GEC1010
AY22/23 Sem 2
github.com/securespider

01. Energy

By constant force

work done by a force == force * displacement
$W = FS$

Law of conservation of energy

Energy can neither be created nor destroyed, it can only be transformed from one form to another

Kinetic energy

linear motion - $K = \frac{1}{2}mv^2$

angular motion - $\frac{1}{2}I\omega^2$

- I = Moment of inertia of object (dependent on mass distribution of object)
- ω = angular velocity of the rotating object
  - Rad/second
  - $v = \omega * radius$

Gravitational potential energy

$U = mgh$

Power

Rate of doing work or rate of consumption of energy
$P = \frac{\triangle W}{\triangle t}$
Work done, W, by a system in time t

Requirements of an energy system

Energy resource

- Clean energy
  - Wind Energy
  - **Hydro energy** - Come from river and dams
  - Ocean energyOnly refers to energy coming from ocean currents etc
  - Solar energy
  - Biomass
  - Non-Renewables:
  - Geothermal
  - Nuclear
- Fossil fuels
  - Coal
    * Greater carbon content and more impurities - More carbon dioxide and greater air pollution
    * Solid so difficulty in extraction, transportation and use
  - Natural Gas
    * Cleaner alternative
  - Oil

Problems
- Unsustainable - reserves depleting
- Global warming - Enhanced greenhouse effect by earth atmosphere
- Greater absorption of long wavelength IR in earth's atmosphere
- Rising temperature anomaly from 1965-now by about 100mm
- Global sea level rising
  - Thermal expansion of water
  - Melting alpine glaciers and ice sheets
- Earlier timing of spring events
- Poleward and upward shift in plant and animal species

Solution:
Clean energy
- Replace existing supply of fossil fuels
- Use energy more efficiently and judiciously minimizing environmental pollution

High power

High energy conversion efficiency

Singapore

Singapore uses LNG primarily (95%) piped from indonesia and malaysia
Switching to **solar** and biofuels to reduce reliance

Energy conservation

- Outdoor LED initative
- Electric car sharing

02. Fundamentals of thermal energy

$Q = mc\triangle T$

Q Heat energy supplied
m mass
c Specific heat capacity of material
T temperature change resulting from heat energy

$Q = mL$

Q Heat energy supplied
m mass
L Specific latent heat of vaporization/fusion

Types

- Conduction
  - Dominant in solids
  - No bulk motion of matter
  - Heat flows from region of high temperature to region of low temperature
- Convection
  - Dominant in fluids (liquid and gases)
  - Works by circulating fluids and thermal expansion properties of materials
  - Cold fluids sink, warm fluid rise
- Radiation
  - Uneven, black bodies absorb/emit better

Stefan Boltzmann Law

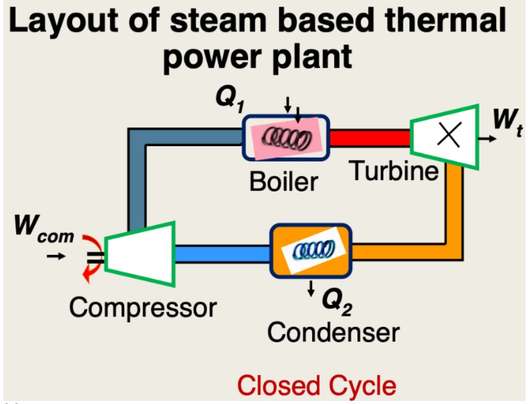
Power of black body radiation
$P = \epsilon\sigma T_0^4$

P Energy absorbed per unit second per unit area via radiation
ϵ Emissivity of surface(lies between 0-1)
σ $5.67 * 10^{-8}$ = Stefan Boltzmann constant

First law of thermodynamics

Difference between the heat absorbed Q and the work done W on object is equal to change in internal energy of the thermodynamic system
$Q - W = \triangle U$

Steam based thermal power plant



Key stages

Compression Work done on system to compress cold water to high pressure

Boiling Heat added to the system to convert cold water into steam

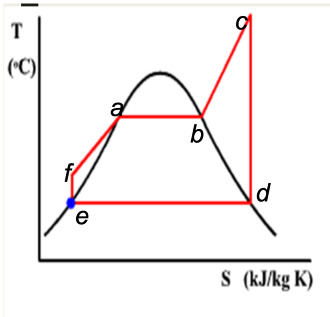
Turbine rotation Work W_t done by the system on turbine blades

Condensation Heat lost from the system to the environment in converting steam back to cold water

- Working fluid have the same amount of energy U as it had in the beginning of the cycle
- Net heat absorbed = $Q_2 - Q_2$

Efficiency of cycle is given by
$\eta = \frac{Net\ output\ work}{heat\ input} = \frac{W_t - W_{com}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$

Rankine cycle



Steam power plant energy generation (Temperature - entropy graph)

- EF - Compressor increases the pressure of water
- FA - Economiser, Water heated at high pressure until it boils
- AB - Evaporator, 2 phase mixture of water and steam is heated at constant pressure until all water converted to dry steam
- BC - Superheater, Dry steam heated at constant pressure in superheater
- CD - Dry steam enter turbine at high pressure and rotate the turbine
- DE - Steam converted to water
  - Problem: Unable to completely eliminate the formation of water droplets @ CD
  - Solution: Reheat the steam at CD to rotate the turbine again
  - Temperature is raised again, leading to greater efficiency
  - Achieve 40% efficiency
  - Cannot go beyond 650c to prevent metal fatigue

Brayton cycle

Use gas instead of water leading to no worry of water droplets and can go higher temperatures

03. Wind energy

How wind forms

Dominant

- **Coriolis Effect** - Sideward component of wind due to earth rotation
- **Solar radiation** - Warm air rise up in the equator leading to difference in densities

Other factors

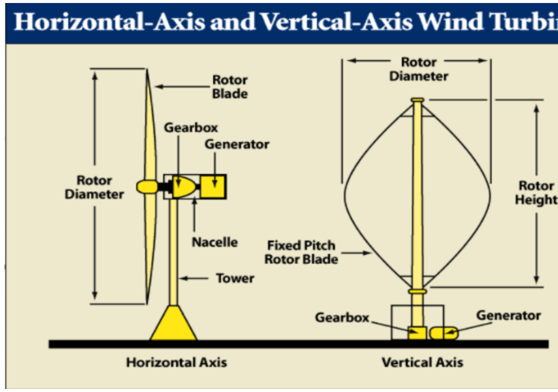
- Ocean
  - Water absorbs/releases heat slower than land
  - Day: Water less hot, sea - land
  - Night: Water hotter, land - sea
- Surface friction
- Eddy motion
- Seasonal effects

Power of wind

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

Wind speed affected by height of the turbines
- Wind speed rises proportionally to 7th root of altitude

Wind turbines



- **Yaw control** - Orientates the nacelle in direction of incident wind
  - Note: Better for rotor to face the wind
  - Less wind shadowing effect
  - Blades flex less
  - Less fatigue in the blades

Forces

Drag Net force in direction of wind

Lift Net force perpendicular to wind

Blades

Turbines cause turbulence for surrounding blades so cannot have too many blades

Tip Speed Ratio (TSR) - $\frac{Speed\ of\ rotation\ of\ outer\ tip\ of\ blade}{incident\ wind\ speed}$

Betz limit - Maximum theoretical efficiency of rotor

Capacity factor - $\frac{yield}{rated\ power}$

Dependent on wind speed

Offshore vs Onshore

+ Wind speed is faster offshore
+ Less obtrusive
+ Bigger in size
+ CF higher

- Harder to maintain cus in the sea (But easier to build because transportation over water easier)
- Might spoil faster due to seawater

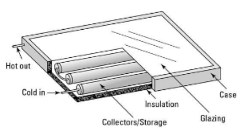
04a. Solar Power

Renewable form of energy with $3.9x10^{26}W$
Only half reach surface of earth

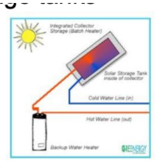
Types of systems

- **Passive** - Uses no external power
  - Allows fluid heated by the sun to circulate by natural means
  - Conduction of heat from fluid in tubes to storage cylinder
- **Active** - Solar heated fluid is circulated by a fan or pump
  - Evacuated Tube Collector based heating system (active)

Solar fluid collectors



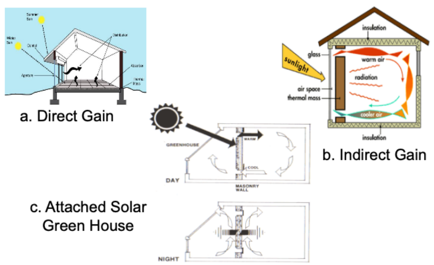
•Flat Plate Collectors



•Batch Collectors

•Evacuated Tube Solar Collectors

Passive space heating system

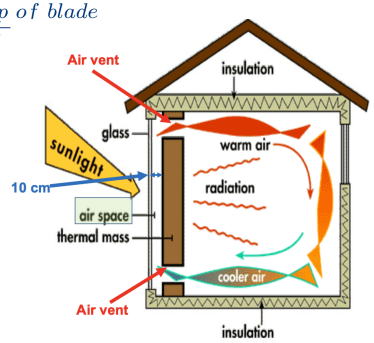


a. Direct Gain

b. Indirect Gain

c. Attached Solar Green House

Trombe wall



Principles of passive cooling

- Minimise solar heat gain
  - Increase building mass
  - Increase thermal protection
  - REflective coating on exposed surface
  - shading device
  - Air tightness in building
- Remove unwanted heat
  - Evaporative cooling
  - Nocturnal ventilation
  - Thermo-active ceiling

Solar power energy

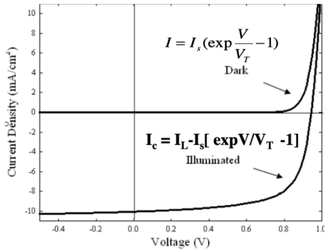
Using the heat by the sun to drive rankine cycle

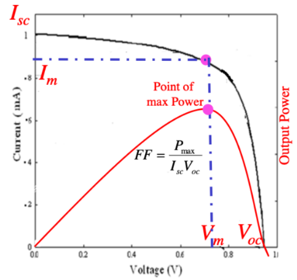
- using mirrors to focus sun light into a tower to heat molten salt
- Run focus pipes surrounded my mirrors to heat the fluid in the pipes to be used to generate heat

04b. Solar Photovoltaics

$E = hf = \frac{hc}{\lambda} | \ h = 6.63 * 10^{-34}, c = 3 * 10^8$

Solar Cell Current-Voltage (IV) Characteristics





Band gap

Minimum energy that is required to excite an electron up to a state in the conduction band where it can participate in conduction
Higher short circuit current - lower bandgap
When intensity of light increase,

- Voltage for max power increases
- Output current increase
- Open circuit voltage increases

Silicon

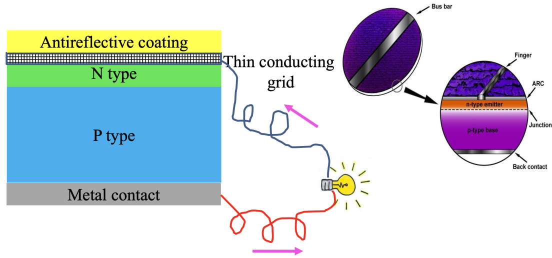
Types

- Polycrystalline
- Crystalline
- Amorphous

Mechanism

Transfer of electrons from n-types and p-types to maintain electric potential

- **N-type** - Electron rich (conduct via electrons)
  - Doped with elements with more valence electrons (P)
  - Cathode (negative terminal where current flows into when illuminated)
- **P-type** - Electron deficient (conduct via holes)
  - Doped with elements with less valence electrons (Al)
  - Anode (postive terminal where current flows out of when illuminated)
- Pink arrow denotes conventional current (current flows from p- to n- side thr outer circuit when load is high)



Efficiency

- 23% of photons has less energy than bandgap
- 30% heat energy and 10% loss from electron hole-pair recombination
- Increase efficiency by using anti-reflective coating
- Smaller bandgap - greater photocurrent but decrease output voltage (optimum 1.4eV gap)

05a. Hydro power

Ocean vs River

River

1. Hydroelectricity

Ocean

1. Tidal power
2. Wave power
3. Ocean thermal

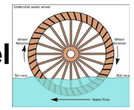
Water wheels

Water mills

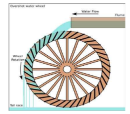
- Ancient application for replacing physical labour
- Replaced with water turbines for energy generation

Types of water wheels

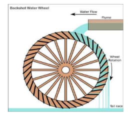
Undershot Water Wheel



Overshot Water Wheel



Backshot Water Wheel



- Undershot
  - Vertically mounted with water flowing at the bottom of the wheel
  - Cheapest and least efficient
- Overshot
  - Falling water on the top of the wheel in direction of rotation
  - Use all water flow for power production
  - Does not require rapid flow of water
  - Uses the difference in weight between the 2 sides of the wheel to turn
- Backshot

- Introduced behind the apex of the wheel
- Water flows opposite the direction of rotation
- Continues to function even when water in wheel put rises beyond height of axle
- Technique useful for streams that experience extreme seasonal variations in flow

Types of Hydro Power

- Dam based
- Run of the river plants(diversion)
- Pumped storage technology
- Damless hydro power

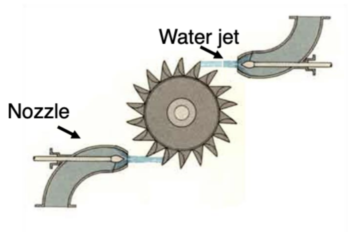
Principles of power generation

Production of electricity by using gravitational force of falling water
$P = \eta\rho g h Q$
η = efficiency, ρ = density of water, Q = Volume of water flowing per second on turbine, h = Vertical distance between turbine and water surface

Types of water turbines

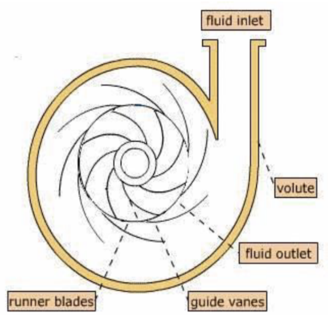
Impulse

- Simpler and cheaper design - Easier to fabricate and maintain
- Needs higher head height
- Higher volume flow rate
- Greater tolerance of sand and other particles in water
- Better access to working parts



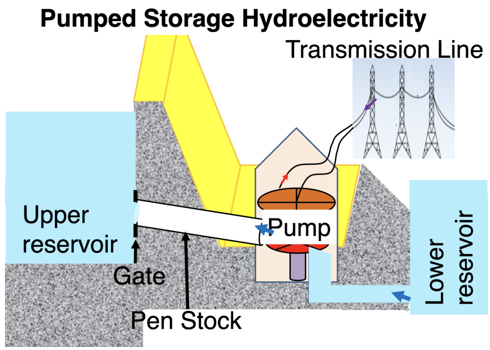
Reaction

- Rotating element in reaction turbine enclosed in pressure casing to generate energy
- Rotates faster than impulse turbines given same head and flow conditions
- More expensive



Run of the river

- Low-level diversion weir/stream bed instead of dam
- Located on fast flowing, non seasonal stream
- Minimize impact on environment



Pumped storage hydro

- Load balancing by storing energy pumped from lower elevation reservoir up
- Low cost off peak power to run pumps and released when high demand
- Net consumer of energy but largest capacity form of grid energy storage

Damless hydro

- Little to no maintenance
- Low initial setup cost and environmental impact
  - No risk of flash flooding/dam-related accidents
  - No silt accumulation and fish ladders

Advantage of hydroelectric

- Clean renewable energy (Low level of greenhouse gases)
- Low operating cost and highly automated
- Plant life is long $\approx$ 40 years
- Available on demand as flow rate is controlled

Problems with hydroelectric

- Capital cost is high and payback time is long
- Social issues with displacement of population
- Environmental impact (Diversion of water)

05b. Ocean Power

1. Tidal energy
   - Gravitational field of sun and moon
2. Ocean wave energy
3. Ocean thermal energy

Tidal energy

- Derived from gravitational interaction between Earth and Moon
- Bulge on opposite side due to earth's attraction
- Low and high tide occuring simultaneously at 2 places with longitudes differing by 90
- Along same latitude, there are 2 high tides and 2 low tides simultaneously
- Interval between high tides approximately 12h
- **tidal range** - Difference between height of high and low tides
- **Spring tides** - Moon and sun align leading to unusually high tides
- **Neap tides** - Moon perpendicular to sun wrt earth leading to weak tides

Tidal barrage

- Dam built across river estuary
- High tides: Seawater flows into reservoir of barrage and rotate the turbine blades
- Low tides: Seawater stored in barrage is allowed to flow back out into sea turning turbines
- Output power $P = \dfrac{\eta\rho g A h^2}{T}$
  - T is tidal period (time interval between 2 successive high tides)

Advantages

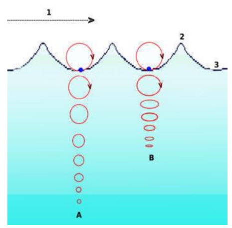
- Free, reliable and green (low maintenance)
- Turbines are cheap and do not cause large environmental impact

Disadvantages

- Only provides power for about 10 hours each day (when tides moving)
- Tidal barrage sites are limited
- Fish ladders have to be installed and total cost is expensive

Ocean current and waves

- Horizontal movement of seawater in the ocean
- Factors affecting:
  - Intensity of solar radiation
    - Fast moving air from sea surface to land
    - Water dragged along the wind
  - Air temperature
  - Wind speed and direction
  - Gravitational pull of sun and moon
- Moving up and down in circles



Motion of a particle in an ocean wave.
A - At deep water. The orbital motion of fluid particles decreases rapidly with increasing depth below the surface.
B - At shallow water (ocean floor is now at B). The elliptical movement of a fluid particle flattens with increasing depth.
1 - Direction of propagation of wave.
2 - Wave crest.
3 - Wave trough.

Types of devices

- Oscillating water column devices
  - Traps air which increases and decreases in volume as the sea surface moves up and down
- Buoyant moored device
  - Floating on surface of water and rotate to generate electricity
  - Requires depth of 80m with almost constant tension to mooring cables
- Archimedes Wave Swing
  - Hydraulic system that compresses air within cylinder when pressure on top of cylinder increases (crest approaching) and vice versa
  - Only one moving part so more reliable with less maintenance
- Pelamis (Hinged countour device)
  - Semi submerged construction generating power from motion at joints
  - Rocking back and forth with waves activates hydraulic pumps driving electricity generators

Impacts

- Large global potential
- Destroys scenic beauty and generates noise pollution
- Have to withstand extreme weather conditions at sea

Ocean Thermal Energy Conversion (OTEC)

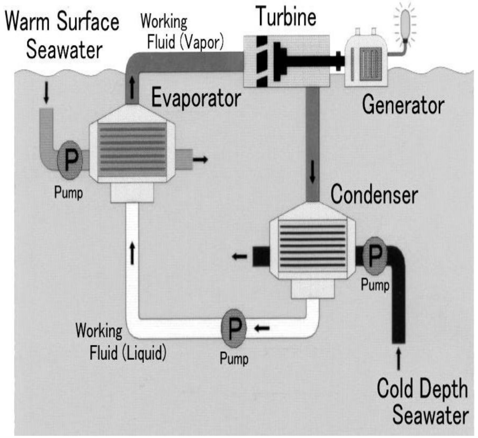
- Using heat energy stored in oceans to generate electricity (best $\approx$ 20c at 1000m)
- Difference in high[shallow] and low[deep] temp to rotate turbine
- Uses rankine cycle (closed/open/hybrid cycles) in low-pressure turbine and ammonia
- Set up industries alongside OTEC power plant to increase efficiency

Benefits

- Provides air conditioning for buildings and refrigeration
- Rich in mineral - used for aquaculture
- Production of fuels concurrently (hydrogen, ammonia and methanol)

Concerns

- Marine organism entrainment and impingement from water current
- Chemicals used to reduce/control biofouling buildup
- **Upwelling** - Rise of deep cold water to surface



06. Biofuels

- Plant and animal derived materials that are renewable and carbon neutral
- Efficiency of photosynthesis 0̃.5%
- Items: Corn, soy, sorghum, sugar cane, waste, sawdust
- Low energy content per kilogram and low density - bulky and expensive

Methods of conversion

Thermochemical

1. Direct conversion
   - Burning solid biomass and production of thermal energy
2. Gasification
   (a) Decompose starting material without oxygen to produce hydrocarbon gases and tar by-product
   (b) Heat char again with oxygen to synthesize more gases
   - Advantage: Gaseous fuels mix better than liquid and burns more efficiently and cleanly
   - Most economically competitive use of biomass
3. Pyrolysis
   - Liquefied by heating in the absence of air

Biochemical

1. Anaerobic digestion
   - Decomposition of organic matter in the absence of air by bacteria
   - Occurs naturally at 30-60c producing methane for heating, cooking and powering generators
   - **biogas** - Methane and C02
2. Fermentation
   - Using yeast or bacteria to convert to ethanol and CO2
   - Produce Bioethanol from Starch (corn)

Extraction

- **trans esterification** - Reaction with oil using sodium/potassium hydroxide as catalyst to form ethyl/methyl esters (biodiesel)

Impact

- Energy security since biomass is more evenly distributed over earth's surface
- Rural economic growth
- Good and easy storage options

07. Geothermal

- Energy extracted from heat stored in the earth
- Formation of the planet, **radioactive decay** of mineral, volcanic activity and from solar energy absorbed by surface
- Flowing from the hot core by conduction and convection
- Dissipates to atmosphere and space
- Strongest along tectonic plate boundaries

Methods

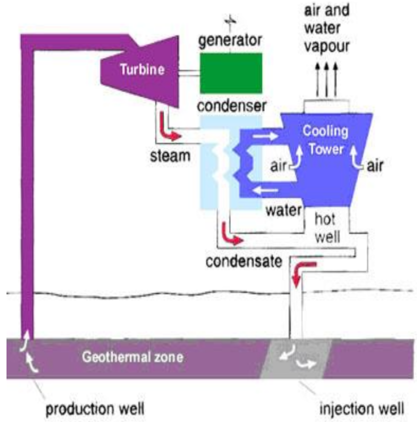
1. Borehole heat exchangers
   - Heat extraction from ambient rock formation
2. Hydrothermal systems
   - Heat extraction from thermal groundwater
3. Hot-dry rock
   - Water circulation through stimulated fractured rock

Sources

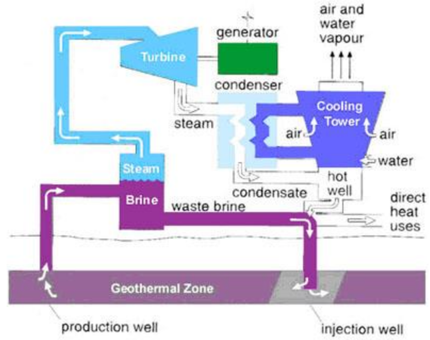
- Hot springs
  - Gushes of hot water found on land surface
  - Water vapor emission from cooling molten which rises through rocks to condense at surface
- Fumaroles
  - Vents from which volcanic gas escapes into the atmosphere
  - Persistent for decades and centuries
  - Dangerous gas at around 70-100c
- Geysers
  - Hot spring erupting periodically ejecting a column of hot water and steam

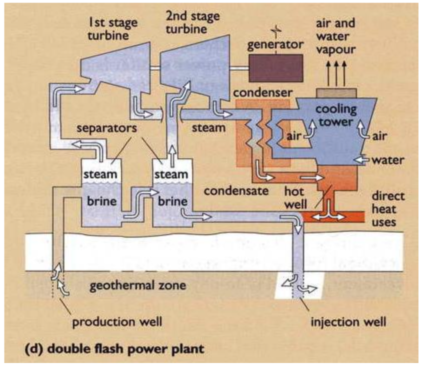
Extraction

1. Dry steam system
   - 180-225c, 4-8 MPa at 200km/h
   - Drive steam generator at 1 kWh/6.5kg of steam
   - Suitable where geothermal steam is not mixed with water
   - Wells drilled to aquifer and superheated pressurised steam brought to surface at high speeds
   - Efficiency: 30%, simplest and most economical technology



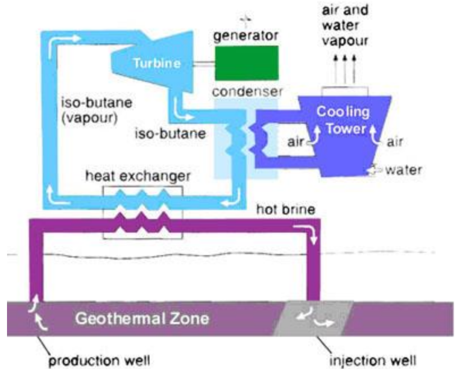
2. Flash system
   - Steam with water extracted and water flashes to steam when pressure drops suddenly
   - Steam separated from water and used to drive a turbine
   - Generates 5-100MW using 6-9 tonnes of steam per hour
   - Single or double[More efficient but higher cost] flashed systems





(d) double flash power plant

3. Binary cycle system
   - Used for geothermal resource with low temperatures with liquids with low boiling points
   - Liquids boiled to drive turbine which condenses and recycles continuously
   - 7-12% efficient
   - More expensive but can have higher efficiencies than flash plants



4. Geothermal heat pumps
   - Storing and retrieving heat from earth using anti-freeze/water solution circulated in plastic pipe loops 200m into ground

Application

- Electric Generation
- Geothermal Direct Space Heating
- Geothermal Direct Space Cooling

Concerns

- Environmental impacts (tremors, **subsidence** - sinking of ground)
- Non-steady state source
- High initial capital cost but minimal operating cost

08. Nuclear

Nucleons Protons and neutrons in nucleus of atom

Mass defect Mass difference between sum of masses of nucleons and mass of nucleus

Nuclear force Short range and attractive force pulling nucleons together(unless separation very close)

Binding energy Energy needed to break nucleus into constituent nucleons

Mass energy relationship $E = \triangle M c^2$

- E = Binding energy, $\triangle M$ = mass defect, c = speed of light in vacuum

Nuclear Fission

- Bombardment of large atoms by slow moving neutrons resulting in splitting of nucleus into smaller nuclei, neutrons and energy

Chain reaction

- Neutrons released by fission of one atom causing fission of other nuclei
- Dependent on the probability of neutron-induced fission compared to neutron loss
- Behaviour of neturons after reaction: (dependent on energy of incident neutrons)
  1. Scattering
  2. Capture and induced fission

- Neutron loss arises from neutron capture and gamma ray emissions
- Neutrons have to have low energy to ensure chain reaction (need smaller nucleus U-235 instead of 238)
  - Enrichment is done to increase concentration of U^{235}
  - **Moderators** - Nuclei with low atomic number , are added to reduce energy of neutrons on emission
  - **Thermal Neutrons** - Neutrons with low enough energy to cause chain reaction

Fuels

- U^{235} used for fission as it readily undergoes fission after absorbing neutron
- U^{238} cannot sustain chain reaction so enrichment by separating my mass (centrifuge)
- **Breeder reactor** - Produce Pu^{239}_{94} by combining with U^{238}_{92}, neutron and 2 β^-

Thermal Nuclear Reactor

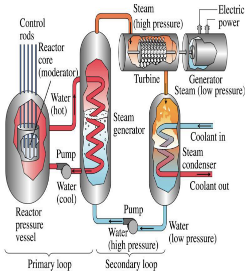
Fuel Rods

Chemically Inert Fluid

Moderator

Control Rods

Heat Exchangers



Mechanism

- Rods contains fuels which are immersed in chemically inert fluids for heating
  - Easy refuelling
- Control rods located above core to control reaction
- Hot fluid pumped through loop and release heat to heat exchanger
- Moderator induces chain reaction

Loops

Primary loop

- Energy from mission heat water directly in steam generator through heat exchanger
- Pressure is high, 15 MPa, 315c
- Fluid is radioactive from neutrons in reactor core

Secondary loop

- Water at relatively low pressure at 5MPa
- Steam is formed from heating of water in primary loop

Maintenance

- High neutron flux causes embrittlement of reactor vessel
- Metal becomes less ductile
- Corrosion in steam generating tubes

Control

- Neutron decreasing as fuel is burnt - Control rods have to be inserted or removed to maintain reaction
- Adding chemical containing nucleus with high neutron absorption property to alter absorption of coolant (eg. boric acid/burnable poisons)

Effects

- Long lived actinides by-product arising from successive neuton capture reaction on uranium
- Waste products separated for storage (millenia)
- **Radiation** - Ionisation that beaks molecules apart to give free radicals
  - Damage cells
  - Could come from charged particles such as α-particles, γ-rays or electrons

09. Energy storage

Fuel Cells

- Electrochemical device that converts fuel into electric current
- Electricity generated from chemical reaction between fuel and oxidant
- Reactant flow into cell and reaction products flow out of the cell while electrolyte remains within it
- Consist of 3 parts: anode, electrolyte and cathode

Anode Contains catalyst made up of fine platinum powder that accelerates dissociation of fuels into electrons and ions

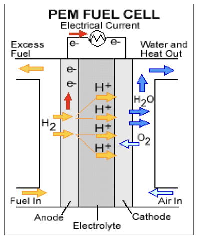
Fed on H2

Cathode Nickel catalyst that converts ions into waste chemicals like water or carbon dioxide

Fed on Oxygen/air

Polymer/Proton Electrolyte Membrane Fuel Cell

- Use solid polymer as electrolyte and porous carbon electrodes containing a platinum catalyst
- Operate at 80c with high-power density at low weight and volume
- Used for transportation applications due to fast startup time, low sensitivity to orientation and favourable power-to-weight ratio
- Difficulty in hydrogen storage
  - Hydrogen has low energy density so difficult to store enough hydrogen for long distance travel



Solid Oxide Fuel Cells

- 2 porous electrodes sandwiching electrolyte
- Air flows along cathode and catalytically acquire 4 electrons from cathode to split into ions
- Diffuse into electrolyte material and migrate to anode to give off water, co2 and electrons

Electrolyte Ceramic material with sufficient ionic conductivity, chemical stability and mechanical strength (eg. Yttrium-doped zirconium oxide (YSZ))

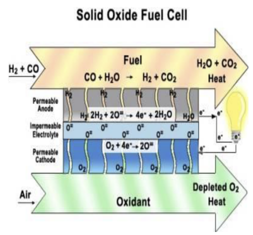
Cathode Good electronic conduction, porosity, thermal stability and thermal expansion (eg. Ca or Sr substituted Lanthanum Manganite)

Anode Ni-YSZ composite - Contains catalyst for fuel oxidation + YSZ constrains nickel aggregation and decreases effective thermal expansion coefficient for better adhesion with electrolyte

- Design configuration

Planar Components assembled in flat stacks with air and fuel flowing through channels built into cathode and anode

Tubular Assembled in hollow tube with air flowing inside tube and fuel flowing around tube



Hydrogen Production and Storage

From fossil fuels

- Steam Methane reforming
  - Endothermic conversion of methane and water vapour into hydrogen and carbon dioxide
  - $CH_4 + H_2O + heat \rightarrow CO + 3H_2$ (1)
  - $CO + H_2O \rightarrow CO_2 + H_2 + heat$ (2)
- Partial oxidation of natural gas
  - Partial combustion of methane and oxygen gase to produce CO and H2
  - Exothermic - no external heating required for more compact design of reactor
  - $CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 + heat$ (3)
- Autothermal Reforming
  - Combination of both reactions to maintain temperature of reactor
- Gasification Process (Coal)
  - Carbon converted to CO and H2
  - Endothermic reaction that requires additional heat
  - $C(s) + H_2O + heat \rightarrow CO + H_2$

Splitting water

- Water electrolysis
  - $H_2O + electricity \rightarrow H_+ \frac{1}{2}O_2$
- Photo-electrolysis
- Photo-biological production
- High-temperature water decomposition

Hydrogen Storage

Storage in Gaseous state

- Steel/low-weight composite tanks
  - Require no internal heat exchange and commercially available
  - Large physical volume required
  - Rapid loss of H2 in accidents
- **Cryogas** - Gaseous hydrogen cooled to near cryogenic temperature to increase volumetric energy density
- Glass microspheres
  1. Hollow glass spheres are filled with H2 at 350-700Bar and 300c by permeation in high-pressure vessel
  2. Microspheres cooled to room temperature and low-pressures
  3. Controlled release of H2 via gradual heating to 200-300c
  - Low volumetric density and high pressure requirement for filling
  - Slowly leak hydrogen at ambient temperatures
  - High temperature requirement for H2 release
  - Inherently safe because H2 is stored at relatively low pressures onboard

Storage in liquid state

- Cryogenic Hydrogen
  - Higher gravimetric density and energy density at low pressures
  - Boil-off loss during dormancy and requirement of super-insulated cryogenic containers for storage
- Hydrogen as constituent in NaBH4 solutions
- Hydrogen as constituent in rechargeable organic liquids

Storage in solid state

- Carbon and high surface materials
  - H2 molecular physisorption/adsorption at cryogenic temperatures with extremely high surface area carbons
- H_2O-reactive chemical hydrides
- Thermal chemical hydrides
- Rechargeable hydrides

Advantages

- Higher purity H2 output
- Lower volume and pressure
- Not as commercially viable

Batteries

- Converts chemical energy to electrical energy via cathodes, anodes and electrodes
- Electrons spontaneously flow from negative to positive potential when electrodes are connected with external load
- Battery characteristics dependent on internal chemistry, drain and temperature

Primary batteries

- Used once only as active material is consumed in single discharge via irreversible electrochemical reaction
- Low price, easy to carry due to low-weight and high energy density
- Zn-MnO2 and Li-MnO2

Secondary batteries

- Rechargeable by applying electrical current which reverses chemical reaction occuring during use
- Active materials are regenerated and are more eco-friendly

Battery Spec	Key Parameter
Light Weight	High Gravimatric Energy Density (Wh/kg)
Small Size	High Volumetric Energy Density (Wh/l)
High Power Output	High Voltage x Current
Recharge conditions and Limits	Strict for Battery Protection

LIBs

- Reversible insertion/extraction of Li ions to/from a host electrode material during discharge/charge
- Li intake/uptake happens with flow of ions through electrolyte + redox reaction of host matrix
- Li-containing oxides are the cathodes and graphitic carbon/amorphous Sn-Co-C composites are anodes
- Known as rocking chair as Li-ions move reversibly
- Advantages:
  - Wide varity of shapes and sizes
  - Much higher energy density
  - High open circuit voltage - increases amount of power at low current
  - No memory effect (reduction of longevity of rechargeable battery charge due to incomplete discharge in prev uses)
  - Low self-discharge rate
- Disadvantages
  - Low shelf life as deposits form inside electrolyte that inhibits ion transport - cell capacity diminishing
  - Increase internal resistance over time that reduce cell ability to deliver current
  - High internal resistance causing voltage at terminals to drop under load
  - Not as durable and may rupture if overheated or overcharged