

Wind Supply Chains

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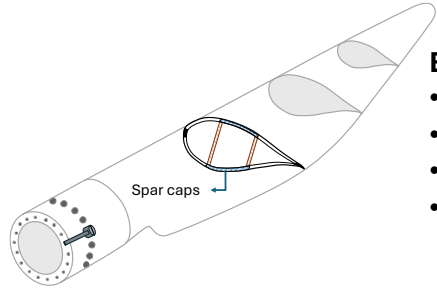
 SOVERÄN



List of Abbreviations

- EESG-DD: Electrically Excited Synchronous Generator with Direct Drive
- PMSG-DD: Permanent Magnet Synchronous Generator with Direct Drive
- HTS: High Temperature Superconducting generator
- DFIG: Doubly Fed Induction Generator
- SCIG: Squirrel Cage Induction Generator
- PMSG-GB: Permanent Magnet Synchronous Generator with Gearbox
- TST: Tubular Steel Tower
- HT: Hybrid Tower

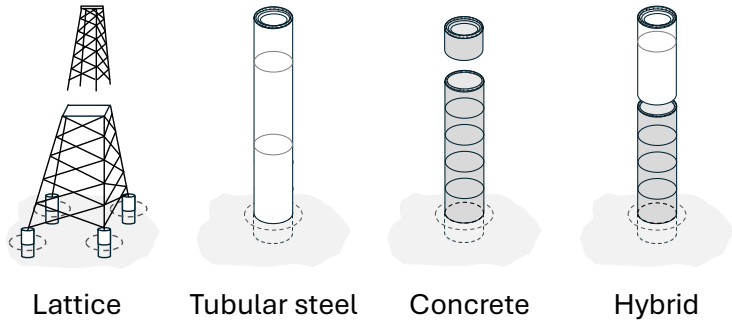
Technology and Component Overview



Blade sub-technologies:

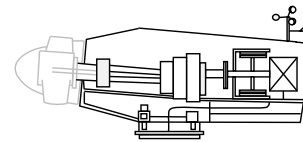
- Glass fiber
- Carbon fiber
- Biological fiber
- Hybrid fiber (glass fiber blade with carbon fiber spar caps)

Tower sub-technologies:



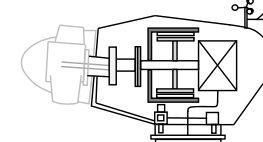
Nacelle sub-technologies:

with gearbox



- DFIG
- SCIG (with and without full converter)
- PMSG-GB
- WRIG

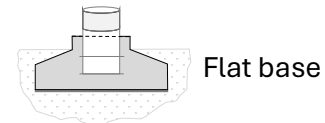
direct-drive



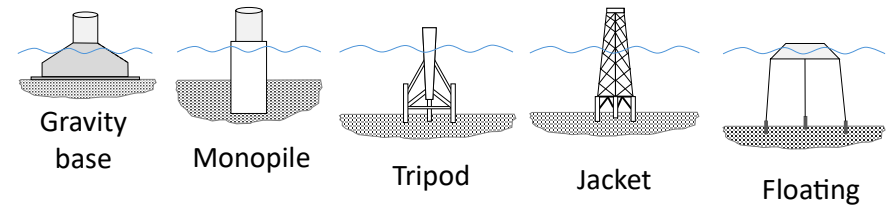
- EESG-DD
- PMSG-DD
- HTS

Foundation sub-technologies:

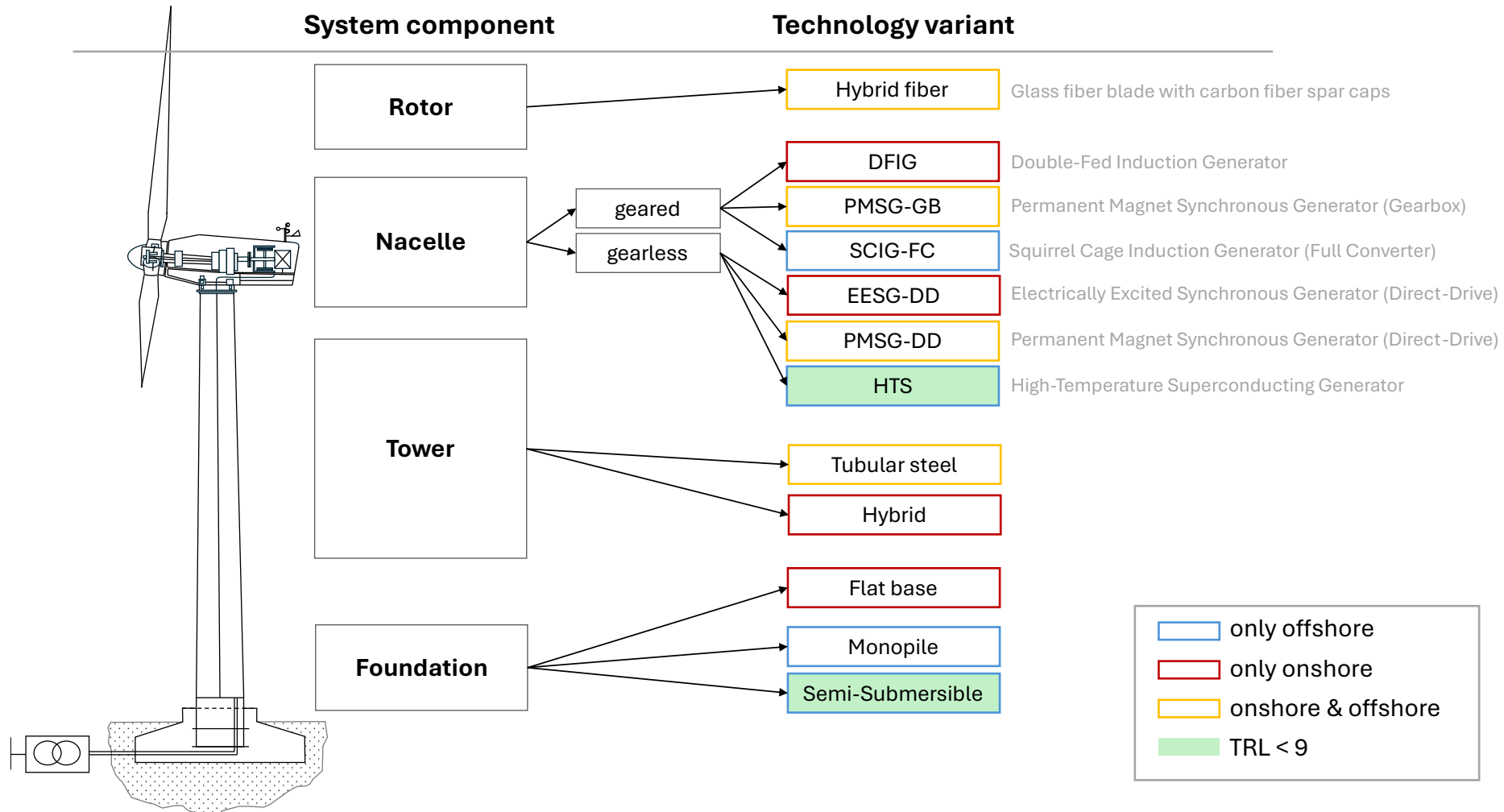
Onshore:



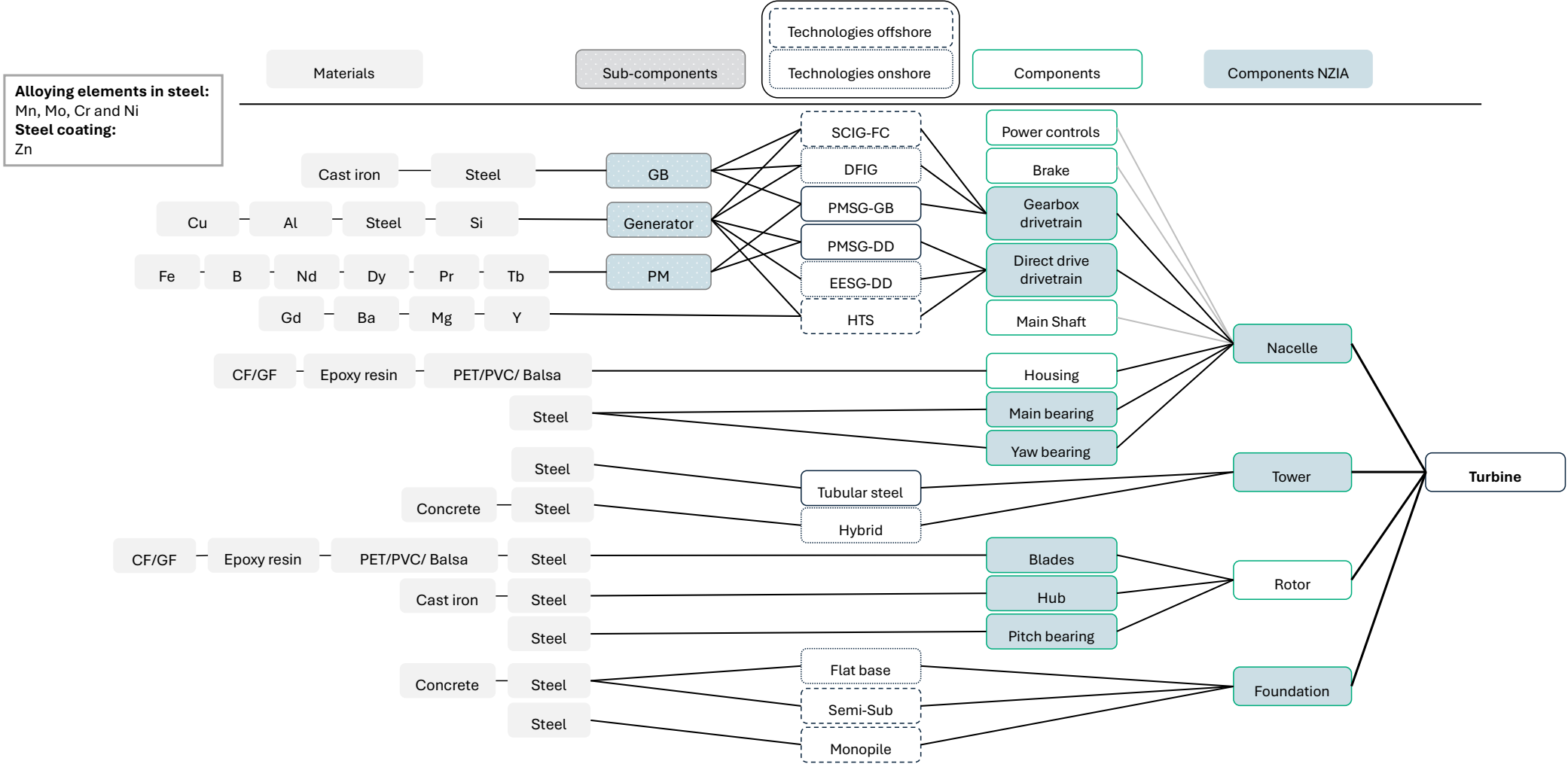
Offshore:



Technology and Component Selection



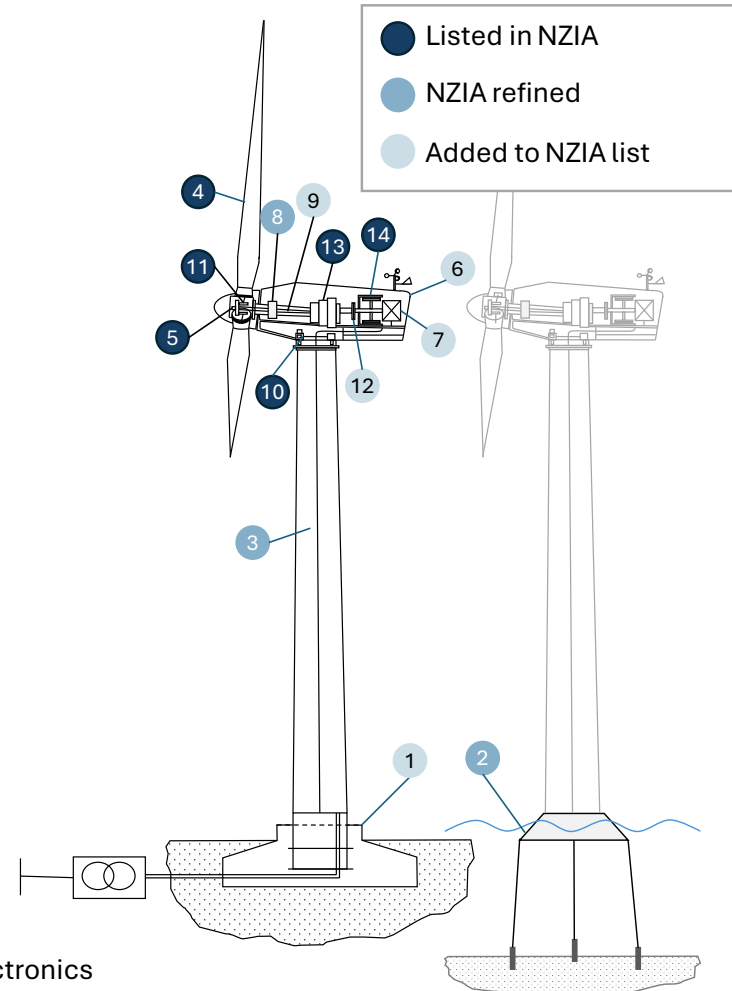
Material Supply Chain Overview



Products of Interests Overview

FOUNDATION		NACELLE	
Foundation/Floaters	●	Nacelle (assembly)	●
Flat base	1	Housing	6
Floating	2	Power Controls*	7
Monopile	●	Main, yaw and pitch bearing	●
		Main bearing	8
TOWER		Main shaft	9
Towers	●	Yaw bearing	10
Tubular steel tower	3	Pitch bearing	11
Concrete tower	3	Brake	12
Hybrid tower	3	Direct drive drivetrains (including generators)	●
		Gearbox drivetrains (including generators)	●
ROTOR		Gearboxes	13
Blades	4	Generator	14
Rotor hubs	5	Permanent magnets	●

*This includes converter, transformer, cooling and control electronics



Rotor

- At rotor blade lengths ≥ 70 m the majority of turbine platforms use carbon fiber spar caps [1]

Tower

- With increasing tower height > 80 m cost and transport issues for tubular steel towers increase [2], prompting hybrid concrete-steel solutions for large hub heights (>120 m [3])
- Vulnerability to harsh conditions and weight makes hybrid solutions less suitable for offshore wind [3]

Foundation

- In waters ≤ 50 m depth monopile will dominate (2022: > 80 % in Europe [4] and 60 % globally [5])
- In waters > 50 m depth floating structures will have full market lead (mainly semi-submersible: 26 % share of all announced projects in 2022 globally) [5]

Nacelle

Relevant drivetrain configurations [6]:

- Onshore: DFIG, PMSG-GB, EESG-DD, PMSG-DD
- Offshore: PMSG-DD, HTS, PMSG-GB, SCIG-FC

[1] Ennis et al., 2017

[2] Pons et al., 2017

[3] Hernandez-Estrada et al., 2021

[4] Jiang et al., 2025

[5] DOE, 2023

[6] Carrara et al., 2025

Drivetrain Market and its development



Deployment share status quo 2023 [1]:

ONSHORE: 46 % DFIG, 35 % PMSG-GB, 14 % SCIG, 4 % EESG-DD and 1 % PMSG-DD

OFFSHORE: 60 % PMSG-DD and 40 % PMSG-GB

Future development estimates:

ONSHORE:

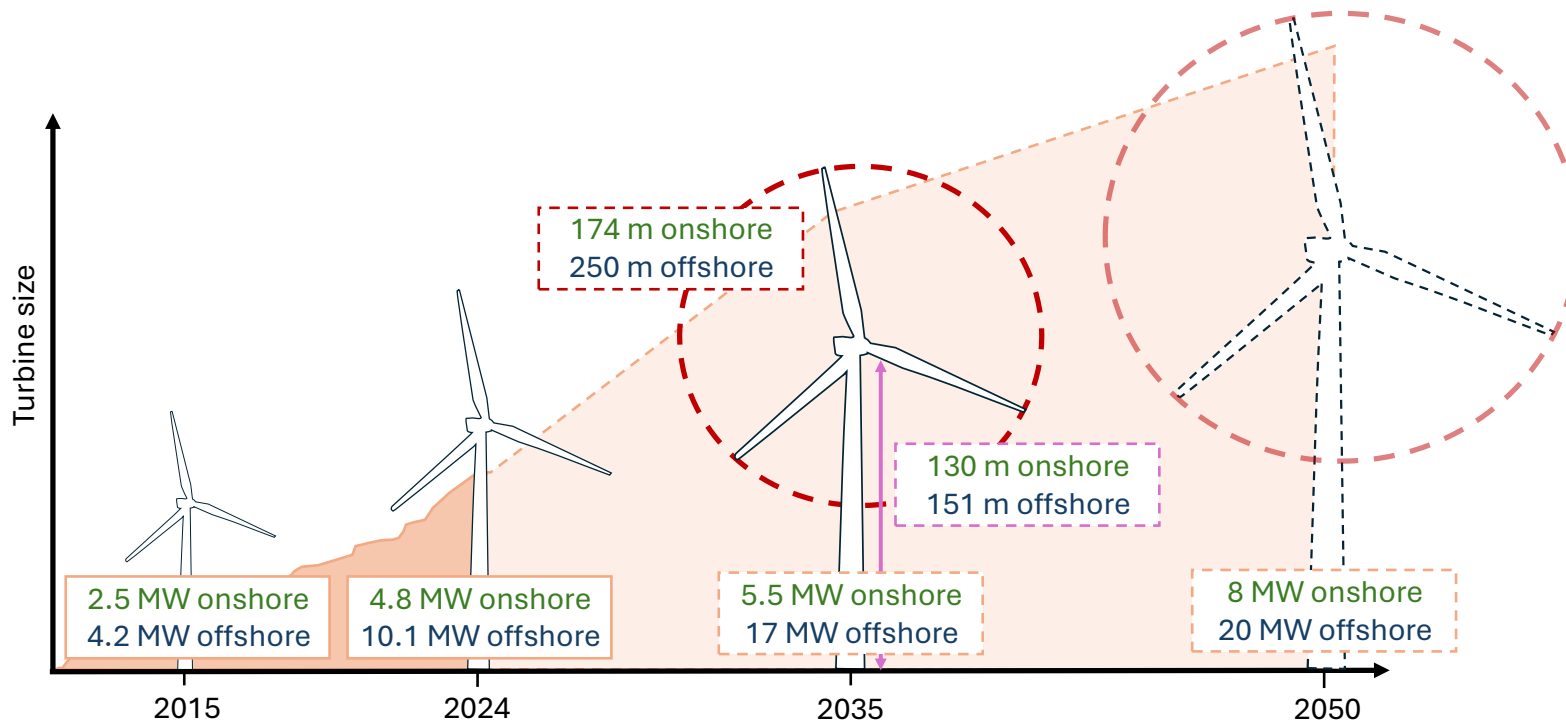
Development 2025 to 2050:

- 46 to 35 % DFIG, 35 to 50 % PMSG-GB, 4 to 10 % EESG-DD, 1-5 % PMSG-DD (Assumptions based on OEM reports)
- PMSG-GB emerging as compromise between efficiency and rare earth content

OFFSHORE:

- HTS enters market as efficient PMSG-DD alternative for large 10 MW+ models post 2030, reaching ~25-30 % by 2050 [6]
- PMSG-GB pushed out of market due to maintenance issues.
- Estimation: by 2050 65 % PMSG-DD; 10% PMSG-GB, 25 % HTS

Turbine Size Development



- 2015 & 2024: values derived from WindEurope [7]
- 2035: Predictions published in multiple scientific studies [9,10,11]
- 2050: Predictions based WindEurope [8] and on prototypes of key players (including China)

[7] WindEurope (2025): 2024 Statistics and the outlook for 2025-2030

[8] WindEurope (2019): Our energy, our future: How offshore wind will help Europe go carbon neutral

[9] Wisser et al., 2021; [10] Beiter et al., 2022; [11] Reuter & Sørensen, 2021

Physical and Logistical Constraints of Sub-Technologies

Blades	Towers	Nacelle	Foundation (off)
<ul style="list-style-type: none"> • Material composition changes with size: small blades are mostly glass fiber; large blades contain increasing share of carbon fibers [1] • Lengths ≥ 70 m majority have carbon fiber spar caps [13] • Length < 50m 100% glass • Length ≥ 70 m : carbon spar caps 	<p>Sub-tech choice size-dependent: With increasing height, tendency toward hybrid towers [3]</p> <p>Constraint: Transport of sections Weight of concrete unfit for offshore</p>	<p>EESG not available for offshore applications</p> <p>HTSG only in offshore applications [6]</p> <p>Constraint:</p> <ul style="list-style-type: none"> • Floating + Nacelle weight • Nacelle weight and truck max. load (onshore) 	<ul style="list-style-type: none"> • Floating water depth > 50 m • Monopile max. water depth = 50 m [12]

Selection of sub-techs onshore:

- Nacelle: DFIG, EESG, PMSG-GB, PMSG-DD
- Rotor: hybrid fiber
- Tower: TST, HT
- Foundations: flat base

Selection of sub-techs offshore:

- Nacelle: PMSG-GB, PMSG-DD, HTS
- Rotor: hybrid fiber
- Tower: TST
- Foundations: monopile, floating(semi-sub)

[1] Ennis et al., 2019

[3] Hernandez-Estrada et al., 2021

[6] Carrara et al., 2025

[12] ICF, 2020

[13] Animsaun et al., 2025

Global and EU Production Landscape

Manufacturing [20]

- In 2020 EU has around 250 sites for manufacturing various wind turbine components
- 10 companies cover 88% of global demand (5 headquartered in the EU: Vestas, Siemens Gamesa Renewable Energy, Enercon, Nordex SE, GE Renewable Energy)
- China is the biggest competitor: having 4 of the global top 10 manufacturers, and they control more than 90% of their home market
- EU is home of two of the top five offshore manufacturers
- EU's dominance: 85% of the EU market (94% in offshore), 66% in North America, 67% in Latin America, leading to a 42% global market share (up from 33% 10 years ago)
- Germany, Spain, France, Italy, & Denmark are the leading producers of strategic wind turbine components in EU
- Towers, due to their relatively low complexity are the component most widely spread in terms of manufacturing footprint, globally
- China supplies about half of the required raw materials

Financial Competition [21,15]

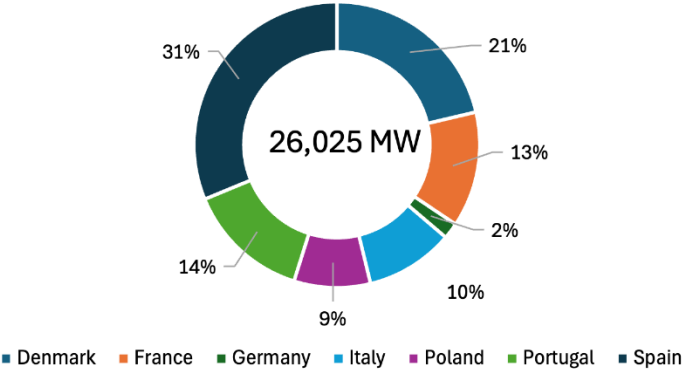
- 2019-2024 the median price of Chinese onshore turbines sold outside China was ca. 25% lower than prices from EU & US
- There is a price difference of about 20-30% for a magnet produced in Europe compared to its equivalent produced in China, depending on the application

Main Challenges [23]

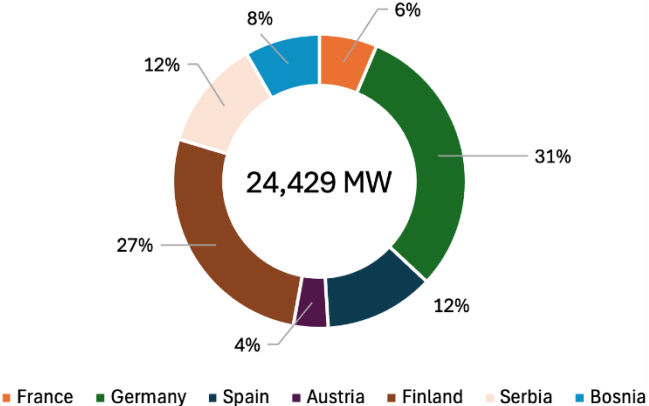
- Under-utilization of manufacturing capacities (due to uncertain demand)
- Restricted raw material access and high inflation impede manufacturers financial performance
- No appropriate compensation for the high socio-ecological standards of
- Rising international competition (mostly through China)

Manufacturing Capacities in EU

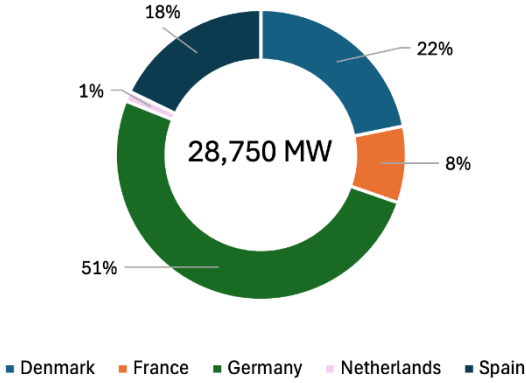
Blade Manufacturing Capacity 2023 [MW]



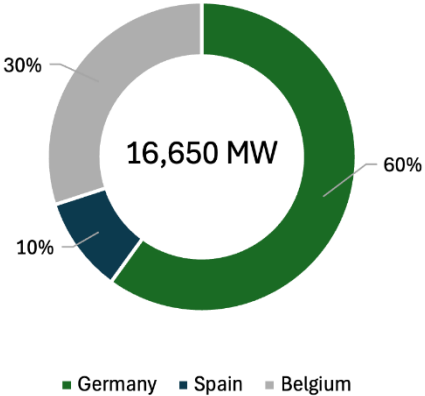
Generator Manufacturing Capacity 2023 [MW]



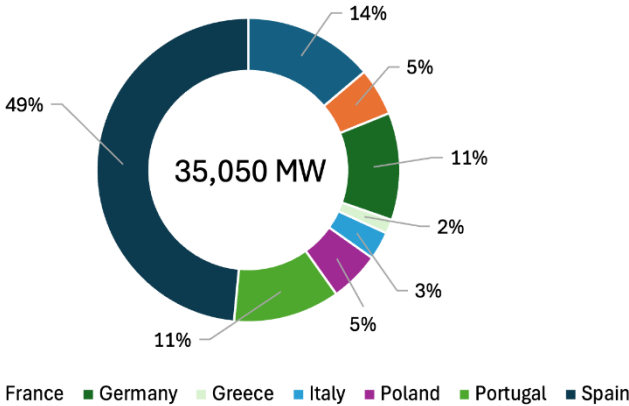
Nacelle Manufacturing Capacity 2023 [MW]



Gearbox Manufacturing Capacity 2023 [MW]

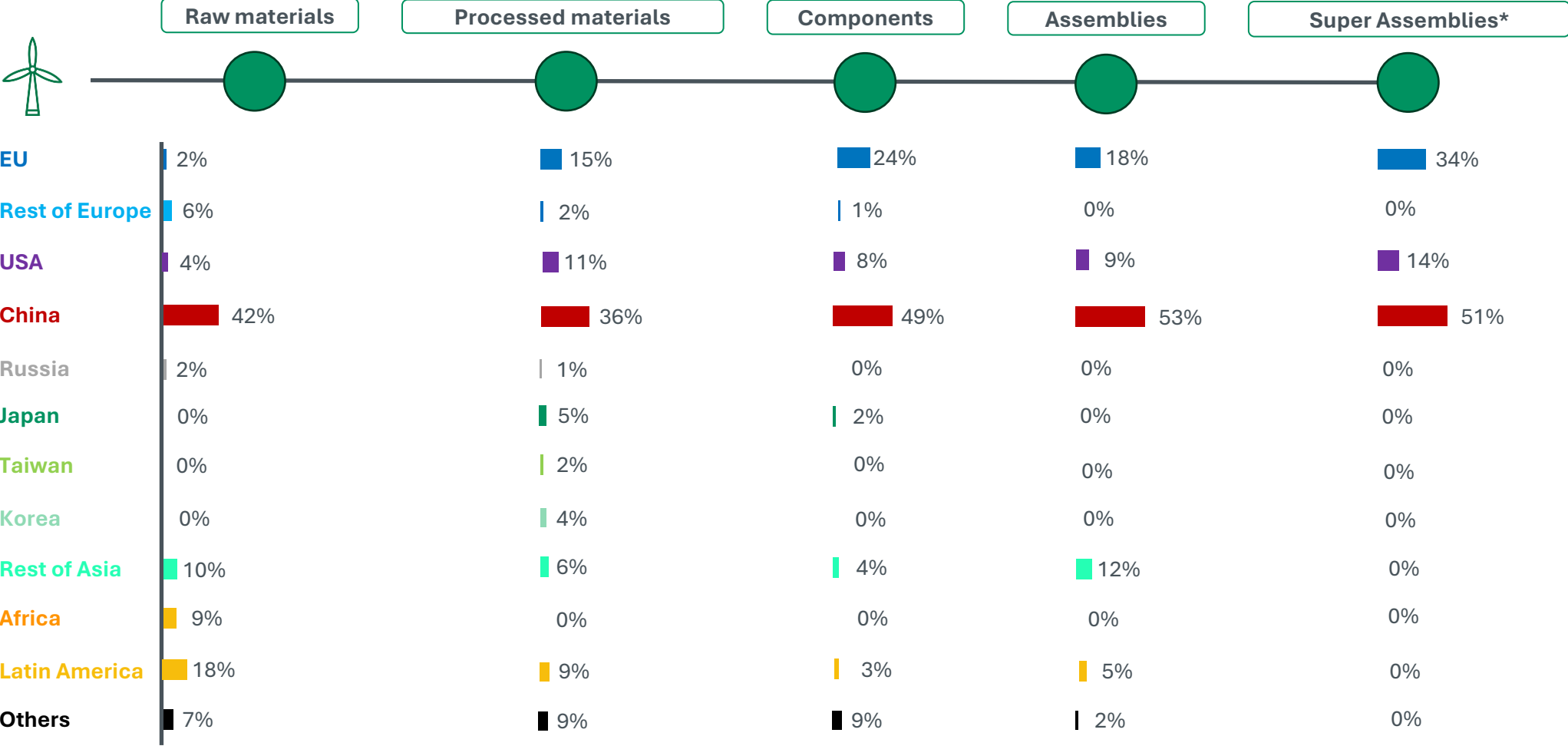


Tower Manufacturing Capacity 2023 [MW]



[16] Publications Office of the European Union, 2023
 [17] Global Wind Energy Council & Boston Consulting Group, 2023

Key players along the wind turbine supply chain in 2023

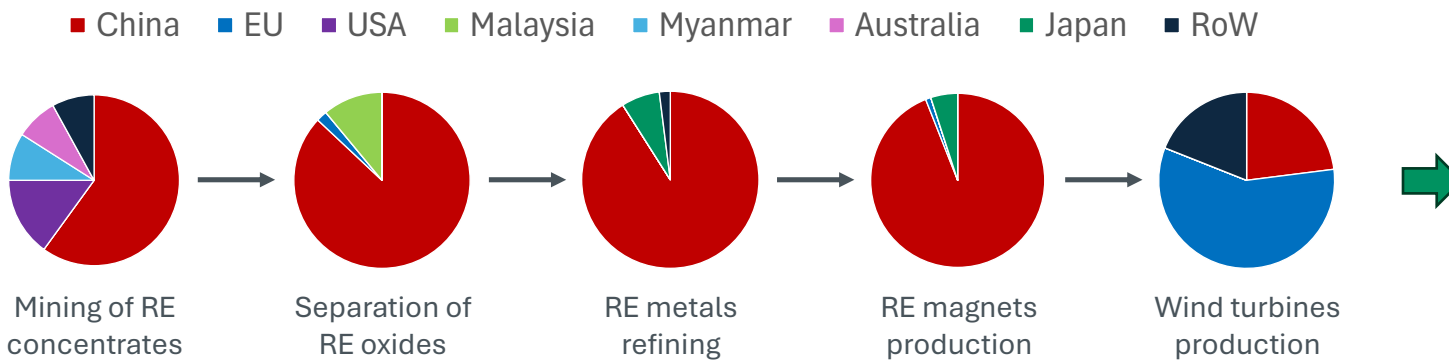


Own illustration based on sources [6,22]

*Conceptually, a super assembly groups components that jointly fulfil a core system function. For example, the rotor can be understood as a super assembly because it integrates the blades, hub, and pitch system into one aerodynamic and mechanical unit responsible for energy capture.

PM Supply Chain and Role of Europe

PM supply chain and geographical distribution modeled after [18]:



Resilience roadmap for permanent magnets by the European wind industry [19]:

	Permanent magnets	Rare Earths
2029	15 %	5 %
2030	30 %	35 %
2035	50 %	35 %

Share of PMs and REs from resilient sources through diversification, technological advancement, recycling, ...

[18] Rizos et al., 2022
 [19] WindEurope, 2025a

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