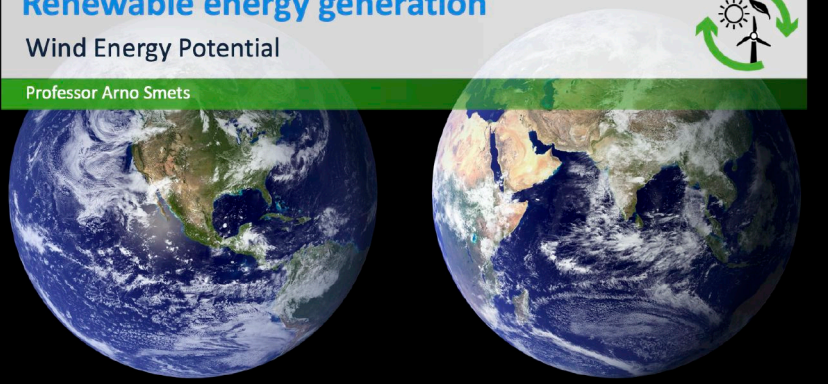
Renewable energy generation

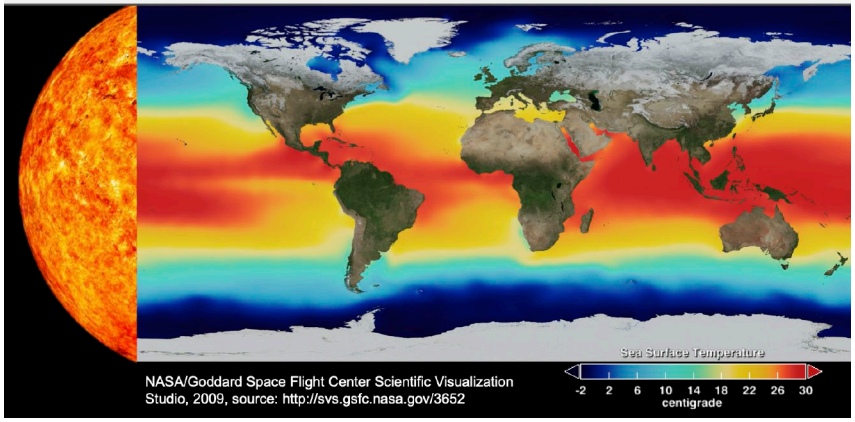
Wind Energy Potential

Professor Arno Smets



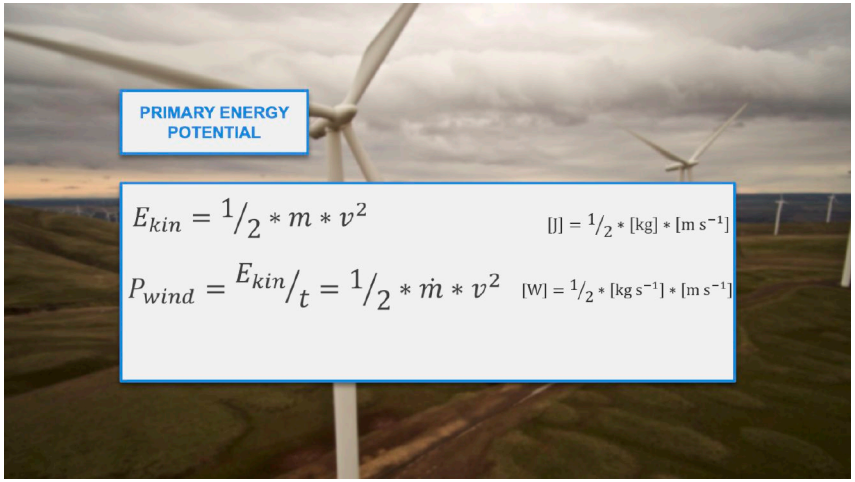
Wind Energy Technology

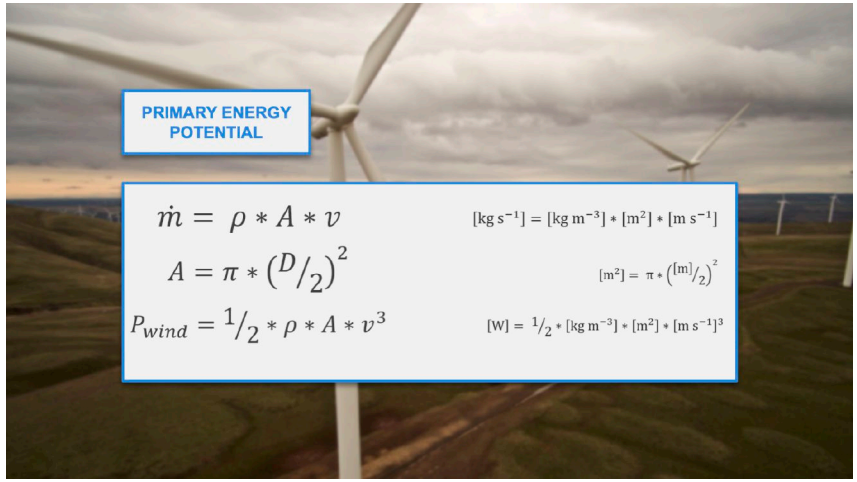
The Principles



NASA/Goddard Space Flight Center Scientific Visualization Studio, 2009, source: http://svs.gsfc.nasa.gov/3652

The Principles

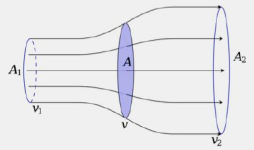

PRIMARY ENERGY POTENTIAL
$E_{kin} = {}^{1}/_{2} * m * v^2$
[J] = ${}^{1}/_{2}$ * [kg] * [m s^{-1}]
$P_{wind} = {}^{E_{kin}}/_{t} = {}^{1}/_{2} * \dot{m} * v^2$
[W] = ${}^{1}/_{2}$ * [kg s^{-1}] * [m s^{-1}]


PRIMARY ENERGY POTENTIAL
$\dot{m} = \rho * A * v$
[kg s^{-1}] = [kg m^{-3}] * [m^2] * [m s^{-1}]
$A = \pi * \left({}^{D}/_{2}\right)^2$
[m^2] = π * $\left({}^{[m]}/_{2}\right)^2$
$P_{wind} = {}^{1}/_{2} * \rho * A * v^3$
[W] = ${}^{1}/_{2}$ * [kg m^{-3}] * [m^2] * [m s^{-1}]^3

SYSTEM EFFICIENCIES

$$Cp = \frac{Electricity\ produced\ by\ the\ turbine}{Total\ Energy\ Available\ in\ the\ Wind}$$

SYSTEM EFFICIENCIES



Betz Limit

Maximum mechanical efficiency 59.3%

ENERGY YIELD

Seasonal & Daily Intermittency

Cut-off Speed

Maintenance & Repair

Calculation Example

Given Information

Rotor Diameter $D = 126\ [\mathrm{m}]$ & Power Coefficient $Cp = 0.483$ at $v = 10\ [\mathrm{m\ s^{-1}}]$

Gather Useful Values

$\rho = 1.23\ [\mathrm{kg\ m^{-3}}]$

$A_{rotor} = \pi * (1/2 * 126)^2 = 12469\ [\mathrm{m^2}]$

$v_{avg} = 10\ [\mathrm{m\ s^{-1}}]$

Calculate Potential

$P_{wind} = 1/2 * 1.23[\mathrm{kg\ m^{-3}}] * 12469[\mathrm{m^2}] * 10^3[\mathrm{m^3\ s^{-3}}] = 7.7\ [\mathrm{MW}]$

Calculation Example

Calculate Potential

$$P_{wind} = {}^{1}/_{2} * 1.23[\mathrm{kg\ m^{-3}}] * 12469[\mathrm{m^2}] * 10^3[\mathrm{m^3\ s^{-3}}] = 7.7\ [\mathrm{MW}]$$

Calculate Actual Power

$$P_{Real} = 7.7\ [\mathrm{MW}] * 0.483 = 3.7\ [\mathrm{MW}]$$

Calculation Example: Wind turbine in Denmark

Given Information

Nominal Capacity = 5.07 [GW] & Energy Yield = 14.13 [TWh]

Calculate Capacity Factor

$$Cf = 14.3[\mathrm{TWh\ year^{-1}}] * {}^{1}/_{8760}\ [\mathrm{year\ h^{-1}}] * {}^{1}/_{5.07}\ [\mathrm{GW^{-1}}] = 0.32$$

ADVANTAGES	CHALLENGES
• Large Energy Potential	• Low Capacity factor • Endanger Grid Stability • Good Wind Sites in Remote Locations

Global Perspective

Given Information

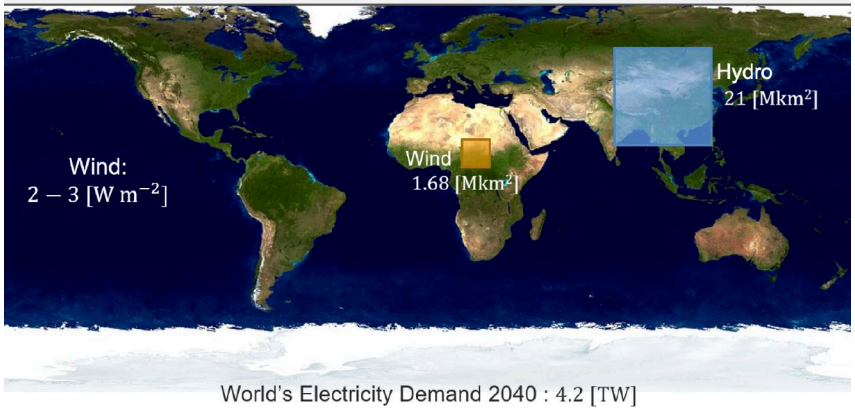
Global Energy Yield= 960 [TWh year^{-1}] Global Population = $7.5 * 10^9$[person]

Other Units

$$E_{GlobalYield} = 960\ [\mathrm{TWh\ year^{-1}}] * {}^{1}/_{7.5\ * 10^9}\ [\mathrm{person^{-1}}] * {}^{1}/_{365}\ [\mathrm{year\ day^{-1}}]$$

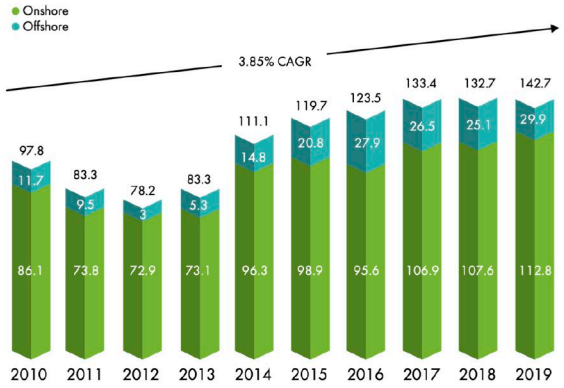
$$E_{GlobalYield} = 351\ [\mathrm{Wh\ person^{-1} day^{-1}}]$$

Global Perspective



World's Electricity Demand 2040 : 4.2 [TW]

Annual Investment in Wind Energy between 2009 – 2019 (bn USD)

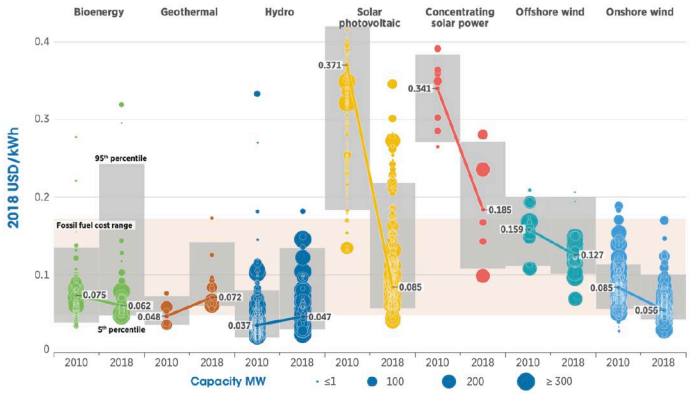


Source: BloombergNEF Clean Energy Investment database (Status January 16th, 2020)

New Installations (GW)

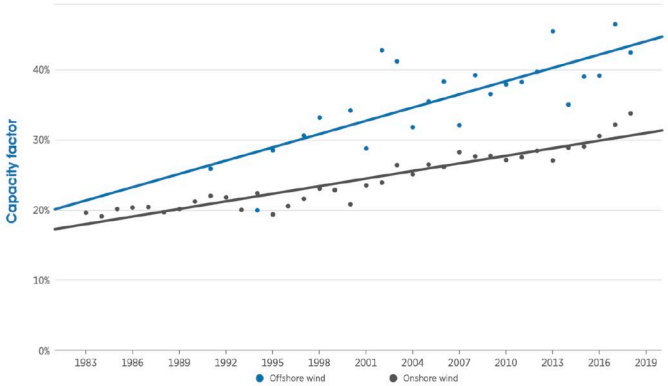
Source: GWEC - Global Wind Report 2019

LCOE for Renewables, 2010 — 2018



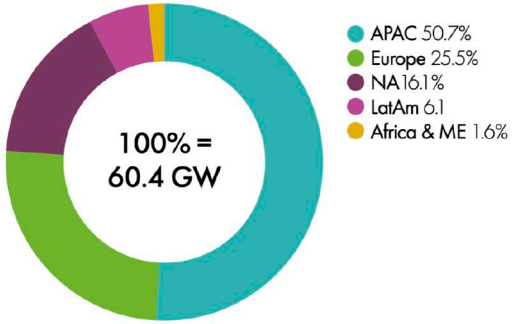
Source: IRENA - Renewable Power Generation Costs in 2018

Capacity Factors for Onshore and Offshore Wind Power Plants, 1983 — 2018



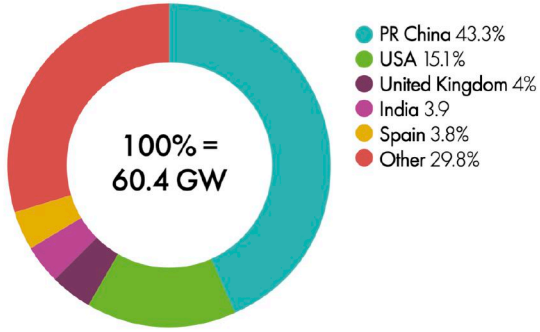
Source: IRENA - Renewable Power Generation Costs in 2018

New Capacity 2019 Installed by Region (%)



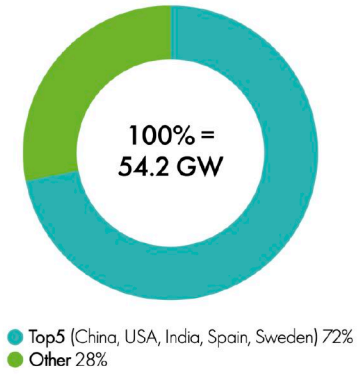
Source: GWEC - Global Wind Report 2019

New Capacity 2019 and Share of Top 5 Markets (%)



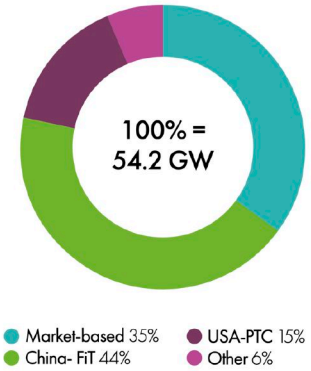
Source: GWEC - Global Wind Report 2019

Onshore Wind Market
New Capacity 2019 and Share of Top 5 Markets (%)



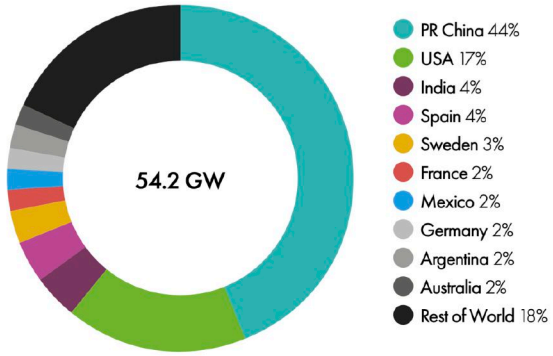
Source: GWEC - Global Wind Report 2019

Onshore Wind Market
New Capacity 2019 by Support Mechanism (%)



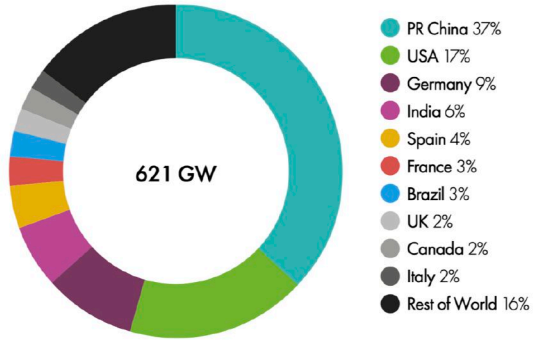
Source: GWEC - Global Wind Report 2019

Onshore Wind Market
New Installations (%)



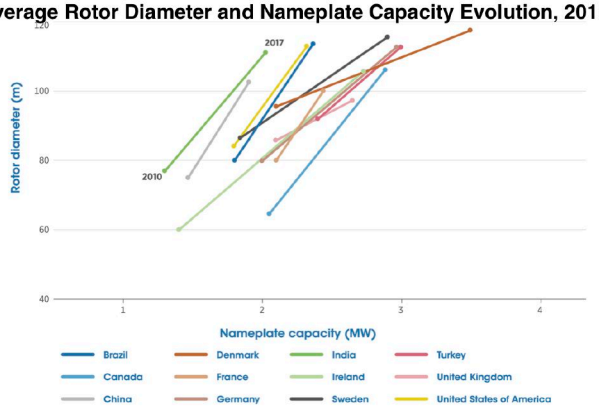
Source: GWEC - Global Wind Report 2019

Onshore Wind Market
Total Installations (%)



Source: GWEC - Global Wind Report 2019

Onshore Wind Market
Weighted Average Rotor Diameter and Nameplate Capacity Evolution, 2010 – 2018



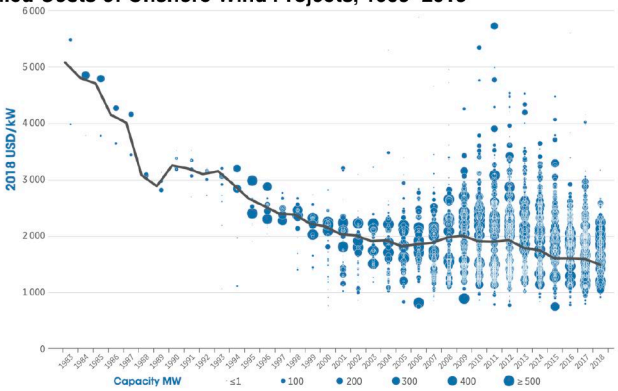
Source: IRENA - Renewable Power Generation Costs in 2018

Onshore Wind Market
Wind Turbine Price Indices and Price Trends, 1997 – 2018

	Period	% Decrease
United States of America <5 MW	2007–2011	17%
United States of America 5–100 MW	2010–2015	44%
United States of America >100 MW	2008–2016	56%
BNEF WTPI	2009–2019	64%
BNEF WTPI <100 m ø	2009–2019	53%
BNEF WTPI >=100 m ø	2010–2019	56%
Chinese turbine prices	1998–2017	78%
Vestas average selling price	2008–2017	50%

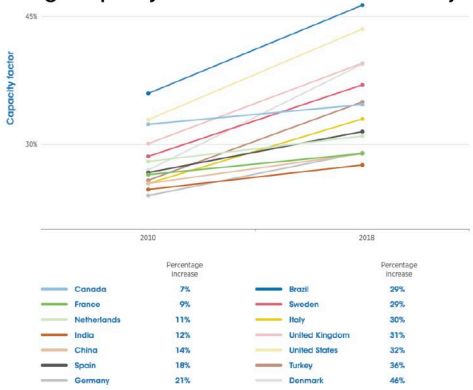
Source: IRENA - Renewable Power Generation Costs in 2018

Onshore Wind Market
Total Installed Costs of Onshore Wind Projects, 1983–2018



Source: IRENA - Renewable Power Generation Costs in 2018

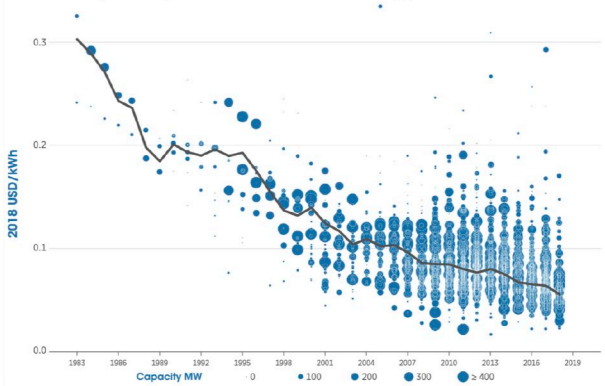
Onshore Wind Market
Country-Specific Average Capacity Factors for New Onshore Projects, 2010 — 2018



	Percentage increase		Percentage increase
Canada	7%	Brazil	29%
France	9%	Sweden	29%
Netherlands	11%	Italy	30%
India	12%	United Kingdom	31%
China	14%	United States	32%
Spain	18%	Turkey	36%
Germany	21%	Denmark	46%

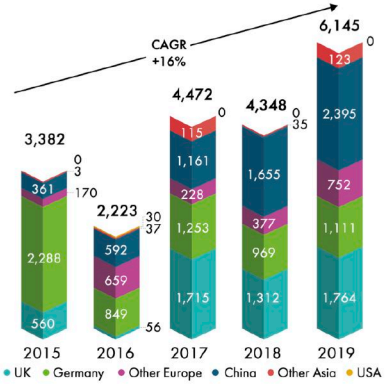
Source: IRENA - Renewable Power Generation Costs in 2018

Onshore Wind Market
LCOE of Onshore Projects by Year of Commissioning, 1983–2018



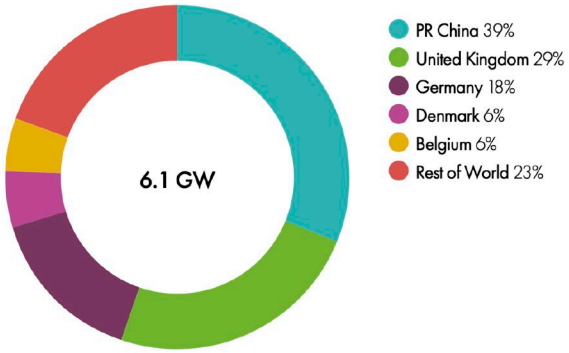
Source: IRENA - Renewable Power Generation Costs in 2018

Offshore Wind Market
New Installations (GW)



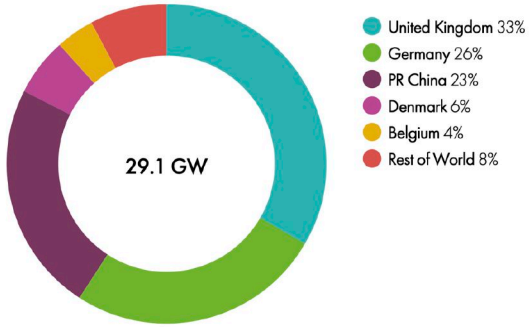
Source: GWEC - Global Wind Report 2019

Offshore Wind Market
New Installations (%)



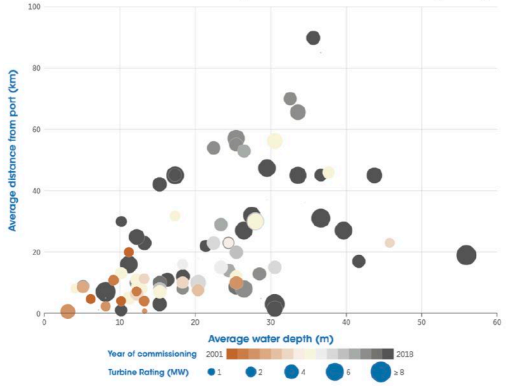
Source: GWEC - Global Wind Report 2019

Offshore Wind Market
Total Installations (%)



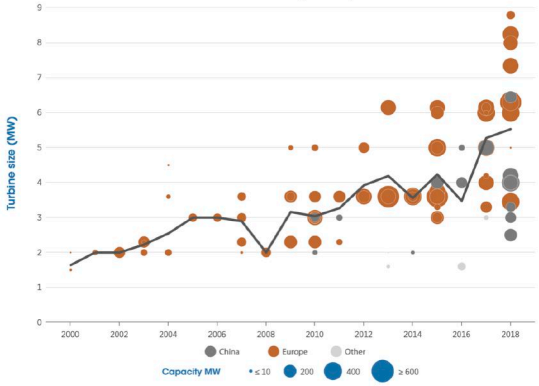
Source: GWEC - Global Wind Report 2019

Offshore Wind Market
Average Distance from Port and Water Depth for Offshore Projects, 2001 – 2018



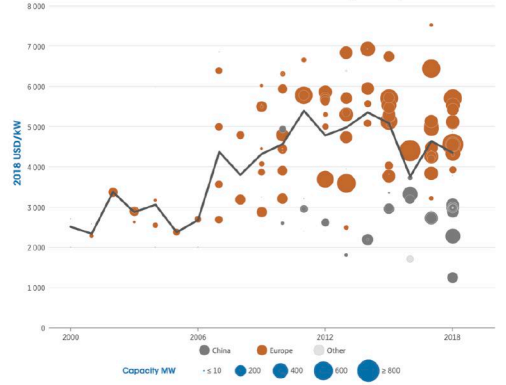
Source: IRENA - Renewable Power Generation Costs in 2018

Offshore Wind Market
Turbine Sizes for Commissioned Offshore Projects, 2000 – 2018



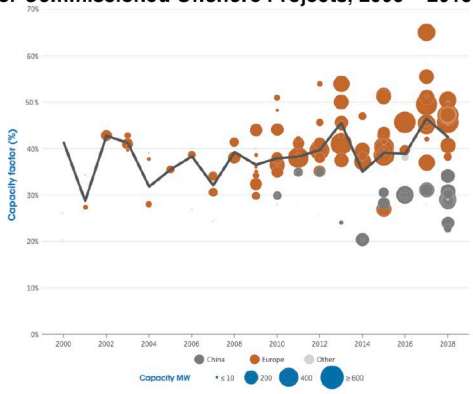
Source: IRENA - Renewable Power Generation Costs in 2018

Offshore Wind Market
Total Installed Costs for Commissioned Offshore Projects, 2000 – 2018



Source: IRENA - Renewable Power Generation Costs in 2018

Offshore Wind Market
Capacity Factors for Commissioned Offshore Projects, 2000 – 2018



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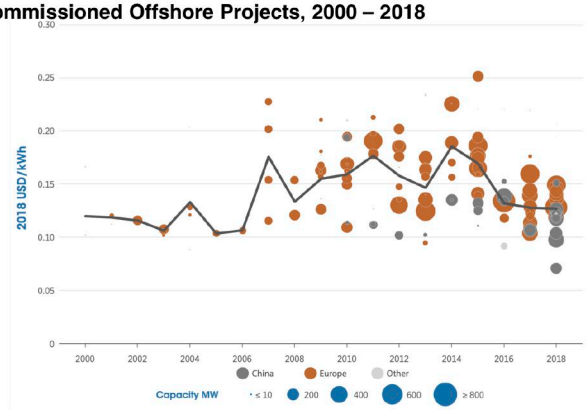
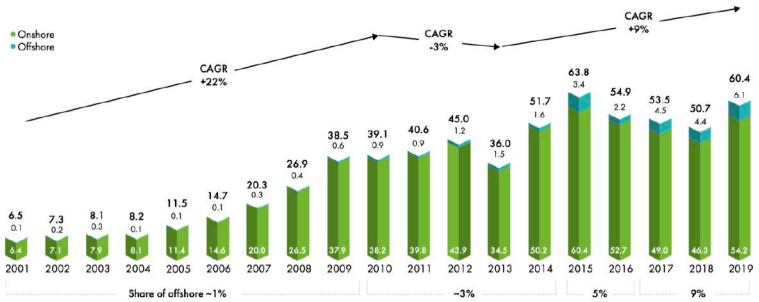
Offshore Wind Market
LCOE for Commissioned Offshore Projects, 2000 – 2018



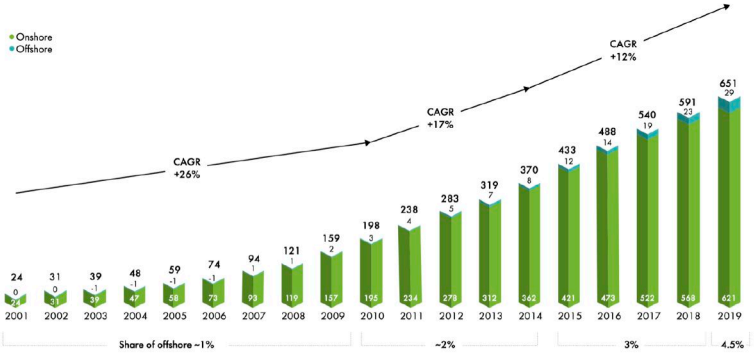
Source: IRENA - Renewable Power Generation Costs in 2018

Historic Development of New Installations (Onshore&Offshore)



Source: GWEC - Global Wind Report 2019

Historic Development of Total Installations (Onshore&Offshore)



Source: GWEC - Global Wind Report 2019

Historic Development of Total Installations

Onshore

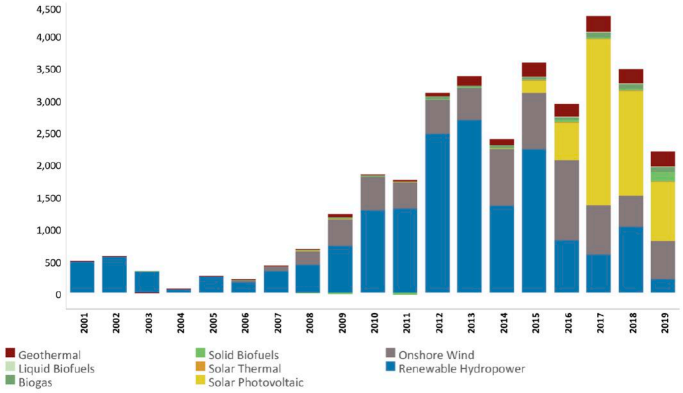
MW, onshore	New installations 2018	Total installations 2018	New installations 2019	Total installations 2019
Total onshore	**46,345**	**567,592**	**54,206**	**621,421**
Americas	11,891	134,843	13,427	148,072
USA	7,588	96,488	9,143	105,436
Canada	566	12,816	597	13,413
Brazil	1,939	14,707	745	15,452
Mexico	929	4,933	1,281	6,215
Argentina	445	673	931	1,604
Chile	204	1,619	526	2,145
Other Americas	220	3,605	204	3,807
Africa, Middle East	**970**	**5,728**	**944**	**6,673**
Egypt	380	1,190	262	1,452
Kenya	312	338	0	338
South Africa	0	2,085	0	2,085
Other Africa	278	2,115	682	2,798
Asia-Pacific	**24,468**	**255,937**	**28,094**	**284,024**
China	20,200	205,804	23,760	229,564
India	2,191	35,129	2,377	37,506
Australia	549	5,362	837	6,199
Pakistan	400	1,189	50	1,239
Japan	261	3,652	274	3,921
South Korea	127	1,229	191	1,420
Vietnam	32	228	160	388
Philippines	0	427	0	427
Thailand	568	1,215	322	1,538
Other Asia	140	1,702	123	1,822
Europe	**9,016**	**171,084**	**11,741**	**182,652**
Germany	2,402	52,932	1,078	53,913
France	1,563	15,307	1,336	16,643
Sweden	717	7,216	1,588	8,804
United Kingdom	589	13,001	629	13,817
Turkey	497	7,370	686	8,056
Other Europe	3,248	75,258	6,424	81,619

Offshore

MW, offshore	New installations 2018	Total installations 2018	New installations 2019	Total installations 2019
Total offshore	**4,348**	**22,997**	**6,145**	**29,136**
Europe	**2,658**	**18,280**	**3,627**	**21,903**
United Kingdom	1,312	7,963	1,764	9,723
Germany	969	6,382	1,111	7,493
Belgium	309	1,186	370	1,556
Denmark	61	1,329	374	1,703
Netherlands	0	1,118	0	1,118
Other Europe	7	302	8	310
Asia-Pacific	**1,690**	**4,687**	**2,518**	**7,204**
China	1,655	4,443	2,395	6,838
South Korea	35	73	0	73
Other Asia	0	171	123	292
Americas	**0**	**30**	**0**	**30**
USA	0	30	0	30

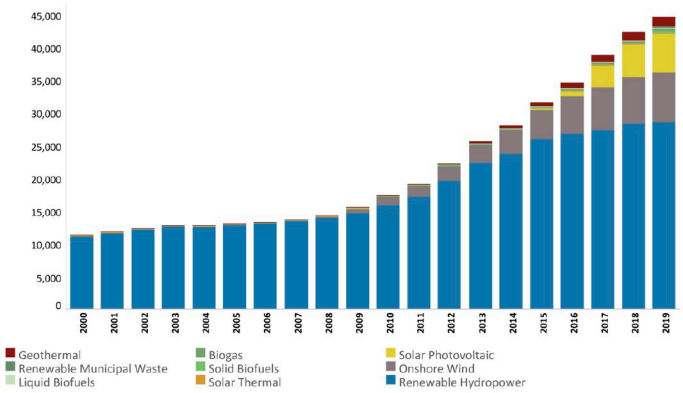
Source: GWEC - Global Wind Report 2019

Net Additions in Turkish Installed Renewable Power Capacity, 2001 — 2019 (MW)



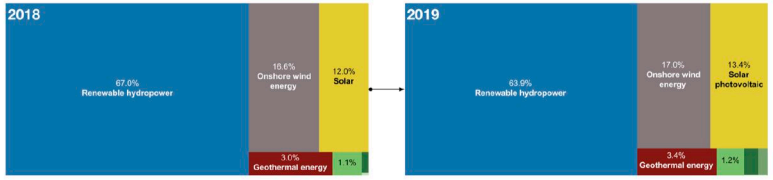
Source: IRENA - Data & Statistics

Turkish Cumulative Installed Renewable Power Capacity, 2001 — 2019 (MW)



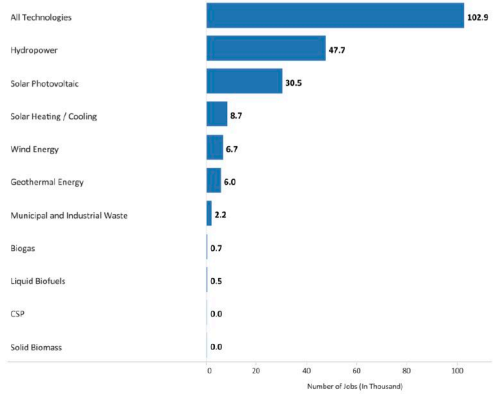
Source: IRENA - Data & Statistics

Distribution of Turkish Installed Renewable Power Capacity, 2018 — 2019 (%)



Source: IRENA - Data & Statistics

Turkish Renewable Energy Employment by Technology



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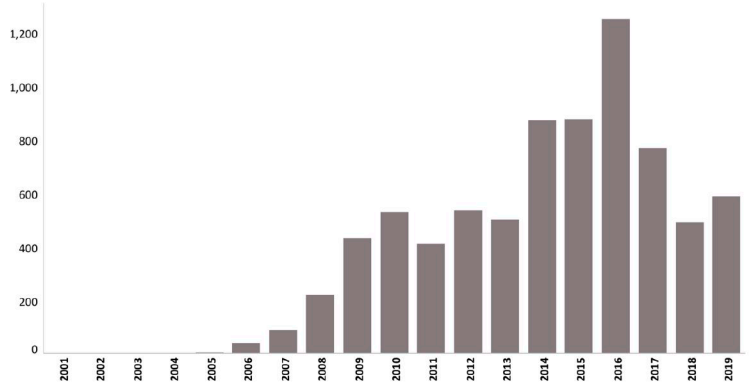
Net Additions in Turkish Installed Wind Power Capacity, 2001— 2019 (MW)



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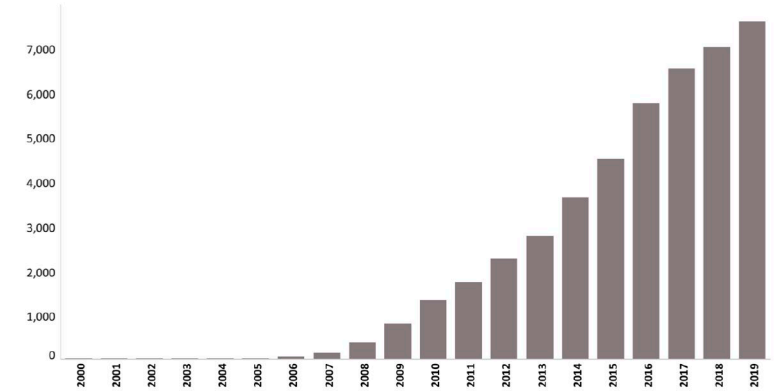
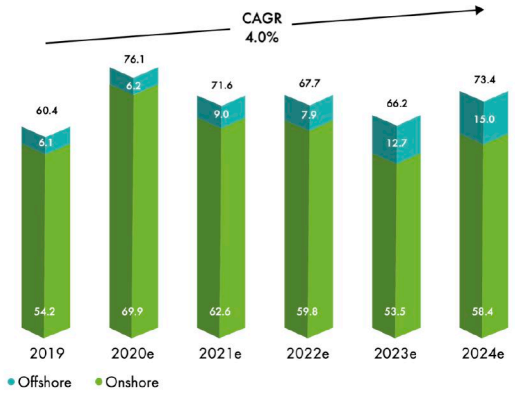
Turkish Cumulative Installed Wind Power Capacity, 2001— 2019 (MW)



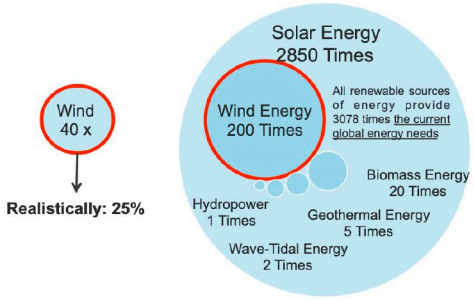
Source: IRENA - Data & Statistics

New Installations Outlook (GW) [*Published before COVID-19 Pandemic]



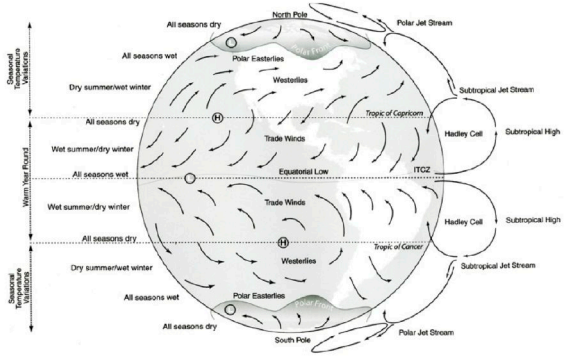
Source: GWEC - Global Wind Report 2019

The wind energy resource

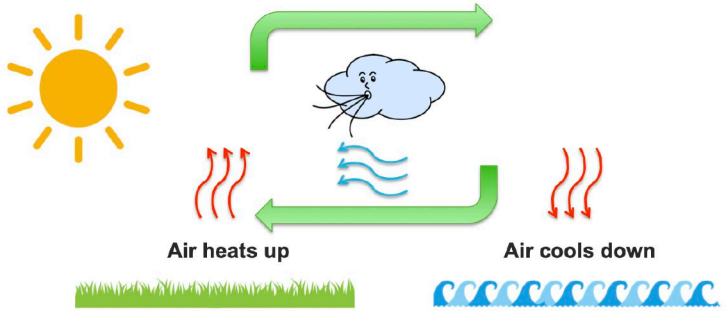


Data from the German Advisory Council on Global Change

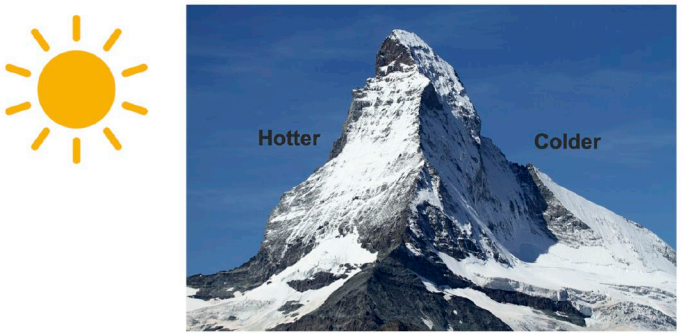
Where does the wind come from?



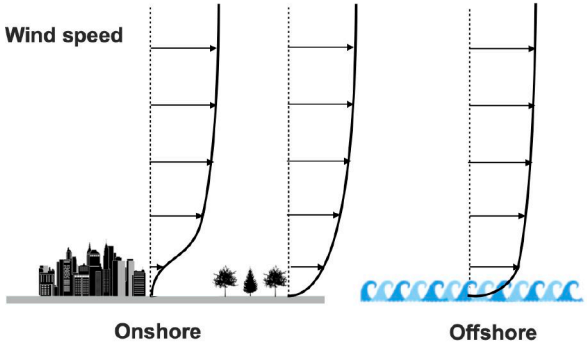
Where does the wind come from?



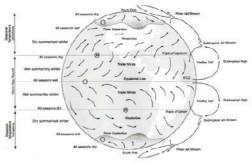
Where does the wind come from?

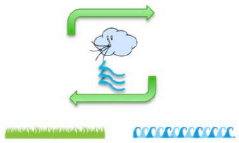


Effect of the terrain on the wind speed



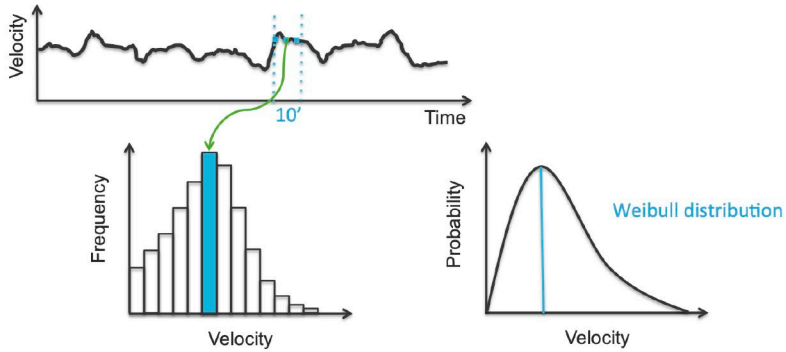
Wind variability

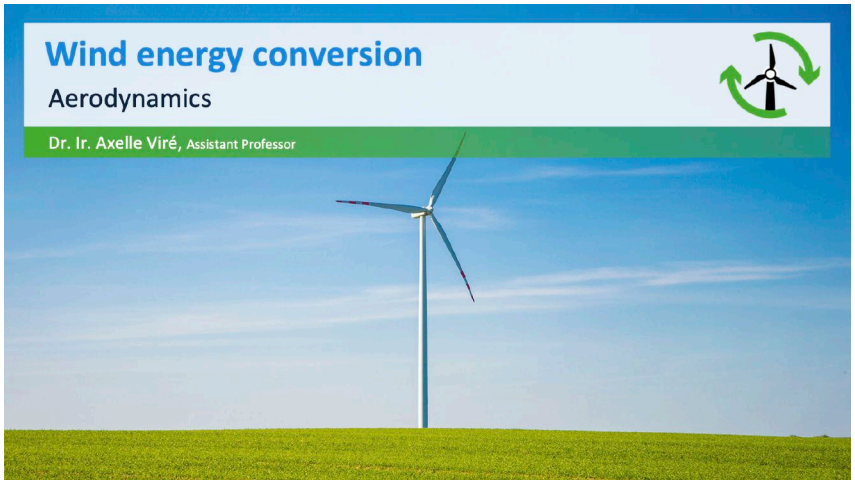




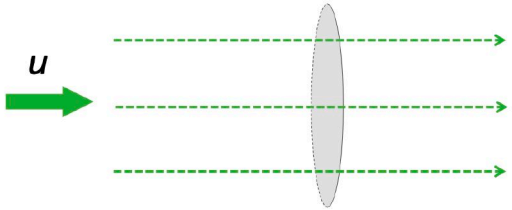
Length scale:	100 – 1000 km	< 1 km	< 10 m
Time scale:	Month	Day	Mins

Wind characteristics

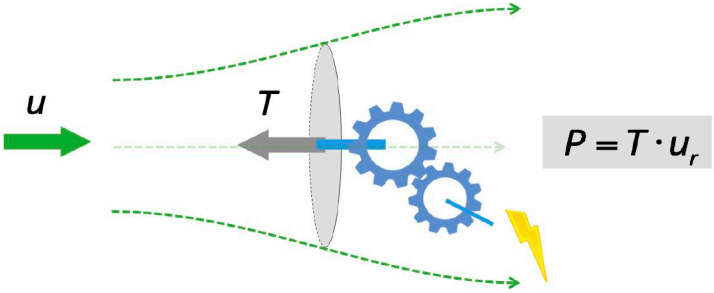




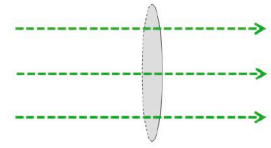
Effect of a plate on a wind flow



Effect of a plate on a wind flow

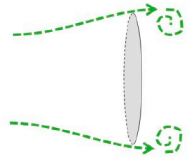


Effect of a plate on a wind flow



$u_r = \max$
$T = 0$

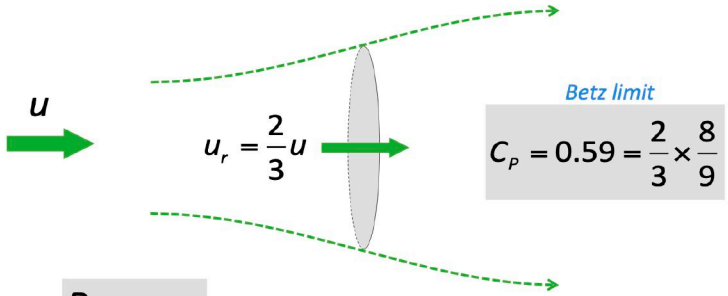
$P = 0$



$u_r = 0$
$T = \max$

$P = 0$

Optimum power extracted

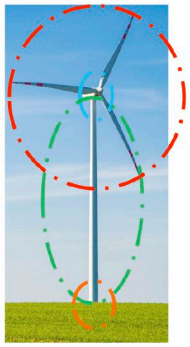


Betz limit

$$C_P = 0.59 = \frac{2}{3} \times \frac{8}{9}$$

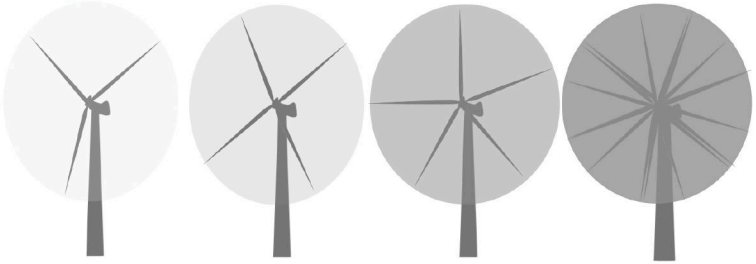
$$P = \max$$

Wind turbine components



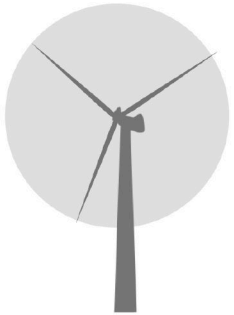
- Blades
- Rotor hub and nacelle
- Tower
- Foundation

Why 2 or 3 blades?

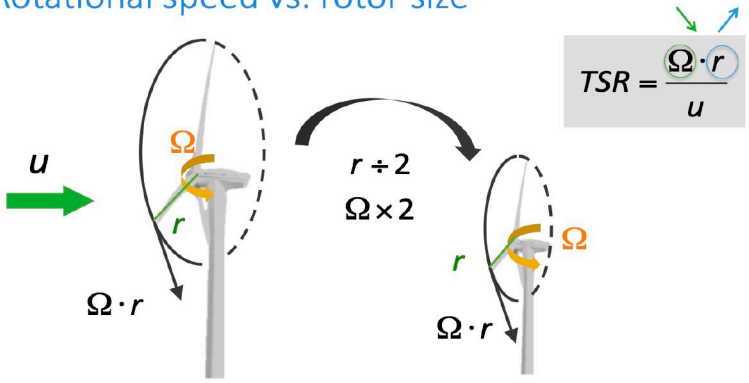


3 blades *4 blades* *5 blades* *6 blades*

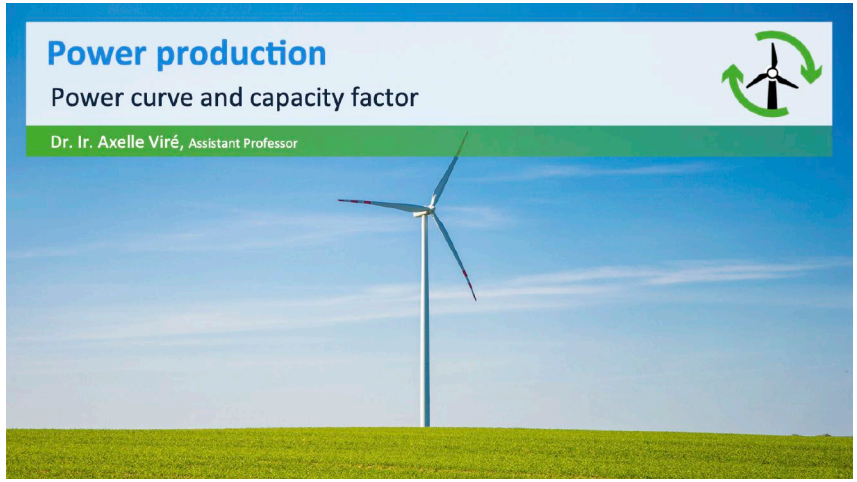
Effect of the rotation speed



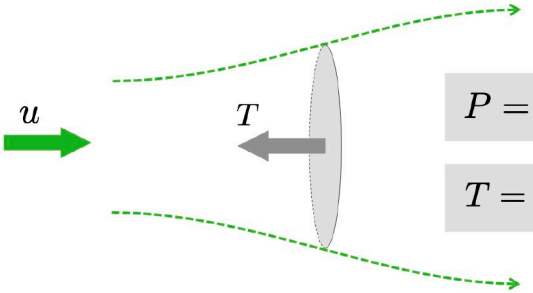
Rotational speed vs. rotor size



$$TSR = \frac{\Omega \cdot r}{u}$$



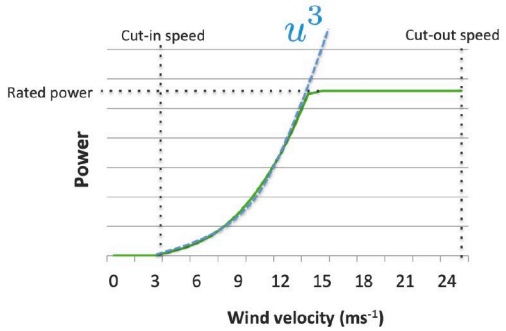
Power produced by a wind turbine



$$P = T \cdot u_r \sim u_r^3$$

$$T = \dot{m} \cdot u_r \sim u_r^2$$

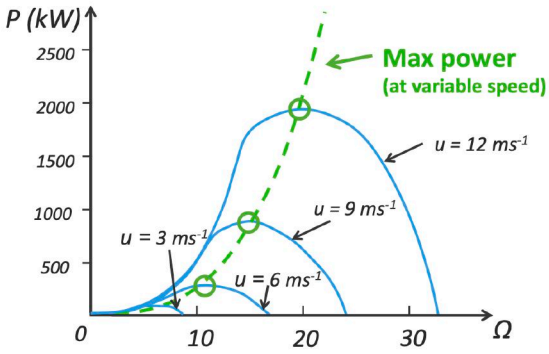
Power produced by a wind turbine



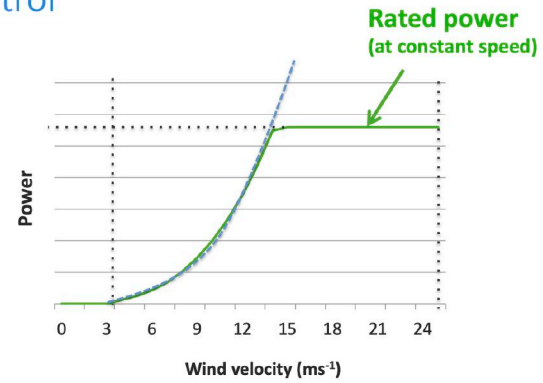
Wind turbine control

- Control in normal conditions
- Control in off-design conditions

Torque control



Pitch control



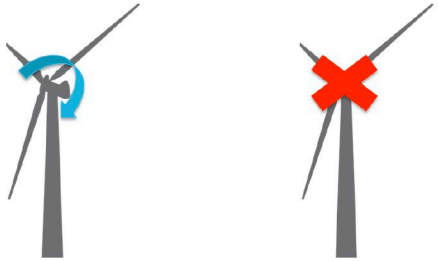
Capacity factor

$$c_f = \frac{T_{equivalent}}{T_{actual}}$$

T_{actual} = actual time to achieve production (e.g. 1 year for the yearly production)

$T_{equivalent}$ = equivalent time to achieve the same production if running constantly at full power

Capacity factor

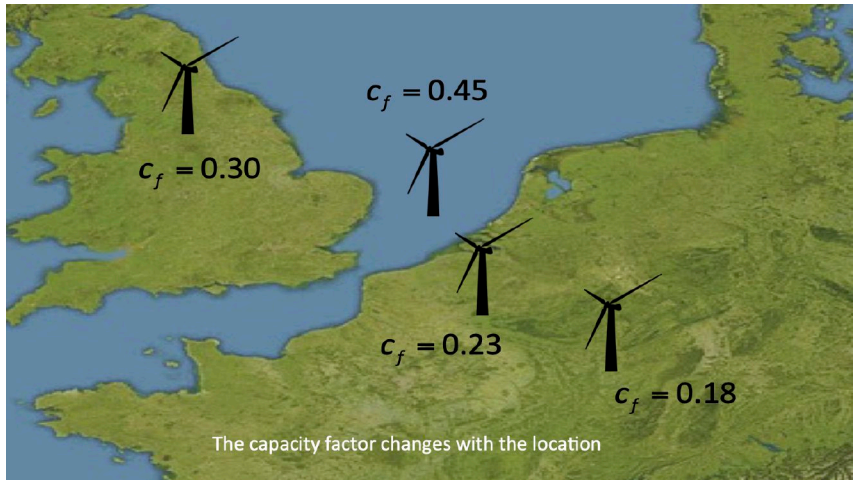


Full power all year

$c_f = 1$

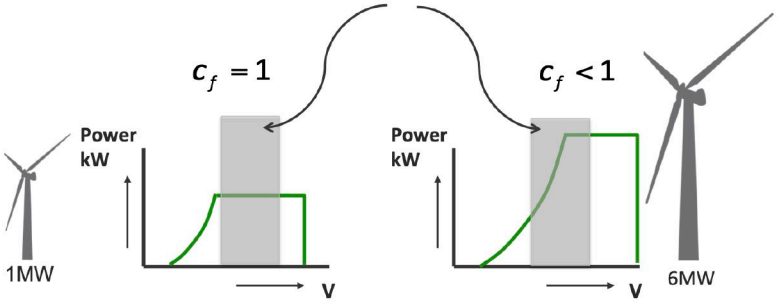
Switched off all year

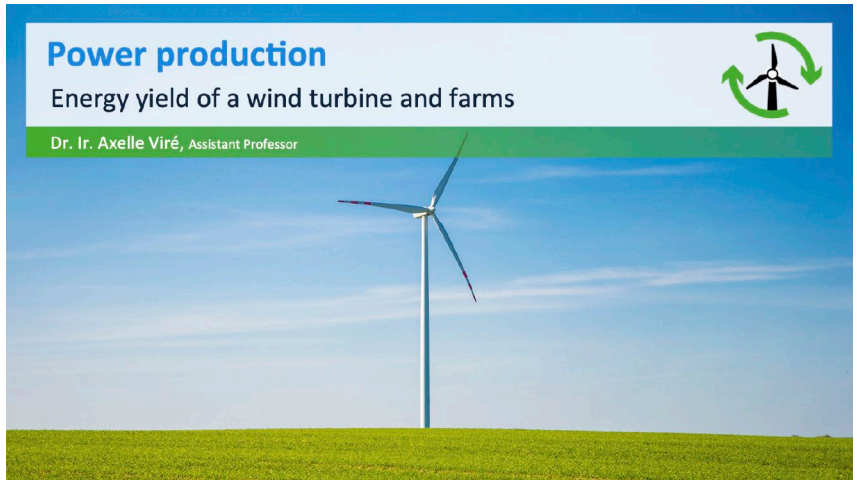
$c_f = 0$



Capacity factor

Wind speeds between 10 m/s and 20 m/s

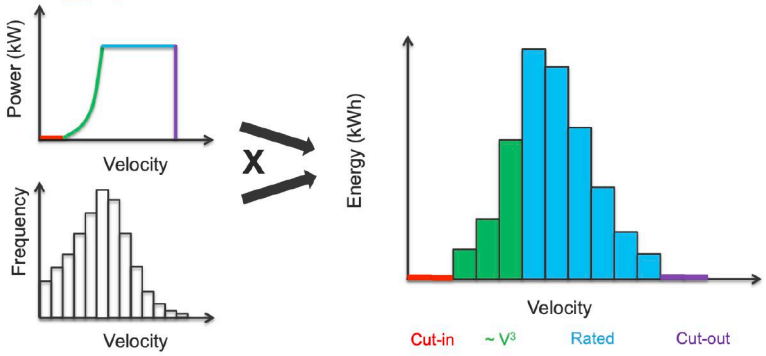




Prerequisites

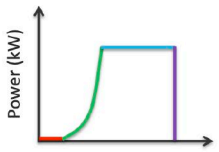
- Wind characteristics through probability density functions (histograms)
- Power curve
- Capacity factor

Energy yield of one wind turbine



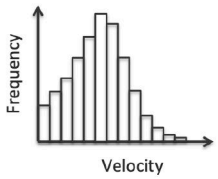
Energy yield calculation

Do you have turbine data?



X

Do you have wind data?



Energy yield calculation

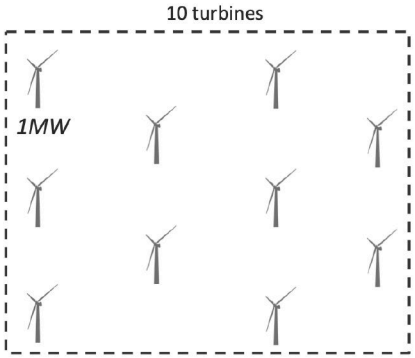
Or do you have 'nothing'?

Energy yield = hours/year * installed power * cf

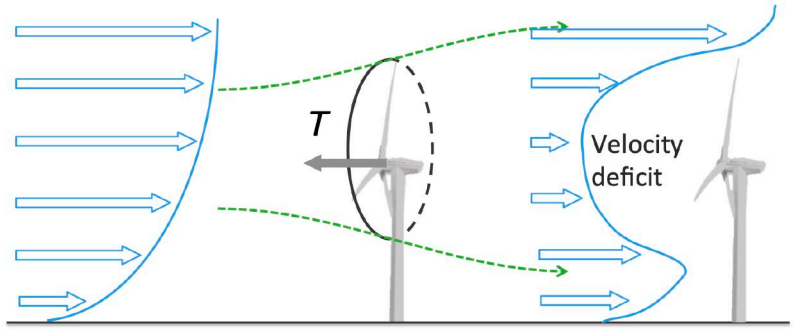
Estimate: capacity factor (cf) ≈ 0.25 onshore
≈ 0.35-0.45 offshore

Energy yield of a farm

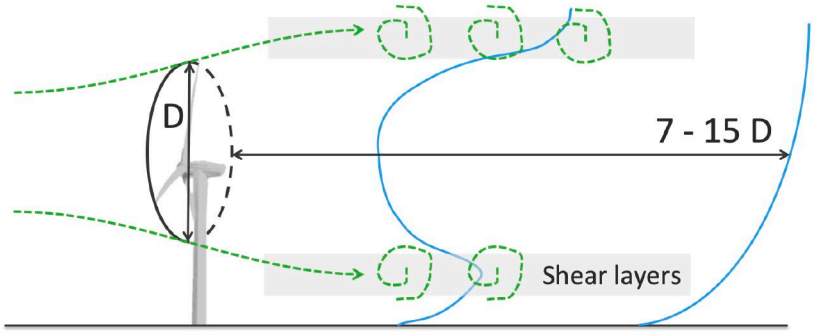
Does this farm produce 10 MW?



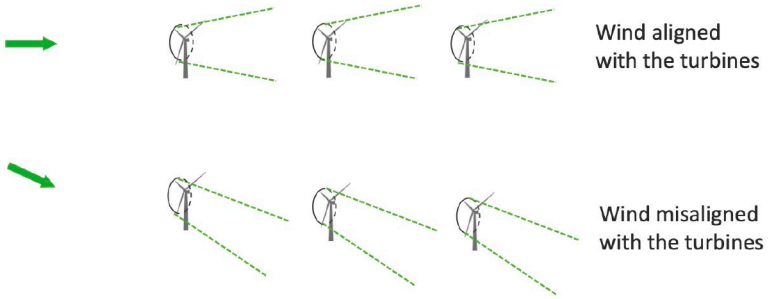
Wake effects

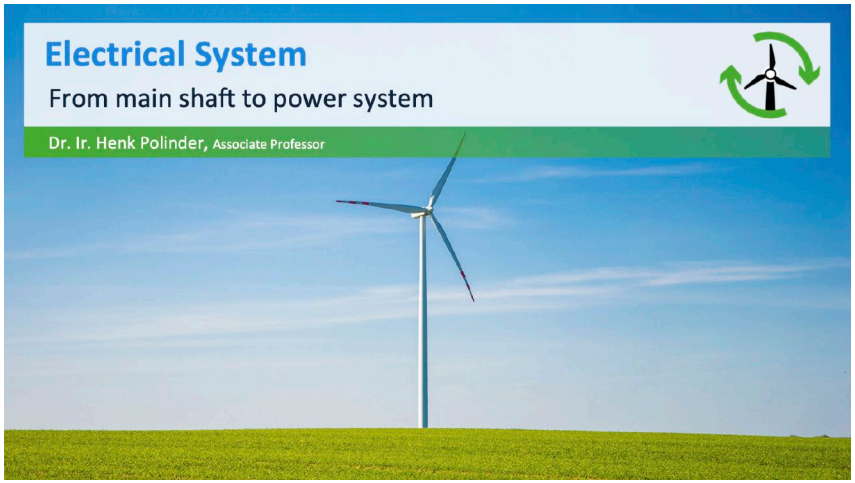


Wake effects



Wake effects

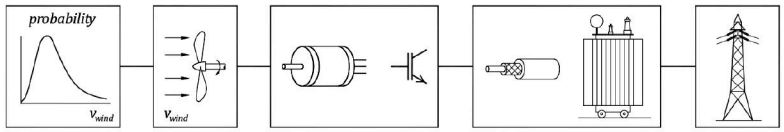




Requirements electrical system

1. Power curve
2. Speed range
3. Voltage and frequency for grid connection
4. Minimum cost of energy
5. Control, safety and protection

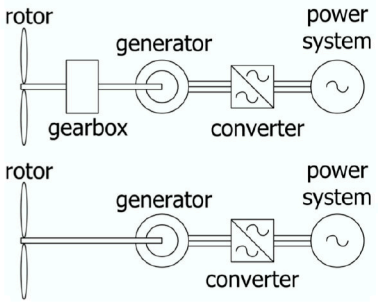
From main shaft to power system



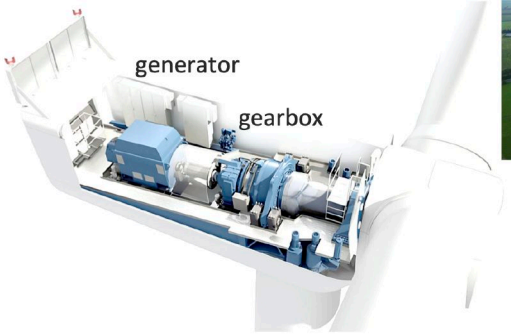
Secondary conversion: two main systems

Geared drive
- Gearbox
- Small high speed generator

Direct drive
- No gearbox
- Large low speed generator

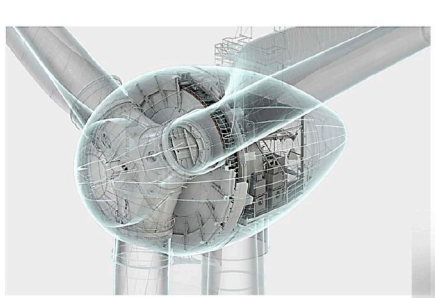


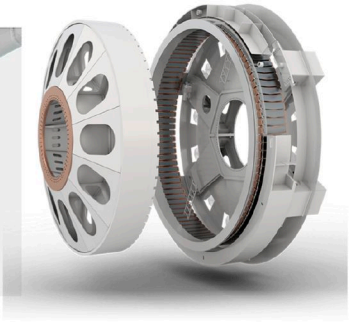
Geared drive: Nordex N117/3000 3 MW



1. Source: https://www.wind-energy-market.com (May, 2016), courtesy Nordex.
2. Source: www.nordex-online.com (May, 2016).

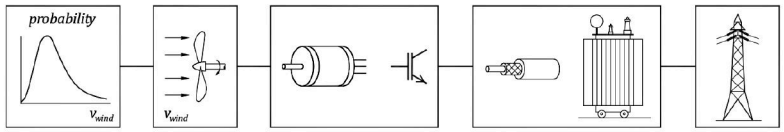
Direct drive: Enercon E-126 7.6 MW





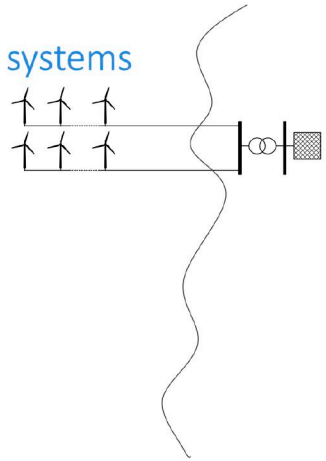
Source: www.enercon.de (May, 2016)

From main shaft to power system



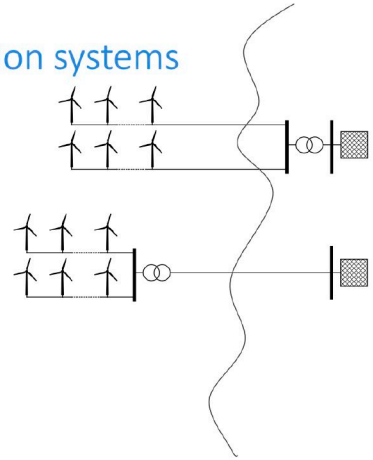
Collection and transmission systems

- OWEZ
  - 108 MW
  - 10 km



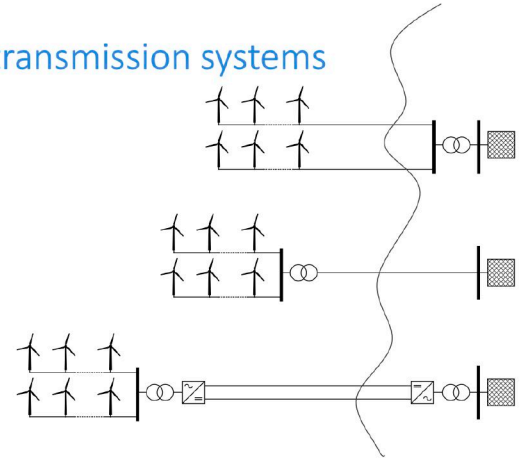
Collection and transmission systems

- OWEZ
  - 100 MW
  - 10 km
- Prinses Amalia
  - 120 MW
  - 23 km

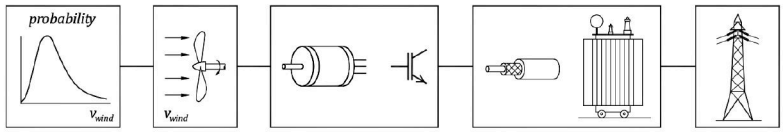


Collection and transmission systems

- OWEZ
  - 108 MW
  - 10 km
- Prinses Amalia
  - 120 MW
  - 23 km
- Bard Offshore 1
  - 400 MW
  - 90 km

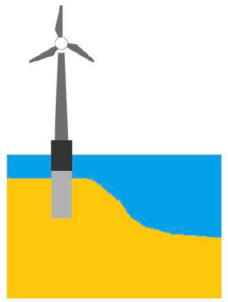


From main shaft to power system



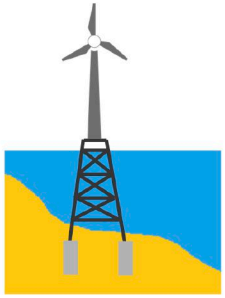
Moving offshore

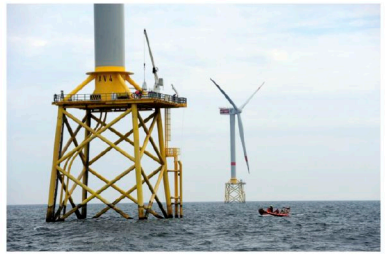
Moving offshore



Source: www.londonarray.com (May, 2016)

Moving offshore





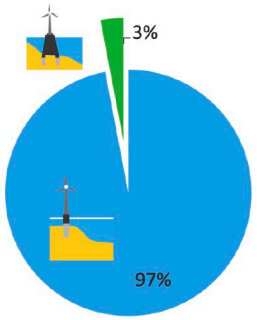
Source: www.offshorewind.biz (May, 2016)
Location: Alpha Ventus wind farm, Germany, www.4coffshore.com (May, 2016).

Types of offshore foundations

Newly installed foundations in Europe in 2015

- 97% monopiles (385 structures)
- 3% jackets (12 structures)

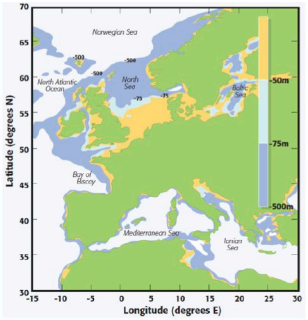
In 2015, there were 3,313 foundations installed offshore in Europe



1. *The European offshore wind energy industry*, EWEA (2016) .

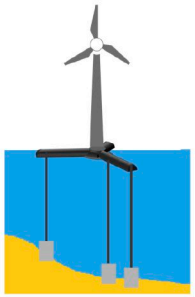
Water depths in Europe

- Most seas are deeper than 50 metres
- Existing commercial foundations are not economically viable in deep seas

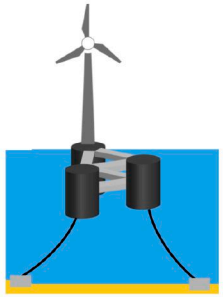


Source: N. Anscombe, *Turbines take float*, Power Engineer, Vol. 18, Issue 3 (2004)

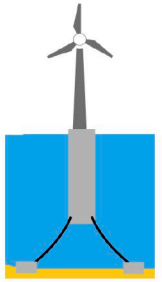
Floating wind turbines



Tension leg platform

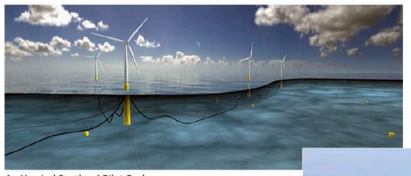


Semi-submersible

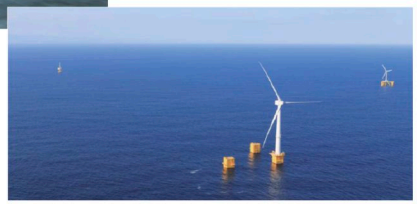


Spar buoy

Floating wind turbines



1. Hywind Scotland Pilot Park



2. Fukushima floating offshore wind farm demonstration project

1. Source: http://www.statoil.com (Aug. 2016)
2. Source: http://www.fukushima-forward.jp (Aug. 2016)

Innovative wind turbine rotors

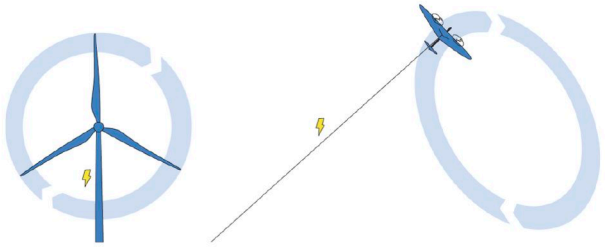
1. Vertical-axis wind turbine

2. Two-blade downwind wind turbine

3. Segmented Ultralight Morphing Rotor

1. Source: http://floatingwindfarms.com/about.html (Aug. 2016)
2. Source: http://2benergy.com/windturbine/key-features/#prettyPhoto (Aug. 2016)
3. Source: Ichter, Steele, Loth, Moriarty, 42nd AIAA Fluid Dynamics Conference and Exhibit, New Orleans (2012), http://arc.aiaa.org/doi/pdf/10.2514/6.2012-3270

Airborne wind energy



Source: Airborne Wind Energy, Ahrens, Diehl, Schmehl Eds., Springer (2013)