Introduction to Energy Engineering

Course Introduction

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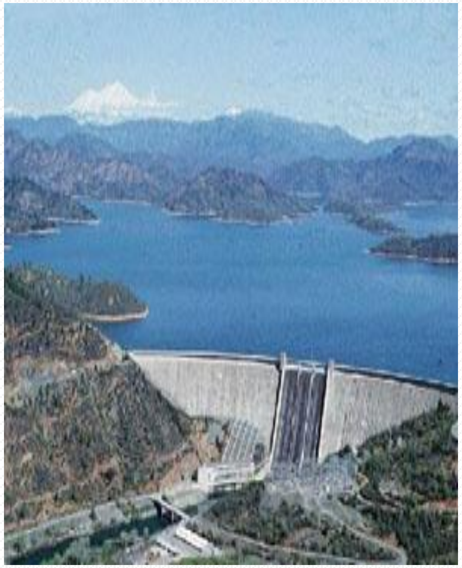
Course Outline

- This is an introductory course teaching you some basic stuff about:
  - Where our energy comes from
  - How electricity is produced
  - How much energy is produced and consumed
  - How the future is looking



Course Outline

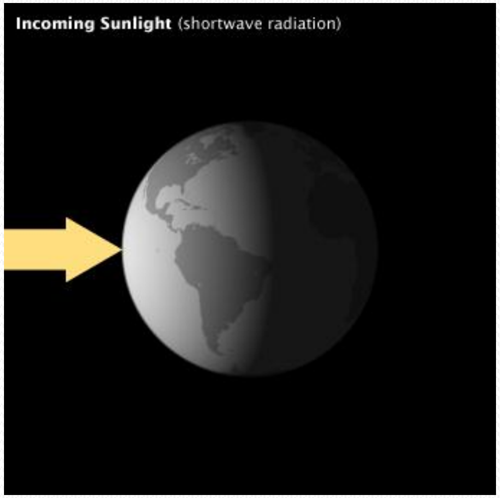
- These lectures are ‘interest only’ as assessment is by group assignment (discussed later)
  - So no exam!
- Pre-requisite knowledge?
  - Some basic knowledge of physics (I’m a physicist!)
    - Conservation of energy is a good starting point!

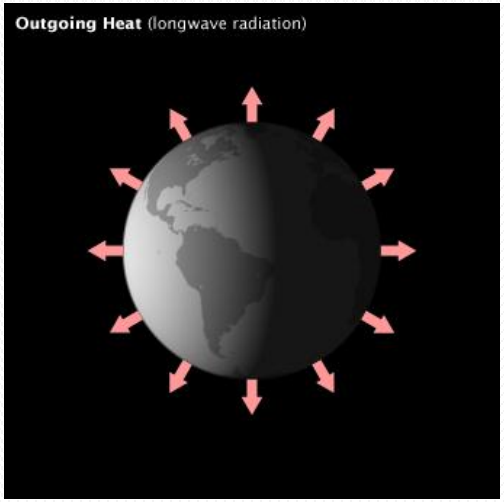
Course Outline

- 3 double lecture sessions in this time slot
  - Lecture 1: Earth's Energy Budget and Global Energy Resources
  - Lecture 2: Electrical Energy Generation
  - Lecture 3: Energy Consumption and Future Energy Challenges (will the lights go out?)

Course Resources

- Your first port of call should be the course Canvas page for lecture material and any supporting material
  - https://canvas.bham.ac.uk/login
- There is no set text book as most of the material is sourced online but I will update the Canvas page with references
  - However, if you want a great bedtime read, try 'Sustainable Energy – Without the Hot Air' by David MacKay
- A very good online resource discussing the Earth's energy balance is:
  - Climate and Earth's Energy Budget by Rebecca Lindsey, Earth Observatory, NASA Goddard Space Flight Center, January 14, 2009





http://earthobservatory.nasa.gov/Features/EnergyBalance/

Lecture 1

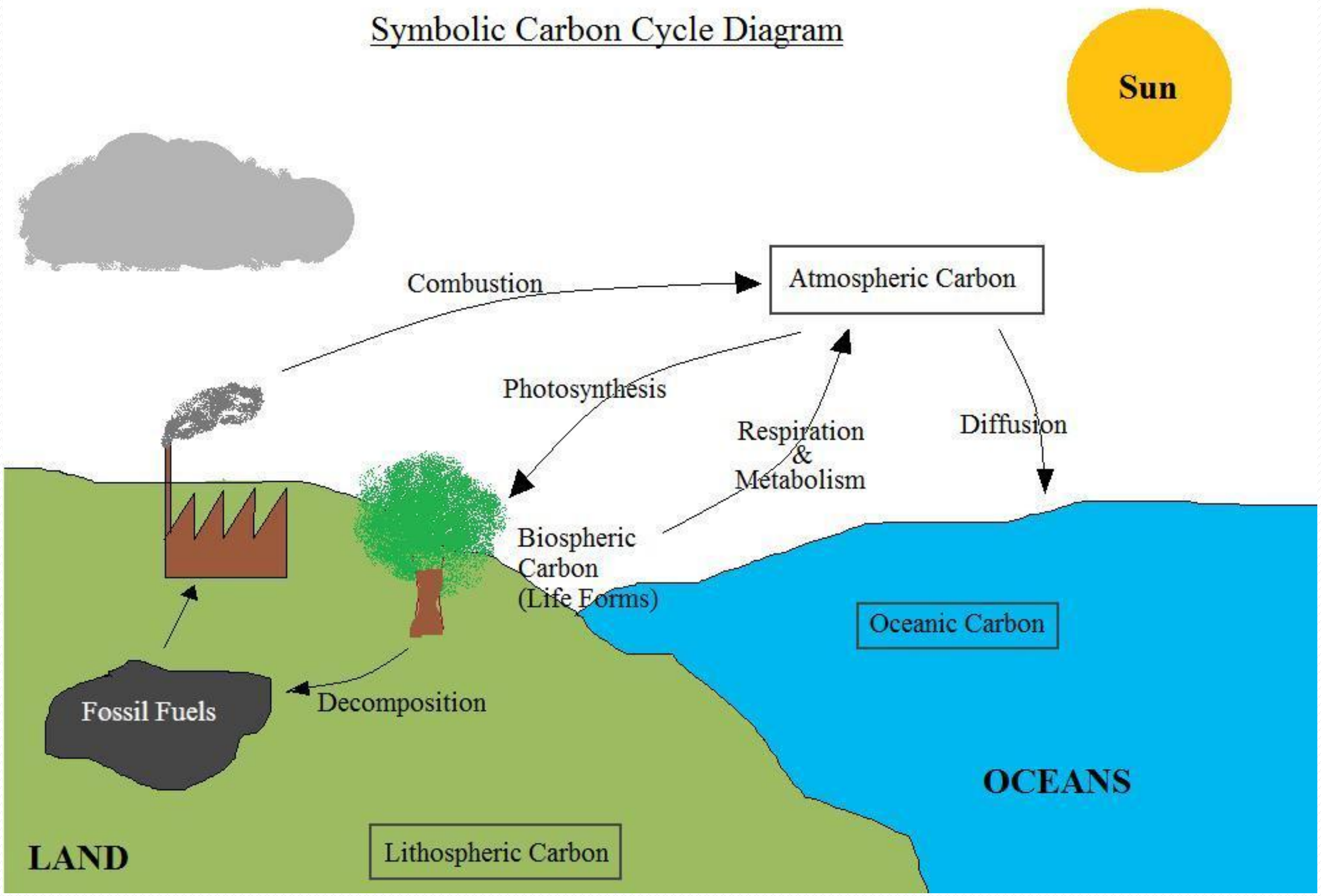
Earth's Energy Budget and Global Energy Resources

Part I

Earth’s Energy Budget

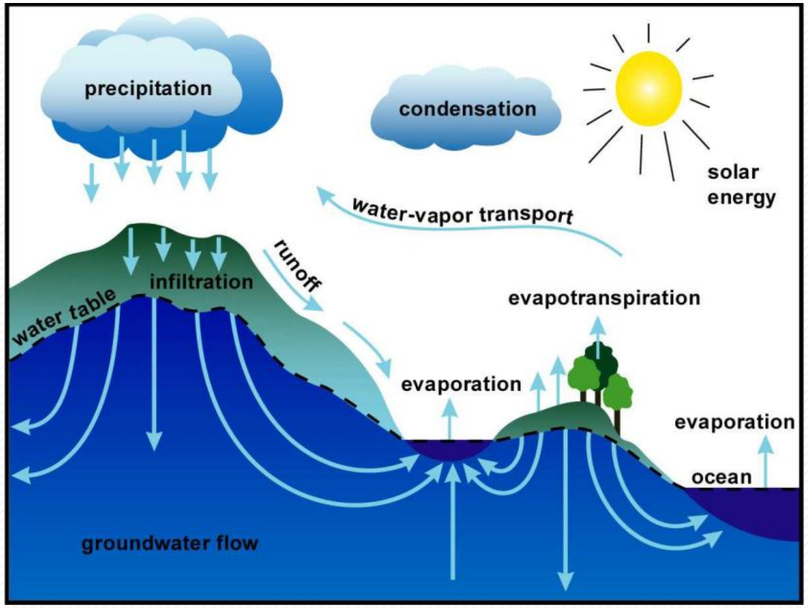
Introduction

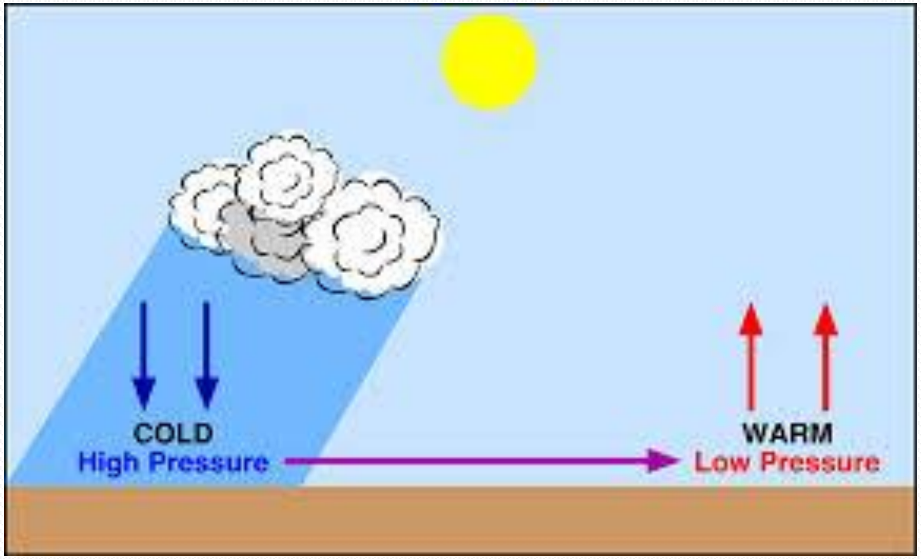
- Where do Earth's natural resources come from?
  - Fossil fuels
  - Uranium
  - Solar energy
  - Wind Energy
  - Tidal energy
  - etc
- Most are driven ultimately by solar radiation
- On Earth there is a complex interaction between sub-systems involving oceans, cloud, land, volcanoes, plants, animals, etc
  - So called 'natural cycles'
  - Although man has intervened somewhat to disrupt these
- Scientists define specific cycles to model flows between sub-systems, for example
  - Carbon cycle
  - Hydrological (water cycle)



Symbolic Carbon Cycle Diagram
Sun
Combustion
Atmospheric Carbon
Photosynthesis
Respiration
&
Metabolism
Diffusion
Biospheric
Carbon
(Life Forms)
Oceanic Carbon
Fossil Fuels
Decomposition
OCEANS
LAND
Lithospheric Carbon

Hydrological Cycle



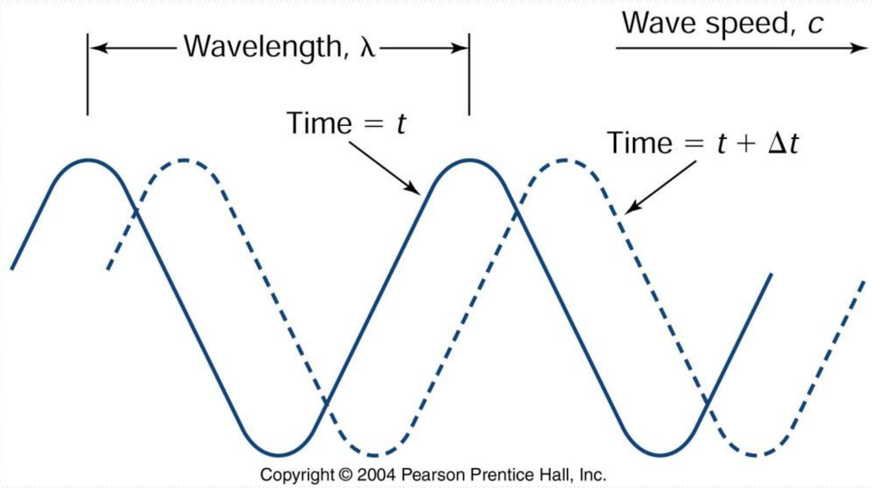


Earths Energy Budget

- The sun is responsible for most of the Earth's energy resources
- The surface of the Sun has a temperature of about 5,800K
- At that temperature, most of the energy the Sun radiates is visible and near-infrared light
- The Earth is in 'energy balance'
  - That's why it maintains a roughly constant temperature of about 288K
  - The sun's (short-wave) radiation impacting on Earth is balanced by the thermal (longwave) radiation emitted by Earth

Some basic physics

- Hot bodies (or any body with a temperature above zero degrees Kelvin) emits electro-magnetic radiation
  - This is propagated as a transverse wave
  - Waves are defined by their speed (c), wavelength λ, and frequency ν
  - Frequency and wavelength are inversely related

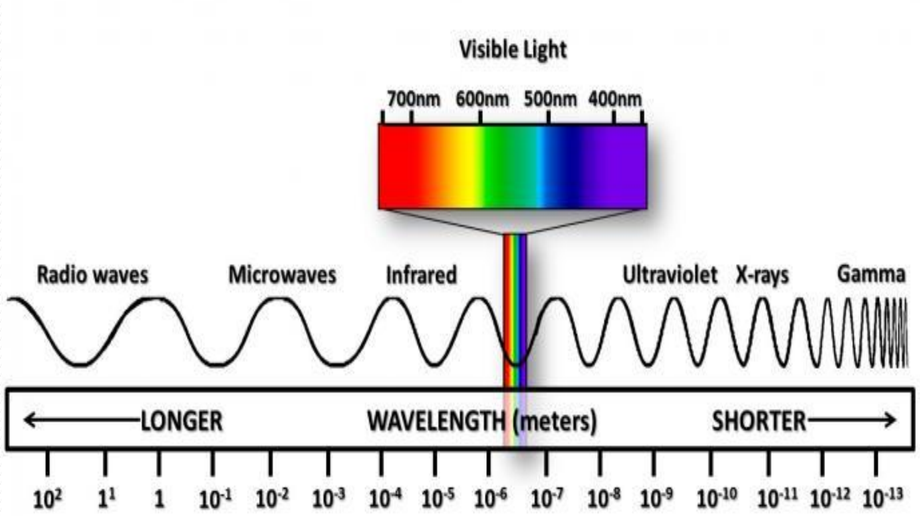


$c = \lambda\nu$

$c = 3.8 \times 10^8$ m/s

Some basic physics

- The ‘electro-magnetic’ spectrum gives different names to these EM waves according to their wavelength (or frequency/energy)
  - For example visible light has a wavelength between 0.4 and 0.7µm
  - X rays and gamma rays have much shorter wavelength and hence higher frequency/energy explaining why they are more dangerous



$E = h\nu$

h is Planck’s constant ($6.62606957 \times 10^{-34}$ m^2 kg / s)

Some basic physics

- A word on units:
  - Energy is expressed as Joules (J) – measures heat, electricity and mechanical work
    - The Joule is the SI unit of energy
      - 1 kg m^2 s^{-2}
    - 1 Joule is a *tiny* unit of energy which is why it's almost always prefixed with M(10^6), G(10^9) ……
  - We will consider some other more exotic units for energy later
    - For example the British thermal unit (Btu) is the energy to raise 1 lb of water 1°F
      - 1 Btu ≈ 1kJ

Power and Energy – Re-cap

- Power is the *flow* of energy
- A good analogy is to compare it with fluid flow
- A useful unit of energy is the kilowatt-hour
  - That's the energy delivered by a power source of 1kW in 1 hour
  - It's equal to 1000 x 3600 J = 3.6MJ
  - Quite often people refer to average energy consumption (for example kWh per day) which is a power

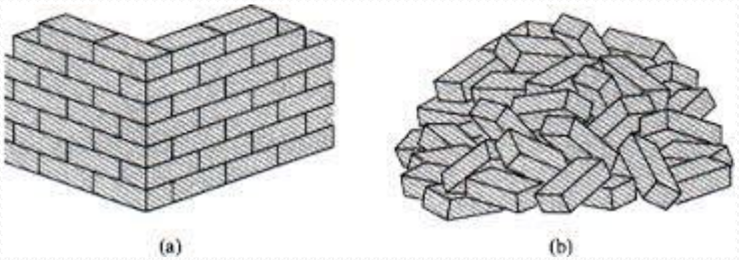
energy = power x time

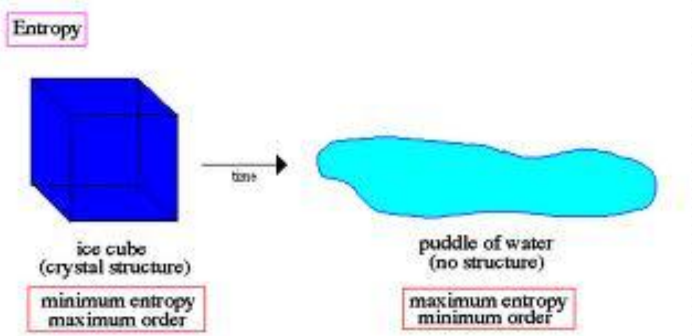
volume = flow x time

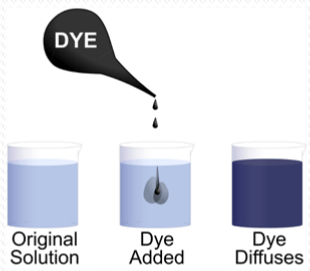
Energy (kWh)	**Power (kW)**
Volume (litres)	Flow (litres/second)

Energy and Entropy

- Is all energy the same?
  - Yes and no!
    - Yes
      - In the sense of energy conservation
    - No
      - In the sense of *useful* (low entropy) and *less useful* (high entropy) energy
- Entropy is the amount of disorder (randomness) in a system
  - Highly disordered = High entropy
  - Entropy always increases meaning systems get more disordered
    - A wall of bricks will collapse
    - An ice cube melts
    - A dye will diffuse in a liquid

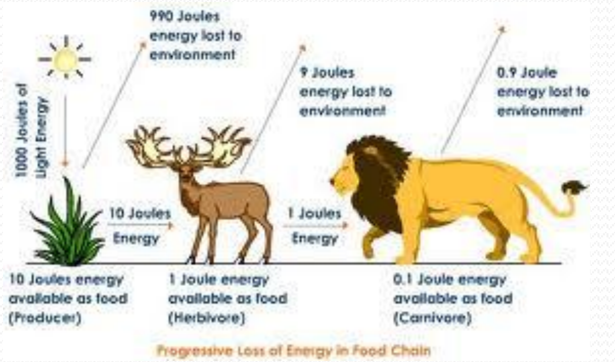


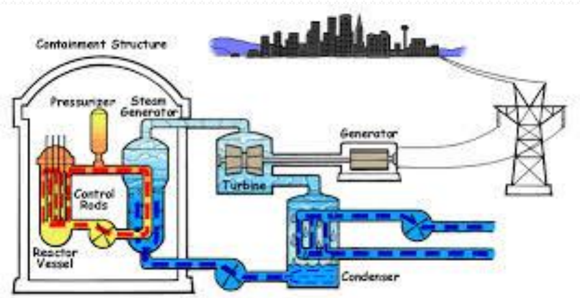




Energy and Entropy

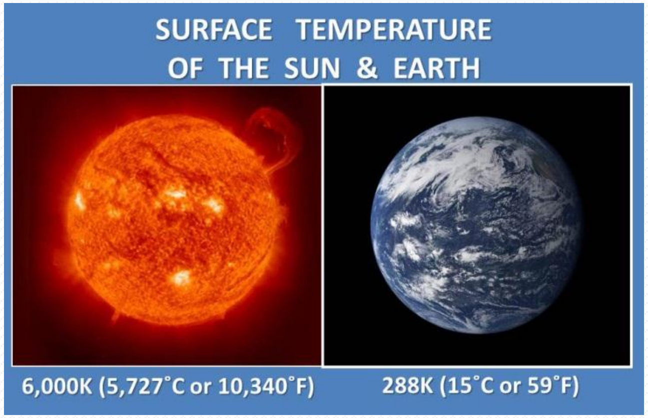
- So we can distinguish different grades of energy
- Electrical, chemical, mechanical and nuclear energy are all useful forms
- Thermal energy (especially in tepid things) is less useful
  - Your can use electrical energy to run your TV or convert it to heat to boil a kettle
  - You can't do either with a tepid bath full of water
- Often the energy 'grade' is reflected in the units kWh(e) – electrical and kWh(th) – thermal
- Conversion between energy grades incurs losses usually as thermal
  - Burning chemical energy (oil) to produce electrical energy is about 40% efficient
  - The food chain is essentially a chain of increasing entropy!
  - A steam turbine needs a low temperature (condenser) to 'dump' entropy

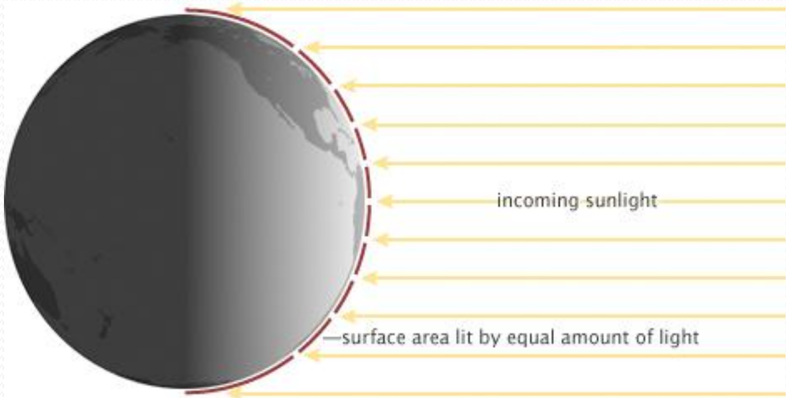




Some basic physics

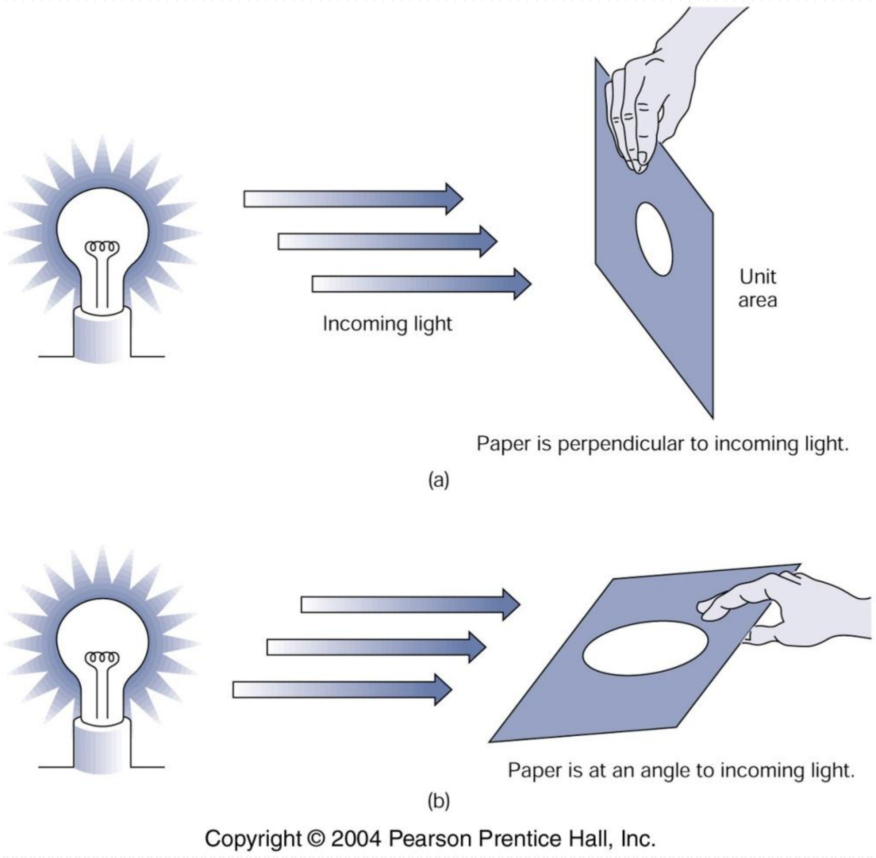
- The amount of heat energy reaching the Earth's surface (measured in watts per square metre) depends on 3 things
  - The energy flux
  - The sun's temperature
  - The distance to the sun
- (Obviously there are other factors such as the amount of reflection in the upper atmosphere)





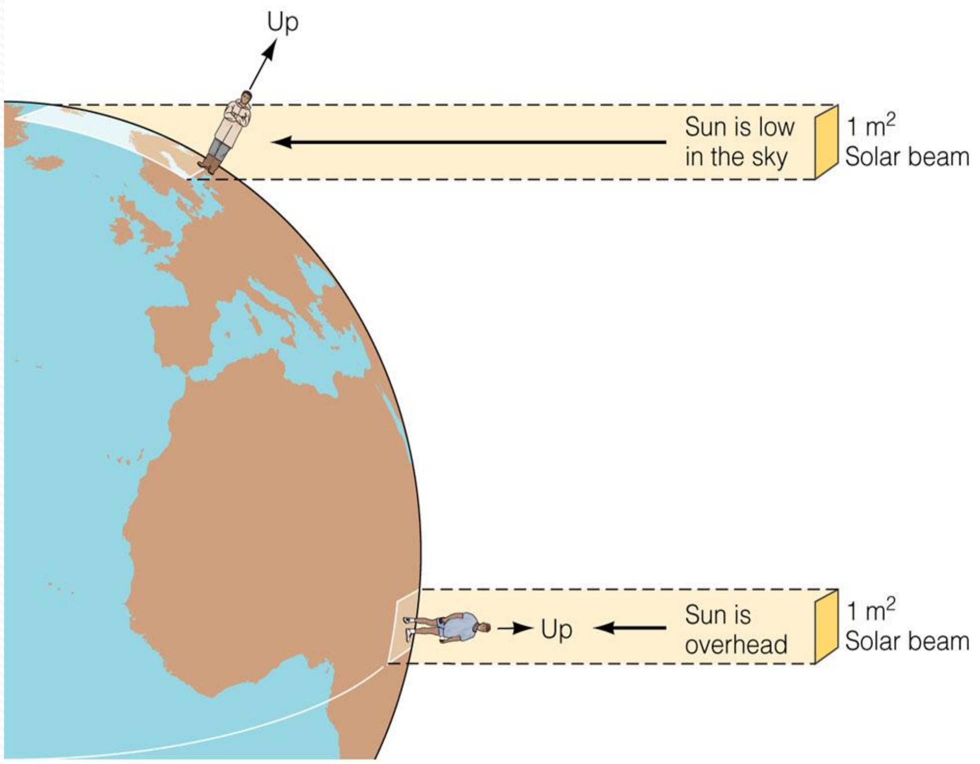
Some basic physics

- Energy flux is how much energy (or any material) passes through a unit surface area per unit time
  - Units: W/m^2
  - $J/m^2/s$



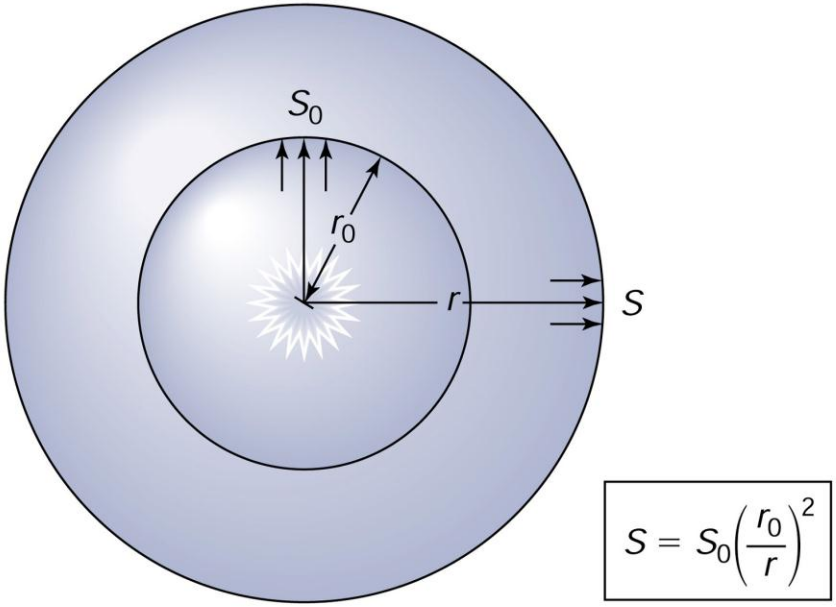
Some basic physics

- The angle of the impacted earth's surface to the sun affects the flux
- Clearly the flux depends on the latitude
- Nearer the equator – higher flux
  - More watts per square metre
- Polar regions cooler due to lower energy flux



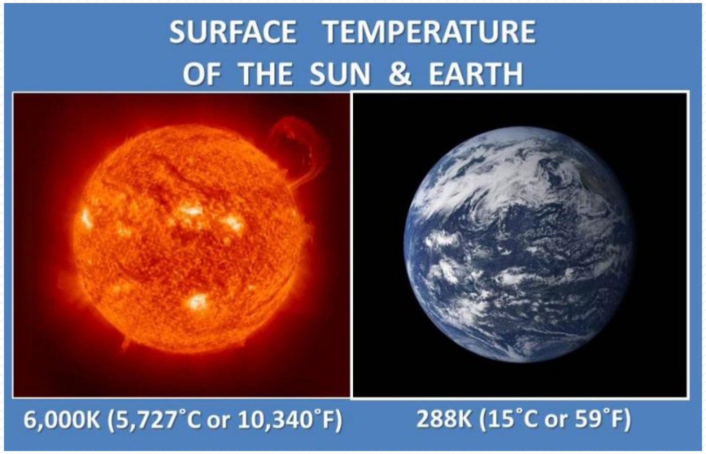
Some basic physics

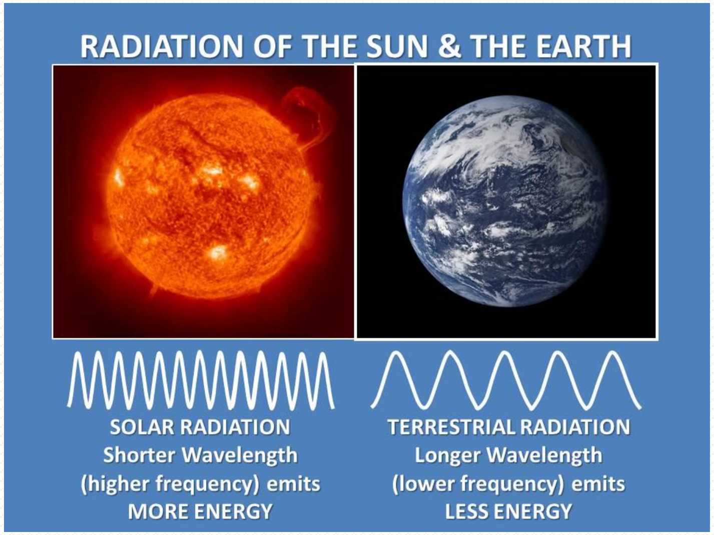
- Flux also depends on distance of an object or observer from the object emitting the radiant energy
  - Flux of solar energy decreases with distance from the sun
  - Relationship is an inverse-square law



Solar Radiation

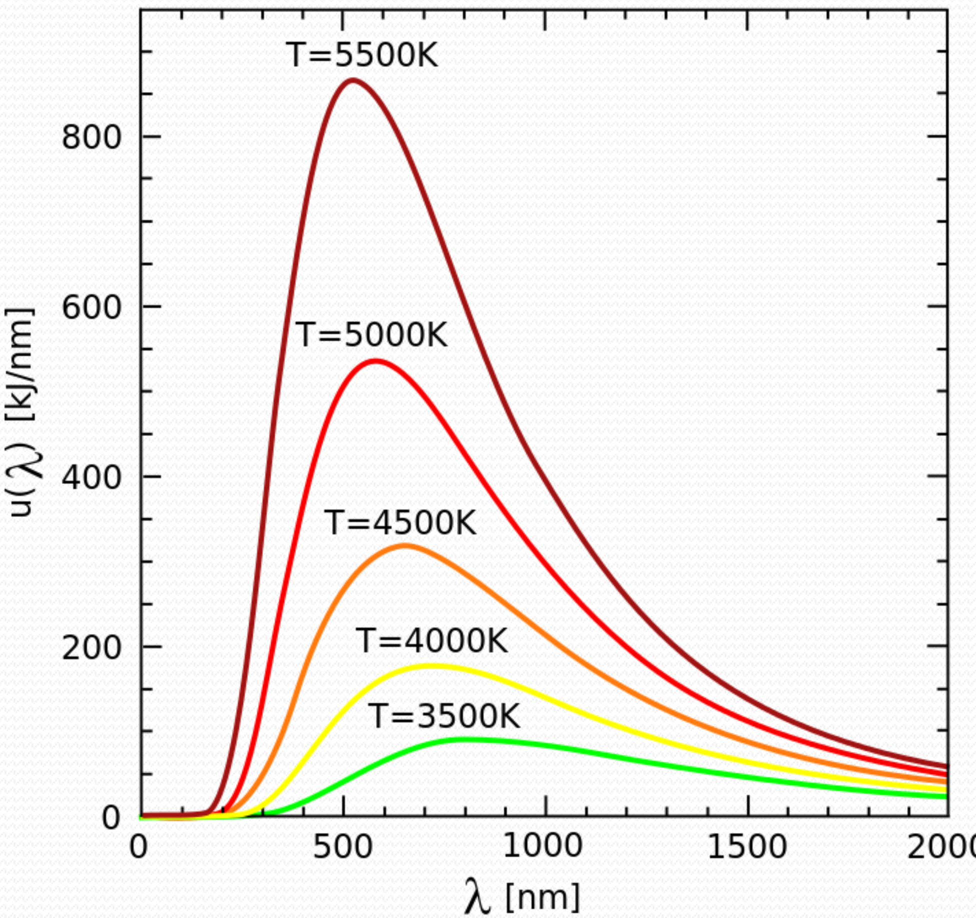
- All matter in the universe that has a temperature above absolute zero radiates energy across a range of wavelengths in the electromagnetic spectrum
- The hotter something is, the shorter its peak wavelength of radiated energy is
  - The hottest objects in the universe radiate mostly gamma rays and x-rays
  - Cooler objects emit mostly longer-wavelength radiation, including visible light, thermal infrared, radio, and microwaves





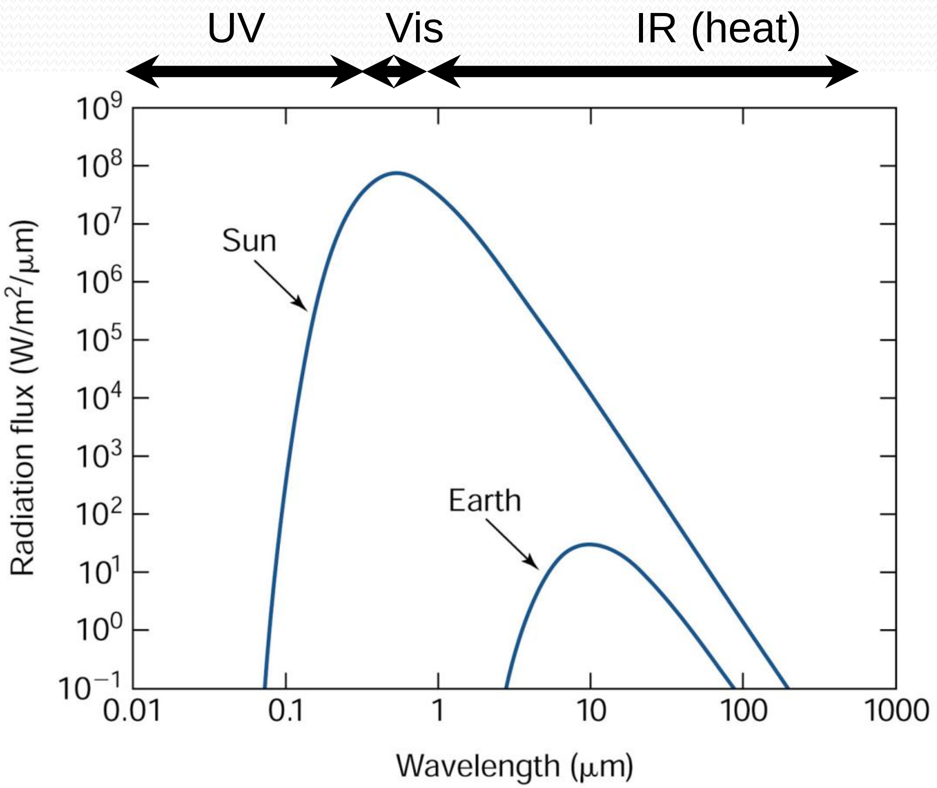
Solar Radiation

- Wien's law describes mathematically the amount of radiation emitted from hot bodies
  - These bodies are assumed 'black' bodies
    - Perfect absorbers and emitters in thermal equilibrium
    - The radiation emitted by the sun and planets are good approximations to black body radiation



Solar Radiation

- The sun and Earth both are 'hot' bodies
  - Because the sun is much hotter, its emissions (measured as energy flux) are at a much shorter wavelength according to Wien's law
  - Earth emits relatively long wave radiation (in the IR band)



Solar Radiation

- Wien's law is quite complicated as it describes the energy 'density' distribution
  - Energy density is the amount of energy per unit wavelength or frequency
- Wilhelm Wein derived it in 1893 based on thermodynamics
  - It is only an approximation and was later superseded by Planck's law which is a better approximation over range of wavelengths

$$I(v,T)=\frac{8\pi hv^3}{c^3}\frac{1}{e^{\frac{hv}{kT}}-1}$$

- I is the energy per unit time per unit frequency per unit solid angle per unit area!
  - k is Boltzmann's constant
  - c is the speed of light
  - h is Planck's constant
  - T is the temperature
  - v is the frequency

Solar Radiation

- The main application of this formula is in deriving Wien's *displacement law*
  - This is the wavelength giving the maximum radiative energy at a certain temperature
  - In other words, can we measure the temperature of a star (or the sun) from it's emission!
- We need some maths to derive the wavelength at which the energy emitted is maximum
  - Here are the main details. I will leave you to fill in the gaps ☺

$$I(v,T) = \frac{8\pi h v^3}{c^3} \frac{1}{\exp(\frac{hv}{kT}) - 1}$$

$$I(\lambda,T) = \frac{8\pi hc}{\lambda^5} \frac{1}{\exp(\frac{hc}{\lambda kT}) - 1}$$

$$\frac{dI}{d\lambda} = 0 \Rightarrow \lambda_{\max} = b/T$$

$$b \approx 2.9 \times 10^{-3} mK$$

Solar Radiation

- There is an inverse relationship between the wavelength of the peak of the emission of a black body and it's temperature
  - This is the wavelength giving the maximum radiative energy at a certain temperature
- This is an important relationship in areas such as astrophysics and plasma physics

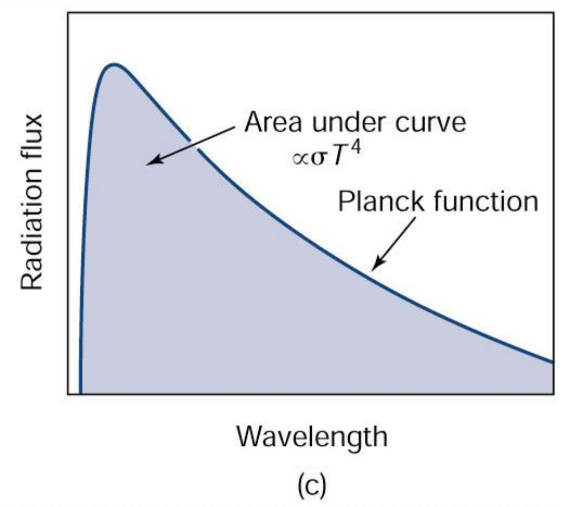
- Examples:
  - A wood fire at 1500 K puts out peak radiation at $2.9 \times 10^{-3}/1500 \approx 2$ μm. This is far more energy in the infrared than in the visible band, which ends about 0.7μm
  - Mammals at roughly 300 K emit peak radiation at about 10 μm, in the far infrared
    - Hence the use of thermal imaging cameras
  - The effective temperature of the Sun is 5778 K. This corresponds to a peak emission at a wavelength of around 5 μm. This is the wavelength of green light

Solar Radiation

- An alternative formulation of Wien's law can be obtained by integrating $I(\nu, T)$ over all frequencies to get the *total* energy radiated as a function of temperature
  - Quite advanced calculus required
  - The result is the *Stefan-Boltzmann law* and is a very simple relationship

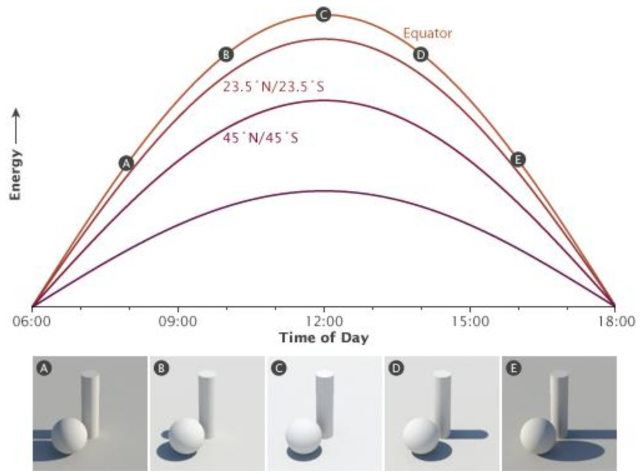
$$E = \sigma T^4$$

- E is the radiant heat energy emitted from a unit area in one second and T is the absolute temperature (in degrees K)
- σ *Stefan-Boltzmann* constant (5.67×10^{-8} J s^{-1} m^{-2} K^{-4})
  - It's not actually a new constant of nature as it's expressed in terms of other physical constants



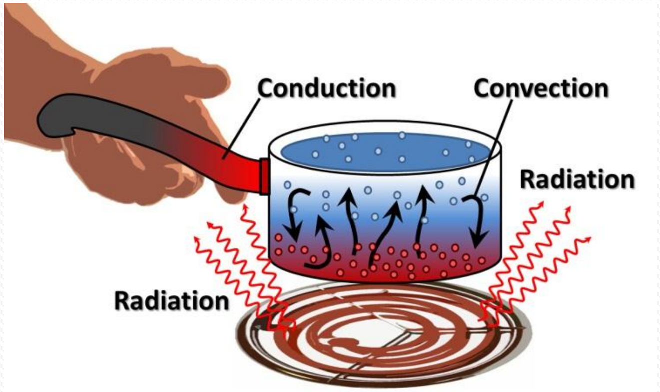
Solar Radiation

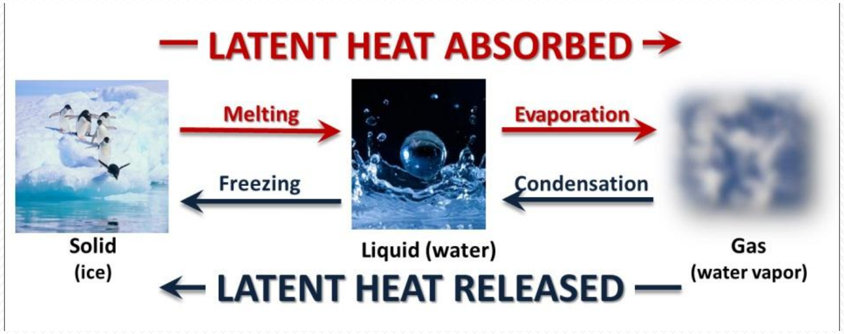
- What all this amounts to is that at Earth's average distance from the Sun (about 150 million kilometres), the intensity of solar energy reaching the top of the atmosphere directly facing the Sun is about 1,360 watts per square meter
  - This is often known as the total solar irradiance or sometimes the insolation
- You could run a refrigerator all day with the total solar irradiance falling on 1 square metre in 1 hour
- It's important to understand that this is a *maximum*
  - For example this assumes that the radiation hits the surface perpendicularly (maximum flux)
  - Also the value varies significantly with time of day and latitude
  - Averaged over the entire planet, the amount of sunlight arriving at the top of Earth's atmosphere is only 1/4 of the total solar irradiance, or approximately 340 watts per square meter



Earth's Energy Balance

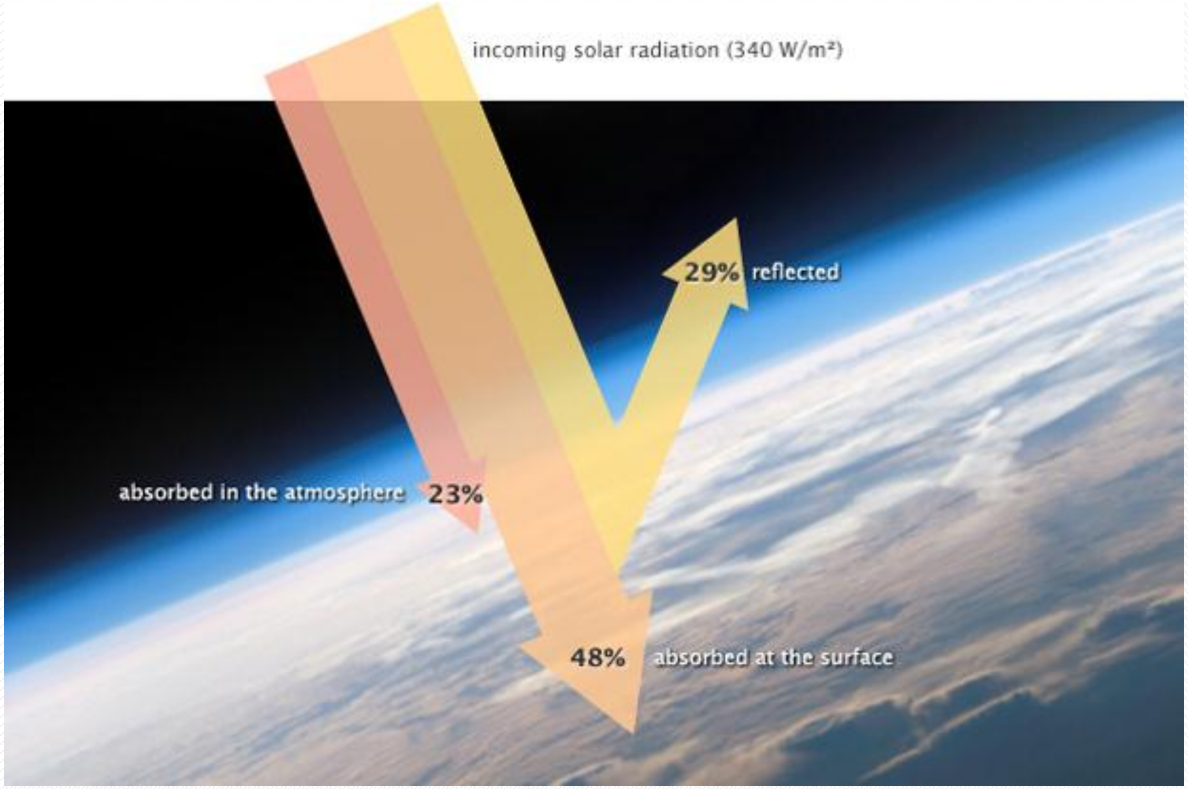
- If Earth's temperature is constant, the planet has to be in radiative balance
- Many complex processes are at work to maintain a constant temperature and these are responsible (amongst other things) for our climate
  - However, the physical principles at work are basically simple mechanisms of heat transfer
    - Radiation
    - Conduction
    - Convection
    - Latent heat





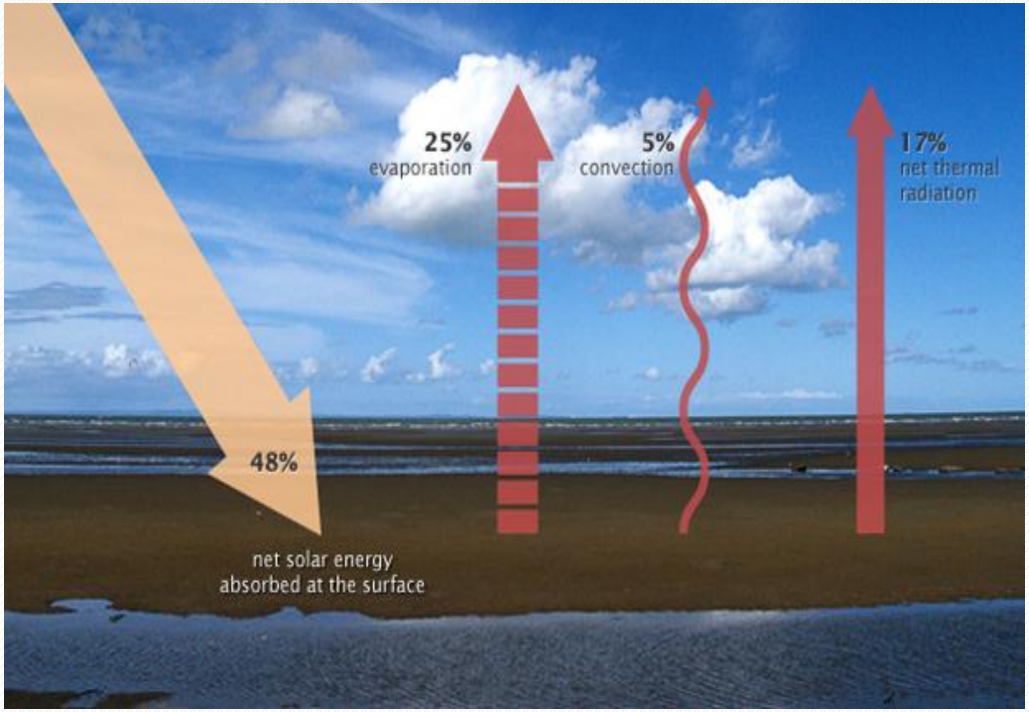
Earth's Energy Balance

- Only around 50% of incoming solar radiation gets through the atmosphere to the Earth's surface
  - Around 70% of the radiation is absorbed by Earth and ultimately returned to space as IR
  - Energy input = energy output



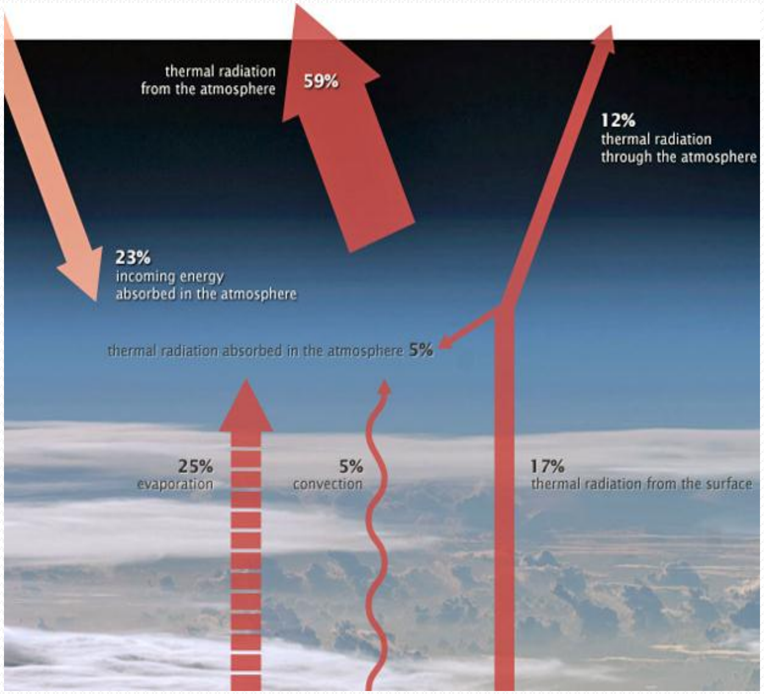
Earth's Energy Balance

- There must be an energy balance for the 48% of radiation reaching Earth's surface
- This is emitted through evaporation (25%)
  - Latent heat
- Convection (5%)
  - Heated warm air rising causing air currents
- Radiation (17%)
  - Thermal infrared energy (heat) radiated by atoms and molecules on the surface



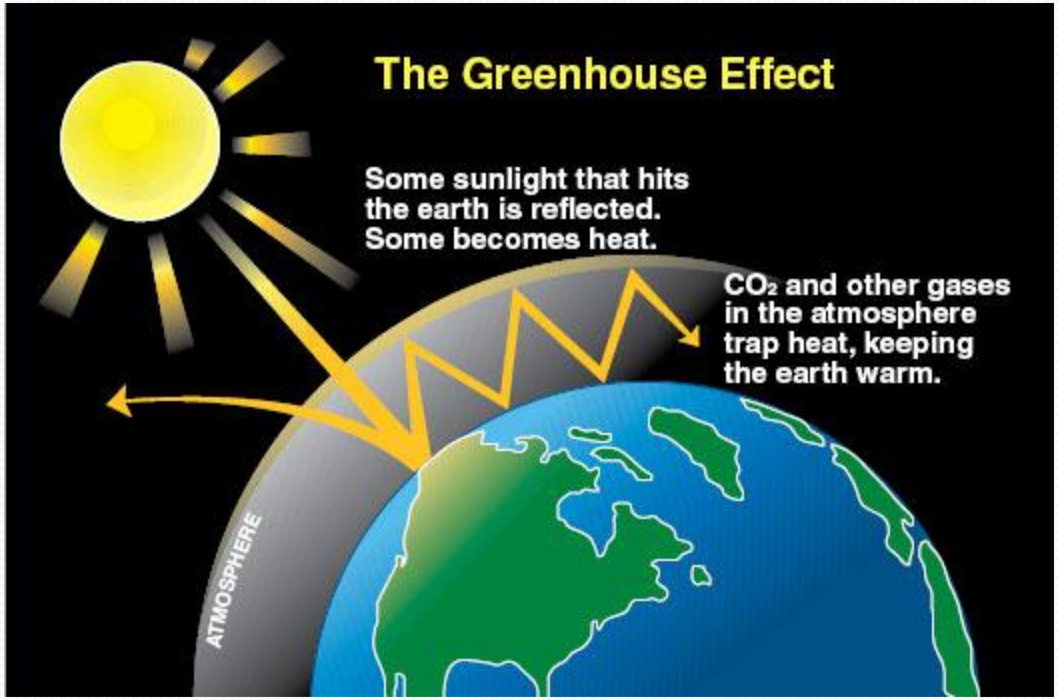
Earth’s Energy Balance

- We can work out an energy balance also for Earth’s atmosphere which demonstrates the natural greenhouse effect
  - Satellite measurements indicate that the atmosphere radiates thermal infrared energy equivalent to 59% of the incoming solar energy
  - Clouds, aerosols, water vapour, and ozone directly absorb 23% of incoming solar energy
  - Evaporation and convection transfer 25% and 5% of incoming solar energy from the surface to the atmosphere totalling the equivalent of 53% of the incoming solar energy to the atmosphere
  - The remaining 5-6% comes from the Earth’s surface
    - Absorbed by greenhouse gases, these greenhouse gas molecules radiate heat in all directions, some of it spreads downward and ultimately comes back into contact with the Earth’s surface, where it is absorbed – ‘natural greenhouse’ effect



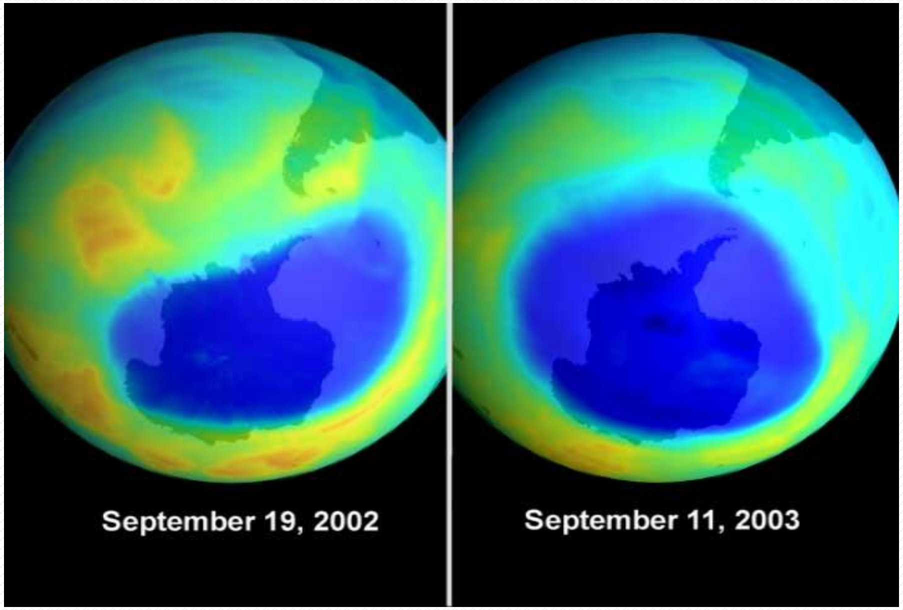
Earth's Energy Balance

- The 'natural' greenhouse effect is essential to support life
  - Major role in warming atmosphere
  - Traps heat
  - Without greenhouse gases, planet would be much colder (~ -20°C)
- Note that 'greenhouse' is an unfortunate term
  - Real greenhouses suppress convection through the glass whereas the 'greenhouse effect' is all about radiated heat



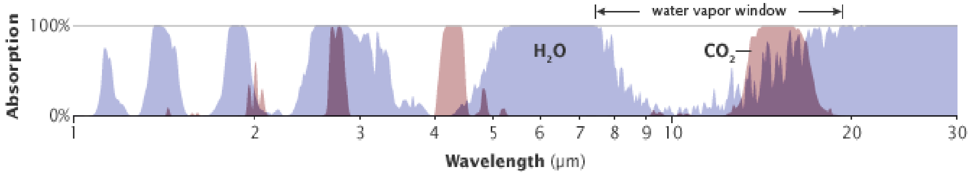
Earth's Energy Balance

- Incidentally, this explains the importance of the O_3 layer
  - Absorption takes place in the O_3 layer
  - A depleted O_3 layer is very harmful to humans
  - The size of the Antarctic ozone hole reached 11.1 million square miles on September 24, 2003, slightly larger than the North American continent
  - Check out Nasa's ozone watch web site for up to date animations
    - http://ozonewatch.gsfc.nasa.gov/



Earth's Energy Balance

- It's worth mentioning the man-made greenhouse effect
- About 17% of incoming solar radiation is radiated by Earth's surface
    - Of this, 12% escapes into space and 5-6% is captured by greenhouse gases and re-radiated in all directions
    - This is a fine energy balance which keeps a stable temperature on Earth
- There are many man made phenomena which effect this energy balance and hence Earth's surface temperature
    - Pollution (aerosols), which absorb and reflect incoming sunlight
    - Deforestation, which changes how the surface reflects and absorbs sunlight
    - The rising concentration of atmospheric carbon dioxide and other greenhouse gases, which decrease heat radiated to space



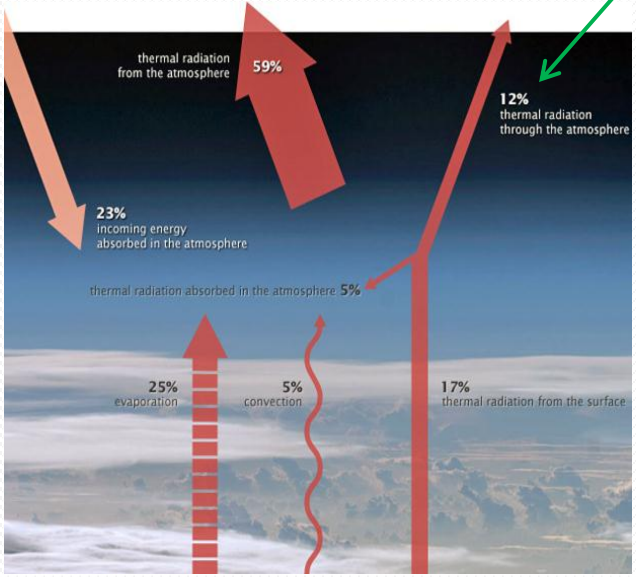
Earth's Energy Balance

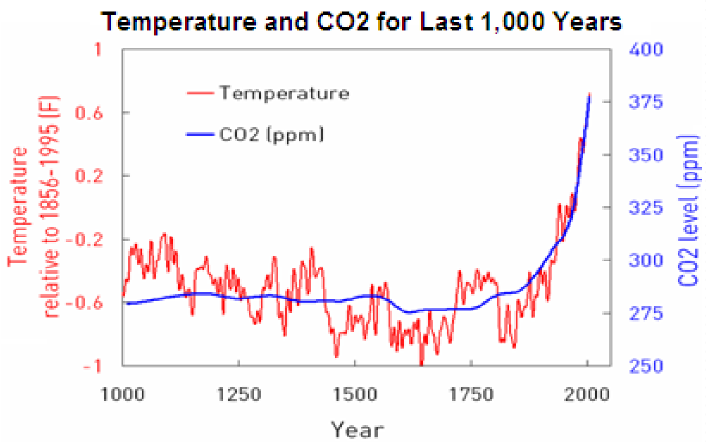
Man made reduction
12% -> ~11%

- Effectively the energy imbalance changes the temperature
  - However, remember the Stefan-Boltzmann law

    $$E = \sigma T^4$$

  - Changes in temperature are negligible because of the 4^{th} power
  - Global average surface temperature has risen between 0.6 and 0.9K in the past century
  - The concern is continued and increasing concentrations of greenhouse gases





Part II

Global Energy Resources

Global Energy Resources

- Obviously the first distinction is into renewable and non-renewable
  - A nonrenewable resource is a natural resource that cannot be re-made or re-grown at a scale comparable to its consumption
  - Renewable resources are natural resources that can be replenished in a short period of time
  - Sustainable???

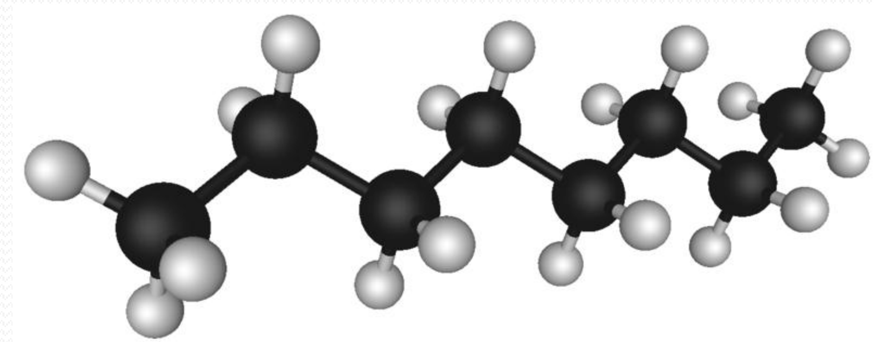
Global Energy Resources

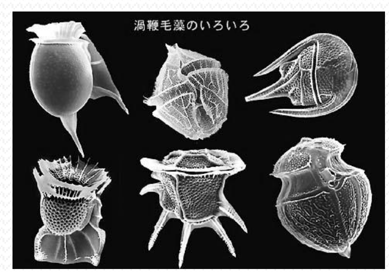
- We are all familiar with examples of each
  - A nonrenewable resource is a natural resource that cannot be re-made or re-grown at a scale comparable to its consumption
  - Nonrenewable
    - Coal
    - Oil
    - Gas
    - Nuclear
  - Renewable
    - Solar
    - Wind
    - Water (Hydro-electric, wave)
    - Biomass
    - Geothermal

HOOVER DAM

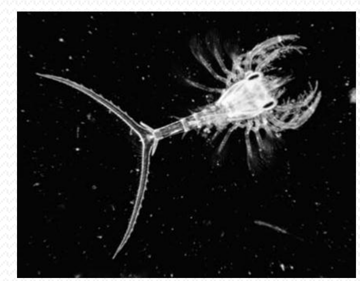
Oil and Gas

- Coal, Oil and Gas are often called "fossil fuels" because they have been formed from the fossilized remains of prehistoric plants and animals
- They are made of a mixture of different hydrocarbons
- Oil and gas have the same origin
  - Decaying microscopic marine life
  - When the plankton dies, it forms an organic mush on the sea bed
  - Under anaerobic conditions (when there is no oxygen) other animal life to feed on the plankton can't be supported and the mush accumulates





Plant plankton

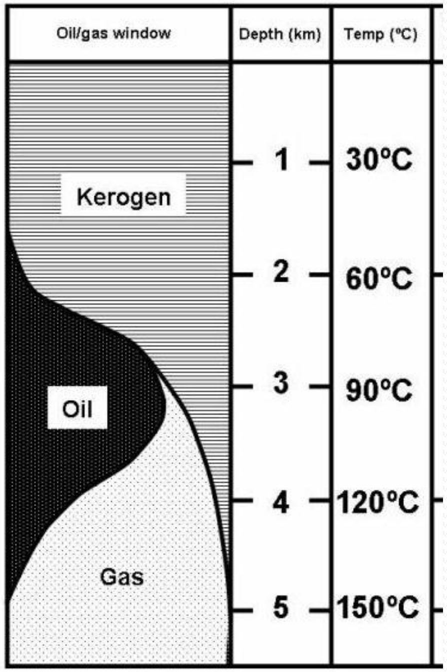


Animal plankton

Oil and Gas

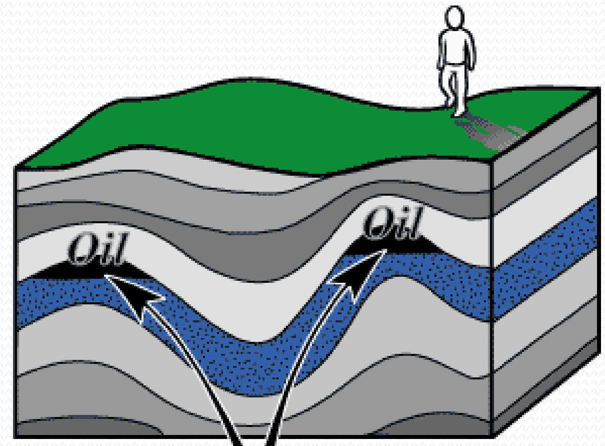
- When sediment (the sea bed) contains more than 5% organic matter, it is called black shale and it is the pre-curser to hydrocarbon reserves
- As black shale is buried, it comes under more pressure so it is heated
- The depth (and hence temperature of heating) determines if it ultimately becomes kerogen
- As kerogen is heated further, it releases oil and gas
- Shales rich in kerogens that have not been heated to a warmer temperature to release their hydrocarbons may produce oil shale deposits

Black shale deposits



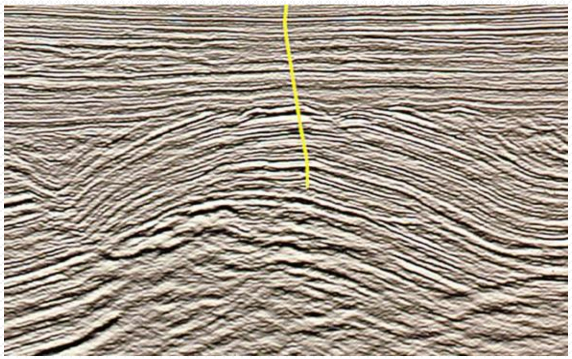
Oil and Gas

- Around 90°C, it is changed into the liquid state, which we call oil
- Around 150°C, it is changed into gas
- A rock that has produced oil and gas in this way is known as a source rock
- The last stage of the process is the hydrocarbons permeating up through the rock to form reservoirs
- Some rocks are permeable and allow oil and gas to freely but others are impermeable and block the upward passage of oil and gas
- Where oil and gas rises up into a dome (or anticline) capped by impermeable rocks it can't escape
    - Seismic surveys are used to locate likely rock structures underground in which oil and gas might be found
    - Dome like structures are a good indication of hydrocarbon reserves



Anticline Traps

Drill here!

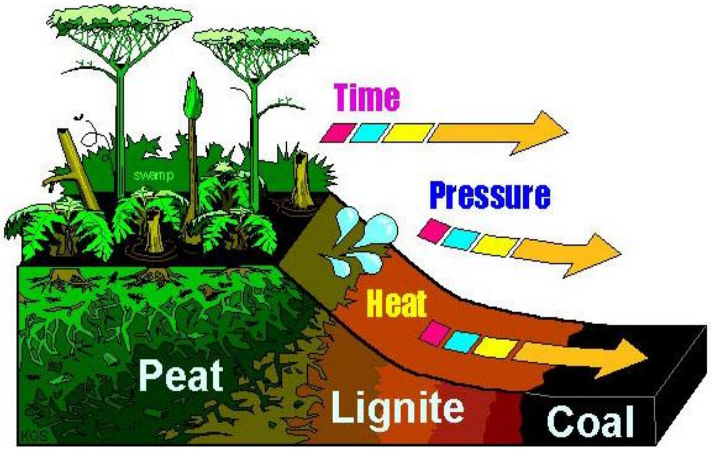


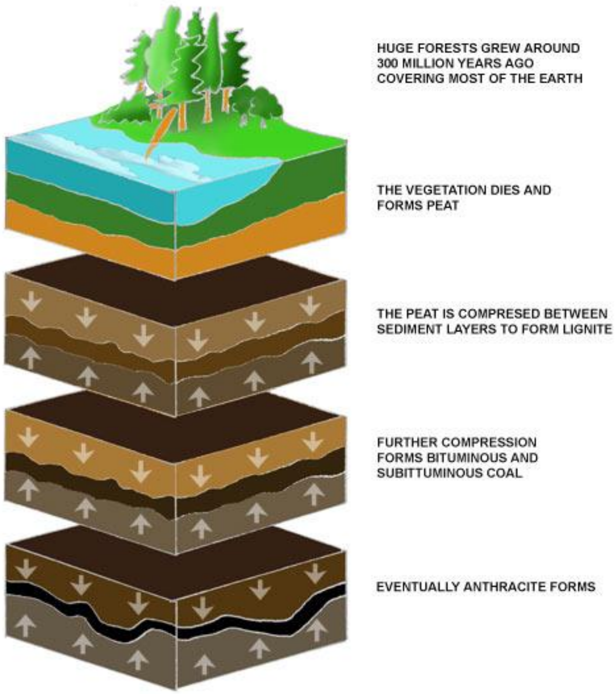
Coal

- Coal currently provides about 30% of the total UK energy production (with gas at around 40%)
- Now that oil and gas are dwindling, many energy producers and users are looking again at the potential of coal
- Unlike oil and gas, coal is not formed from marine organisms, but from the remains of land plants
- A swampy setting, in which plant growth is lush and where there is water to cover fallen trees, dead leaves and other plant debris, is ideal for the initial stages to create coal

Coal

- The formation of coal from dead plant matter requires burial, pressure, heat and time
- The process works best under anaerobic conditions (no oxygen) since the reaction with oxygen during decay destroys the organic matter
- It is the carbon content of the coal that supplies most of its heating value
- The greater the carbon to oxygen ratio the harder the coal, the more potential energy it contains
- Over time there are different stages to coal deposit formation





Coal

- The products of coalification are divided into four major categories based on the carbon content of the material
  - Peat
  - Lignite
  - Bituminous
  - Anthracite
- Peat is an accumulation of partially decayed vegetation matter and is the first stage in the formation of coal
- Peat forms in wetlands
- It contains a large amount of water and must be dried before use
- Historically, it has been used as a source of heat and burns with a long flame and considerable smoke

Coal

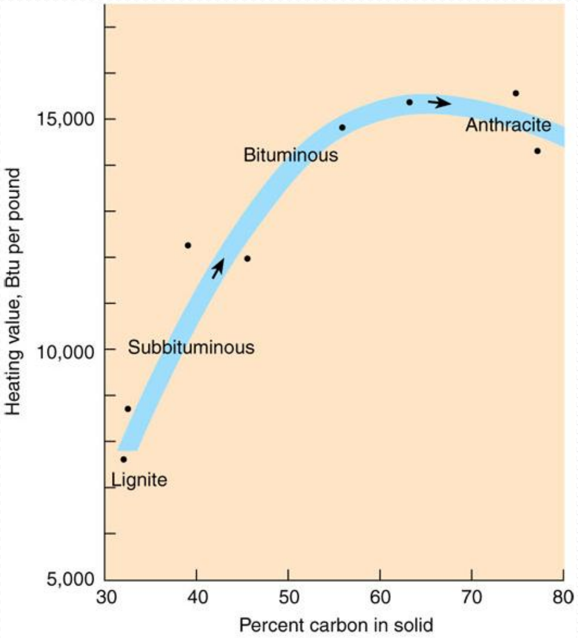
- Lignite is the second step in the formation of coal and is formed when peat is subjected to increased vertical pressure from accumulating sediments
- Lignite, often referred to as brown coal, is the lowest rank of coal and used almost exclusively as fuel for steam-electric power generation. It's inefficient to transport and often burn in power stations close to the mines
- Bituminous coal is the third stage of coal formation
- Additional pressure over time has made it compact and virtually all traces of plant life have disappeared
- It is of higher quality than lignite coal but of poorer quality than anthracite coal
- It is greatly used in industry as a source of heat energy

Lignite

Bituminous coal

Coal

- Anthracite is formed during the forth stage of coal formation
- It is the most valuable and highest grade of coal, and has a carbon content
- It burns far more efficiently with less smoke
- The principal use of anthracite is for a domestic fuel It delivers high energy per its weight and burns cleanly with little soot but it's prohibitively expensive to use in power stations
- As the coals becomes harder, their carbon content increases, and so does the amount of heat released
  - Anthracite produces twice the energy (BTUs) of lignite



Pro’s and Con’s of Fossil Fuels

- Pro’s
  - Transporting coal, oil and gas to the power stations is easy
  - Fossil fuels are cheap and reliable sources of energy. They are excellent types of fuel to use for the energy base-load, as opposed to some of the more unreliable energy sources such as wind and solar energy

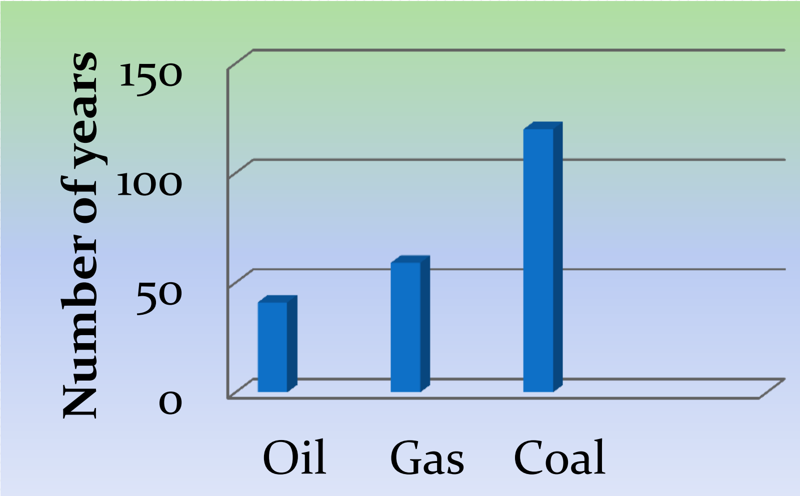
- Con’s
  - Basically, the main drawback of fossil fuels is pollution
  - Coal is by far the worst pollutant and has the highest carbon density
  - Burning any fossil fuel produces carbon dioxide, which contributes to the "greenhouse effect", warming the Earth.
  - Burning coal produces sulphur dioxide, a gas that contributes to acid rain.
  - Mining coal can be difficult and dangerous. Strip mining destroys large areas of the landscape

So how much fossil fuel is left?

- We can get an estimate of this by dividing the ‘known recoverable’ resources by the rate of usage
- The figure can change because of
  - Increased conservation
  - New discoveries
  - Better technologies leading to more efficient electricity production
  - Existing known reserves will become more profitable as the supply dwindles leading to more exploitation

So how much fossil fuel is left?

- Oil
  - 1,300 billion barrels of proven reserves still in the ground, worldwide
  - At current rates of consumption, 87 million barrels a day, oil will run out in roughly 41 years
- Coal
  - Worldwide, there is roughly 3,100 billion BOE of coal
  - Consumption is 71 million BOE of coal a day so we have 120 years' supply of coal left
- Gas
  - 6,400 trillion cubic feet of natural gas reserves around the world about the same as having 1,140 billion barrels of oil (BOE), in terms of its energy content
  - The world is consuming roughly 53 million barrels of oil equivalent (BOE) of natural gas every day. At that rate gas will run out in 59 years



So how much fossil fuel is left?

- Don’t panic!
  - Existing and new resources will expand to fill the gap
    - Nuclear power will expand
    - Existing fossil fuel technologies such as fracking to extract shale gas will come on stream
      - Shale gas already constitutes 20% of US gas reserves
      - But controversial
    - Also carbon capture technology may lengthen the lifespan of coal
    - Massive expansion of renewable energy sources are planned

- Think of it as an opportunity ☺

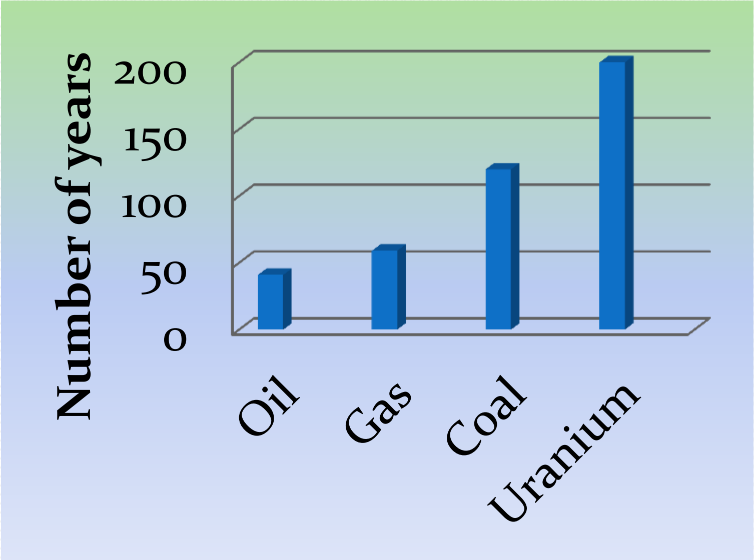
Uranium

- Uranium is the basis of nuclear power which currently produces about 17% of the world's electricity needs
- Uranium is one of the more common elements in the Earth's crust and it can be found almost everywhere in rock, soil, rivers, and oceans
- Uranium ore is processed near the mine to produce "yellow cake", a material rich in U_3O_8
  - 200 tons of this are needed per year for a 1GW nuclear power plant
- Only 0.7% of U in yellow cake is ^{235}U. Most of the rest is ^{238}U which does not work for fission power
  - There is a huge amount of processing to convert yellow cake to useable nuclear fuel
- Whilst some reactors run on unenriched uranium, in most cases it must be enriched so it contains about 5% ^{235}U

Uranium ore concentrate – "yellowcake"

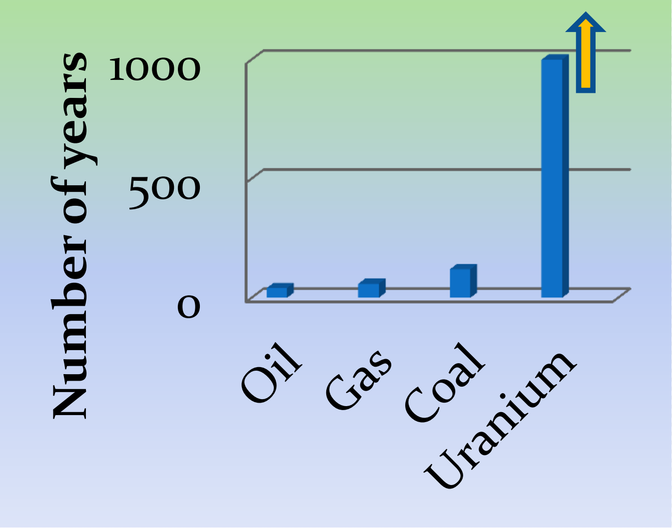
Uranium

- How long will our uranium reserves last?
- Most current nuclear reactors are light water reactors (LWRs) which use low enriched uranium (LEU)
- There are about 400 civil nuclear power plants currently operating in the world and each requires about 200 metric tons of uranium to operate per year
  - So present-day reactors require about 80,000 metric tons of natural uranium a year
- Identified uranium resources total 5.5 million metric tons, and an additional 10.5 million metric tons remain undiscovered—a roughly 200-year supply at today's consumption rate in total



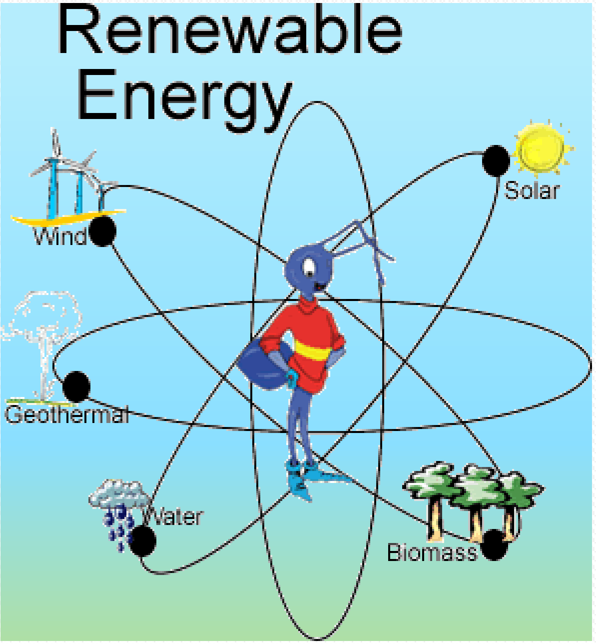
Uranium

- Likely to be an underestimate
  - Developments in technology could reduce the uranium needs of LWRs by as much as 30 percent per metric ton of LEU
  - Development of fuel-recycling fast-breeder reactors, which generate more fuel than they consume, would use less than 1 percent of the uranium needed for current LWRs. Breeder reactors could match today's nuclear output for 30,000 years
  - Extraction of uranium from seawater would make available 4.5 billion metric tons of uranium—a 60,000-year supply at present rates
  - Thorium?? Far more abundant than uranium
- Nuclear power is likely to be a significant contributor to our energy needs within a few decades



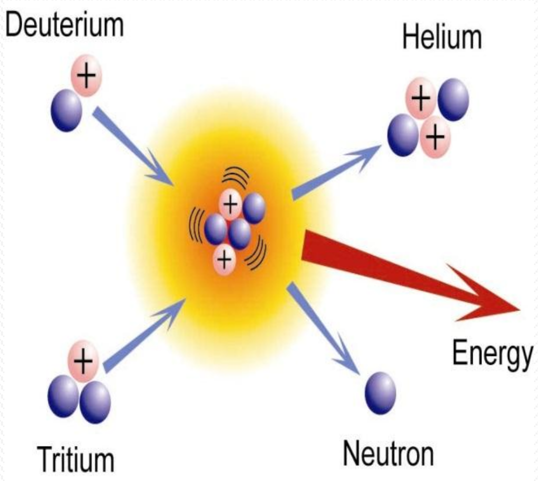
Renewable Energy Resources

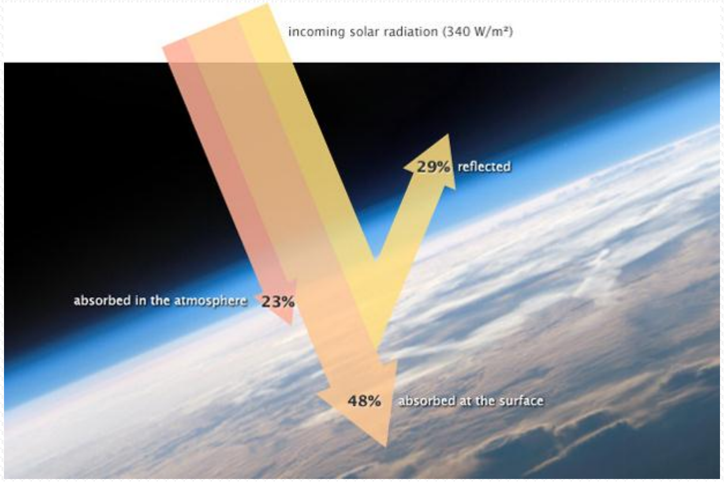
- We will briefly look at renewable energy resources although in theory these are infinite by definition
  - Limitations only come about because of lack of economic viability or technical restrictions
  - We will look in more detail about how energy is produced from these resources later
  - There's no doubt that these will play an increasing role in our energy supply over the next few decades



Solar Energy

- Solar power comes from thermonuclear reactions in the sun and is the 'ultimate' renewable energy source
- We have seen that around 48% of the sun's energy is absorbed at Earth's surface
  - Only this is useable
- The potential for exploitation of this resource is massive
  - The amount of solar energy that reaches the Earth's surface every hour is greater than humankind's total demand for energy in one year
- There are 2 main principles to exploit solar power
  - Direct heating
  - Photovoltaic cells

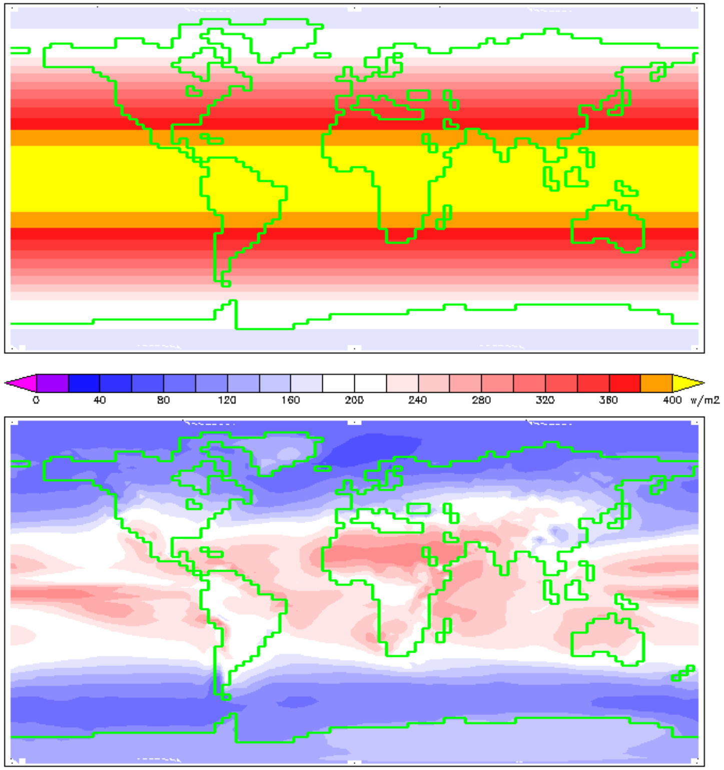




Solar Energy

- We measure the potential for a location to be suitable for solar energy generation by the amount of *insolation*
  - **Insolation** is the total amount of solar radiation energy received on a given surface area during a given time
  - It is also called **solar irradiation** and expressed as "hourly irradiation" if recorded during an hour or "daily irradiation" if recorded during a day
  - The unit is the megajoule per square metre (MJ/m²) or joule per square millimetre (J/mm²)
  - Practitioners in the business of solar energy may use the unit watt-hour per square metre (Wh/m²)
  - The average solar radiation arriving at the top of Earth's atmosphere is 1366W/m² but the amount arriving at the surface is a fraction of this

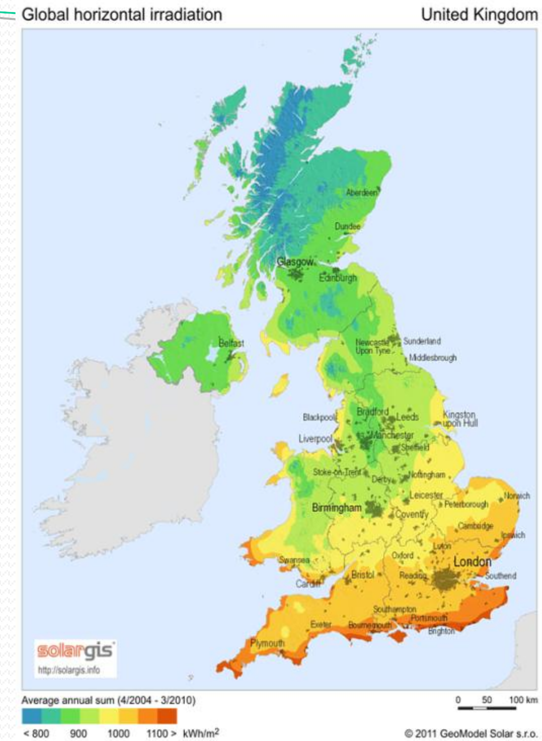
Top of atmosphere

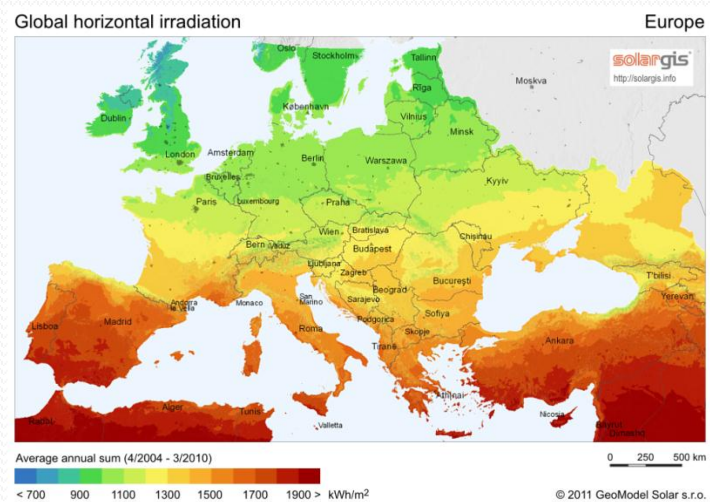


Surface

Solar Energy

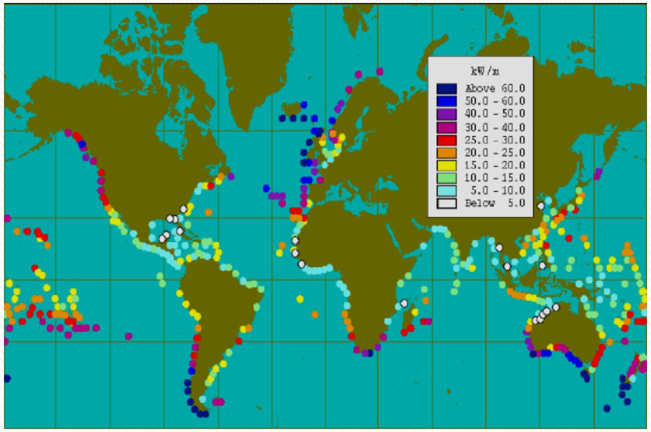
- The UK's insolation is around 2.9 kWh/m²/day — a fraction of that in southern Europe and North Africa
- Even so, 1,000 km² (10% of the area of Scotland), where the insolation is about 900 kWh/m²/year would provide 180,000 GWh/year, equal to all of Scotland's energy demand
  - Since most of that would be in the summer, when Scotland receives 12–14 hours of sun, the excess would need to be stored or exported





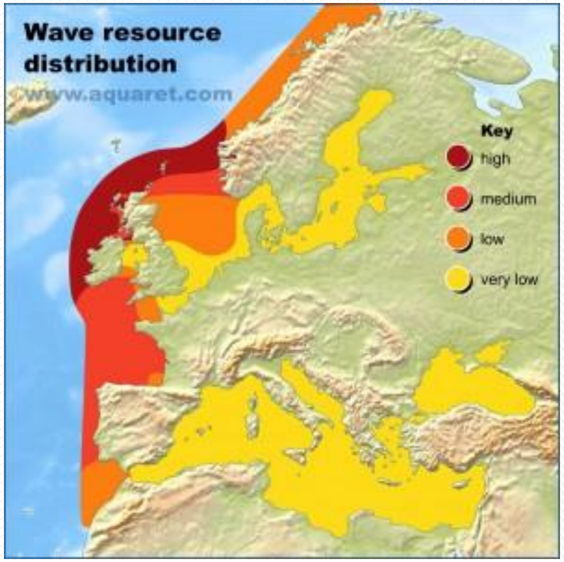
Wave Energy

- Among other types of renewable energy, oceans contain energy in the form of waves and tidal currents
- Differential warming of the earth causes pressure differences in the atmosphere, which generate winds
- As winds move across the surface of open bodies of water, they transfer some of their energy to the water and create waves
- The amount of energy transferred and the size of the resulting wave depend on
  - the wind speed
  - the length of time for which the wind blows
  - the distance over which the wind blows
- Therefore, coasts that have exposure to the prevailing wind direction and that face long expanses of open ocean have the greatest wave energy levels

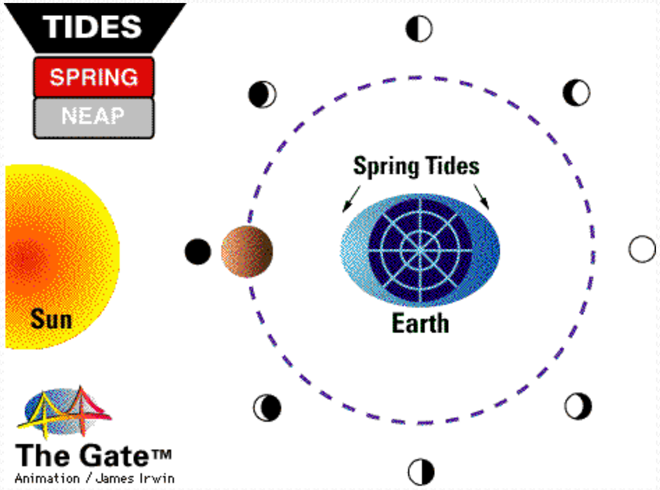


Wave Energy

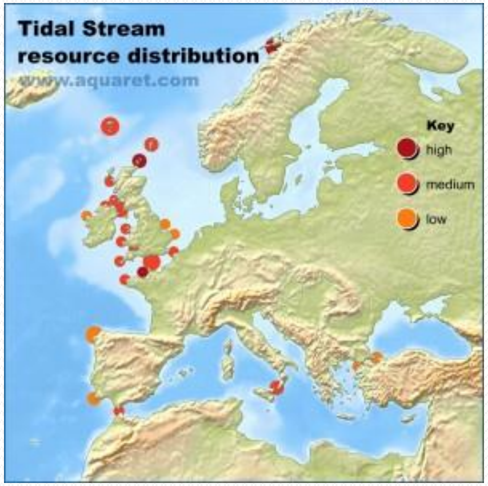
- The best wave resources occur in areas where strong winds have travelled over long distances
- The best wave resources in Europe occur along the western coasts which lie at the end of a long fetch (the Atlantic Ocean)
- Nearer the coastline, wave energy decreases due to friction with the seabed, therefore waves in deeper, well exposed waters offshore will have the greatest energy
- There are 2 basic principle that designs exploit
  - A change of water level by tide or wave can move or raise a float, producing linear motion from sinusoidal motion
  - Water current can turn a turbine to yield rotational mechanical energy to drive a pump or generator



Tidal Energy

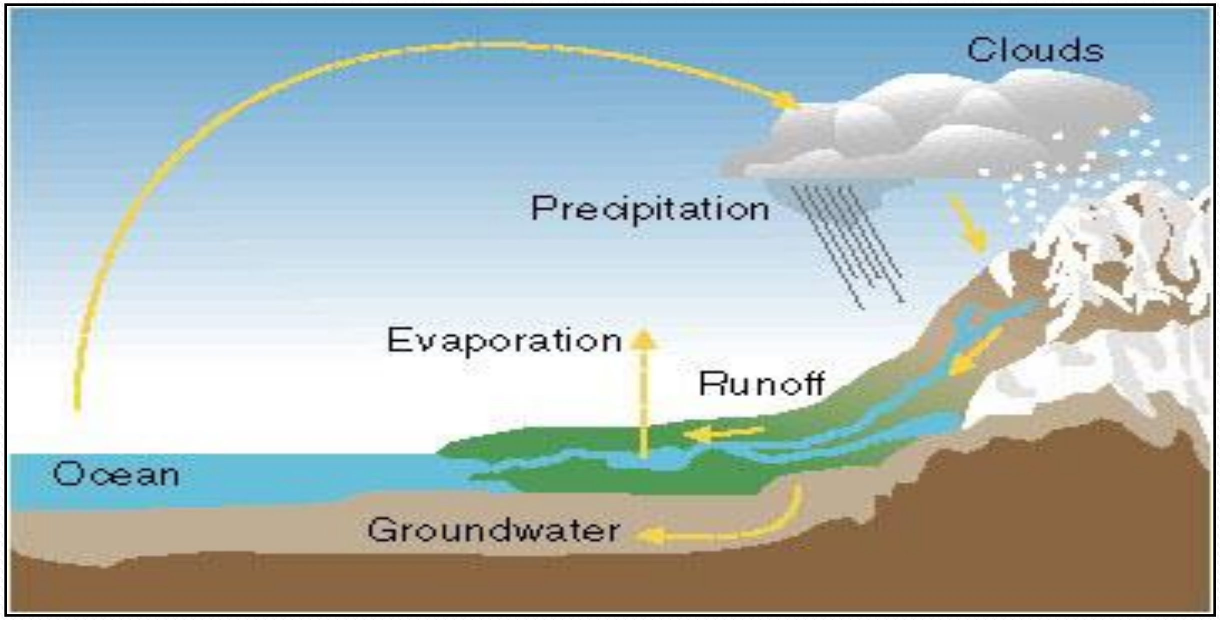


- Tidal streams are created by the constantly changing gravitational pull of the moon and sun on the world's oceans
- Tidal stream technologies capture the kinetic energy of the currents flowing in and out of the tidal areas
- Since the relative positions of the sun and moon can be predicted with complete accuracy, so can the resultant tide. It is this predictability that makes tidal energy such a valuable resource
- Tidal stream resources are generally largest in areas where a good tidal range exists, and where the speed of the currents are amplified by the funnelling effect of the local coastline and seabed, for example, in narrow straits and inlets, around headlands, and in channels between islands



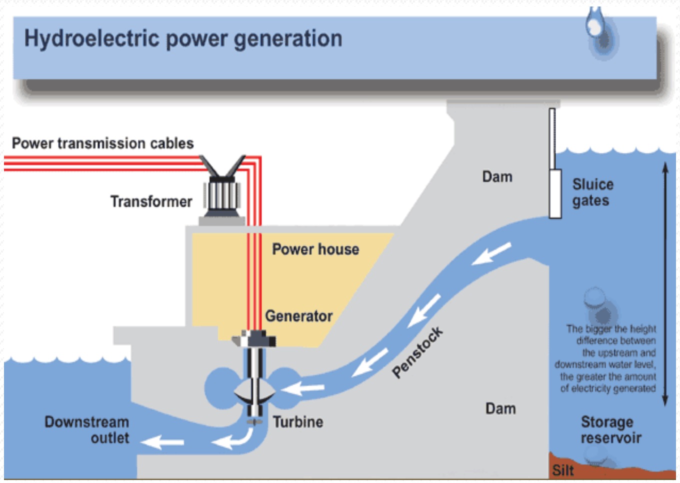
Hydro-Electric Energy

- Hydropower energy is ultimately derived from the sun, which drives the **water cycle**
  - Rivers are recharged in a continuous cycle. Because of the force of gravity, water flows from high points to low points
  - There is **kinetic energy** embodied in the flow of water



Hydro-Electric Energy

- Man-made dams create a large difference in height and hence in potential energy between the reservoir and the run-of area
  - The flow of water through sluice gates can be controlled by valves
  - This controls the power output
- Since hydroelectric dams do not burn fossil fuels, they do not directly produce carbon dioxide
  - While some carbon dioxide is produced during manufacture and construction of the project, this is a tiny fraction of the operating emissions of equivalent fossil-fuel electricity generation
  - Reservoirs created by hydroelectric schemes often provide facilities for water sports, and farming fish in the reservoirs is common



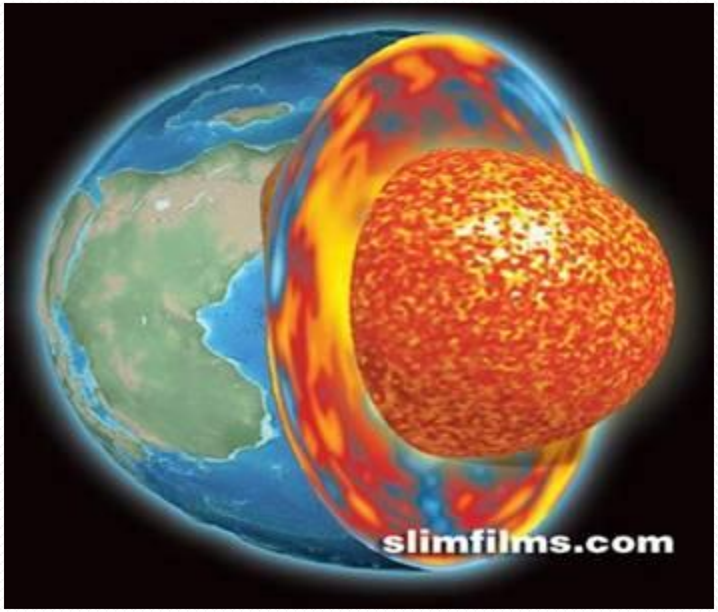
Hydro-Electric Energy

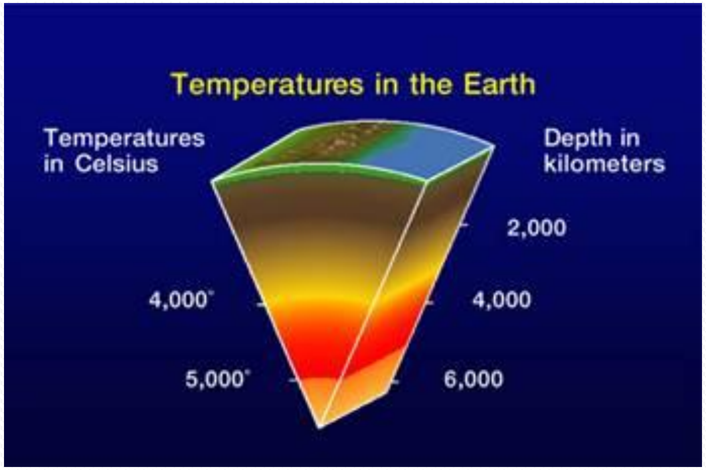
- In the UK hydropower has had some renewed interest because of UK and EU targets for reductions in Carbon emissions
- Typical sites for hydropower projects tend to be in remote areas including areas of outstanding beauty so possibilities for development are limited
  - So called 'run of the river' schemes use the flow of the river to drive turbines and require little storage
  - Less impact to the environment as no dams are required

The Dinorwig power station in North Wales is a 1,800 MW pumped-storage hydroelectric scheme, in north Wales, and the largest hydroelectric power station in the UK

Geothermal Energy

- Geothermal energy is a renewable source
- It is energy ‘stored’ in Earth usually at great depth
- 70% comes from the decay of radioactive nuclei with long half lives that are embedded within the Earth
- Some energy is from residual heat left over from Earths formation
- The rest of the energy comes from meteorite impacts



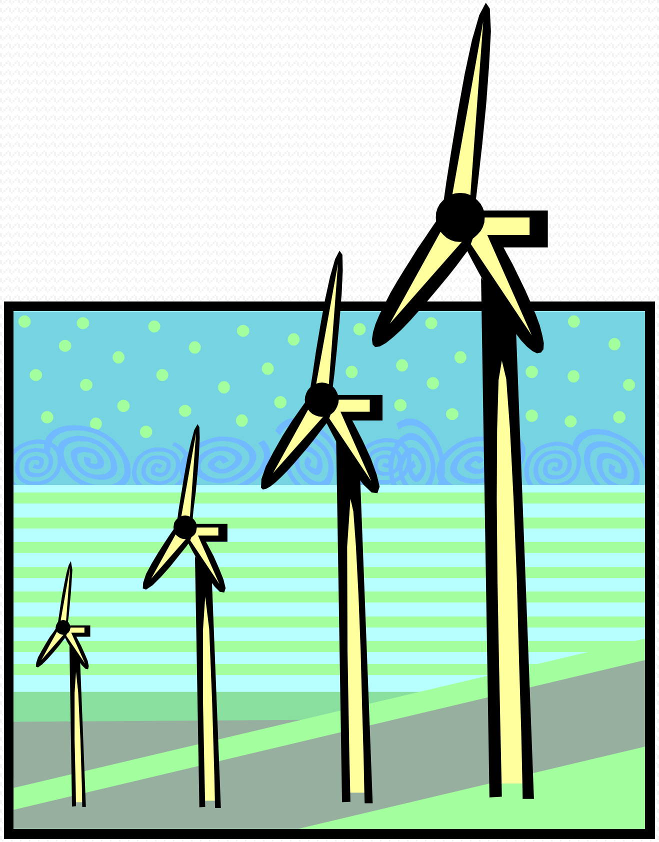


Geothermal Energy

- On average, the Earth emits 1/16 W/m^2. However, this number can be much higher in areas such as regions near volcanoes, hot springs and fumaroles
- As a rough rule, 1 km^3 of hot rock cooled by 100°C will yield 30 MW of electricity over thirty years
- It is estimated that the world could produce 600,000 EJ over 5 million years
- There is believed to be enough heat radiating from the center of the Earth to fulfill human energy demands for the remainder of the biosphere's lifetime
- Geothermal production of energy is 3rd highest among renewable energies. It is behind hydro and biomass, but before solar and wind
  - For example Iceland is one of the more countries successful in using geothermal energy where 86% of their space heating and 16% of their electricity generation uses geothermal energy

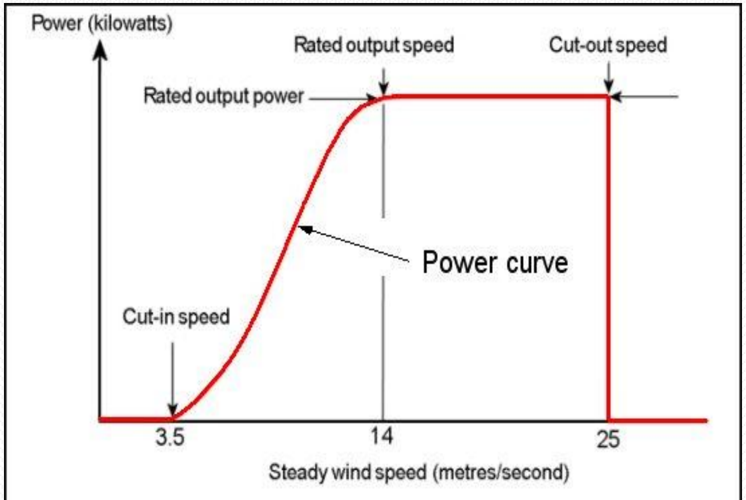
Wind Energy

- Wind energy is essentially a limitless and inexhaustible resource
- Differential heating of the earth's surface and atmosphere induces vertical and horizontal air currents that are effected by Earth's rotation and contours of the land -> WIND
- There is enough power in the wind blowing at any one time on Earth to provide all of our energy needs
  - The practical problems are of building enough wind turbines and finding the area to put them to harness it



Wind Energy

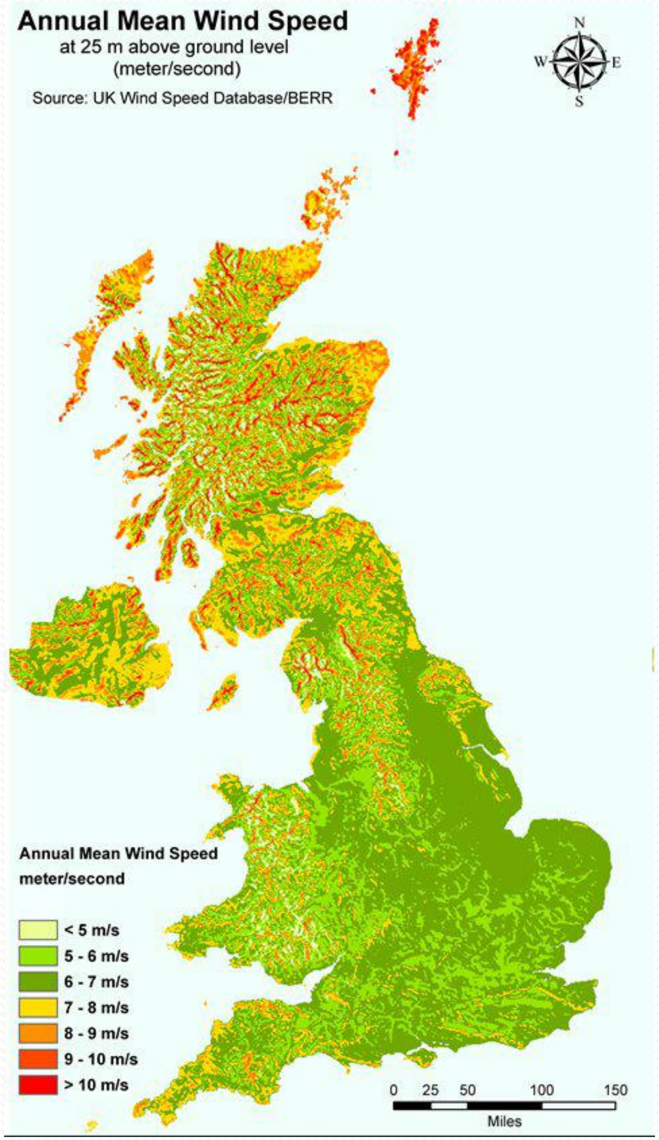
- Measuring wind speeds is crucial for planning the development of wind farms
- Average wind speeds over a 10-15 minute deadline taken over several years are typically used
- Heights of 10, 25 and 45m are used
  - Typical heights of wind turbines
- Typically wind speeds of around 10m/s are optimum
  - As we shall see, the energy generated varies with the cube of the wind speed
- Wind speeds greater that 25m/s cause a shut off of the turbine



Typical wind turbine power output with steady wind speed.

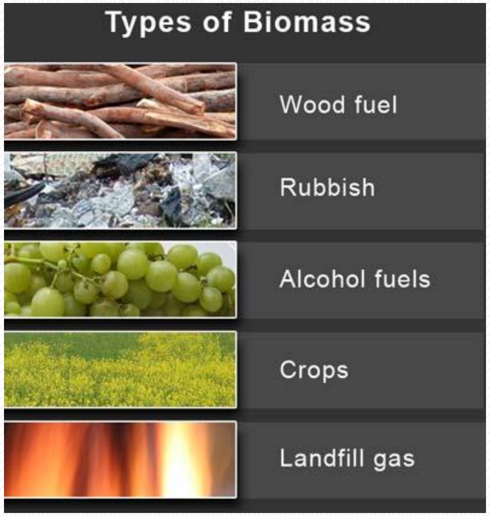
Wind Energy

- The UK is one of the best locations for wind power in the world, and is considered to be the best in Europe
  - Wind power produced about 9% of our electricity in 2013
- In fact we are ranked as the world's sixth largest producer of wind power, having overtaken France and Italy in 2012
- A growing proportion of our wind energy is off shore



Biomass

- Biomass is a renewable energy source that is derived from living or recently living organisms
- Biomass includes biological material, not organic material like coal.
- Energy derived from biomass is mostly used to generate electricity or to produce heat
- Biomass can be sourced locally, from within the UK, on an indefinite basis, contributing to security of supply and has a much lower carbon footprint than fossil fuels
- The waste matter will rot anyway if we don't use it producing methane which is a potent greenhouse gas
  - Drax power station now burns a large range of biomass, mostly imported from the USA and Canada



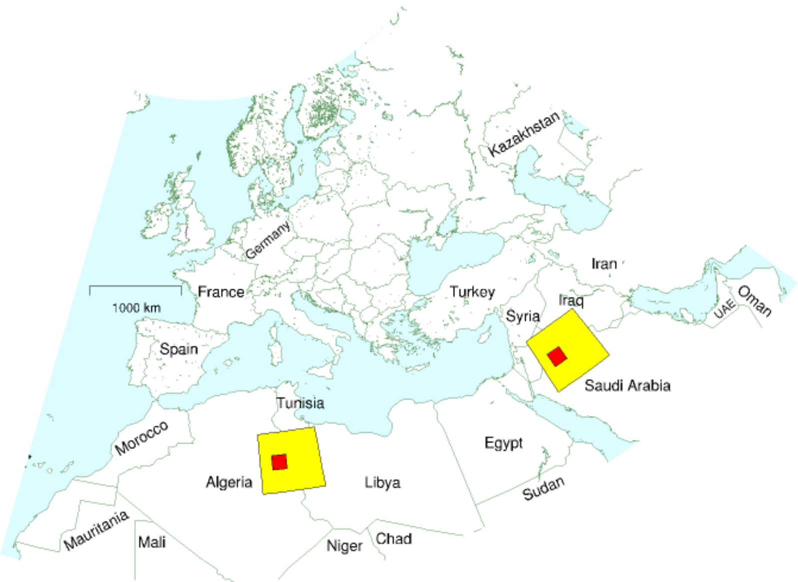
A Comparison of Renewables

- There are a number of ways to compare renewables such as cost/kWh, human disruption and so on
- Renewables are *diverse* energy sources
  - They take up space, unlike a fossil or nuclear fueled power station which can produce 1GW in less than $1 km^2$
  - We can compare the power per unit area of various renewables
  - We can work out how much area it would take to run UK electricity (about 40GW)
  - For example it would take $40 \times 10^9 / 3\ m^2$ of offshore wind
    - About an area of 100km x 100km which is half the size of Wales!

POWER PER UNIT LAND OR WATER AREA	
Wind	$2\ W/m^2$
Offshore wind	$3\ W/m^2$
Tidal pools	$3\ W/m^2$
Tidal stream	$6\ W/m^2$
Solar PV panels	$5–20\ W/m^2$
Plants	$0.5\ W/m^2$
Rain-water (highlands)	$0.24\ W/m^2$
Hydroelectric facility	$11\ W/m^2$
Solar chimney	$0.1\ W/m^2$
Concentrating solar	$15\ W/m^2$

A Comparison of Renewables

- However, *concentrated solar power* is a realistic possibility of supplying the UK (and the World's) energy needs
- In deserts solar power can deliver typically 15W/m^2 of power
- So, chose your local desert
- All the worlds *power* consumption (15000GW) could be delivered by an 1000km x 1000km of the Sahara desert
    - Or taking the Sahara as the local desert for Europe, 600km x 600km (yellow square)
    - Or the UK's would be 145km x 145km (red square)
- Easily transported using HVDC cables
- Check out the DESERTEC video



Summary

- We have looked in detail at the sun's incident radiation and Earth's energy budget
- Also we have looked at both non-renewable and renewable energy sources briefly
  - In the next lecture we will look in a bit more detail about the generating power from these sources
    - Including how much power is produced