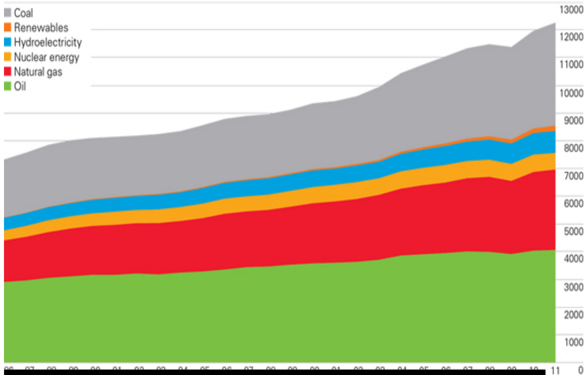
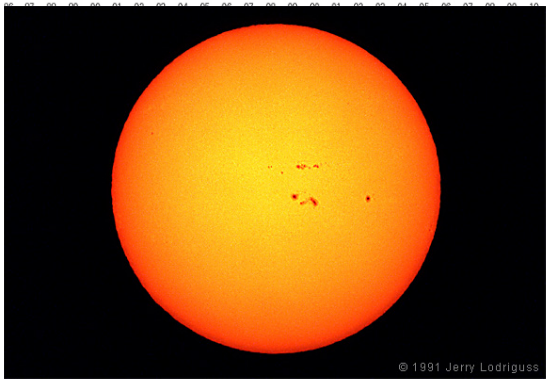
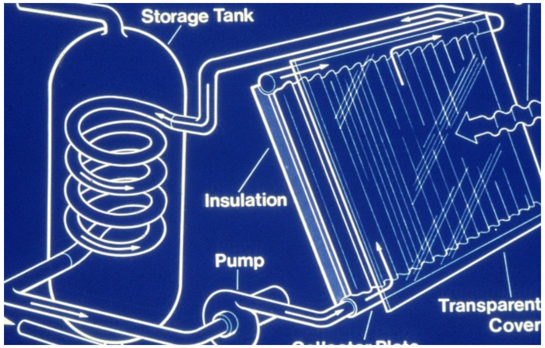
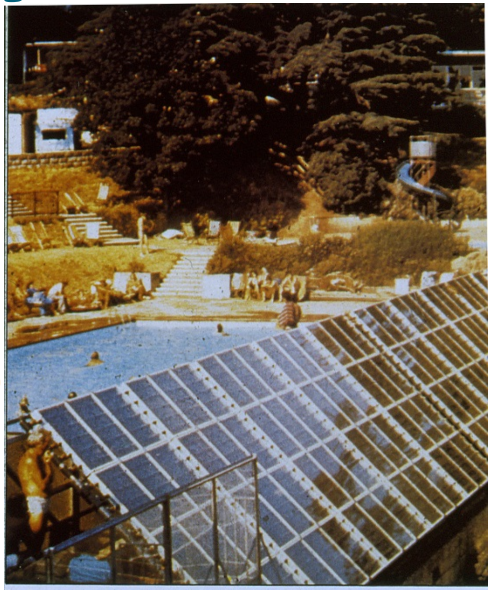
Sustainable Energy



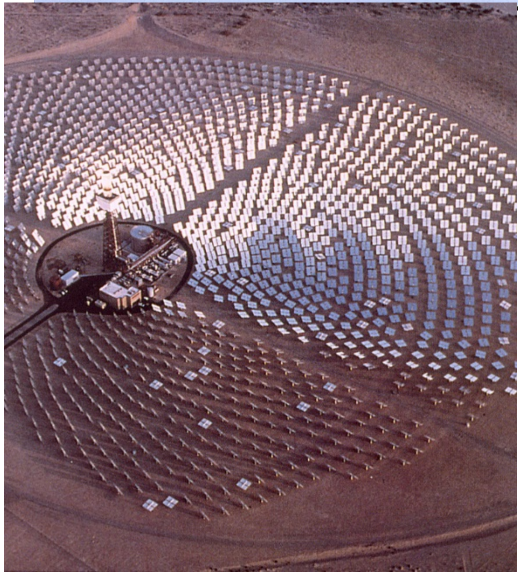
Solar Energy - Part 1 (Intro. & Solar Thermal)







3 A solar-panel for heating water for a swimming pool



Solar Energy

- Introduction - Solar energy as a resource
  - Insolation
  - Solar heating of AIR
  - Solar heating of WATER
- Capturing Solar Energy

  SOLAR THERMAL

  - Low temperature applications
    - Flat-plate Collector
  - High temperature applications
    - Solar Power Tower
    - Solar Concentrator Farms

  SOLAR PHOTOVOLTAIC

  - Principles
  - Characteristics
  - Applications
  - Future Prospects

Solar Energy – Input to Earth

Solar radiation arriving at Earth $I_{SC} = 1367\ W/m^2$ (empirical)

Diametric Plane of Earth = $\pi . R_{\oplus}^2$

Mean Input Radiation = $I_{SC.}\ \pi . R_{\oplus}^2$

$= 1.73 \times 10^{17}$ W $= 1.73 \times 10^{17}$ J / s

$= \underline{5.46 \times 10^{24}}$ J / year

World Primary Energy consumption (2011) (includes fossil, nuclear, hydro) used to generate electricity $= \underline{5.11 \times 10^{20}}$ J (source: BP)

i.e. Annual Input Radiation = $(5.46 \times 10^{24}) / (5.11 \times 10^{20})$

$\approx$ 10,700 x Primary Energy Demand !!

…so, Q: Why do we claim there is an 'energy shortage'?!?

Solar Energy – the ideal resource?

- Solar energy is plentiful and inexhaustible during the remaining lifetime of the Earth (~5 billion years).
- Solar energy is clean and generally beneficial and so 'should not attract any irrational prejudice'.
- The only problem is how to harness it effectively and economically.
- As the cost of fossil fuels rises, the economic case for solar energy will keep improving.

{Aside: Solar Energy 'in disguise'}

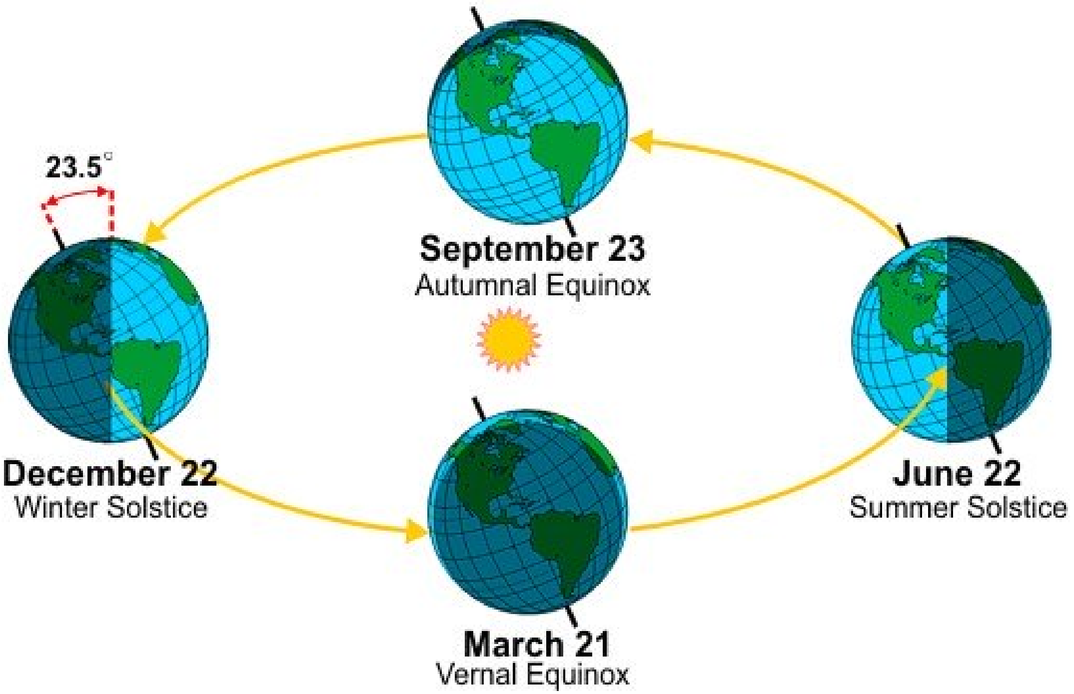
- Remember that coal, oil and gas represent fossilized solar energy from previous generations of plant and animal life of around 200 million years ago.
- Hydroelectric energy comes from rainfall driven by solar evaporation.
- Tidal power is driven by the gravity of the moon and sun.

This lecture will discuss *direct* uses of the energy in sunlight incident on the earth.

Solar Energy – Insolation

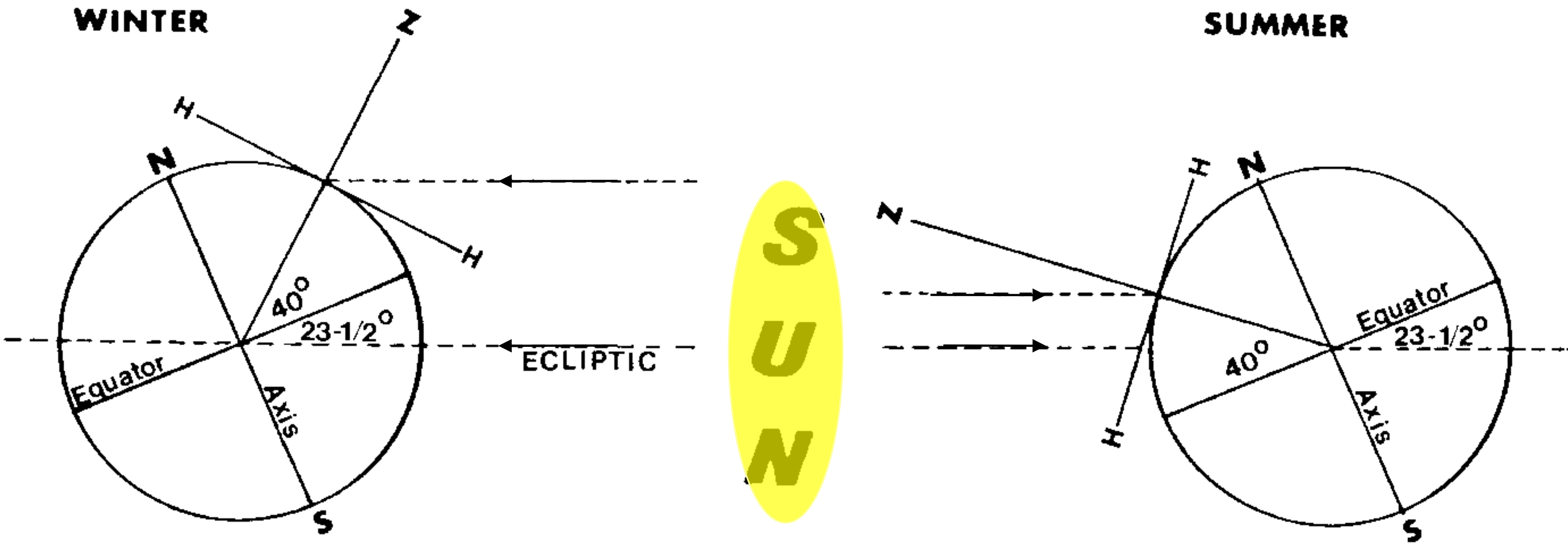
Direction of axial tilt remains unchanged.

- Earth's position changes → aspect presented to sun changes.



Solar Energy – Insolation

- At a given latitude (λ), angle (elevation, altitude) (α) of midday sun above horizon (**H**) is higher in summer, lower in winter by +/- axial tilt (τ)

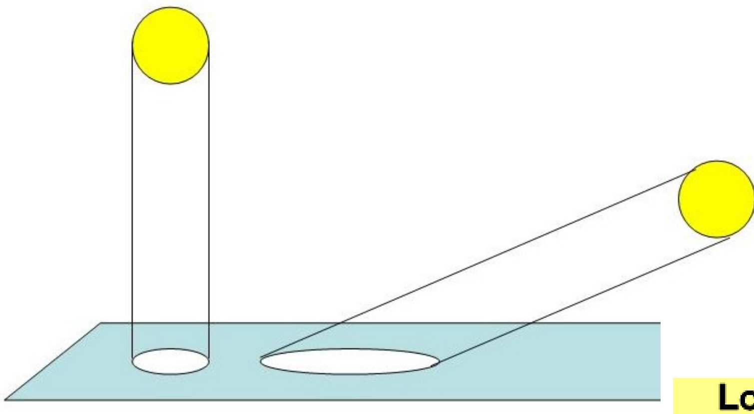


Solar Altitude α (Equinox) = $(90 - \lambda)$ = 50 deg

Max. Solar Altitude α (Summer) = $((90 - \lambda) + \tau)$ = 73.5 deg

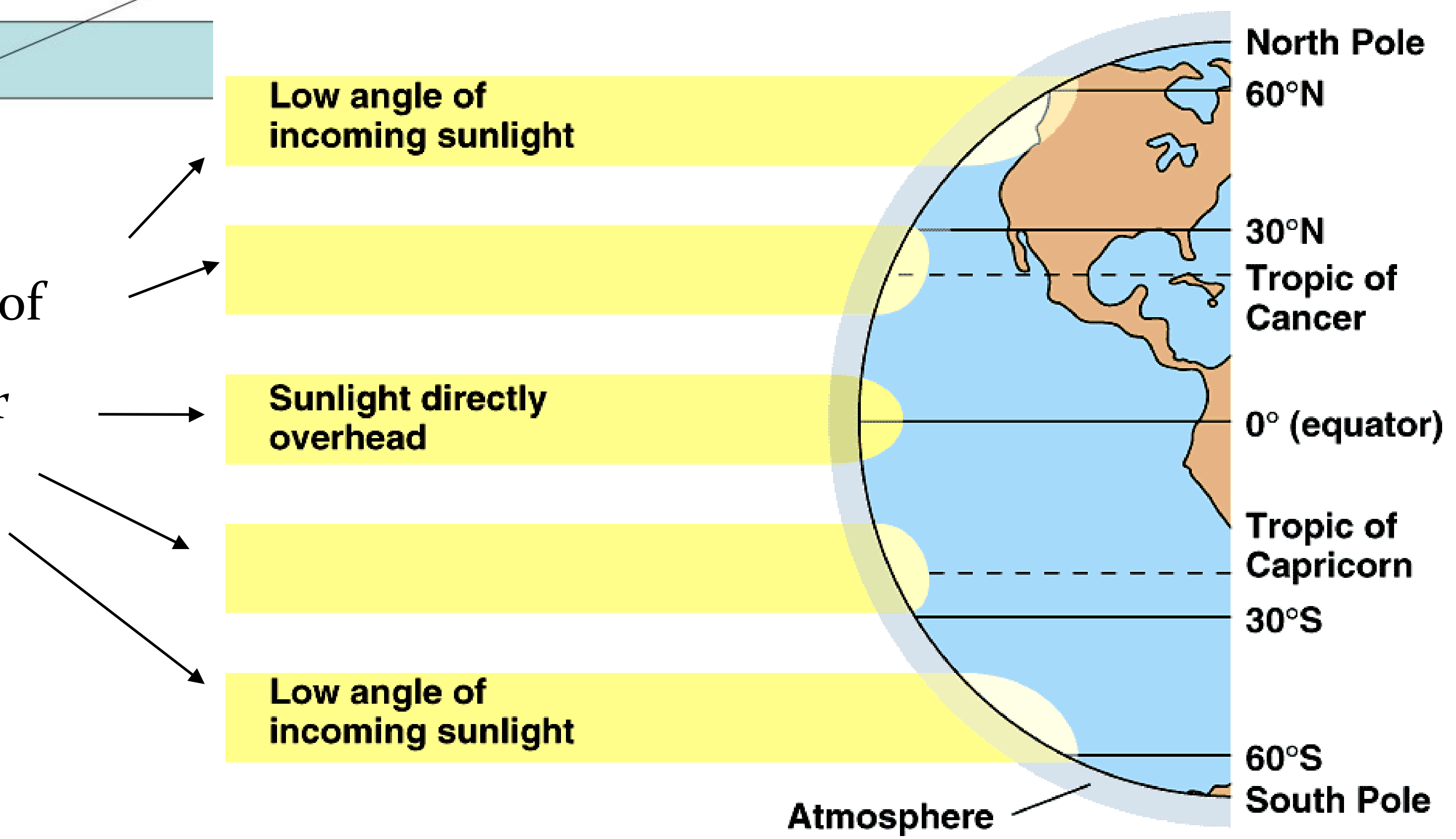
Max. Solar Altitude α (Winter) = $((90 - \lambda) - \tau)$ = 27.5 deg λ(Dubai) = 25 deg

Solar Energy – Insolation



Low angle packets projected over larger ground area → less insolation / unit area.

Equal packets of incoming solar radiation.



Solar Energy – Insolation

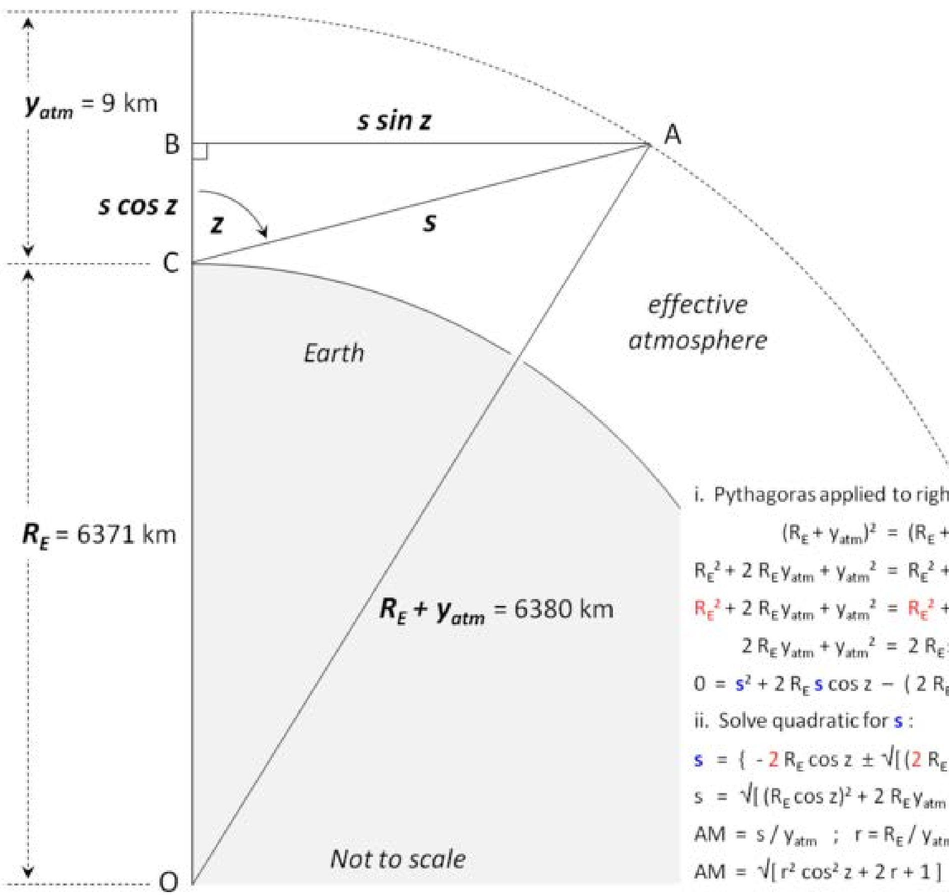
Lower altitude →

Sunlight has to pass

through a greater

thickness of

atmosphere (**air mass**



i. Pythagoras applied to right-angle triangle OAB :

$$(R_E + y_{atm})^2 = (R_E + s\cos z)^2 + (s\sin z)^2$$

$$R_E^2 + 2R_E y_{atm} + y_{atm}^2 = R_E^2 + 2R_E s\cos z + s^2\cos^2 z + s^2\sin^2 z$$

$$R_E^2 + 2R_E y_{atm} + y_{atm}^2 = R_E^2 + 2R_E s\cos z + s^2(\cos^2 z + \sin^2 z)$$

$$2R_E y_{atm} + y_{atm}^2 = 2R_E s\cos z + s^2$$

$$0 = s^2 + 2R_E s\cos z - (2R_E y_{atm} + y_{atm}^2)$$

ii. Solve quadratic for s :

$$s = \{-2R_E\cos z \pm \sqrt{[(2R_E\cos z)^2 + 4(2R_E y_{atm} + y_{atm}^2)]}\}/2$$

$$s = \sqrt{[(R_E\cos z)^2 + 2R_E y_{atm} + y_{atm}^2]} - R_E\cos z$$

$$AM = s/y_{atm} \;;\; r = R_E/y_{atm} \approx 708$$

$$AM = \sqrt{[r^2\cos^2 z + 2r + 1]} - r\cos z$$

(*Proof not examinable*)

Solar Energy – Insolation

Altitude of Sun depends on

- Latitude
- Season
- Time of day

Two factors contribute to loss of insolation for low-altitude sun:

- Projection of sunlight over oblique area
- Greater Airmass (m) (→ more atmospheric losses)

Solar Energy – Insolation

- Solar irradiance arriving at Earth (m=0, or 'AM0')

  $I_{sc} = 1367\ W/m^2$ → "*solar constant*"

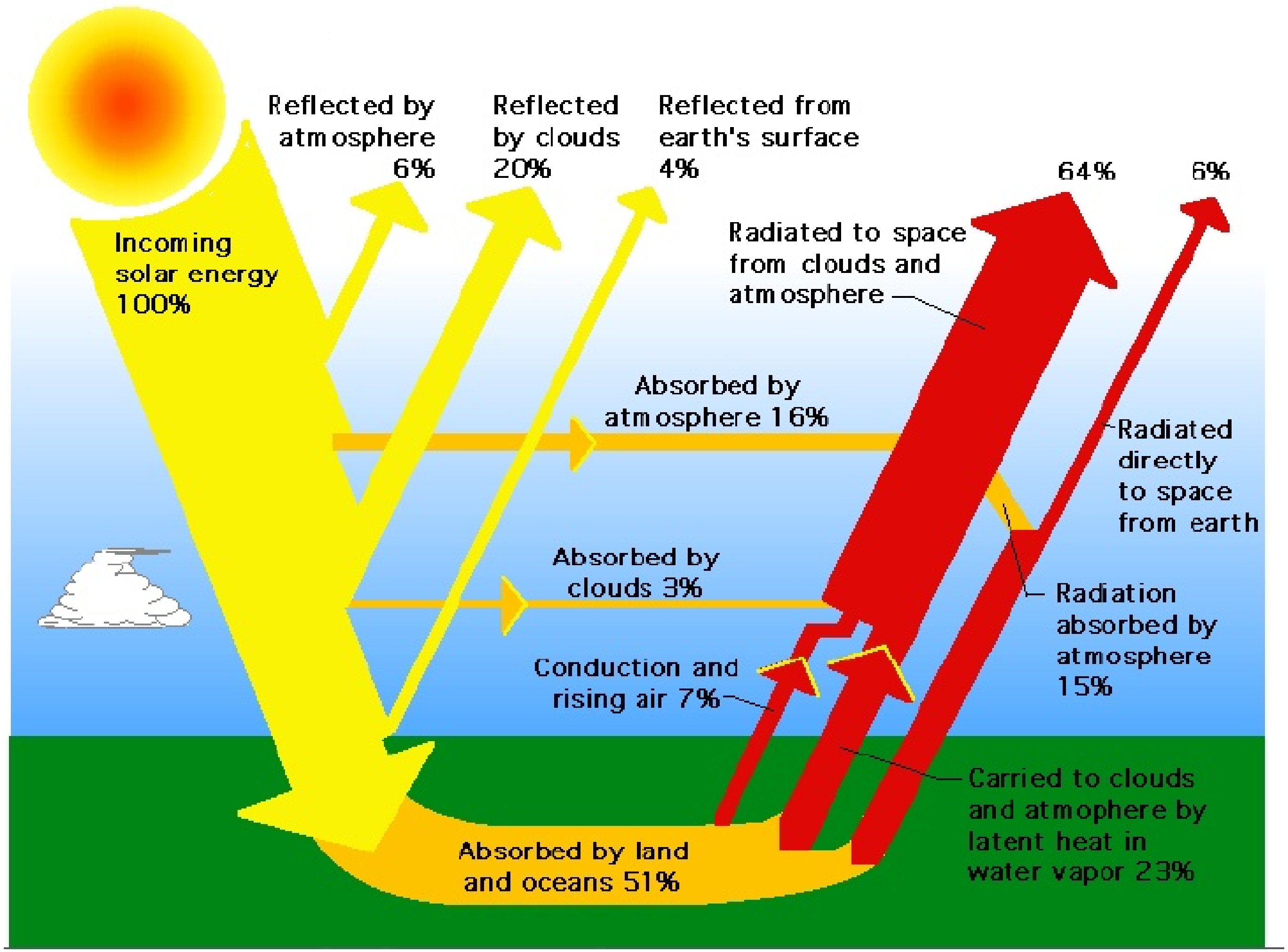
- Measured by orbital satellites
- Variations due to orbital ellipticity, sunspots ≈ +/- 1.5%
- Suffers many losses before reaching sea level (m=1, or 'AM1').

  - Reflection (Earth's albedo = 0.367)
  - Scattering (Rayleigh)
  - Absorption/extinction (by dust & molecules)

Rayleigh scattering causes blue sky; contributes to red sunsets

Solar Energy – Insolation

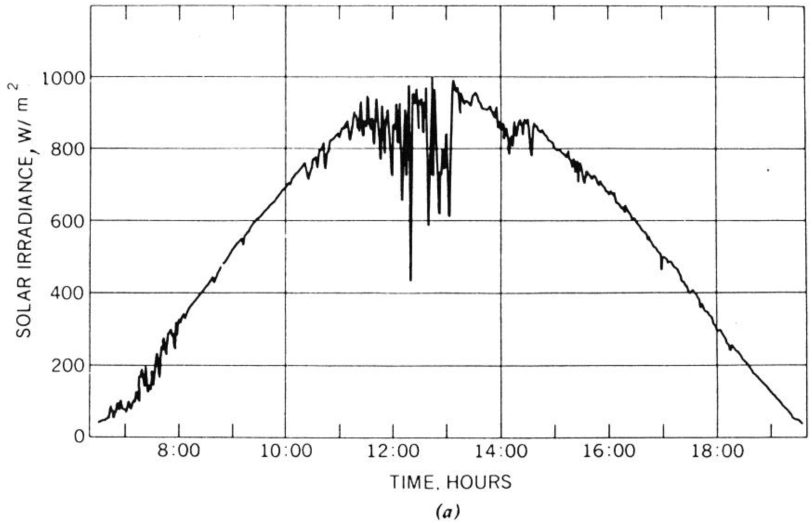
Radiation flows within the atmosphere



Solar Energy – Insolation

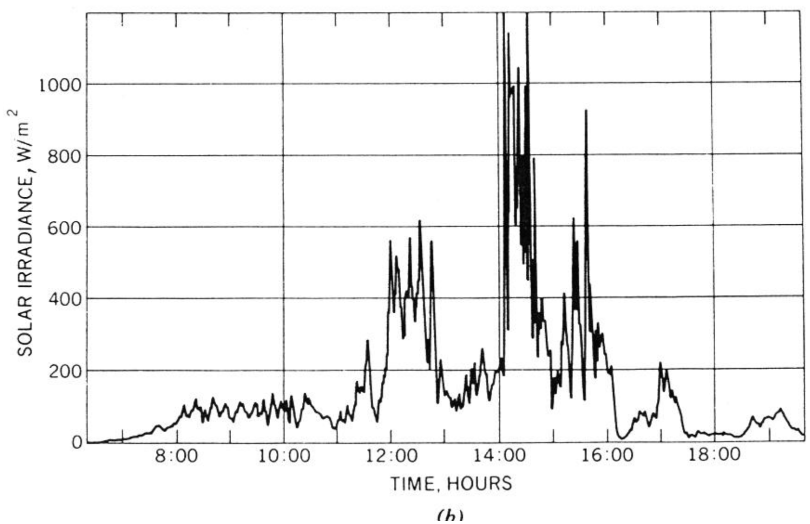
Irradiance at ground level in any location depends critically on cloud cover:

Mostly Sunny Day:



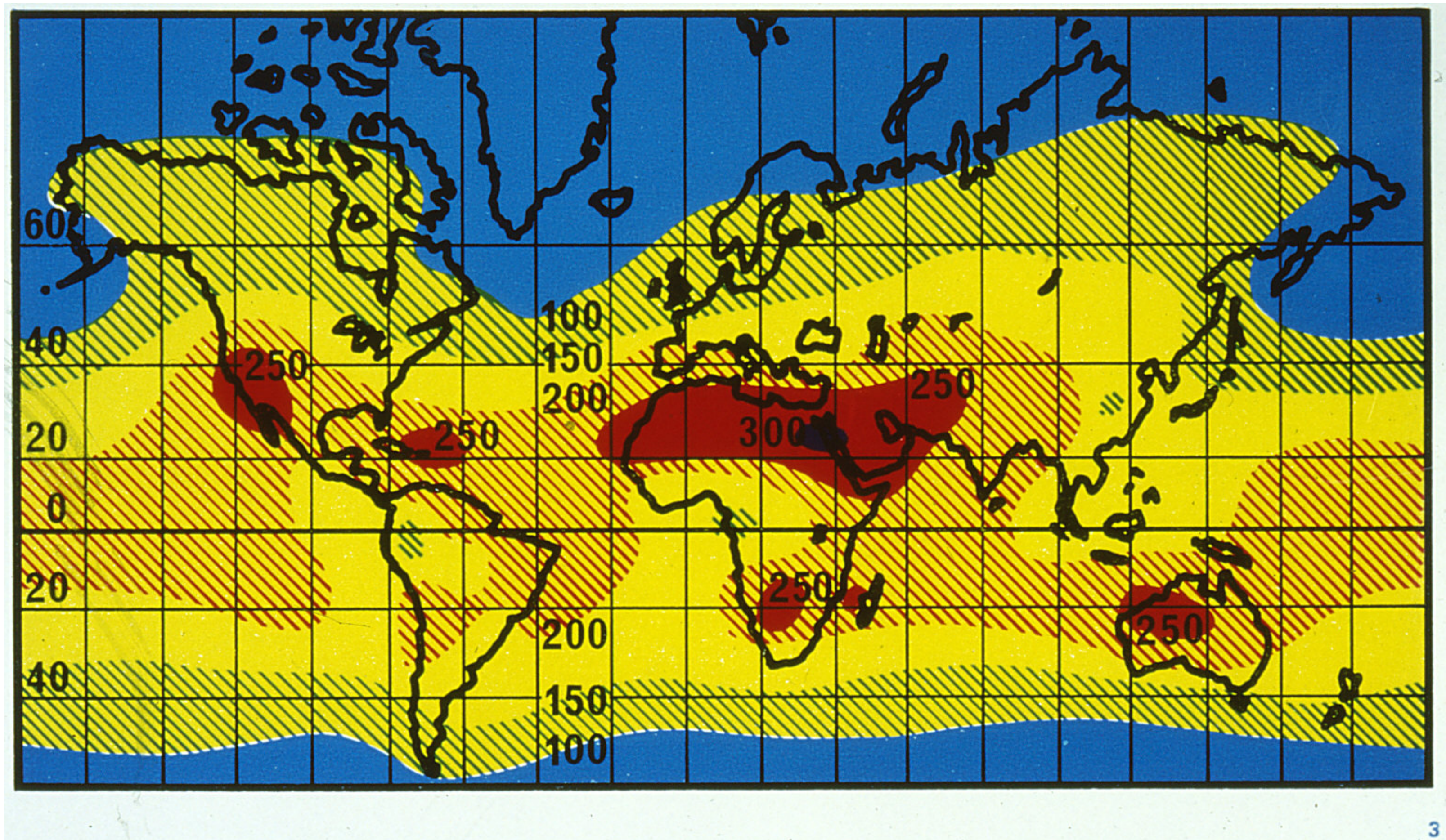
(Typical Bradford value: 4.5 kWh/m²)

Mostly Cloudy Day:



(Typical Bradford value: 1.3 kWh/m²)

Solar Energy – Insolation



Solar Energy – Insolation

Solar Energy Intensity (observed, horizontal surface)

(kW.h/m²)

UK: **8.4 to 0.8 daily**

1700 yearly*

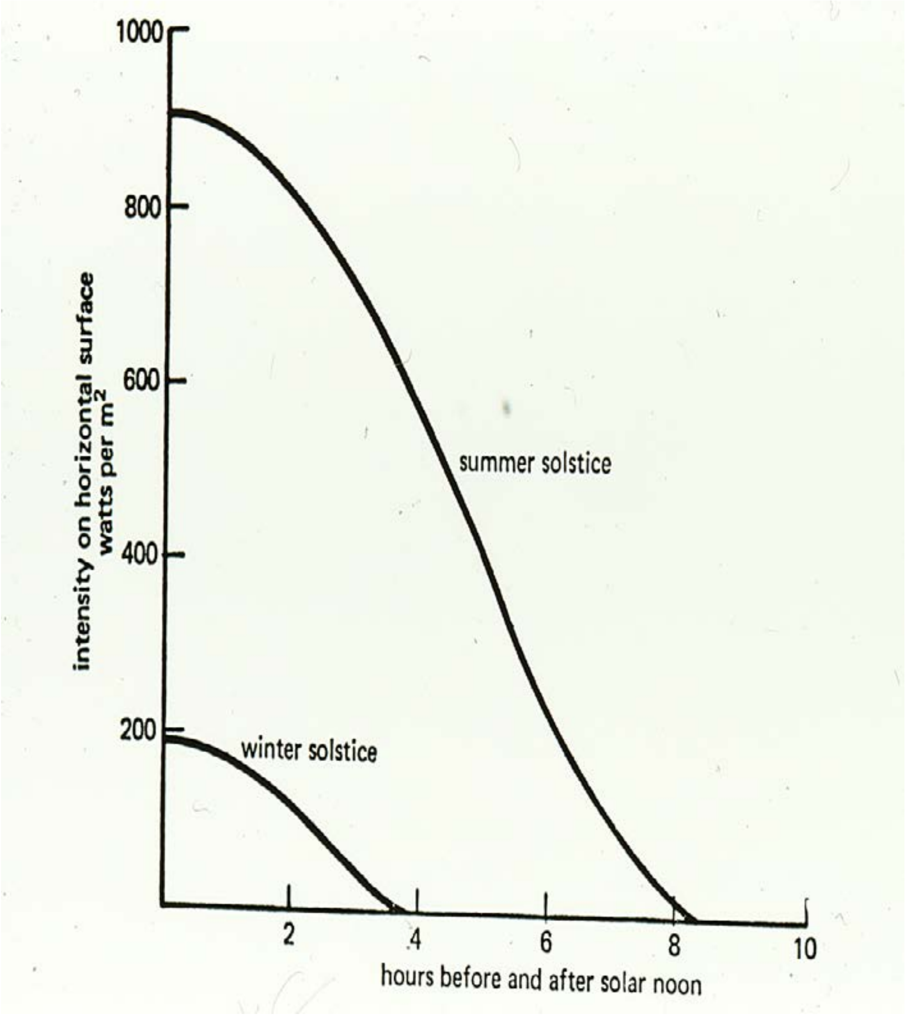
Lat 45°: **8.5 to 1.7 daily**

1900 yearly

Tropics: **8.3 to 4.2 daily**

2300 yearly

(* = clear atmospheric conditions)



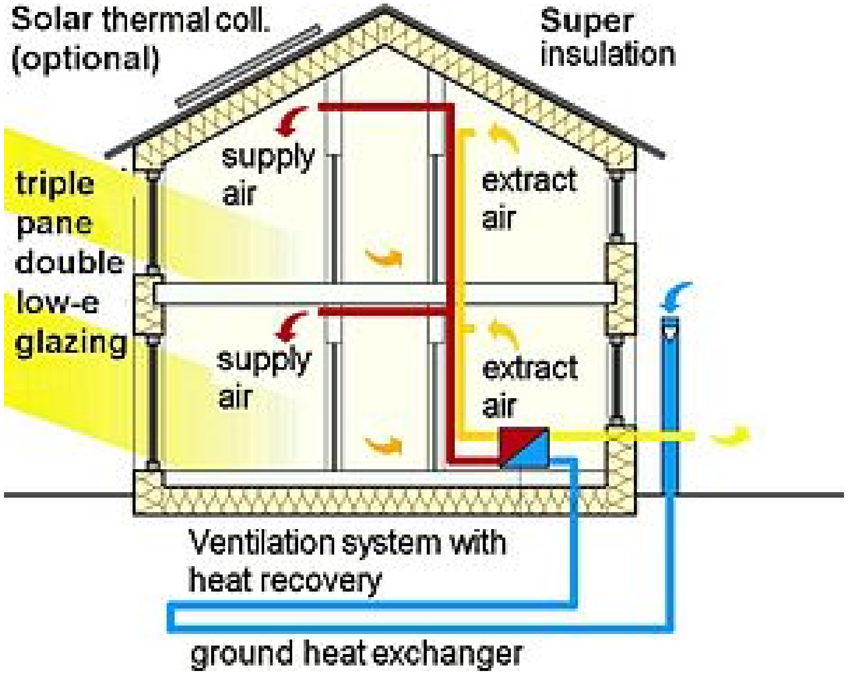
Solar Heating

- Anything up to one-quarter of energy used in USA and Europe is used for either “low grade” heating or cooling – i.e. involving relatively small temperature differences.

- If we can harness solar power either directly or indirectly then this makes very effective use of it and frees up “high-grade” energy (fossil fuels & electricity) for other purposes.

Solar Heating - Air - Passive

- Energy efficient building construction can make use of solar heating.
- Insulation, ventilation, heat-storage walls, etc.
- Ground heat-exchangers complement this strategy.
- Initial building costs will be higher; but due to energy costs, long-term savings can be considerable.
- Full implementation depends on rate of new construction, or investment/grants to improve efficiency of older houses.



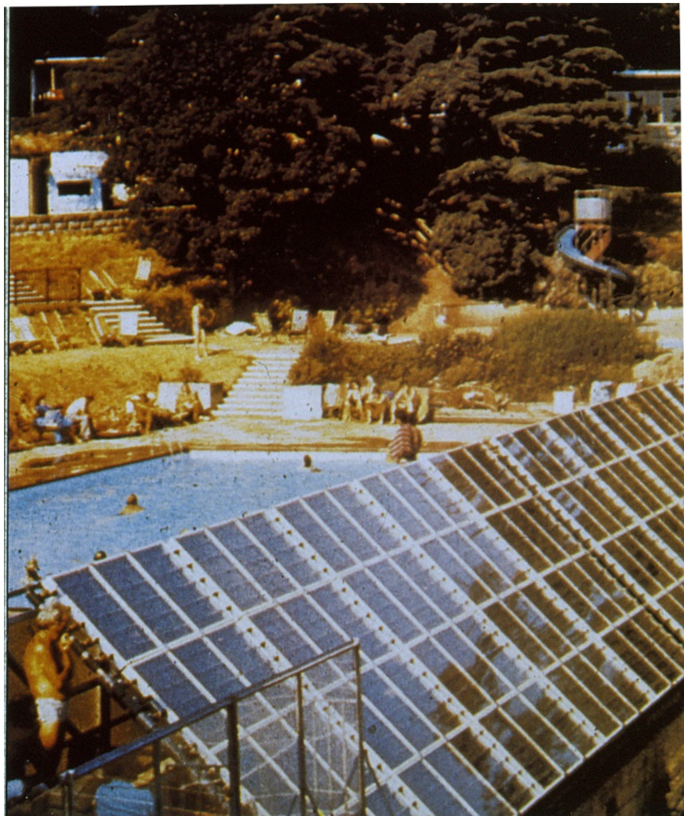
Solar Heating - Air

- Simple technology based on garden "greenhouse".
- Glass has a transparency which varies by wavelength.
- Visible radiation is largely transmitted (around 90%) and warms the floor and objects inside.
- Re-radiated energy from inside has longer wavelengths & cannot transmit (typically less than 1%). Result → greenhouse captures heat as well as benefiting from direct visible radiation.

Note: The so-called 'greenhouse effect' referring to earth's atmosphere is <u>not a true greenhouse</u>, as the top of the atmosphere re-radiates large amounts of energy to space.

Solar Water Heating

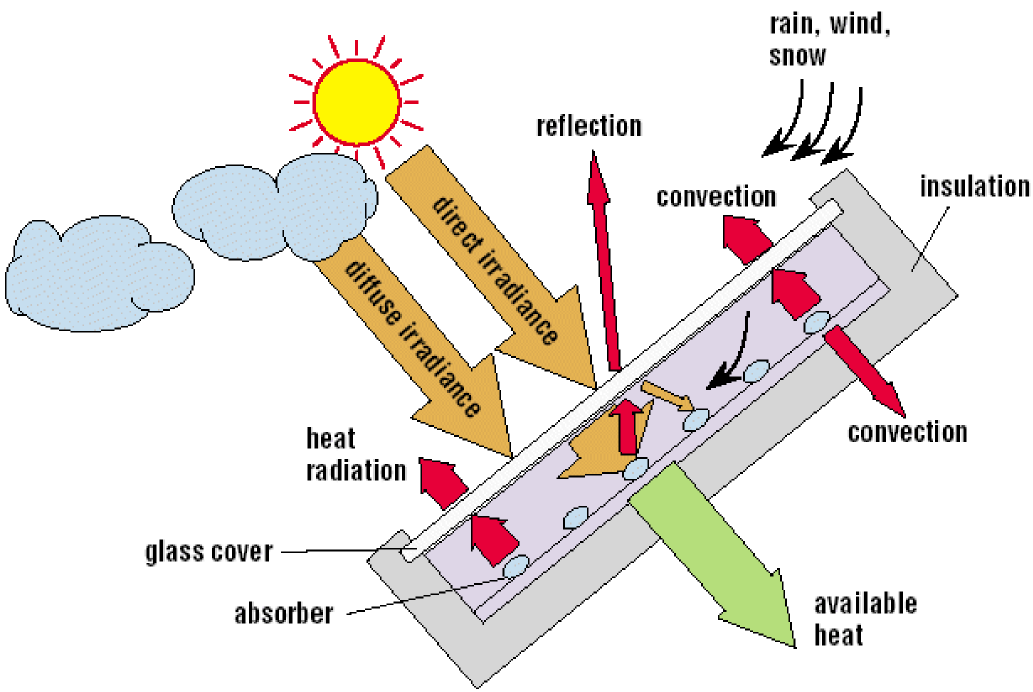
- By placing water-filled tubes beneath glass plates the water can be warmed and circulated for heating or stored for domestic or industrial purposes.
- The ideal arrangement is a sloping south-facing roof panel to maximise the energy collected.
- Water temp. rise of 10 to 15 ^{o}C can be achieved and pay-back times for the investment can be just a few years, especially in sunny climates.
- Example of an ideal use: heating swimming pools where only a small temperature rise is needed.

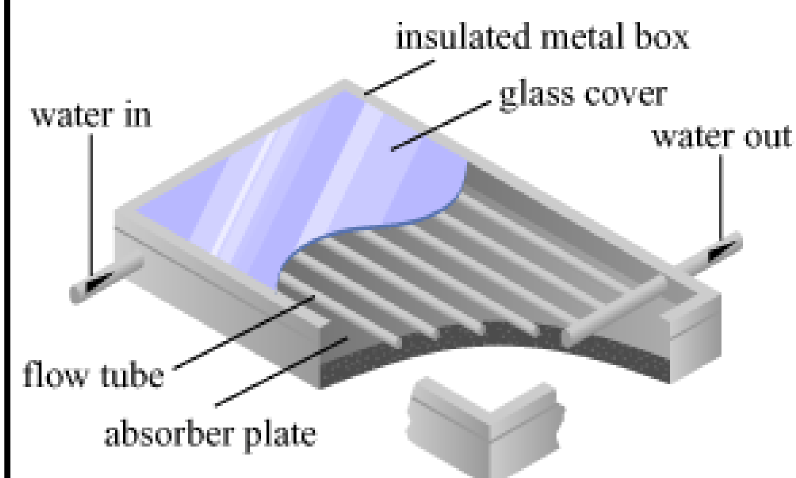


3 A solar-panel for heating water for a swimming pool

Solar Water Heating

- Use greenhouse principle, but instead of heating air, enclose circulating water inside a 'greenhouse'. ("Flat-plate collector").





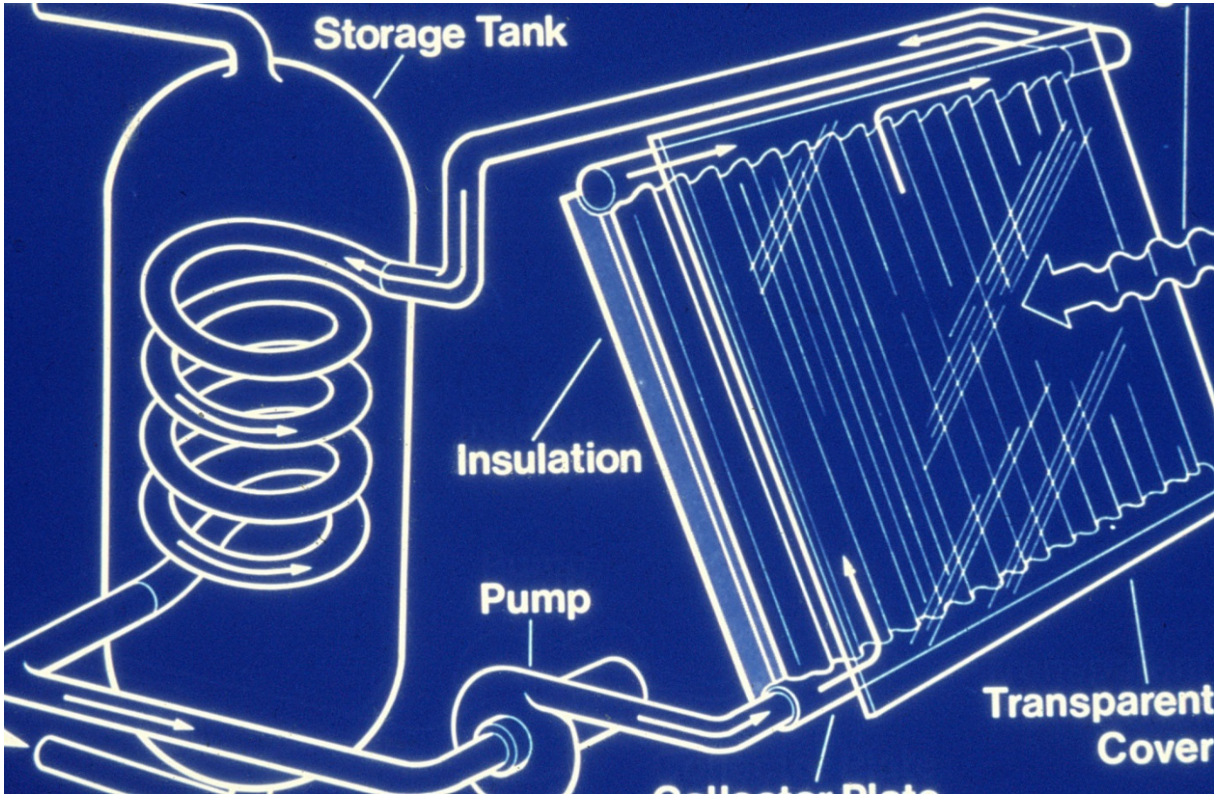
Capturing Solar Energy

- **Solar Thermal**
  - Low temperature applications
    - Flat-plate collector
  - High temperature applications
    - Solar Power Tower
    - Solar Concentrator Farms

Flat-Plate Solar Collector

Concept:

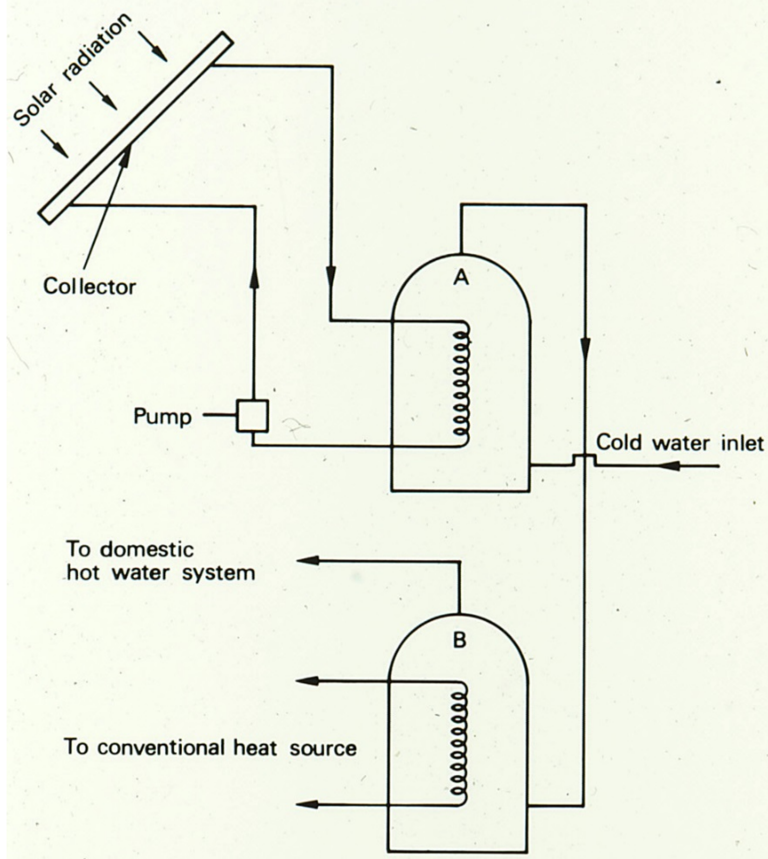
- Use incident solar energy to heat water passing through the collector plate.
- Pump the warmed water to heat exchanger, replace with colder water.
- Exchange heat with storage tank water.
- Stored water will now require less electrical heating to reach useful temperature.



Flat-Plate Solar Collector

Concept:

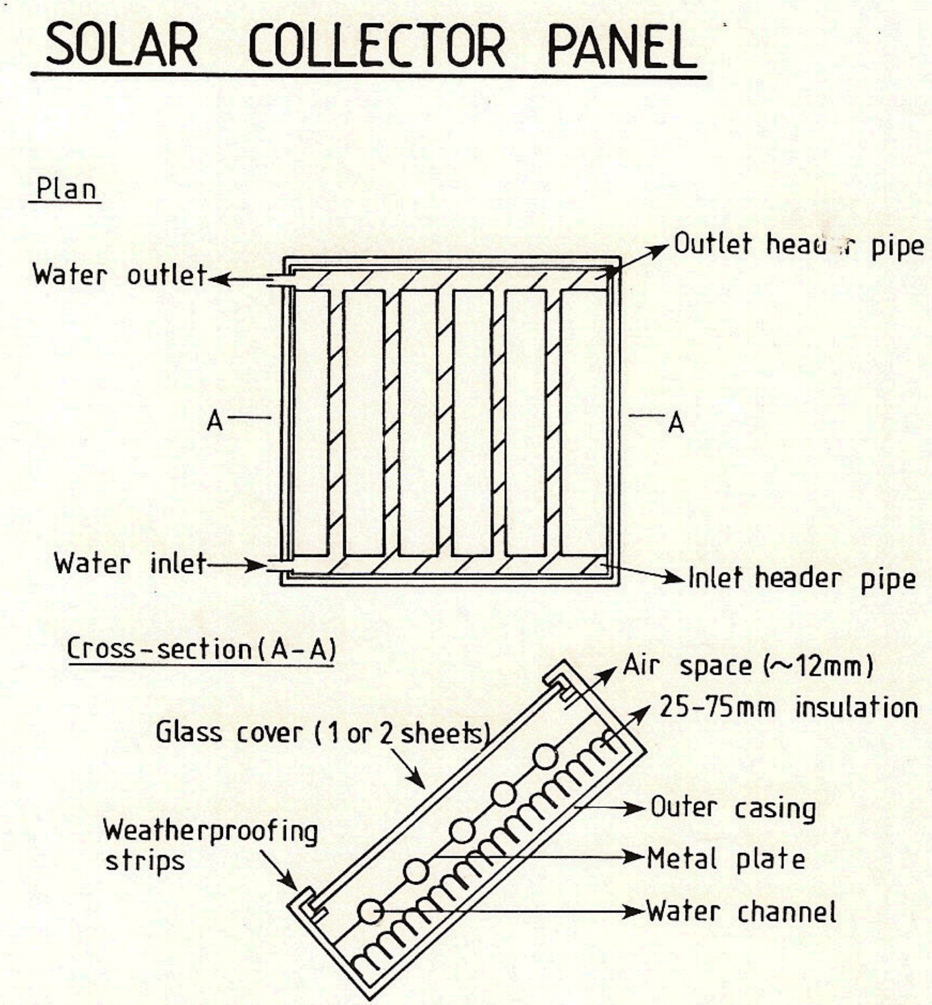
Solar <u>pre-heating</u> of cold water reduces operating cost of conventional hot water heating.

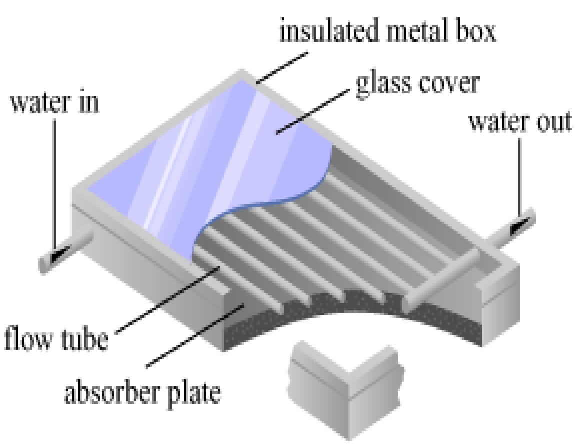


Improved solar collection system (note vent pipes and controls omitted)

Flat-Plate Solar Collector

Design:





Flat-Plate Solar Collector

Design criteria

$$\boxed{Q = F\,[\,G.\,\tau.\alpha - U\,(T_c - T_a)\,]}$$ {empirical}

Q = quantity of heat collected per unit area

T_c = collector fluid temp. (K)

T_a = ambient temp. (K)

G = total normal incident radiation (W/m^2)

U = heat loss coefficient (depends on glazing, wind conditions)

τ = transmittance of covers

α = absorptance of collector plate

F = design factor of collector construction

Thermal performance is defined by the design factors F, U, and (τ times α)

Flat-Plate Solar Collector

Efficiency of Flat-Plate Collector

$Q = F\ [\ G.\tau.\alpha\ -\ U\ (T_c - T_a)\ ]$

$$\eta = Q\ /\ G$$

$$= F\ [\ \tau.\alpha\ -\ (U/G).(T_c - T_a)\ ]$$

Using typical values for glazed collectors:

$$\eta = 0.78 - ((1/G).(7.7).(T_c - T_a))$$

note: if $T_c \uparrow \quad \eta \downarrow$

Example: If typical UK incident radiation (G) = 850 W/m², T_c = 333K, T_a=288K

$$\eta = 0.78 - ((1/850)\ .\ (7.7)\ .\ (333\text{-}288)) \quad = \quad \underline{\mathbf{0.372}}$$

Flat-Plate Solar Collector

$\eta = F\,[\tau.\alpha \;-\; (U/G).(T_c - T_a)\,]$

Improving Efficiency

$\eta \uparrow$

- Increase the 'effective' incident radiation — $G \uparrow$
  - Install facing South
  - Incline plate to better angle; Tracking(?)
  - Use a 'concentrator'(?)
- Reduce conduction/convection losses — $[U\,(T_c - T_a)] \downarrow$
  - Lower working temp. of collector fluid — $T_c \downarrow$
  - Improve collector geometry (honeycomb) — $F \uparrow$
  - Reduce temp diff. between cavity and ambient — $(T_c - T_a) \downarrow$
  - Evacuate the collector cavity — $U \downarrow$
- Reduce radiation losses
  - Selective* absorbers on plate — $\alpha \uparrow$
  - Selective** windows — $\tau \uparrow$

* = blackened copper/chrome ** = high-transmittance glass

Flat-Plate Solar Collector

Example of Domestic Installation

- 3-5 m^2 collector for water heating (~ 1 m^2 per person)
- Pre-cylinder capacity 100-200 L
- Working efficiency ~ 30-40%

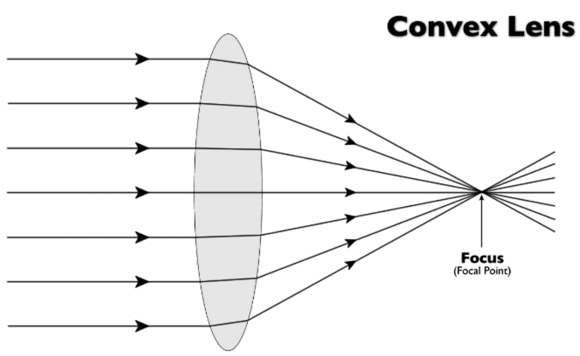
(Compare – overall efficiency of coal-fired electricity generation ≈ 30-40%)

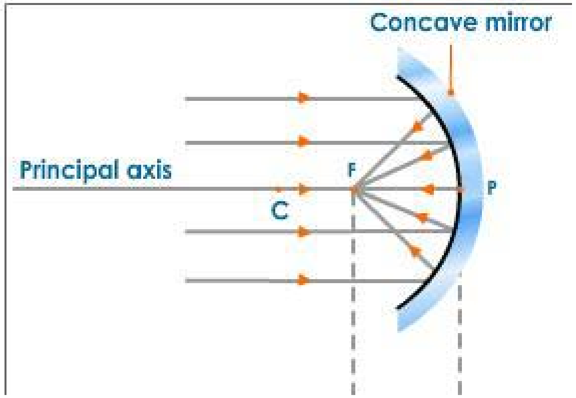
Conclusion → Flat-plate collectors are a viable option for energy augmentation/conservation for a low-temp. application such as water pre-heating.

Commercial Solar Flat-Plate collectors

High Temperature Solar Energy

- By concentrating solar radiation it is possible to achieve extremely high temperatures.
- Simple concentrators: magnifying glass, concave mirror.
- The theoretical maximum is 5,800K ($T_{\text{sun surface}}$).
- A practical limit ~4300K by using a many mirrors to concentrate large area of sunlight onto a small target.
- A target temperature of 870K is adequate to drive an efficient steam-powered generator.





Solar Concentrator Systems

<u>Concept</u>

$$\text{Concentration Ratio} = \frac{\text{Collector Area}}{\text{Absorber Area}}$$

For flat-plate, CR = 1

For designed concentrator systems, 10 < CR < 10,000

With a Fixed Collector Area:

$$\text{Absorber Area} \propto (1 / \text{CR})$$

High CR requires only small absorber area -> reduced radiation losses -> higher efficiency.

Solar Concentrator Systems

<u>Design</u>

Heat losses in absorber $\propto$ T^4 {Stefan law}

==> Compromise must be found between

- high CR (small absorber size)
- small losses (lowest possible working temp.)

Solar Concentrator Systems

"Heliostat"

Mirror which tracks the Sun to keep the reflection on a pre-determined target.

- Cleaning required.
- Prone to high wind.
- Typical area $(6\text{-}11\ m)^2$

Solar Power Tower

'Solar Two' (1994-1999) – Mojave Desert USA

~10MW rating 1926 heliostats cover 82750 m^2.

Molten salt transfer fluid (improves storage).

Solar Power Tower

THEMIS Experimental Solar Power Plant, France
approx. 2MW output (1983-1986)

Solar Power Tower

'PS10' and

'PS20',

S. Spain.

30MW total capacity.

1879 x 120m^2 heliostats

Annual generation 71.4 GW.h

Solar Power Tower

Solar Power Tower design criteria:

$$\boxed{P = I_D \,.\, A_L \,.\, \varepsilon_H \,.\, \eta_H \,.\, \eta_{real}}$$

P = power rating of absorber

$\mathbf{I_D}$ = direct component of solar radiation

$\mathbf{A_L}$ = land area of collector site

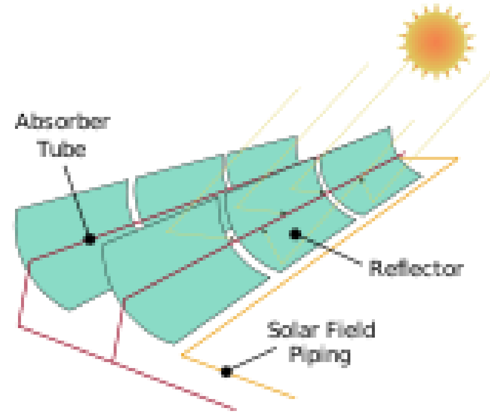
$\boldsymbol{\varepsilon_H}$ = fraction of site covered by heliostats {typically ¼}

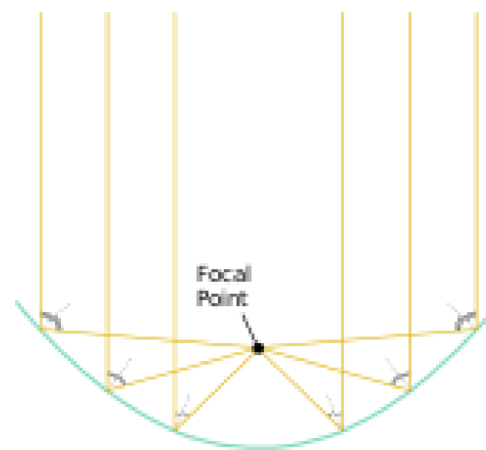
$\boldsymbol{\eta_H}$ = thermal efficiency of heliostats {typically 50%}

$\boldsymbol{\eta_{real}}$ = realistic proportion of the Carnot efficiency for HIGH temp systems {0.7}

where $\eta_{CARN} = (T_H - T_C) / T_H$ {T_C and T_H in Kelvin}

Solar Thermal – Parabolic Trough





SEGS, Mojave Desert USA – 354MW – avg gross 75MWe
936,000 parabolic trough mirrors (94% refl.) cover 6.5 km²
Central tube at focus carries synthetic oil -> heat water.
Turbines powered by natural gas at night.

Solar Thermal

Applications – Power Stations

- Ivanpah SPT[1], USA 2014, capacity 392 MW
- SEGS, USA 1984, capacity 354 MW
- Mojave Project[2], USA, 2014, 280 MW
- Solana[3], USA, 2013, 280 MW
- Genesis Solar[4], USA, 2009, 250 MW

Worldwide, ~14.46 GW* (2014)

In construction or planning

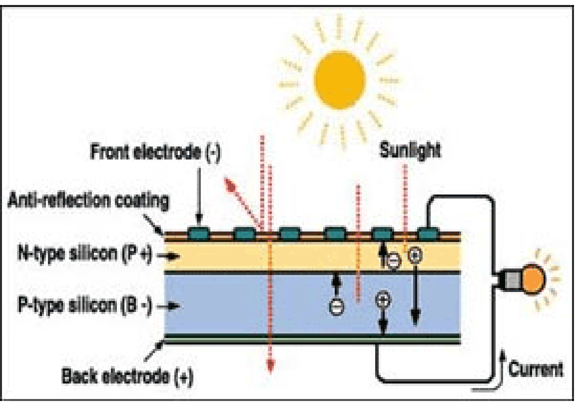
Worldwide, > 6 GW, mainly Spain, + Morocco China, India.

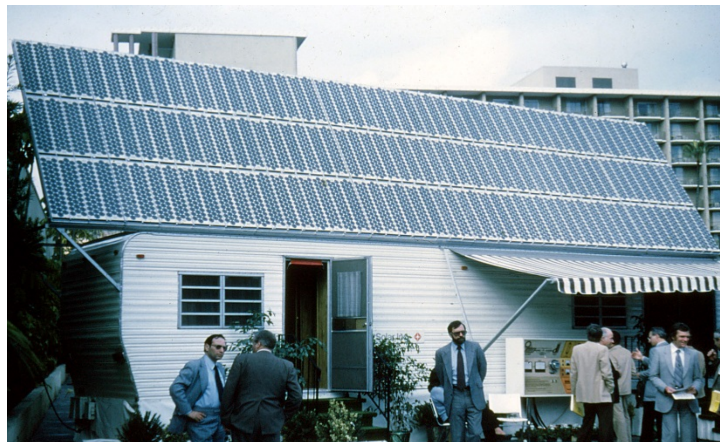
(* → power stations, not total capacity)

High Temperature Solar Energy

- Solar thermal power plants require large land area BUT:
  - For given electricity output use less land than hydroelectric (including lake area) or coal (including area of land for mining).
  - Ideal for deserts where alternative uses for land are few and insolation is high.
- Salt storage strategy allows solar plant to be online 60% more than water/steam plant – can release stored energy at night(!).
- Cost of construction high, but running costs low.

Part 2 - Solar Photovoltaic





Solar Photovoltaic

<u>Introduction</u>

- Definition – "*Direct conversion of solar radiation to energy*"

- Direct conversion to electricity is attractive because you immediately get "high-grade" energy with no moving parts in the actual generation system.
- Simple in principle – "solar cells" can be made of silicon semiconductor materials using well-understood technology.
- Silicon itself is cheap & abundant.

Solar Photovoltaic

<u>History</u>

- 1839 – Photovoltaic⁺ effect – Becquerel
- 1883 – First PV cell – Fritts
- 1887 – Photoelectric* effect discovered – Hertz
- 1889 – First PE cell – Stoletov
- 1905 – PE effect explained – Einstein
- 1945 – Modern junction semiconductor cell – Ohl

* PE → Electrons are <u>ejected</u> from a material

⁺ PV → Electrons excited within material to become free electrons

Solar Photovoltaic

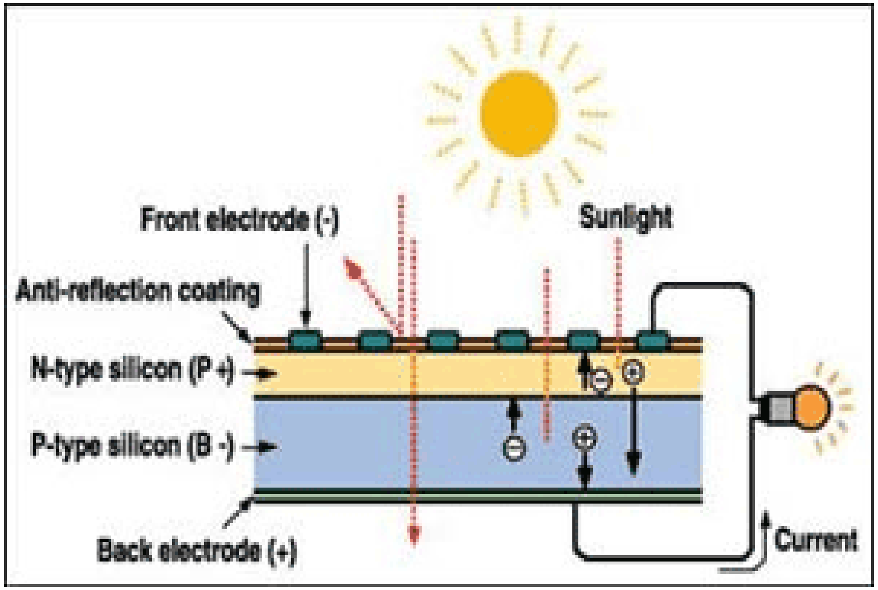
Principles

- A semiconductor p-n junction can be switched on by irradiation.
- Released electrons flow to terminals, producing a DC current in any connected circuit.
- A minimum energy is required to release an electron (varies by material used, temperature).
- Current produced is only few mA,

power only a few mW, but many cells

connected in arrays can produce

viable output.



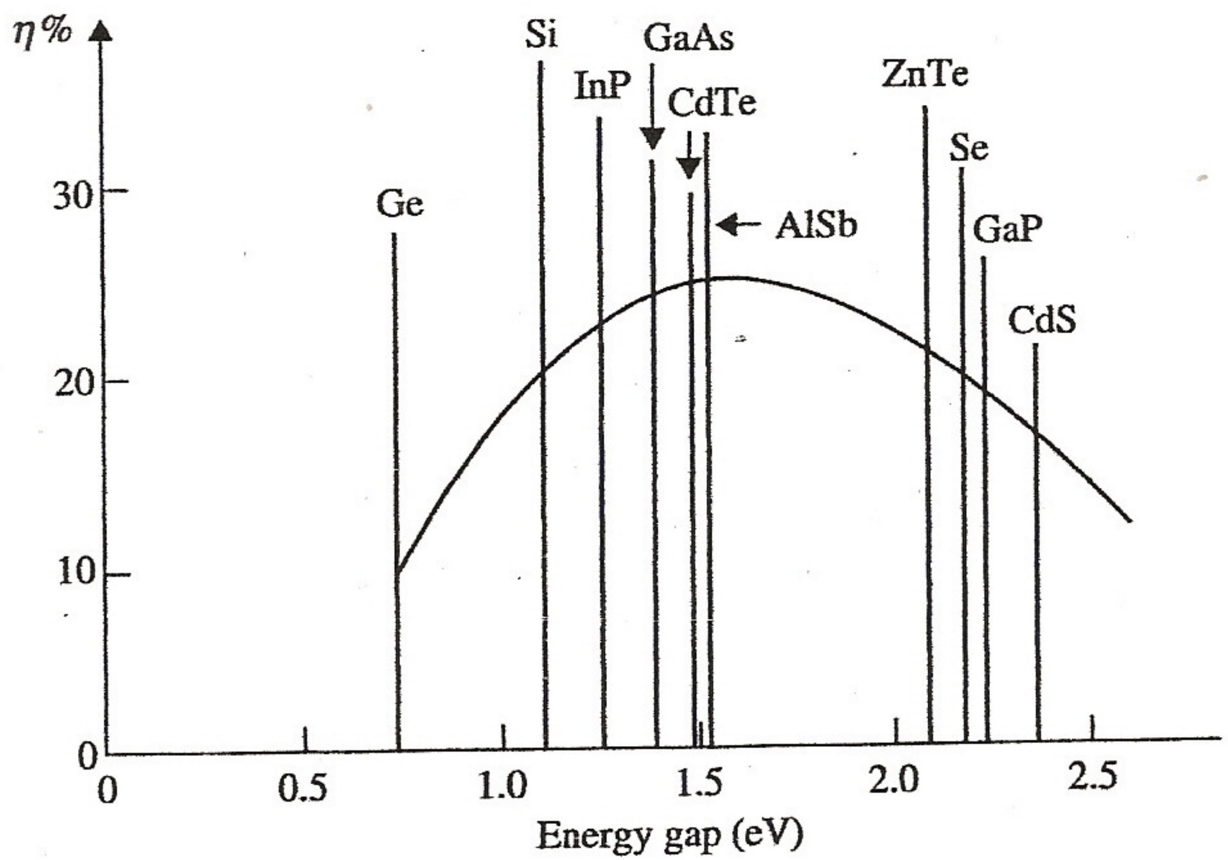
The photovoltaic effect

Solar Photovoltaic

Max. <u>realisable</u> solar cell efficiencies for various materials <u>at o°C</u>

- Efficiency curve falls as temp ↑

- Materials other than silicon more efficient but more expensive.



Ref: Panasonic solar cells technical handbook 2000

Solar Photovoltaic

Applications - General

Mid 20th century, PV applications few and rare – common only in photographic equipment and a few other applications (e.g. powering buoys).

Late 20th century, proliferation of ICs and LCDs allowed more PV applications in small, low-power applications e.g. clocks, torches, radios, doorbells, garden lights, fountains, calculators, chargers, motion-sensors, security lights, automatic on/off switches. Becomes common power supplement on Earth-orbit spacecraft.

21st century: increased use in remote locations where grid connection would be expensive: street/road lighting, traffic signs, emergency telephones, etc., Ancillary power for buildings. Power stations (see below).

Solar Photovoltaic

Applications:

Specialist

GaAs and Si layered multi-junction cells, up to 29% efficient.

- ISS: 8 'wings' each 32m x 11m. Output ~200kW, life-time of 15-20 y.

Solar Photovoltaic

Applications – Power Stations

- Agua Caliente[1], USA 2014, capacity 250->400 MW
- Golmud, China 2011, capacity 200 MW
- Perovo Park[2], Ukraine[+], 2011, 100 MW
- Sarnia[3], Canada, 2009, 80-97 MW
- Viterbo[4], Italy, 2009, 84 MW

Worldwide, ~12 GW* (March 2013)

In construction or planning

Worldwide, > 11 GW, mainly China, India, USA.

(* → power stations, not total capacity)

Solar Photovoltaic

Applications – Buildings

Mount PV array on/near building.

Appreciable impact on electricity demand if widely implemented.

e.g. 80% of Germany's 9 GW* of operating PV is installed on rooftops.

(compare: UK: 750MW) (* ~12% of Germany's total electricity demand)

Building-Integrated Photovoltaics (BIPV)

PV materials replace conventional building parts; roof, glazing, facades, providing ancillary electrical power.

Solar Photovoltaic

Global

installed

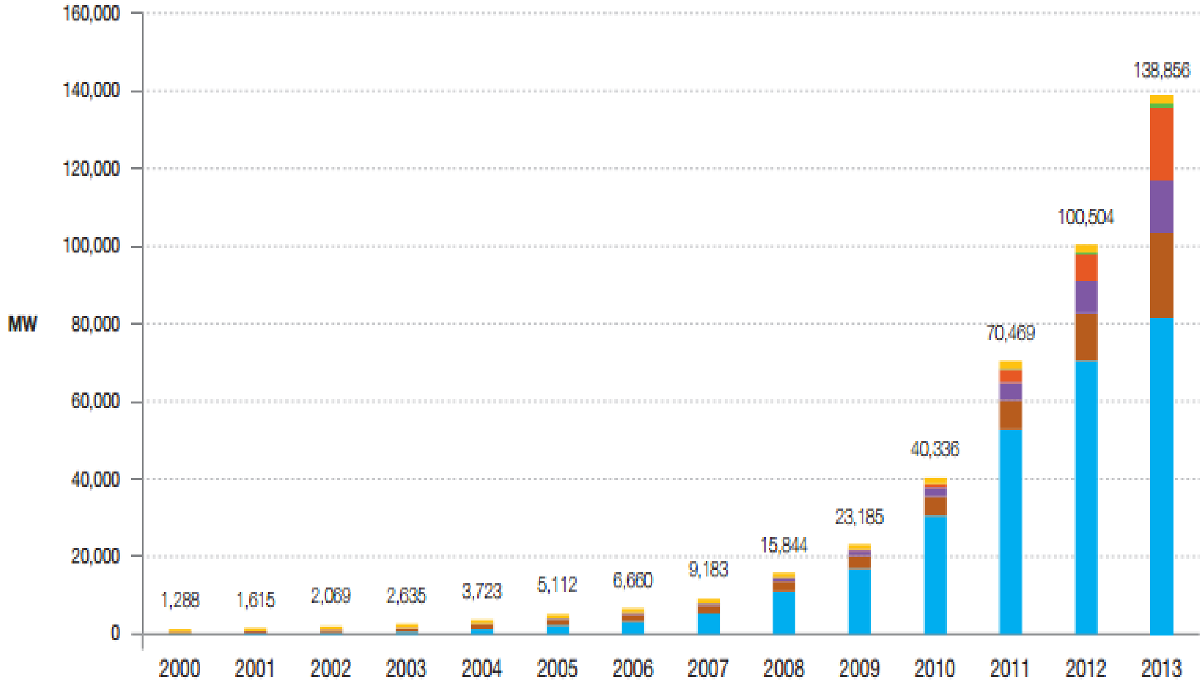
PV capacity

2013:

139 GW

(European PV

Industry Association)



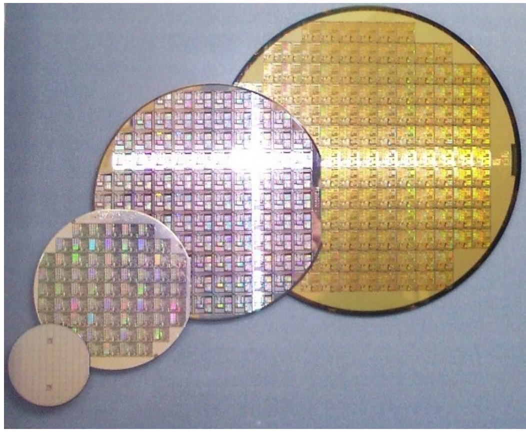
RoW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,600
Americas	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,727
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	129	265	399	601	1,306	2,291	3,289	5,312	11,020	16,854	30,505	52,764	70,513	81,488
Total	1,288	1,615	2,069	2,635	3,723	5,112	6,660	9,183	15,844	23,185	40,336	70,469	100,504	138,856

RoW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.
Methodology used for RoW data collection has changed in 2012.

Solar Photovoltaic

Future prospects

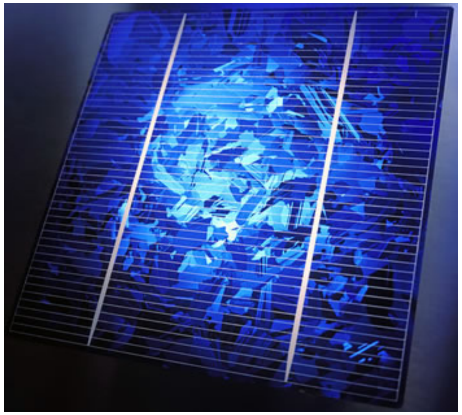
Advances in materials science, crystallography, electronics industry, thin-film technology, polymers, nanotechnology and organic electronics make potential growth and improved efficiencies not only attainable but expected within a relatively short time span.



Silicon wafers

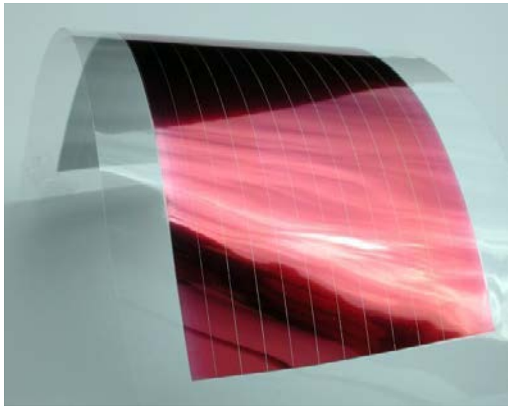
Monocrystalline

Polycrystalline

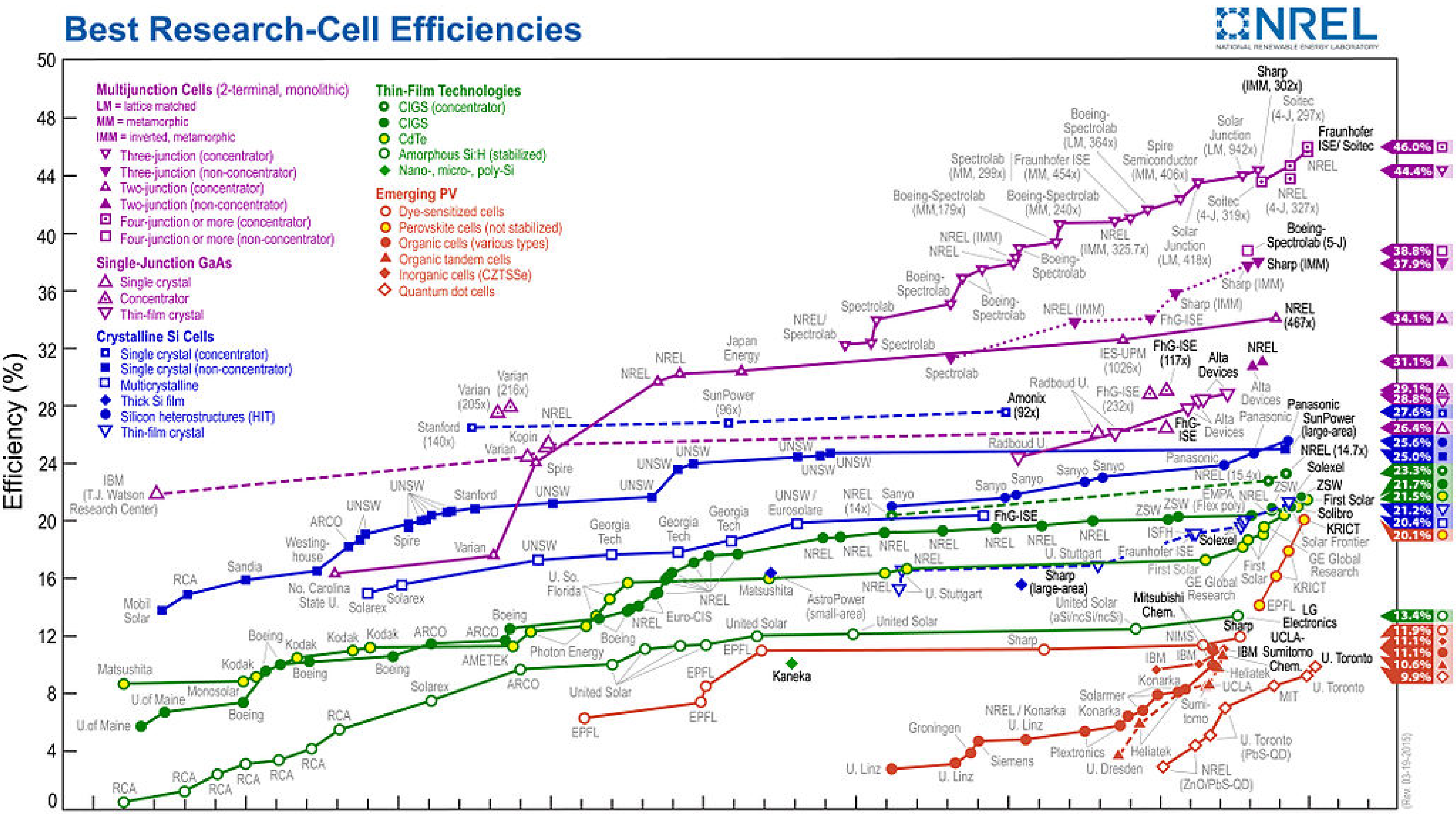


Thin Film

Organic



Solar Photovoltaic – Progress



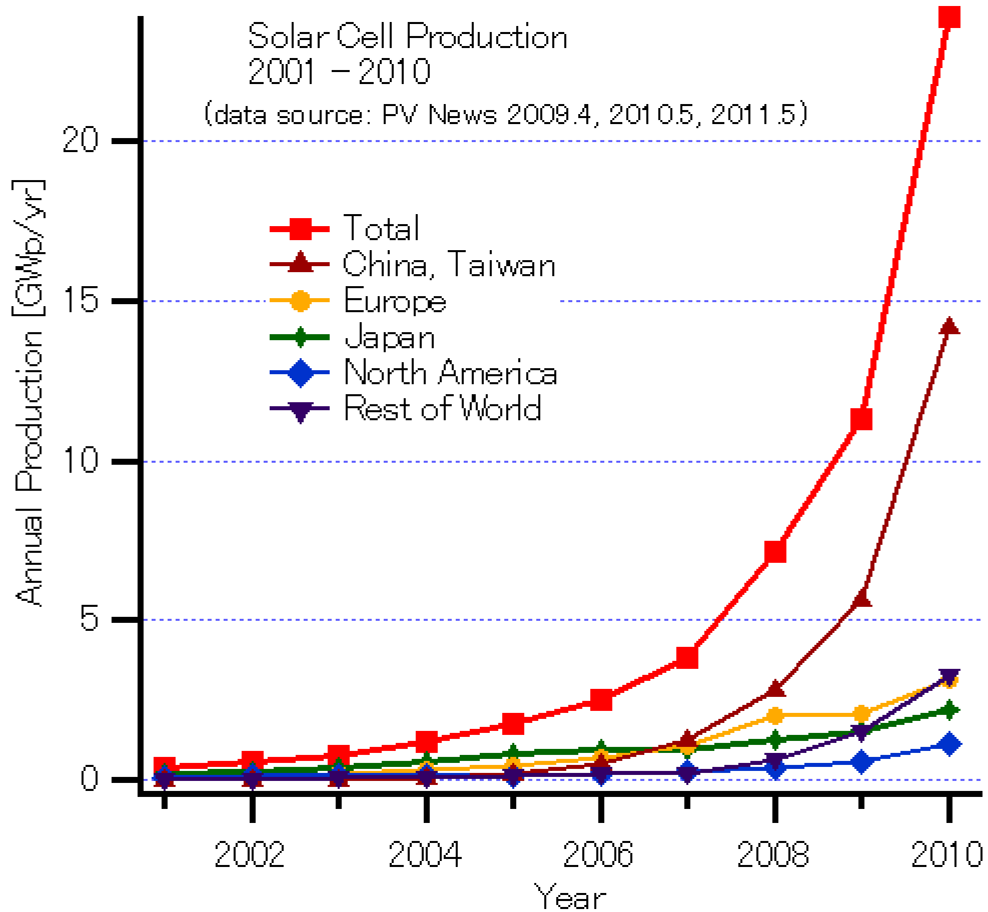
Solar cell efficiency timeline

Solar Photovoltaic

Future prospects

Within the last 7 years, worldwide solar cell production and installed PV capacity have both increased by a factor of ten.

The production boom is being led almost entirely by China & Taiwan.



Solar (Thermal & Photovoltaic)

ADVANTAGES

- No moving parts (unless tracking) → low maintenance.
- Infinitely renewable energy source.
- Extremely low safety hazard.
- Zero pollution and low carbon footprint.
- Improves energy diversity and energy independence.
- Light, portable → useful in remote locations.
- High power/weight ratio → desirable in aerospace applications
- Developed, scientific, well-funded industry which keeps improving.
- Preserves fossil fuel reserves

DISADVANTAGES

- Some PV materials include metals restricted in usage.
- Expensive (but relative expense is diminishing due to technological improvements and increasing cost of traditional fuels).
- Large land area required to achieve large capacity.

The answer, my friend, is blowin' in the wind …
Bob Dylan (1962)

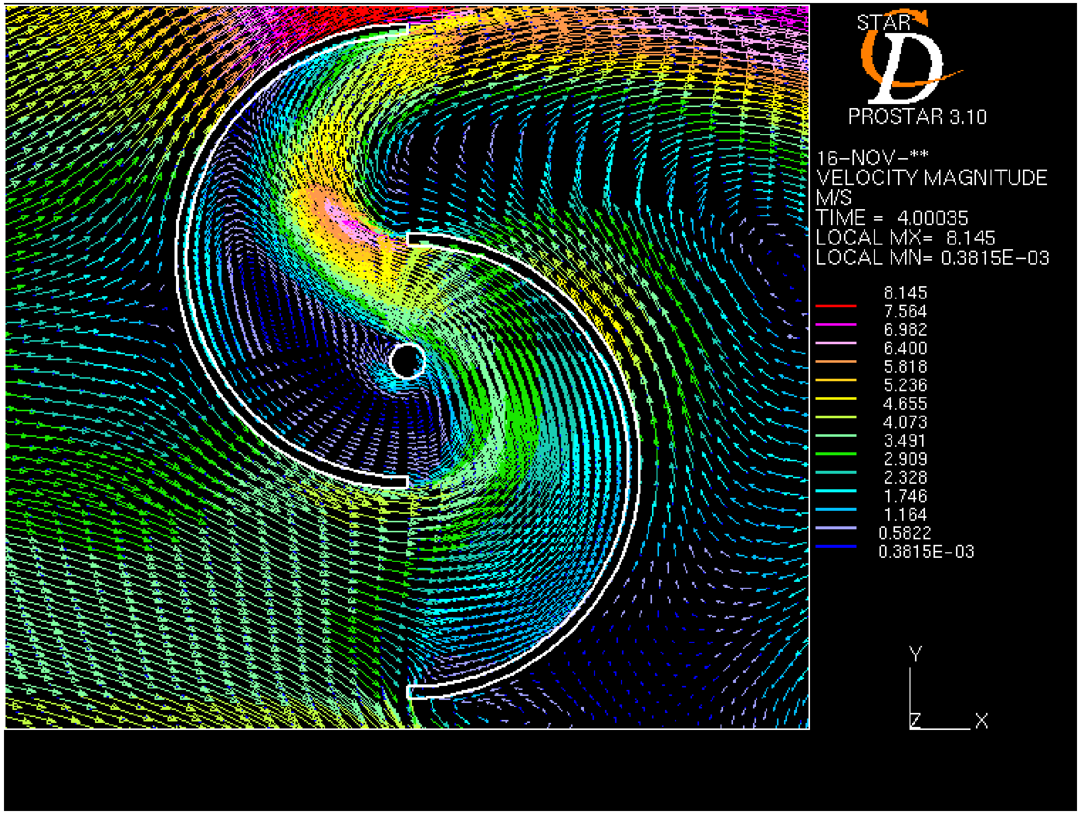
Sustainable Energy

Wind Power

Revised from Dr. HS Rajamani and Dr. David Shepherd

Wind power – Outline

- Wind Turbines
- The Power in the Wind
- Wind availability
- Realisable Power
    - Betz limit
    - Tip-speed ratio
    - Wind distribution
    - Cut-in & cut-out
- Economics
- World Installed Wind Capacity



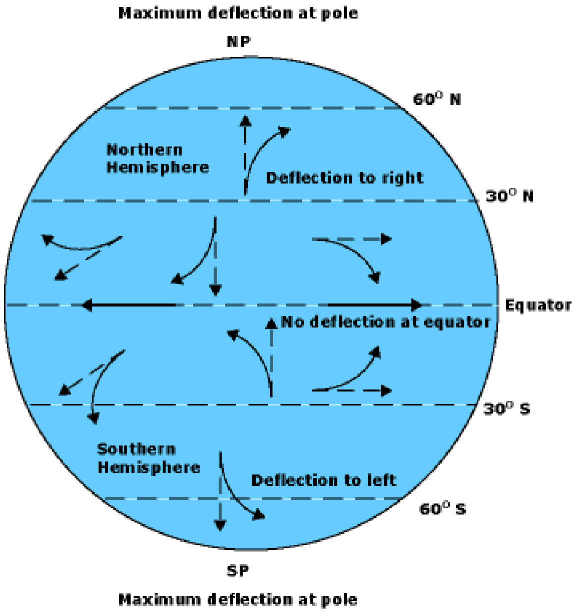
Wind

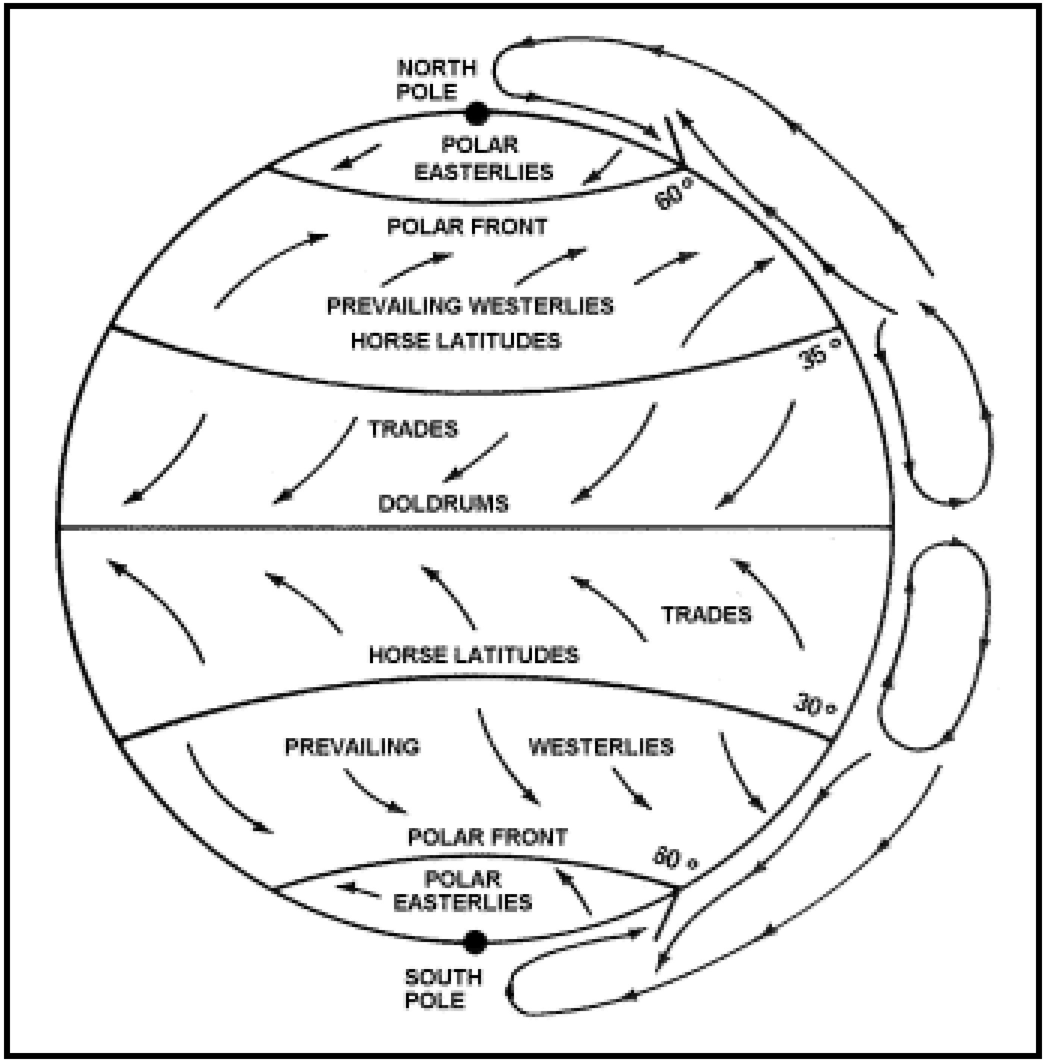
World winds

Rotating sphere

High to low pressure

Coriolis force





Wind turbines

Operation - overview

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

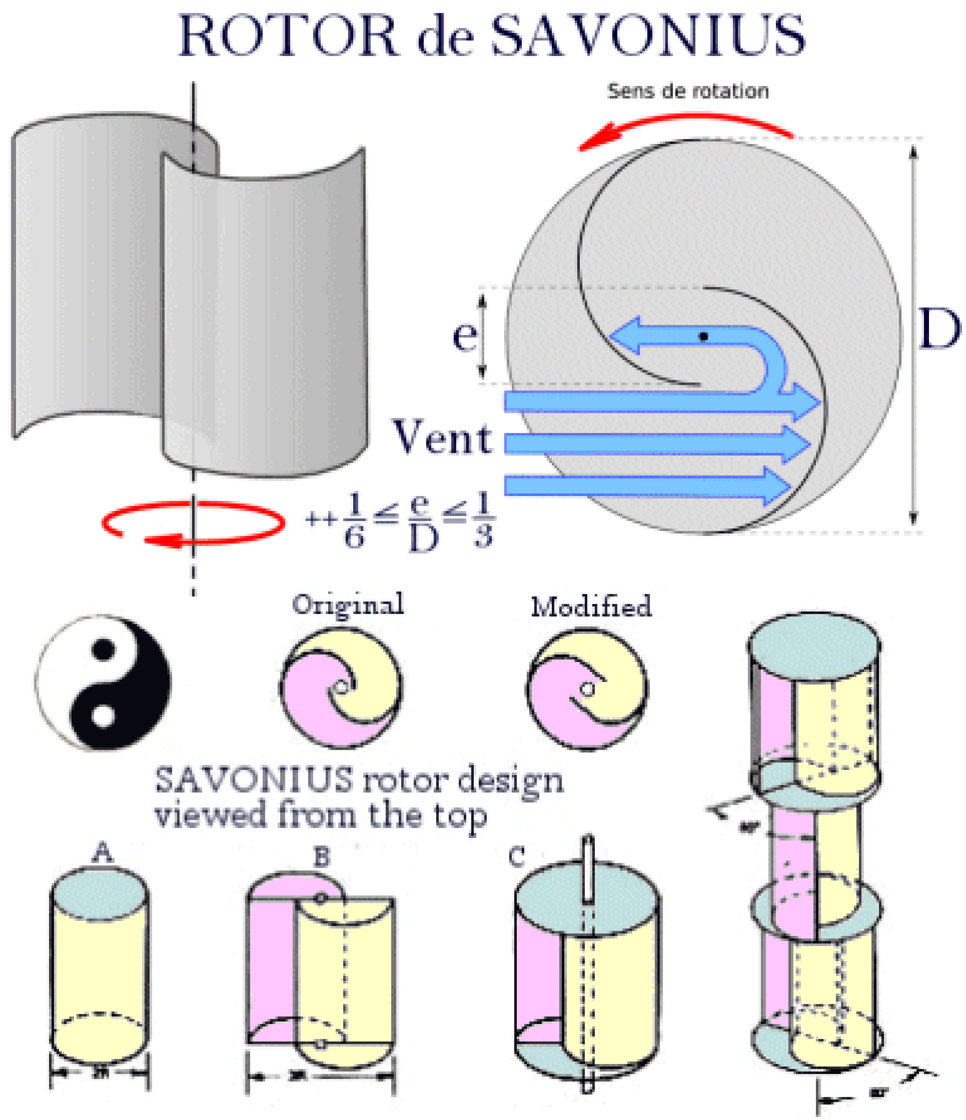
https://www.youtube.com/watch?v=LNXTm7aHvWc

https://www.youtube.com/watch?v=ktseLRAj_N4

Wind turbines

Savonius design

- Vertical Axis
- Simple construction
- Low start threshold



Wind turbines

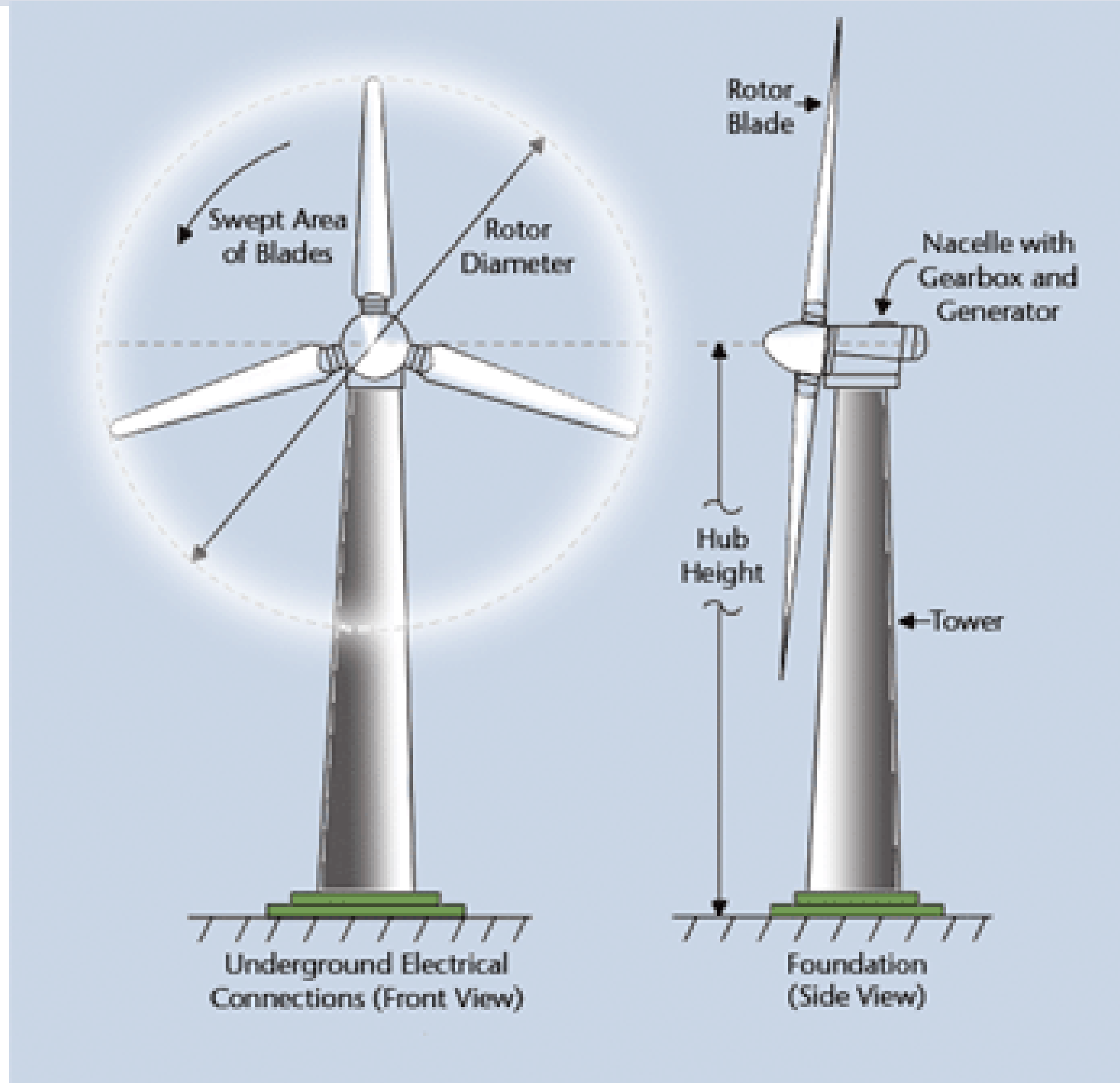
Darrieus design

-Vertical Axis

- High rotation speed relative to wind => more suitable for elec. generation
- Aerofoil blades flex and bow
- Not self-starting

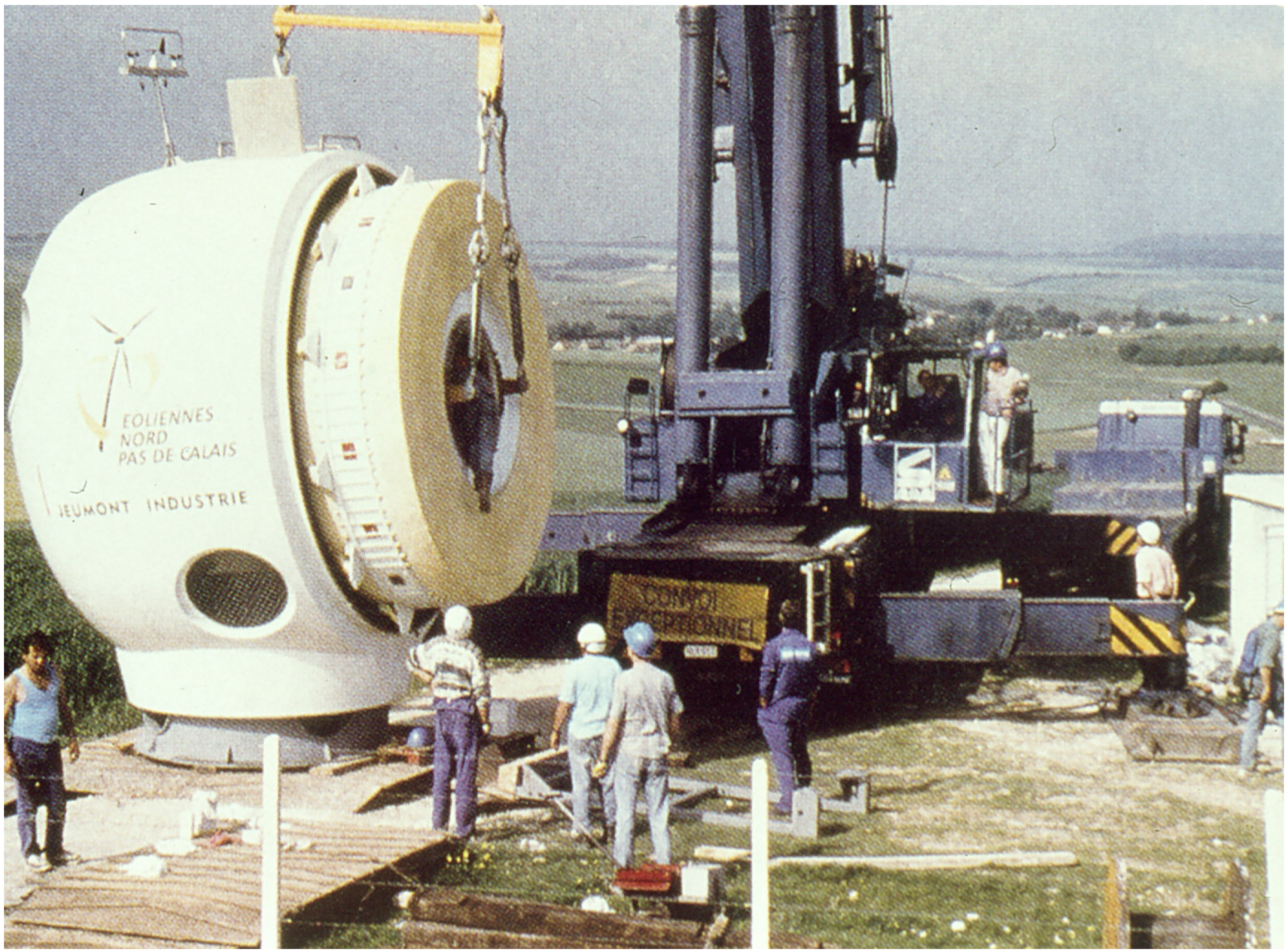
Wind turbines – operation (1)

Extract energy (momentum) from wind by providing a barrier to air flow, usually using aerofoil-bladed rotors.

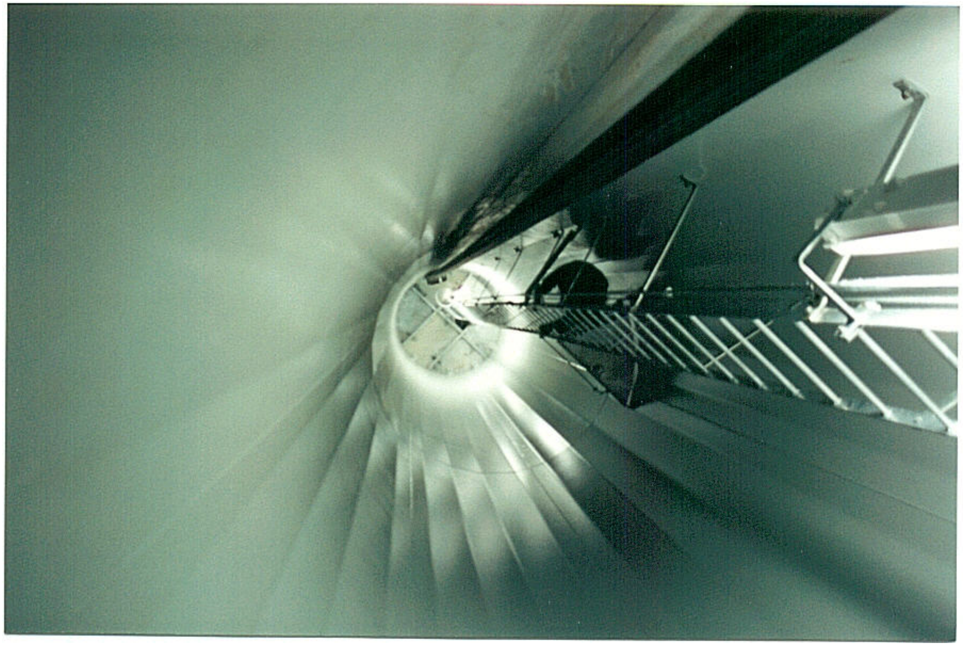


Drawing of the rotor and blades of a wind turbine, courtesy of ESN

Wind turbines



Wind turbines



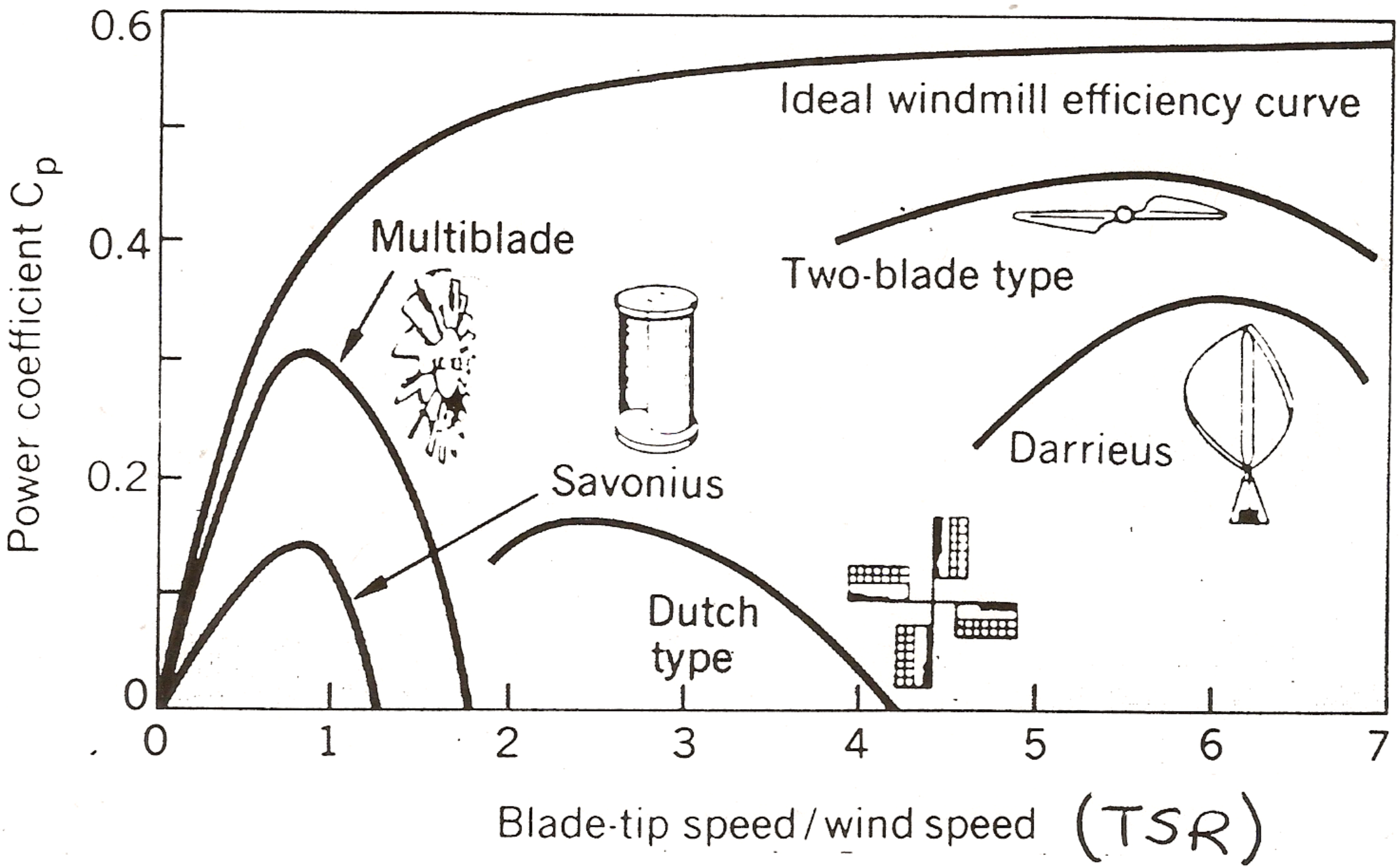
Wind turbines

Turbine assembly,

Calais, France.

- Horizontal Axis
- 2 or 3 blades
- Rotation 2-4 radian/second

Typical performance of conventional types of wind machines.



Wind turbines: operation

Wind

[1] Air flow hits blades

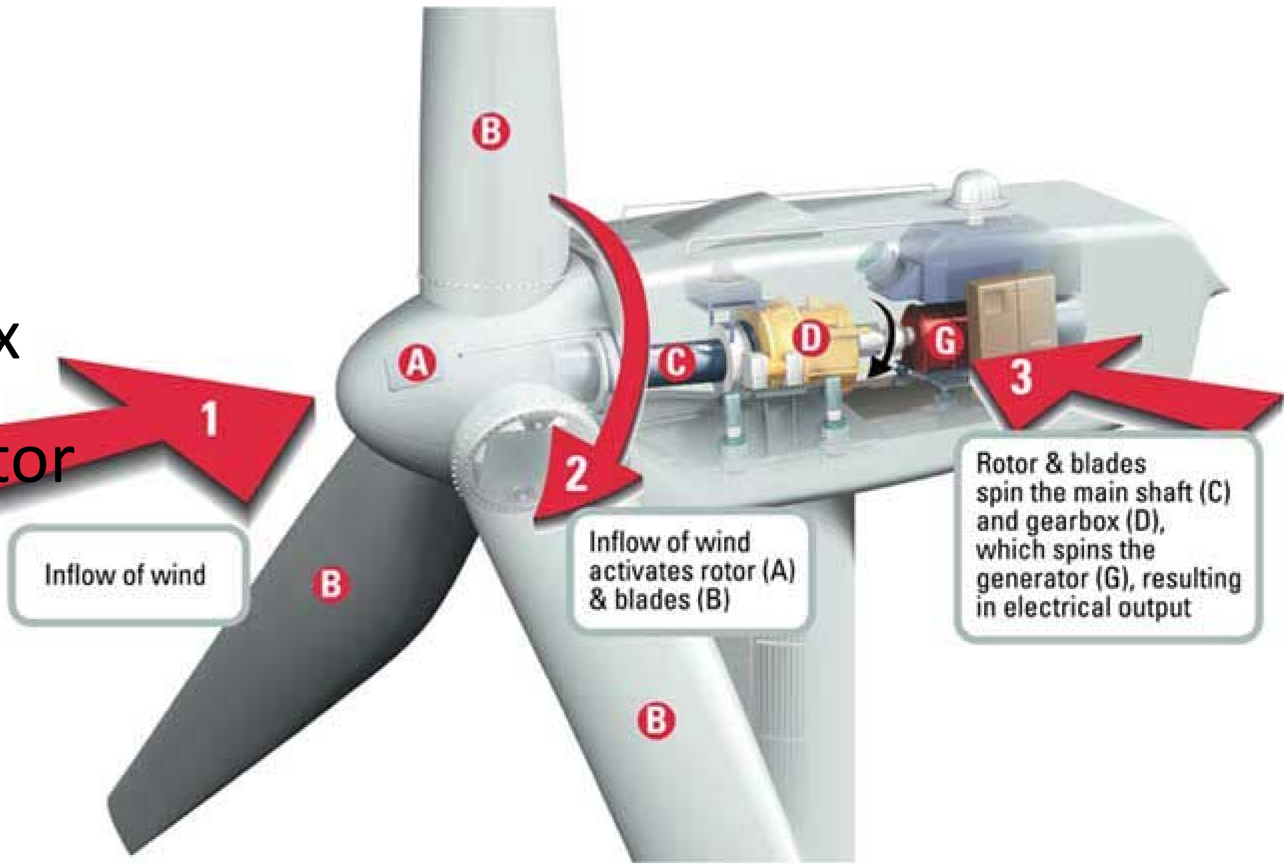
[2] Turns rotor

Spins shaft

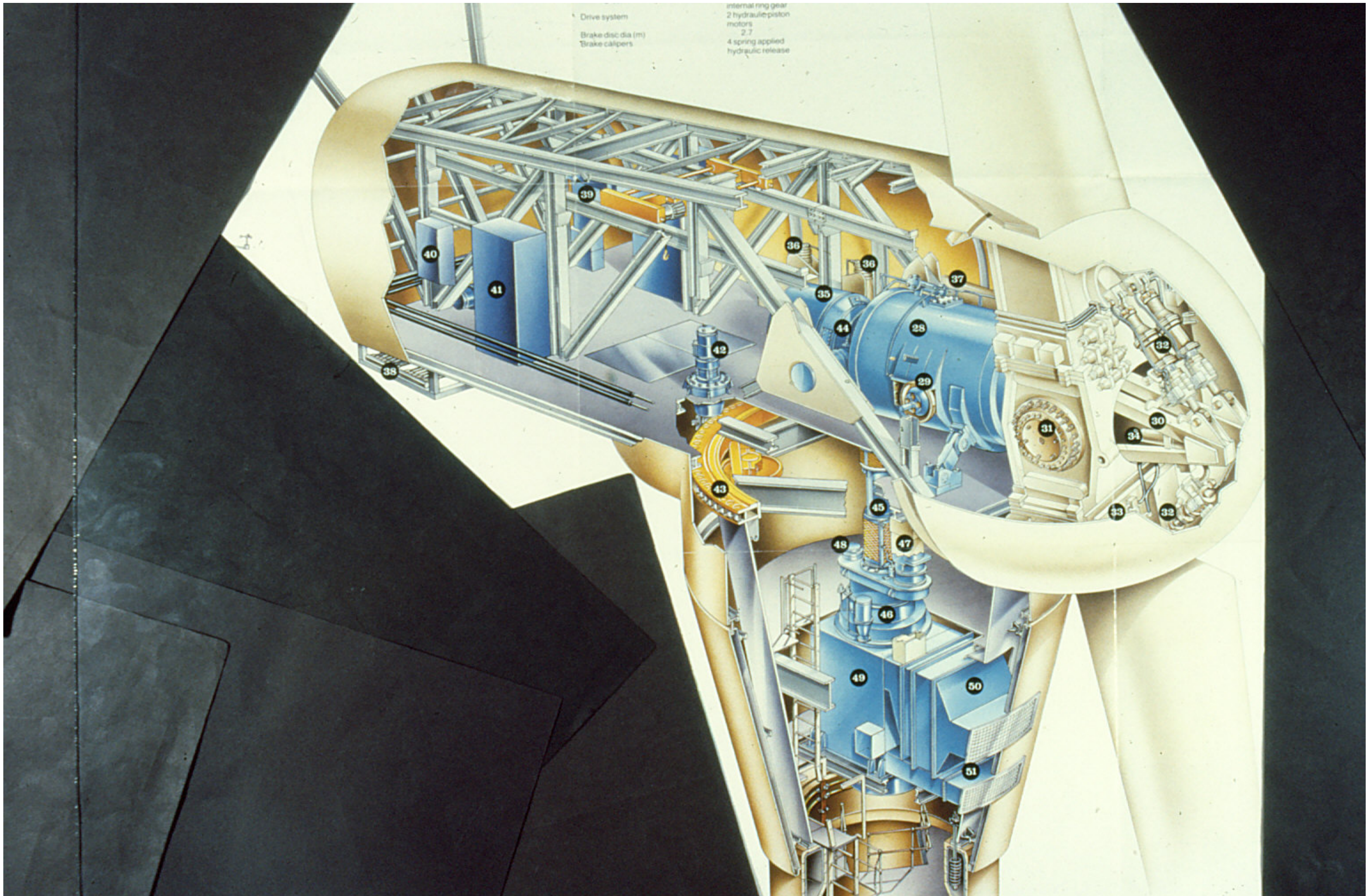
Drives gearbox

[3] Drives generator

Electricity

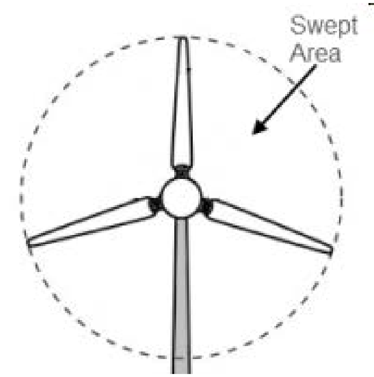


Wind turbines: operation



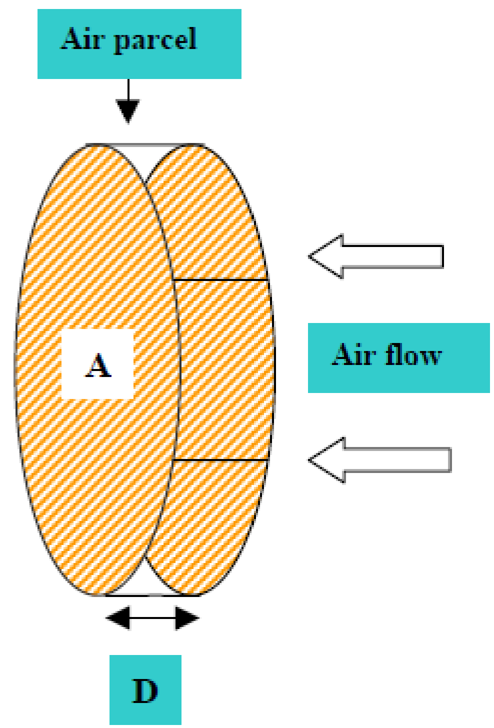
Wind power (1)

Consider plug of air	mass (kg)	m
	air speed (m/s)	v
impacting upon	area (m²)	A



Kinetic energy (J) $$E = \frac{1}{2} \times mv^2$$

Power (J/s) $$P = \frac{1}{2} \times \dot{m}v^2$$

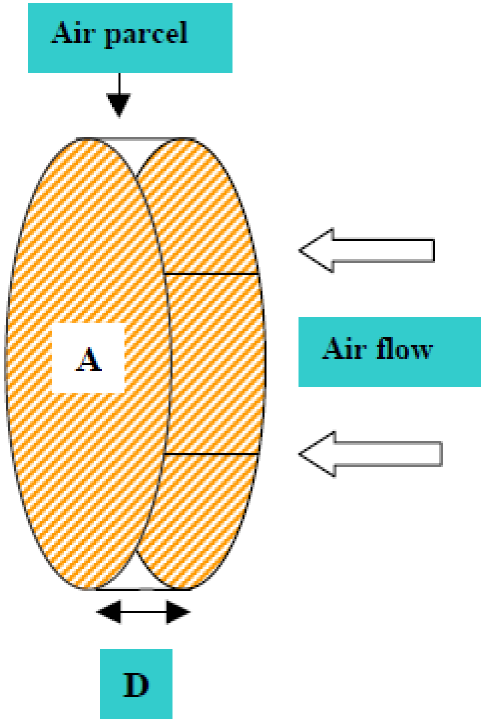


Wind power (2)

Power (in J/s) $$P = \frac{1}{2} \times \dot{m} v^2$$

Mass flow (in kg/s) $$\dot{m} = \rho A v$$

Power (P_{wind}) $$P = \frac{1}{2} \times \rho A v^3$$

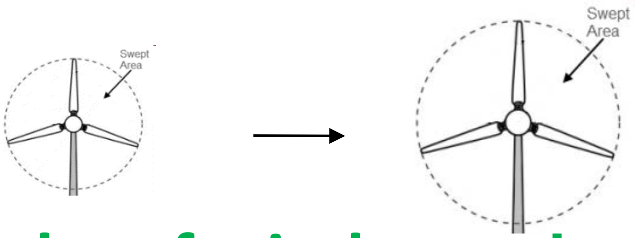


Power = 0.5 x Air Density x Swept Area x Velocity^3

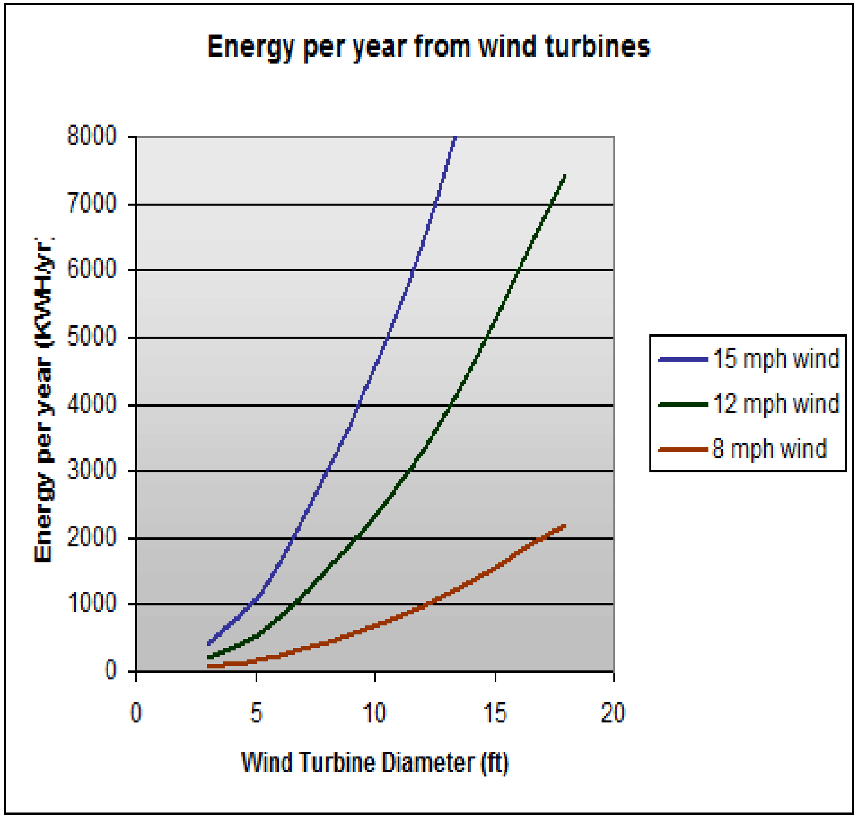
Wind power (3) – key facts

i.e. **Power impact** on wind turbine **is proportional to …**

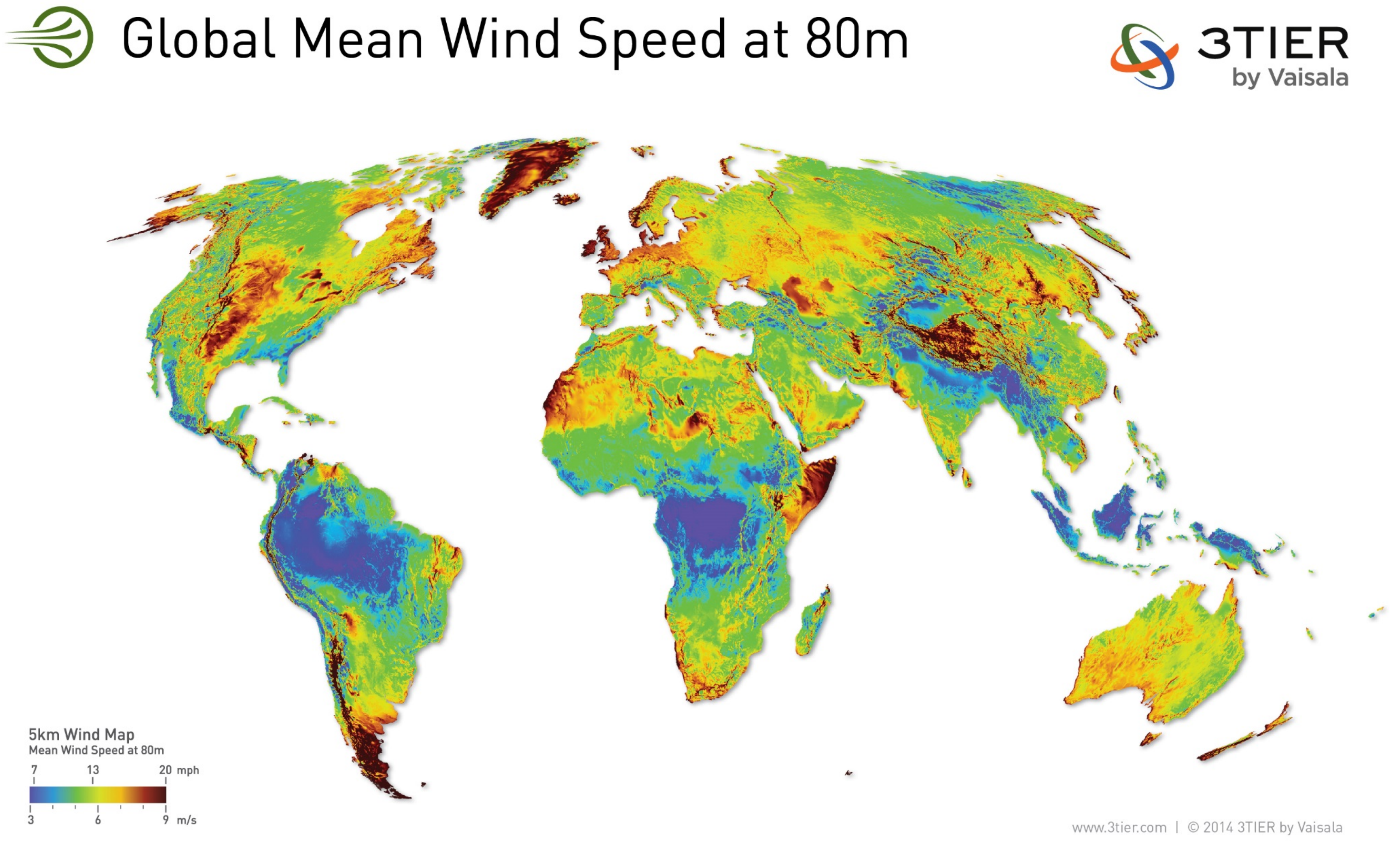
- ❑ **area swept by rotor** (2x *swept area* doubles power output)



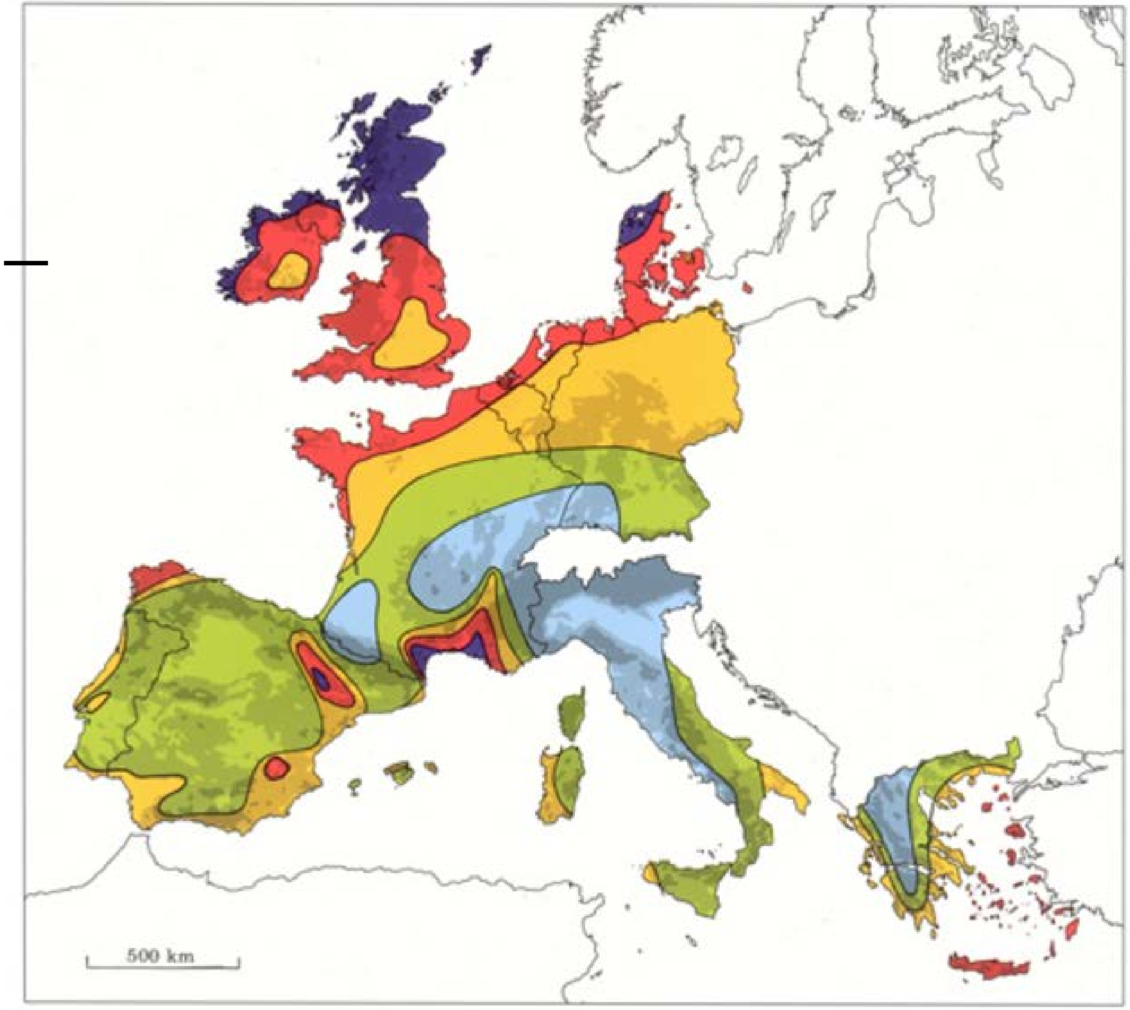
- ❑ **cube of wind speed** (2x *wind speed*, power output increases by factor of **8**)



Wind availability



Wind resources – Europe.



Wind resources[1] at 50 metres above ground level for five different topographic conditions

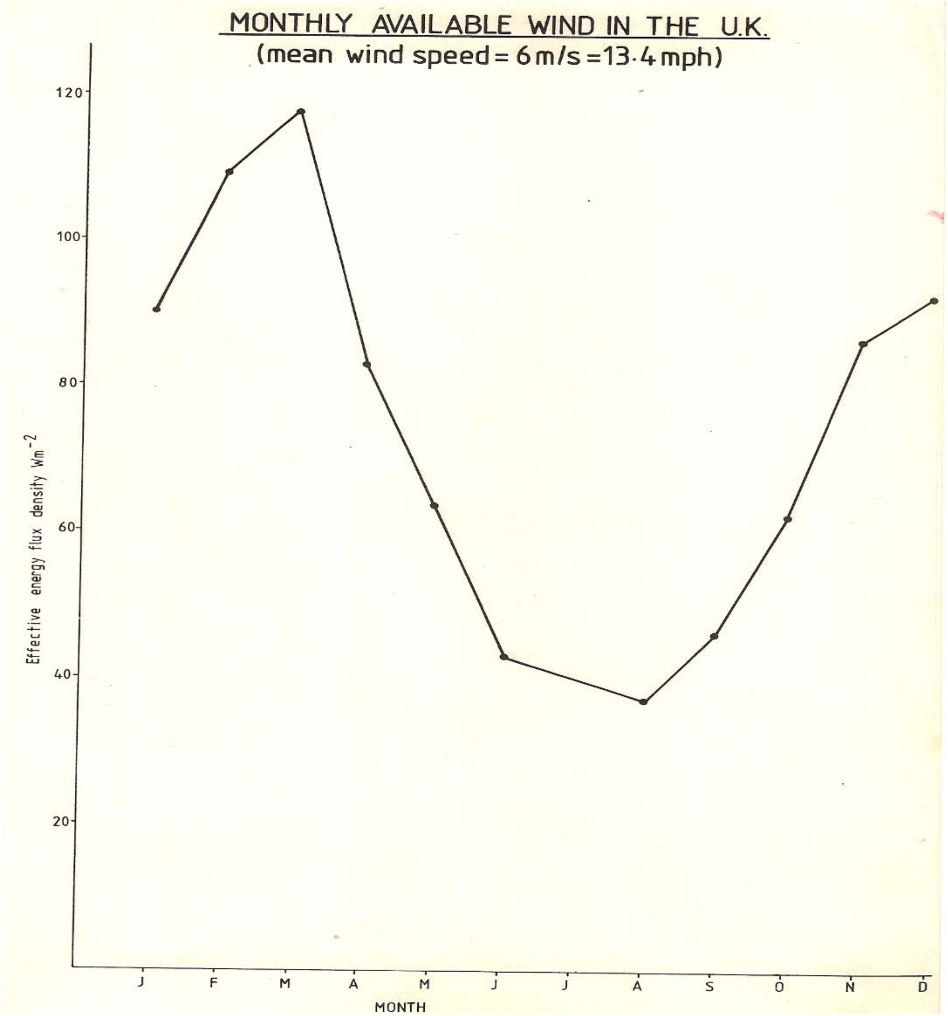
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
(purple)	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
(red)	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
(yellow)	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
(green)	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
(light blue)	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Source: Risø National Laboratory, Denmark, see Appendix A for colour version

Wind availability

- Varies seasonally

- Does wind supply fit demand?



Wind availability

- Varies in wind-speed hours.

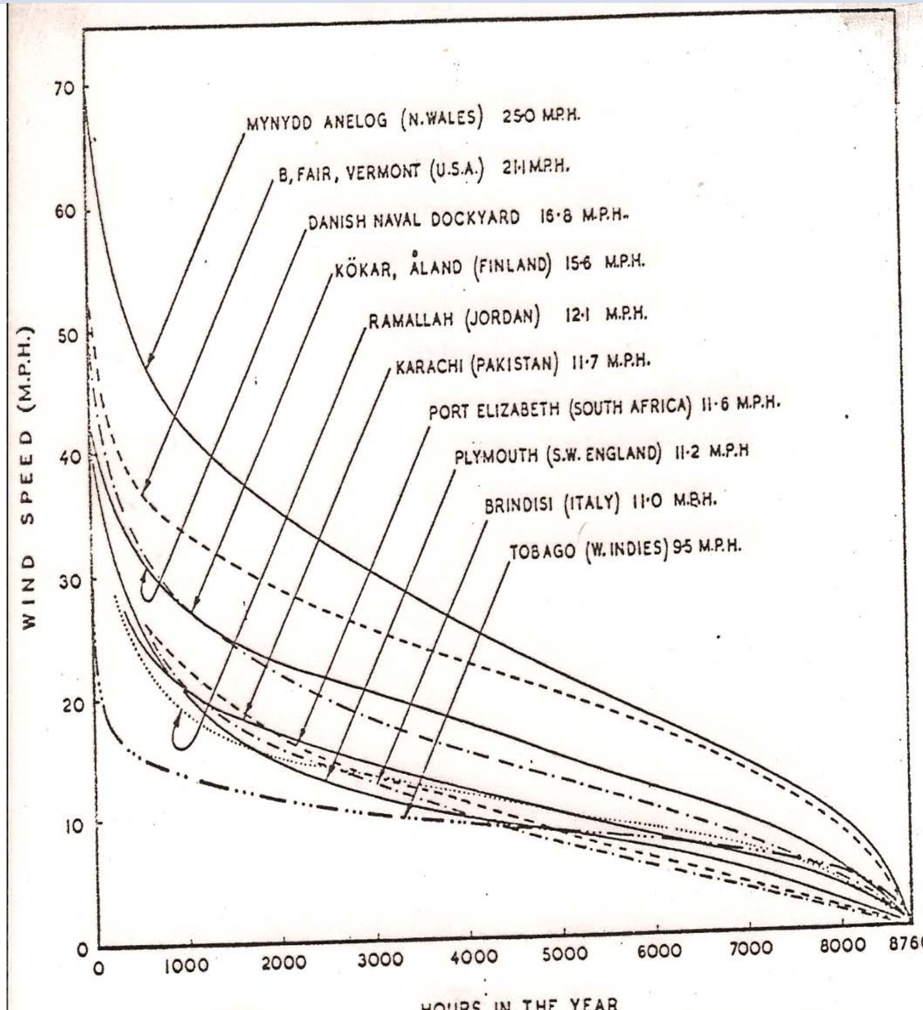
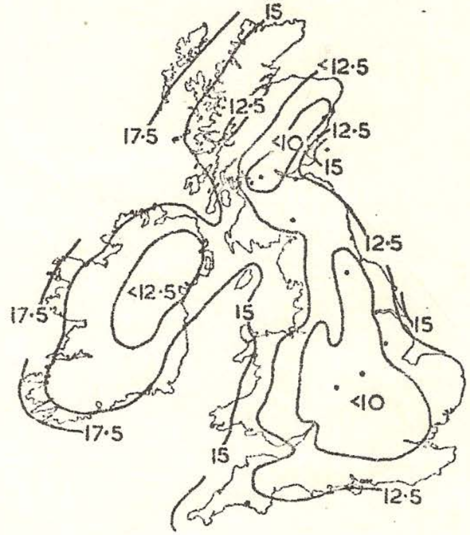


FIG. 2: *Velocity-duration curves for widely separated sites* [2]

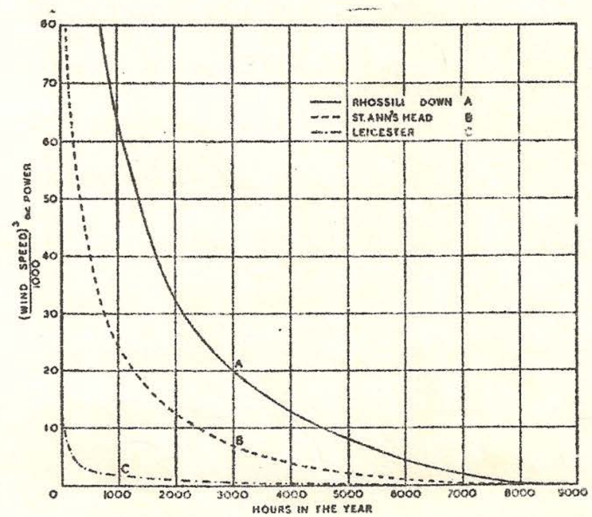
Wind availability

- Varies by local geography.

- Uplands & coasts generally better than inland, sheltered lowlands.



Contours of mean wind speed (mph)
[33ft (10m) above ground, open conditions]



mid-Wales coast
Lancs coast

A: V_{av} = 24 mph
B: V_{av} = 16·2 mph
C: V_{av} = 6·2 mph

Wind power duration characteristics

Live data on existing generation

http://rwe-renewableslive.com/#/map/EU

Worked Example (page 1 of 4)

Current world's largest wind turbine generator situated offshore

blade diameter 126m
air density 1.23 kg/m^3

Rated at 5MW in 30mph (14m/s) wind

Worked Example (p2 of 4)

Wind Power

$$
\begin{aligned}
P &= \frac{1}{2}\rho A v^3 \\
&= \frac{1}{2} \times 1.23 \times \pi \times 63^2 \times 14^3 \\
&= 21042153.98 \quad \text{Watts}
\end{aligned}
$$

Why does wind power (21MW) dominate rated power of turbine generator (5MW)?

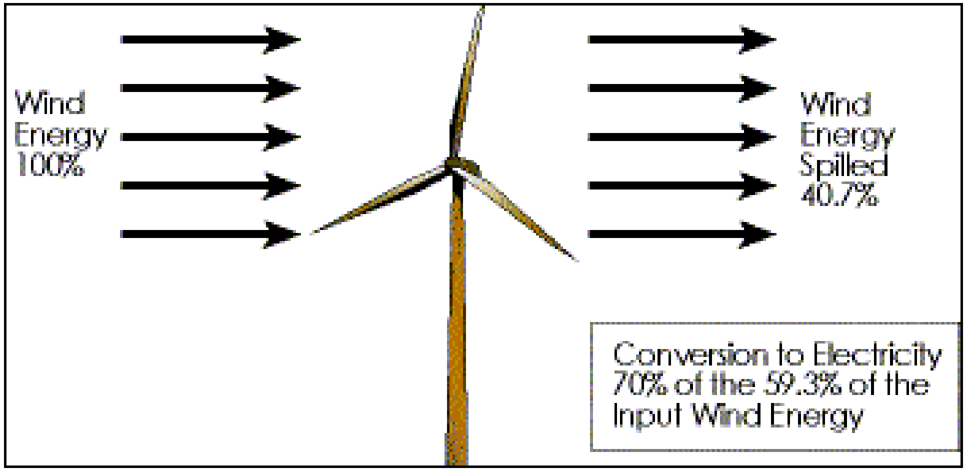
Answer lies in [Betz Limit]() and <u>system inefficiencies</u>.

Betz limit (1) - Principles

Albert Betz (German physicist, 1919) concluded:

No turbine can convert more than 16/27 (59.3%) of wind energy into mechanical energy by turning a rotor

Betz Limit or **Betz' Law**



Limit has nothing to do with inefficiencies in the generator, but in the very nature of wind turbines

Betz limit (2) - Principles

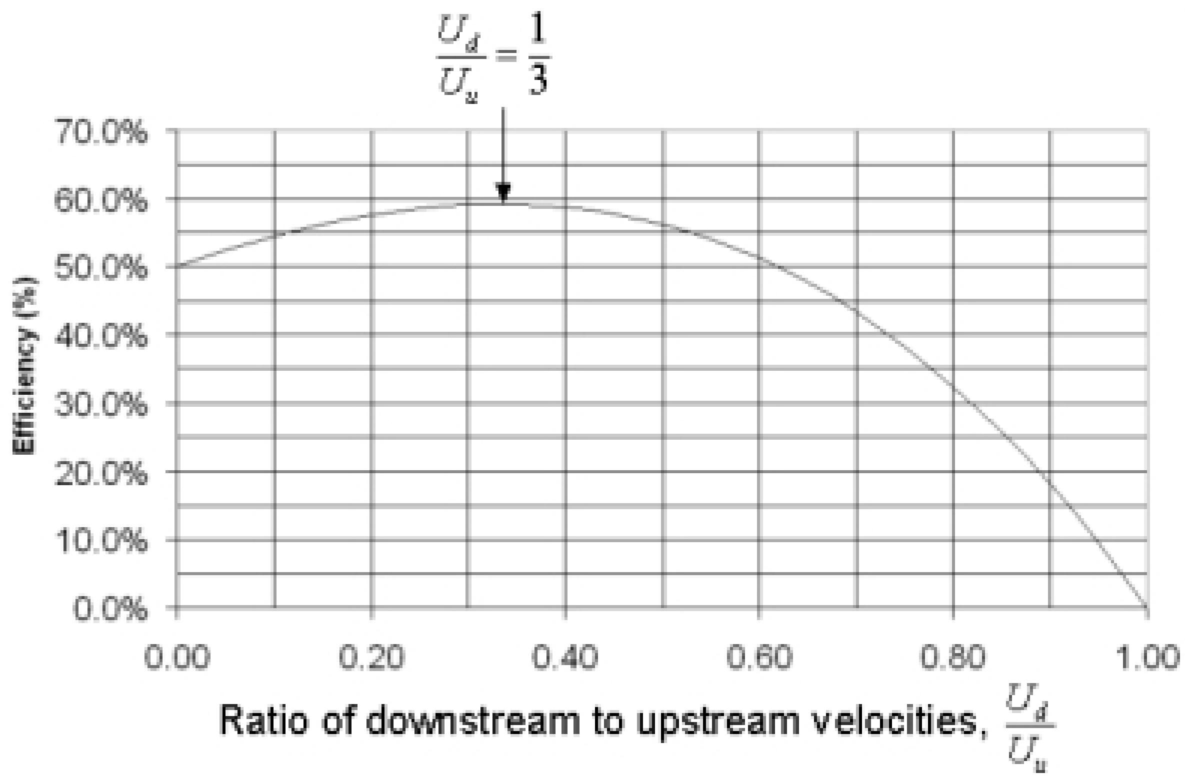
Wind turbines extract energy by slowing down wind.

A 100% efficient turbine stops 100% of the wind, but rotor would be a solid disk (would not turn) and no kinetic energy would be converted.

Other extreme (turbine with one rotor blade), most wind passing through swept area would miss blade and kinetic energy would be kept by wind.

Betz limit (3)

A "best" intermediate conversion must exist



Variation of efficiency with the ratio of downstream to upstream velocity

Betz Law (5) - Summary

<u>Betz Law (1927)</u>

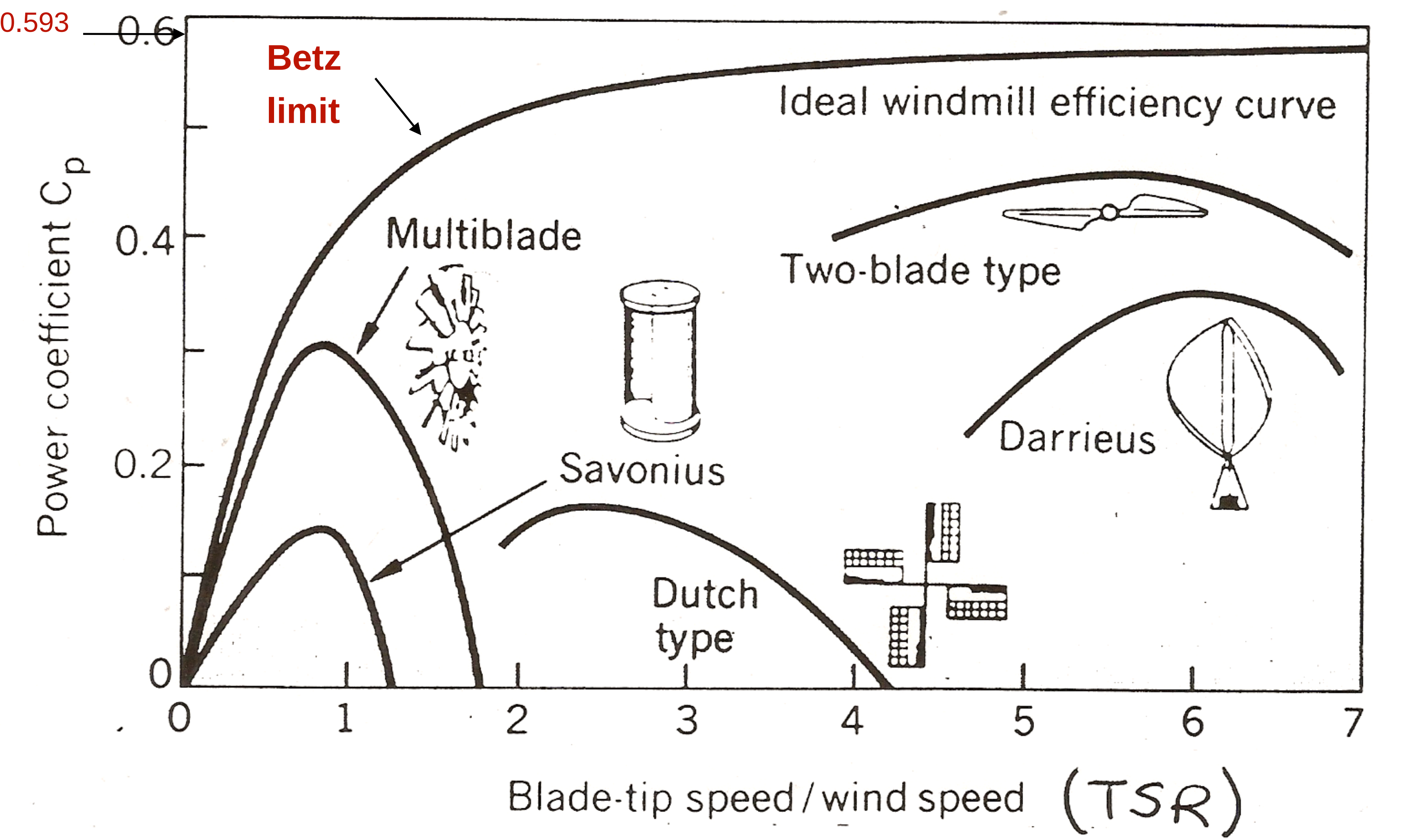
For an ideal propeller (normal to a laminar flow, no friction)
Power extracted is a maximum when $\left(\frac{v_{\text{out}}}{v_{\text{in}}}\right) = \frac{1}{3}$

An ideal turbine can extract ~ 0.593 of the power in the wind

Theoretical max. extractable power

$$P_{(\text{max. extractable})} = P_{(\mathbf{betz})} = 0.593 \,.\, \tfrac{1}{2} \,.\, \rho \,.\, A \,.\, v^3$$

· Typical performance of conventional types of wind machines.



Worked Example (p3 of 4)

Multiplying previous power calculation by Betz limit:

$$
\begin{aligned}
P_{\text{betz}} &= 21042153.98 \times \frac{16}{27} \\
&= 12469424.58
\end{aligned}
$$

► Betz-limited power for this machine is ≈ 12.5 MW

Betz limit is a **power coefficient**, NOT an efficiency.

Turbine Efficiency

Real turbines are not 'ideal': losses due to

- Friction
- Turbulence & drag
- Non-normal or non-laminar flow

These effects are incorporated into a power coefficient C_p

Value of C_p depends on (a few examples are listed)

- Wind velocity
- Turbine rotational velocity
- Pitch angle

For a practical wind machine $0 \leq C_p \leq 0.4$

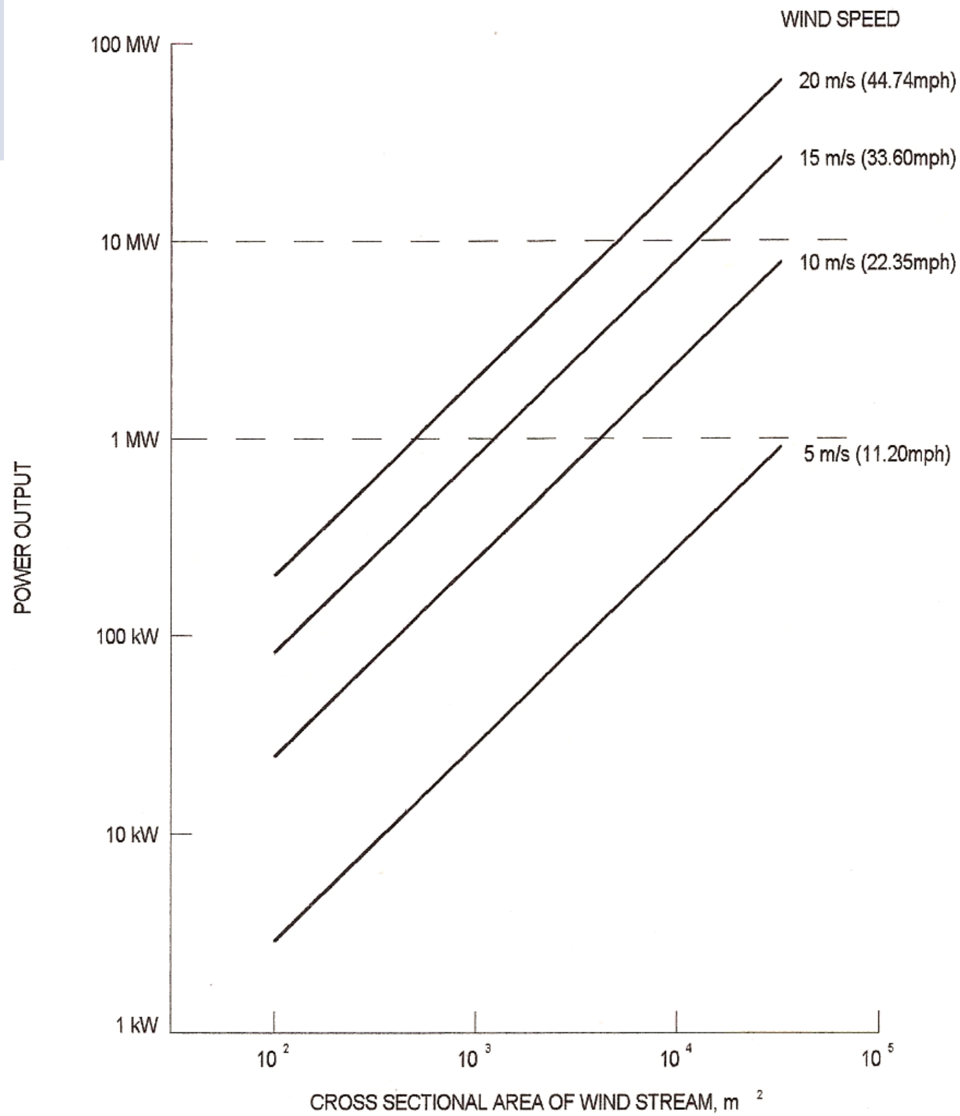
Extractable Power

Power extractable

when power coeff.

$C_p = 0.4$

for various wind speeds



Power extractable from a freely flowing windstream. Power coefficient 0.40.

Worked Example (p4 of 4)

Mech. / Elec. inefficiencies

- Turbine (C_p)
- Generator
- Gearbox (large machines) => typically 80%-90%
- Gearbox (small machines) => typically 60%-70%

Best theoretical power (large machine) *after Betz limit, C_p losses & Mech./Elec. losses* **is typically 25%-30% of Power in the Wind**.

Similarly, a D=126m turbine in Norway is rated 6-7 MW (29%-33%).

Tip speed ratio (1)

Tip Speed Ratio (**TSR**) is of vital importance in design.

*** If turbine rotor turns too slowly, most wind will pass undisturbed through gap between rotor blades.

*** If turbine rotor turns too quickly, turning blades appear as solid wall to wind.

Therefore, turbines are designed with optimal tip speed ratios to extract as much power from wind as possible.

Tip speed ratio (2)

Rotor blade passing through air leaves turbulent wake.

If next rotor blade arrives at this point while air is still turbulent, it cannot extract power from the wind efficiently.

However, if rotor spins little more slowly, air hitting each turbine blade would no longer be turbulent.

Therefore, **tip speed ratio (TSR)** is chosen so that the blades do not pass through turbulent air.

Tip speed ratio (3)

TSR too low: (e.g. poorly designed rotor blades), wind turbine will tend to slow and/or stall.

TSR too high: turbine spins very fast through turbulent air, power will not be optimally extracted from wind, turbine will be highly stressed (risk of structural failure)

Tip speed ratio (4)

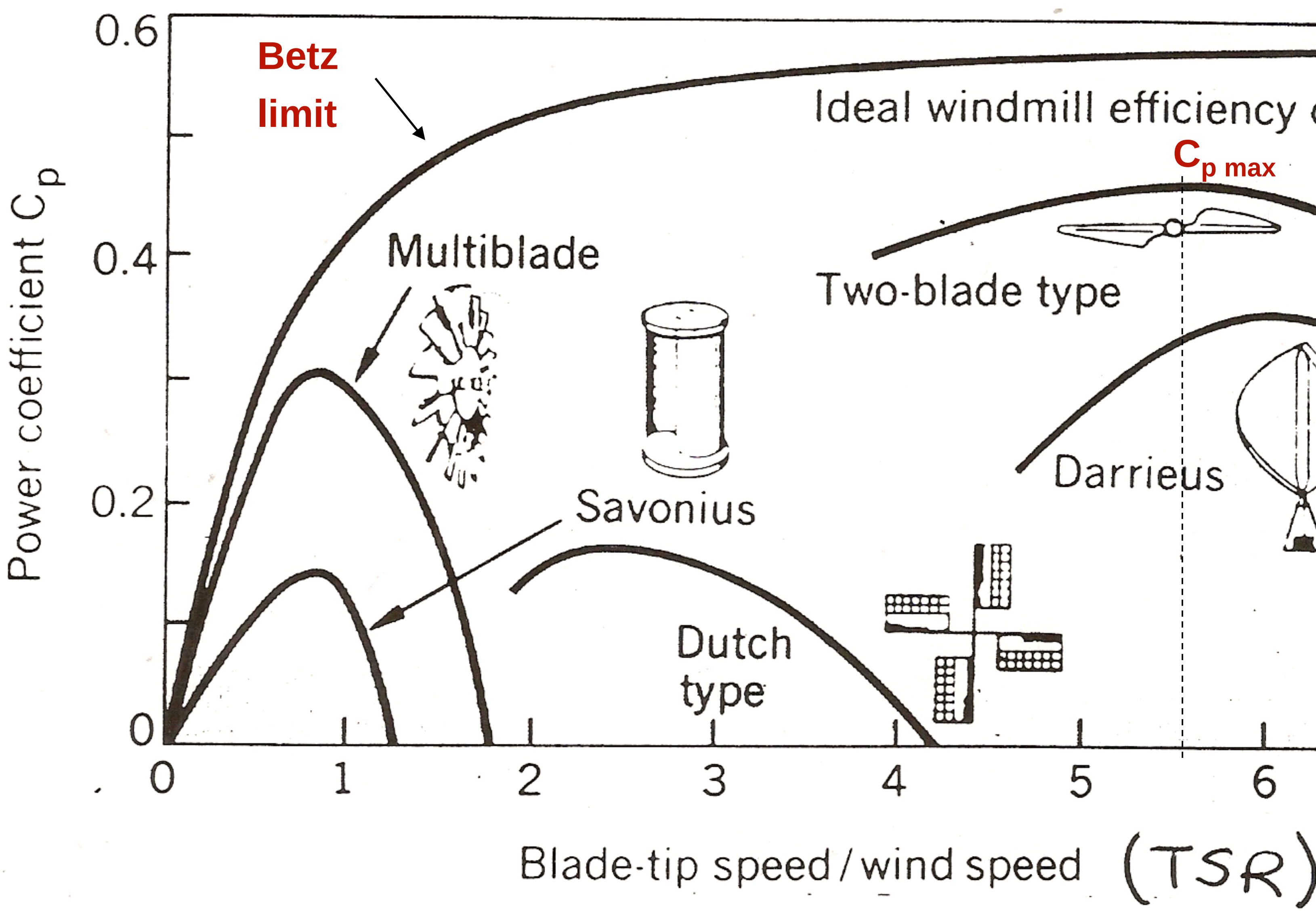
Tip-speed ratio (TSR) allows C_p to be expressed in terms of wind velocity (V) and rotor angular velocity (ω).

Good design requires max. value of C_p to occur near rated value of rotational speed.

Plotting C_p vs. TSR gives the universal characteristic of a given wind turbine.

High performance machines have TSR ~ 5 – 6.

Typical performance of conventional types of wind machines.



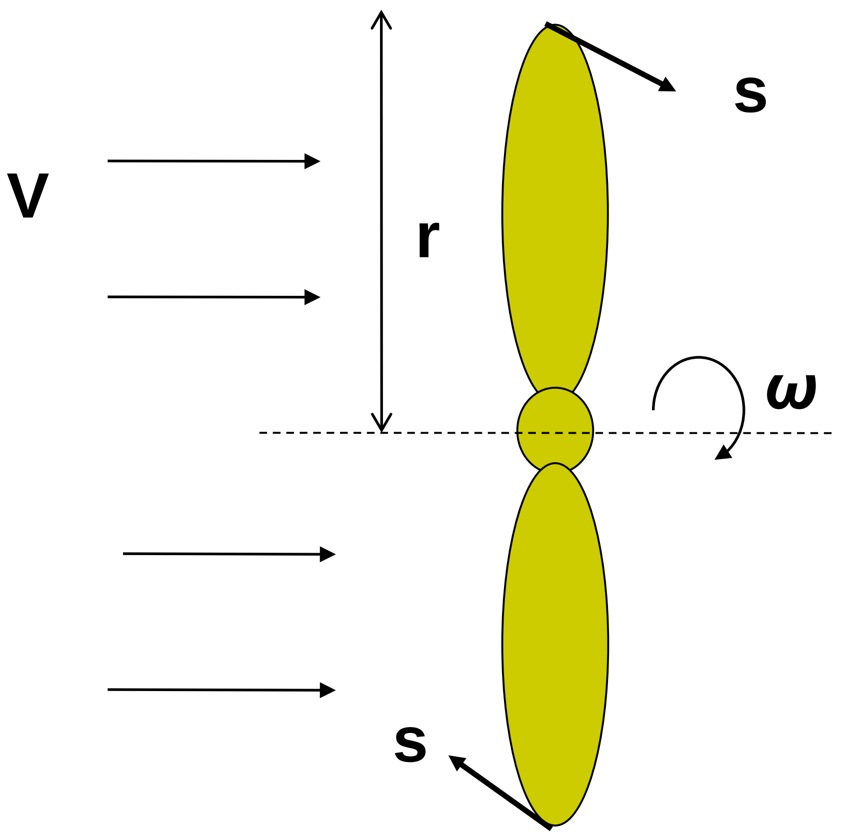
Tip speed ratio (5)

r = blade radius (m)

ω = angular velocity (rad/s)

V = wind velocity (m/s)

s = tip-speed = (r.ω) (m/s)



$$TSR = \left(\frac{r.\omega}{V}\right) = \left(\frac{s}{V}\right)$$

Tip speed ratio - calculations

engineering design + technology

Worked Example 1:

If turbine blade tips travel at 40 m/s through oncoming wind of 10 m/s what is TSR?

For V = 10 m/s and s = 40 m/s

TSR = s / V

Tip speed ratio is 40/10 = 4 (dimensionless)

Worked Example 2:

A wind turbine has its max. power coefficient value at TSR = 6 when wind velocity is 11.18 m/s. If blade diameter = 30.5m what is the recommended speed of rotation?

s = r.ω = V.[TSR]

= 6 . 11.18 = 67.1 m/s

ω = s/r = 67.1 / (D/2) = <u>4.4 rad/s</u>

Rated Power/TSR - calculations

Worked Example 3:

A wind-turbine-driven generator is required to deliver 1.5 MW of power at the generator terminals. The rotor is designed to operate at a fixed rotational speed of 2.3 rad/s. If the turbine delivers its rated power at an average wind speed of 11.175 m/s, calculate the corresponding diameter of the propeller and its tip-speed ratio, assuming a typical value for overall efficiency. [air density $\rho = 1.29\ kg/m^3$].

Assume efficiency $\eta = 0.3$

$\mathbf{P}_{\mathbf{wind}} = \mathbf{P}_{\mathbf{required}} / \eta \quad = 1.5 \times 10^6 / 0.3 \quad = 5 \times 10^6\ W$

But wind power $\mathbf{P}_{\mathbf{wind}} = ½ \cdot \rho \cdot A \cdot V^3$

$\Rightarrow A = [(2 \times 5 \times 10^6) / ((1.29 \times (11.175)^3)] \quad = 5555\ m^2$

$A = \pi . D^2 / 4 \quad \Rightarrow \quad \underline{D = 84.1\ m}$

Rated Power/TSR - calculations

Note that in Worked Example 3, the given value is not the Power in the wind, (P_{wind}) but instead the Power required ($P_{required}$) at the generator!

Thus the given value of Power is $P_{required}$ and has to be divided by the efficiency to get P_{wind}.

Reminder/Hint: Always do a Double-check..

P_{wind} has to be larger than $P_{required}$!

Tip speed ratio - calculations

Example 3 (contd):

$TSR = r.\ \omega\ /\ V$

$r = D\ /\ 2 = 42.05$ m

→ $TSR = (42.05 \times 2.3)\ /\ (11.175) = \underline{8.65}$ (high!)

Wind Farms

- Arrays of turbines are grouped in <u>suitable locations</u>.
- Minimum spacing required to minimise loss of power to downstream turbines. (8-10 rotor diameters downstream keeps losses under 10%).
-

- Spacing of properties in towns too small (wind shadow, building shelter /turbulence)

Domestic Wind Power Generation?

D = 3.7 m

V = 5 m/s

$P_{wind} = ½.\rho.A.V^3$

P_{wind} (max) ≈ 826 W

P(betz) = 490 W

P(realistic) = 272 W *(optimistic estimate!)*

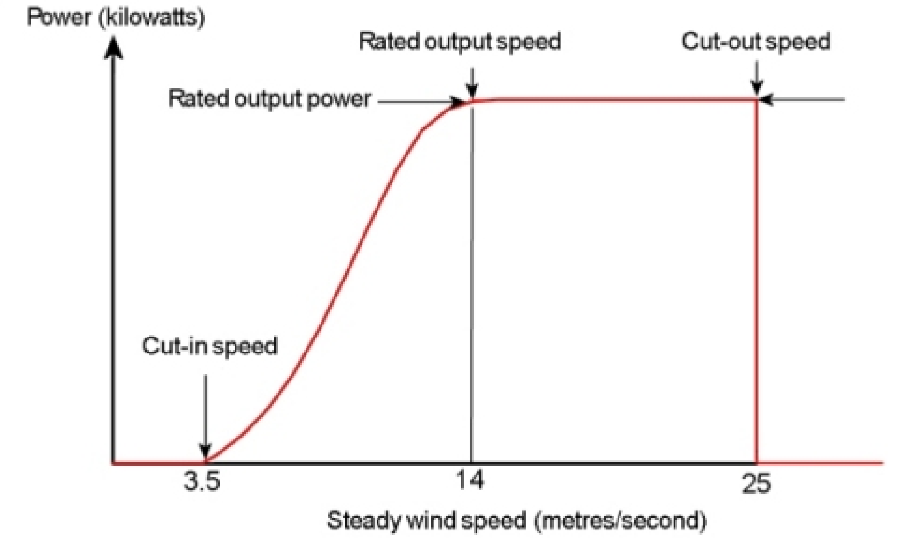
Wind distribution

To calculate likely **power output** from wind turbine we must understand wind in planned turbine location.

Average wind speed in location is only one consideration

cut-in speed – below this speed turbine does not produce power

cut-out speed – above this speed forces on structure risk damage; blades furled

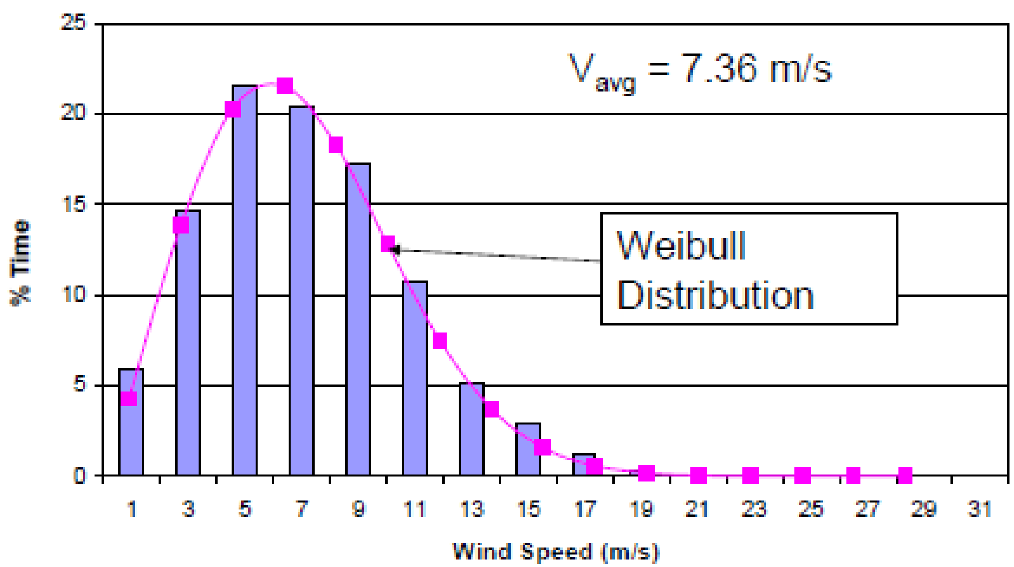


Typical wind turbine power output with steady wind speed.

Wind distribution

If comprehensive wind-speed data for a location is not available, wind speed can be modeled by **Weibull distribution..**

..statistical model which estimates how often winds of different speeds occur at a location with given average wind speed.



Wind distribution

- Compute hours/year that certain wind speeds are likely to be recorded (use data or Weibull)

- Calculate power generated by wind turbine at different wind speeds, knowing rotor **diameter** and *overall* **efficiency** of turbine (below Betz Limit, 59%)

- Multiply hours at each wind speed by power generated at that wind speed to give kWh of power generated

=> potential total annual power output of wind turbine

Furling (1)

Wind turbines designed to convert wind energy to electricity: stronger wind is better, usually.

If wind is too strong then turbine can spin so fast that it destroys itself with **turbine blades** ripped off, alternator damaged by excessive heat, damage to **turbine tower**

Furling is a method of preventing **wind turbine** from spinning too quickly simply by turning blades away from wind direction

Furling (2)

Furling can be achieved manually (cranking turbine away from wind) or automatically (hydraulics & springs), with goal of turning turbine blade edges into wind when wind is dangerously strong

Simple **furling:** passive system where turbine is yawed sideways away from wind as maximum power is reached

Furling (3)

Complicated **furling**: (more moving parts, stressed components) weights added to tail and sprung hinge to point where turbine alternator meets mast. When wind is very strong, it blows over turbine, pushing it out of wind. By adjusting spring strength and weights on tail, can fine tune exact furling wind speed.

Wind Power - Overgeneration

- Wind   ystems vary in output due to variability of wind/ water supplies. Sometimes generation exceeds demand -> overgeneration.
- Consequences of overgeneration are not severe, but it is inefficient and preferably should be avoided.
- Possible counters include more furling control

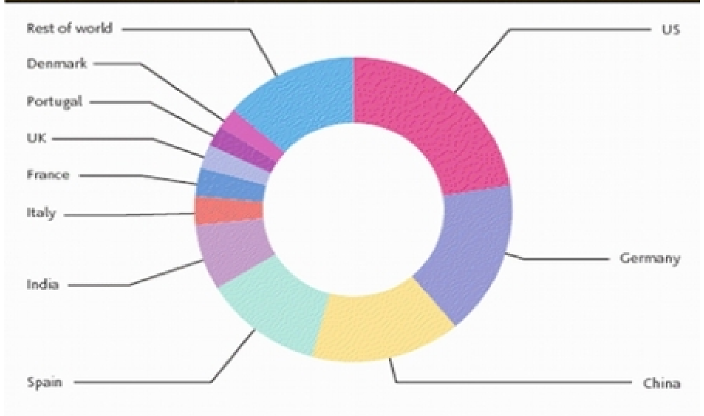
Wind Power - Economics

- Income from electricity generation must exceed costs of installation + operation + maintenance.
- Cost per kW.h must be competitive with other options.
- Governments' obligations to reduce CO_2 emissions make renewables more attractive (-> subsidies).
- Accidents (e.g. Deepwater Horizon, Fukushima, mining disasters) may steer policy-makers and public opinion towards less disaster-prone options.
- Greater energy independence is attractive to struggling economies.

Wind installed capacity 2014

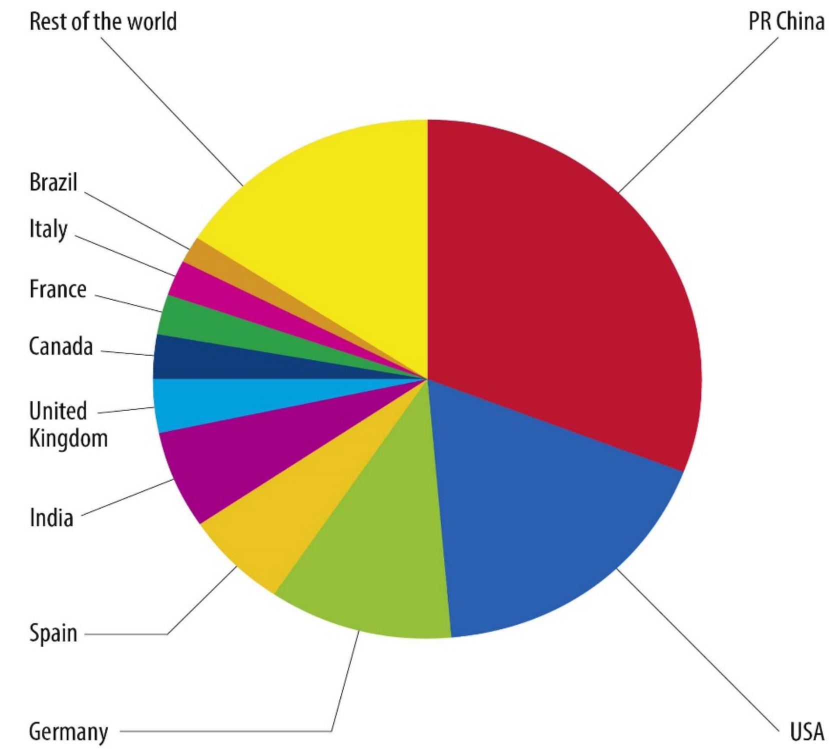
2009, for comparison

TOP 10 CUMULATIVE CAPACITY DEC. 2009



	MW	%
US	35,159	22.3
Germany	25,777	16.3
China	25,104	15.9
Spain	19,149	12.1
India	10,926	6.9
Italy	4,850	3.1
France	4,492	2.8
UK	4,051	2.6
Portugal	3,535	2.2
Denmark	3,465	2.2
Total top 10	**136,508**	**86.5**
Rest of the world	**21,391**	**13.5**
World total	**157,899**	**100**

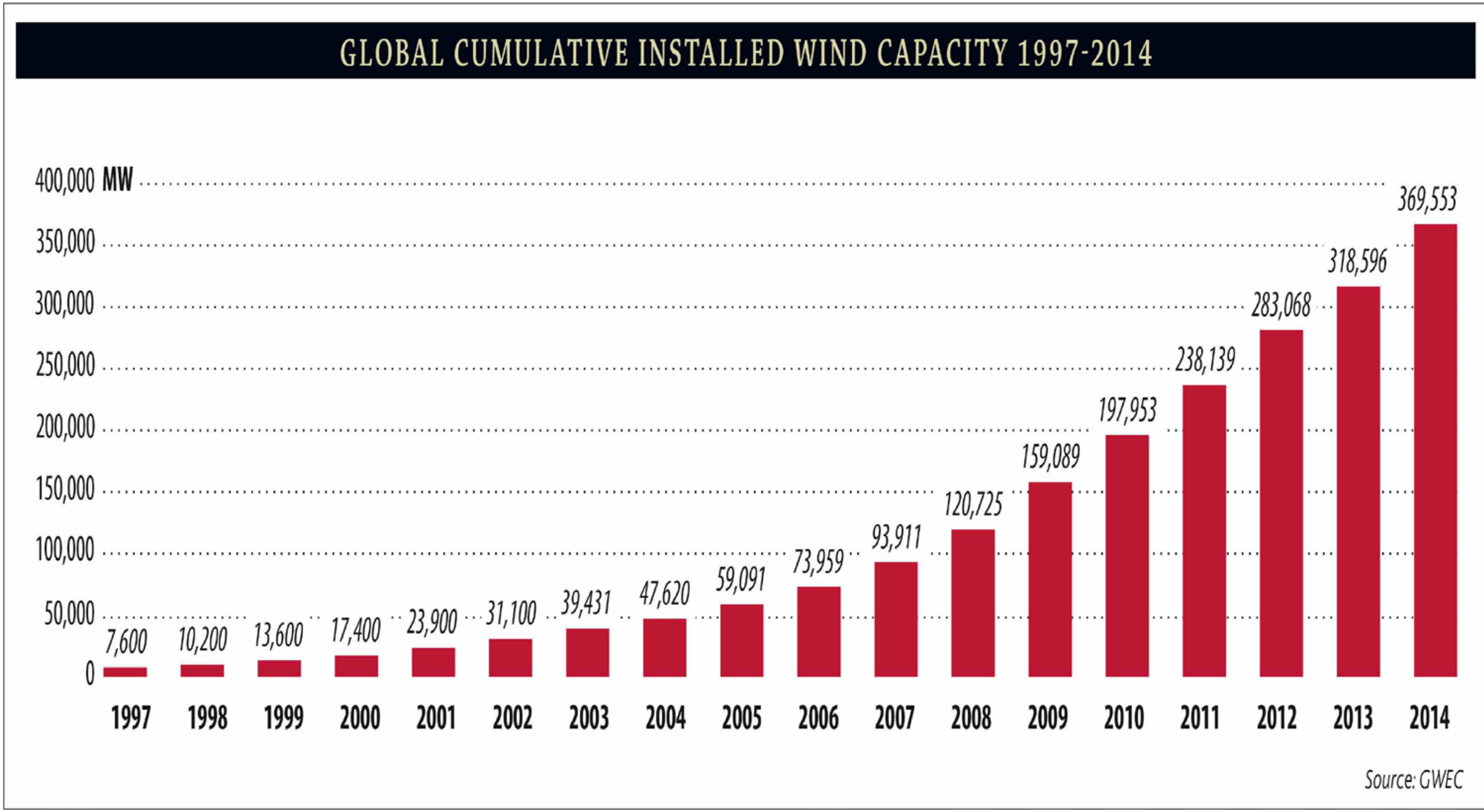
TOP 10 CUMULATIVE CAPACITY DEC 2014



Country	MW	% SHARE
PR China*	114,763	31.0
USA	65,879	17.8
Germany	39,165	10.6
Spain	22,987	6.2
India	22,465	6.1
United Kingdom	12,440	3.4
Canada	9,694	2.6
France	9,285	2.5
Italy	8,663	2.3
Brazil**	5,939	1.6
Rest of the world	58,275	15.8
Total TOP 10	**311,279**	**84.2**
World Total	**369,553**	**100**

Source: GWEC

Global installed capacity - growth



Wind installed capacity 2014

Nation	2014 (GW)	% growth last year	growth since 2009
China	115	26	460%
USA	66	8	86%
Germany	31	11	50%
Spain	23	0	21%
India	18	11	106%
UK	12	16	210%
WORLD	370	16	134%

Wind installed capacity

Steady growth by orders of magnitude

Growth of global installed capacity is proof in itself that wind power is a viable, economic and thriving industry.

Installed windpower capacity (MW) 2002-2009

This table provides end-of-year installed wind power capacity (in megawatts) for the countries of the world for the years 2002 through 2009. The data source for the 2002 through 2007 figures is the World Wind Energy Association. [1]

Rank	Nation	2002	2003	2004	2005[2]	2006[2]	2007[2]	2008[2]	2009[3]	1 Yr % growth	5 Yr avg % growth
-	**World**	**31,180**	**39,295**	**47,693**	**59,024.1**	**74,150.8**	**93,926.8**	**121,187.9**	**157,899**	**30.3**	**25.3**
-	European Union				40,722	48,122	56,614	65,255	74,767	12.1	
1	United States	4,685	6,370	6,725	9,149	11,603	16,818.8	25,170.0	35,159	39.7	31.6
2	Germany	12,001	14,609.1	16,628.8	18,427.5	20,622	22,247.4	23,902.8	25,777	7.8	10.3
3	China	468	567	764	1,266	2,599	5,912	12,210.0	25,104	105.6	84.8
4	Spain	4,830	6,202	8,263	10,027.9	11,630	15,145.1	16,740.3	19,149	14.4	22.0
5	India	1,702	2,110	3,000	4,430	6,270	7,850	9,587.0	10,925	14.0	35.4
6	Italy	785	904	1,265	1,718.3	2,123.4	2,726.1	3,736.0	4,850	29.8	32.8
7	France	148	248	386	757.2	1,567	2,455	3,404.0	4,410	29.6	68.9
8	United Kingdom	552	648	888	1,353	1,962.9	2,389	3,287.9	4,070	23.8	38.4
9	Portugal	194	299	522	1,022	1,716	2,130	2,862.0	3,535	23.5	57.1
10	Denmark	2,880	3,110	3,124	3,128	3,136	3,125	3,160.0	3,465	9.7	0.3
11	Canada	236	322	444	683	1,460	1,846	2,369.0	3,319	40.1	49.1
12	Netherlands	682	908	1,078	1,224	1,559	1,747	2,225.0	2,229	0.0	19.6
13	Japan	334	506	896.2	1,040	1,309	1,528	1,880.0	2,056	9.4	30.0
14	Australia	103	197.2	379	579	817.3	817.3	1,494.0	1,712	14.6	49.9
15	Sweden	345	404	452	509.1	571.2	831.0	1066.9	1,560	28.4	21.4

Wind Energy - Summary

Advantages

- Primary Fuel is Free & On-site
- Fuel Supply ‘Inexhaustible’
- Zero Pollutant Emissions/Effluents
- Zero Greenhouse gas emissions
- Matches seasonal demand (UK)
- Large generators can be located on remote sites
- Preserves fossil fuel supplies
- Reduces need for conventional power stations
- Provides energy diversity
- Increases energy independence
- Increasing exploitation worldwide indicates high confidence in viability

Disadvantages

- Risk of blade failure
- Suitable small generators not readily available
- Not suitable for urban areas
- Cost of storage battery or mains converter system
- Large structures, costly to construct tower & access roads
- (e/m interference if metal rotor used)
- Noise of gearbox
- Opposed by established fuel suppliers
- Unlikely to supply more than a portion of total demand even when fully exploited
- Wind is variable
- 10%-20% of EU/US population oppose windfarms (4% strongly)