Course: EE 599d Wind energy conversion systems (WECS)

Brief introduction of instructor

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Kindly introduce yourself

1. Name:
2. Registration #
3. Organization name, your job description?
4. Where are you from?University
5. Email* & mobile#
6. 1st/last semester
7. MATLAB/SIMULINK understanding?

Please select your Class representative & make WhatsApp group

Compulsory Text

- Power Conversion and Control of Wind Energy Systems by B. Wu, Y. Lang, N. Zargari, and S. Kouro Wiley-IEEE Press,2011, ISBN: 978-0-470-59365-3.

- Download pdf from: http://b-ok.org/

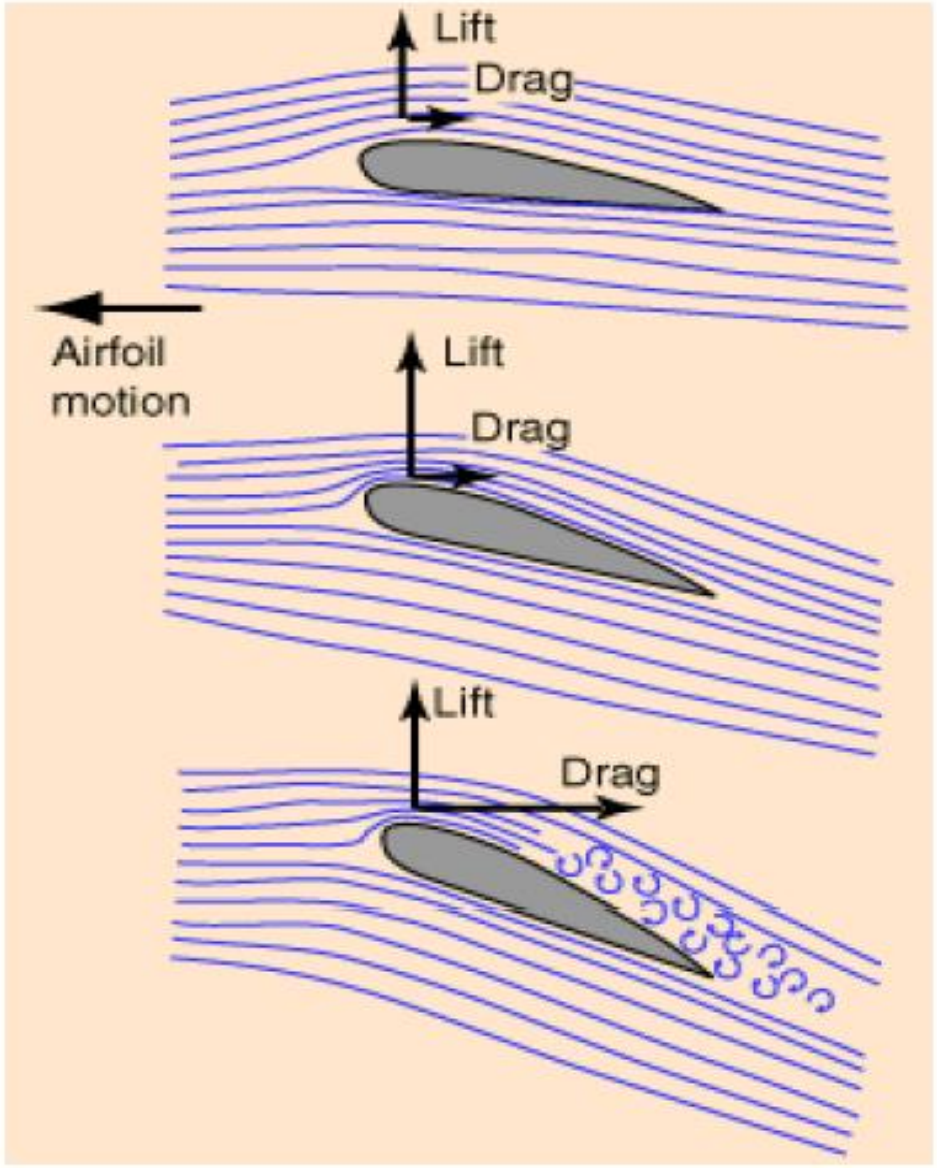
Lecture notes would be available on

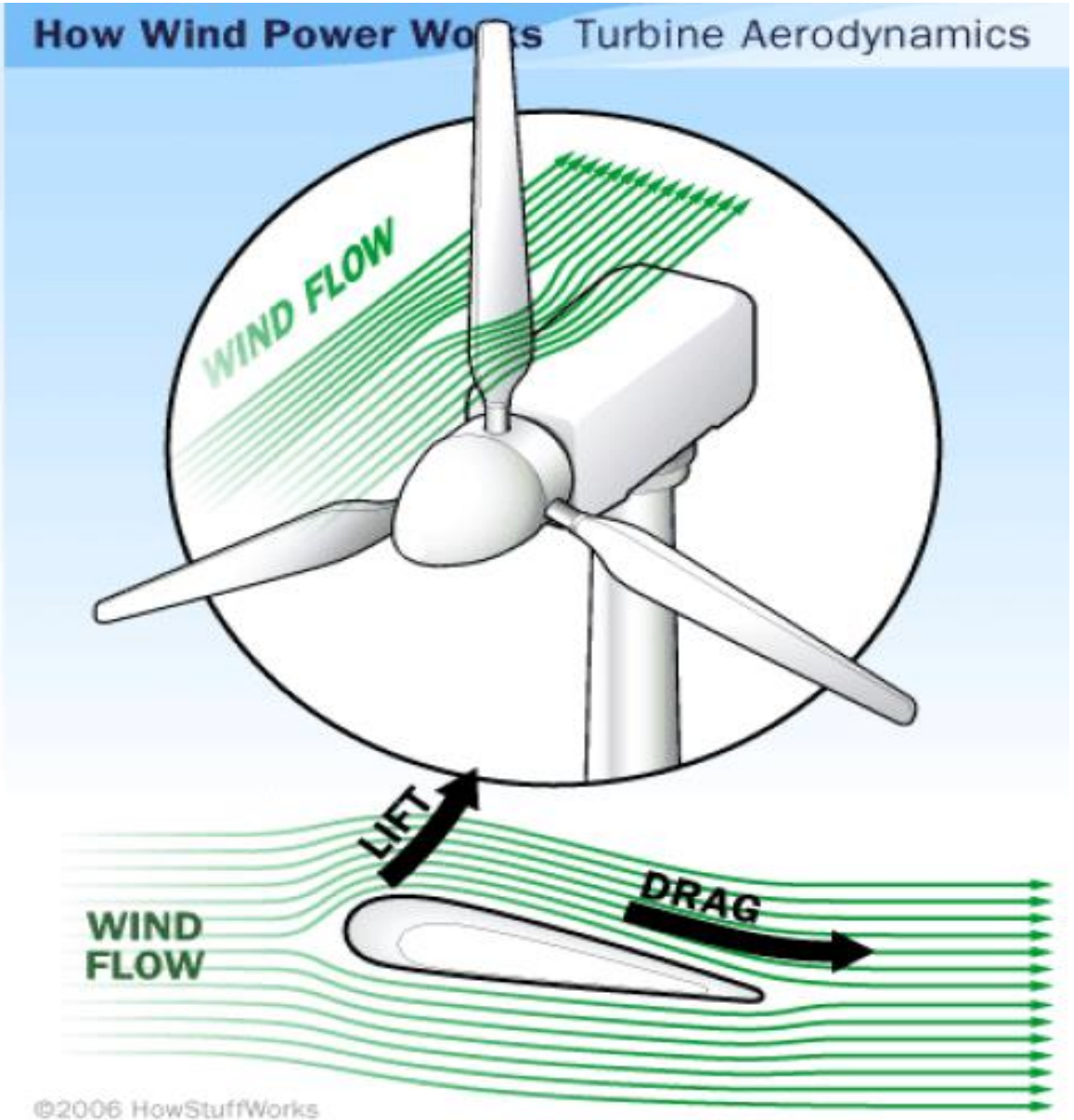
- https://piazza.com/configure-classes/spring2019/ee599d
- Access code:ee599d

Wind energy conversion systems (WECS) comprise of:

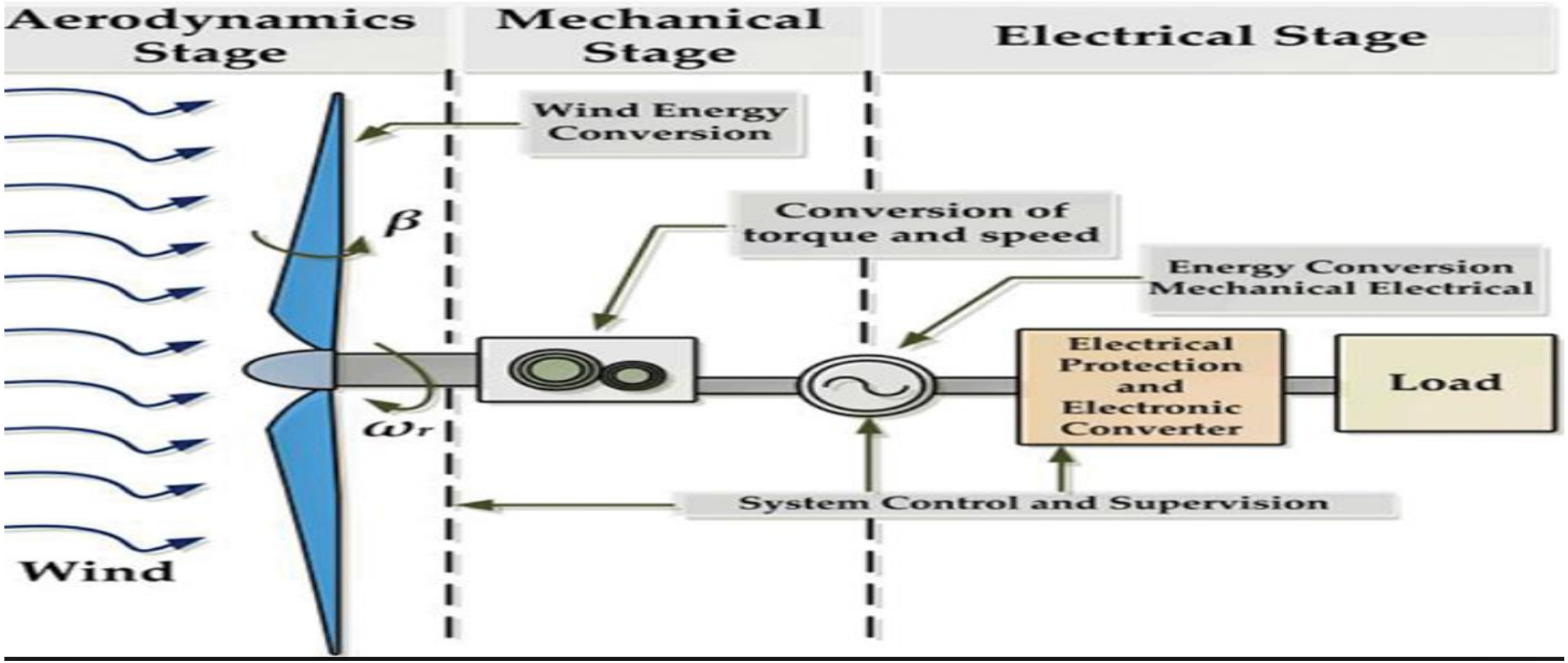
6 parts

1.Aerodynamics

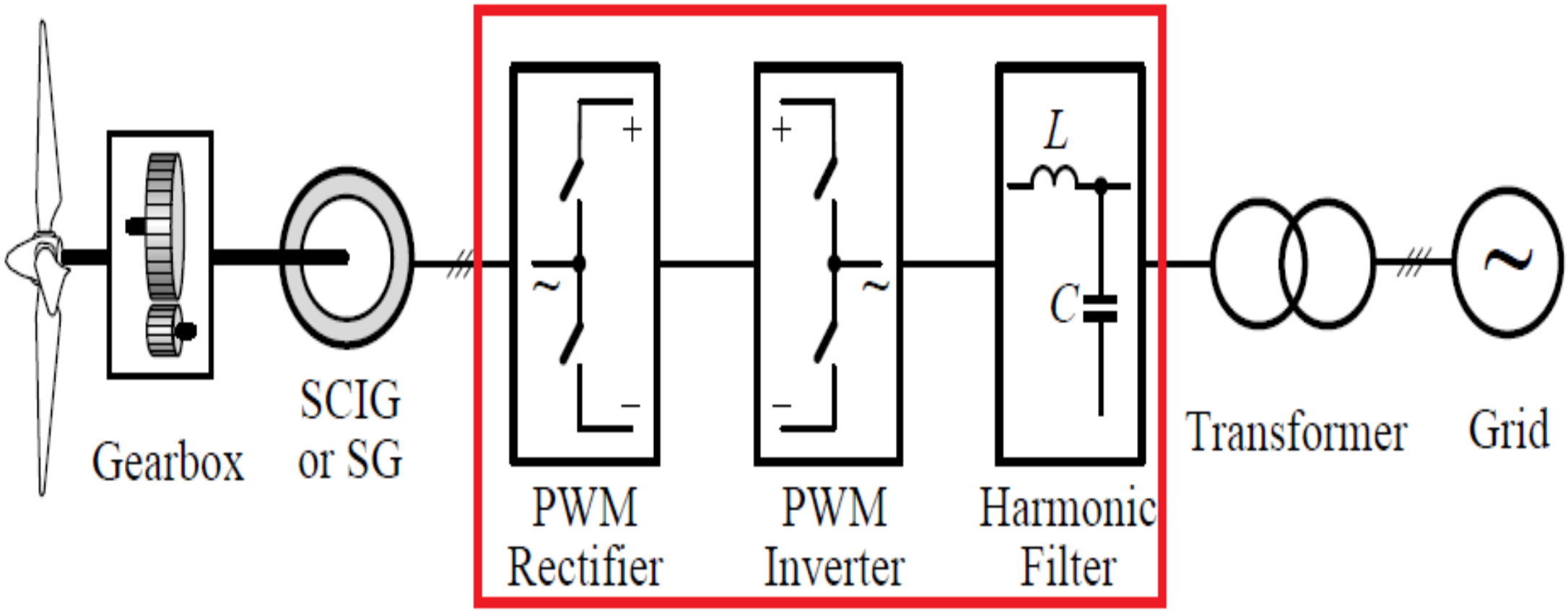




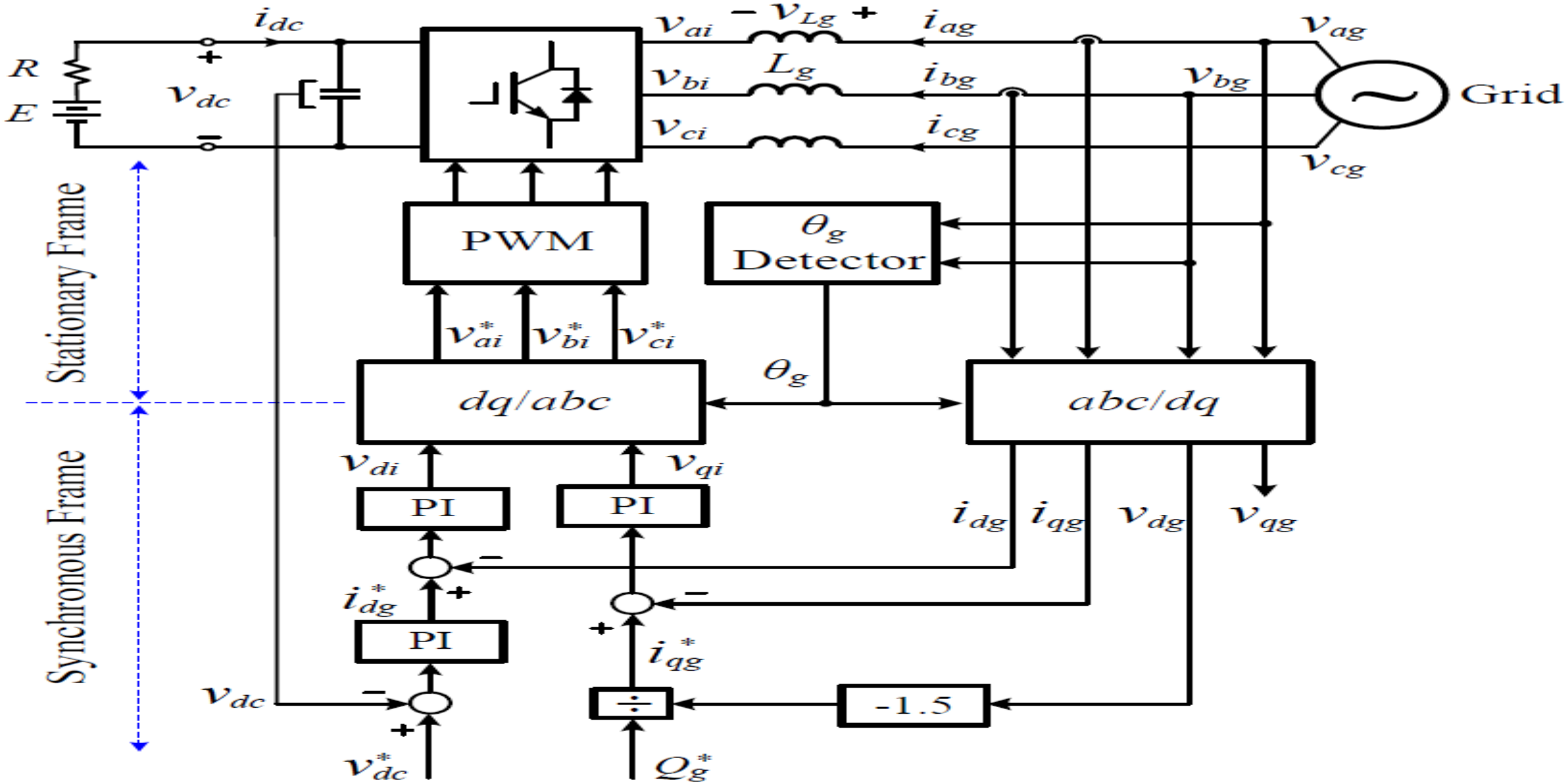
2. Mechanical systems and 3.Electrical machines



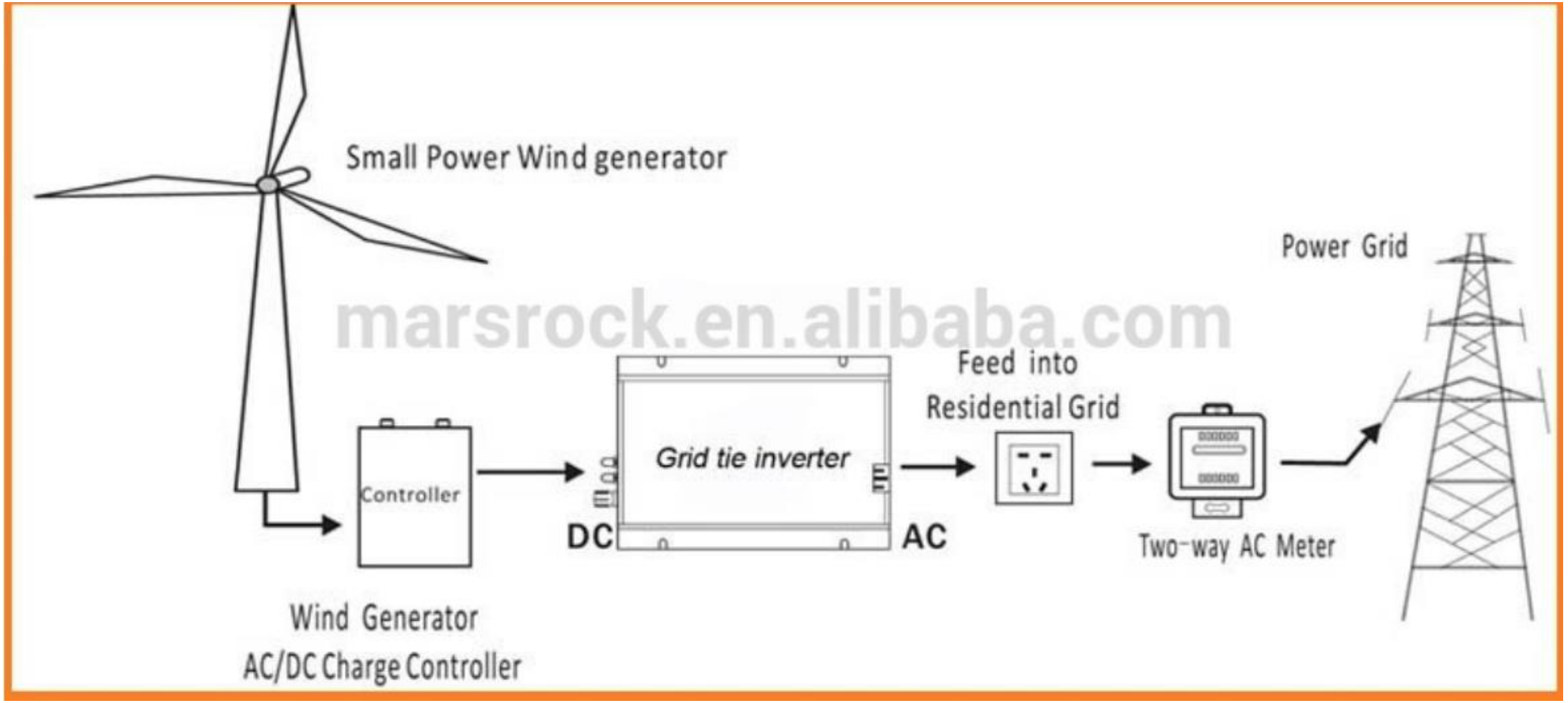
4.Power converters



5.Control theory



6.Power systems



We shall study all parts excepts 2 and 6

1. Aerodynamics
2. ~~Mechanical systems~~
3. Electric machines
4. Power electronics
5. Control theory and
6. ~~Power systems.~~

Course Description

This course shall provide a comprehensive and in-depth analysis on:

1. wind generators
2. system configurations;
3. power converters,
4. control schemes, and
5. dynamic steady-state performance of various practical wind energy systems.

In Chapter 1 we shall study:

1. Overview of market survey,
2. Wind turbine technology,
3. Wind energy system classifications,
4. Costs, &
5. Grid codes for wind power integration.

In Chapter 2 we shall study:

- The fundamentals and control principles of wind energy systems including:
- wind turbine components,
- aerodynamics,
- stall and pitch controls, and
- maximum power point tracking schemes.

In Chapter 3 we shall study:

- Commonly used wind generators, including:
- squirrel cage induction generators,
- double fed induction generators and
- synchronous generators.
- Derivation of the dynamic and
- steady-state models of these generators to facilitate the analysis of wind energy systems.

In Chapter 4 we shall study:

- Various power converters and
- PWM schemes used in wind energy systems.
- Both voltage and current source converters with an emphasis on high-power wind energy system.

In Chapter 8 we shall study:

1. Discussion on doubly fed induction generator (DFIG) systems,
2. investigation of the sub-synchronous and super-synchronous modes of operation,
3. Stator Voltage Oriented Control of DFIG WECS.

We can understand theory with the help of:

1. Associated problems
2. Simulation models &
3. Case studies.

Lecture#01(Section 1.1 to 1.2)

1.1 Introduction……Wind energy potential in Pakistan

1.2 Overview of Wind Energy Conversion Systems

1.2.1 Installed Capacity and Growth Rate

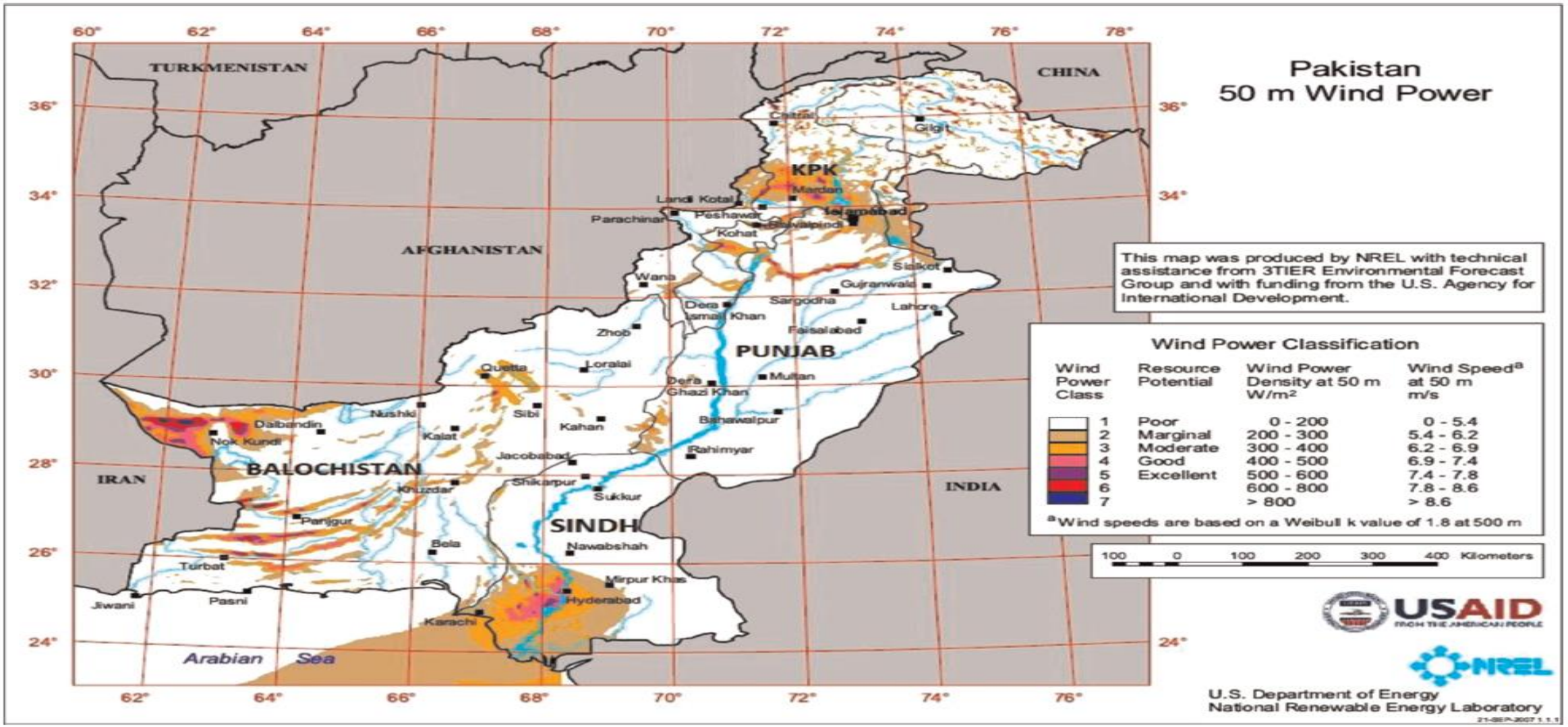
1.2.2 Small and Large Wind Turbines

1.2.3 Standalone and Grid-Connected Applications

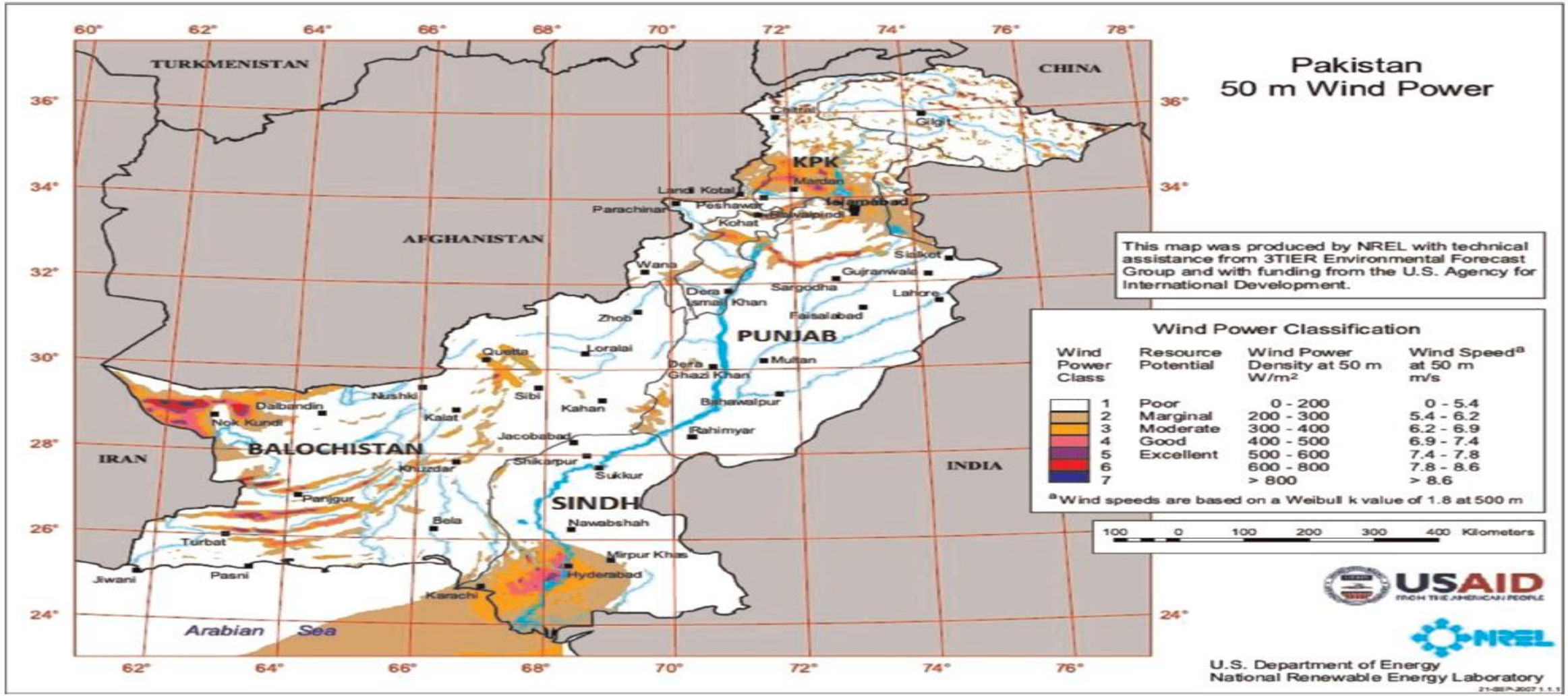
1.2.4 On-land and Offshore Applications

1.2.5 Costs of Wind Energy Conversion System

Wind energy potential in Pakistan



Pakistan has massive wind energy potential, especially in 3 of its 4 provinces. Guess from wind-map of Pakistan?



1. Khyber Pakhtun Khwa (KPK)

2. Sindh

3.Balochistan

Pakistan is facing increasing power shortage.How many years?

Last 2 decades

Government of Pakistan (GoP) is offering incentives for private investment to generate electricity at cheap rates.

New hydropower dams were proposed in the past, e.g Kalabagh Dam, but could not be commissioned to date.

Fossil fuels are depleting & oil has to be imported for oil-fired power plants, which is highly expensive & a burden for country’s economy.

In this frustrating situation, there is dire need for exploration & installation of alternate renewable energy resources, in particular, wind energy & solar energy, to be integrated with the national power grid.

Please read paper that how much wind energy can be harnessed from the 3 provinces?

Renewable and Sustainable Energy Reviews 53 (2016) 408–421

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Evaluating wind energy potential in Pakistan's three provinces, with proposal for integration into national power grid

Sajjad Haider Shami [a,*], Jameel Ahmad [a], Raheel Zafar [a], Muhammad Haris [a], Sajid Bashir [b]

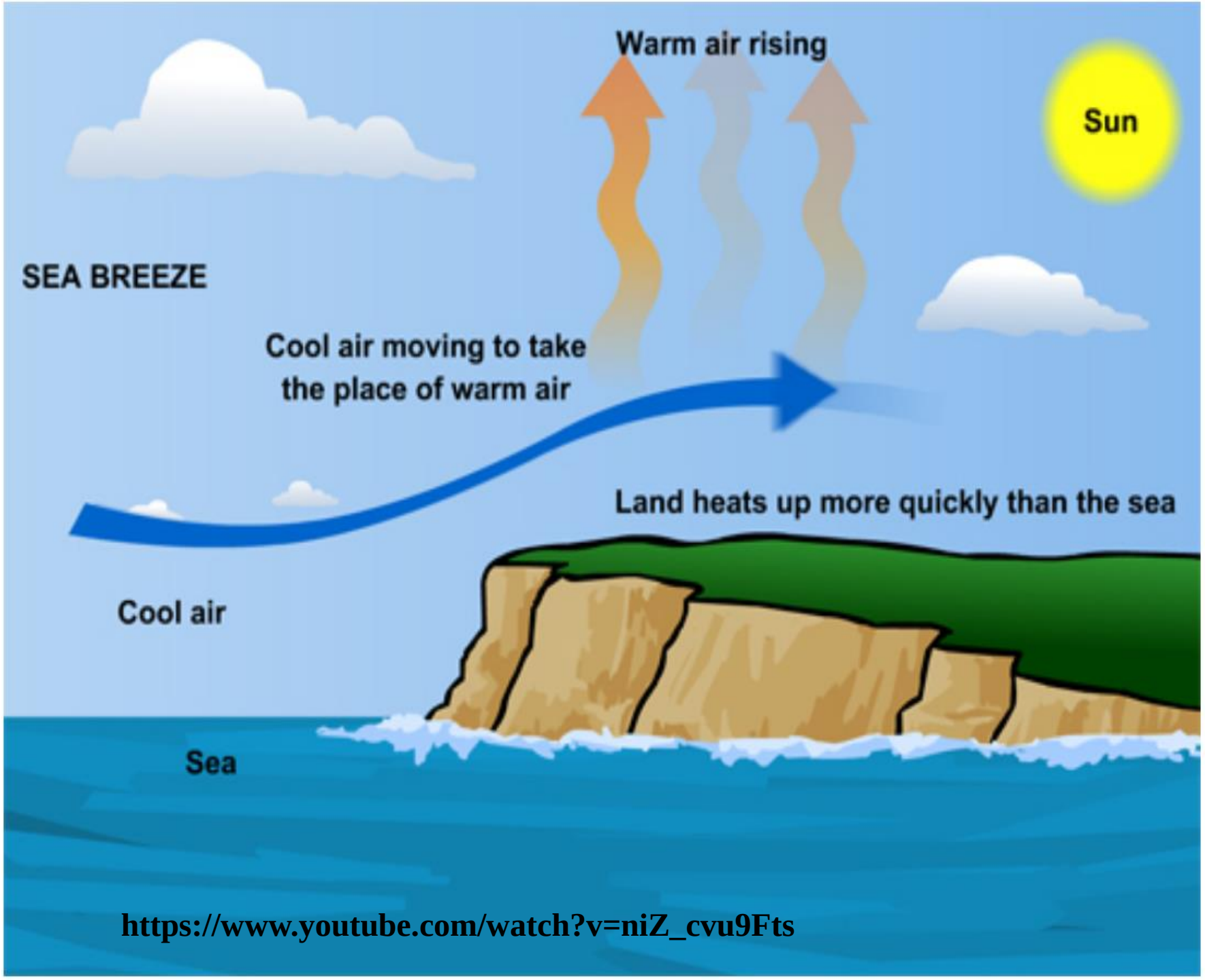
Let’s discuss some basic terminologies

Q.What is the difference between air and wind?

What Makes Wind?

1.The sun shines on land and water.
2.Land heats up faster than water?
3.Warm air over land rises.
4.Cool air over water moves in.
Thus:

Wind is moving air



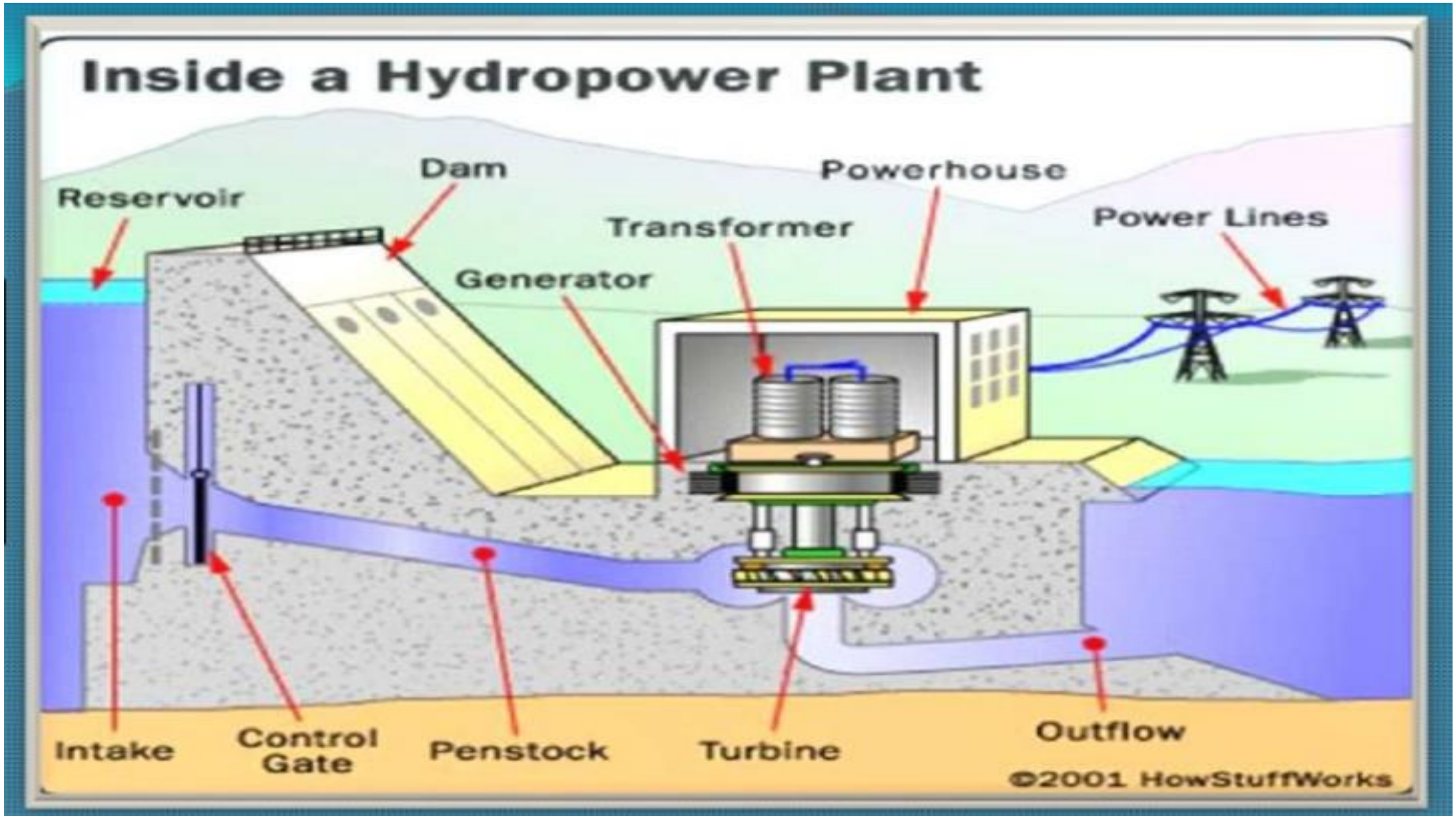
https://www.youtube.com/watch?v=niZ_cvu9Fts

Q. What are renewable energy sources?

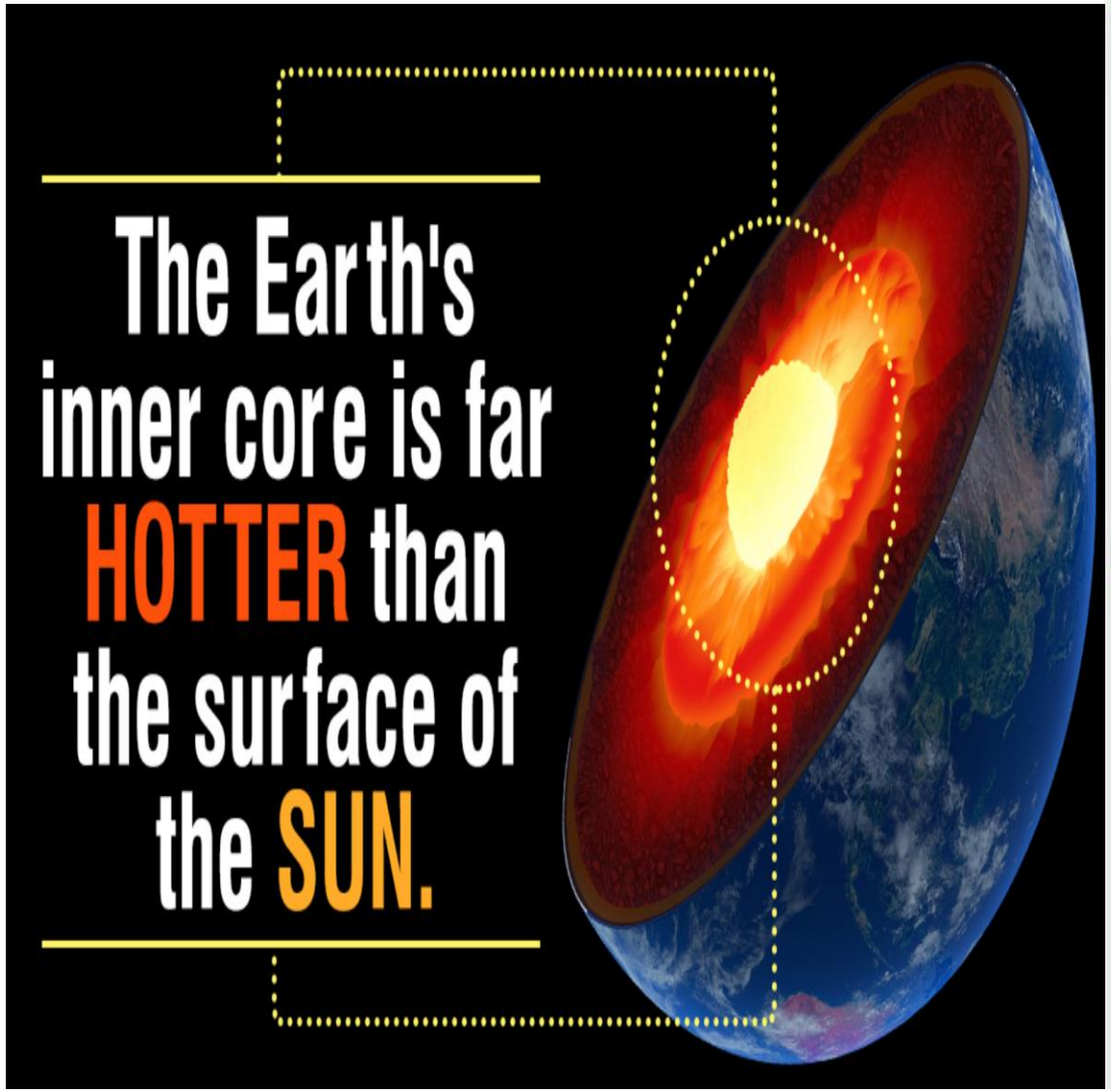
1. Solar **energy**

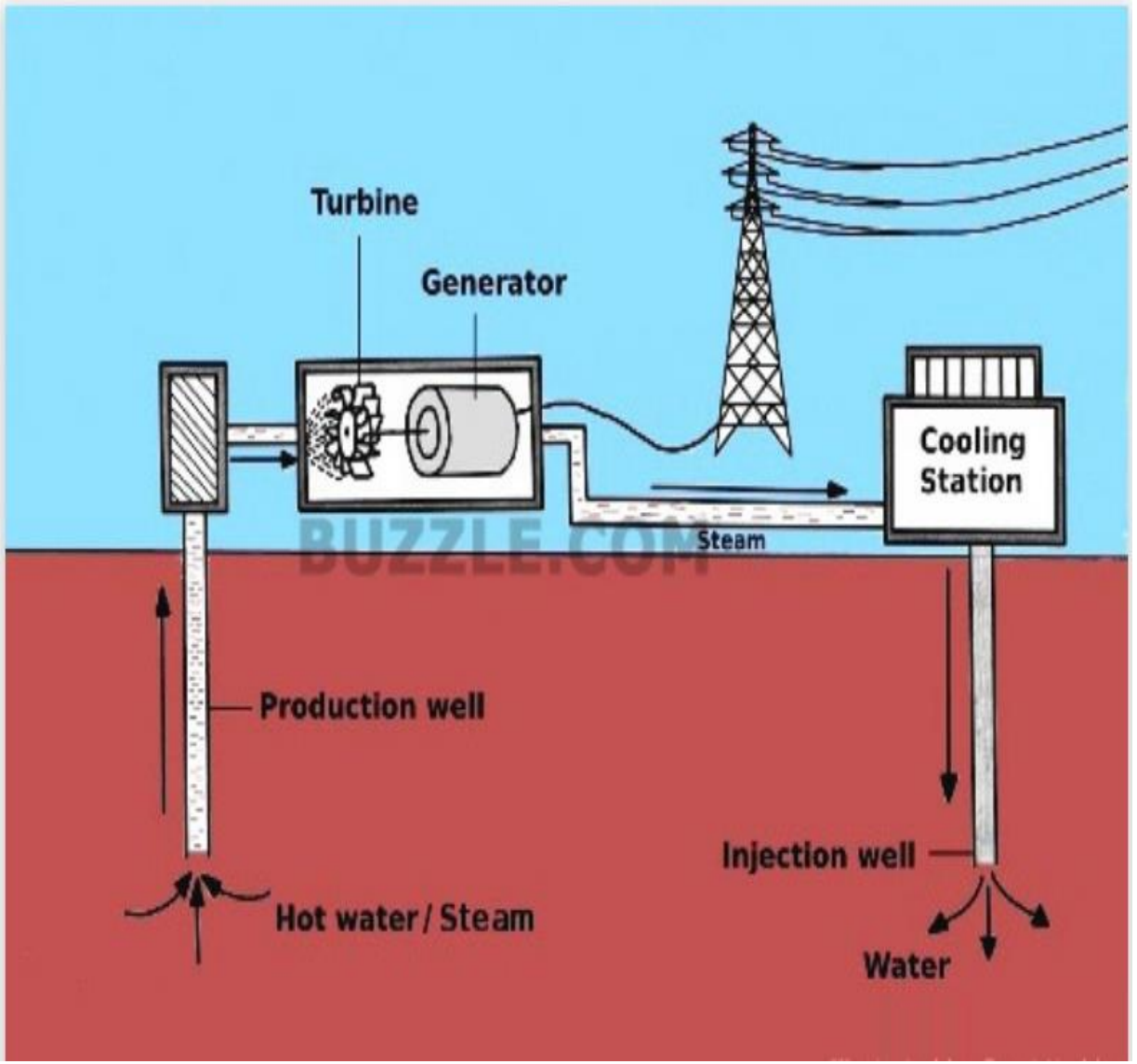
2-Wind **energy**

3-Hydropower

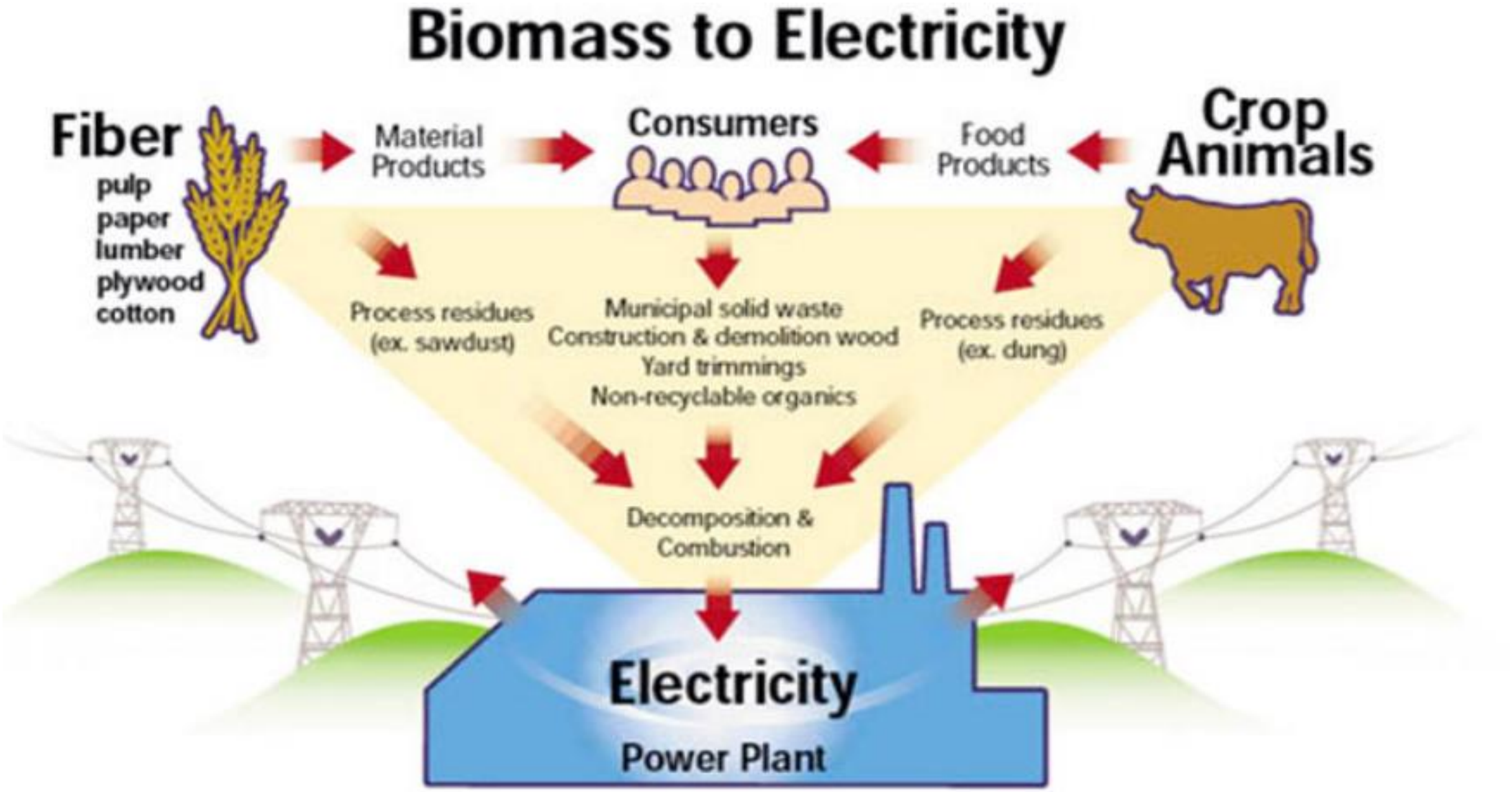


4-Geothermal **energy**





5-Biomass **energy**



Q. What are fossil fuels?

1-Coal

2- Oil

3- Natural gas

Remember the three fossil fuels are:

coal

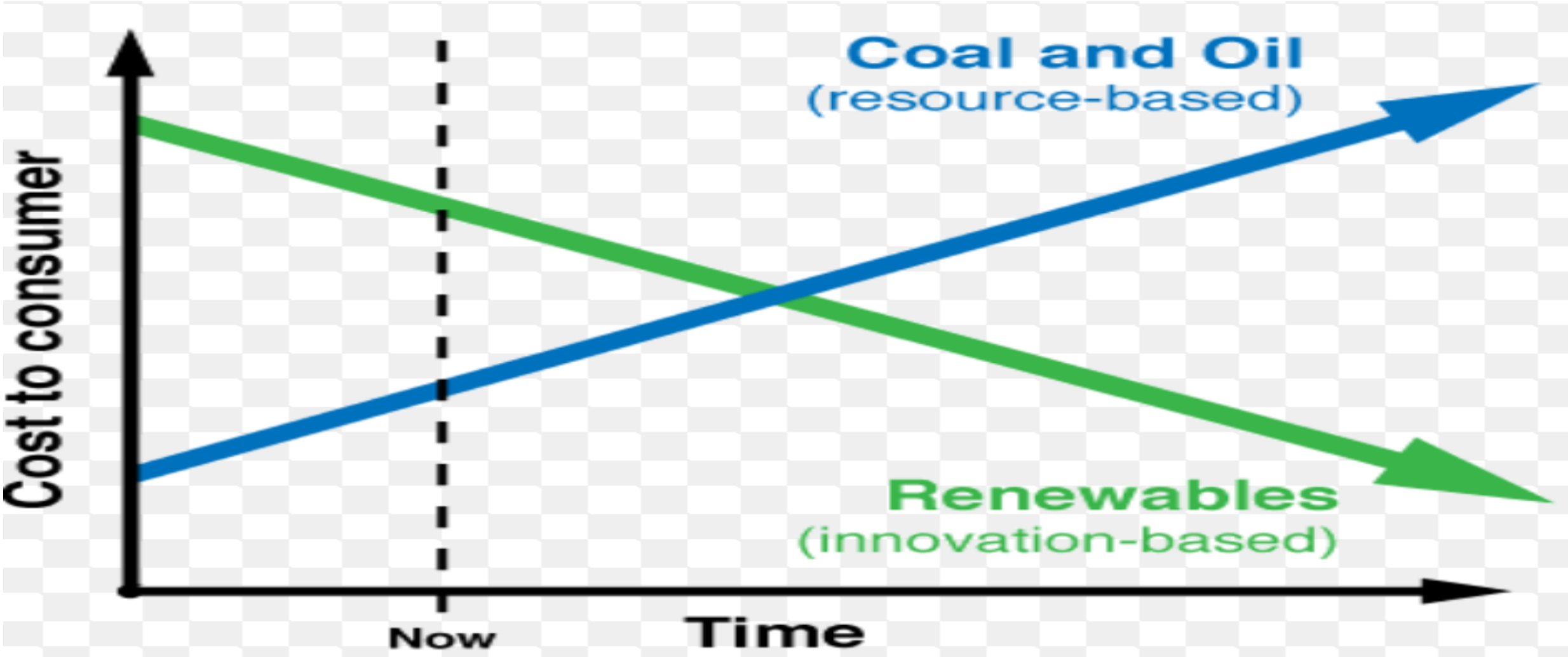
crude oil

natural gas

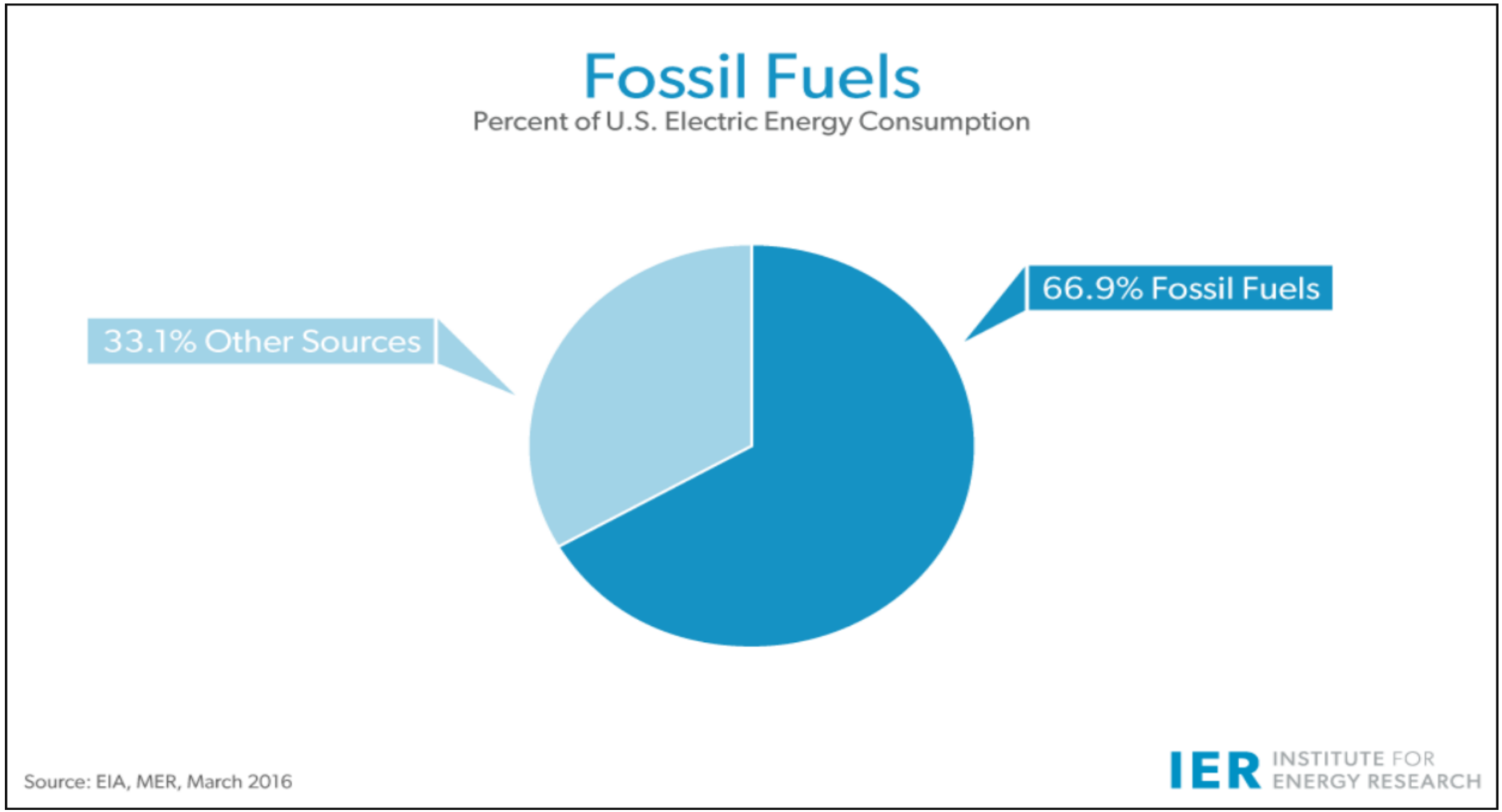
Renewable energy sources versus fossil fuels

Over last 2 decades renewable energy sources have been attracting great attention due to?

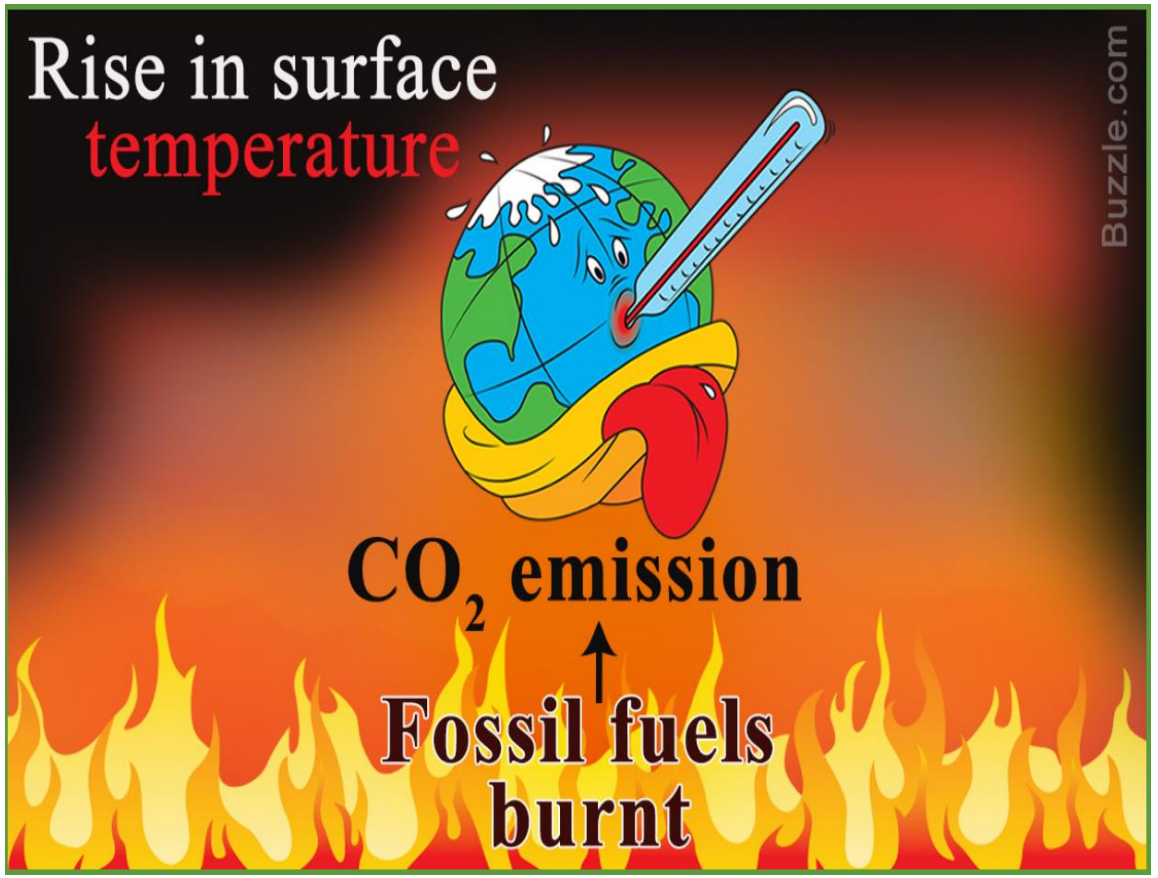
1.Cost increase



2-Limited reserves, and

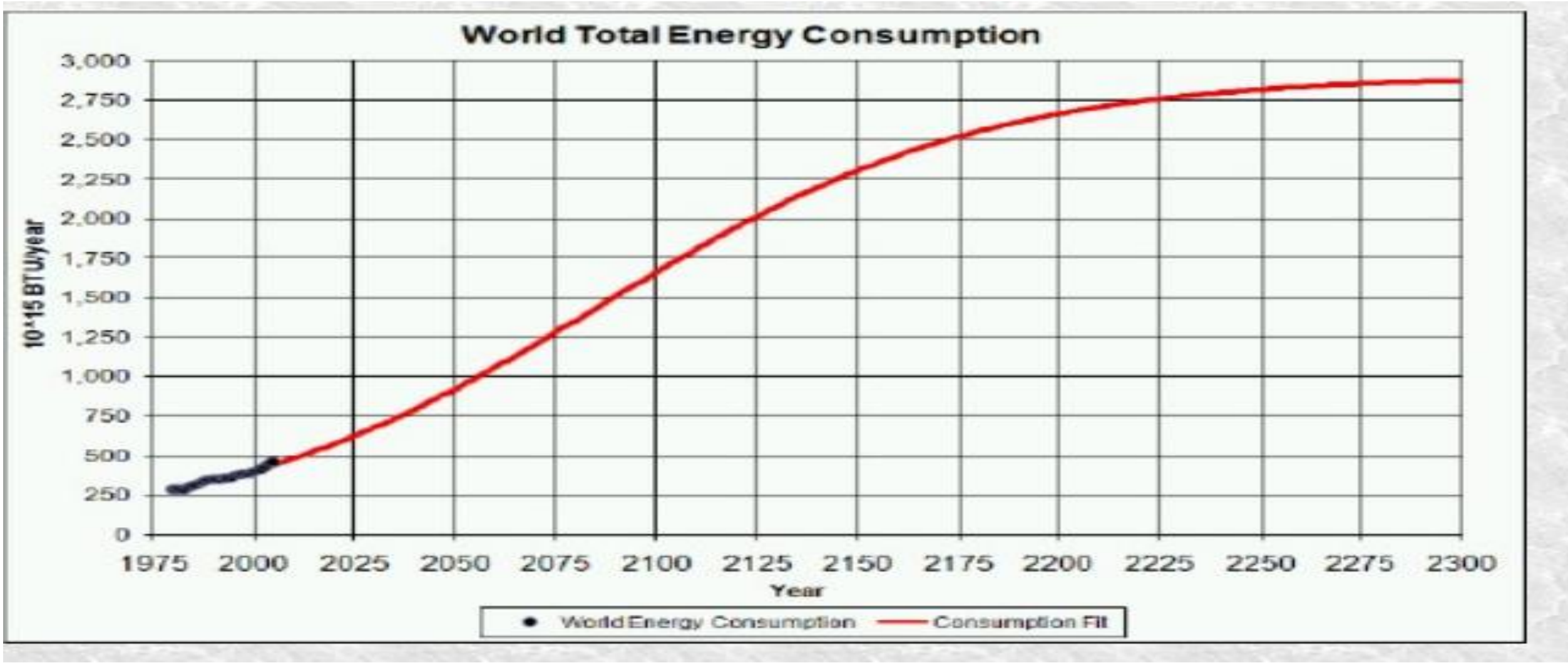


3. Adverse environmental impact of fossil fuels.



World’s need for energy likely to____ before 2050?

World's need for energy likely to double(×2) before 2050



If we further sort out renewable energy sources then which 1 would be the fastest growing?

- Solar energy
- Wind energy
- Hydropower
- Geothermal energy
- Biomass energy

Wind energy is 1 of the fastest growing renewable energy sources.

Why Wind Energy?

- Clean, 0 emissions
  - NO2, SO2, CO, CO2
  - Air quality, water quality
  - Climate change
- Reduce fossil fuel dependence
  - Energy independence
  - Domestic energy—national security
- Renewable
  - No fuel-price isssues

Video

History of Wind Energy

- Wind energy has been used for 100 of years for:

1. milling grains,
2. pumping water, &
3. sailing at sea.

History of Wind Energy(cont…)

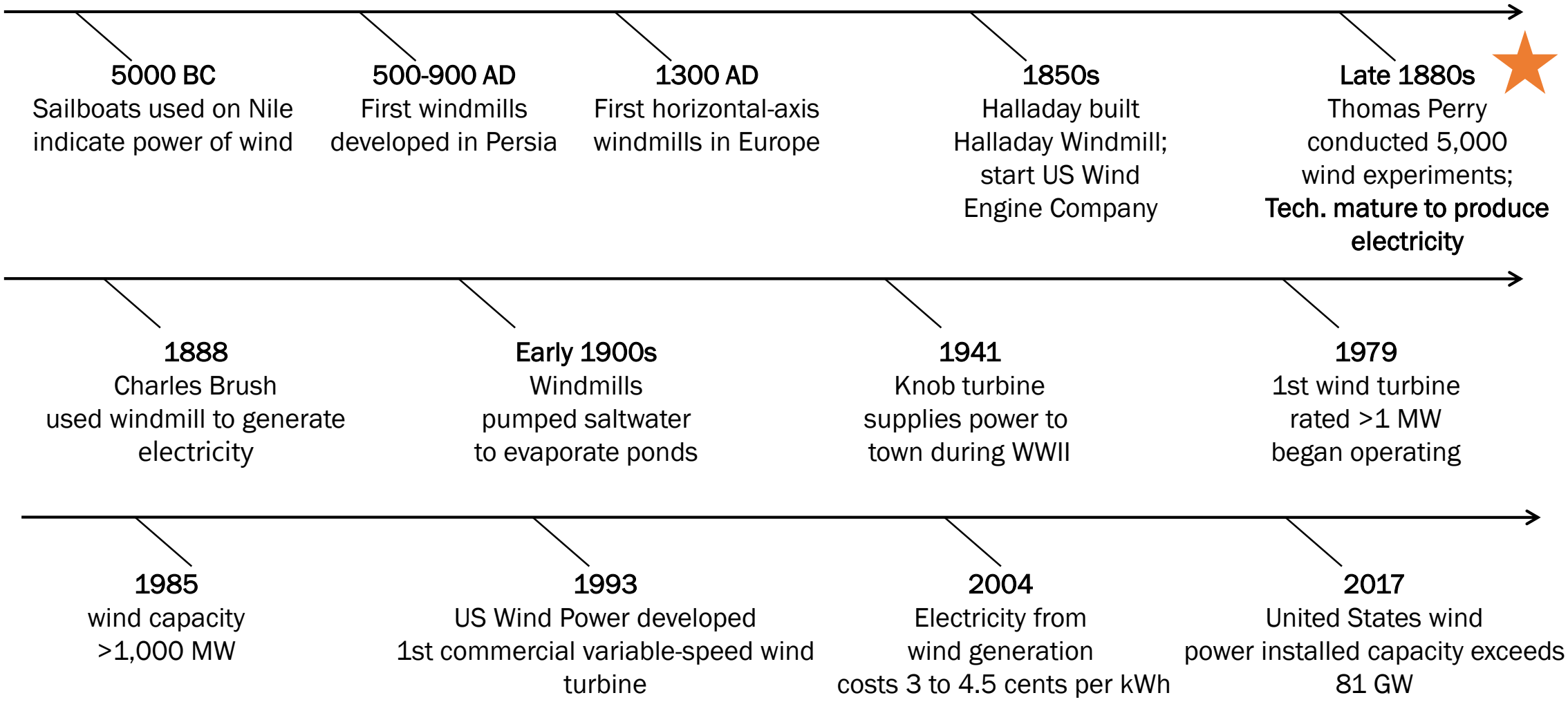
- Use of windmills to generate electricity can be traced back to late 19^{th} century with development of a:
- **12 kW dc windmill generator .**

Technology maturity

- Since 1980s the technology has become sufficiently mature to produce electricity:

1. **Efficiently &**
2. **Reliably.**

History of Wind Energy



Video-The past, present and future of wind turbine

Is there any Kinetic energy in the wind?

What is its equation?

Kinetic energy in the wind is given by:

$$E = \frac{1}{2} m v^2$$

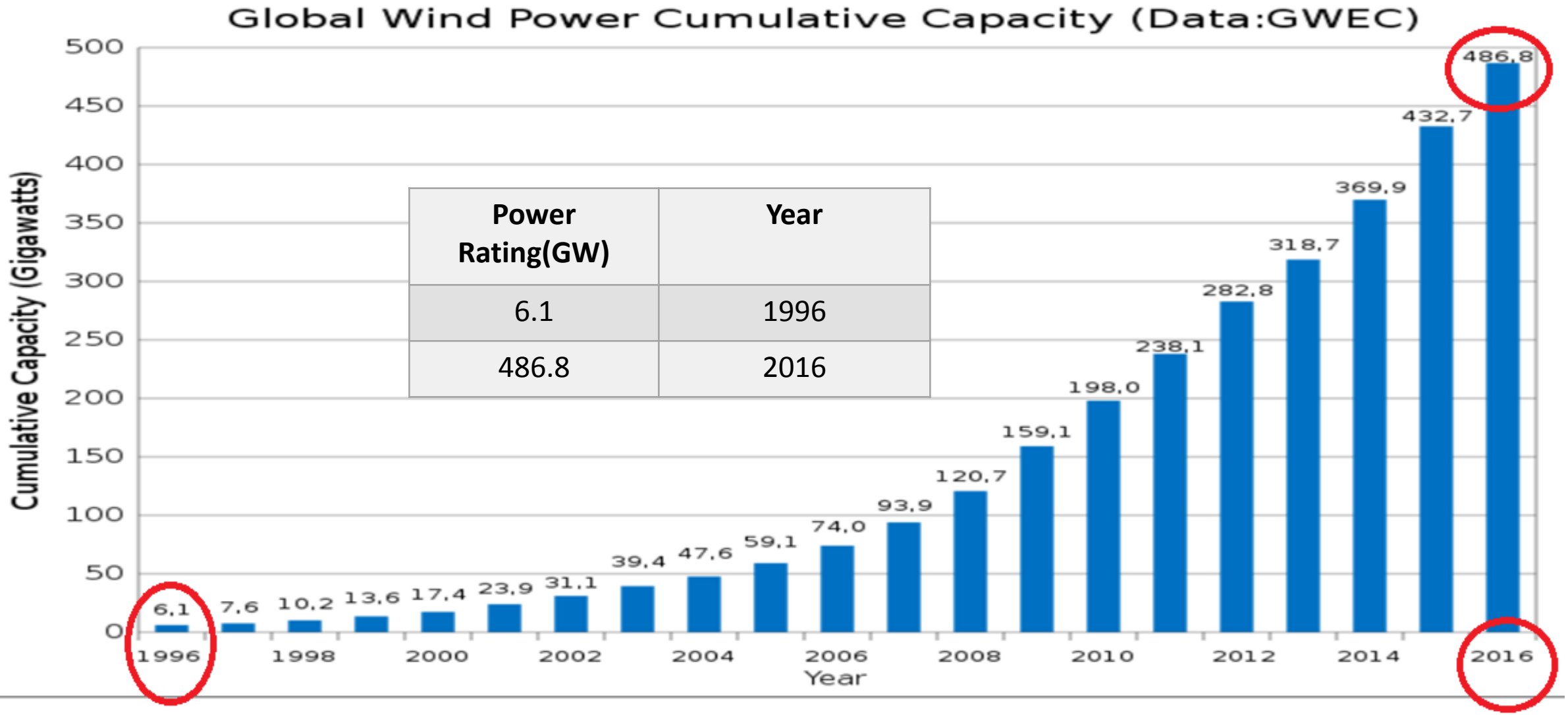
we shall discuss this at later stage

1.2 Overview of Wind Energy Conversion Systems

1.2.1 Installed capacity & growth rate

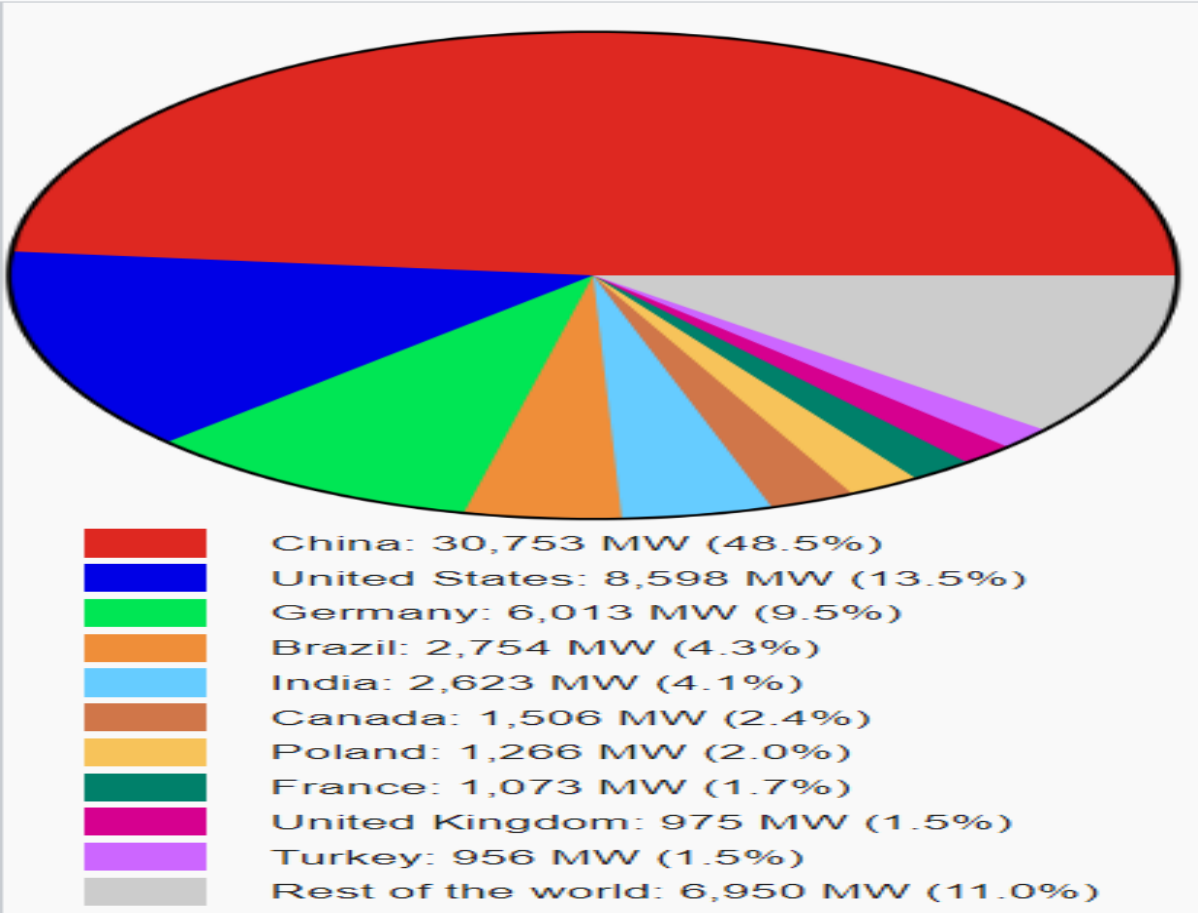
- Wind industry has achieved an average growth rate of over 25% since 2000, and
- is expected to continue this trend in coming years.

Installed capacity of global wind power increased exponentially from 6.1 GW in 1996 to 486.8 GW by 2016.



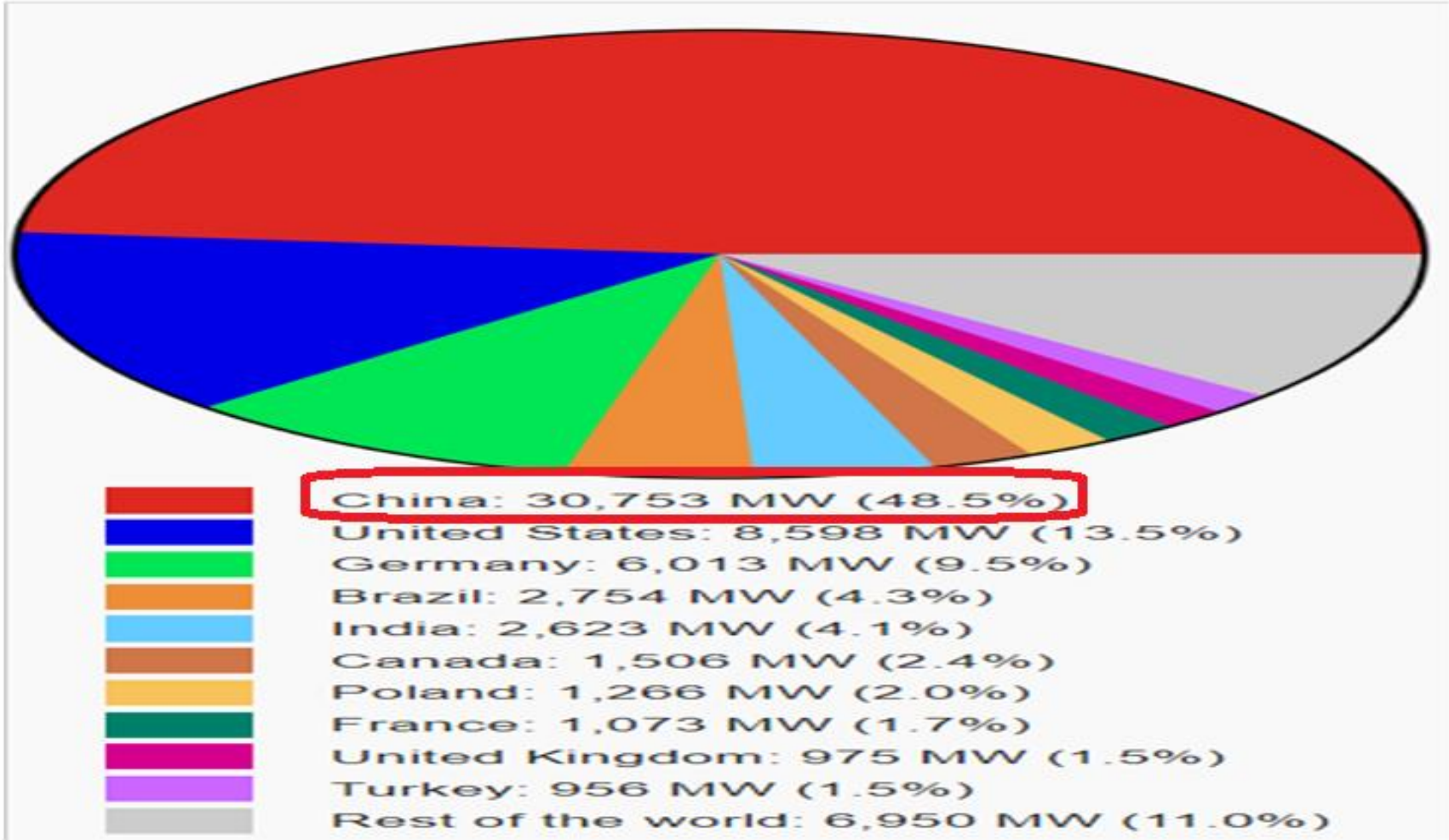
Power Rating(GW)	Year
6.1	1996
486.8	2016

Cumulative installed wind power capacity of top 10 countries in world



- Since 2010 more than 1/2 of all new wind power was added outside of traditional markets of Europe & North America, mainly driven by continuing boom in China & India.

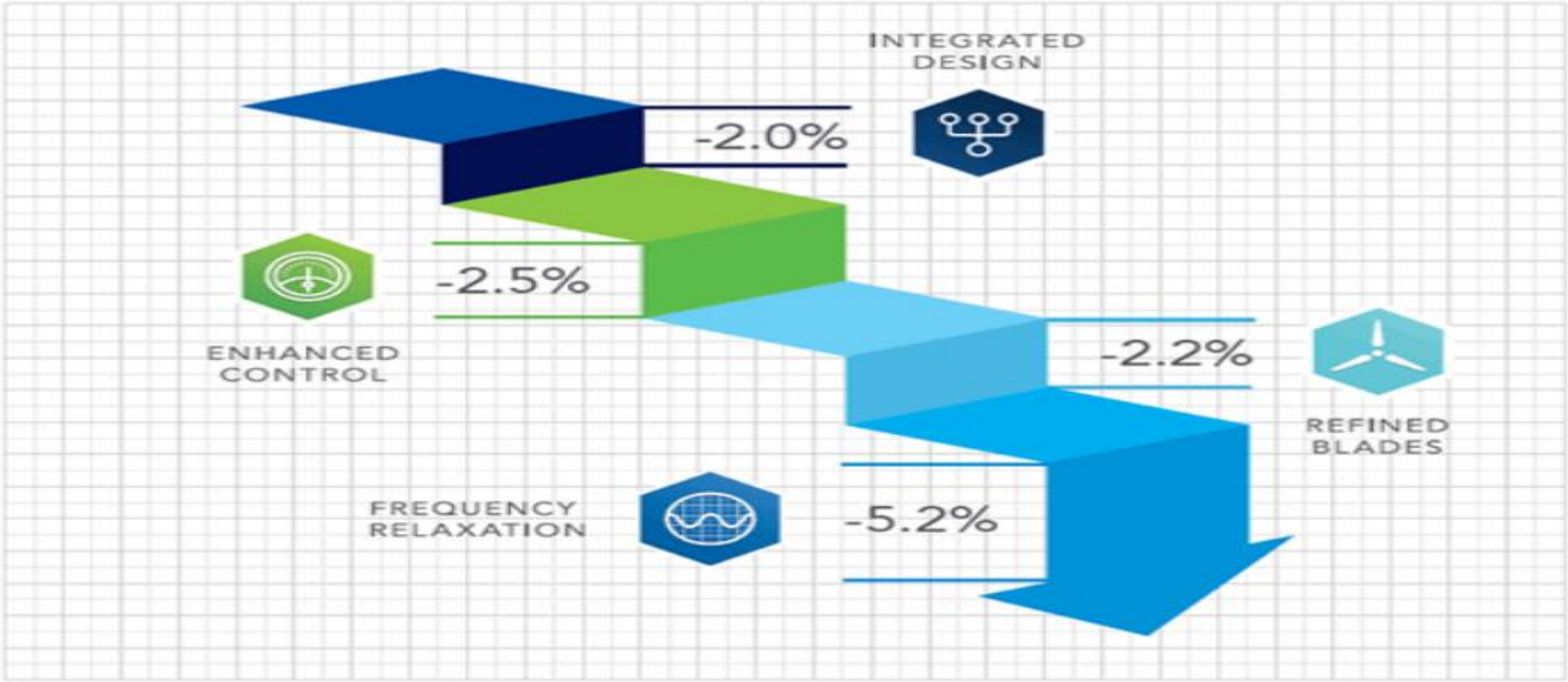
In 2015, China installed close to 1/2 of the world's added wind power capacity(48.5%).



There are 4 Reasons for such the fastest growth rate

1.Continuous cost increase of classic energy sources

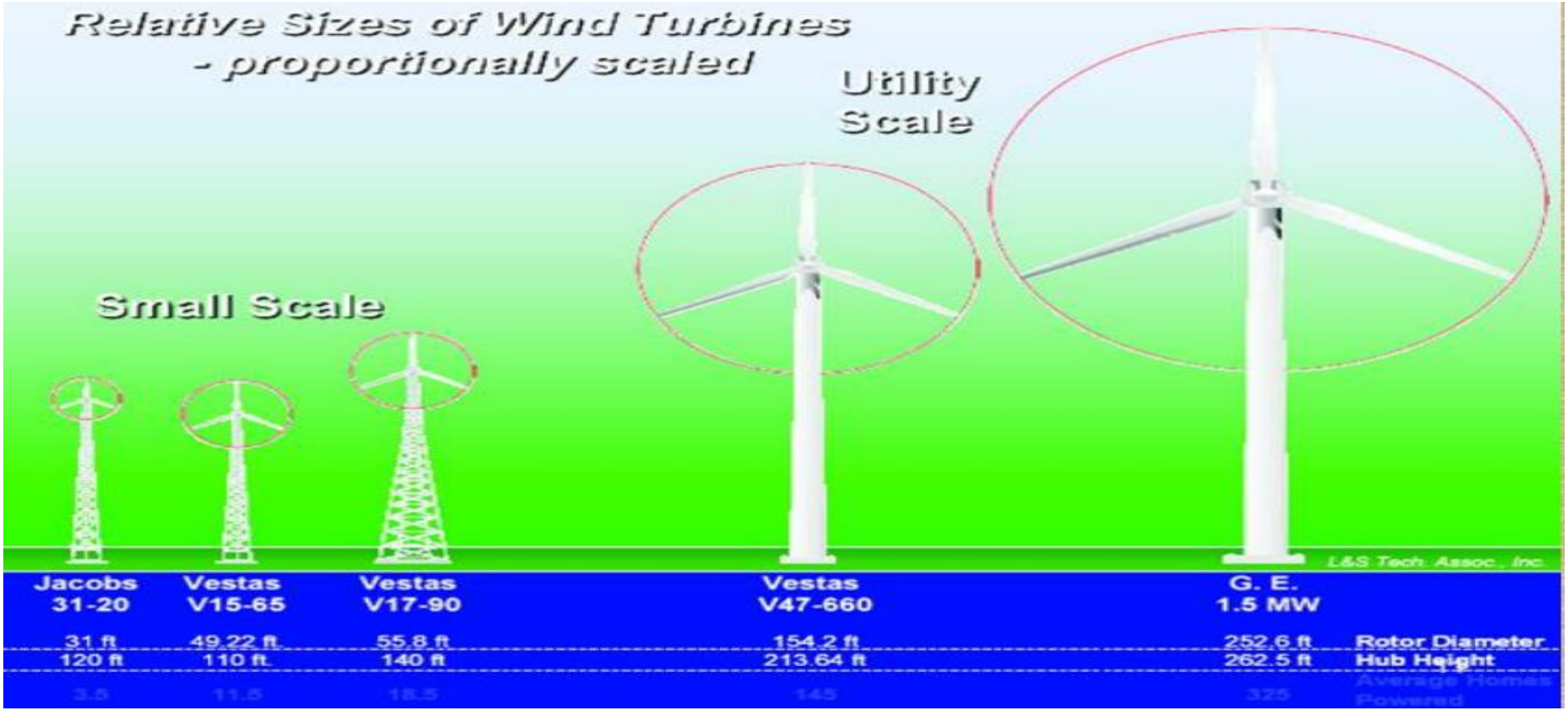
2.Cost reduction of wind turbines



3.Governmental support

4. Public demand for cleaner energy sources.

1.2.2 Small & Large Wind Turbines



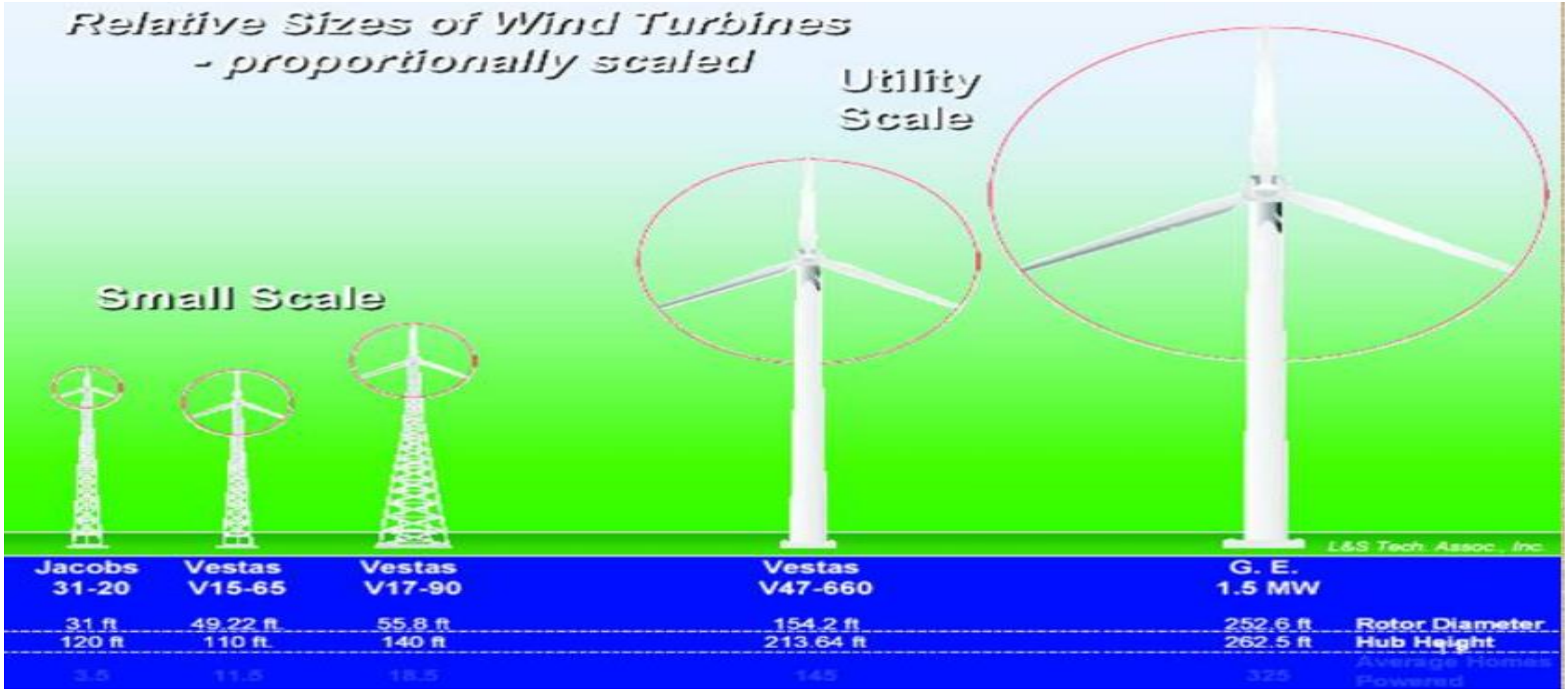
Range of wind turbine for Residential or commercial wind turbine

Wind turbines range for residential use is few KW.

Range of wind turbine for Residential or commercial wind turbine

Wind turbines range for Commercial use____?

Wind turbines range for Commercial use(large wind farms) is in MW



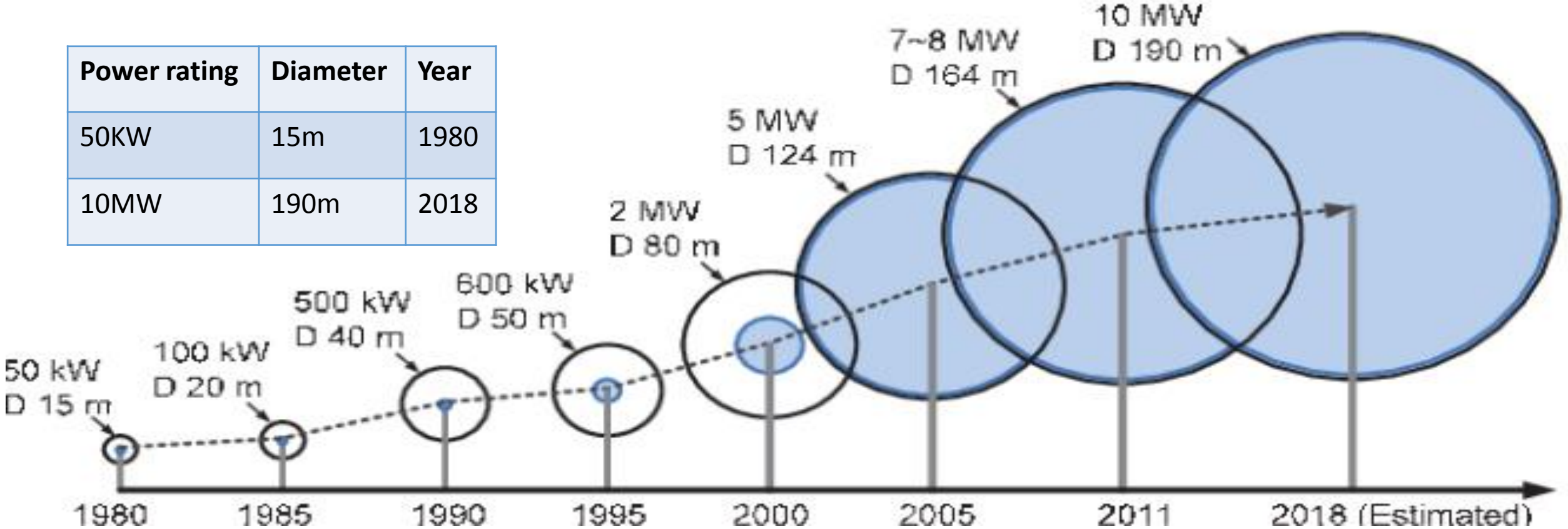
Small to medium size wind turbines (Normally<300 kW)

They can be installed at homes, farms & businesses

Size of large wind turbines has steadily increased over years.

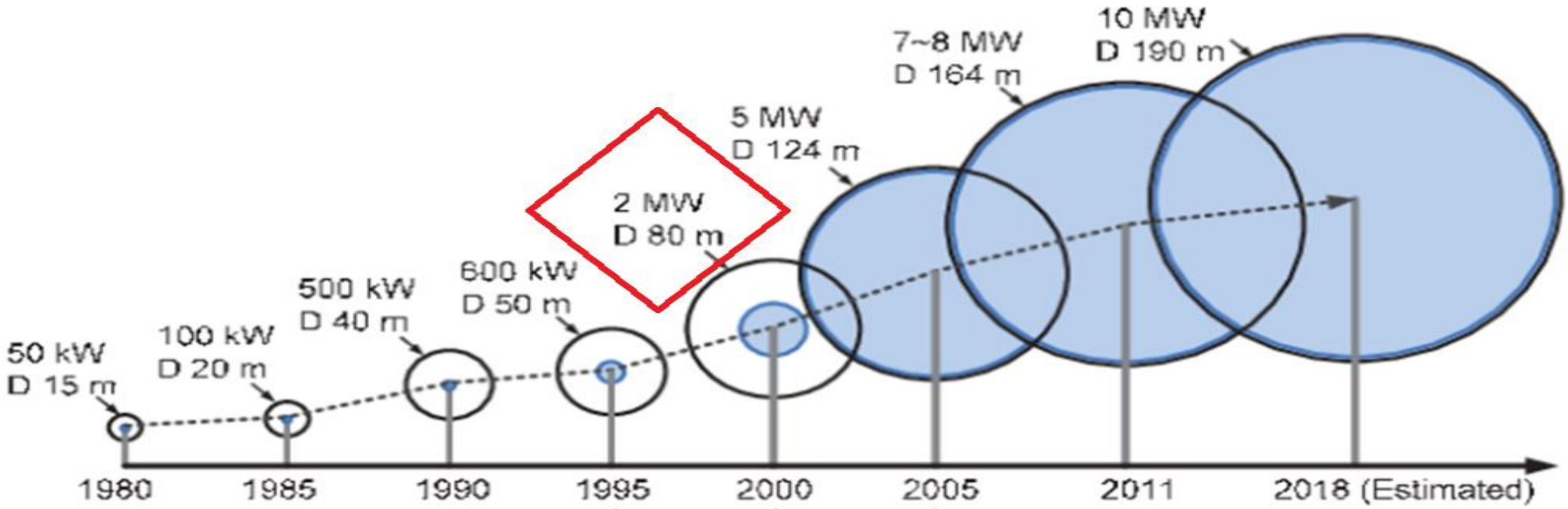
- Starting with a 50 kW power rating & a 15 m rotor diameter in 80s, wind turbines can be found today up to 10MW with a rotor diameter of 190 m.

Power rating	Diameter	Year
50KW	15m	1980
10MW	190m	2018



How to calculate maximum power generated by the wind turbine?

For a three-blade turbine with a rotor diameter of 80 m and power coefficient of Cp = 0.36, the captured power is 2 MW at a wind speed of 12 m/s and air density of p = 1.225 kg/m3.



How to calculate maximum power generated by the wind turbine?

In Lamma Winds, rotor diameter of the wind turbine = 50 m; velocity of wind = 10 m s^{-1} (constantly); air density = 1.225 kg m^{-3}

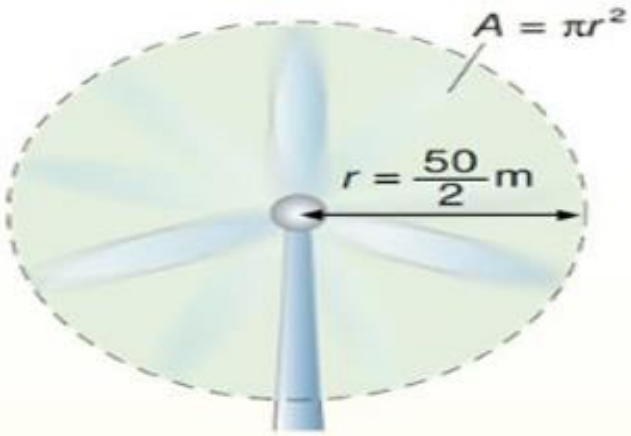
(a) Max. power generated by the wind turbine = ?

Max. power

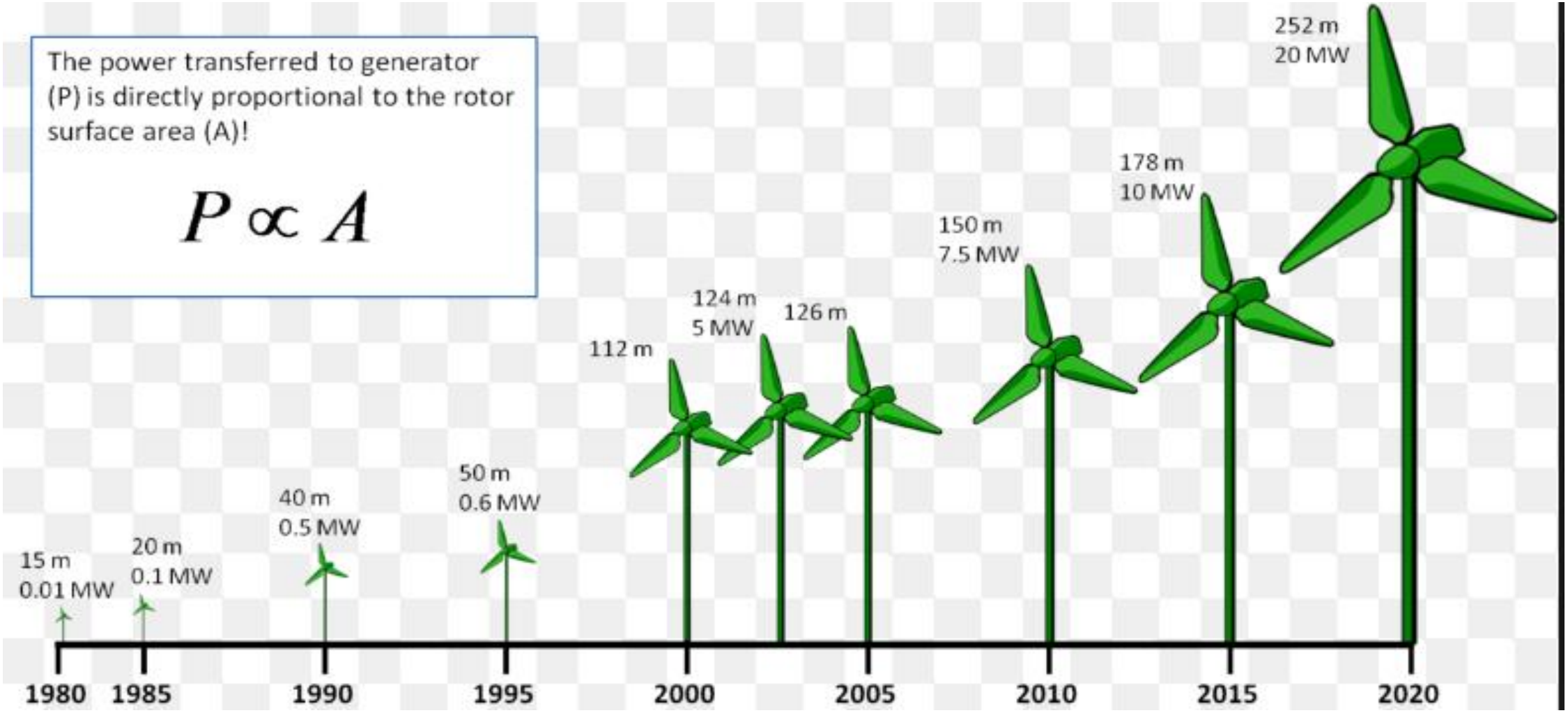
$$= \frac{1}{2}\rho A v^3$$

$$= \frac{1}{2} \times 1.225 \times \left[\pi \times \left[\frac{50}{2}\right]^2\right] \times 10^3$$

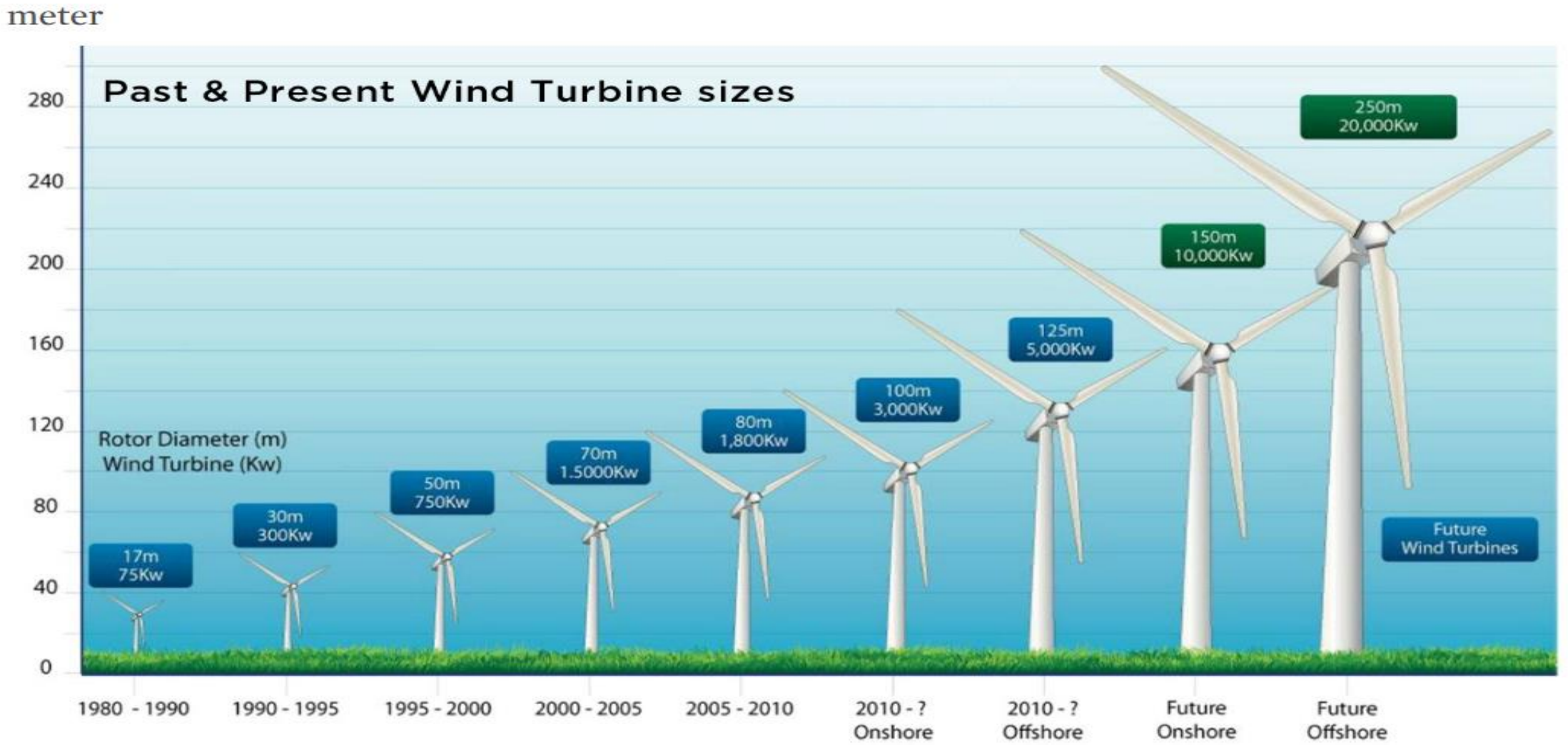
$$= 1.20 \text{ MW}$$



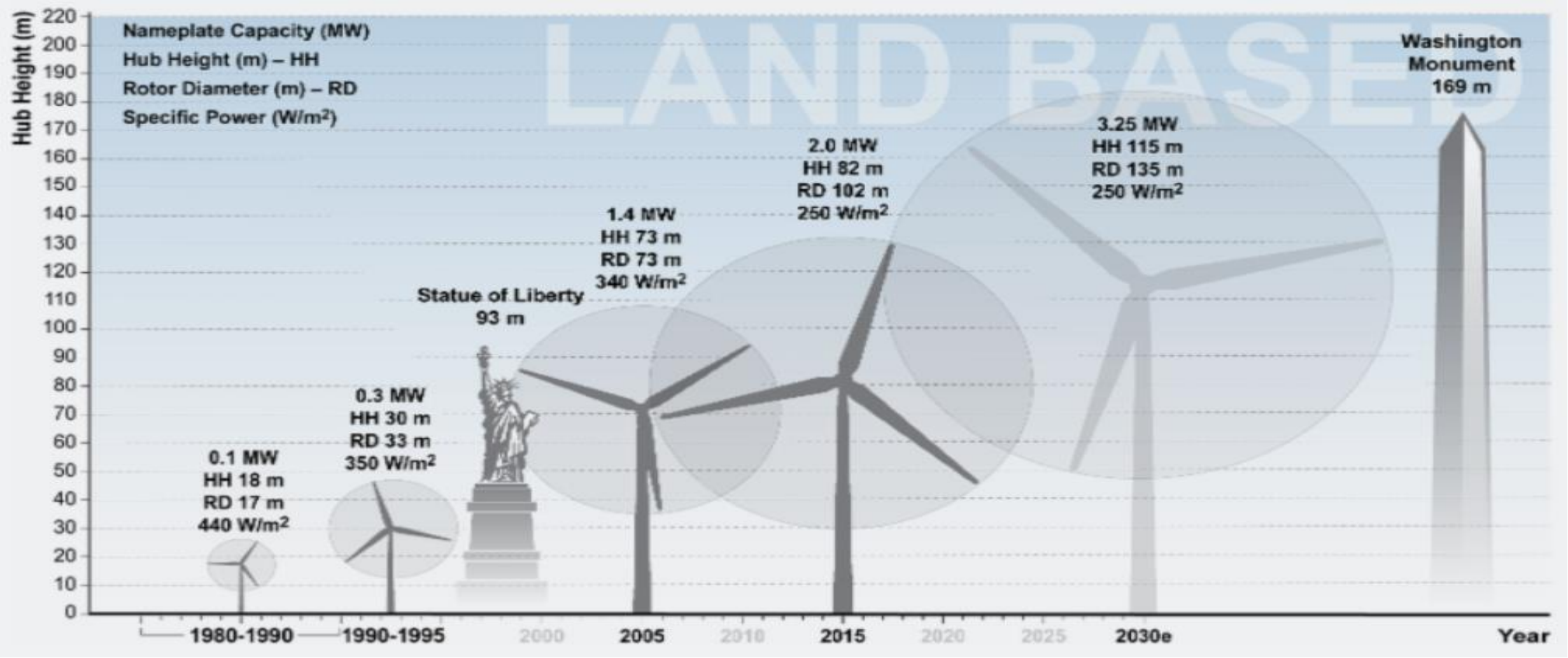
The world's largest installed wind turbine is an Enercon turbine with a 758 MW capacity



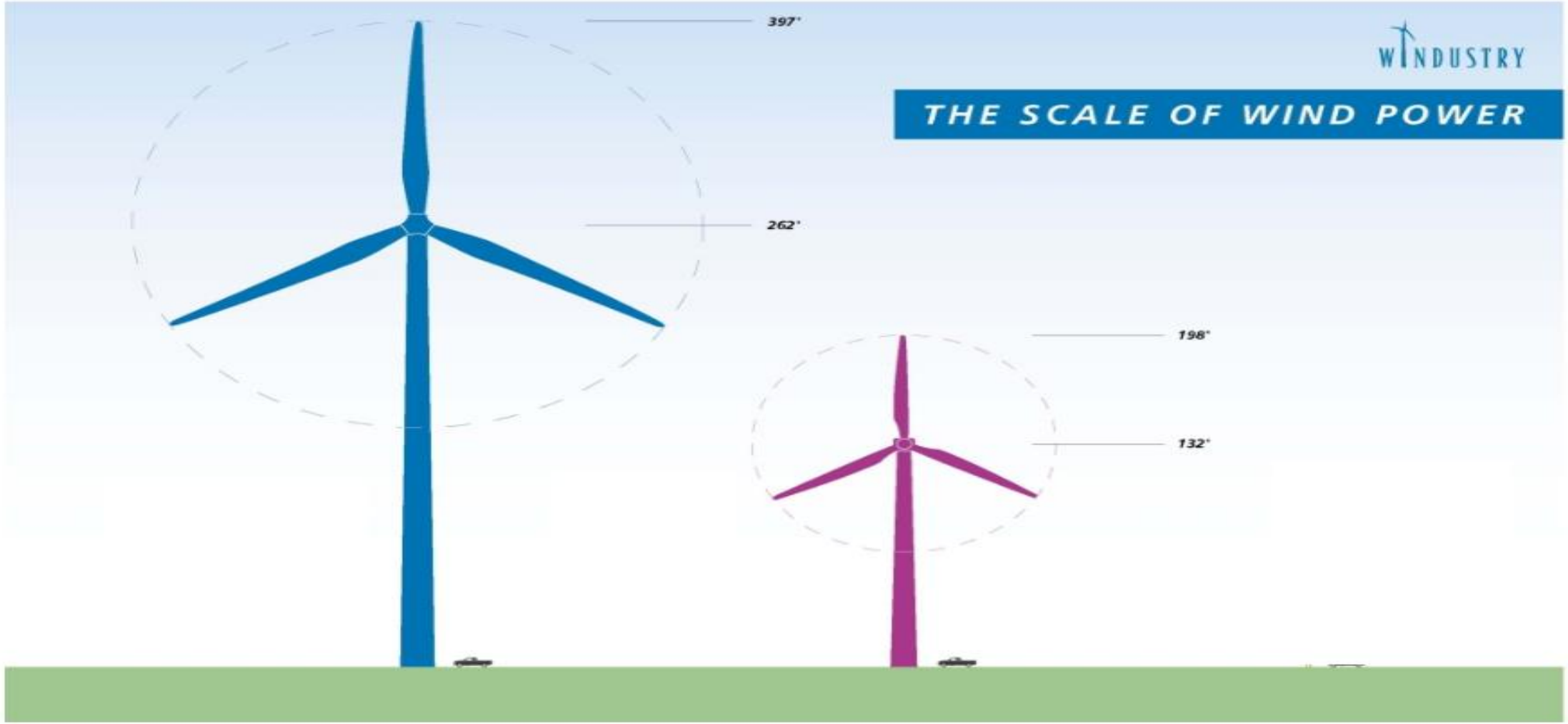
Increase in wind turbine size implies more power output since energy captured is a function of square of rotor diameter.



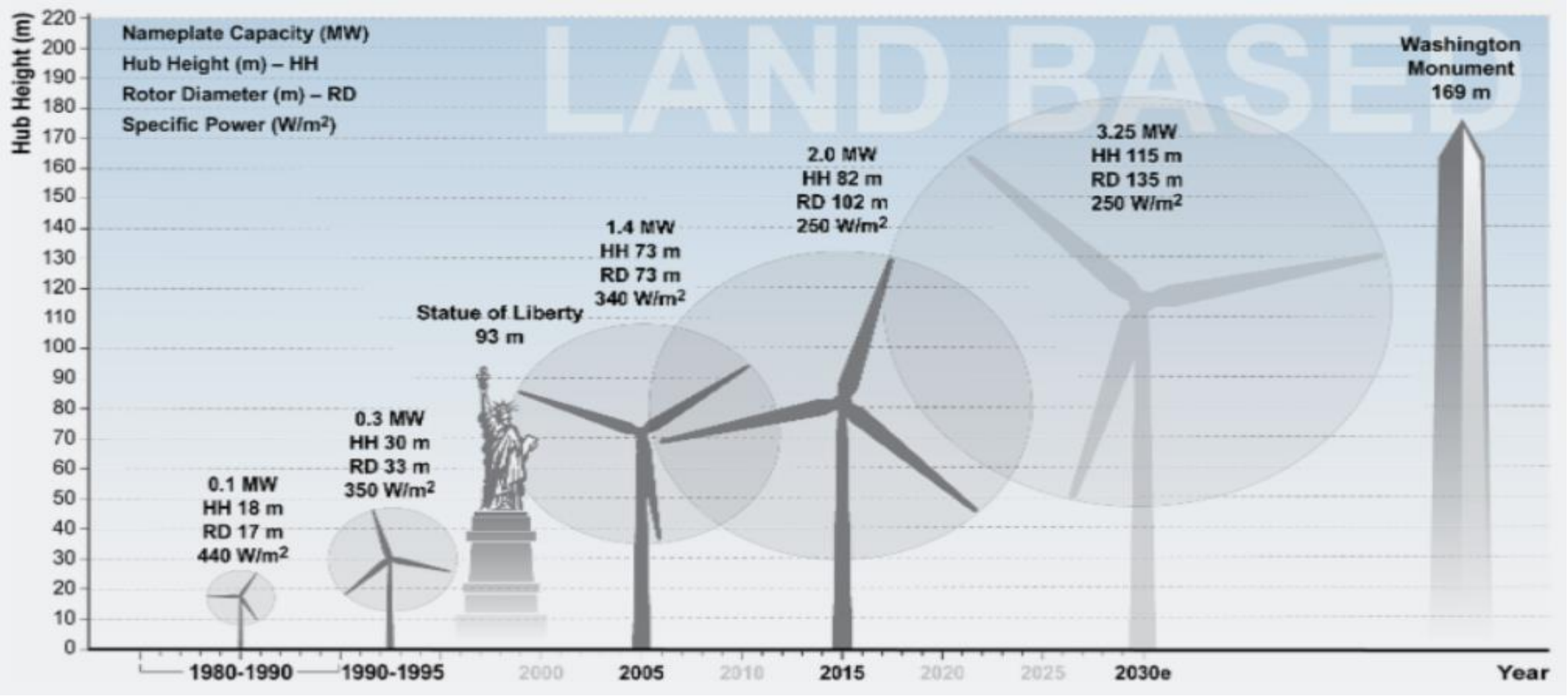
Get ready for 24-30% reduction in cost of wind power by 2030



Q. The Larger wind turbine are costly as compare to smaller wind turbine?



Larger wind turbines are cheaper since production + installation +maintenance costs are < the sum of smaller wind turbines achieving same power output.



1.2.3 Standalone and Grid-Connected Applications

Q. What should we do for areas where access to utility grid is remote or costly?

Solution:

- Wind turbines can operates standalone in small power capacity.

Standalone wind energy system

- Since power generated from wind is not constant,
- other energy sources are normally required in standalone systems.

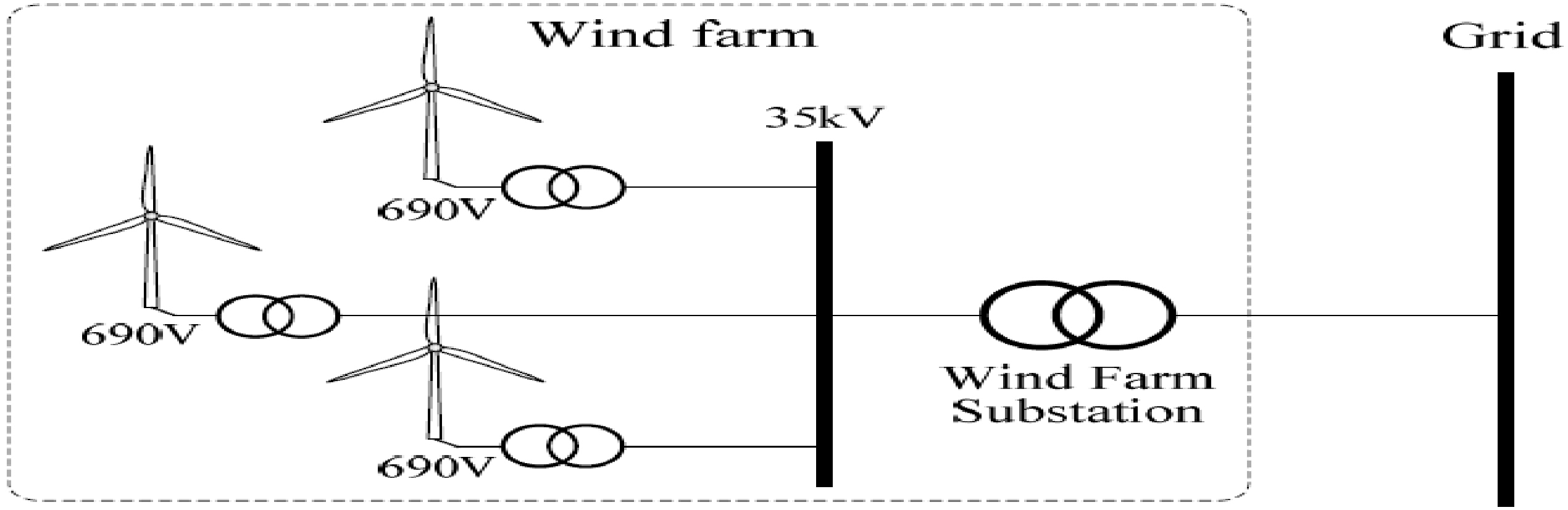
Standalone wind energy system operates with:

1. Diesel generators,
2. photovoltaic energy systems, or
3. energy storage systems

- to form a more reliable distributed generation (DG) .

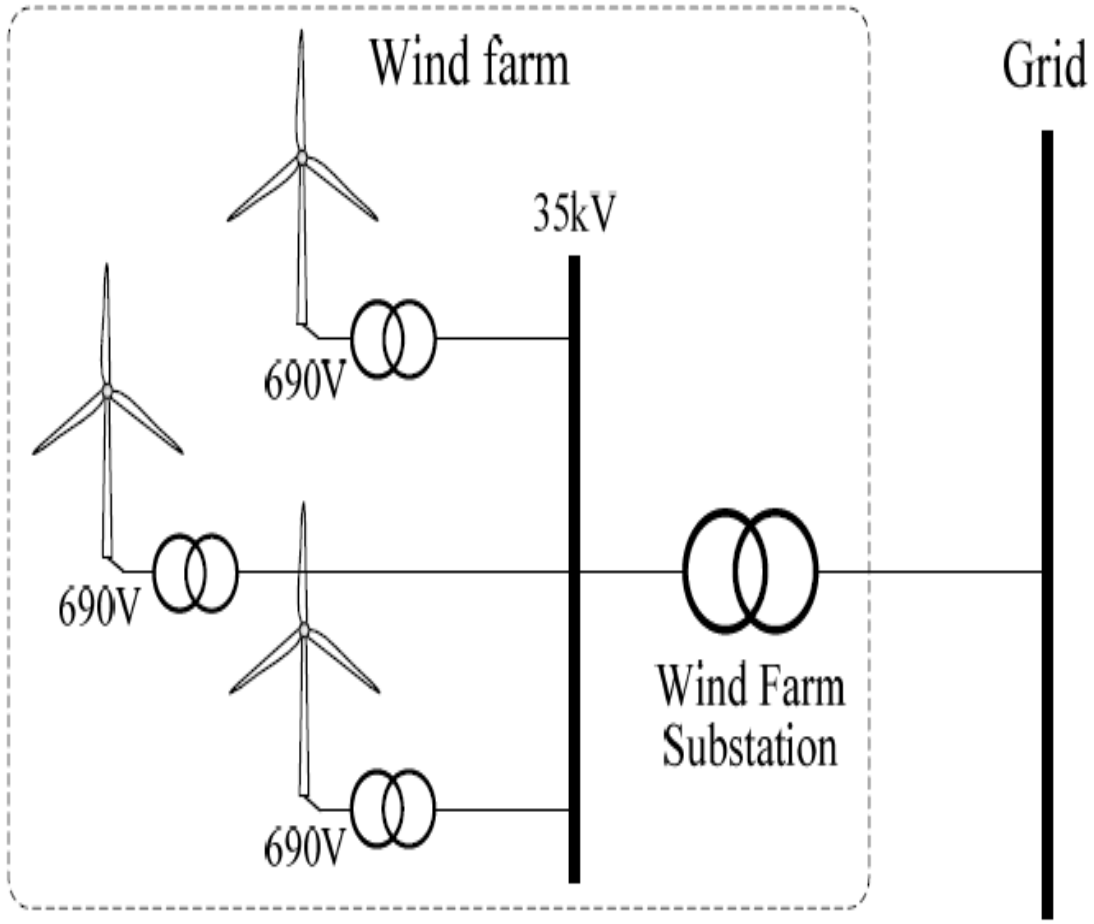
Grid-connected wind farm

- Majority of wind turbines are grid-connected & power generated is directly uploaded to grid.

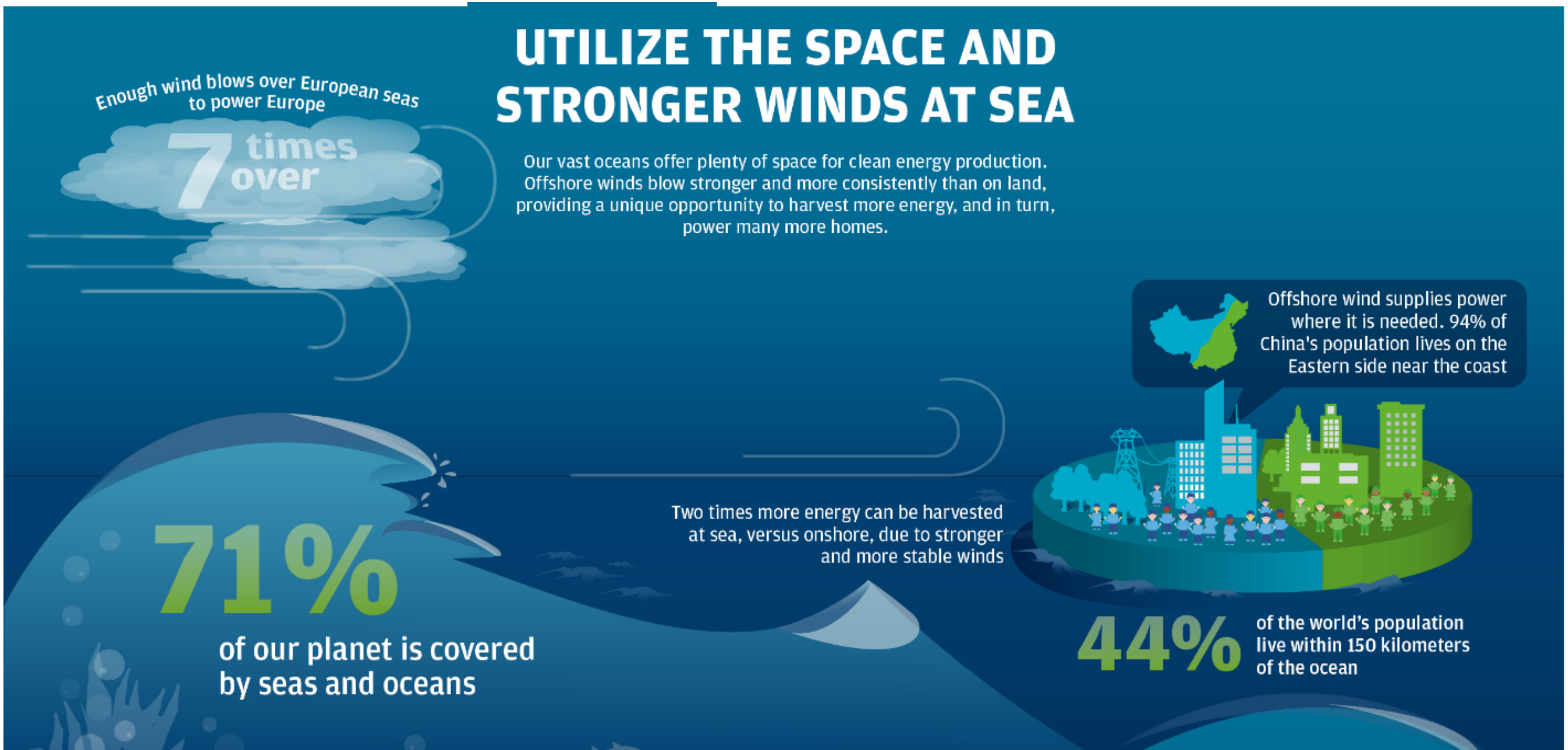


Grid-connected wind farm-Generators operate at 690V

- Step-up transformers increases generator voltage from 690V to 35kV for wind farm substation.
- 35kV is stepped up further by substation transformer, which connects wind farm to grid.



1.2.4 On-land versus offshore wind turbines



What are the 3 reasons for installing large capacity on-land wind farms?

1. Easy construction

2. Low maintenance cost

3. Close to transmission lines

Offshore Wind turbines with sub-station

Q.In densely populated areas such as some European countries can we install on-land wind farms?

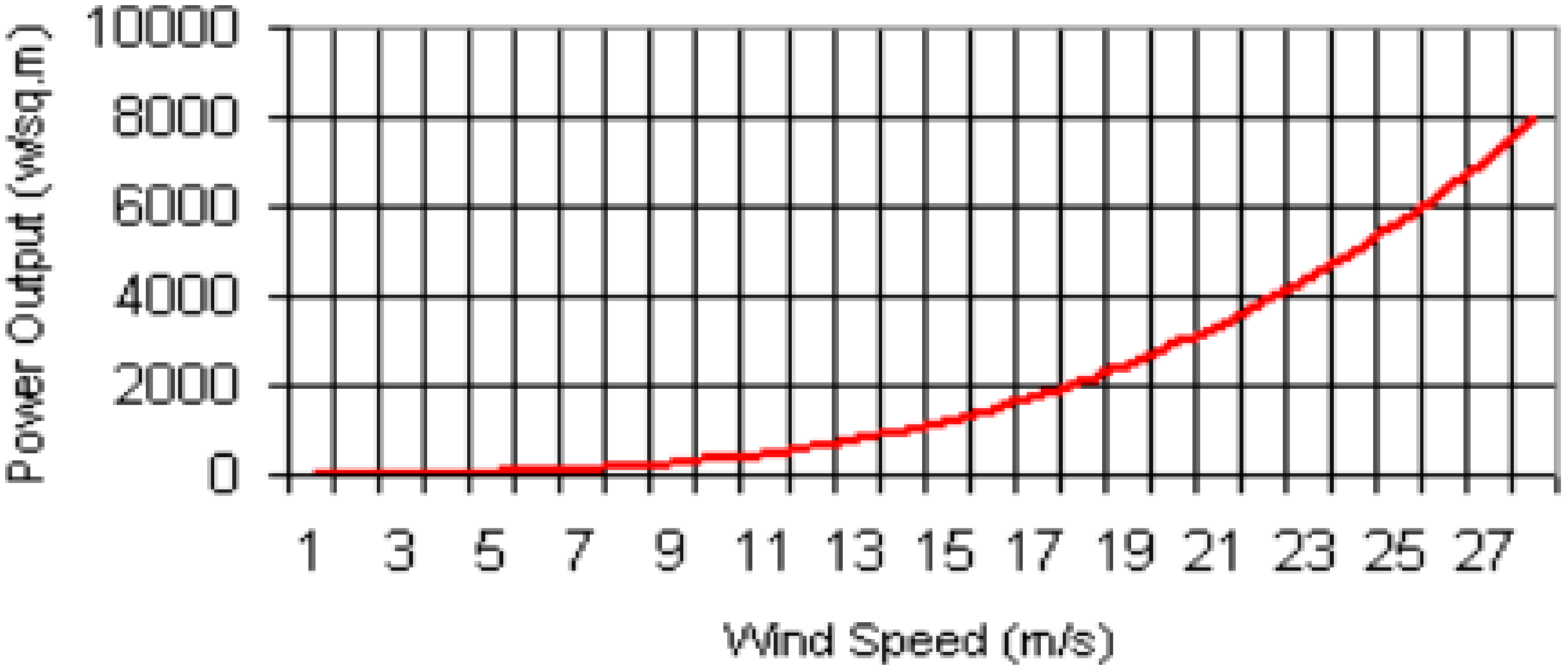
5 primary drives for development of offshore wind turbine technology.

1. Commercially viable.

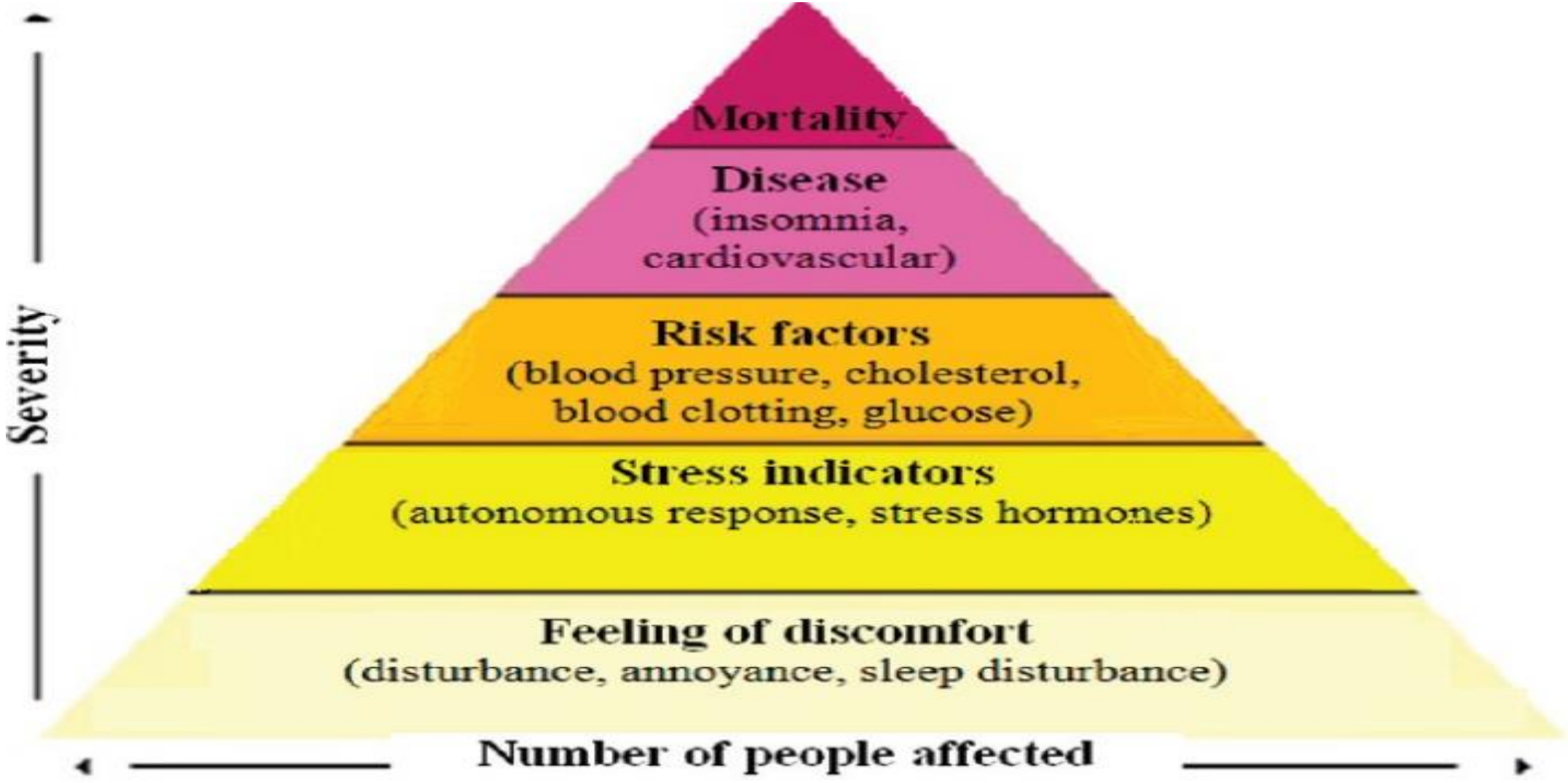
2. Lack of suitable wind resources on land.

3. Offshore wind speed is higher(30-40%) & steadier than that on-land.

4.Offshore turbines can capture more energy as power obtained by wind turbines is proportional to cube of wind speed ($P_m \propto \omega_r^3$)



5. Environmental impact, such as audible noise & visual impact, is 0



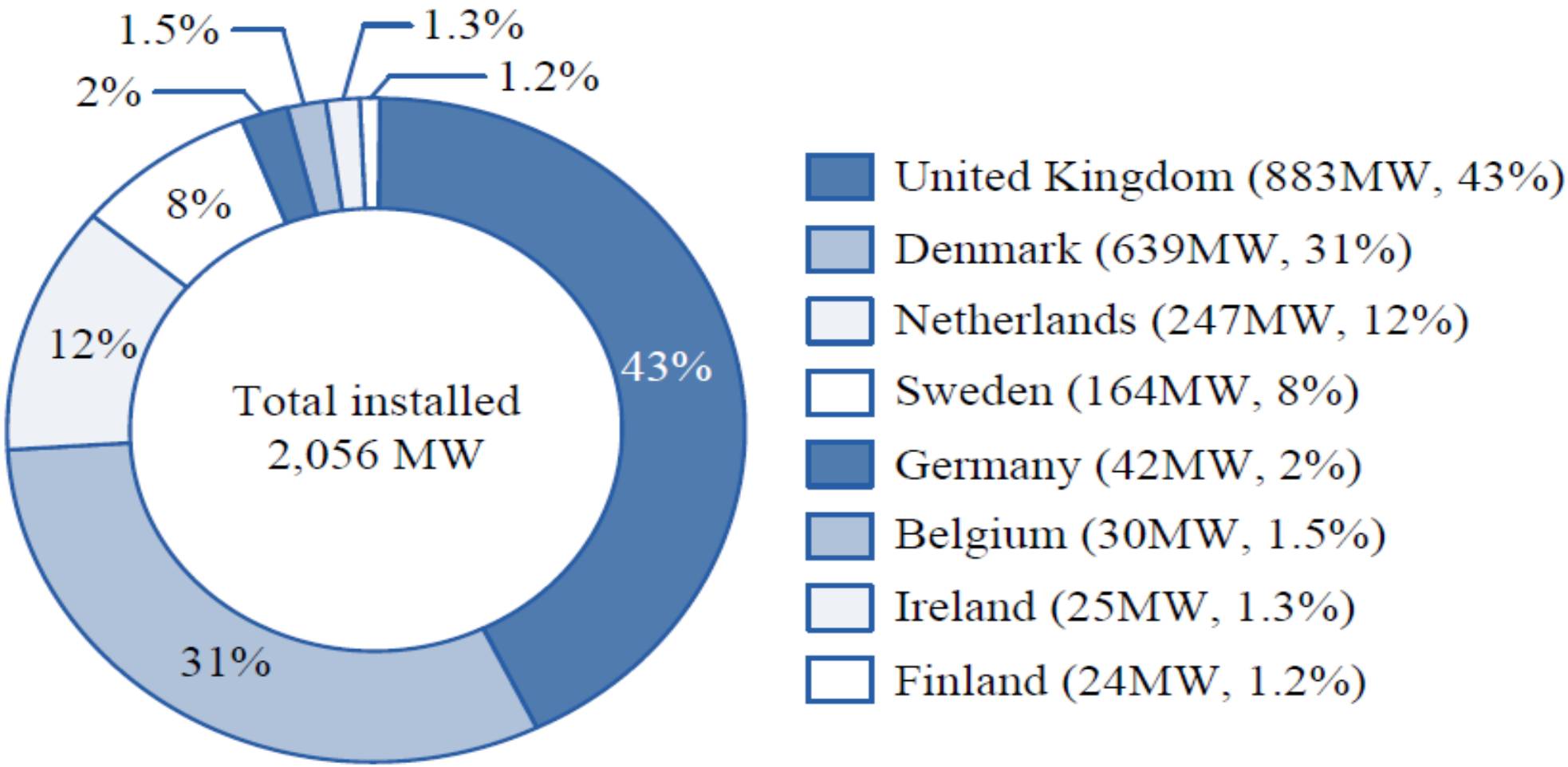
Comparison between offshore & on-land wind turbines

Offshore wind turbines

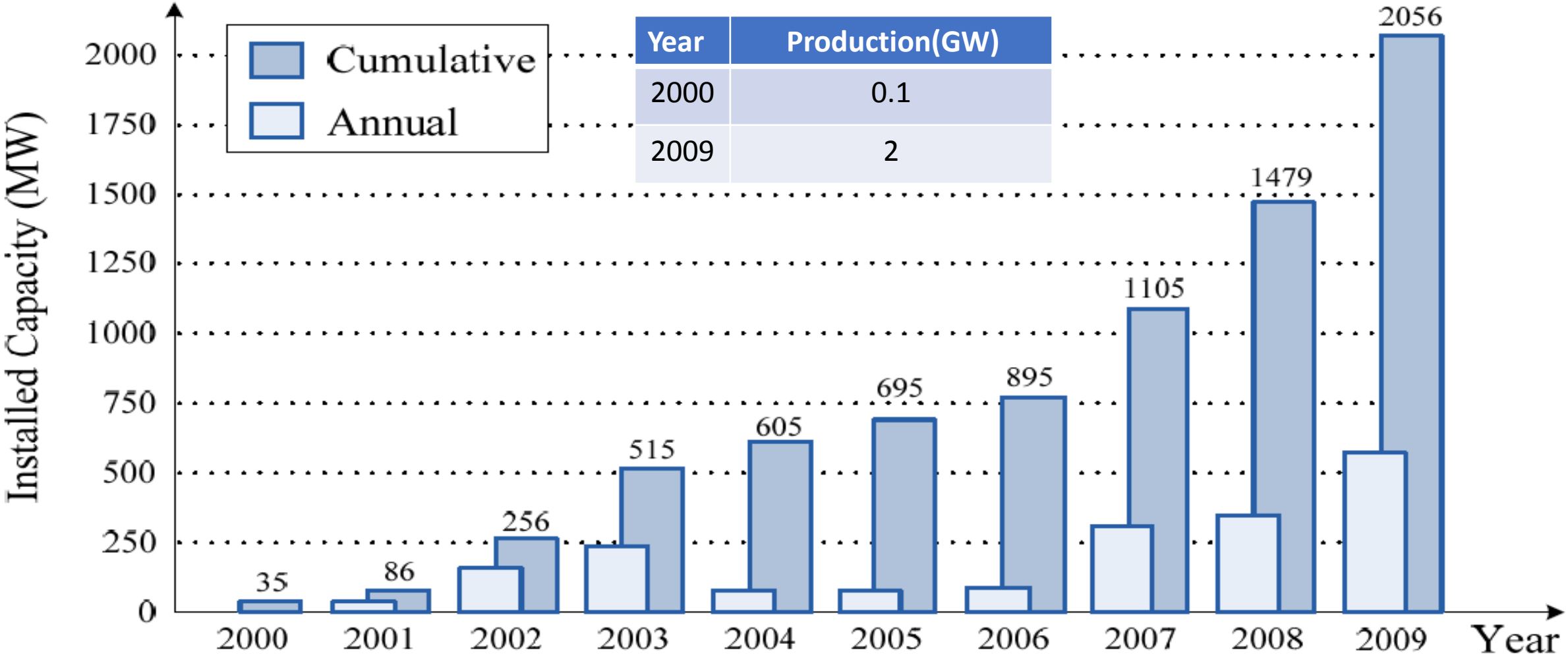
On-land wind turbines

	Description	On-land	Offshore
Resources	• Wind speed	Adequate	Higher and steadier
	• Limits in available land/area	Yes	No
Power Transmission	• HVDC/HVAC	Location dependent	Required
Environmental impact	• Visual impact	Yes for nearby residents	No
	• Acoustic noise	Yes for nearby residents	No
Operation	• Access	Convenient	Inconvenient
	• Erosion	Low	High
	• Capital cost	Low	High
	• Maintenance cost	Low	High
	• Energy production	Good	Better

Only limited # of European countries have operational offshore wind farms. e.g. UK, Denmark & Netherlands

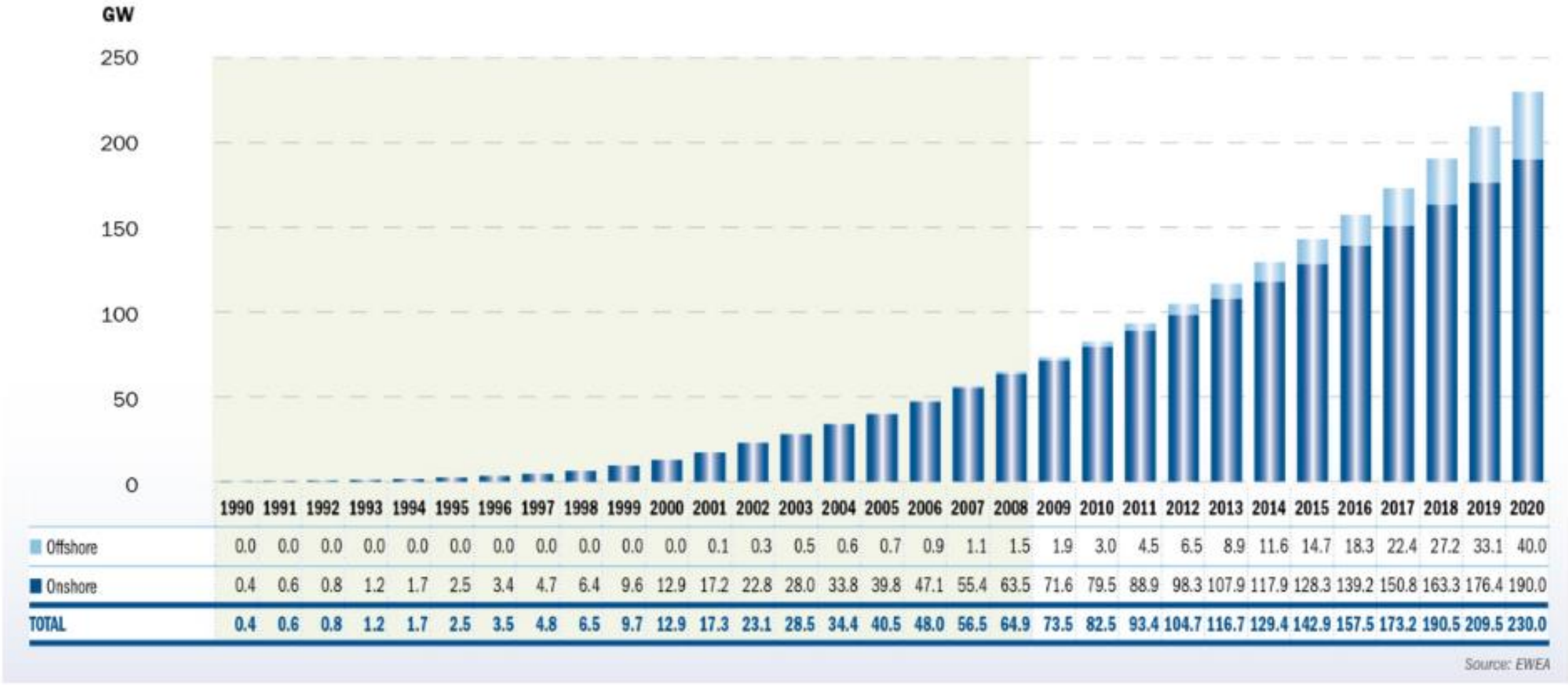


Installed capacity is increased from less than 0.1 GW in 2000 to more than 2 GW in 2009.



Year	Production(GW)
2000	0.1
2009	2

Cumulative EU wind energy capacity. In 2009 installations were 10.163 Mw while in 2020 230GW(expected).



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.5	0.6	0.7	0.9	1.1	1.5	1.9	3.0	4.5	6.5	8.9	11.6	14.7	18.3	22.4	27.2	33.1	40.0
Onshore	0.4	0.6	0.8	1.2	1.7	2.5	3.4	4.7	6.4	9.6	12.9	17.2	22.8	28.0	33.8	39.8	47.1	55.4	63.5	71.6	79.5	88.9	98.3	107.9	117.9	128.3	139.2	150.8	163.3	176.4	190.0
TOTAL	0.4	0.6	0.8	1.2	1.7	2.5	3.5	4.8	6.5	9.7	12.9	17.3	23.1	28.5	34.4	40.5	48.0	56.5	64.9	73.5	82.5	93.4	104.7	116.7	129.4	142.9	157.5	173.2	190.5	209.5	230.0

Source: EWEA

Examples of on-land wind farms

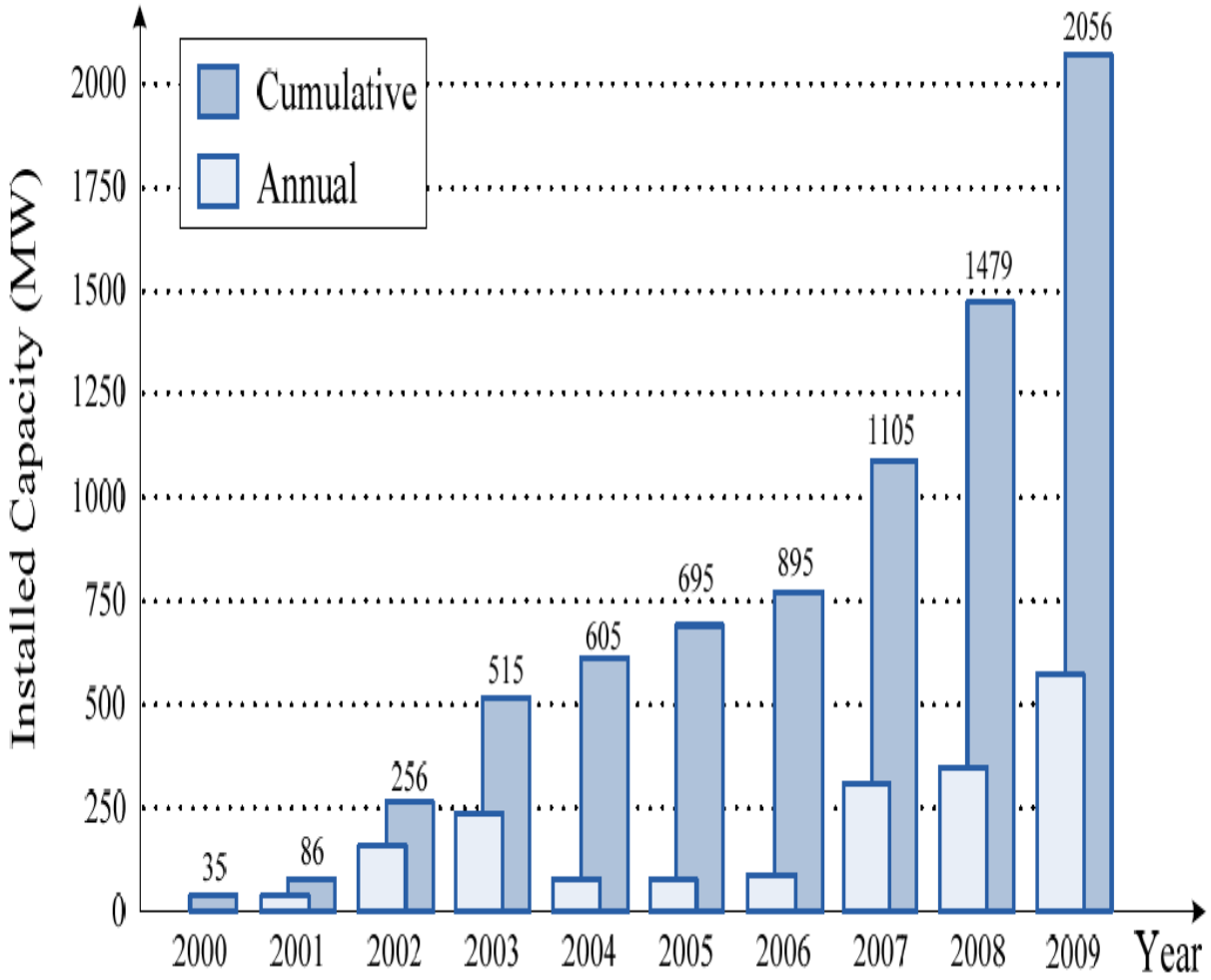
Parameter	Roscoe	Whitelee	Bowbeat
Location	Texas, USA	Glasgow, Scotland	Moorfoot Hills, Scotland
# Turbines	627	140	24
Power rating	781.5 MW	322 MW	31.2MW
Area	404.7 km^2	72.52 km^2	
Turbine model/supplier	Mitsubishi 1000A, GE and Siemens	Siemens 2.3 MW	Nordex N60
Production date	2009	2009	2002

Examples of offshore wind farms

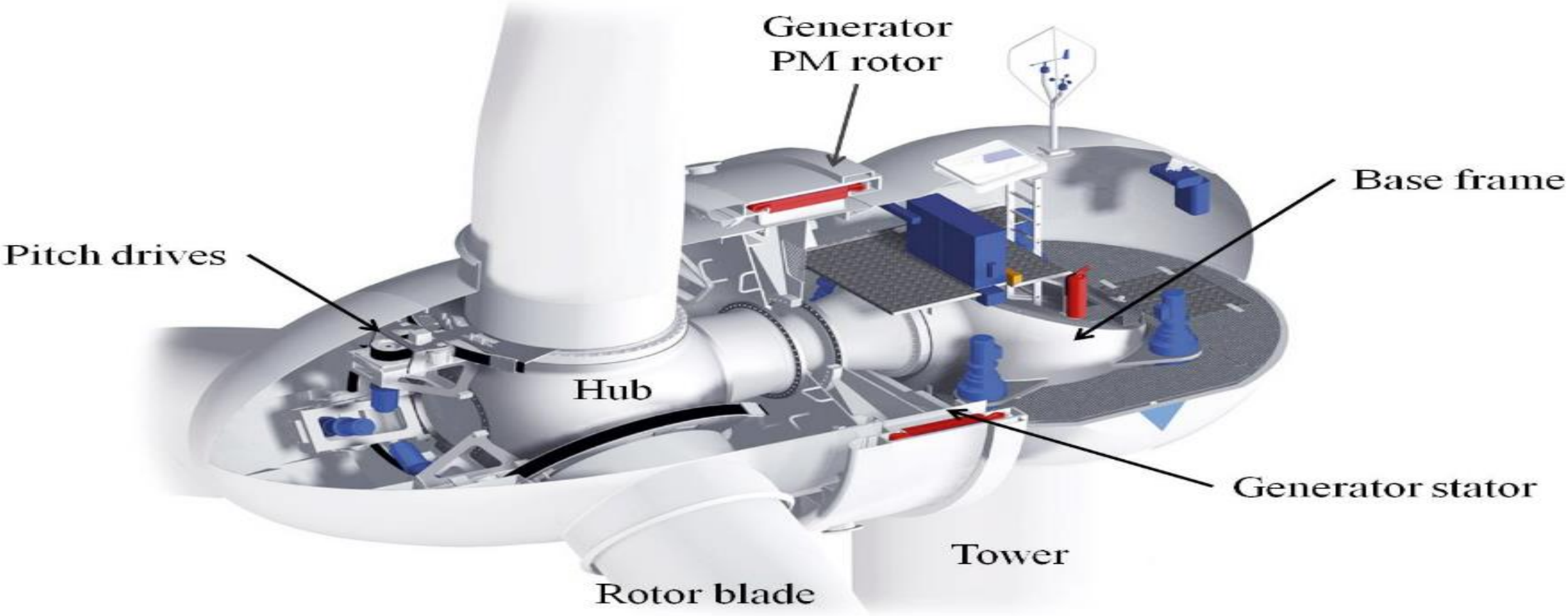
Parameter	London Array	Horns Rev	Nysted/Rodsand I
Location	London, UK	Jutland, Denmark	Lolland, Denmark
Distance from shore	20km	14-24km	10.8km
# Turbines	341	80	72
Power rating	1GW	160MW	166MW
Area	245km^2	20 km^2	26 km^2
Internal bus voltage	33kV	34kV	33kV
Turbine model/supplier	Siemens SWT-3.6	Vestas V80 2MW	Siemens SWT-2.3
Transmission line	150kV subsea cable	150kV subsea cable	132kV subsea cable
Offshore substations	Two	One	One
Production date	2012	2002	2003

Increase of turbine power capacity & reduction of maintenance costs are crucial for offshore wind farms.

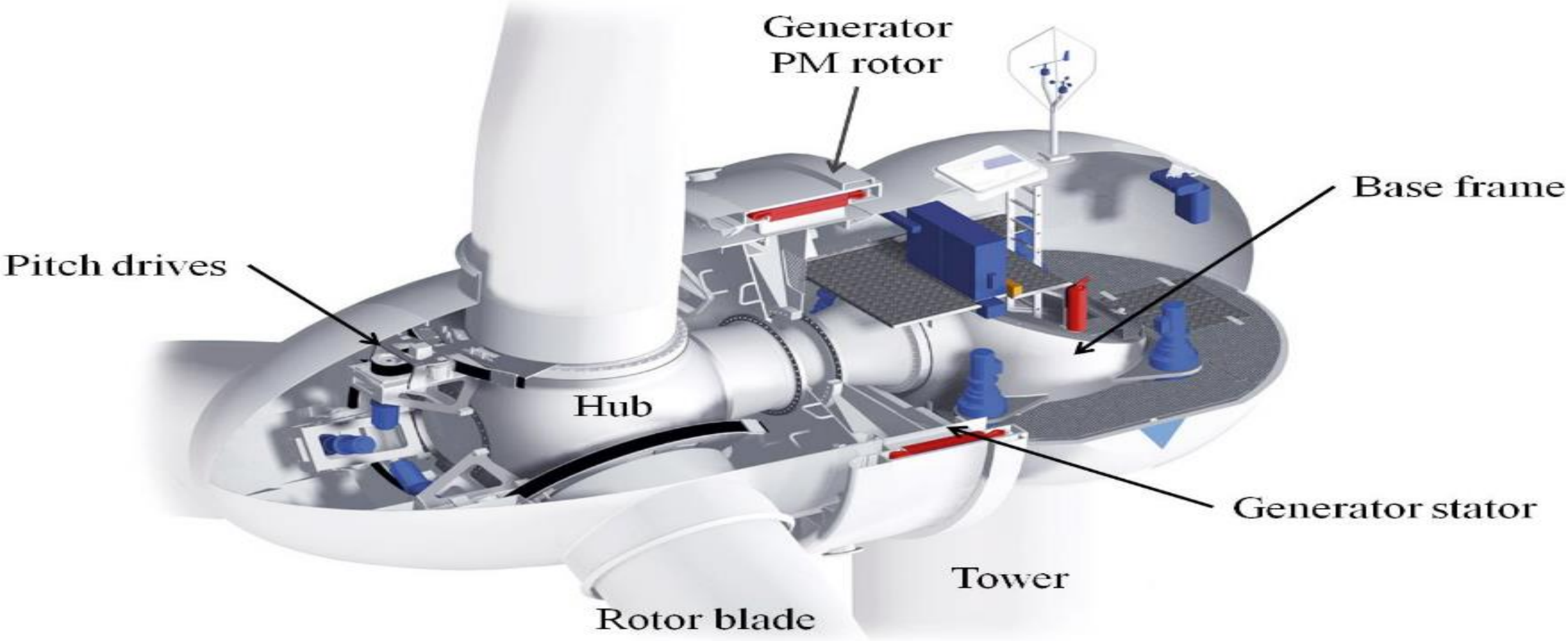
- Average power rating of installed offshore wind turbines is around 2.9MW as of 2009.
- Power rating of generators for offshore applications is expected to increase in the next decade.



To reduce maintenance cost: Direct-driven wind turbines using low-speed synchronous permanent magnet generators (PMSG) is a viable technology.



Maintenance costs for these turbines are reduced due to: **elimination of gearbox and brushes.**



For offshore wind farms these 2 factors add significantly to total project costs.

1. Foundation &
2. transmission cable

Few critical factors to be considered in the development of offshore wind farms:

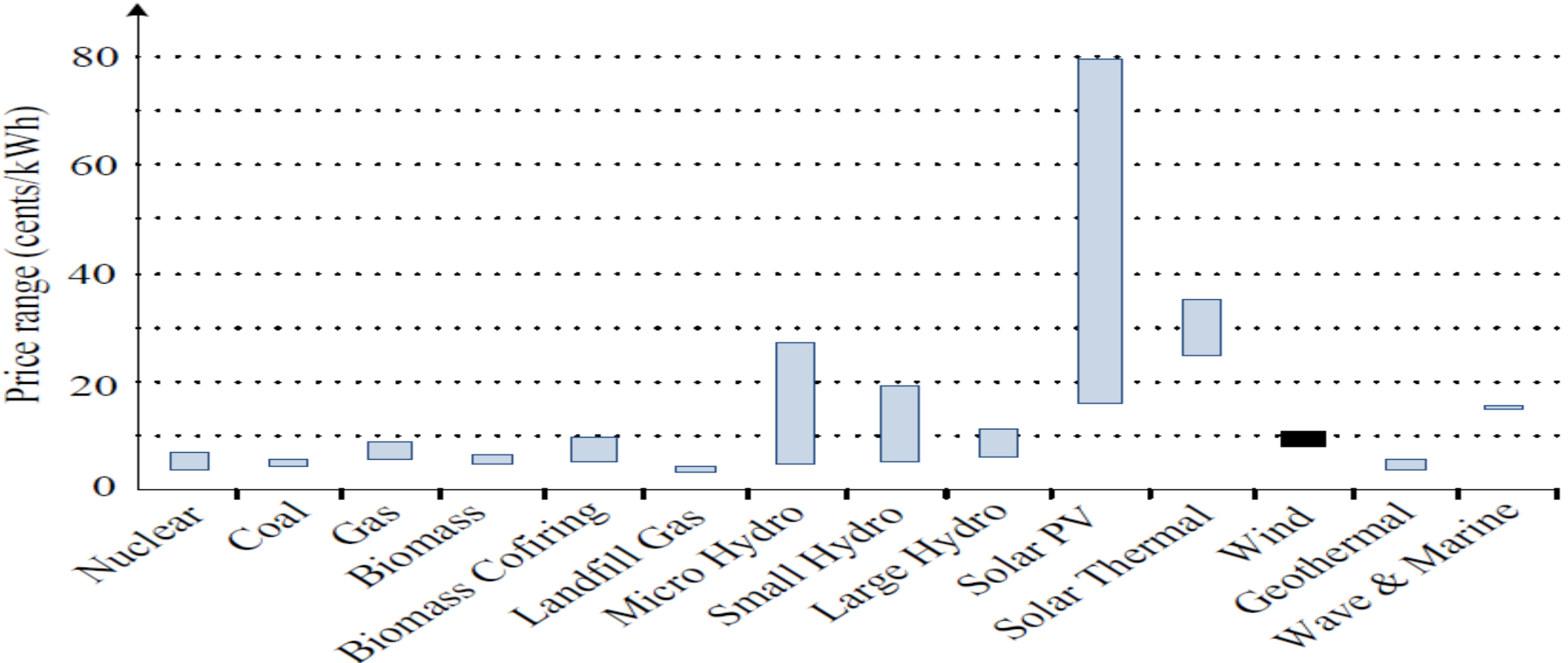
1. Wind resources
2. capital/maintenance costs and
3. energy production

1.2.5 Costs of Wind Energy Conversion System

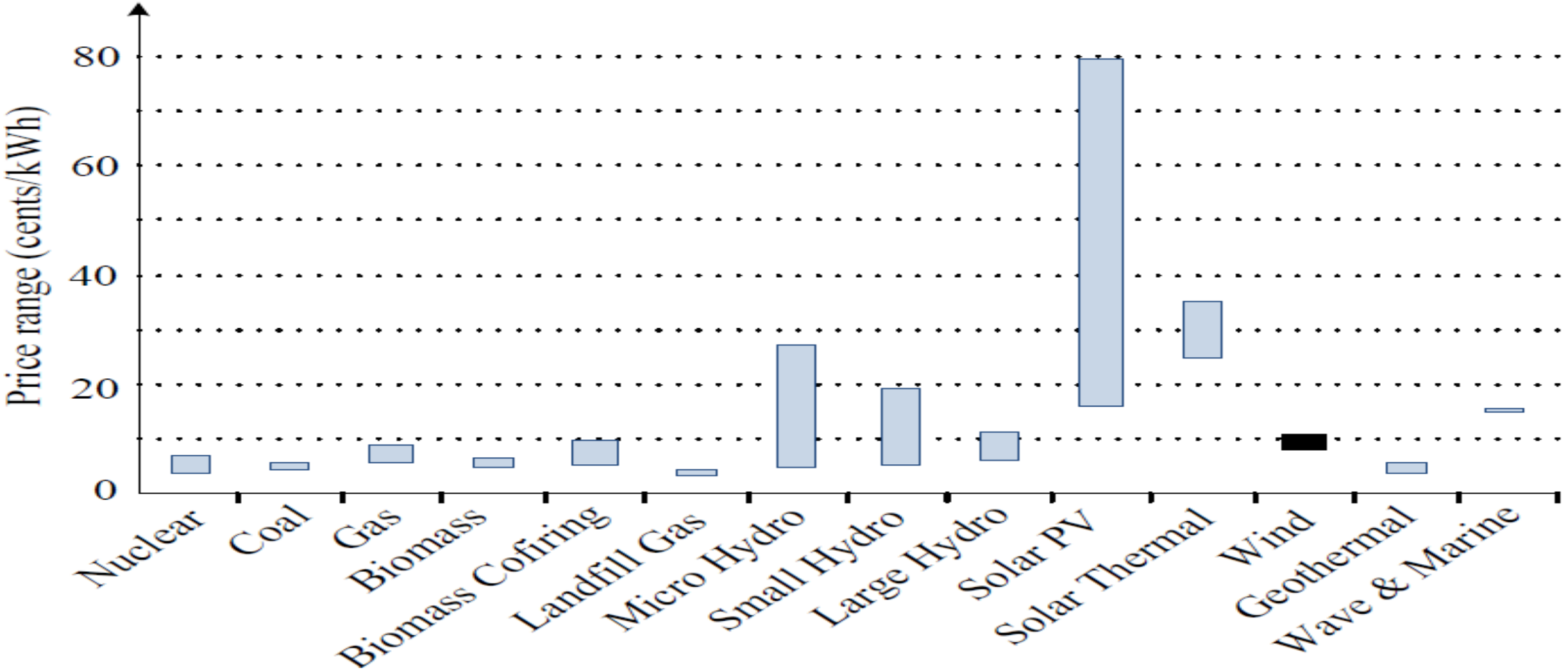
Cost of electricity from wind power has reduced steadily over past 2 decades.

- When 1st utility-scale turbines were installed in early 1980s, wind-generated electricity cost $0.3 per kWh.
- Today, wind power plants can generate electricity for $0.07-$0.12 per kWh .

Compare wind energy with other clean energy resources, such as **photovoltaic (PV) energy and solar thermal energy.** What result you obtained?



Note that for a given energy source, cost range for energy production is not constant, but varies with?



1. Power rating

2. operating condition,

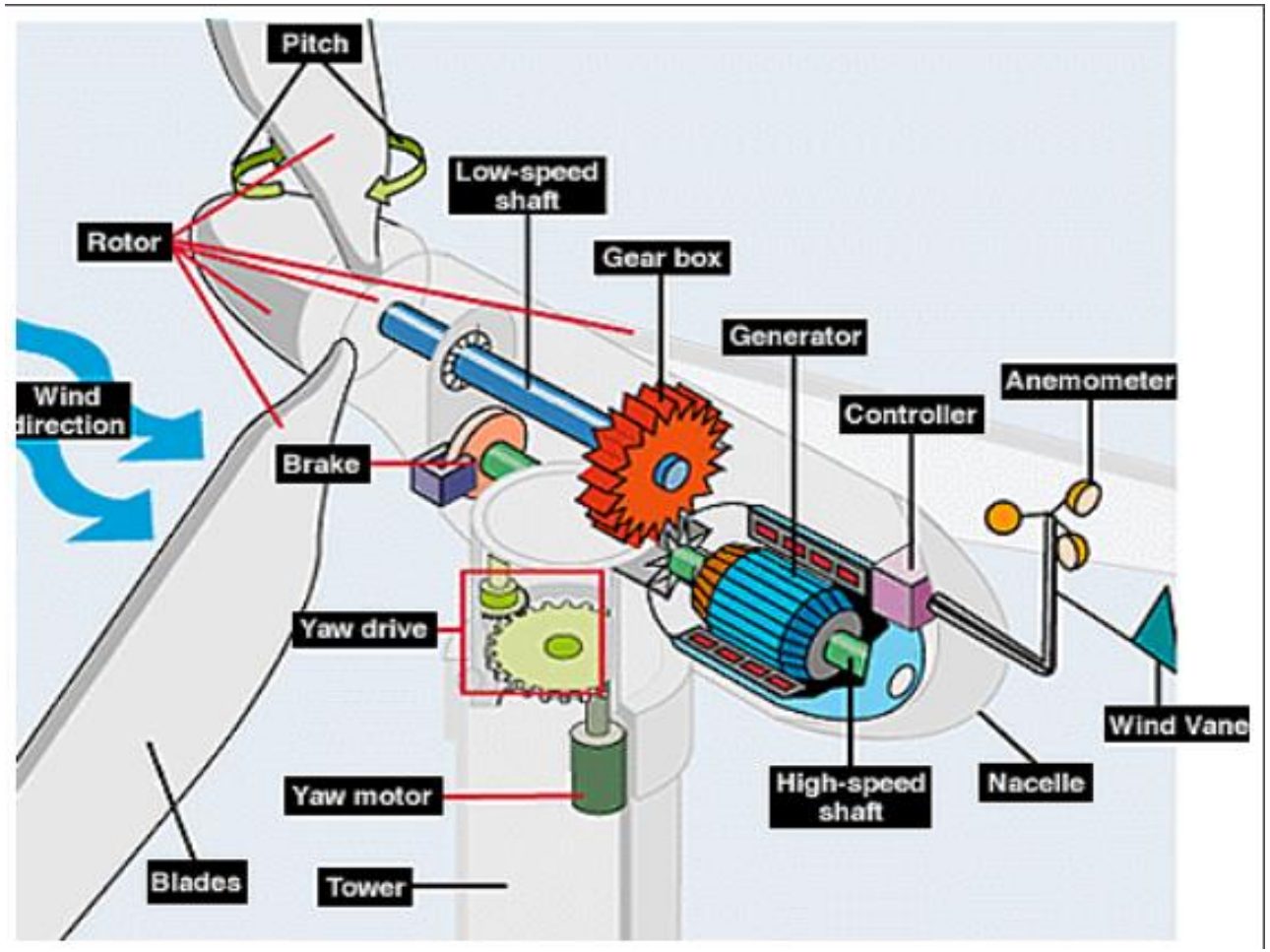
3.location

4. technology used

Breakdown cost of a typical 2MW wind turbine.

- Around 75% of total cost is directly related to turbine, which includes:

1. rotor blades,
2. gearbox,
3. generator,
4. power converters,
5. nacelle and
6. tower.



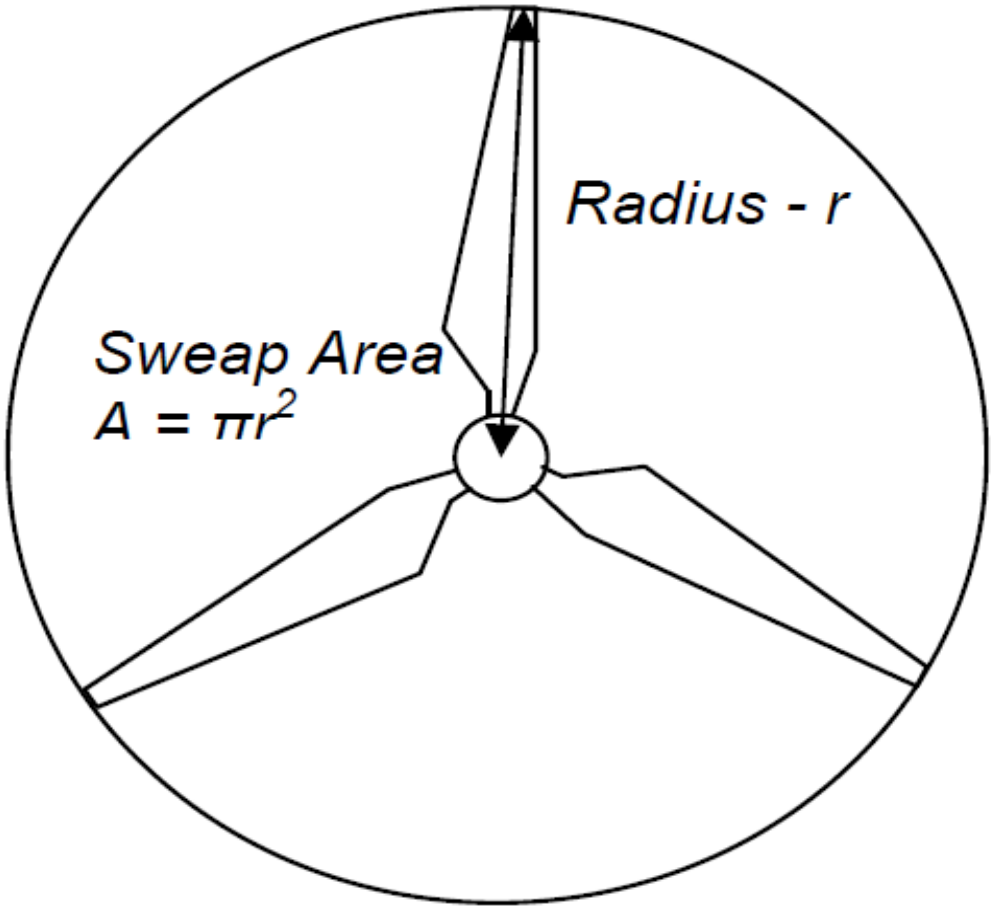
Other costs include:

Component	Share of total cost %
Turbine	75.6
Grid connection	8.9
Foundation	6.5
Land rent	3.9
Electric installation	1.5
Consultancy	1.2
Financial costs	1.2
Road construction	0.9
Control systems	0.3

Most effective methods for reduction in cost of per installed kW

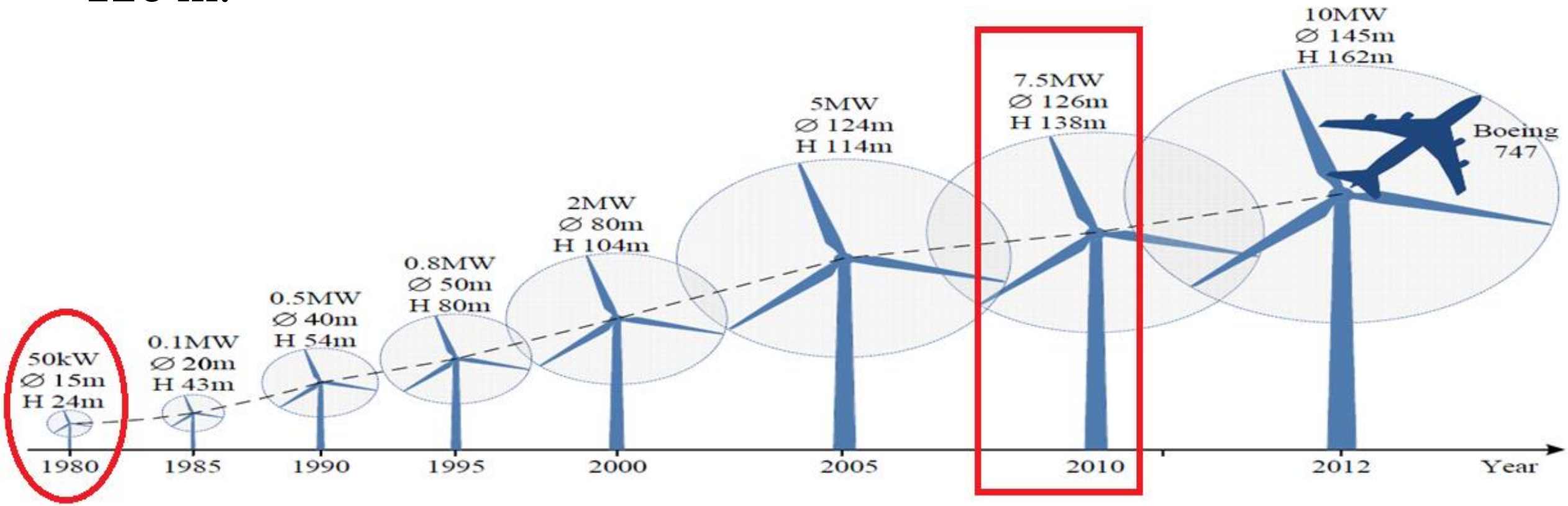
1. Increase the turbine size.
2. As swept area covered by rotor blades grows proportional to square of blade length.

$$A \alpha r^2$$

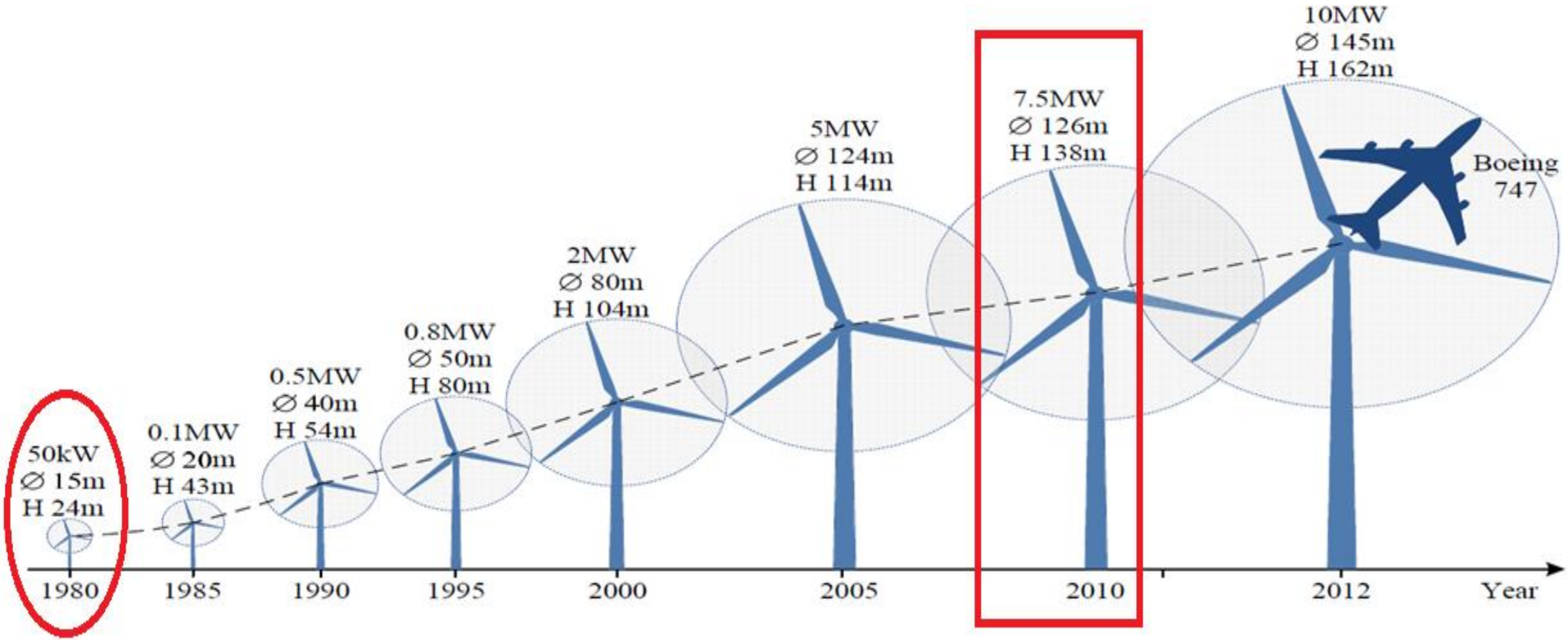


There is a favourable non-linearity between **blade length & captured wind power**

- 50 kW wind turbine in 1980 had a rotor diameter=15 m, while turbine size was increased to 7.5MW in 2010 with a rotor diameter =126 m.



Turbine rotor diameter & power rating have been increased by 126/15= 8.4 and 75000000/50000=150 times, respectively.



Question?

- Is the large MW turbine technology more costly?
- If yes then why?
- In no then why?

Cost per installed kW for 10kW, 50kW & 1.7MW wind turbines was $5,760, $3,300 and $1,680, respectively.

Item	Small Wind Turbine		Large Wind Turbine
Rated Output Power	10 kW	50 kW	1.7 MW
Turbine Cost	$32,500	$110,000	$2,074,000
Installation	$25,100	$55,000	$782,000
Total Installed Cost	$57,600	$165,000	$2,856,000
Total Cost Per kW Installed	$5,760	$3,300	$1,680

The larger the wind turbines, the lower the cost for per kW installed.

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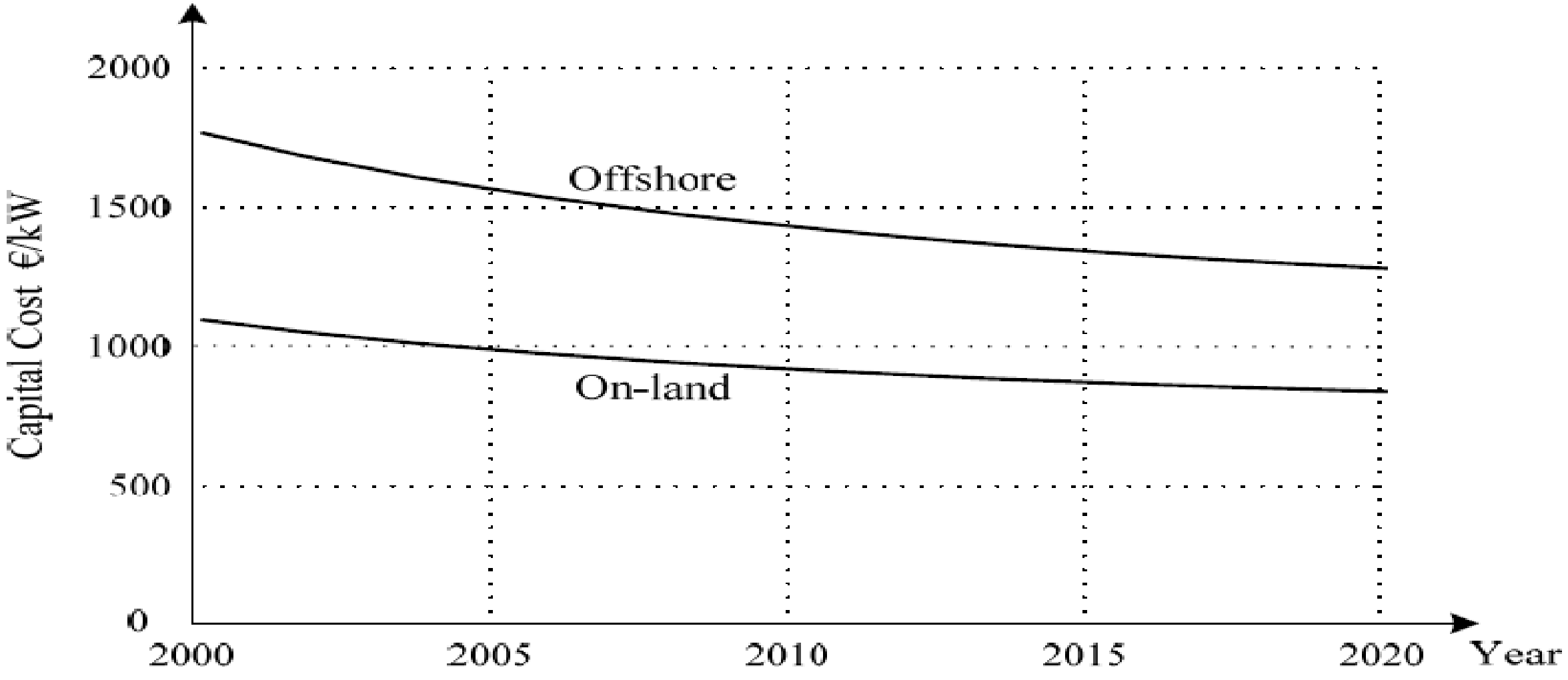
Total cost of wind energy systems is also affected by location of wind turbines.

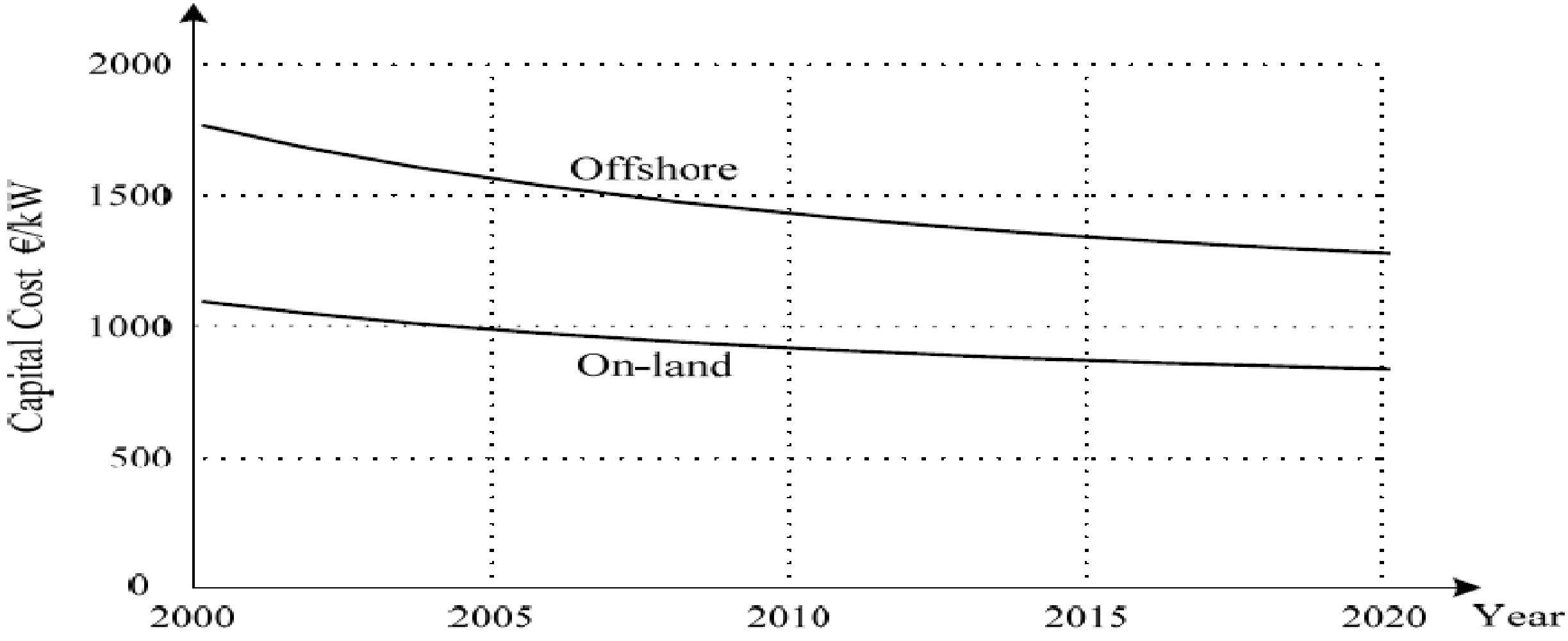
- Offshore wind turbines are normally more costly than on-land turbines mainly due to costs of:

1. higher turbine installation &
2. power transmission .

One of the reasons to make offshore wind power generation attractive.



Although offshore wind turbines cost>on-land turbines, greater energy output of offshore turbines can compensate higher initial costs.



Summary

- **BASIC TERMINOLOGIES**
- **RENEWABLE ENERGY SOURCES VS FOSSIL FUELS**
- **HISTORY OF WIND ENERGY**
- **GROWTH RATE OF WIND INDUSTRY**
- **SMALL VS LARGE WIND TURBINES**
- **STANDALONE & GRID-CONNECTED APPLICATIONS**
- **ON-LAND VS OFFSHORE WIND TURBINES**
- **COSTS OF WIND ENERGY CONVERSION SYSTEM**