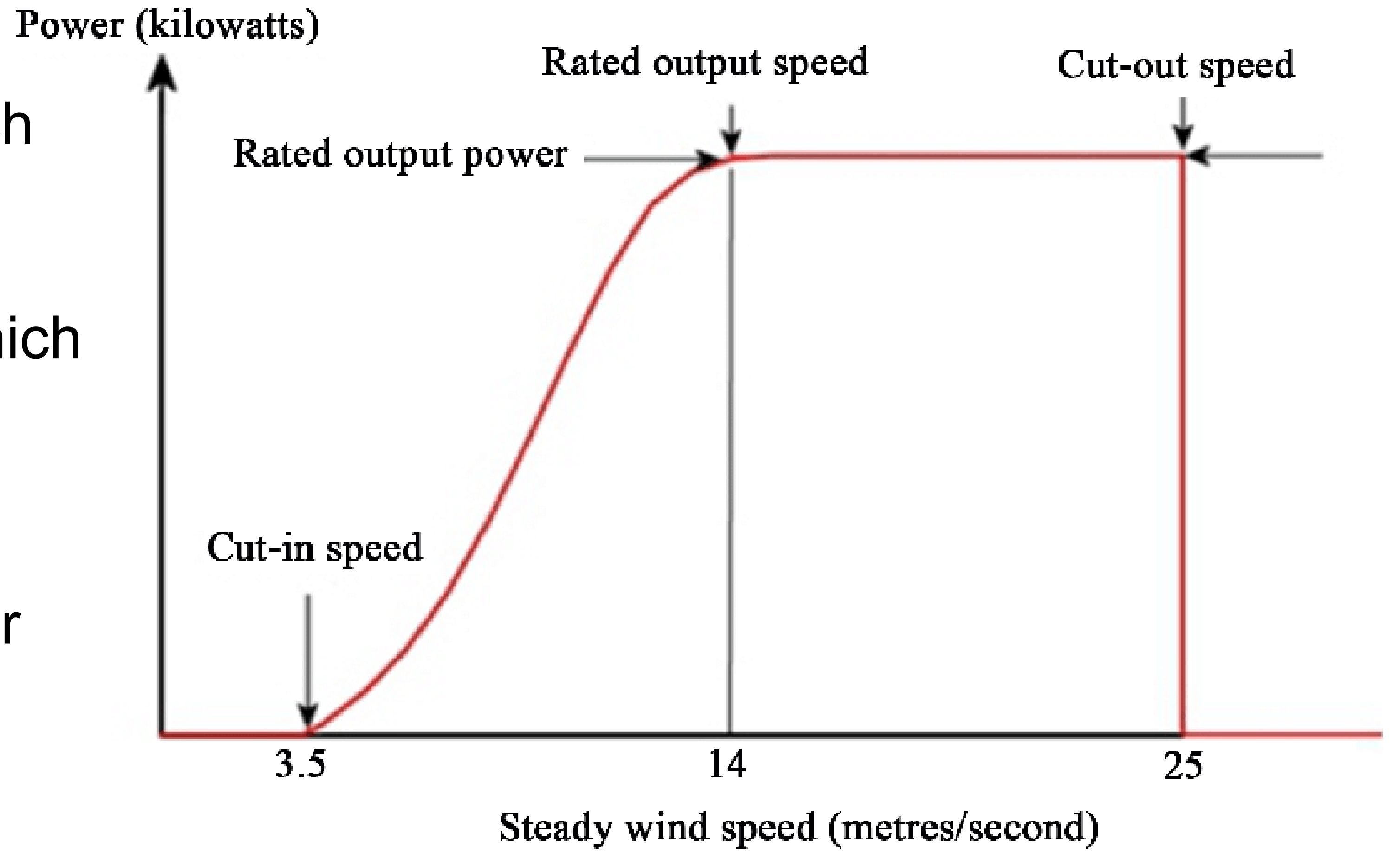

Figure. Example power curve for a wind turbine

Source: Monnerie et al. (2015)

Wind Turbine Components

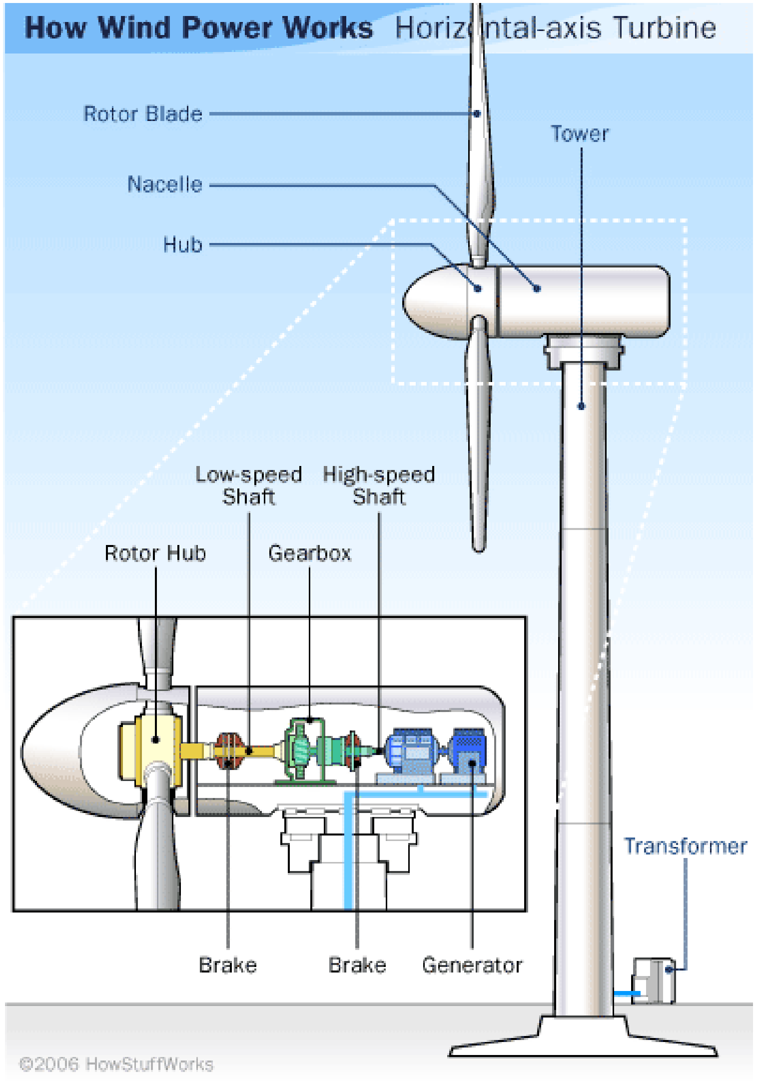

Figure. Wind turbine components

Image: HowStuffWorks (2006)

Figure. Wind turbine blade testing facility in Massachusetts, U.S.A

Image: NREL

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Utility-Scale vs. Distributed Wind

Utility-scale: "Dozens or hundreds of large-scale (>1 MW) wind turbines in the same location and connected to the transmission system, with a total capacity typically over 20 MW."

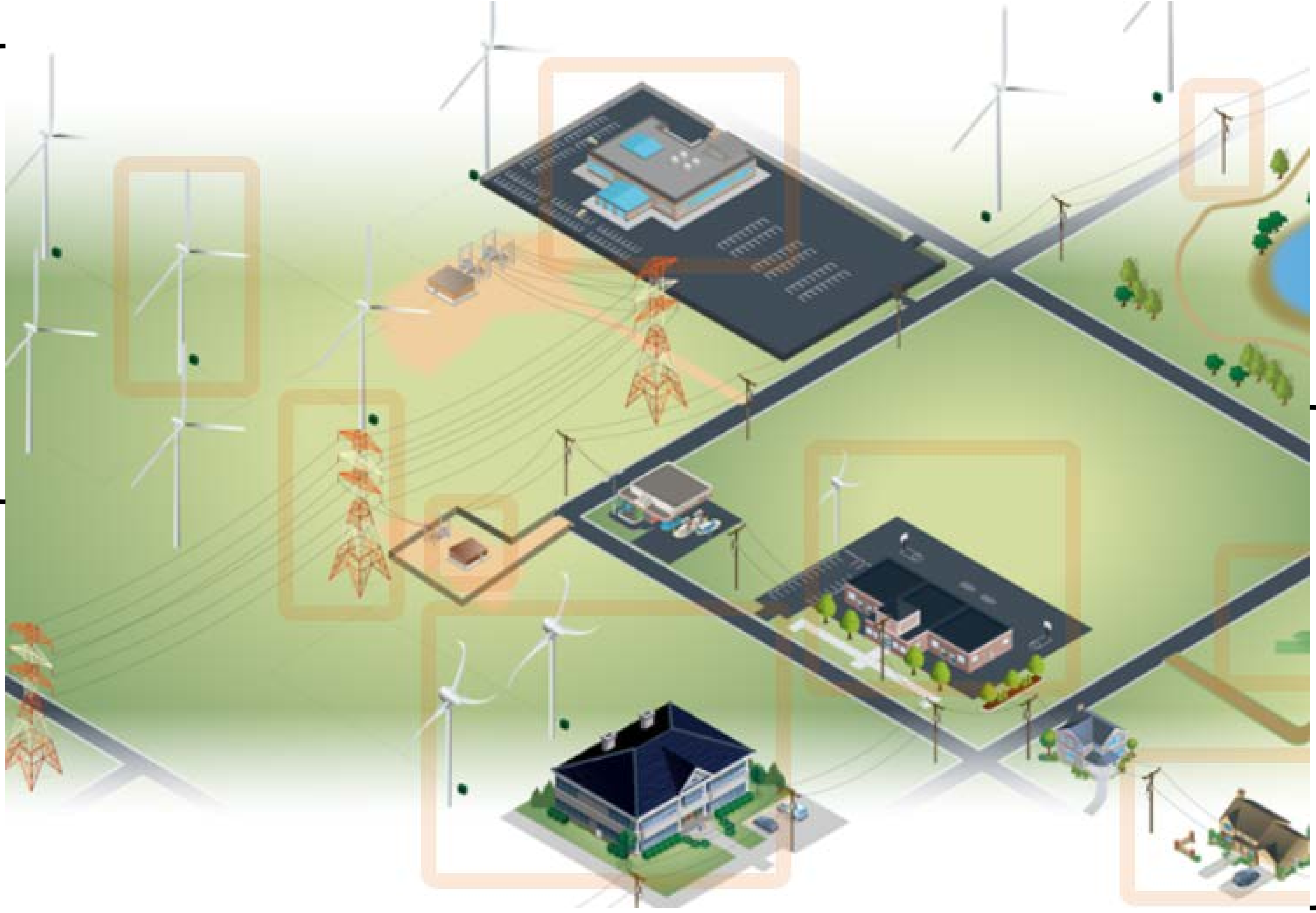

Figure. System with utility-scale and distributed wind

Distributed: "One or several wind turbines in the same location and connected to the distribution system or off-grid to serve specific or local loads."

Source: U.S. Department of Energy (2022)

Distributed Wind

Figure. Distributed wind turbine size classifications

Small
(≤100 kW)

Mid-size
(101 kW–1 MW)

Large-scale
(>1 MW)

Images: Bergey Windpower, Ian Baring-Gould (NREL), and Warren Getz (NREL)

Applications

- Isolated grids (e.g., villages, island communities, military bases, etc.)
- Backup power for normally grid-connected systems (e.g., cell towers)
- Microgrids that can connect and disconnect from the main distribution system
- Industrial facilities
- Academic and commercial campuses
- Residences and farms

Source: Reilly et al. (2021)

Onshore vs. Offshore Wind

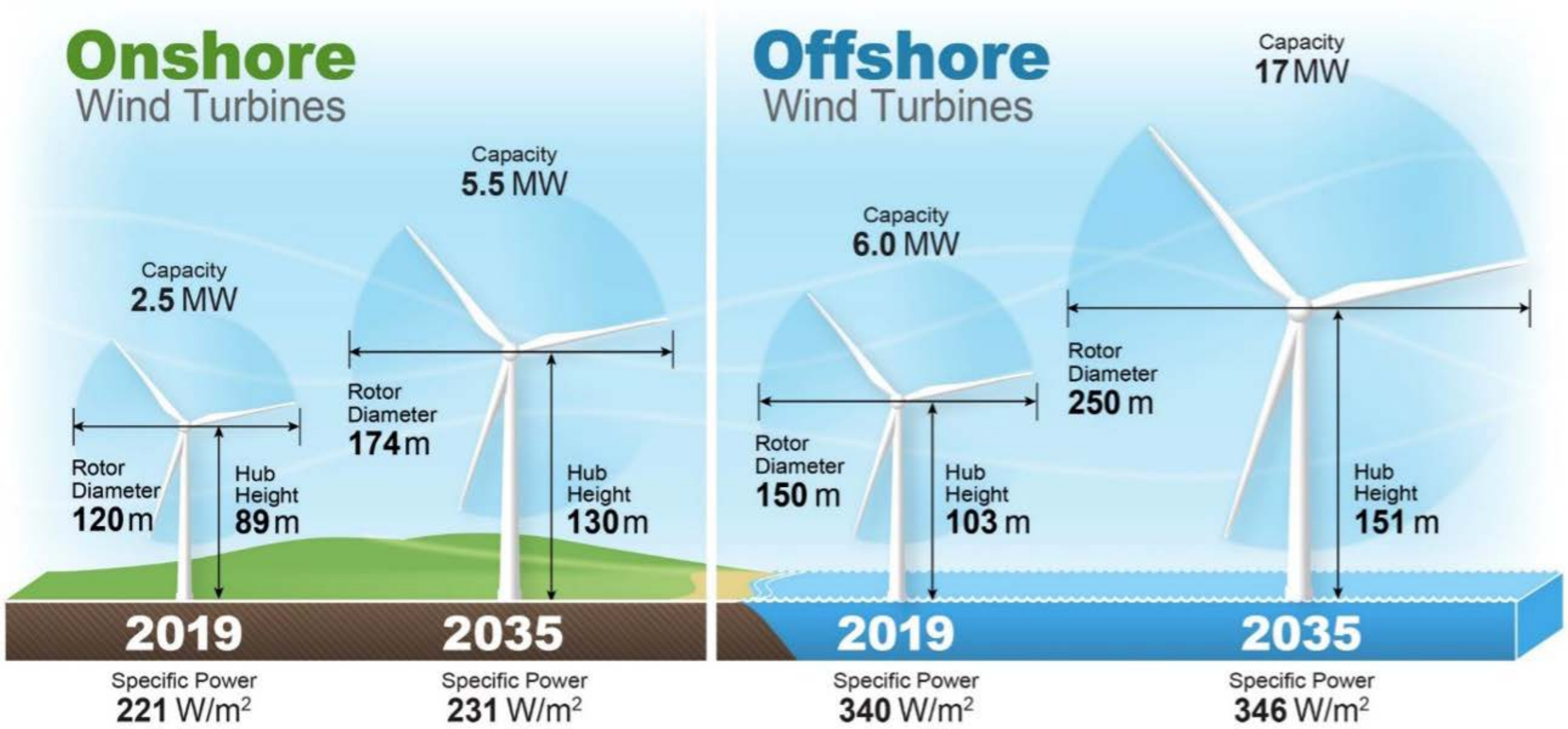

Figure. Current and projected characteristics for onshore and offshore wind turbines

Image: Lawrence Berkeley National Lab

Image: Dennis Schroeder (NREL)

- Offshore wind turbines have higher hub heights and larger rotor diameters.
- Wind speeds are typically higher, more consistent, and less turbulent offshore.
- Offshore wind farms are not constrained by land availability but have separate permitting considerations.
- Barriers to offshore wind include a lack of supporting infrastructure (vessels, cranes, ports), difficult construction conditions, and higher costs.

Source: Beiter et al. (2021)

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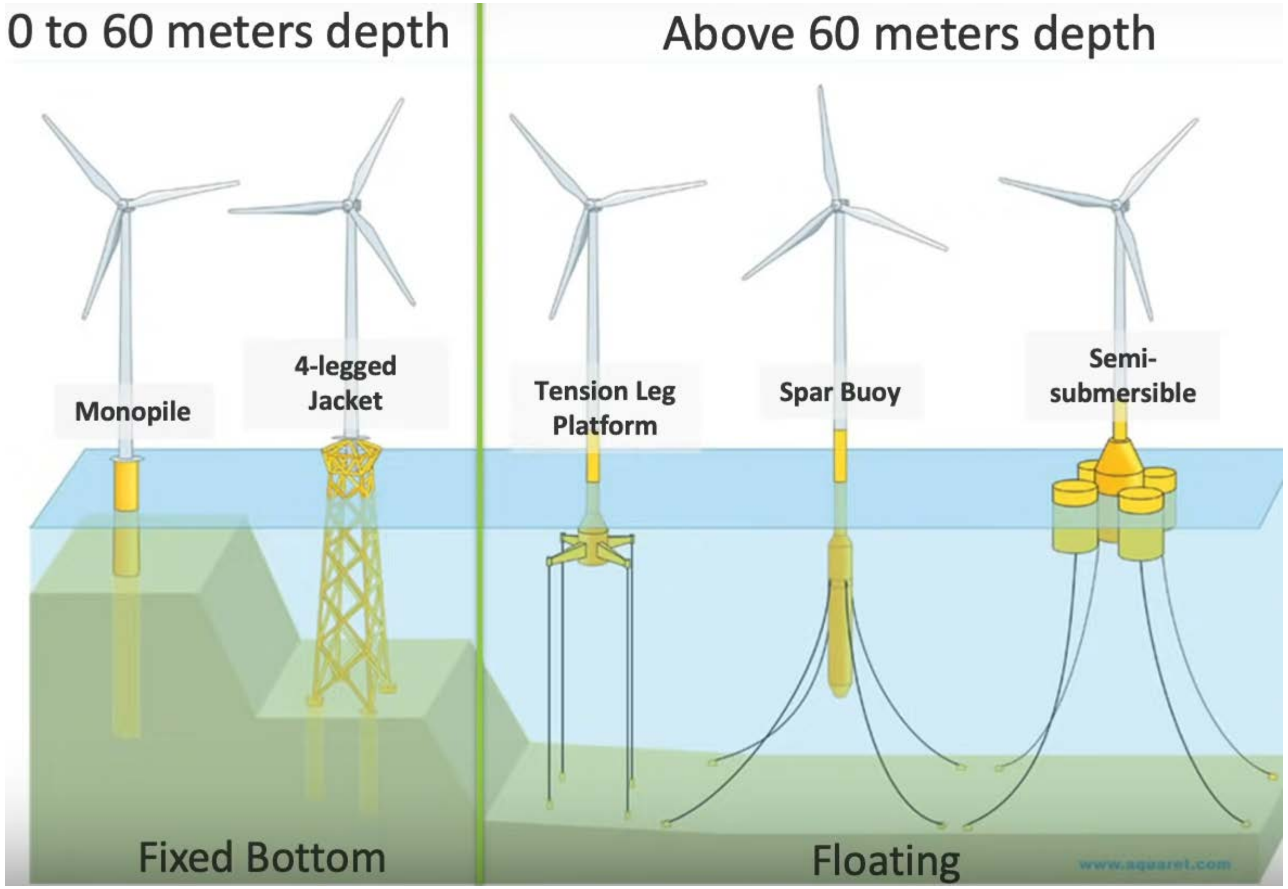
Fixed vs. Floating Offshore Wind

Figure. Structures for fixed bottom and floating offshore wind, with installed capacities as of February 2020



27,208 MW Installed

82 MW Installed

Source: Musial (2021)

- In water depths greater than 60 m, floating structures may be more economical.
- "~80% of offshore wind resources are in waters greater than 60 m deep."
- Floating wind enables sites to be located further from shore, with better wind resources.
- Floating wind technology is expected to be widely deployed at utility scale starting in 2024.

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Wind Resource Characteristics

Mean Wind Speed: "Average annual (or longer term) wind speed"

Wind Speed Distribution: "How many hours per year does the wind blow at (x) m/s?"

Wind Direction: "How often and how strong are the winds from particular directions?"

Diurnal Wind Distribution: "What time of day has the most wind energy?"

Seasonal Wind Distribution: "What time of year has the strongest wind resource?"

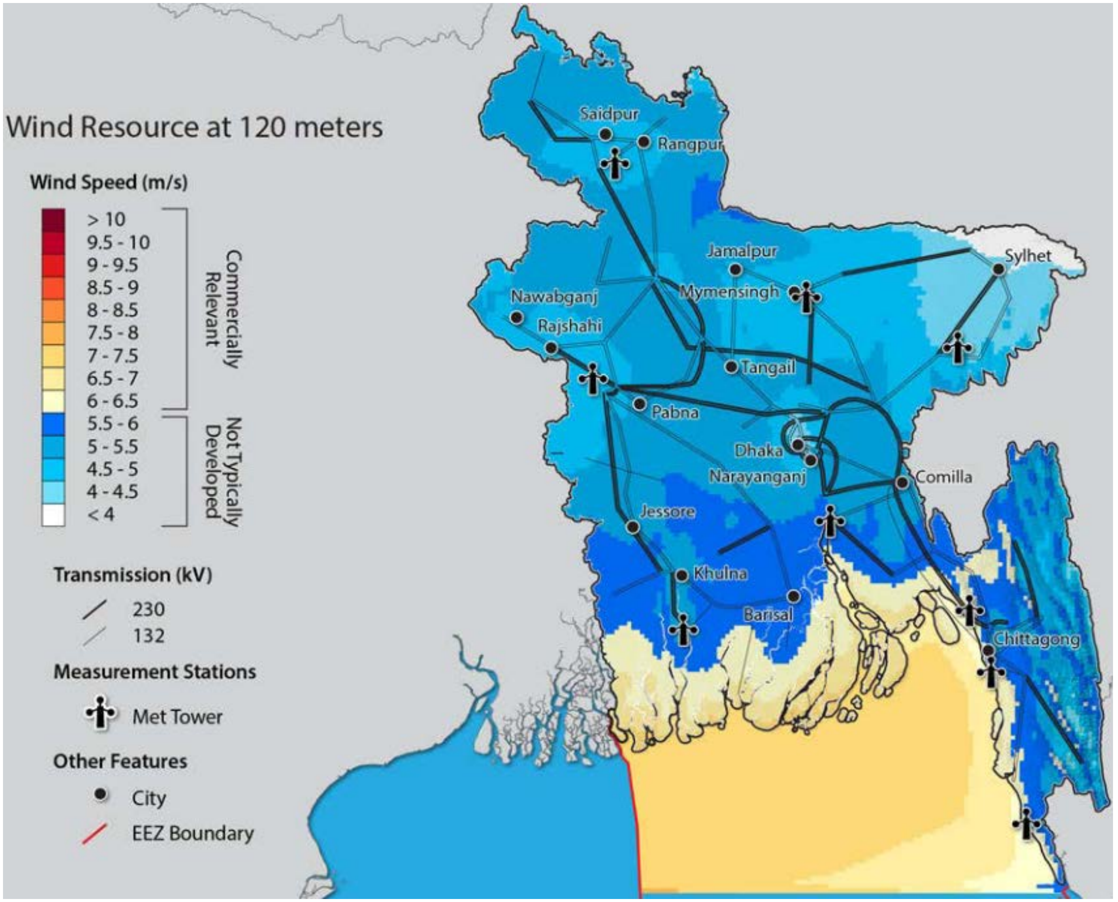

Figure. Modeled and measured wind speeds at 120m in Bangladesh

Source: Jacobson et al. (2018)

Source: Robichaud (2018)

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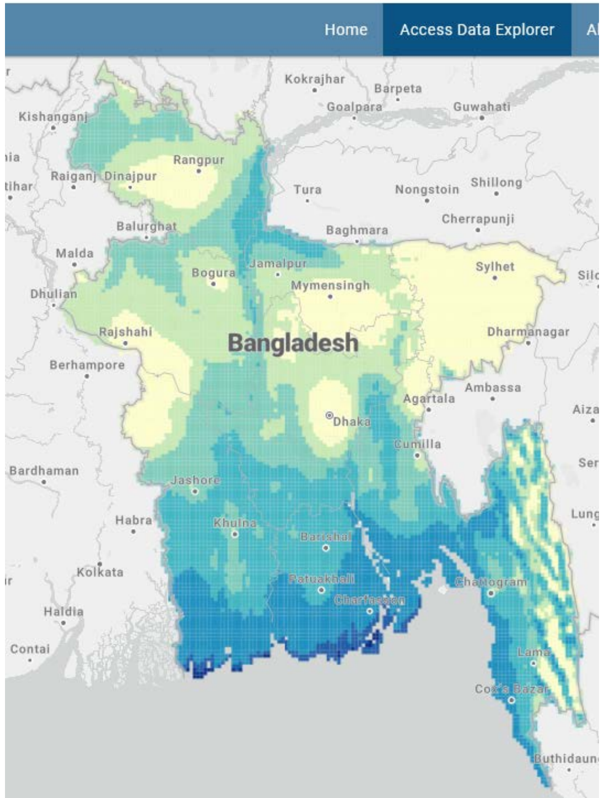
Wind Data

Wind Data for Prospecting

Available from governments, research organizations, etc.

Identifies locations for potential development.

RE data explorer



https://www.re-explorer.org/re-data-explorer/

Wind Data for Development

Responsibility of developer to obtain site-specific data.

MET towers installed to validate the resource.

Land contract can have an option period that will allow for wind measurement and permitting activities.

Image: Scott Wilde (NREL)

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Land Considerations

Land ownership profile:

- Private
- Public

Environmental factors:

- Wildfire or avian habitat
- Protected environmental areas
- Slope and topography

Permitting requirements:

- National and local
- Zoning ordinances
- Application requirements and schedule
- Public hearings

Legal Contracts

Image: Joshua Bauer (NREL)

- Wind turbine spacing is important to reduce wake effects.
- Wind turbines can be co-located with agricultural land, and the actual footprint of the turbines is a small fraction of the total area.

Source: Jacobson et al. (2020)

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Interconnection Agreement

- Signed between developer (project owner) and utility (transmission line owner):
  - Needed for PPA and project financing

- Steps:
  - Developer selects a site (completes preliminary due diligence)
  - Signs land lease(s) at interconnection point
  - Signs study agreement with utility:
    - Feasibility Study & System Impact Study
    - Facility Study
  - Execute Interconnection Agreement
  - Designates amount (MWs) of power that can be connected to system at a specific location:
    - Designates all equipment needed to interconnect (X-MWs) and who is responsible for which equipment (network vs. developer)
    - Designates construction schedule
    - Designates payment schedule and cost

Image: Dennis Schroeder (NREL)

Source: Jacobson et al. (2020)

Thank you!

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https://www.nrel.gov/usaid-partnership/reinforcing-advanced-energy-systems-bangladesh.html

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