Energy Sources





Fossil Fuels

Coal, Oil and Gas are
called "fossil fuels"
because they have been
formed from the fossilized remains of prehisto

They provide around 66% of the world's electrical power, and 95% of the world's total energy demands

How Fossil Fuels Work

- Coal is crushed to a fine dust and burnt. Oil and gas can be burnt directly.

Burn fuel> heat water to make steam> steam turns turbine>turbine turns generator>electrical power sent around the country

vides around

oil provides 40%.

n")
is easier to get out of the ground
than coal, as it can flow
along pipes. This also
makes it cheaper
to transport.

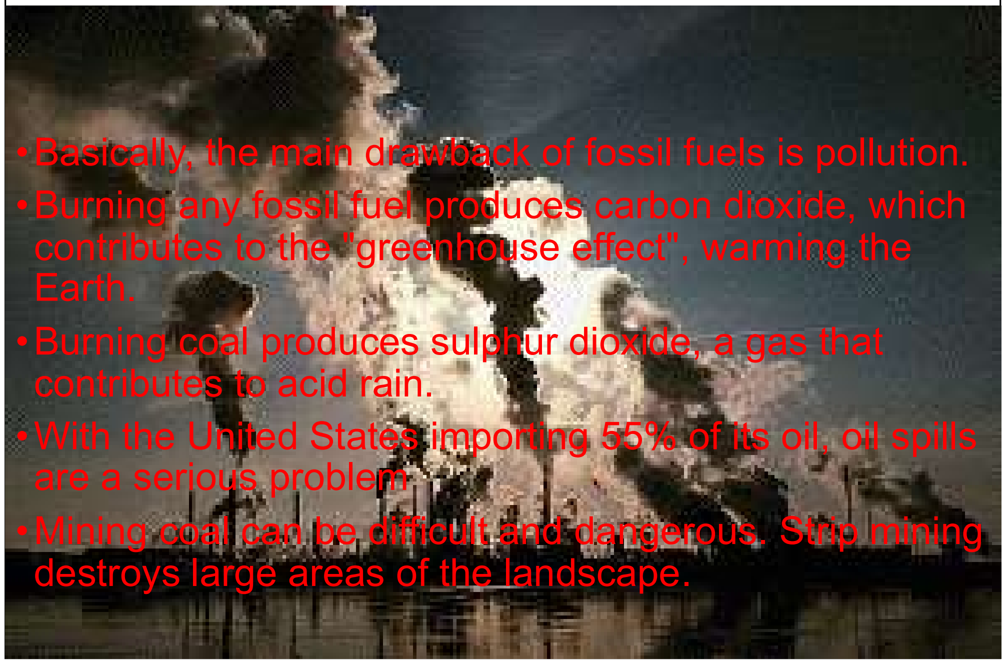
- Natural gas provides around 20% of the world's consumption of energy

Advantages to Using Fossil Fuels

- Very large amounts of electricity can be generated in one place using coal, fairly cheaply.
- Transporting oil and gas to the power stations is easy.
- Gas-fired power stations are very efficient.

- A fossil-fuelled power
- station can be built
- almost anywhere

Disadvantages of Using Fossil Fuels



- Basically, the main drawback of fossil fuels is pollution.
- 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.
- With the United States importing 55% of its oil, oil spills are a serious problem.
- Mining coal can be difficult and dangerous. Strip mining destroys large areas of the landscape.

- Some power stations are built on the coast, so they can use sea water to cool the steam instead. However, this warms the sea and can affect the environment, although the fish seem to like it.

Is it Renewable?

Fossil fuels are **NOT** a renewable energy resource

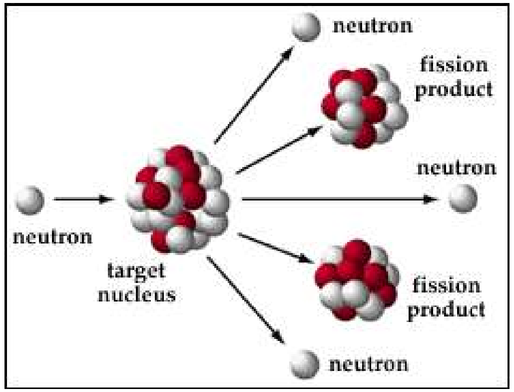
- Once we've burned them all, there isn't any more, and our consumption of fossil fuels has nearly doubled every 20 years since 1900.
  This is a particular problem for Oil, because we also use it to make plastics and many other products.

Nuclear Power

- Nuclear power is generated using Uranium, which is a metal mined in various parts of the world.
- Nuclear power produces around 11% of the world's energy needs, and produces huge amounts of energy from small amounts of fuel, without the pollution that you'd get from burning fossil fuels.

How Nuclear Power Works

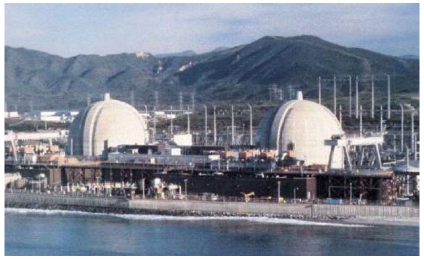
- Nuclear fission makes heat>heated water makes steam>steam turns turbines>turbines turn generators>electrical power is sent around the country



- The reactor uses Uranium rods as fuel, and the heat is generated by **nuclear fission**. Neutrons smash into the nucleus of the uranium atoms, which split roughly in half and release energy in the form of heat.

Advantages to Using Nuclear Power

- Nuclear power costs about the same as coal, so it's not expensive to make.
- Does not produce smoke or carbon dioxide, so it does not contribute to the greenhouse effect.
- Produces huge amounts of energy from small amounts of fuel.
- Produces small amounts of waste.
- Nuclear power is reliable.



Disadvantages of Nuclear Power

- Although not much waste is produced, it is very, very dangerous. It must be sealed up and buried for many years to allow the radioactivity to die away.

Is it Renewable?

- **Nuclear energy from Uranium is NOT renewable.**

•Once we've dug up all the Earth's uranium and used it, there isn't any more.

Solar Power

Solar Cells really called photovoltaic" or "photoelectric" cells) convert light directly into electricity.

- In a sunny climate, you can get enough power to run a 100W light bulb from just one square meter of solar panel.

Solar Water Heating

- heat from the Sun is used to heat water in glass panels on your roof.
- Solar heating is worthwhile in places like California and Australia, where you get lots of sunshine.

Solar Furnaces

- use a huge array of mirrors to concentrate the Sun's energy into a small space and produce very high temperatures.

Advantages to solar power

- Solar energy is free - it needs no fuel and produces no waste or pollution.
- In sunny countries, solar power can be used where there is no easy way to get electricity to a remote place.
- Handy for low-power uses such as solar powered garden lights and battery chargers

Disadvantages to Solar Power

- Doesn't work at night.
- Very expensive to build solar power stations. Solar cells cost a great deal compared to the amount of electricity they'll produce in their lifetime.
- Can be unreliable unless you're in a very sunny climate.

Is Solar Power Renewable?

- **Solar power <u>is</u> renewable.**

- **The Sun will keep on shining anyway, so it makes sense to use it.**

Wind Power

We've used the wind as an energy source for a long time.
The Babylonians and Chinese were using wind power to pump water for irrigating crops 4,000 yea oats were around long before that.

- Wind power was used in the Middle Ages, in Europe, to grind corn, which is where the term "windmill" comes from.

How Wind Power Works

- The Sun heats our atmosphere unevenly, so some patches become warmer than others.
- These warm patches of air rise, other air blows in to replace them - and we feel a wind blowing.
- We can use the energy in the wind by building a tall tower, with a large propellor on the

Advantages to Wind power

- Wind is free, wind farms need no fuel.
- Produces no waste or greenhouse gases.
- The land beneath can usually still be used for farming.
- Wind farms can be tourist attractions.
- A good method of supplying energy to remote areas.

Disadvantages of Wind Power

- The wind is not always predictable some days have no wind.
- Suitable areas for wind farms are often near the coast, where land is expensive.
- Some people feel that covering
- the landscape with these towers is unsightly.
- Can kill birds - migrating flocks tend to like strong winds. Splat!
- Can affect television reception if you live nearby.
- Noisy. A wind generator makes a constant, low, "swooshing" noise day and night.

Is Wind Power Renewable?

- **Wind power <u>is</u> renewable.**
- **Winds will keep on blowing, it makes sense to use them.**

Hydroelectricity

- A dam is built to trap water, usually in a valley where there is an existing lake.
- Water is allowed to flow through tunnels in the dam, to turn turbines and thus drive generators.
- Hydro-electricity provides 20% of the world's power

Advantages of Hydroelectricity

- Once the dam is built, the energy is virtually free.
- No waste or pollution produced.
- Much more reliable than wind, solar or wave power.
- Water can be stored above the dam ready to cope with peaks in demand.
- Hydro-electric power stations can increase to full power very quickly, unlike other power stations.
- Electricity can be generated constantly.

Disadvantages to Hydro-electricity

The dams are very expensive to build.

- Building a large dam will flood a very large area upstream, causing problems for animals that used to live there.
- Finding a suitable site can be difficult - the impact on residents and the environment may be unacceptable.
- Water quality and quantity downstream can be affected, which can have an impact on plant life.

Is it Renewable?

- Hydro-electric power **is renewable.**

The Sun provides the water by evaporation from the sea, and will keep on doing so.

How Biomass Works

- Plant and animal waste is used to produce fuels such as methanol, natural gas, and oil. We can use rubbish, animal manure, woodchips, seaweed, corn stalks and other wastes.

Sugar cane is harvested and taken to a mill, where it is crushed to extract the juice. The juice is used to make sugar, whilst the left-over pulp, called "bagasse" can be burned in a power station.

Other solid wastes, can be burned to provide heat, or used to make steam for a power station.

Burn fuel>heat water to make steam>steam turns turbine>turbine turns generator>electrical power sent around the country

Advantages to Biomass

- It makes sense to use waste materials where we can.
- The fuel tends to be cheap.
- Less demand on the Earth's resources.

Disadvantages to Using Biomass

- Collecting the waste in sufficient quantities can be difficult.
- We burn the fuel, so it makes greenhouse gases.
- Some waste materials are not available al

Is It Renewable?

- **Biomass <u>is</u> renewable**

- **We will always make waste products. We can always plant & grow more sugar cane and more trees, so those are renewable too.**

Geothermal Power

ks underground heat water to produce steam.
We drill holes down to the hot region, steam comes up, is purified and used to drive turbines, which drive electric generators.

- There may be natural "groundwater" in the hot rocks anyway, or we may need to drill more holes and pump water down to them.

Advantages to Geothermal Power

- Geothermal energy does not produce any pollution, and does not contribute to the greenhouse effect.
- The power stations do not take up much room, so there is not much impact on the environment.
- No fuel is needed.
- Once you've built a geothermal power station, the energy is almost free. It may need a little energy to run a pump, but this can be taken from the energy being generated.

Disadvantages to Geothermal Power

- The big problem is that there are not many places where you can build a geothermal power station. You need hot rocks of a suitable type, at a depth where we can drill down to them. The type of rock above is also important, it must be of a type that we can easily drill through.
- Sometimes a geothermal site may "run out of steam", perhaps for decades.
- Hazardous gases and minerals may come up from underground, and can be difficult to safely dispose of.

Is it Renewable?

- **Geothermal energy <u>is</u> renewable.**
  - The energy keeps on coming, as long as we don't pump too much cold water down and cool the rocks too much.

Tidal Power

- Tidal power works rather like a hydro-electric scheme, excep that the dam is **much** bigger.
- A huge dam (called a "barrage") is built across a river estuary When the tide goes in and out, the water flows through tunne in the dam.
- The ebb and flow of the tides can be used to turn a turbine, c it can be used to push air through a pipe, which then turns a turbine. Large lock gates, like the ones used on canals, allow ships to pass.
- Only around 20 sites in the world have been identified as possible tidal power stations.

Advantages to Tidal Power

- Once you've built it, tidal power is free.
- It produces no greenhouse gases or other waste.
- It needs no fuel.
- It produces electricity reliably.
- Not expensive to maintain.
- Tides are totally predictable.

Disadvantages to Tidal Power

A barrage across an estuary is very expensive to build, and affects a very wide area - the environment is changed for many miles upstream and downstream. Many birds rely on the tide uncovering the mud flats so that they can feed. there are few suitable sites for tidal barrages.

Only provides power for around 10 hours each day, when the tide is actually moving in or out.

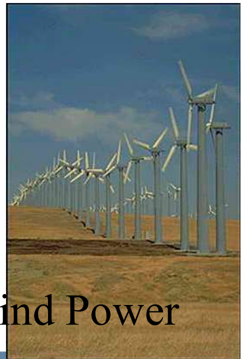
Is it Renewable?

- Tidal energy is renewable.

- **The tides will continue to ebb and flow, and the energy is there for the taking.**

Which Energy Sources are Produced in the California Central Valley?

- Hydroelectricity



Wind Power

Biomass

Geothermal

Fossil Fuels

sources

- http://www.darvill.clara.net/altenerg/fossil.htm
- http://www.umich.edu/~gs265/society/fossilfuels.htm

FUELS AND COMBUSTION

Dr.Joseph Daniel

SMBS

Fuel

- ***Fuel*** is any substance that contains ***energy*** which can be extracted and used to perform work in a controlled manner
- Most fuels undergo ***combustion*** (oxidation reaction) and release heat energy
- Other methods of extracting energy from fuels is by an exothermic reaction and nuclear reactions

Types of Fuels

Hydrocarbons are the most common source of fuel used by humans

- **Solid Fuel** (Coal, Wood, Charcoal, Rice Husk, Bagasse)
- **Liquid Fuel** (Gasolene, Diesel, Kerosene, Furnace Oil, LSHS)
- **Gaseous Fuel** (Natural Gas, Naphtha, LPG)

A type of fuel may be chosen based on the application, pollution, availability, handling and cost.

Properties of Fuels

- Calorific Value
- Density
- Viscosity
- Flash Point
- Pour Point
- Specific Heat

Fuel Analysis

Proximate Analysis
- Moisture
- Volatile Matter
- Fixed Carbon
- Ash

Volatile Matter and Fixed Carbon determine the quality of fuel.

Conducted as per ASTM D3172

Ultimate Analysis
- Carbon
- Hydrogen
- Oxygen
- Nitrogen
- Sulphur

Used to determine fuel feed rate, combustion air requirement, heat release rate etc.

Conducted as per ASTM D3176

Proximate Analysis-Moisture

- Moisture content in a fuel is determined by heating the fuel of 1 g mass to a specified temperature (~105 ^{0}C) for a period of 1 hour
- The loss in mass is equal to the moisture contained

Proximate Analysis-Volatile Matter

- The amount of volatile matter is determined by heating 1 g of fuel in a covered crucible at 950 ^{0}C for a period of 7 minutes
- The loss in mass accounts to the moisture and volatile matter
- The moisture content obtained from the previous experiment is used to calculate the volatile matter content

Proximate Analysis-Ash

- Ash is the un-combustible mineral matter that is left over at the end of complete combustion
- The amount of ash is determined by heating 1 g of fuel to 720^{o}C in an uncovered crucible until no further mass loss is observed
- The amount of mass remaining is equal to the ash content

Proximate Analysis-Fixed Carbon

- Fixed Carbon content is obtained by difference

%FC=100-(%M +%VM+%Ash)

FC=Fixed Carbon

M=Moisture

VM=Volatile Matter

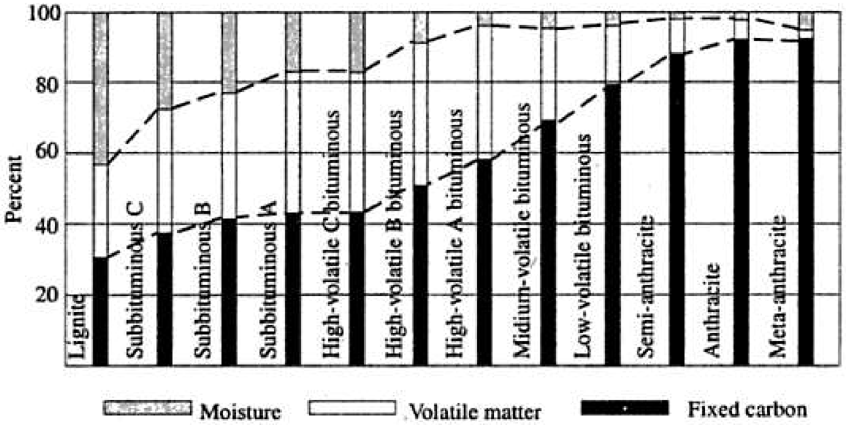
Types of coal

Lignite

Bituminous Coal

Anthracite

Proximate Analysis of Various Types of Coals



Typical Analysis Report

Table 4
Coal Analyses on As-Received Basis
(Pittsburgh Seam Coal, West Virginia)

Proximate Analysis Component	% by wt	Ultimate Analysis Component	% by wt
Moisture	2.5	Moisture	2.5
Volatile matter	37.6	Carbon	75.0
Fixed carbon	52.9	Hydrogen	5.0
Ash	7.0	Sulfur	2.3
Total	100.0	Nitrogen	1.5
		Oxygen	6.7
Heating value,		Ash	7.0
Btu/lb	13,000	Total	100.0
(kJ/kg)	(30,238)		

Source: Steam: Its Generation and Use, Babcock and Wilcox, Page 9-6

Calorific Value (Heating Value)

- Calorific Value is the amount of heat released per unit mass of a fuel on complete combustion
- It is also called as Heating Value
- It is expressed in Energy Units per Unit Mass, J/kg, kJ/kg, MJ/kg for solid and liquid fuels
- Calorific Value is expressed in Energy per Unit Volume basis (eg. kJ/m^3) for gaseous fuels

Higher Heating Value (HHV)

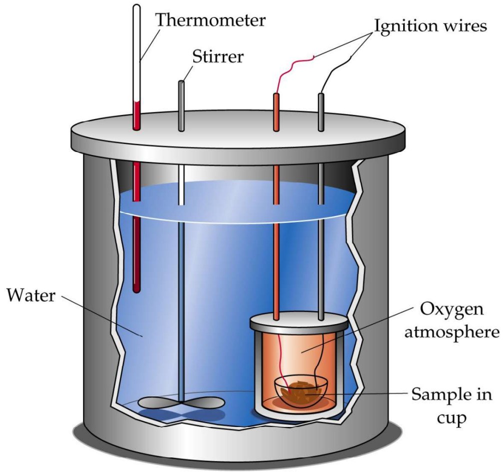
- Higher Heating Value: Also known as Gross Heating Value is the heat released from combustion of a unit fuel quantity, with the products in the form of ash, gaseous CO_2, SO_2, Nitrogen and liquid water
- This is the maximum theoretical heat energy available from a fuel undergoing combustion
- It is determined in an adiabatic bomb calorimeter

Lower Heating Value (LHV)

- Lower Heating Value: Also known as Net Heating Value is the heat released from the combustion of a unit mass of fuel when all the moisture in the products remains as vapour
- LHV is obtained by deducting the enthalpy of evaporation of water, 2,396 kJ/kg
- Magnitude of LHV is lower than that of HHV

Calorimetry-Bomb Calorimeter

- The fuel is placed in a bomb and ignited
- The combustion products are cooled to the initial temperature
- Heat absorbed by the cooling medium is the HHV
- Experiment is conducted in an O_2 environment



Dulong's Formula

$$HHV = 33.83C + 144.45\left(H - \frac{O}{8}\right) + 9.38S$$

- Units of HHV are MJ/kg
- Composition of each element are in mass fractions
- Good when Oxygen is less than 10% by mass
- LHV=HHV-2.396mw

Liquid Fuels

- Liquid fuels (natural and synthetic) are versatile and easily transportable
- Most commonly used in automobiles
- Usage in ovens and furnaces is increasing due to development of efficient burners
- Petroleum is most commonly used
- Coal tar, crude benzol and synthetic liquid fuels made from coal, shale oil and alcohol are few examples

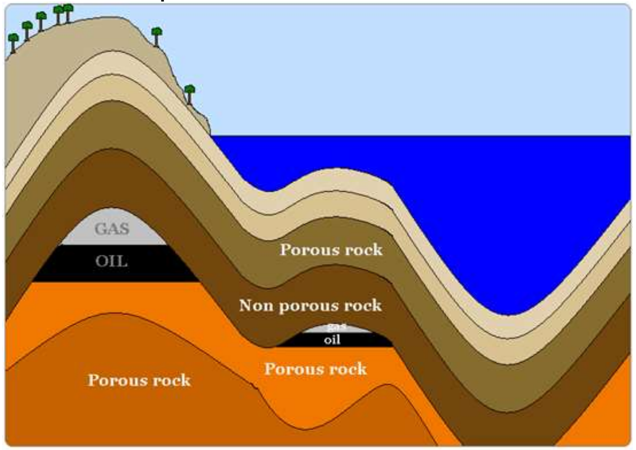
Petroleum

- Petroleum means oil from earth
- Also called as mineral oil, crude oil or simply oil
- Appearance varies from straw coloured liquid to black
- Mostly it is dark coloured, highly mobile liquid in which gas is dissolved and solids are dissolved as well as dispersed
- Sometimes, the gas separates naturally and gives rise to natural gas reserves

Petroleum Deposits

- Petroleum occurs in the space between reservoir rock (porous) and cap rock (non-porous)
- Reservoir rocks are sedimentary rocks formed consisting of coarse-grained minerals such as sand, sandstone, grit, limestone and dolomite
- The upward movement of the fluid from reservoir rock is prevented by cap rock (clay and shales)
- Cap rock has very fine pores and low permeability
- Migration of oil in other directions is prevented by suitable geological formation of the reservoir rock and cap rock

Petroleum Deposits…



The trapping of oil can also be facilitated by the presence of water or brine seals

Petroleum Formation

- Oil formation process begins with the mixing of marine organisms with sand and salt to form sedimentary deposits
- Marine organisms are marine plankton, marine algae, sea grass and larger marine animals
- Continued deposits over millions of years with increasing pressure and temperature leads to compaction and formation of sedimentary rock
- During this process the organic matter is transformed to oil/fluid embedded in source rock under anaerobic conditions

Composition of Petroleum

Crude petroleum is a mixture of hydrocarbons. Paraffins, Naphthenes and Aromatics are present in varying proportions.

The ultimate analysis of crude petroleum:

- C: 83-87%
- H: 11-14%
- S: 0.5-3%
- N: 0.1%
- O: 2-3%
- Ash: <0.1%

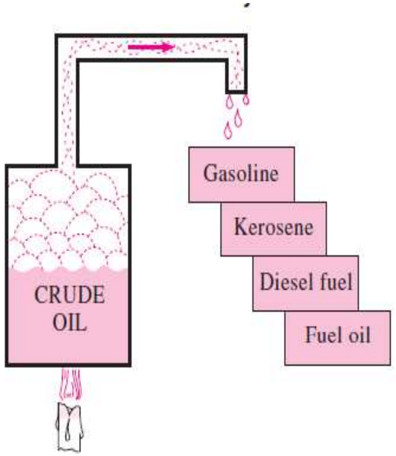
Petroleum Processing

After removal of dirt, water and natural gas, the crude is separated into fractions by distillation and the resultant fractions are further subject to simple to complex processes

- **Physical separation**: Eg. distillation
- **Breakdown process**: Eg. cracking
- **Rebuilding process**: Eg. Reforming

Important Petroleum Products

- Motor gasoline, aviation gasoline, kerosene, jet fuels, diesel fuels and fuel oils
- Lubricating oils, petroleum wax, bitumen, coke and LPG
- Transformer oil, spray oils, insecticidal oils and machine oils



Properties and Testing

- Specific Gravity
- Viscosity
- Distillation Range
- Flash and Fire Point
- Pour Point and Cloud Point
- Smoke Point and Char Value
- Carbon Residue

Properties and Testing…

- Sulphur Content
- Moisture
- Ash
- Calorific Value
- Octane Number
- Cetane Number
- Aniline Point

A comparison of some alternative fuels to the traditional petroleum-based fuels used in transportation

Fuel	Energy content kJ/L	Gasoline equivalence,* L/L-gasoline
Gasoline	31,850	1
Light diesel	33,170	0.96
Heavy diesel	35,800	0.89
LPG (Liquefied petroleum gas, primarily propane)	23,410	1.36
Ethanol (or ethyl alcohol)	29,420	1.08
Methanol (or methyl alcohol)	18,210	1.75
CNG (Compressed natural gas, primarily methane, at 200 atm)	8,080	3.94
LNG (Liquefied natural gas, primarily methane)	20,490	1.55

Advantages of Gaseous Fuels

- No mineral impurities
- Clean combustion
- Consistent quality
- Ease of use
- Efficiency of combustion
- Handling less expensive
- No or minimal storage needed at domestic level
- Automatic supply to door step

Types of Gaseous Fuels

Fuel gases occurring in nature:
- Natural gas
- Methane

Fuel gas made from solid fuels:
- Producer gas
- Water gas
- Coal gas
- Blast furnace gas
- Wood gas

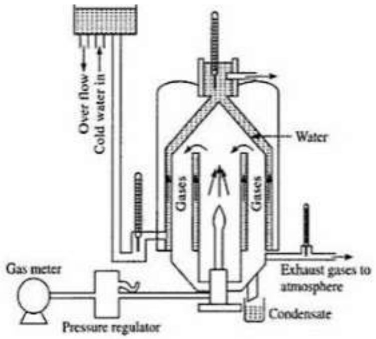
Types of Gaseous Fuels…

Fuel gases made **from petroleum:**
- Refinery gases
- Liquified petroleum gas (LPG)
- Gases from oil gasification process

Fuel gases made by fermentation of organic waste:
- Biogas

Industrial Gases (Based on Usage)
- Hydrogen
- Acetylene

Gas Calorimeter



combustion

- A chemical reaction during which a fuel is oxidized and a large quantity of energy is released is called combustion.
- Air is the commonly used oxidizer which is readily available.
- It has 20.9% Oxygen, 78.1% Nitrogen and 0.9% Argon. For convenience argon can be approximated as Nitrogen and so it is 21% Oxygen and 79% Nitrogen by mole numbers.
- Each Mole of oxygen is accompanied by 3.76 Moles of Nitrogen while supporting combustion.

- Air is assumed to be dry and CO_2 free
- Air contains 21% O_2 and 79% N_2 by volume
- Air contains 23% O_2 and 77% N_2 by mass
- Average molecular weight of air is taken as 29 g/mol.
- Theoretical air is the amount of air stoichiometrically required for the complete combustion of the combustibles
- Theoretical products of combustion refer to the flue gas or exhaust gas obtained by the complete combustion of the fuel using theoretical air
- Excess air is the amount of air used in excess of the theoretical air

- Fuels must be brought above ignition temperature to start combustion.
- 260^{o}C for gasoline
- 400^{o}C for carbon
- 580^{o}C for hydrogen
- 610^{o}C for CO
- 630^{o}C for methane

Combustion Stoichiometry

- Combustible elements in solid and liquid fuels are C, H and S
- Combustible components of gaseous fuels are H_2, CO, CH_4 and hydrocarbons
- Molecular formula for coal gas is $C_{1.25}H_{4.5}$
- Formula for producer gas from coal, C_2H_4
- Formula for coke oven gas, $C_{2.5}H_5$

Combustion Reactions

The combustibles undergo complete combustion by the following reactions:

$C + O_2 \rightarrow CO_2$

$2H + ½\ O_2 \rightarrow H_2O$

$S + O_2 \rightarrow SO_2$

$H_2 + ½\ O_2 \rightarrow H_2O$

$CO + ½\ O_2 \rightarrow CO_2$

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

1) $C + O_2 \rightarrow CO_2$

12 + 32 = 44

1+8/3 = 11/3

1 kg of carbon requires 8/3 kg of oxygen for its complete combustion and forms 11/3 kg of CO_2

2) $H_2 + ½\, O_2 \rightarrow H_2O$

2+16 = 18

1+8=9

1 kg of hydrogen requires 8 kg of oxygen to form 9 kg of water vapor

3) $S + O_2 \rightarrow SO_2$

32+32 = 64

1+1 = 2

Kg of sulphur requires 1 kg of oxygen to form sulphur dioxide

The net amount of oxygen required to complete the combustion of 1kg of the fuels is

$(8/3*C+8(H_2-O_2/8)+S$

Problem 1

- Estimate the HCV and LCV of a fuel having the following composition by mass

C= 88%, H_2=10%, O_2=3%, S=2%, N_2=20% rest of them are incombustibles.

Solution: By Dulong's formula

HCV = (33800C+144000(H-O/8)+9270S)kJ/kg

= (33800*0.88+144000(0.1-0.03/8)+9270*0.02)

= 27040+13860+185.4

= 41085 kJ/kg or 41 MJ/kg

- Amount of steam formed = 0.1*9 = 0.9 kg/kg of fuel

Hence heat absorbed in the formation of steam is 0.9* 2460 = 2214 kJ

Dulong suggested that 4 kg of Hydrogen combines with 32 kg of oxygen to form 36 kg of water vapor, meaning that water vapor formed is 9 times the mass of hydrogen in the fuel..

Therefore LCV = HCV- 2214

= 41085.4-2214

= 38871.4 kJ/kg

Problem 2

- The following data pertains to the test run made to determine the calorific value of a sample of coal having hydrogen content of 5%.

Mass of coal burnt = 0.85 g

Mass of fuse wire burnt = 0.028 g

Calorific value of FW= 6700 kJ/kg

Mass of water in calorimeter = 1800 g

water equivalent of calorimeter = 350 g

Initial and final temp of water = 16.5 and 20.25^{o}C

Cooling correction = 0.08^{o}C

Calculate the HCV and LCV of the fuel

- The energy balance goes like this

Heat liberated by fuel and fuse wire = Heat absorbed by water and calorimeter.

m_f*CV+$(m$*$CV)_{fuse}$= $(m_w+m_c)C_p$*(FT-I.T)+corr.fr

0.85*CV+0.028*6700=(1800+350)*4.186(20.25-16.5)+0.08

0.85 CV+187.6=34469.6

CV= 40331.76 kJ/kg

This fuel has 5% hydrogen which means it may form 0.05*9 = 0.45 kg of water vapor

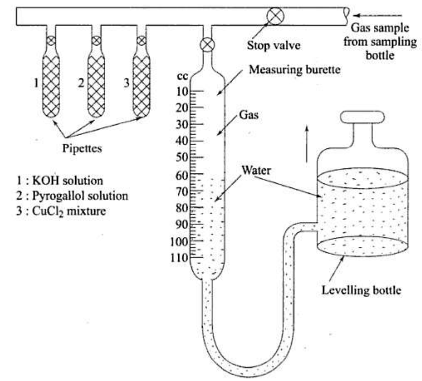
Heat absorbed in formation of steam = 0.45*2465 = 1109.25 kJ/kg

LCV = 40331-1109 = 39222.51 kJ/kg

Flue gas analysis

- Flue gas (exhaust gas) is the gaseous by product of combustion process
- Flue gas consists majorly of CO_2, O_2, N_2, H_2O
- Flue gas analysis indicates the extent of completeness of combustion
- Flue gas analysis can be used to estimate the amount of air supplied for combustion
- Flue gas analysis is carried out using (i) Orsat Apparatus, (ii) Haldane Apparatus, (iii) Infra-red analyzer, and (iv) Gas Chromatograph

Orsat apparatus



KOH to absorb CO_2
Pyrogallol ($C_6H_6O_3$) solution to absorb O_2
$CuCl_2$ to absorb CO

- A sample of coal supplied to a boiler has the following composition by mass

C= 88%, H=5%, O=3%,N= 1%, S= 0.5%, Incombustibles= 2.5%

Calculate a)mass of air required for complete combustion of 1 kg of coal b) dry analysis by mass and volume of products of combustion when 15% EA is supplied

To estimate total oxygen needed for combustion

1)C + O_2 → CO_2
12 + 32 = 44
O_2 required = 8/3*0.88 = 2.347 kg
CO_2 produced = 11/3*0.88 = 3.227 kg
2) **H_2 + ½ O_2 → H_2O**
2+16 = 18
1+8=9
O_2 required = 8*0.05 = 0.4 kg
Water vapor formed = 9*0.05 = 0.45 kg
3) S + O_2 → SO_2
32+32 = 64
1+1 = 2
1*0.005 = 0.005 kg O_2 needed
2*0.005 = 0.01 kg

- Total oxygen needed = 2.347+0.4+0.005
  = 2.752 kg

0.03 kg oxygen is in coal inherently

Therefore net oxygen needed = 2.752-0.03 = 2.722 kg

Since air has 23% oxygen on mass basis then

Air required for complete combustion of 1 kg of coal = 2.752/0.23 = 11.965 kg

Stoichiometric A/F ratio = 11.965

But actual air supplied = 11.965*1.15 = 13.76 kg

- This air has 0.77*13.76 kg nitrogen = 10.472 kg Nitrogen

13.76-10.472 = 3.288 kg oxygen

While analyzing the products we have

CO_2 = 3.227 kg, H_20= 0.45 kg, SO_2 = 0.01 kg and Nitrogen = 10.472 kg+1% Nitrogen in fuel = 10.482 kg

Excess oxygen = 3.228-2.722= 0.566 kg

Product	mass	% mass	mol Wt	pro vol	% vol
CO2	3.227	22.59	44	0.0733	15.76
SO2	0.01	0.07	44	0.000227	0.049
N2	10.482	73.38	28	0.374	80.39
O2	0.566	3.96	32	0.01769	3.80
Total	4.285	100		0.4652	

- A hydrocarbon fuel of unknown composition is burned with air and orsat analysis yielded the following results
- $CO2 = 7.26\%$, $CO = 2.42\%$, $O2 = 7.5\%$

Determine the empirical formula of the fuel

Composition of the fuel on mass basis

- Step 1: Find out Nitrogen

$N2 = 100\% - (CO_2\%+CO\%+O_2\%)$

$= 100\% - (7.26\%+2.42\%+7.50\%)$

$= 82.82\%$

Step 2: Elemental balance

$C_xH_y + aO_2+a(79/21)N_2 = 7.26\ CO_2+2.42\ CO+7.5\ O_2+82.82\ N_2+bH_20.$

Carbon balance :

$x = 7.26+2.42 = 9.68$

Nitrogen balance

$(79/21)a = 82.82$, $a = 22.01$

Oxygen balance

$a = 7.26+(2.42/2)+7.5+(b/2)$, $b= 12.08$

Hydrogen balance

$y = 2b$, $y=2 \times 12.08 = 24.16$

Therefore the empirical formula of the fuel is

$C_{9.68}H_{24.16}$

Step 3: Mass basis of the fuel elements

$C= (9.68 \times 12)/(9.68 \times 12 + 24.16 \times 1)$

$= 82.78\%$

$H= (24.16 \times 1)/(9.68 \times 12 +24.16 \times 1)$

$= 17.22\%$

Step 4 : Actual and Theoretical ratio

Actual air fuel ratio = Moles of air/Moles of fuel

$= (a +(79/21)a)/1 = 104.81$

- Step 4: Equation balancing

$C_{9.68}+H_{24.16} + 15.72\ O_2 = 9.68\ CO_2+12.08\ H_2O$

Theoretical ratio = ((15.72+(79/21*15.72))/1

= 74.86

- The fuel supplied to an I.C engine has the following composition by mass

  C= 87%, H=13%

- Air fuel ratio is 13:1. If all the carbon is burnt to either CO or CO_2 and no free O_2 is left

Determine: a) volumetric analysis of the products of combustion

b) Heat lost by incomplete combustion as %GCV

Assume the following heat values

- C to CO_2 – 34320 kJ/kg
- C to CO – 10360 kJ/kg
- Hydrogen to H_2O – 144420 kJ/kg

Oxygen required for burning

1) $C +O_2= CO_2$

12 +32 = 44

2) $2C+O_2 = 2CO$

24+32 = 56

3) $2H_2+O_2 = 2H20$

4+ 32 = 36

- Air supplied per kg of fuel = 13 kg

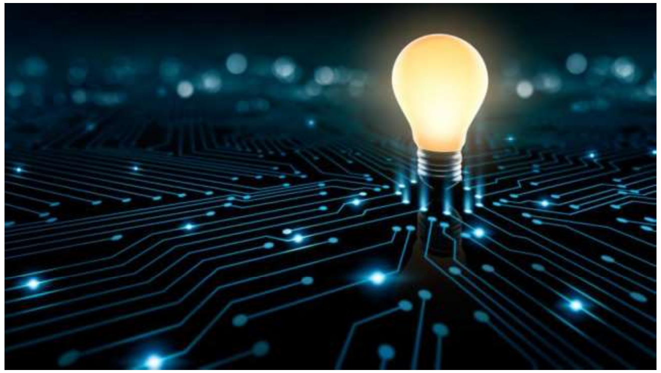
Air has 23%oxygen by mass basis

13 * 23% = 2.99 kg O2

While undergoing combustion

X kg burns to CO2 and remaining to CO

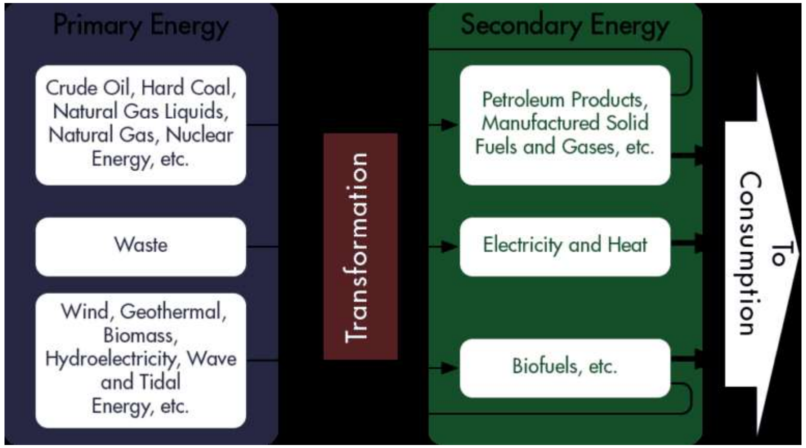
O

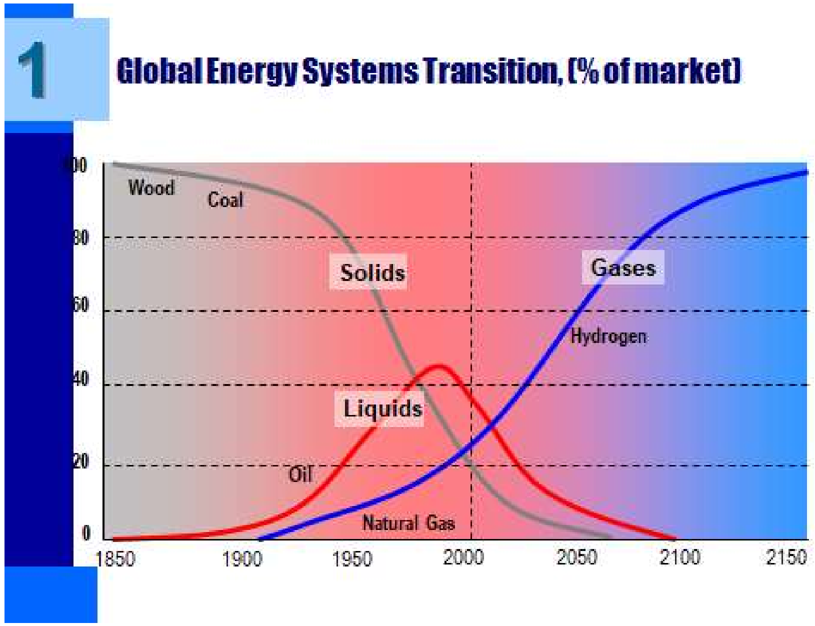


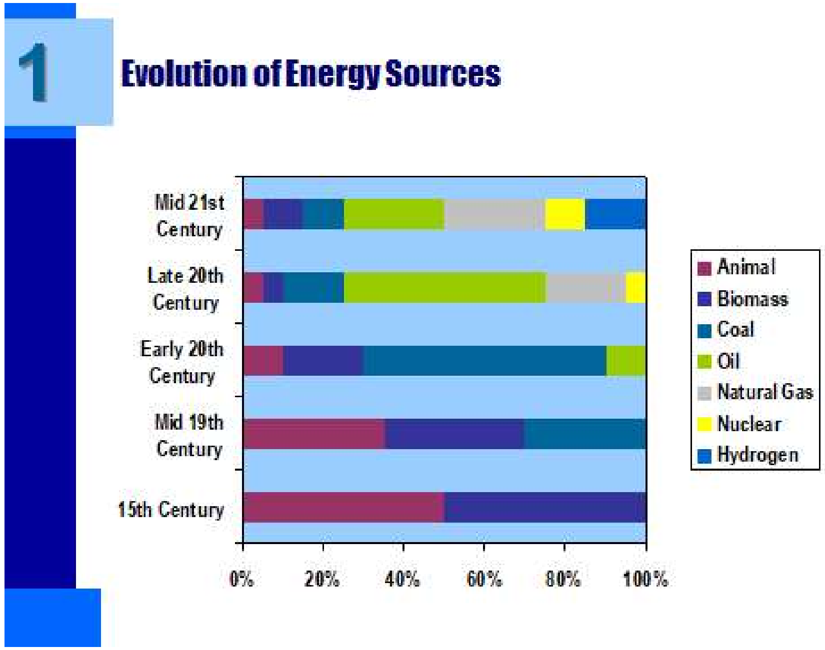
ENERGY,FUELS AND ALTERNATE FUELS

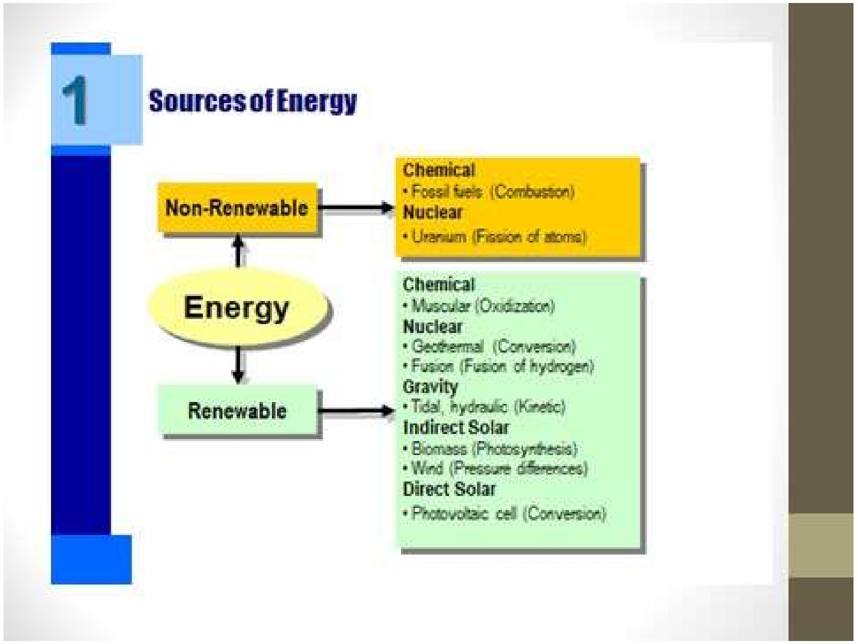
Primary and Secondary Energy

- Primary energy sources are those that are either found or stored in nature.
- Common primary energy sources are coal, oil, natural gas, and biomass (such as wood).
- Other primary energy sources available include nuclear energy from radioactive substances, thermal energy stored in earth's interior, and potential energy due to earth's gravity.
- Primary energy sources are mostly converted in industrial utilities into secondary energy sources; for example coal, oil or gas converted into steam and electricity.









FUELS

What is a Fuel?

- ***Fuel*** is any substance that contains ***energy*** which can be extracted and used to perform work in a controlled manner
- Most fuels undergo ***combustion*** (oxidation reaction) and release heat energy
- Other methods of extracting energy from fuels is by an exothermic reaction and nuclear reactions

- Fuels undergo

✓Combustion

✓Gasification

✓Pyrolysis to yield energy in a controlled manner

You need

✓Fuel in the first place

✓Oxygen in quantities determined by the methods of fuel expedition

✓Environment to facilitate energy yield

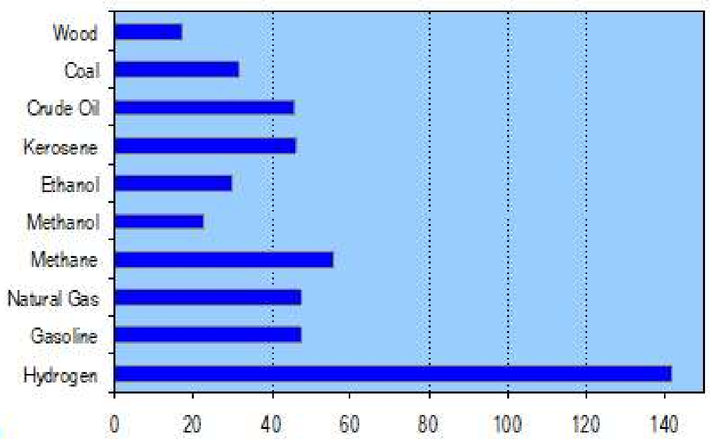
Types of Fuels

Hydrocarbons are the most common source of fuel used by humans

- **Solid Fuel** (Coal, Wood, Charcoal, Rice Husk, Bagasse)
- **Liquid Fuel** (Gasolene, Diesel, Kerosene, Furnace Oil, LSHS)
- **Gaseous Fuel** (Natural Gas, Naphtha, LPG)

A type of fuel may be chosen based on the application, pollution, availability, handling and cost.

1 Chemical Energy Content of some Fuels (in MJ/kg)



MEE1012 ALTERNATIVE FUELS

- **L T P J C – 3 0 0 0 3**
- **Course Objectives**
- To provide the students with sufficient background to understand the need for alternative fuels.
- To enable the students to understand different sources of alternative fuels, production and storage methods.
- To teach students how to use alternative fuels in internal combustion engines and their performance and emission characteristics.
- To provide the knowledge of zero emission vehicles using clean technologies.

Expected Course outcome

- Student will be able to
- Possess the knowledge of alternative fuels and their production methods.
- Understand the safety aspects of using alternative fuels.
- Conduct experiments with alternative fuels in internal combustion engines.

Modules....

Module:1	**Introduction**	**2 hours**	**SLO: 1, 2, 10**
Status of petroleum reserves, economics; Need for alternative fuels; Review of fuel properties.			
Module:2	**Hydrogen – Production and Storage**	**6 hours**	**SLO: 1, 2**
Properties; Production and storage methods; Safety aspects; Use in SI and CI engines; Engine modifications required; Performance and emissions.			
Module:3	**Organic gaseous fuels**	**10 hours**	**SLO: 1, 2**
Natural Gas, LPG, biogas, producer gas, syngas etc.; Properties; Production and storage methods - CNG and LNG, gasification, digesters; Use in SI and CI engines; Performance and emission characteristics; Modes of operation in internal combustion engines.			
Module:4	**Alcohols and ethers**	**10 hours**	**SLO: 1, 2**
Methanol and ethanol; DME and DEE; Properties; Production methods; Use in SI and CI engines –Fuel and engine modifications required; Performance and emissions.			
Module:5	**Vegetable oils**	**10 hours**	**SLO: 1, 2**
Types, composition and properties; Challenges of use in CI engines, solutions - preheating, blending; Transesterification; Pyrolysis; Performance and emissions; Oils from waste - cooking oil, wood, rubber, plastic etc.			

Modules.... Textbook, Ref books

Module:6	**Solid fuels**	**2 hours**	**SLO: 1, 2**
Biomass - processing and usage, forms - municipal solid waste, wood.			
Module:7	**Clean technology**	**3 hours**	**SLO: 1, 2, 10**
Fuel cells - types, working; Hybrid and electric vehicles; Solar power; Challenges; Engine modifications; Performance.			
Module:8	**Contemporary issues**	**2 hours**	
	Total lecture hours	**45 hours**	

Text Book(s)

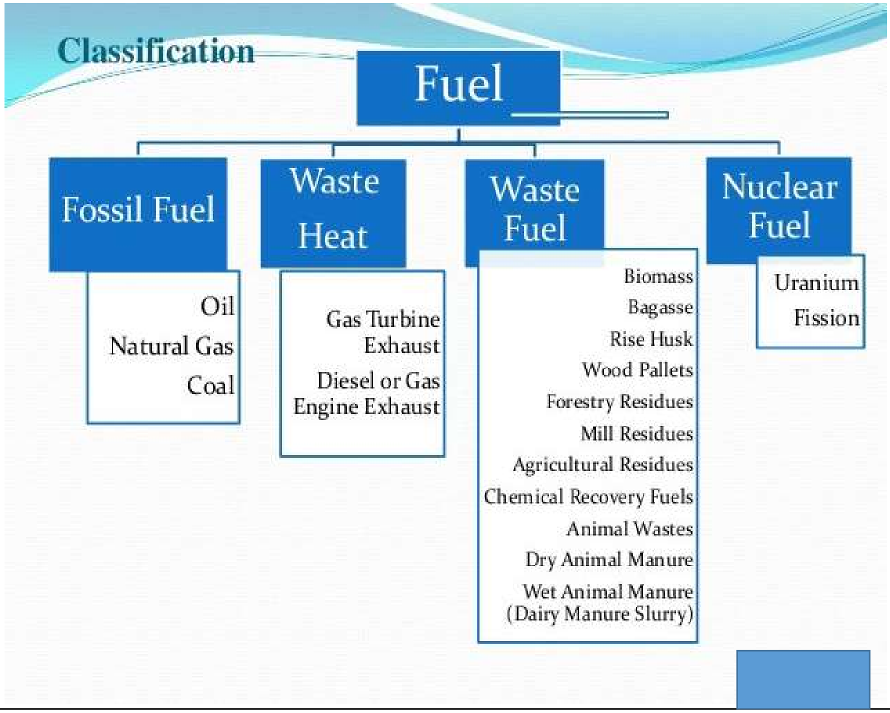
1. Thipse S. S., Alternative Fuels: Concepts, Technologies and Developments, Jaico Publishing House, 2010.

Reference Books

1. Ganesan V, Internal Combustion Engines, McGraw-Hill Education India Pvt. Ltd, 2012.
2. Michael F. Hordeski, Alternative Fuels: The Future of Hydrogen, The Fairmont Press, Inc, 2013.
3. Sunggyu Lee, James G. Speight, Sudarshan K. Loyalka, Handbook of Alternative Fuel Technologies, 2nd edition, CRC Press, 2014.
4. James Larminie, John Lowry, Electric Vehicle Technology Explained, 2nd edition, John Wiley & Sons, Ltd, 2012.
5. Richard L.Bechtold, Alternative Fuels Guidebook, Society of Automotive Engineers (SAE), 2014.

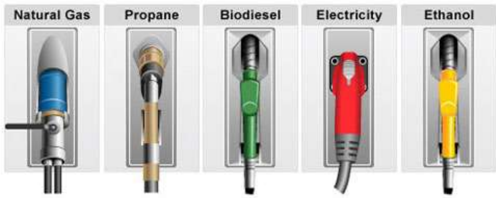
Name some fuels

- Name fuels and classify them



Alternative fuels???

Possible Solutions



- What is an alternative fuel?

  Any fuel material or a substance, other than petroleum, which is consumed to provide energy to power an Engine

  Some alternative fuels are biodiesel, ethanol, chemically stored electricity (batteries and fuel cells), hydrogen, methane, gas, wood and vegetable oils

- Gasoline type biofuels
  - Butanol as a direct replacement for gasoline
  - Ethanol or mixtures with Gasoline E85
- Diesel type biofuels
  - Straight vegetable oils
  - Biodiesel
- Gaseous
  - Natural gas (Compressed or liquefied)
  - Propane
  - Syngas, biogas
- Alternative drive trains (EV's, solar cell powered, Hydrogen fuel cell, Air car)

Properties of Alternative fuels.

- *Combustion and Performance*: Heat of combustion, heat content of stoichiometric mixture, octane number (SI engine) , cetane number (CI engine), boiling point (esp., cold start), flammability limits
- *Emissions*: Chemical composition and nature, adiabatic flame temperature
- *Storage and Handling:* Boiling point, volumetric energy density, vapour pressure, flammability limits

WORLD ENERGY COUNCIL
CONSEIL MONDIAL DE L'ÉNERGIE
For sustainable energy.

World energy resources

Sourced from World Energy council

World Energy Council

- The World Energy Council is the principal impartial network of leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all.
- Formed in 1923, the Council is the UN-accredited global energy body, representing the entire energy spectrum, with more than 3000 member organisations located in over 90 countries and drawn from governments, private and state corporations, academia, NGOs and energy-related stakeholders.

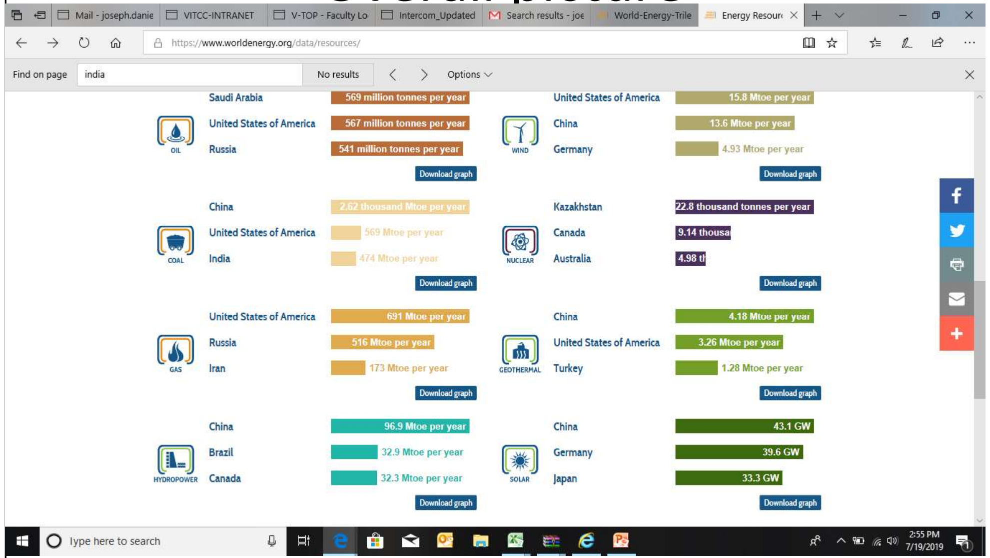
What they do

- The World Energy Council informs global, regional and national energy strategies by hosting high-level events, publishing authoritative studies, and working through its extensive member network to facilitate the world's energy policy dialogue.
- World Energy Council works with governments, agencies and companies to help inform policy development and strategic decision-making and planning.
- The Council works with partner organisations to facilitate access to our network of experts and provides impartial advice to intergovernmental organisations and national governments on specific issues affecting what we call the energy trilemma.

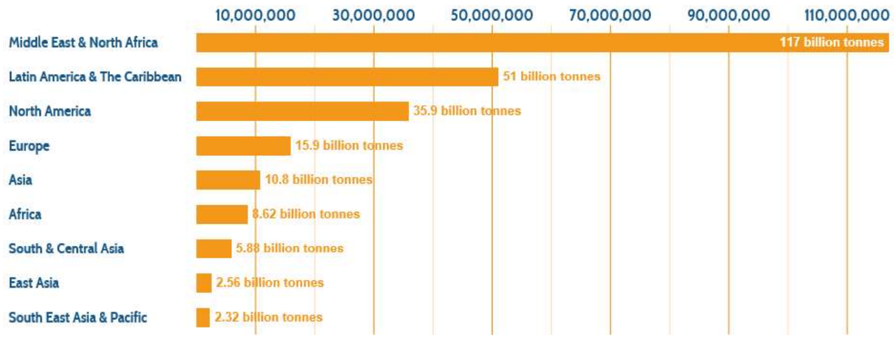
Data…

- [World Energy Resources](), a survey of global resources and technologies**.** It identifies what energy resources we have and what technologies are being used to exploit these resources.
- [World Energy Trilemma]() report, an independent assessment of national energy and climate policies. This work seeks to identify how we can make better policies to improve our energy systems.
- [World Energy Issues Monitor](), an annual monitor identifying what issues are affecting the global energy leaders' community**.**
- [World Energy Scenarios](), an in-depth explorative energy scenarios**.** This work seeks to identify what may happen in our future energy systems based on quantitative computer modelling and the knowledge of our global network of energy experts.

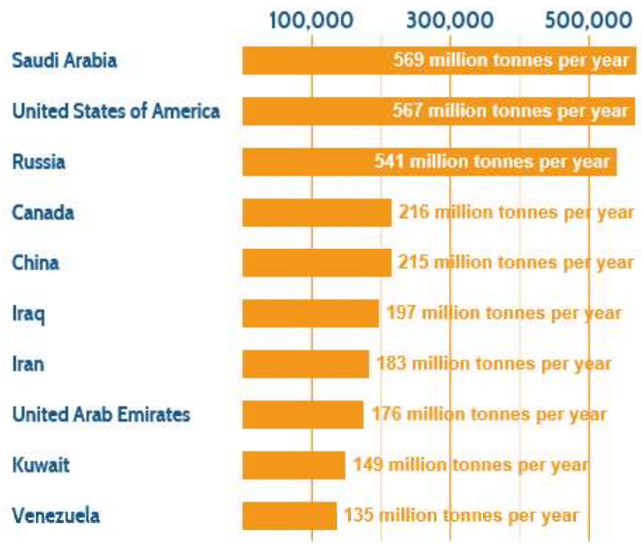
Overall picture



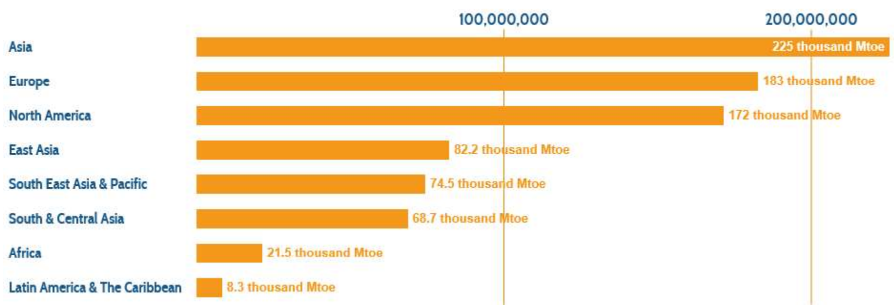
Region wise-Oil



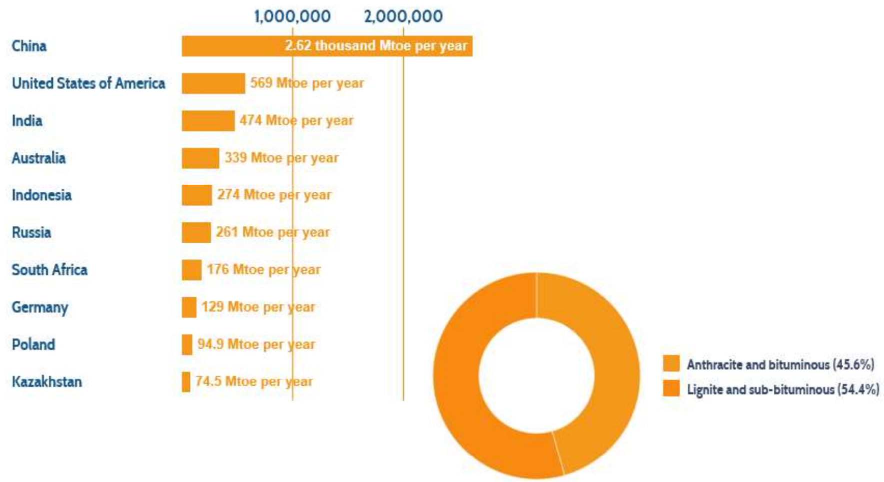
Country wise-Oil



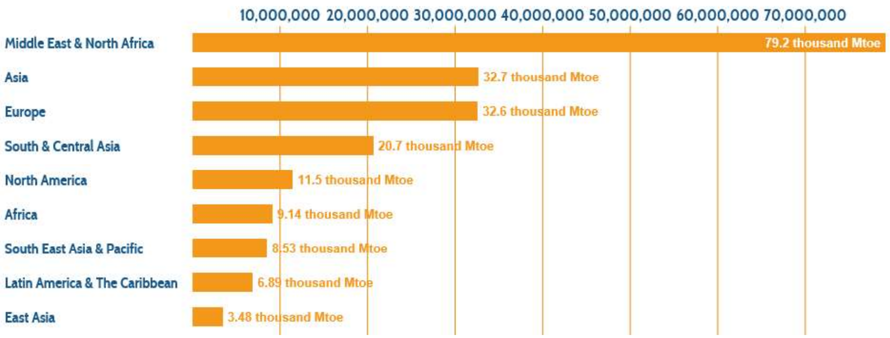
Region wise-Coal



Country wise-Coal

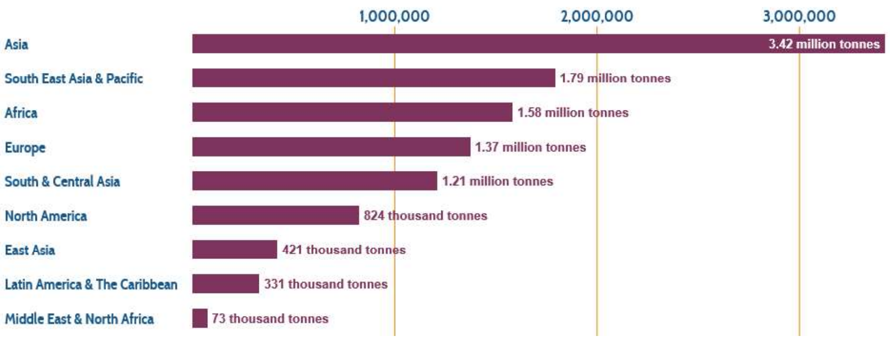


Region wise- Gas



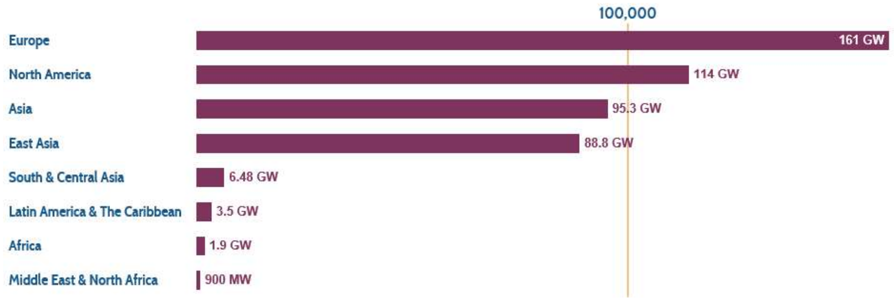
Country wise- Gas

Identified Uranium



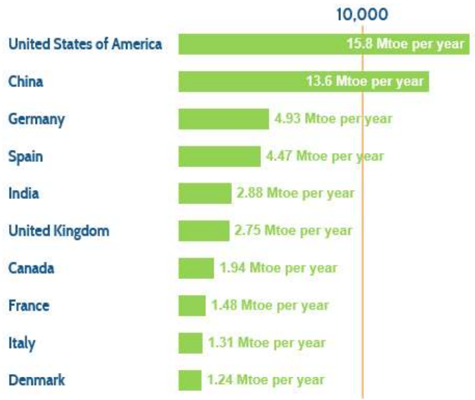
Uranium Producing countries

Installed capacity

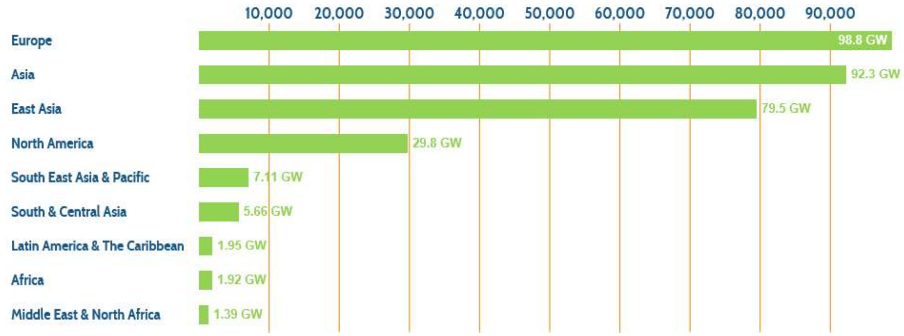


Wind Power- Region wise

Top wind power producers



Solar-Installed capacity

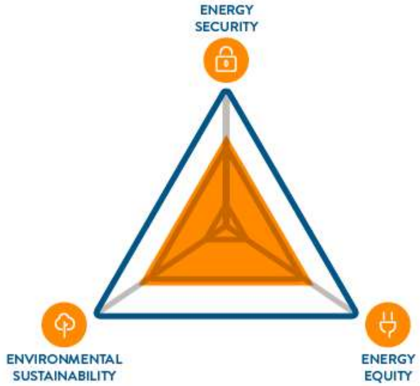


Trilemma

ENERGY SECURITY
Effective management of primary energy supply from domestic and external sources, reliability of energy infrastructure, and ability of energy providers to meet current and future demand.

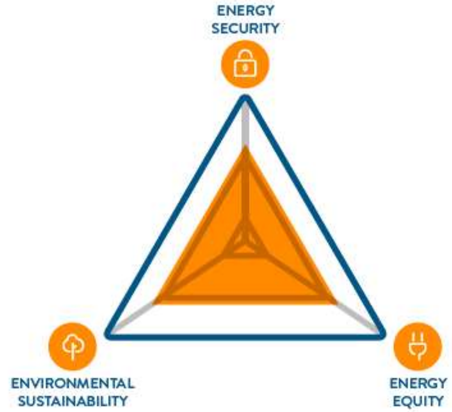
ENERGY EQUITY
Accessibility and affordability of energy supply across the population.

ENVIRONMENTAL SUSTAINABILITY
Encompasses achievement of supply- and demand-side energy efficiencies and development of energy supply from renewable and other low-carbon sources.

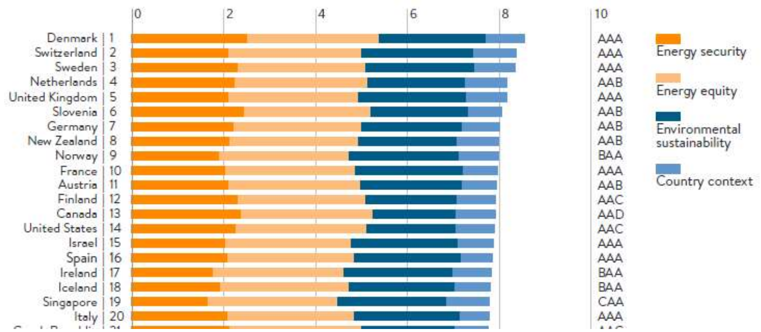


TOP 10
OVERALL RESULTS

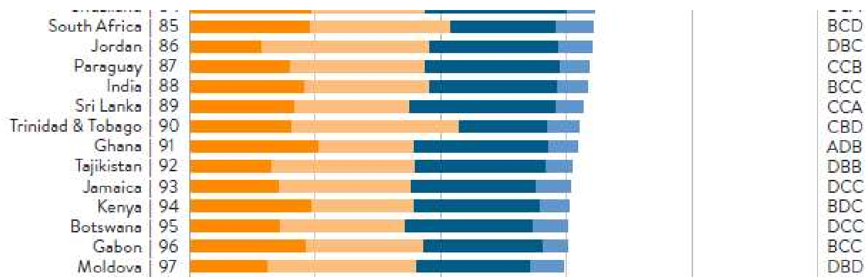
1. Denmark
2. Switzerland
3. Sweden
4. Netherlands
5. United Kingdom
6. Slovenia
7. Germany
8. New Zealand
9. Norway
10. France



Global Top performers



India ??



How to interpret?

Industrial sector (% GDP)	% of total GDP that is in the industrial sector (World Bank, 201
GDP per capita, PPP US$ (GDP Group)	Gross domestic product (World Bank 2015) and Index GDP group
Energy intensity (koe per US$)	Measures how much energy is used to create one unit of GDP (Enerdata & World Energy Council, 2016)
Diversity of international energy suppliers	Indicates to what extent the country is dependent on energy trading partners. Diversity of international energy suppliers calculated through the Herfindahl-Hirschman Index (HHI), (UNCTAD, 2014).
Population with access to electricity (%)	Share of population with access to electricity (SE4All, 2016)
Access to clean cooking in urban | rural areas (%)	% of households that have access to non-solid fuels (SE4All, 2016)
Household electricity prices (US$/kWh)	Average cost of electricity (IEA, Eurostat, World Energy Council, World Bank, 2015)
Rate of transmission and distribution losses (%)	The ratio between the quantity of energy lost during transport and distribution and the electricity consumption. Indicates efficiency of infrastructure (Enerdata and World Energy Council, 2015
CO2 intensity (kgCO2 per US$)	Measures CO2 from fuel combustion to generate one unit of GDP in PPP (Enerdata and World Energy Council, 2015/16
GHG emission growth rate 2010 – 2014 (%)	Greenhouse gas emission growth rate from the energy sector between 2000 and 2014, (WRI/CAIT, 2014)

DENMARK

TRILEMMA INDEX RANKINGS AND BALANCE SCORE

RANK

1

SCORE

AAA

Index rank for each energy trilemma dimension and contextual performance for 2016, 2017 and 2018

Overall 2018 balance score. The first letter refers to energy security, the second to energy equity and third to environmental sustainability

	2016	2017	2018	Trend	Score
Overall rank and balance score	1	1	1	▶	AAA
Energy performance					
Energy security	1	1	1	▶	A
Energy equity	10	12	11	▶	A
Environmental sustainability	6	4	17	▶	A
Contextual performance	11	15	15	▶	

Trend for each energy

TRENDS AND OUTLOOK

Trend for each energy trilemma dimension and contextual performance over the three-year period

Overview of current Index rating and commentary on recent trends and outlook for a country's energy performance

- Denmark maintains its position in the top 10 this year at number 1. It manages the trade-offs ac… excellently, resulting in a balance score of AAA. Energy Security remains a particular highlight where it ranks 1st globally.
- …Denmark. The Agreement contains a wide range of ambitious initiatives. This should bring Denmark closer to reaching the target of 100% renewable energy in the energy and transport sectors by 2050 by committing to large investments up to 2020 in energy efficiency, renewable energy and the overall energy system. Targets to reach by 2020 include approximately 50% of electricity consumption supplied by wind power, and more than 35% of final energy consumption supplied from renewable energy sources.
- To overcome the challenges and reach its ambitious targets of becoming independent of fossil fuels and reducing CO_2 emissions, Danish policymakers are focusing on the implications of: being fossil fuel free for the transport sector; the future role of the Danish natural gas grid; and the introduction of huge amounts of fluctuating renewable energy in the electricity grid.

KEY METRICS

Industrial sector (% of GDP)	22.93	GDP per capita, PPP US$ (GDP Group)	49,029 (I)
Energy intensity (koe per US$)	0.07	Diversity of international energy suppliers	Medium (HHI = 1,818)
Population with access to electricity (%)	100	Access to clean cooking (%)	100
Household electricity prices (US$/kWh)	0.34	Rate of transmission and distribution losses (%)	5.86
CO_2 intensity (kCO_2 per US$)	0.17	GHG emission growth rate 2010 – 2014 (%)	-2.90

TRILEMMA REPORT 2018

INDIA

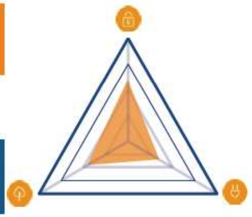
TRILEMMA INDEX RANKINGS AND BALANCE SCORE

RANK

88

SCORE

BCC



	2016	2017	2018	Trend	Score
Overall rank and balance score	91	92	88	▶	BCC
Energy performance					
Energy security	51	66	54	▶	B
Energy equity	93	96	93	▶	C
Environmental sustainability	97	92	75	▶	C
Contextual performance	100	86	81	▲	

TRENDS AND OUTLOOK

- India improves by 4 places this year to rank 88 with a balance score of BCC. While the Energy Security score moves from C to B, the country also demonstrates substantial improvement in Environmental Sustainability rank.
- India's Nationally Determined Contribution to the 2015 Paris agreement, aiming to achieve a 33% decrease in GHG intensity of GDP compared to 2005 and 40% renewable installed capacity by 2030, guide energy policy in India.
- India's energy policy schemes cover the following categories:
  1) Energy diversity: the target is to achieve 175 GW renewable energy capacity by 2022 (from 70GW in 2018), including 100 GW solar and 60 GW wind, while increasing the share of gas in the energy mix. Steps for gas include expansion of city gas distribution and plans for an LNG trading hub; regulation encourages the implementation of energy storage for large solar plants, domestic PV manufacturing and combination of wind and solar in hybrid systems.
  2) Energy access: the targets are 100% Household Electrification by December 2018 and '24x7 Power for all' by March 2019. The use of cooking gas is subsidised by the 2013 Direct Benefit Transfer programme.
  3) Energy security. The implementation of the common Hydrocarbon Exploration Licensing Policy (HELP) aims to boost domestic production. The national policy on biofuels frames and subsidises the use of several types of biomass for fuel.
  4) Energy efficiency measures include demand-side management through the Smart Meter Programme and industrial energy efficiency certifications delivered by the third cycle of the Perform, Achieve and Trade (PAT) scheme.
- Key challenges include: 1) Improving the financial performance of distribution companies; 2) mitigating rising oil prices and import dependence; 3) expanding energy access; 4) integrating large variable renewable energy capacity.

KEY METRICS

Industrial sector (% of GDP)	29.61	GDP per capita, PPP US$ (GDP Group)	6,571 (III)
Energy intensity (koe per US$)	0.08	Diversity of international energy suppliers	High (HHI = 800)
Population with access to electricity (%)	85	Access to clean cooking (%)	41
Household electricity prices (US$/kWh)	0.08	Rate of transmission and distribution losses (%)	19.93
CO_2 intensity (kCO_2 per US$)	0.29	GHG emission growth rate 2010 – 2014 (%)	6.09

ENERGY PROFILE

<u>**Portions for CAT**</u>

- CAT 1 – Module 1, 2 3
- CAT 2 – Module 4, Module 5 and partly Module 6
- FAT - All modules from 1-8.

Question pattern

- CAT 1 – Part- A (5x10=50 Marks) (Five out of Six questions with 10 marks each).
- CAT 2 (open book exam) – Part- A (2 x15 = 30) Part- B (1x20=20), Total = 50 marks
- FAT – (10 Q's out of 12) x 10 marks = 100 marks

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Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector

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HIGHLIGHTS

- Hydrogen could be a potential contributor to a more sustainable transport system.
- Major challenges are to reduce costs and to build up infrastructure.
- A stable policy framework with technical and environmental standards is essential.
- For electrolysers economies-of-scale and learning effects have to be harvested.
- The best prospects for hydrogen and fuel cells in mobility are in large capacity vehicles.

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ABSTRACT

Hydrogen and fuel cell vehicles are often discussed as crucial elements in the decarbonisation of the transport systems. However, in spite of the fact that hydrogen and fuel cell vehicles have a long history, they are still seen only as a long-term mobility option. The major objective of this paper is to analyse key barriers to the increasing use of hydrogen and fuel cell vehicles. A special focus is put on their economic performance, because this will be most crucial for their future deployment. Mobility costs are calculated based on the total cost of ownership, and future developments are analysed based on technological learning. The major conclusion is that to achieve full benefits of hydrogen and fuel cells in the transport sector, it is necessary to provide stabile, long-term policy framework conditions, as well as to harmonize actions across regions to be able to take advantage of economies of scale.

Introduction

The current transport system, relying mostly on fossil energy carriers, is not sustainable. The rising greenhouse gas (GHG) emissions from the transport sector are an increasingly important subject of discussions and regulations all over the world, particularly in Europe.

Moreover, reduction of the air pollution is becoming a regulatory priority, especially in urban areas. Currently, more than 80% of the world's urban population is exposed to air quality level below minimum standards. According to the World Health Organization, air pollution caused about 4.2 million premature deaths worldwide [1].

In Europe, the transport sector is responsible for about a third of total energy use and about a quarter of total

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greenhouse gas emissions. The largest amount of these emissions is coming from the road transport, especially passenger cars [2].

To reach a significant emission reduction in the transport sector, different policies and measures are already implemented and targets for the future are set. A major effort is put on the increasing use of energy efficient and alternative automotive powertrains, as well as low-carbon fuels. Among these, hydrogen and fuel cell vehicles are often discussed as crucial elements in the decarbonisation of the transport systems.

Over the last decade, the major attention has been given to electric vehicles (EVs). Since there are different types of EVs, their potential to the reduction of GHG emissions is very different. For the reduction of GHG emissions, of especial interest are battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). These vehicles have zero emissions at the point of use, and could significantly reduce total emissions if electricity and hydrogen are produced from renewable energy sources [3]. In contrary, to BEVs, which are almost a mature technology used in many countries, FCVs are still seen as a future technology. Although the number of BEVs has been increasing over the last years, especially in China, the USA and the EU, there are still different weaknesses related to this technology. Most important are: (i) short driving range, (ii) long charging time, (iii) high investment costs, and (iv) limited infrastructure. In the case of BEVs, the battery is the major challenge. To increase the driving range of BEVs, it is necessary to increase battery capacity, and this lead to increasing weight of vehicles and consequently to efficiency reduction. The most significant advantage of hydrogen is high energy density.

Although, hydrogen and fuel cells are often seen as a future solution, it is important to state that they have a long history. Hydrogen was identified as a distinct element already in 1766. Almost since its discovery, hydrogen was seen as important part of the future energy system. Already in 1874, the French writer Jules Verne in his novel "The Mysterious Island" saw hydrogen and oxygen as the energy sources of the future [4].

The first demonstrations of water electrolysis were in the beginning of the 19th century. Hydrogen was used as fuel in one of the first internal combustion engine (ICE) vehicles, already over 200 years ago [5]. The major steps and milestones in the development of hydrogen and fuel cell vehicles are depicted in Fig. 1.

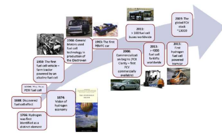

Fig. 1 – Major historical steps and milestones in the development of hydrogen and fuel cell vehicles.

Many times hydrogen was identified as a critical and indispensable element in the future low-carbon energy system [6–10]. Until now, there have been many "hydrogen hypes" but the reality is that hydrogen is currently used mostly just for different industry purposes. With the approximately 13 000 FCVs, hydrogen use in the transport sector can be neglected.

However, there are new prospects for hydrogen and fuel cell vehicles. Large-scale production of fuel cell has begun [11]. Hydrogen and fuel cells are being commercialised in several sectors, from portable electronica to forklift trucks [12,13]. Moreover, with the increasing use of renewable energy sources (RES) in electricity generation, as well as increasing need for flexible and storable energy carriers [14,15] hydrogen and fuel cell face again increasing popularity. Demand for hydrogen has grown more than three times since 1975 [5].

Over the last years, many aspects of hydrogen use have been analysed in scope of different studies, indicating its environmental benefits in the transport sector, as well as the high corresponding mobility costs in comparison to conventional and other electric vehicles. Miotti et al. [3] assessed the environmental impacts and costs of a polymer electrolyte membrane fuel cell system for use in passenger FCVs conducting a detailed cost- and life cycle assessment in two scenarios. According to the results of this study, FCVs can decrease life cycle GHG emissions by 50% compared to gasoline ICE vehicles if hydrogen is produced from renewable electricity. Ajanovic and Haas [16] have investigated the overall environmental impact of electric vehicles in different regions indicating relation between the environmental benignity of electric vehicles and electricity mix, travel activity, as well as emissions related to car production and recycling, showing that the highest sensitivity is with respect to the electricity mix. Moreover, Liu et al. [17] have shown that even when FCVs are fuelled by hydrogen produced via steam reforming of natural gas, 15%–45% lower well-to-wheels GHG emissions could be reached compared to conventional gasoline ICE vehicles. However, also here the results are sensitive to the source of electricity used for hydrogen compression or liquefaction. Some papers have investigated suitability of hydrogen use in the transport systems in specific countries or regions (e.g. Malaysia [18], China [19,20], Austria [21], Canada [22], Korea [23], Norway [24]) with the goal to provide recommendations to national policy makers and relevant government bodies. Moreover, some papers are providing assessment of hydrogen and fuel cells in the global energy system [25]. Common conclusion of most studies is that future role of hydrogen is very dependent on predictable and consistent policy framework.

Ajanovic et al. [26] provide a comprehensive review of the most important issues related to the economic and environmental assessment of battery electric- and fuel cell vehicles. Beside the transport sector, Staffell et al. [25] analyse possible role of hydrogen in the provision of also other energy services such as electricity, heat, and energy storage with the special critic on the stop-and-go policies.

The major objective of this paper is to analyse perspectives and key barriers to the increasing use of hydrogen and fuel cell vehicles with a special focus on their economic performance. Moreover, required policy framework and targets set for the

uptake of hydrogen and FCVs are analysed and documented. Mobility costs are calculated based on the total cost of ownership, and future developments are analysed based on technological learning, as well as in harvesting economics-of scale.

Hydrogen and fuel cell vehicles: state of the art

For a long time hydrogen has been considered as a future energy carrier which can contribute significantly to the decarbonisation of the energy system. Its special role has been seen in its possible contribution to the transition towards a clean, emission-free and, hence, considerably more sustainable transport system. However, in spite of the fact that hydrogen and FCVs have some advantages in comparison to other fuels and automotive technologies, they are currently still rather a long-term option for mobility.

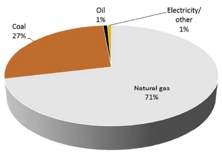

Fig. 2 – Hydrogen production worldwide by energy sources (Data source [5]).

Hydrogen production and use

Hydrogen is a secondary energy carrier, which can be produced from any primary energy source, e.g. fossil energy, nuclear or renewable. As an emission-free energy carrier, it can tackle some of the critical energy and environmental challenges. It can be produced using various energy sources and production methods, see Table 1. However, these different production methods are on different stages of maturity.

Currently, hydrogen production by steam reforming of natural gas is most widely used production method, see Fig. 2. About 71% of hydrogen is produced in this way. However, using this production method per every kilogram of hydrogen about 10 kg of CO_2 are produced [5].

For the future of special interest is hydrogen production from RES. Electrolysis is only mature technology, which can use RES for hydrogen production. Globally, this process accounts only for 0.1% of hydrogen production. Moreover, currently electricity used in this process is mostly not from RES. Besides electricity, this process requires also water. For every kg of hydrogen, about 9 L of water are needed, what can be an issue in water-stressed areas [5].

The major reason for the currently high use of natural gas in hydrogen production is the relatively low production costs. As shown in Fig. 3, the range of hydrogen production costs using steam reforming of natural gas is currently significantly lower than hydrogen production by electrolysis. This figure shows the range of the costs from literature [3–5,15] with different energy prices in different regions and different assumptions (e.g. for electricity price, natural gas prices, with or without costs for carbon capture and storage, etc.). The bold lines present the costs for hydrogen production by steam reformers and electrolysers resulting from own calculations based on Ajanovic/Haas [15]. Major input data used for our calculations are provided in Table 2. We did not consider carbon capture and storage costs.

Summing up, the current costs of hydrogen production are lowest in large centralized gas reformers and they are more expensive in any electrolyser system. However, in the future, on the one hand, no remarkable further investment costs reductions are expected for the gas reformers due to the maturity level. Moreover, the prices for natural gas will be increasing, also due to higher CO_2 costs. On the other hand, significant learning effects for electrolysers are expected, and the electricity costs from the variable renewables could be very low, if the hydrogen production takes place at times of excess electricity.

However, currently about one-third of global hydrogen supply is covered with hydrogen produced as a by-product from facilities and processes designed to produce something else [5].

Since 1975 demand for hydrogen has been increasing continuously, see Fig. 4. Current demand for hydrogen in its pure form is around 70 million tonnes per year. As this hydrogen is almost entirely produced from fossil fuels,

Table 1 – Hydrogen production [27].

	Commercial availability	Feedstock/energy source	Production model
Steam reforming	Most common	Natural gas	Centralized or decentralized
Electrolysis	Special applications	Electricity	Centralized or decentralized
Gasification	R&D stage	Biomass	Centralized
Biological	R&D stage	Solar energy and/or organic waste	Centralized
Photochemical	R&D stage	Solar energy	Centralized
Thermochemical	R&D stage	Solar or nuclear energy	Centralized

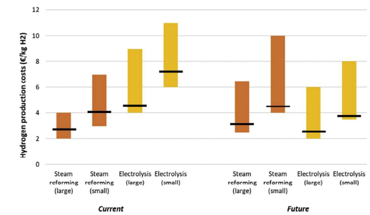

Fig. 3 – Range of current and future hydrogen production costs for small and large steam reformers and electrolyser systems (Data sources: [3–5,15], own analyses).

Table 2 – Input data for our calculation of hydrogen production costs in Fig. 3 (bold lines).

	Steam reforming		Electrolysis	
	Large	Small	Large	Small
Current investment costs (€/kW)	1400	2000	1550	2400
Future investment costs (€/kW)	1200	1500	1050	1600
Current O&M costs (€/kW)	30	60	15	30
Future O&M costs (€/kW)	24	50	12	25
Current full-load hours	6000	6000	2000	2000
Future full-load hours	6000	6000	2800	2800
Current efficiency	0.65	0.55	0.7	0.6
Future efficiency	0.7	0.6	0.75	0.65
Current energy price (cent/kWh)	3	3	2	2
Future energy price (cent/kWh)	5	5	2	2

production of hydrogen is responsible for about 830 million tonnes CO_2 per year [5].

Currently, the largest amount of hydrogen produced is used for different industry purposes, mostly oil refining and ammonia production. However, in principle hydrogen is a versatile energy carrier that can be used for very different purposes. It can enable diversification of energy carriers used in the transport sector, which is almost completely dependent on fossil fuels. Yet, current hydrogen use in the transport sector is less than 0.01 million tonnes hydrogen per year [5].

Fuel cell vehicles

Today, in the transport sector only a very small amount of hydrogen is used due to the low number of fuel cell vehicles. Globally, about 13 000 FCVs were in operation in the year 2019, mostly in the USA, Japan, China and Europe [28], see Fig. 5.

Fuel cell vehicles are currently neither economically competitive with internal combustion engine vehicles nor with other types of electric vehicles and powertrains. However, in opposite to electricity, hydrogen has potential to be used in different transport applications when longer driving range and higher load capacity are required.

Hydrogen in combination with fuel cell is already used in demonstration projects and niche markets for trucks and buses, as well as trains. Hydrogen fuel cell forklifts are already commercial and about 25 000 forklifts are already in use worldwide. The number of fuel cell buses is also increasing due to different demonstrations projects. Globally, more than 10 companies are producing fuel cell buses. Currently more than 500 buses, 400 trucks and 100 vans are in use [5].

At the same time, at least some progress in the deployment of hydrogen infrastructure can be noticed. Japan, Germany and the USA are the countries with the highest number of hydrogen refuelling stations (HRS) worldwide. Many European countries have at least few hydrogen refuelling stations, see Fig. 6.

Major reasons for emerging expectations regarding hydrogen

Recent developments, such as the slow penetration of battery electric vehicles, the unsolved problem with battery recycling, the imbalance between electricity supply and demand due to the increasing use of variable renewable energy sources, demonstrate the urgent need for additional technologies, measures and policies to be on track with the emission reduction targets set by policy makers.

In the following we explain the two major reasons for recently increasing expectations with respect to hydrogen which are: (i) the need to find solutions for the looming excess electricity generation from variable RES and (ii) the restricted capability of EVs to provide solutions in the large vehicle segments.

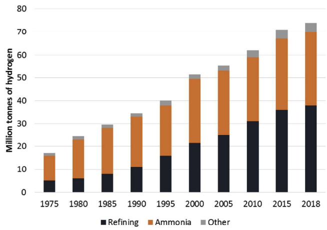

Fig. 4 – Development of the demand for hydrogen since 1975 by type of use (Data source [5]).

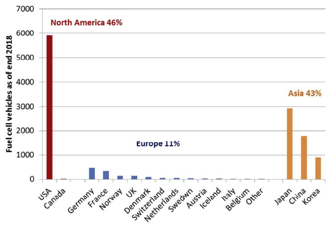

Fig. 5 – Fuel cell vehicles as of end 2018 (Data source [28,29]).

RES integration

Looking at the worldwide future GHG emissions expected it is obvious that emission reduction goals are ambitious. Huge additional efforts are needed for a profound transformation of the energy system including transition from carbon-based energy sources to clean and sustainable ones. Hydrogen has the potential to be a powerful enabler in this energy transition, as it offers a clean, sustainable, and flexible option for overcoming multiple obstacles that stand in the way of a resilient and low-carbon economy [8].

The increasing electricity generation from variable RES in the power sector, which is necessary for the transformation of the energy system towards a more sustainable one, lead to an increasing imbalance between supply and demand. One of the options to solve this challenge is to use hydrogen as a long-term electricity storing option, see Fig. 7.

Hydrogen has potential to improve economic efficiency of investments in renewables, enhance security of power supply and serve as a carbon-free long-term storage [8]. In the energy transition, it could enable large-scale, efficient renewable energy integration, and link different energy sectors,

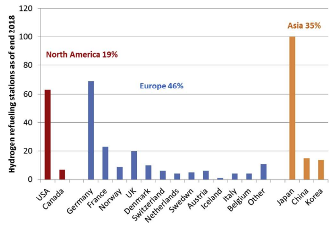

Fig. 6 – Number of hydrogen refueling stations at the end of 2018 (Data source [28]).

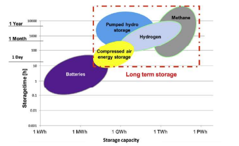

Fig. 7 – Different storage options [30,31].

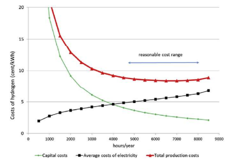

Fig. 8 – Hydrogen production costs depending on full-load hours.

providing needed flexibility to maintain the resilience of the system.

One of the major challenges related to hydrogen-based energy storage systems is rather low efficiency over the whole conversion chain, mostly about 20%–30% [32], due to several energy transformation steps. Other important challenge is to have enough full-load hours per year to make hydrogen-based energy storage system economical. Electrolysers have significant investment costs, and to make them cost effective they have to be operated for a sufficient number of hours per year. However, the basic idea is to store surplus electricity from RES, and periods of availability of surplus electricity are occurring for a limited amount of time.

The relation between hydrogen costs, electricity price and full-load hours of electrolyser is depicted in Fig. 8. The hydrogen costs are calculated as:

$$C_{H_2} = \frac{\frac{C_c + C_{O\&M}}{T} + C_E}{\eta} \ (\mathrm{EUR/kWh}) \quad (1)$$

where, C_C is the capital cost, $C_{O\&M}$ are the operating and maintenance costs, T is the number of full-load hours per year, C_E is the electricity costs, and η is the efficiency of the electrolyser, see Refs. [33].

For this calculation, large-scale electrolyser with investment costs of 1550 EUR/kW, a depreciation time of 25 years, and an efficiency of 70% is taken. The average electricity costs are calculated from the electricity market prices in Germany (EPEX) from 2015 to 2018, calculating the average of prices below specific full-load hours.

As seen from Fig. 8 the capital costs per kWh produced are declining, and the average electricity costs are increasing with full-load hours. Below 2000 full-load hours per year, hydrogen costs are extremely high. The curve starts to become rather flat starting from about 3000 full-load hours per year. However, the cheapest hydrogen costs could be reached between about 4500 and 8000 full-load hours.

To make the energy supply chain more energy efficient, re-electrification of hydrogen can be replaced with the direct use of hydrogen in the transport sector. Hydrogen in combination with fuel cell vehicles could have an important role in the transport decarbonisation. In contrary to BEVs, which are most suitable for small cars, FCVs can be easily used in much broader car-segments, e.g. medium to large cars, buses, trucks, fleets, etc., where a large number of kilometres per day is required.

Limits and restrictions for BEVs

In principle rechargeable EVs could be a good solution for the future. Yet, there is one considerable problem, or at least a challenge: the battery. The battery performances have to be improved and costs reduced. The major problems related to battery are high sensitivity, long charging time, low energy density, and resulting high weight. Actually, there are few problems.

For example, to have vehicle with the range of about 500 km, with BEVs, lithium-ion battery system has a weight of 830 kg, and with FCVs and hydrogen (compressed to 700 bar), energy storage weigh is about 125 kg. Weight of energy storage system of BEVs and FCVs in comparison to conventional ICE vehicles is shown in Fig. 9.

Moreover, an important challenge for the future will be sustainable battery production and recycling [16]. However, thanks to overhead lines electricity use in the transport sector, e.g. in trains or trolleybuses, have already long and successfully tradition.

Major impediments for hydrogen and fuel cell vehicles

Hydrogen has some very good characteristics and a significant potential to contribute to the energy transition and emission reduction, especially in the transport sector. However, there are some key barriers that have to be overcome before the full benefits of hydrogen and FCV can be materialized. The major challenges for hydrogen and FCVs could be divided in the three major categories: (i) economics, (ii) infrastructure, and (iii) policy framework.

Economics

Affordability is one of the major barriers for the broader use and faster penetration of FCVs. Mobility provided by FCVs and hydrogen is still very expensive and not competitive with conventional cars, as well as with other alternatives such as rechargeable electric vehicles.

For the commercialization of FCVs most important is to reduce investment costs. Assuming ambitioned diffusion of alternative automotive powertrains announced in policy targets (e.g. The Paris Declaration on Electro-Mobility and Climate Change and Call to Action [35]) and depicted in scenarios (e.g. Ref. [36]), it can be expected that a further cost reduction of FCVs through technological learning will take place. Technological learning is calculated using following equation:

$$IC_{New}(t) = IC(t_0) \cdot \left(\frac{x_t}{x_{t_0}}\right)^{-b} \quad (2)$$

Where $IC_{New}(t)$ is investment cost of new technology, b is a learning index, $IC(t_0)$ is investment cost at the time t_0, and x refers to cumulative capacities installed at time t and t_0, see Ref. [15].

Since for conventional car further technological learning is not expected, the price difference between ICE vehicles and FCVs will decrease over time, see Fig. 10.

Total mobility costs of FCVs per kilometre driven are dependent on purchase price of vehicles, hydrogen costs and other operating and maintenance costs, energy efficiency of vehicles, specific number of kilometres driven per year, lifetime of vehicles, as well as interest rate. Currently, the largest impact on the total mobility costs has purchase price of vehicles. Fig. 11 shows current and future total mobility costs of FCVs in comparison to conventional ICE vehicles. Driving range of 12 000 km per year over 7 years is assumed. A sensitivity analysis is documented in Ajanovic and Haas [26].

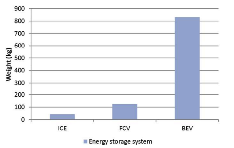

Fig. 9 – Weight of energy storage system in vehicles, driving range 500 km (Data source:[34]).

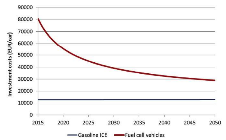

Fig. 10 – Development of the investment costs of vehicles due to technological learning (for average car size of 80 kW) [15,37].

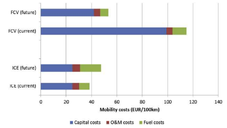

Fig. 11 – Total costs of mobility with FCVs in comparison to ICE vehicles (car power: 80 kW) incl. taxes.

Although, total mobility costs of FCVs are currently very high compared to conventional ICE vehicles, some car manufactures have already moved from prototypes to products. Different models of FCVs are already available on the market (e.g. Toyota Mirai, Honda Clarity, Hyundai Tucson, etc.) With the exception of costs, FCVs are comparable to conventional fossil-fuelled vehicles with respect to driving range, which is between 400 and 550 km per tank, as well as regarding the refuelling time of 3–5 min. In addition, FCVs are quiet and have zero-emissions at the point of use. Even, if hydrogen produced by steam reforming of natural gas is used, FCVs could have compete with emissions from ICE vehicles [3,17].

Deployment of infrastructure

Another important barrier for the adoption of FCVs is requirement for new and expensive infrastructure. Currently there are worldwide just 376 hydrogen refuelling stations. As shown in Fig. 6, there are just five countries with more than 20 HRS.

Moreover, also the utilisation of HRS is currently low, mostly in the range from 10 to 90 FCVs per station [5]. In the future, 2500–3500 FCVs per station are expected [38].

The current deployment of infrastructure is limited mostly to different pilot projects. At this early development stage, it is easier to enable infrastructure for FCV fleets, such as buses and different kind of delivery and service vehicles, which have determined driving routes and can use a central location to refuel. These local infrastructure and related knowledge gained should be used in the development of a broader cross-countries infrastructure network. To achieve this it is important to develop common standards and regulations regarding safety, maintenance, payment, etc. Through the modularisation of technical components and by series production, infrastructure costs could be significantly reduced. However, in the early stage major risk is that refuelling stations will be under-utilized, so that financial support for the deployment of infrastructure is essential.

As discussed by Ogden [39] hydrogen refuelling infrastructure should offer: (i) coverage – enough stations to enable convenient travel, (ii) capacity to meet growing hydrogen demand, (iii) positive cash flow for station owners and network-wide supply, and (iv) cost competitiveness with gasoline (on an EUR per kilometre bases). To meet these goals, coordinated deployment actions, geographically and over time, are needed.

Policy framework and future targets

The future role of hydrogen and fuel cell applications in the transport sector is very dependent on the policy framework and future targets. However, implemented policies, investments, as well as future targets differ significantly from country to country. A relatively low number of policies is applied directly to hydrogen and fuel cell technologies. The policy support for hydrogen and fuel cell vehicles as well as corresponding infrastructure is driven mainly by different national priorities such as air quality, climate change, energy security, etc. [25]. There is also broad portfolio of policies that indirectly support use of hydrogen and FCVs, e.g. standards for CO_2 emissions from new cars, ban of ICE vehicles, etc.

The major problem for the faster and broader deployment of hydrogen and FCVs is a lack of regulations as well as coordinated action between different stakeholders. In addition, technology standards are needed, which would drive economies of scale and reduce risks of the investment. There is still lack of investments in hydrogen and fuel cells in most of countries and regions. Although, the European Commission acknowledges that the market uptake of alternative vehicles and infrastructure roll-out are fundamentally connected, its proposal for post-2021 CO_2 targets for passenger cars and vans does not link the availability of charging and refuelling infrastructure to the future CO_2 targets. However, to be able to reflect the reality of the market, Europe's long-term climate objectives should be linked to future infrastructure availability and consumer acceptance [40].

Further research and developments projects are needed to learn about new technology and increase public acceptance. However, from societies point of view most important is to have clear long-term vision and a stable policy framework. Major elements of needed policy framework are depicted in Fig. 12.

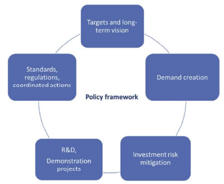

Fig. 12 – Policy framework required for a further uptake of FCVs.

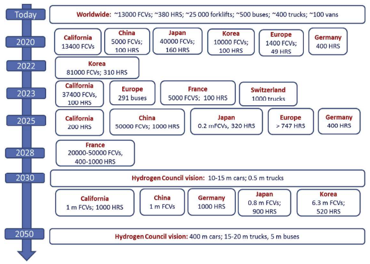

Fig. 13 – Announced targets and visions for fuel cell vehicles [5,25,28,29].

Due to the currently high costs of hydrogen and FCVs, their market uptake is directly correlated to GDP per capita. The highest investment in hydrogen and FCVs are currently concentrated in few countries, the USA, Japan, China, Korea and few EU countries.

The major visions and announced targets for FCVs and HRS are depicted in Fig. 13. The highest future targets regarding the number of FCVs are set in California and China, 1 million FCVs by 2030, followed by Japan and Korea.

Conclusions and outlook

Hydrogen in combination with FCVs is seen as a potential contributor to the transformation of the current fossil fuels based transport system towards a more sustainable one. Interest in this technology had already many ups and downs over time. However, with the increasing use of variable RES and consequently increasing need for additional storage- and sector coupling options, interest in hydrogen and fuel cells rise again.

In the category of passenger cars, FCVs are in strong competition with conventional ICE vehicles, as well as with other electric vehicles. There are still three major challenges, which have to be solved in the future: reduction of investment costs of cars, infrastructure development and stable policy framework conditions that give predictable support to emerging technologies and can reduce risks related to long-term investments. Appropriate policies should increase confidence in alternative technologies, and including externalities, they should make low-carbon transport options more competitive.

From the current point of view, fuel cells could have best prospects in vehicles with high capacities such as trucks and buses, where they have a better performance in comparison to BEVs. Although, the current market share of fuel cell busses is still very small (just about 500 around the world), recent investments and goals set indicate a shift of mass transit to fuel cell mobility solutions. Fuel cell trains are already cost competitive with diesel trains [8].

However, to achieve full benefits of hydrogen and fuel cells in the transport sector, it is necessary to provide stable, long-term policy framework conditions along the whole energy system, as well as to harmonize standards across regions and sectors to be able to take advantage of economies of scale.

Nomenclature

BEVs	Battery electric vehicles
CO_2	Carbon dioxide
EVs	Electric vehicles
EPEX	European Power Exchange
FCVs	Fuel cell vehicles
GDP	Gross domestic product
GHG	Greenhouse gas emissions
HRS	Hydrogen refuelling station
ICE	Internal combustion engine
RES	Renewable energy sources
R&D	Research and development

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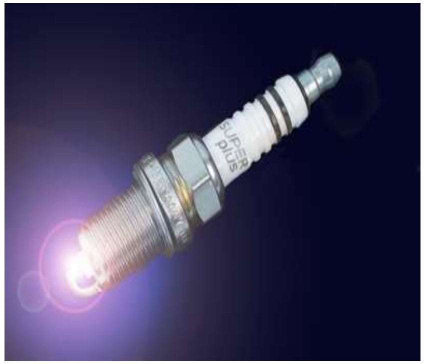
Hydrogen as IC engine fuel

Combustive properties of hydrogen

- Wide range of flammability
- Low ignition energy
- Small quenching distance
- High autoignition temperature
- High flame speed at stoichiometric ratios
- High diffusivity
- Very low density



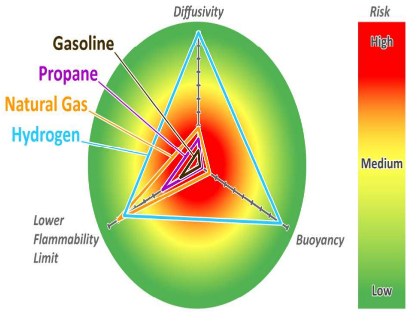
- ***Wide Range of flammability***

  1) Hydrogen has a wide flammability range in comparison with all other fuels.

  2) hydrogen can run on a lean mixture.

  3) Lean Mixture: one in which the amount of fuel is less than the theoretical, stoichiometric or chemically ideal amount needed for combustion with a given amount of air.

  4) This is why it is fairly easy to get an engine to start on hydrogen.



- ***Low ignition energy***

  _1) The amount of energy needed to ignite hydrogen is about one order of magnitude less than that required for gasoline.

  2) This enables hydrogen engines to ignite lean mixtures and ensures prompt ignition.

  3) low ignition energy means that hot gases and hot spots on the cylinder can serve as sources of ignition, creating problems of premature ignition and flashback.

  4) Any mixture can be ignited by a hot spot

- ***Small quenching distance***

  1) Hydrogen has a small quenching distance, smaller than gasoline.

  2) Hydrogen flames travel closer to the cylinder wall than other fuels before they extinguish.

  3) it is more difficult to quench a hydrogen flame than a gasoline flame.

  4) The smaller quenching distance can also increase the tendency for backfire since the flame from a hydrogen-air mixture more readily passes a nearly closed intake valve, than a hydrocarbon-air flame.

- ***High autoignition temperature***

  1) Hydrogen has a relatively high autoignition temperature.

  2) Autoignition temperature is an important factor in determining what compression ratio an engine can use, since the temperature rise during compression is related to the compression ratio.

  3) The high autoignition temperature of hydrogen allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine.

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

where:

V_1/V_2	= the compression ratio
T_1	= absolute initial temperature
T_2	= absolute final temperature
γ	= ratio of specific heats

- ***High flame speed at stoichiometric ratios***

1) Hydrogen has high flame speed at stoichiometric ratios.
2) The order of magnitude higher (faster) than that of gasoline
3) This means that hydrogen engines can more closely approach the thermodynamically ideal engine cycle.
4) At leaner mixtures, however, the flame velocity decreases significantly.

- ***High diffusivity***

1) *ability to disperse in air is considerably greater than gasoline.*
2) it facilitates the forma-tion of a uniform mixture of fuel and air
3) if a hydrogen leak develops, the hydrogen disperses rapidly. Thus, unsafe conditions can either be avoided or minimized.

- ***Low density***

1) Hydrogen has very low density.
2) a very large volume is necessary to store enough hydrogen to give a vehicle an adequate driving range.

- the energy den-sity of a hydrogen-air mixture, and hence the power output, is reduced.

The theoretical or stoichiometric combustion of hydrogen and oxygen is given as:

$2H_2 + O_2$	$= 2H_2O$
Moles of H_2 for complete combustion	= 2 moles
Moles of O_2 for complete combustion	= 1 mole

Because air is used as the oxidizer instead oxygen, the nitrogen in the air needs to be included in the calculation:

Moles of N_2 in air	= Moles of O_2 x (79% N_2 in air / 21% O_2 in air)	
	= 1 mole of O_2 x (79% N_2 in air / 21% O_2 in air)	
	= 3.762 moles N_2	
Number of moles of air	= Moles of O_2 + moles of N_2	
	= 1 + 3.762	
	= 4.762 moles of air	
Weight of O_2	= 1 mole of O_2 x 32 g/mole	
	= 32 g	
Weight of N_2	= 3.762 moles of N_2 x 28 g/mole	
	= 105.33 g	
Weight of air	= weight of O_2 + weight of N	(1)
	= 32g + 105.33 g	
	= 137.33 g	
Weight of H_2	= 2 moles of H_2 x 2 g/mole	
	= 4 g	

Stoichiometric air/fuel (A/F) ratio for hydrogen and air is:

A/F based on mass:	= mass of air/mass of fuel
	= 137.33 g / 4 g
	= 34.33:1
A/F based on volume:	= volume (moles) of air/volume (moles) of fuel
	= 4.762 / 2
	= 2.4:1

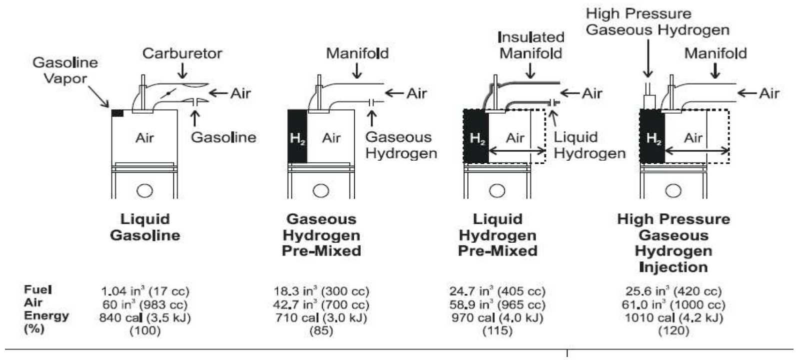
The percent of the combustion chamber occupied by hydrogen for a stoichiometric mixture:

% H_2	= volume (moles) of H_2/total volume	(2)
	= volume H_2/(volume air + volume of H_2)	
	= 2 / (4.762 + 2)	
	= 29.6%	

- When compared to gasoline

The theroretical A/F ratio is 34:1, which means for every gram of hydrogen requires 34 grams of air.

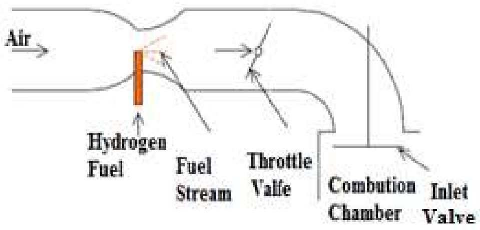
Which is 14.7:1 for gasoline



Fuel induction techniques

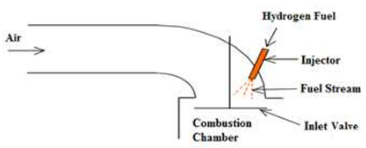
1) Carburetion

- Similar to the gasoline engine
- Does not require a high pressure injector
- Susceptible to irregular combustion due to preignition and backfire problem
- Power output is 15% lower than the gasoline engine.



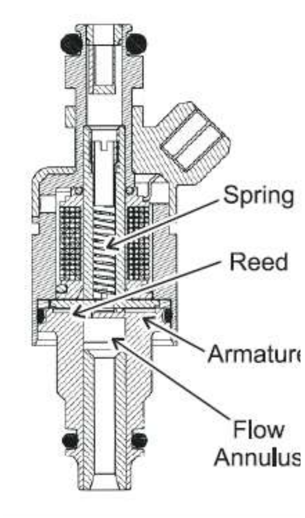
2) Inlet manifold injection

- Injecting fuel directly to the intake manifold
- The timing is controlled so that hydrogen is not injected to manifold until the beginning of the intake stroke.
- The air that is injected separately at the beginning of the intake stroke dilutes the hot residual gases and cools of the hot spots.



3) Inlet Port Injection

Fuel and air are injected from separate ports into the combustion chamber during the intake stroke, not premixed in the intake manifold



A fuel injection system performs two basic functions: fuel pressurization and fuel metering.
When dealing with gaseous fuels, only the metering function is required to be carried out by the injection system as the pressurization is performed separately
The electronic fuel injector system meters the hydrogen to the cylinder

The electronic fuel injection (EFI) system meters the hydr gen to each cylinder. This system uses individual electron fuel injectors (solenoid valves) for each cylinder and a plumbed to a common fuel rail located down the center the intake manifold. Whereas the CVI system uses consta injection timing and variable fuel rail pressure, the EFI sy tem uses variable injection timing and constant fuel ra pressure.

4) Direct cylinder injection

Premature ignition during the intake stroke and back fire can be stopped completely if the fuel is directly injected after the intake valve is closed.

The power output can also be increased (20% more than gasoline engine)

S.Furuhama in Musashi Institute of Technology right from 1970's

2 stroke engines fuelled by high pressure hydrogen. Platinum wire wrapped in porcelain for hot ignition.

- 1974 - Musashi-1[2]
- 1975 - Musashi-2
- 1977 - Musashi-3
- 1980 - Musashi-4
- 1982 - Musashi-5
- 1984 - Musashi-6
- 1986 - Musashi-7
- 1990 - Musashi-8
- 1994 - Musashi-9
- 1997 - Musashi-10

5) Timed Manifold injection

IIT- Hydrogen gas was directly supplied into the cylinder after the closure of the intake valve by introducing it at the appropriate time in the manifold at the appropriate location after the potential hot spots are cooled.

TMI required less sophisticated design (avoidance of sever thermal environment- causing leaking of the injector tip.

Fuel injection delayed to a point after air intake has started (Resulting in cooling of the hot spots)

Other methods to avoid preignition

- ***Thermal Dilution:***

Exhaust gas recirculation- recirculated a portion of th exhaust gases back into the intake manifold. The introduction of exhaust gases reduces the temperatures of hotspot, thereby preignition.Nox etc. Power output is however reduced

Water Injection- Injecting water to Hydrogen stream prior to mixing with air than injecting it with in the manifold. Water can mix with oil.

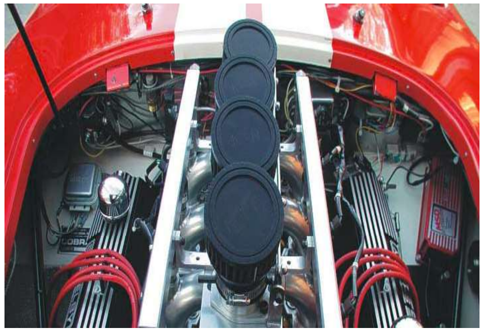
- ***Engine Design***

A disc shaped combustion chamber(flat piston and chamber ceiling) which can reduce turbulence within the chamber. The disc shape facilitates low radial and tangential velocity components.

Large bore to stroke ratio to accommodate wider range of flame speeds.

Cooling system to provide uniform flow to all locations.

Two exhaust valves as opposed to a single valve for effective scavenging

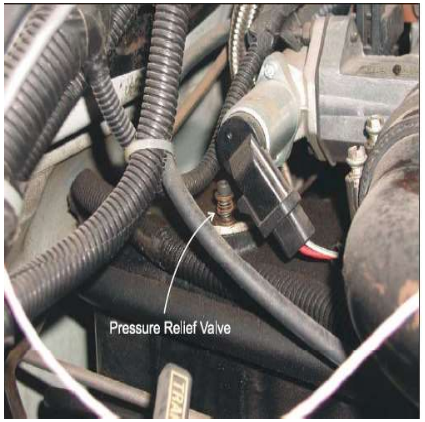


Ignition systems

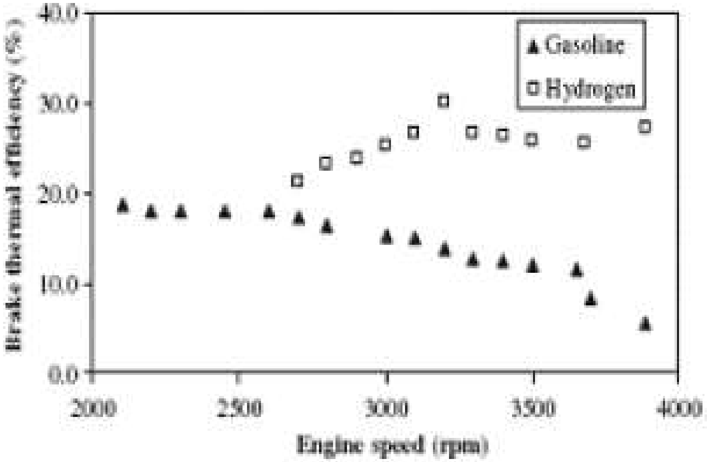
- Igniting Hydrogen is easy, gasoline ignition systems can be used. The flame velocity is reduced, dual spark plug is preferred.
- Spark plugs must have cold rating and non platinum tips (the one that can transfer heat from plug tip to the cylinder head quickly than hot rated plugs).
- Carbon deposits not to accumulate.
- Platinum must be avoided since platinum being a catalyst caused hydrogen to oxidize with air.

Crank case ventilation

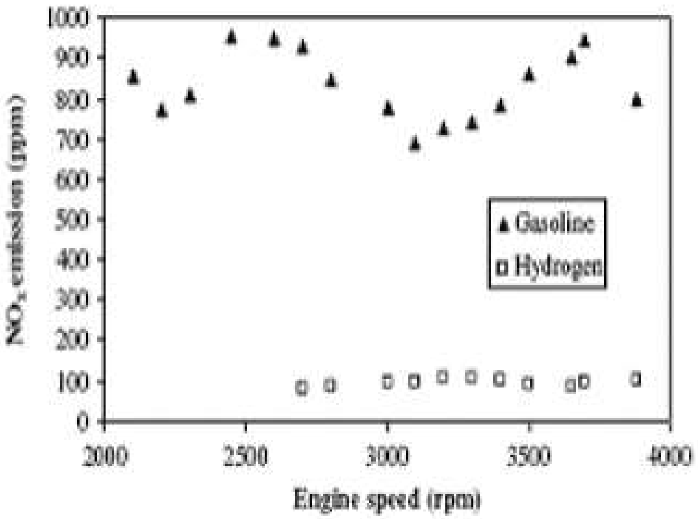
- Any unburnt hydrogen entering crank case has higher chance of igniting.
- Engine firing in crank case can occur.
- In such case a pressure relief valve is installed to relieve any pressure due to crank case ignition.



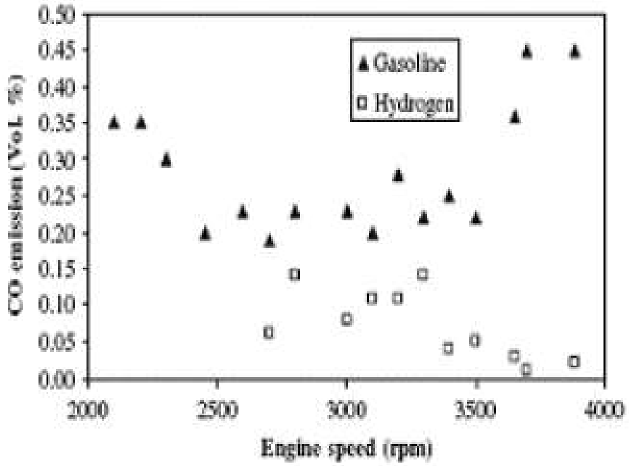
Brake Thermal Efficiency



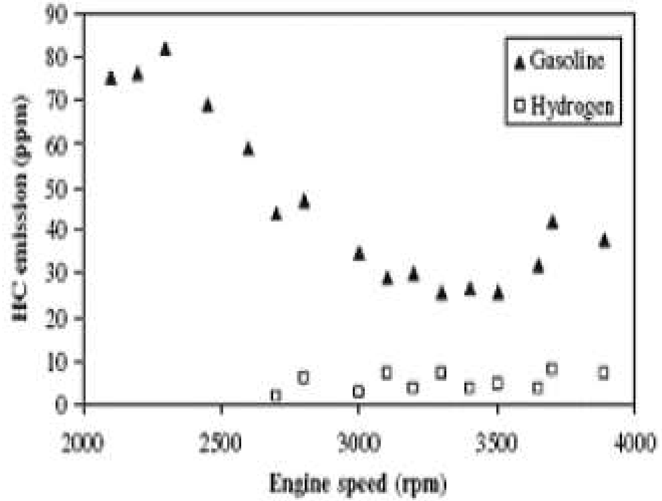
Nox Emission



CO Emission

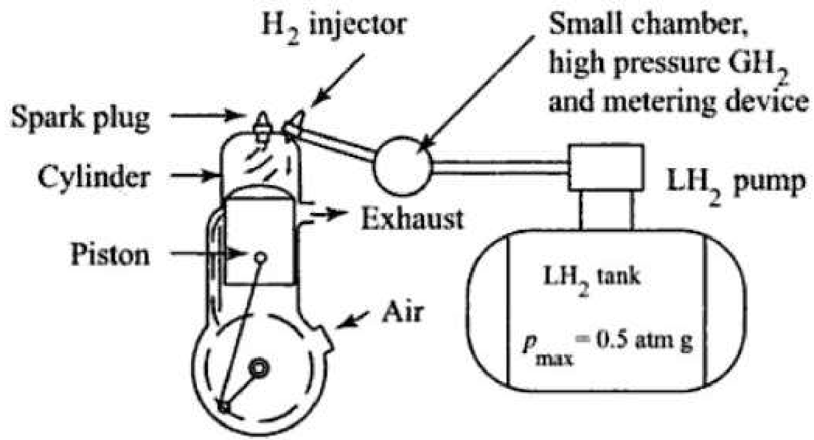


HC Emission

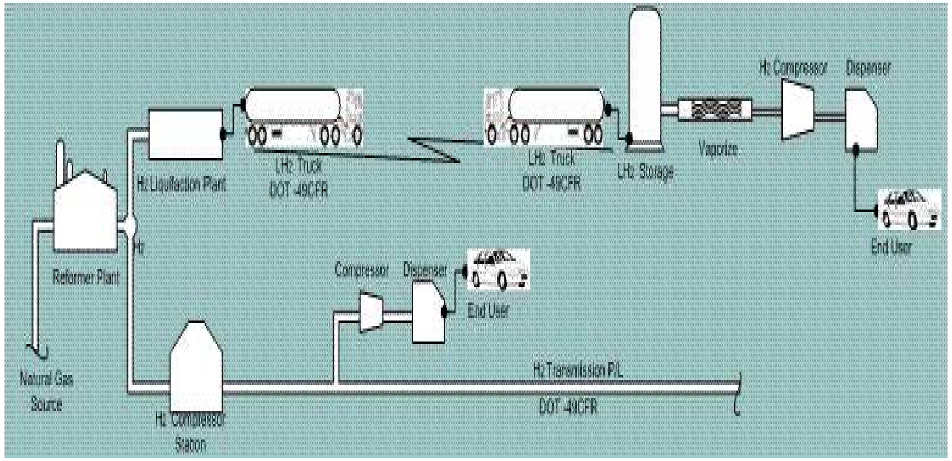


Combustion characteristics of hydrogen and its impact on emissions are given below;

- Hydrogen octane rating is 106 RON making it more suitable for spark-ignited engines.
- The laminar flame speed of hydrogen is 3 m/s, about 10 times that of gasoline and methane.
- Hydrogen has very wide flammability limits ranging from 5 to 75% by volume (f = 0.07 to 9), which may lead to pre-ignition and backfiring problems.
- If inducted along with intake air, the volume of hydrogen is nearly 30% of the stoichiometric mixture decreasing maximum engine power.
- Hydrogen on combustion produces water and there are no emissions of carbon containing pollutants such as HC, CO and CO_2 and air toxics.
- Trace amounts of HC, CO and CO2 however, may be emitted as a result of combustion of lubricating oil leaking into engine cylinder.
- NO_x is the only pollutant of concern from hydrogen engines. Very low NO_x emissions can be obtained with extremely lean engine operation (f < 0.05) and/or injection of water into intake manifold or exhaust gas recirculation which in this case consists primarily of water vapours.

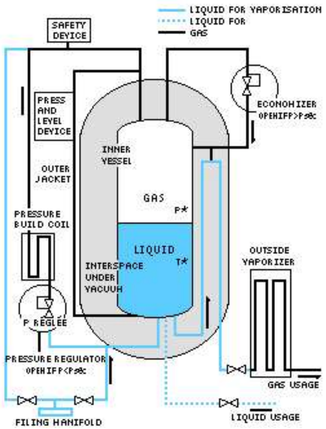


The scheme…



Hydrogen containers

Cryo Vessels



Problems

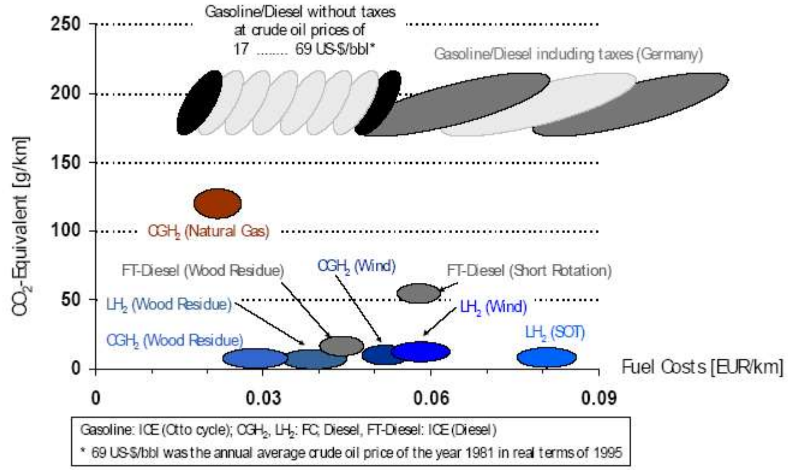
- Hydrogen is a commerical product & chemical commodity and not yet established as a transport fuel.
- Industrial context of hydrogen as a fuel does not exist.
- Hydrogen production and distribution requires a much different infrastructure.
- Safety aspects had to be borne in mind

Onsite versus centralized production

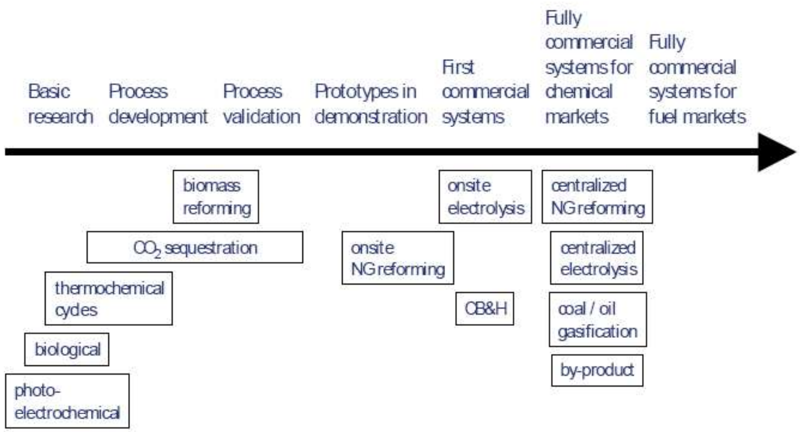
- ***Onsite***
  - ➢ Making maximum use of existing infrastructure
  - ➢ Electrical grid for onsite hydrolysis
  - ➢ Natural gas grid for onsite reforming
  - ➢ Onsite biomass gasification
  - ➢ Not suitable for Liquid Hydrogen

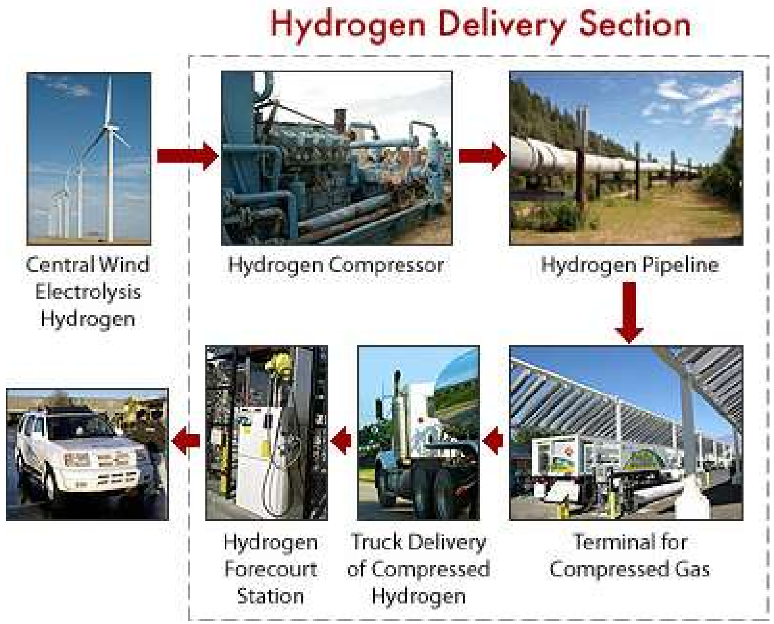
- ***Centralized***
  - ➢ ***Hydrogen*** production and distribution infrastructure needed.
  - ➢ Liquid hydrogen road trailers and containers
  - ➢ Special pipelines
  - ➢ Very much suitable for liquid Hydrogen.

How does it compare?

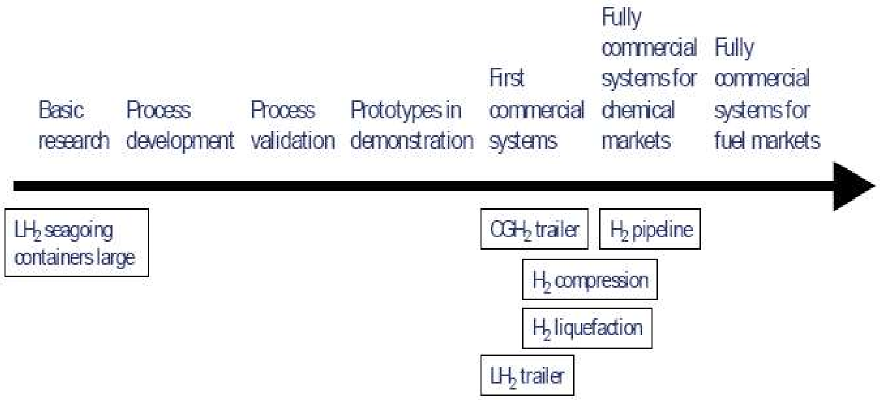


Status of Hydrogen Production technologies





Hydrogen distribution and conditioning



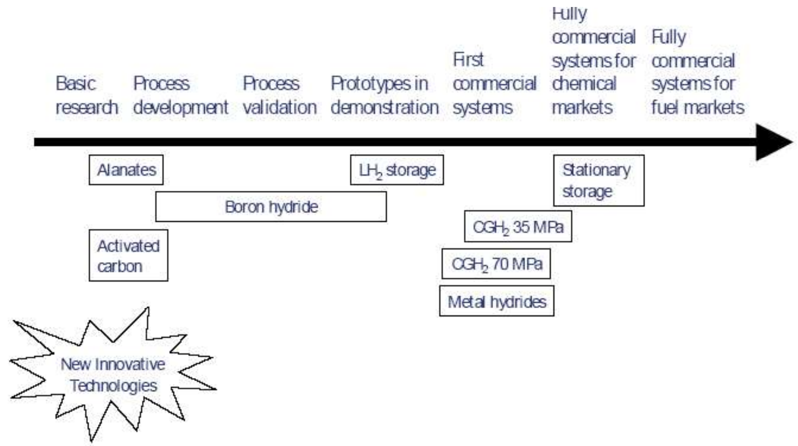
Gaseous Hydrogen transport

- Can be transported in pressurized bottles (20-30 MPa), tube trailers and pipelines and also composite material bottles.
- Compressed Gas hydrogen has size limitations upto 6000 Nm^3.
- In comparison to Natural gas the cost is 1.5 times higher due to 3.5 times higher compression energy requirements.
- Compression is done by hydraulic compressors. Electric power requirements are 0.11-0.13 kWh_e/kWh_{CGH} for delivery pressure of 45-88 Mpa (suction at 0.2 MPa)

LIQUID HYDROGEN

- Had been developed for space technology.
- Major operating cost factors are service capital, electrical energy requirements and maintenance.
- LH_2 is transported in cryo containers or trailers with sizes ranging from 41 to 53 m^3 at cryogenic temperatures of 20K
- LH_2 is transferred to refuelling stations using trailers.

HYDROGEN STORAGE



- Stationary hydrogen storage:
  - It is stored in bottles, tubes, underground aquifiers etc.
  - Liquid storage in cryostats etc
  - Physical storage in metal hydrides
  - Chemical storage in chemical hydrides

- Onboard storage:

  A pressure of 35 MPa in compressed hydrogen tanks are sufficient for city bus and urban storage facilities.

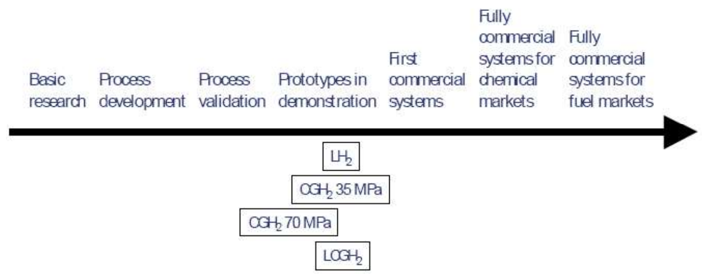
  High temperature hydrides (release temperature of 200^{o}C) has high gravimetric storage densities.

  For large transportation systems liquid hydrogen is an ideal prospect

Risks

- Release of large quantities of hydrogen within a short timeframe or hydrogen accumulation due to slow release of hydrogen.
- Detonation is possible in both the cases.
- Hydrogen has high diffusion rate and it vanishes upwards in an event of a leak.
- Safety risks are inherent for higher pressures.
- But pressure cylinders are robust and can withstand pressures 2.35 times its design value.
- Problem with heat intrusion.

Status of Hydrogen filling stations

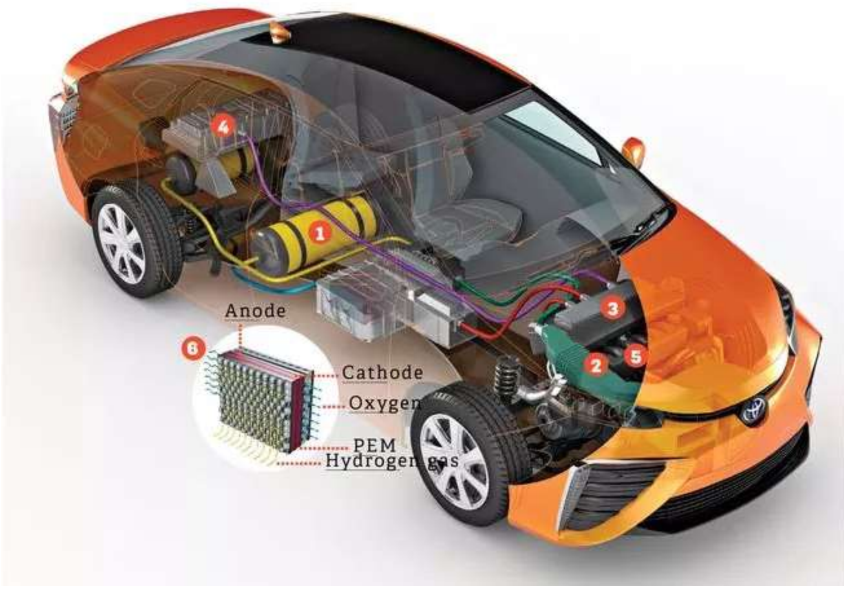


HYDROGEN as a fuel

- Two ways of using hydrogen as a fuel

a) Hydrogen ICE

b) Hydrogen fuel cell vehicles

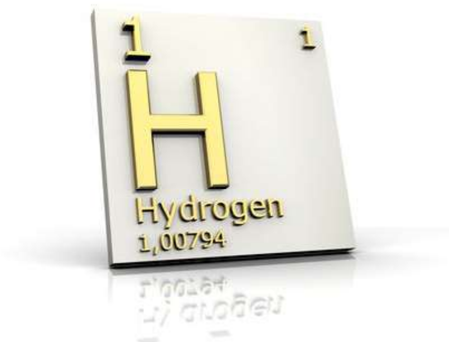


1.Hydrogen cylinder
2.Air flow
3.Power control unit
4.Battery
5.Motor
6.Fuel Cell

HYDROGEN ENERGY

WHY HYDROGEN?

- Can be produced from water which is abundantly available in nature.
- Highest energy content per unit mass of any chemical fuel and can be substituted for hydrocarbons.
- Non polluting burning process.
- Can be used in fuel cells
- Major aspects are Production, storage, utilisation, safety and management and economy.



THE CHALLENGES

- Chemically very reactive and hence not found in free state in earth.
- It is combined with other elements
- Available in water, fossil hydrocarbons, cellulose, starch etc
- Energy must be supplied to break the chemical bonds to release hydrogen.
- Hydrogen is a secondary energy fuel that is produced by utilizing energy from primary source.

PROJECTED NEEDS

- Nitrogenous fertilizers
- Coal liquefaction
- Fuel for GT or for SI Engine
- Direct addition of hydrogen to an existing NG distribution network
- Reduction of iron oxides by means of hydrogen in steel industry
- Aircraft fuel in air transport

PROPERTIES OF HYDROGEN

- Is a light gas with a density of 1/14th of air and 1/9th of natural gas.
- By cooling to -253^{o}C at atmospheric pressure, the gas condenses to liquid with a specific gravity of 0.07
- Standard heating value is 12.1 MJ/m^3 when compared to 38.3 MJ/m^3 for natural gas. Whereas the heating value of liquid hydrogen is 120 MJ/kg or 8400 MJ/m^3.
- The flame speed of hydrogen burning in air is much greater than for Natural gas and energy required to initiate combustion is very less.

Properties of Hydrogen

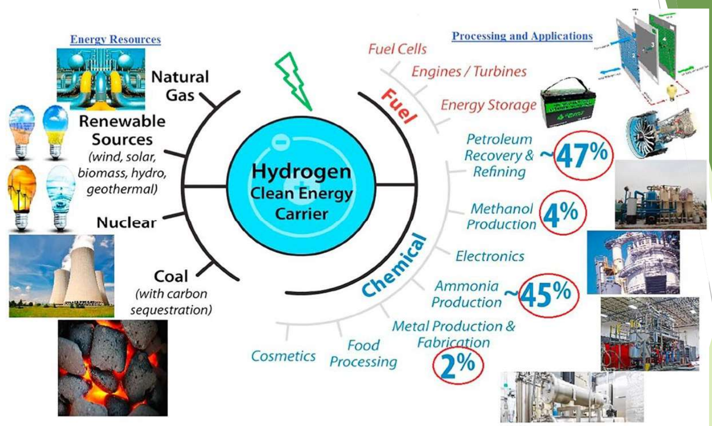
Property	Value
Molecular weight	2.02
Density	0.09 kg/m^3
Freezing Point	-275°C
Specific heat	14.2 kJ/kg-K
Calorific Value	120 MJ/kg
Viscosity	0.009 mPa-s at 20°C
h_{fg}	448 kJ/kg
Flammability Limits	4 - 75
A/F_{stoic}	34.3

Property	Value
Storage pressure	350-700 bar
Laminar flame speed	2.91 m/s
Adiabatic flame temperature	2756°C
Research Octane number	130
Minimum ignition energy	0.02 mJ
Auto ignition temperature	858 K (585°C)
Quenching Gap	0.064 cm
Diffusivity in air	0.63 cm^2/s

- The mixture of hydrogen and air are combustible over an exceptional wide range of compositions.
- The flammability limits at ordinary temperatures range from 4 to 74% by volume of hydrogen in air.
- The adjustment of air fuel ratio this is very important in the functionality of Gasoline Engine.

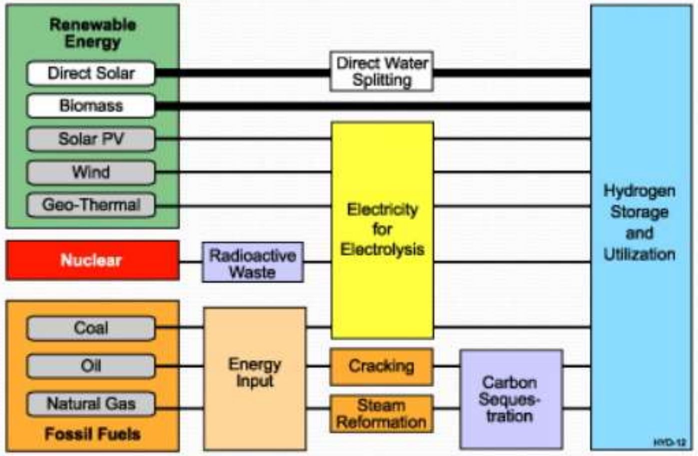
HYDROGEN PRODUCTION

- Electrolysis of water
- Catalytic steam reforming of natural gas
- Partial oxidation of heavy oil
- Coal gasification followed by reforming
- Steam iron process
- Thermal cracking of natural gas
- Thermochemical water decomposition
- Photochemical conversion
- Biological hydrogen generation by algae
- Decomposition of biomass
- Nuclear fission



Hydrogen clean energy carrier as one of most essential clean and sustainable resource with main applications in both research and industry diverse.

Methods of Hydrogen Production

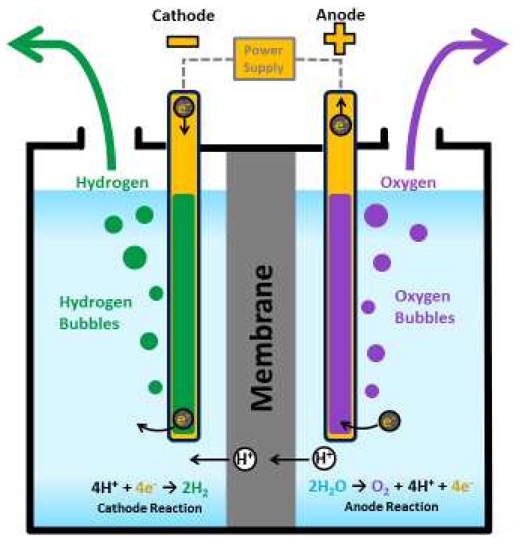


Graphic: http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/images/HydrogenProductionPaths.gif

ELECTROLYSIS

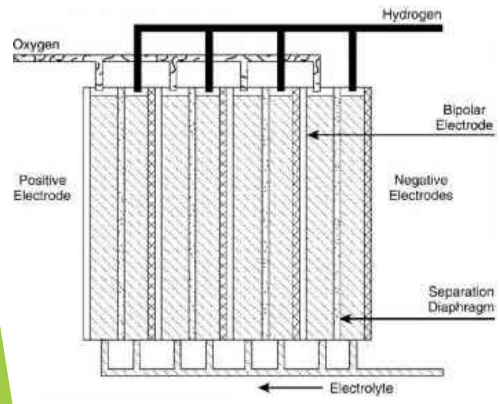
- The process of splitting water into hydrogen and oxygen by means of direct electric current is known as electrolysis.
- Electrolysis cell consists of two electrodes, a flat metal or carbon plates immersed in aqueous conducting solution called the electrolyte.
- A source of DC is connected to the electrodes so that an electric current flows through the electrolyte from positive electrode (anode) to negative electrode (cathode).
- As a result, the water in the electrolyte solution is decomposed into Hydrogen gas released at the cathode and oxygen gas is released at the anode.

- A voltage of 1.23V is sufficient for the electrolysis of water at normal temperature and pressure.
- Slowness of the electrode processes that lead to the liberation of hydrogen and oxygen gases, higher voltages are required to decompose water.
- Theoretically 2.8 kW-hr of electrical energy should produce 1 m^3 of Hydrogen gas.
- Actual energy requirement is 3.9-4.6 kW-hr per m3. The efficiency of the electrolysis is roughly 70%
- Efficiency can be increased by decreasing the decomposition voltage.



- Pt or Ni plated electrodes. Porous nickel on wire gauge.
- Diaphragms prevent electronic contact between adjacent electrodes and passage of dissolved gas from one electrode compartment to other.
- Asbestos is the commonly used diaphragm material

TANK TYPE ELECTROLYZER



- Series of electrodes suspended vertically and parallel to one another in a tank filled with 20-30% solution of KOH in demineralized water.
- Cathodes are surrounded by porous diaphragms impermeable to gas but permeable to electrolyte.

- Advantages: Few parts required, inexpensive, individual cells may be replaced for repair by a temporary bus bar connection between two temporary cells.
- Disadvantages: Inability to handle high current densities, inability to operate under high temperaure

BIPOLAR ELECTROLYZER

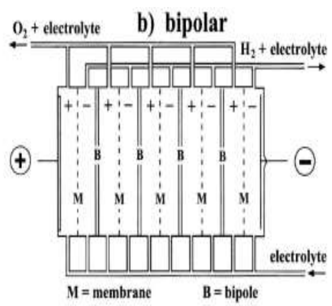


Figure 8. Electrolyzer modules with a) unipolar and b) bipolar cell configurations

- The ends of the cell, one face is cathode and the other is anode.
- Porous diaphragm between adjacent electrodes prevent the mixing of hydrogen and oxygen gases.
- It occupies less space and can be operated at higher current density than the tank type.

Natural Gas as a Source of Hydrogen

Natural Gas Composition:

Compound	Symbol	%
Methane	Ch_4	60-90
Ethane	C_2H_6	0-20
Propane	C_3H_8	0-20
Butane	C_4H_{10}	0-20
Carbon Dioxide	CO_2	0-8
Oxygen	O_2	0-0.2
Nitrogen	N_2	0-5
Hydrogen Sulphide	H_2S	0-5

Catalytic reforming of NG

- Conversion of Hydrocarbon and steam to hydrogen and Carbon dioxides

a) Feedstock purification (removal of sulphur)

b) Steam reformation of hydrocarbons to form hydrogen and carbondioxides

c) Shift conversion of CO to CO2

d) Purification (removal of CO2, CO and HC)

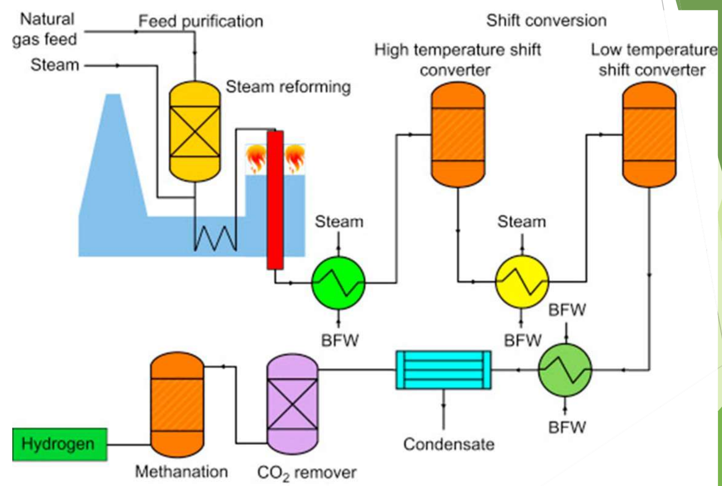
$C_nH_m + nH_2O \rightarrow nCO + (n+m/2)H_2$

$CO + H_2O \rightarrow CO_2 + H_2$

n = 1 and m = 4 for methane and n =1 and m = 2.2 for Naphtha

- Sulphur content in Methane /Naphtha is first removed
- Mixed with process steam
- Passed through steel tubes containing Ni catalysts
- Hydrogen generated has methane and Carbon monoxide impurities
- For this removal it is passed through a heat recovery step
- Gas is passed through WGS reaction where additional Hydrogen is produced
- Finally passed through gas purifier where CO2 is removed (Wet scrubbing with amine solution) 98% pure Hydrogen is produced.
- Operating conditions for steam reformation is 760-925°C and 2 MPa pressure.

Catalytic steam reforming



Partial Oxidation (POX) of Heavy Oil

- This process is similar to reforming
- Heavy oils which contain hydro carbons are oxidized to produce CO and H_2
- CO is separated from the mixture to obtain pure H_2
- POX requires additional facilities like air separation plant to provide pure O_2 and a larger shift and separation equipment
- The additional step in POX is after feed cleaning. Here hydro carbons are oxidized to provide sufficient energy to drive the process and release an additional amount of H_2

Partial Oxidation (POX) of Heavy Oil…

- The chemical reaction can be shown as

  $C_nH_m + n/2\ O_2 \leftrightarrow nCO + m/2\ H_2$
- The reaction is exothermic and proceeds at a temperature of 1150-1315℃
- In contrast to steam reforming, an additional air separation plant is required
- Pure oxygen must be used as nitrogen will contaminate the hydrogen

Partial Oxidation (POX) of Heavy Oil…

- POX can be carried out with or without catalyst
- It is a more sulphur tolerant process than SMR without catalyst
- Without catalyst, the temperatures are higher (1300-1500℃) for complete conversion, feed stock can be methane, heavy oil or coal
- With catalyst, the temperatures are around 950℃, feed stock can be methane to naphtha

Auto Thermal Reforming (ATR)

- ATR is a combination of SMR and POX
- POX is used to produce heat and SMR to increase Hydrogen production
- Hence it is a thermally neutral process
- In this process, the outlet temperatures are in the range of 950-1100℃ and pressure 100 bar

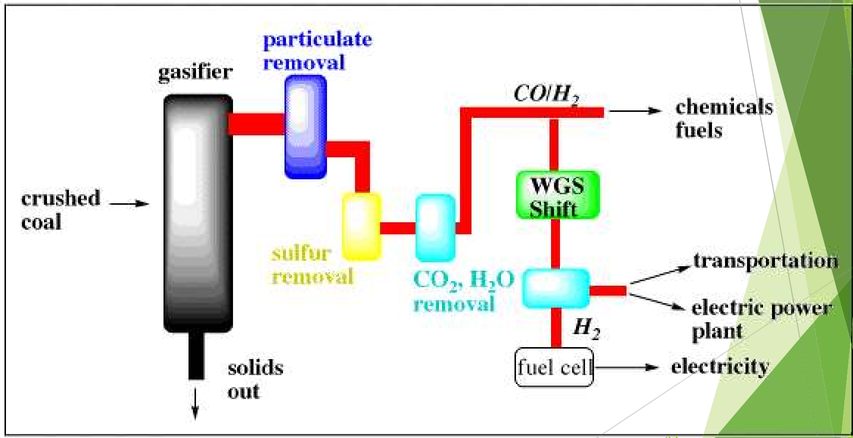
$$C_nH_m + nH_2O \leftrightarrow nCO + (n+m/2)\ H_2$$

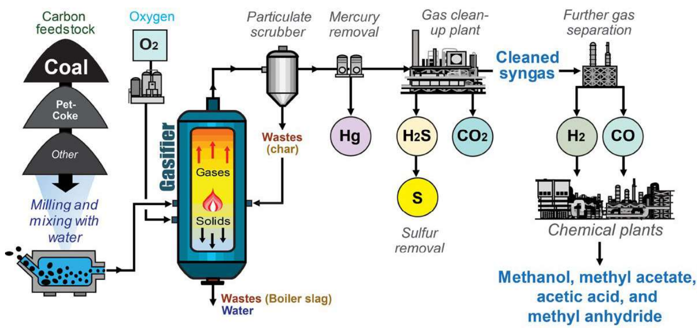
Coal Gasification

- The process is similar to Partial oxidation of heavy oils
- However, due to the variation in composition, physical state, sulphur content and ash content, POX equipment cannot be used
- This makes coal gasification most expensive method of hydrogen production
- Coal gasification can be carried out at atmospheric or elevated pressures

Coal Gasification…

$$C + H_2O + heat \rightarrow CO + H$$





Coal Gasification…

- Coal is fed to a gasification plant
- Air is separated into O_2 and N_2 in a separation plant
- O_2 enters the gasification plant along with steam
- Reaction of coal with steam and oxygen produces a raw gas and some ash
- Ash is removed and raw gas is passed through desulphurization unit to produce syngas
- Syngas is compressed and then subjected to shift conversion process
- Here CO and CH_4 impurities are removed from H_2

Steam-Iron Process

- This process involves reforming steam by reaction with hot iron
- The product of the process is rich H_2 gas and iron oxide

  $3FeO + H_2O \rightarrow Fe_3O_4 + H_2$

  $FeO + CO \rightarrow Fe + CO_2$

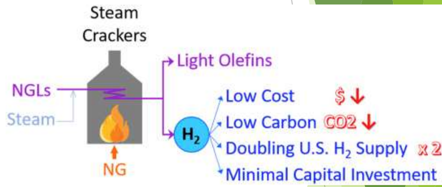
- The hydrogen produced contains impurities like CO and N_2 which can be removed by methanation reaction

Thermal Cracking of Natural Gas

- Thermal decomposition of natural gas is carried out to obtain carbon black and H_2
- The process requires lot of energy some of which comes from the produced H_2

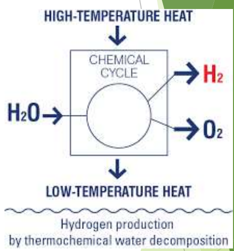
  $CH_4 + \text{Heat} \rightarrow C + 2H_2$

- The process is carried out at atmospheric pressure and a temperature of 1400°C
- Catalysts can be used to hasten the reaction
- This is one of the few low cost processes for H_2



Thermochemical Decomposition of Water

- Instead of electrolysis, heat can be used to split water
- Water molecule can be split directly by using high temperature at 2500°C
- However, materials which can withstand such high temperature continuously are unavailable
- Chemical reagents can be used to lower the temperatures

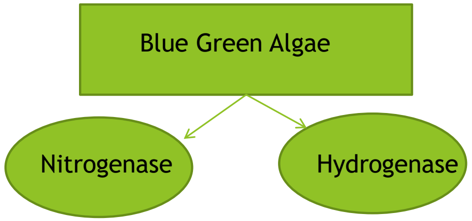


SOLAR ENERGY METHODS

- Photo biological process
- Photo electrolysis

Photobiological Process

- Biological system t produce Hydrogen from Light. Organisms like Cyano bacteria(blue green algae, photosynthetic bacteria and Eukaryotic algae)



- Exposure of certain single cell green algae to sunlight and water yields a mixture of oxygen and hydrogen gases that can be separated in various ways.
- Nitrogenase produces hydrogen and hydrogenase consumes them.
- To produce Hydrogen, cyanobacteria must be kept in an anaerobic environment. Inert gases like Argon or partial vacuum are used to make oxygen free environment.
- Chemicals and genetic processes are used to limit the effect of hydrogenase.
- CO with acetylene or low Ni ion concentrations can be used during the growth of specific cyanobacteria.

- Genetics too is used to produce hydrogenase deficient cyanobacteria.
- Photosynthetic CO2 fixation using water as an electron donor and their capability to thrive in a simple inorganic environment. The conversion efficiency however is 0.1%.

- Photosynthetic bacteria:
- They produce hydrogen at higher rates from organic acids, alcohols and sugars for longer periods than cyanobacteria.
- The effectiveness depends upon availability of substrates, light irradiance and temperatures.
- All they need is electron donors for which bio substances like whey, starches, sugar refinery wastes are ideal candidates for electron donors.
- Photosynthetic bacteria are usually grown under anaerobic conditions to maximize Hydrogen production.

Photo Electrolysis

- In photo electrolysis a current is generated by exposing both electrodes to sunlight.
- Hydrogen and Oxygen gases are liberated at the respective electrodes b y the decomposition of water.
- One of the electrodes is a semi conductor.
- A catalyst may also be included to facilitate the process.
- Electrolysis can be done photo electrolytically or thermochemically.

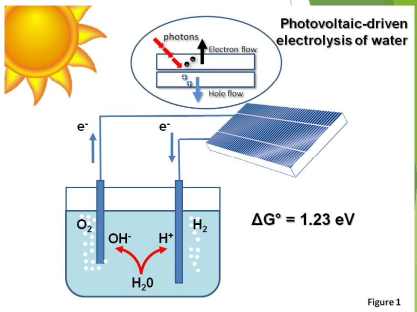


Figure 1

Hydrogen from Biomass

- Biomass is defined as all plant and animal material, not including fossil fuels which can be converted to energy.
- Biomass is organic in nature and derived from a variety of sources including residues, wastes and crops earmarked for that purpose.
- The main method for getting Hydrogen from biomass is by Anaerobic digestion.
- Anaerobic digestion is a versatile bio conversion process that is used to produce methane gas and other residues from homogeneous and heterogeneous carbonaceous materials.

Cellulose and Hemicellulose

Enzymes

Soluble organic compounds

Acid producing bacteria

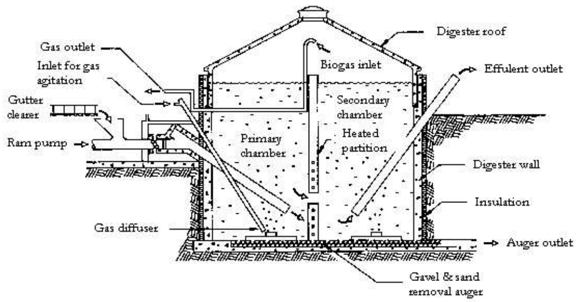
Acid producing bacteria

H2, CO2, formates and acetates

Methane producing bacteria

Methane

A typical anaerobic digester



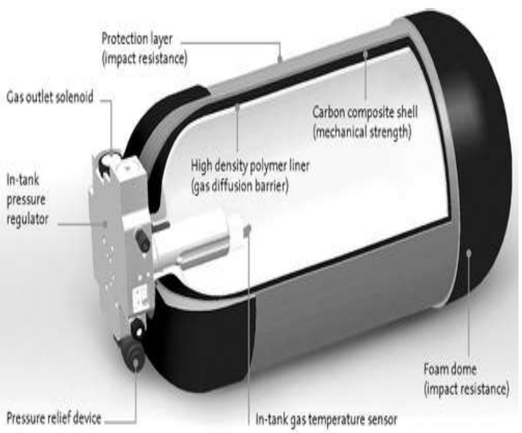
Source: NRCS Agricultural Waste Management Field Handbook

- At ambient temperatures gas production is slow, reactor temp must be increased through the use of thermophilic micro organisms or through direct thermal heating.
- Sewage, MSW, energy crops are used as the feed.
- Total energy production from anaerobic digestion is greater then that of production from a thermal conversion process.
- Resultant gas has medium fuel value and higher concentration of methane.
- Methane through steam reformation can yield hydrogen.

HYDROGEN STORAGE

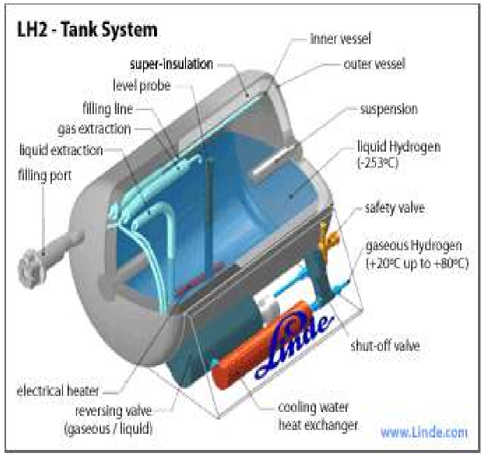
- Compressed gas storage
- Liquid storage (cryogenic storage in vacuum insulated or super insulated storage tank)
- Line Pack system
- Underground storage
- Storage as metal hydrides

COMPRESSED GAS STORAGE



- High pressure cylinders
- Expensive and Bulky
- Vessels are typically aluminium cylinders wrapped with fibre glass
- Pressurized hydrogen at 20 Mpa is 3 times the weight of the liquid hydrogen that is stored and occupy twice the volume.
- Volume further can be reduced by increasing the pressure of the gas to 55 MPa

LIQUID STORAGE



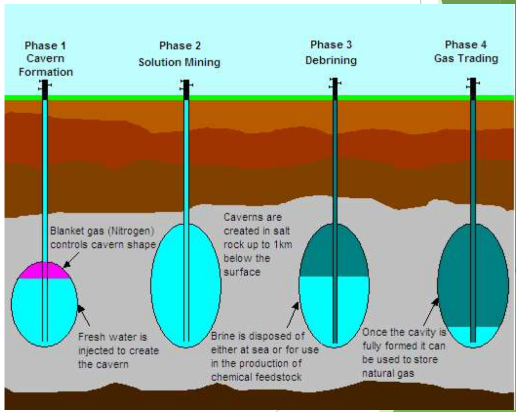
- Suitable for small scale storage
- Vacuum jacketing is done to prevent the air accumulation near the cylinder walls as the liquid hydrogen is below the temperature at which air condenses on the surface.
- Flammability dangers are persistent in that case.
- Precooling of Hydrogen is needed to bring the gaseous hydrogen below Joule Thompson temperature above which liquid hydrogen heats up on expansion.

Activated carbon storage

- Adsorbing Hydrogen to carbon surface. Adsorption increased as the temperature is lowered.
- Carbon Nanotubes (Extremely thin hollow cylinders of carbon atoms)
- Due to the molecular structure of the carbon in Nanotubes, hydrogen easily bonds with carbon and minimal temperature changes can cause hydrogen to be released.

UNDERGROUND STORAGE

- Depleted natural gas reservoirs and acquifiers
- Caverns made by conventional mining.

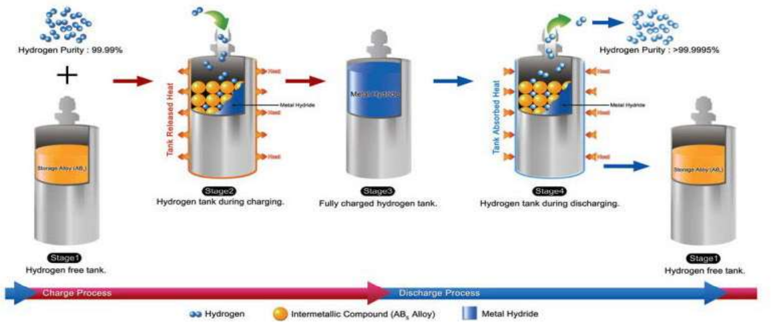


Metal Hydrides

- Gaseous hydrogen readily absorbs in metals forming a weak chemical bond.
- MH are typically granular or powder form , thus having large surface area and large capacity for storage.
- To release gaseous hydrogen from the metal, the hydride is heated to a certain temperature.
- It is one of the safest alternatives for storing Hydrogen.
- Disadvantage is hydride systems have a low mass energy density and thus tends to be heavy.
- Hydride and cooling system can weigh 120-485 kg containing only 0.5-2% of Hydrogen by weight. (10-20 times the weight of gasoline tank for the same energy capacity)
- Oxygen and water contamination is the primary cause of reduction in storage capacity.

METAL HYDRIDES- Essentials

- Metal should be fairly inexpensive
- Hydride should contain a large amount of hydrogen per unit volume and unit mass
- Hydride should be formed without any difficulty by any reaction of the metal with hydrogen gas and should be stable at room temperature.
- The gas should be released at significant pressure from the hydride at moderately high temperature.



MH container

Type of Hydride	Metal/ Alloy	Hydride	Structure	Wt.% Hydrogen	Peq., T(K)
Elemental	Pd	$PdH_{0.6}$	*Fm3m*	0.56	0.02 bar @ 298K
AB_5	$LaNi_5$	$LaNi_5H_6$	*P6/mm*	1.37	2 bar @ 298K
AB_2	ZrV_2	$ZrV_2H_{5.5}$	*Fd3m*	3.01	10^{-8} bar @ 323 K
A_2B	Mg_2Ni	Mg_2NiH_4	*P6mm*	3.59	1 bar @ 555 K
AB	FeTi	$FeTiH_2$	*Pm3m*	1.89	5 bar @ 303 K
BCC	TiV_2	TiV_2H_4	*BCC*	2.6	10 bar @ 313 K

- They are suitable for stationary storage of hydrogen
- For Mobile applications the weight can be a drawback.

- H2 + Me $\longleftrightarrow$ Hydride + Heat
- During charging up with Hydrogen, heat is always produced, in order to withdraw the hydrogen from the hydride, it is always necessary to add heat.
- Low temperature Hydrides: Heat storage density of 0.3 MJ/kg in temp range from -20 to 100 °C at a hydrogen pressur e of 10 bar.
- High temperature Hydrides: heat density of 3 MJ/kg at room temp ranging from 150 to 550 °C

Hazards of Hydrogen

- Leakage – Can't be detected, invisible, odorless. Colorant or odorant can be added
- Fire and Explosion – Presents the greatest fire and detonation hazard. Higher probability of undergoing Deflagration to detonation (DDT). Reason behind is the normal burning velocity is much higher compared to the other fuels. Highest diffusion and buoyant velocity as the leaks will suddenly go to non combustible proportions.

- Overpressure detonation – Confined over pressures as high as 800 kPa can have devastating effects.
- Asphyxiation – Non toxic even when burns. Can cause dizziness, vomitting, passing out and death sometimes.
- Frost bite – Especially due to LH2. All pipelines dealing with cryogenic lines must be properly insulated.

Safety Norms

- Leak detection : Hydrogen detectors in strategic points over refuelling areas. Audible alarms if the concentration reaches 1% by volume of air.
- Fire suppression : Dry chemical powders to extinguish Hydrogen flames (52°C temp limits)
- Electrical protection: Electrostatic sparks must be avoided from electrical connections by proper grounding.
- Purging systems: Inert gas like Nitrogen to be used. Gas Chromatography is an accurate method to check the levels of Oxygen.
- Pressure relief devices: To vent excess gas. Spring loaded safety valve and rupture discs

	Hydrogen	Gasoline Vapor	Natural Gas
Flammability Limits (in air)	4-74%	1.4-7.6%	5.3-15%
Explosion Limits (in air)	18.3-59.0%	1.1-3.3%	5.7-14%
Ignition Energy (mJ)	0.02	0.20	0.29
Flame Temp. in air (°C)	2045	2197	1875
Stoichiometric Mixture (most easily ignited in air)	29%	2%	9%

PROs and CONs

Advantages

- Renewable in Nature
- Cleanest fuel due to low NOx emissions
- From a variety of feed stock
- Suitable for IC engines and fuel cells
- Requires low ignition energy
- Superior combustion characters
- Adulteration free
- High purity levels available

Disadvantages

- High flammability
- Leak detection is difficult
- Probability of pre ignition
- Backfires when the flame travels back to fuel induction systems
- Expensive as production quantity is limited
- Lack of distribution infrastructure.

Electric cars

Electric car by Seimens, 1904

Thomas Edison with a car made by Detroit Electric , 1907-1939

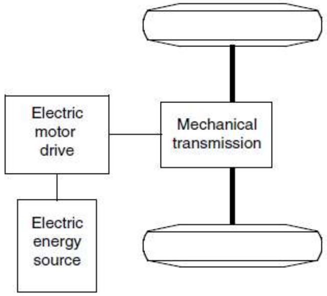
Chevrolet Volt, 2007

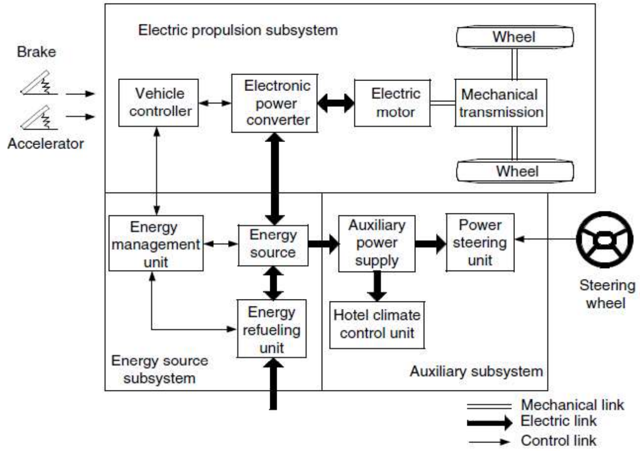
Tesla Roadster, 2008

How they work?

- An Electric car is powered by an Electric Motor rather than a Gasoline Engine.
- The Electric Motor gets its power from a controller.
- The Controller is powered from an array of rechargeable batteries.

components





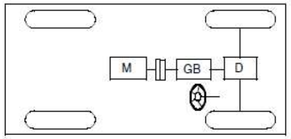
Components

- Drive train has three major subsystems namely
- Electric motor propulsion- Vehicle controller, Power electronic converter, electric motor, mechanical transmission and driving wheels
- Energy Source- Energy source, energy management unit, energy refuelling unit
- Auxiliary- Power steering unit, climate contriol unit, auxiliary supply unit.

Principle of operation

- Based on control inputs from the accelerator and brake pedals the vehicle controller provides proper control signals to the electronic power converter which functions to regulate the power flow between electric motor and energy source.
- Backward power flow is due to the regenerative braking of the EV and this regenerated energy can be restored to the energy source.
- Most batteries, ultracapacitors and flywheels accepts the regenerated energy.
- The energy management unit cooperates with the vehicle controller to control the regenerative braking and its energy recovery.
- Auxiliary power supply provides necessary power at different voltage levels for all the EV auxiliaries especially climate control and power steering.

Possible configurations

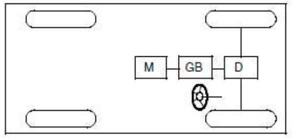


Electric propulsion replaces the IC engine of a conventional vehicle drive train.

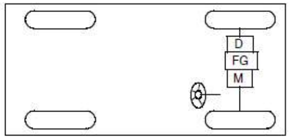
Consists of an electric motor, clutch, gear box and differential.

Clutch is used to connect or disconnect the power of the electric from the driven wheels.

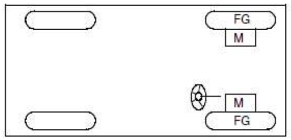
Gear box provides a set of gear ratios to modify the speed power profile to match the load requirements.



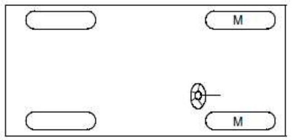
For constant power in long speed range, a fixed gearing can replace the multispeed gear box and reduces the need of clutch.
Reduces the size and weight of the mechanical transmission.



Electric motor, the fixed gearing and the differential can be further integrated into a single assembly while both axles point at both driving wheels.



Traction motor can be placed inside a wheel, known as inwheel drive
A thin planetary gear set may be used to reduce the motor speed and enhance motor torque.

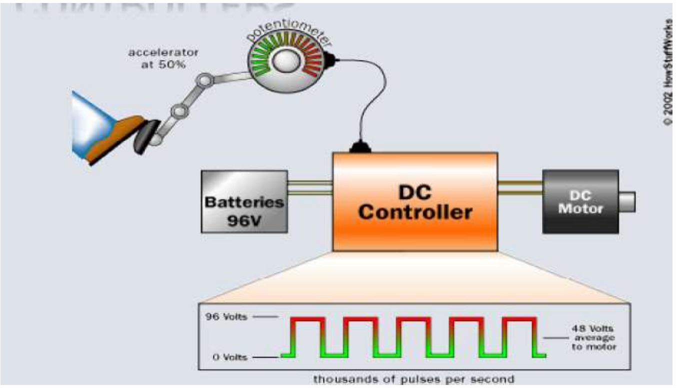


Full abandonment of mechanical gearing between motor and driving wheel.
The out rotor of a low speed electric moor in the inwheel drive can be directly connected to the driving wheel.
The speed control of the electric motor is equivalent to the control of the wheel speed and also the vehicle speed.

ELECTRIC MOTORS

- Electric cars can use AC as well as DC motors.
- DC motors run on a voltage ranging roughly between 96 to 192 volts. Most of them come from Forklift Industry.
- DC installations are simpler.
- Another feature of DC motors is that they can be overdriven for short periods of time (up to a factor of 10), which is good for short bursts of acceleration.
- One limitation is the heat build up. May lead to self destruction.
- Due to these limitations and other advantages provided by AC motors (like better torque and speed output, for same weight and size), DC motors are not used.
- Any of the industrial 3 – phase AC motors can be used.
- They allow the use of regenerative braking.

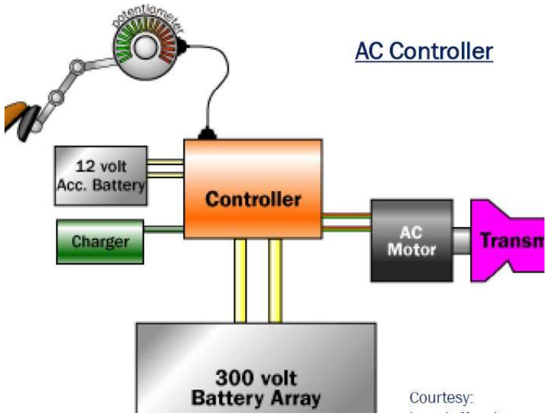
controllers



Courtesy. : howstuffworks.com

The controller delivers a controlled voltage to the motor, depending upon potentiometer output.

PWM controls the speed.



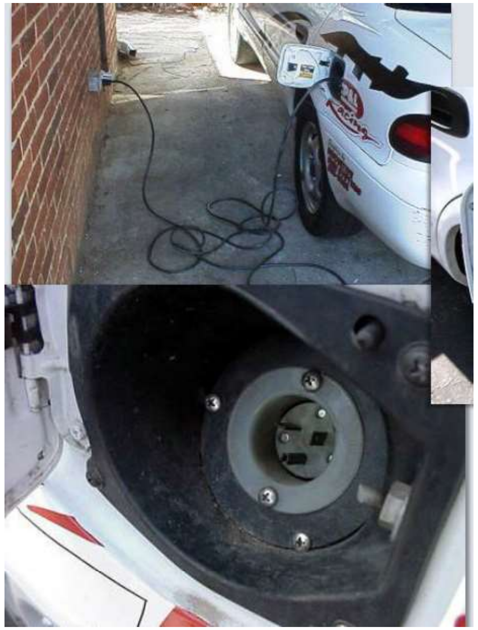
An AC controller creates 3 pseudo sine waves which are 120 degree apart (3-phase AC).

Using six sets of power transistors, the controller takes in 300 volts DC and produces 240 volts AC, 3-phase.

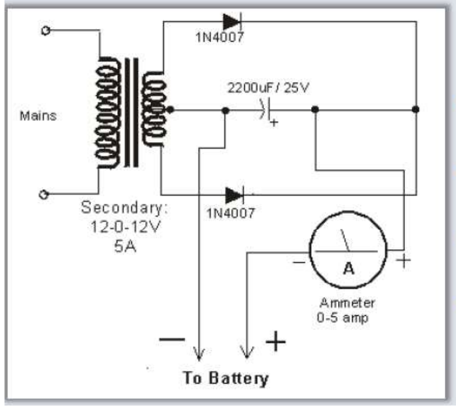
Batteries and chargers

- Lead acid batteries used, until recently.
- A weak link in the electric cars.
- Heavy, Bulky, limited capacity (12 – 15 kilowatt hours), slow charging rate, short life and expensive.
- NiMH batteries give double the range and last 10 years, but expensive.
- Lithium ion and NiMH batteries likely to be used if their prices can be made competitive with lead acid batteries.

Battery type	Energy/weight Watthours/Kg	Energy/Volume Watt-hours/L	Power/weight Watt/kg	Energy/US$ Watt-hr/$
Lead- acid	30-40	60-75	180	4-10
Nickel – Zinc	60-70	170	900	2-3
Lithium-Ion	160	270	1800	3-5
Lithium-Polymer	130-200	300	2800	3-5



BATTERIES AND CHARGERS



- Voltage Outlet: 240/120 V AC.
- Battery Requirement: DC Voltage.
- AC to be converted to DC.
- Rectification needed.

- Charging done from power grid (household/ charging station).
- A good charger monitors battery voltage, current flow and battery temperature to minimize charging time.
- 120/240 Volts.
- Part of the controller/separate box.

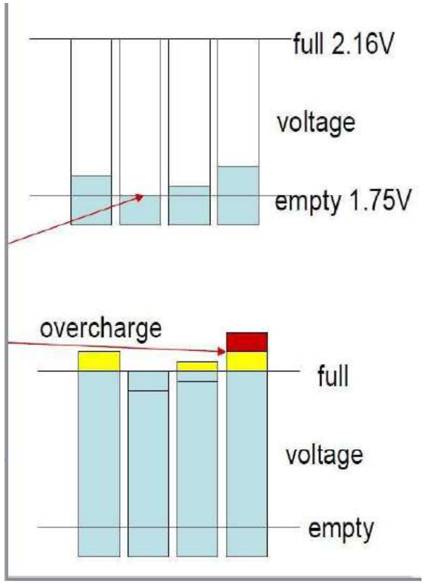
DeltaQ Charger
Courtesy: www.delta-q.com

Charging station mounted to a wall : Sends electricity to the car through an 'inductive paddle'. One half of transformer.

Charging System in the trunk of car : Second half of the transformer. Completed with inserting of the paddle.

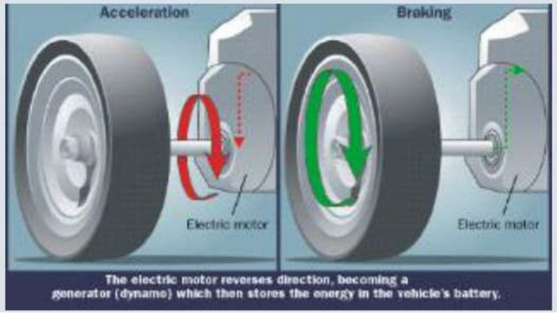
Equalizing

- An electric vehicle has a string of batteries.
- Closely matched, but not identical.
- Weaker batteries need more recharge.
- Weak battery gets weaker.
- Solution is "Equalizing". Gently overcharge the cells to make sure that weakest cells are fully charged.



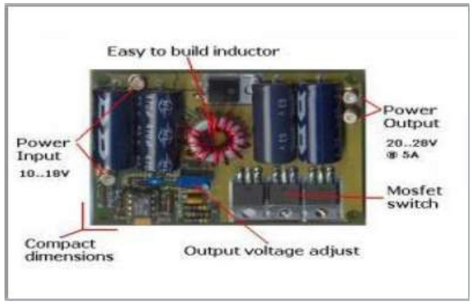
BRAKING

- Regenerative braking along with conventional friction braking.
- Motor as a generator.
- Recaptures car's kinetic energy and converts it to electricity to recharge the batteries.



AUXILIARY BATTERIES AND DC-DC CONVERTERS

- A 14 volt battery which provides power for accessories, like headlights, radios, fans, computers, airbags, wipers, power windows etc. .
- Runs motor controller logic and power electronics.
- To charge the Aux. Battery a DC – to – DC converter converts the voltage from main battery array (say 300 volts) to 14 volts.

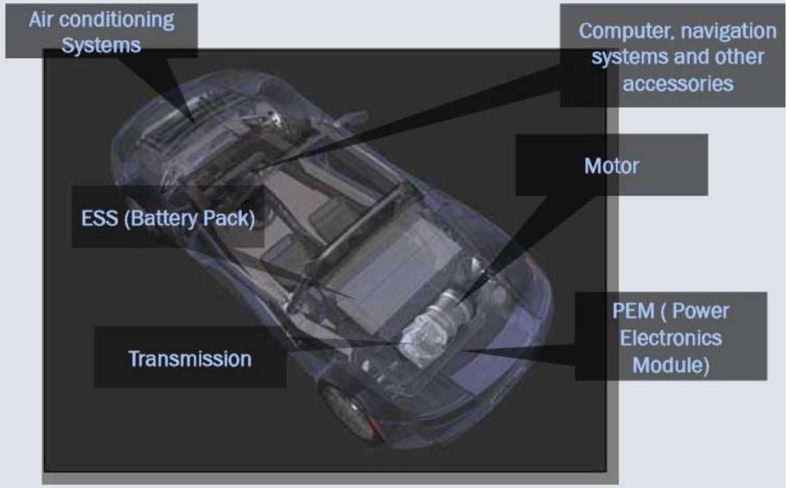


ELECTRIC CARS: TESLA ROADSTER

- Acceleration: zero to 60 mph in about 3.7 seconds.
- Dimensions: 155.4 inches long, 73.7 inches wide, 44.4 inches tall with a 92.6-inch wheelbase.
- Weight: 2,500 pounds (subject to change due to safety regulations).
- Top Speed: Over 130 mph.
- Range: 245 miles Per Charge.
- Battery Life: Useful battery life in excess of 100,000 miles.

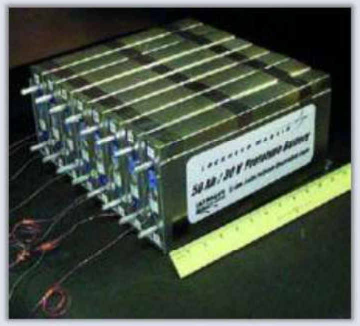
Courtesy:
www.teslamotors.com

TESLA ROADSTER: VEHICLE ARCHITECTURE



TESLA ROADSTER: ESS (BATTERY PACK)

- **6831 standard 18650 Laptop Li- ion cells.**
- Supplies ~375V to motors, heating and air conditioning systems.
- Cooling system.
- Current capacity of each cell: 2100 mAh.
- Energy stored = 2100 mAh*3.7 V*6831 = 53kWh.
- Weight ~ 450 Kg.
- **Energy/Weight ~ 120.**
- **Can be recharged easily with 110/220 V outlet.**

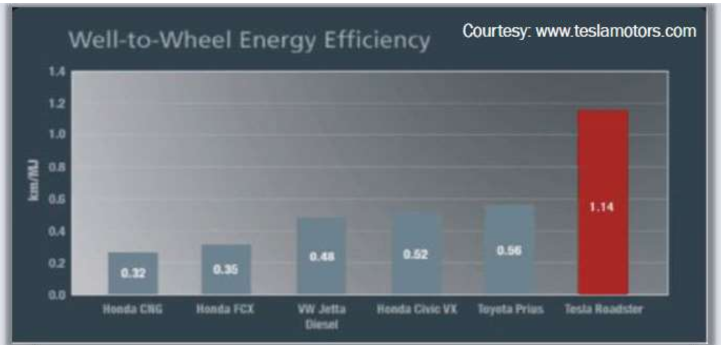


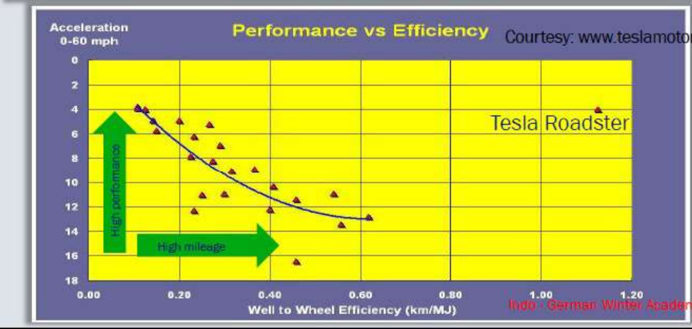
Courtesy: en.wikipedia.org/wiki/tesla_roadster

TESLA ROADSTER: MOTOR

- **3 – phase 4 pole AC motor**
- **Torque:** 273 lb-ft at 0 – 5400 RPM.
- **Horsepower:** 288 HP(215 KW) at 5000-6000 RPM.
- **Max Torque:** 350 Nm at 0 RPM (zero lag).
- **Max Speed:** 13500 RPM.

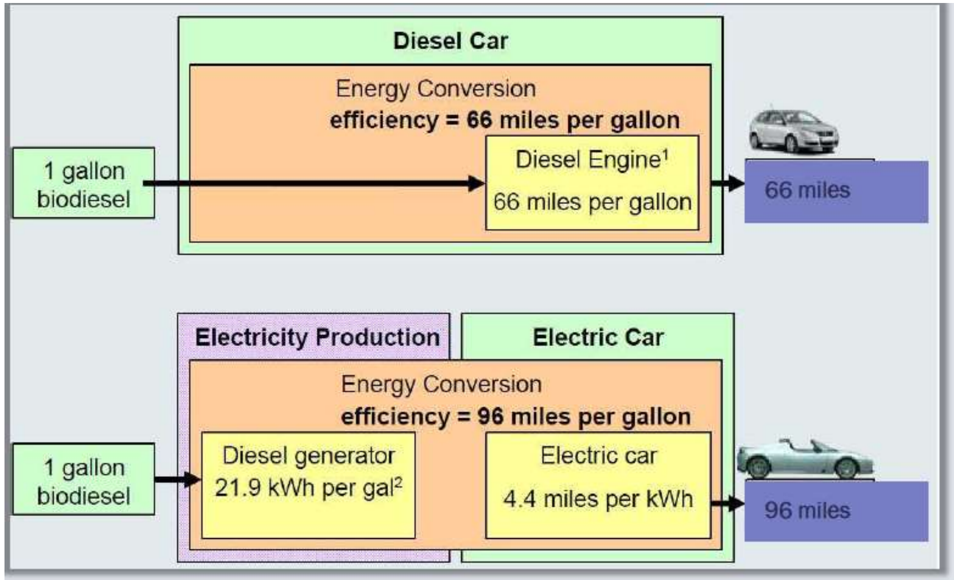
Ref: Brian Randall Tesla presentation 2008





Courtesy: www.teslamotors.com

- a rough estimate of the total round-trip tank to wheel efficiency is:
- 0.90 (motor and drivetrain) x 0.95 (inverter) x 0.90 (battery) x 0.95 (charger) = 73%
- This number jives quite well with the claims of Tesla, which quotes a 75% round-trip efficiency.



- Running Costs
  - 0.03 – 0.04 $/mile.
  - Extremely low as compared to gasoline cars.
  - Motors last long.
- Reduced maintenance
  - No motor oil or oil filters to change.
  - No Smog equipment to check.
  - No Engine Servicing required.
- Environment friendly
  - Zero emissions.
  - Very low sound.

FUTURE DEVELOPMENTS

- Improved Batteries
  - Lithium Polymer.
  - Zinc Air Batteries.
  - Lithium Cobalt Metal Oxide.
- Hydrogen Economy
- Other Storage methods
  - SuperCapacitors(Electric Double layer Capacitors).
  - Flywheel Energy Storage.
- Hybrid Vehicles
- Solar Vehicles

SuperCapacitors
Courtesy: http://en.wikipedia.org/wiki/Electric_double-layer_capacitor

NASA G2 Flywheel
Courtesy. en.wikipedia.org/wiki/flywheel

MODULE 8:

Fuel Cell Hybrid Electric Vehicles

College of the Desert
Revision 0, December 2001

CONTENTS

OBJECTIVES

At the completion of this module, the technician will understand the types and uses of:

- hybrid electric vehicles
- electric motors
- auxiliary power units
- generators
- energy storage systems
- regenerative braking
- control systems

8.1 Hybrid Electric Vehicles

A hybrid electric vehicle (HEV) augments an electric vehicle (EV) with a second source of power referred to as the alternative power unit (APU).

Pure electric vehicles currently do not have adequate range when powered by batteries alone, and since recharging requires several hours, the vehicles are viewed as impractical for driving extended distances. If air conditioning or heating is used, the vehicle's range is further reduced. Accordingly, the hybrid concept, where the alternative power unit is used as a second source of energy, is gaining acceptance and is overcoming some of the problems of pure electric vehicles.

Figure 8-1 Electric Vehicles

The hybrid electric vehicle operates the alternative power unit to supply the power required by the vehicle, to recharge the batteries, and to power accessories like the air conditioner and heater. Hybrid electric cars can exceed the limited 100 mile (160 km) range-per-charge of most electric vehicles and have the potential to limit emissions to near zero. A hybrid can achieve the cruising range and performance advantages of conventional vehicles with the low-noise, low-exhaust emissions, and energy independence benefits of electric vehicles. Two types of hybrid vehicle configurations are the series and the parallel hybrids.

8.1.1 Series Hybrids

A series hybrid is similar to an electric vehicle with an on-board generator. The vehicle runs on battery power like a

Key Points & Notes

1916 Range & Lang Electric

More electric vehicles were in use in 1915 than there are at present.

Key Points & Notes

pure electric vehicle until the batteries reach a predetermined discharged level. At that point the APU turns on and begins recharging the battery. The APU operates until the batteries are charged to a predetermined level.

The length of time the APU is on depends on the size of the batteries and the APU itself. Since the APU is not directly connected to the drive train, it can be run at its optimal operating condition; hence, fuel economy is increased and emissions are reduced relative to a pure IC engine vehicle. A schematic of a series hybrid is shown in Figure 8-2.

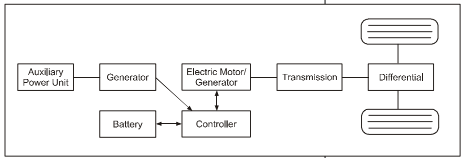


Figure 8-2 Schematic of a Series HEV

8.1.2 Parallel Hybrids

L3 Research Aeris Parallel Hybrid

In the parallel hybrid configuration, an APU capable of producing motive force is mechanically linked to the drive train. This approach eliminates the generator of the series approach. When the APU is on, the controller divides energy between the drive train (propulsion) and the batteries (energy storage). The amount of energy divided between the two is determined by the speed and driving pattern.

For example, under acceleration, more power is allocated to the drive train than to the batteries. During periods of idle or low speeds, more power goes to the batteries than the drive train.

When the APU is off, the parallel hybrid runs like an electric vehicle. The batteries provide electricity to the electric motor where it is converted to mechanical energy to power the vehicle. The batteries also provide additional power to the drive train when the APU is not producing enough and to power auxiliary systems such as the air conditioner and heater.

Key Points & Notes

The drive train for a parallel hybrid is more complex than that of a series hybrid as both the electric motor and the APU must be mechanically linked to the driveshaft. Since parallel hybrids only work with APU's that produce a mechanical output, fuel cells cannot be used for this option. Figure 8-3 shows a schematic of a parallel hybrid.

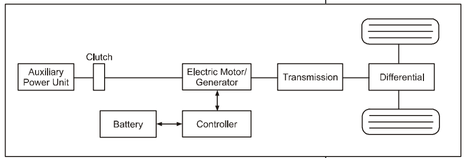


Figure 8-3 A schematic of a Parallel HEV

8.2 Major Components of Hybrid Vehicles

Key Points & Notes

8.2.1 Electric Drive Motors

Hybrid electric vehicles use an electric driveline and motor to provide the power for propulsion. The electric motor is a simple, efficient and durable device that is used every day in all sorts of applications. Electric motors range from those with fractional horsepower that run small appliances, to 5000-horsepower giants used in paper mills and other industries.

An electric motor converts electric energy to mechanical energy (motion) to drive the hybrid vehicle. Every motor can be used as a generator by rewiring it to transform mechanical energy into electrical current, but not all motors make efficient generators. For this dual use, the hybrid may use the electric motor to start the engine and then switch to generating electricity to keep the batteries charged. This reduces both the weight and cost of having two separate devices for engine starting and battery recharging.

In conventional vehicles, engine size determines the total power available to a moving vehicle. Hybrids, on the other hand, have electric motors that provide additional power when needed by the vehicle.

Both electric motors and engines can be rated in kilowatts (kW) — the preferred international standard — or in horsepower (hp). One hp equals 0.746 kW. When comparing horsepower ratings of a motor to an engine, it appears that electric vehicles are drastically under-powered. However, internal combustion engines are rated at the *maximum* power output, while electric motors are rated at their continuous power capabilities. A motor that can produce 10 hp continuously can easily produce three or four times that much power for a few minutes. Unlike internal combustion engines, electric motors emit zero harmful emissions.

The electric motor changes electric energy into mechanical power for work. Operation of the motor is based on three concepts:

- an electric current that produces a magnetic field
- the direction of current in an electromagnet that determines the location of the magnet's poles
- and the magnetic poles attraction or repulsion to each other

Key Points & Notes

An electric motor consists chiefly of a rotating electrical conductor situated between the north and south poles of a stationary magnet. It also contains a conductor known as an armature, a stationary magnet called the field structure, and a commutator.

The field structure establishes a constant magnetic field in the motor. The armature rotates and becomes an electromagnet when a current passes through it. Connection to the driveshaft allows it to drive the load. The commutator reverses the direction of the current in the armature and helps transmit current between the armature and the power source.

There are two types of motors: direct current and alternating current.

8.2.1.1 Direct Current Motors

In the direct current (DC) motors, the current always flows in the same direction. There are three types of DC motors: series, shunt and compound.

In the series motor, the armature and the field magnet are connected electrically in series. Current flows through the field magnet to the armature, increasing the strength of the magnets. The motor can start quickly under a heavy load, but such a heavy load decreases the motor speed.

The shunt motor connects the magnet and armature in parallel. Part of the current goes through the magnet while the rest goes through the armature. It runs at an even speed regardless of the load, but if the load is too heavy, the motor is difficult to start.

In the compound motor, two field magnets are connected to the armature, one in series and the other in parallel. The compound motor has the benefits of both the series and the shunt. It starts easily with a heavy load and maintains a relatively constant speed even when the load is increased.

Key Points & Notes

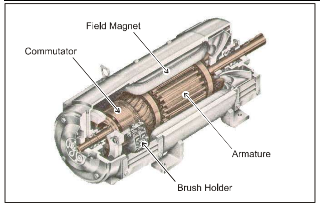


Figure 8-4 Direct Current Motor

8.2.1.2 Alternating Current Motors

Alternating current (AC) motors regularly reverse current flow direction. The reversal is typically 60 times per second or 60 Hz in North America and 50 Hz in Europe. Two changes of direction completes one cycle. The number of cycles per second is called the frequency of the alternating current.

The AC motor has many advantages over the DC motor. It is easy to build and convenient to use. Most AC motors do not require commutators because the current reverses its direction automatically. Those that use commutators do so to conduct the current from the external power source to the moving part of the motor and back.

The two types of AC motors are the induction and the synchronous motors.

In the induction motor, the rotor has no direct connection to an external source of electricity. The current flows around the field coils in the stator and produces a rotating magnetic field. This field induces an electric current in the rotor resulting in another magnetic field. The magnetic field from the rotor interacts with the magnetic field from the stator causing the rotor to turn.

Key Points & Notes

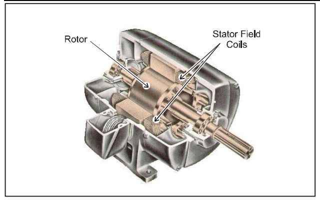


Figure 8-5 Alternating Current Induction Motor

In a synchronous motor, the stator also produces a rotating magnetic field. However, the rotor receives current directly from the power source instead of relying on the magnetic field from the stator to induce an electric current. The rotor moves at a fixed speed in step with the rotating field of the stator. Therefore, the synchronous motor maintains a fixed speed and uses less energy than an induction motor.

8.2.1.3 Electric Motor Configurations

The two possible configurations of electric drive motors in a hybrid vehicle are a single electric motor connected to the wheels through a drive train, or multiple electric motors, one located at each wheel.

The electric motor connected to the wheels through the drive train is the simplest design and is the present design of conventional vehicles.

Multiple electric motors, however, produce better traction and regenerative braking at each wheel, allow more room for other parts, and continue to function even when one or more motors malfunction. This configuration has been used in some all-terrain vehicles.

8.2.2 Auxiliary Power Units

The auxiliary power unit (APU) of a hybrid vehicle supplies the baseline power required to the vehicle, recharges the batteries and powers accessories such as the air conditioner and heater. The APU can consist of a mechanical type engine or a fuel cell. A mechanical type engine can be a spark ignition, compression ignition, rotary, turbine or Stirling engine.

Key Points & Notes

Toyota Prius Hybrid

Honda Insight Hybrid

8.2.2.1 Spark Ignition Engine

In 1862, Beau de Rochas proposed a sequence of operations that remains typical of most spark ignition engines. The four-stroke cycle requires two revolutions of the crankshaft for each power stroke and allows the piston to slide back and forth in the cylinder while transmitting the power to the drive shaft.

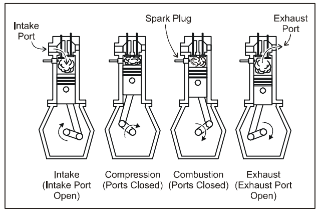


Figure 8-6 Four-Stroke Engine Operation

The spark ignition engine has a simple, mature, well understood design, a good power-to-weight ratio, and the ability to burn gasoline, methanol, ethanol, natural gas, propane or hydrogen. It also has well developed emission controls. The disadvantages, however, are poor part-load efficiency and relatively high uncontrolled emissions of hydrocarbons, carbon monoxide and oxides of nitrogen.

In order to produce a higher output from the same size engine and to obtain some valve simplification, the two-stroke cycle was developed by Dugald Clerk in 1878. This cycle is applicable both to compression ignition and to spark ignition operation, but has been primarily successful only with the latter.

The two-stroke engine's combustion cycle is completed in two strokes (one revolution) of the crankshaft as opposed to the four strokes (two revolutions) required by the four-stroke engine.

Key Points & Notes

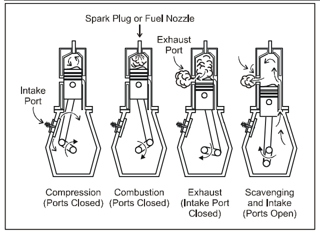


Figure 8-7 Two-Stroke Engine Operation

Compared to the four-stroke, the two-stroke engine has a higher power-to-weight ratio, a simpler design, lower manufacturing costs, and is lightweight. The emissions, however, are a major problem. There are relatively high uncontrolled hydrocarbons and carbon monoxide emissions, and emission control systems have not been sufficiently developed. Two-stroke engines are common in small gasoline motors, such as on chainsaws and smaller motorcycles.

8.2.2.2 Compression Ignition Engines

The compression ignition engine is typified by the diesel engine. The diesel cycle is similar to the Otto cycle except that a high compression ratio and air are required instead of a combustible mixture. Air is admitted to the engine on the intake stroke and the rapid compression of the air raises the temperature to such a point that a fuel, when delivered into the combustion chamber, ignites spontaneously. There is no requirement for a spark to initiate the combustion, or for a homogeneous mixture to propagate the flame.

The advantages of Compression Ignition engines are efficiency at high compression ratios, they are well developed and dependable, and have low carbon monoxide and hydrocarbon emissions. The disadvantages, however, are a high levels of carbon particulate and oxides of nitrogen emissions.

Key Points & Notes

8.2.2.3 Wankel (Rotary) Engines

In 1954, Felix Wankel found that an engine could be made of three variable-volume chambers formed between a stationary epitrochoid-shaped housing and a rotating equilateral triangular rotor. (A epitrochoid is a curve like an epicycloid, but generated by any point on a radius. An epicycloid is a curve described by a point on the circumference of a circle rolling on the outside of the circumference of another circle. Basically, the housing is circular, and the action is rotational.)

Together with proper arrangement of intake, exhaust and ignition mechanisms, this variation of volume in the three chambers makes it possible to carry out the four main events of the Otto cycle within each of the three chambers.

Wankel engines have a compact design, a high power-to-weight ratio, are lightweight, and use the same emission control systems as the four-stroke SI engines. However, they have relatively poor efficiency and high uncontrolled emissions of hydrocarbons, carbon monoxide and oxides of nitrogen. Wankel engines were produced commercially for Mazda cars in the 1980's, but were eventually replaced by conventional spark ignition engines.

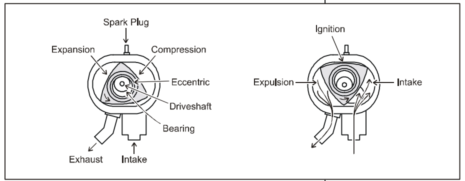


Figure 8-8 Wankel (Rotary) Engine Operation

8.2.2.4 Stirling Engines

An alternative to the internal combustion engine is an external combustion engine known as the Stirling engine. The Stirling cycle has two isothermal processes and two constant-volume processes. The thermal efficiency of the Stirling cycle with perfect regeneration is equal to that of the Carnot cycle for the same temperature range. The Stirling engine has low emissions, good efficiency, and operates quietly. The

Key Points & Notes

disadvantages are a complicated design, a low power-to-weight ratio, high cost and a large cooling requirement.

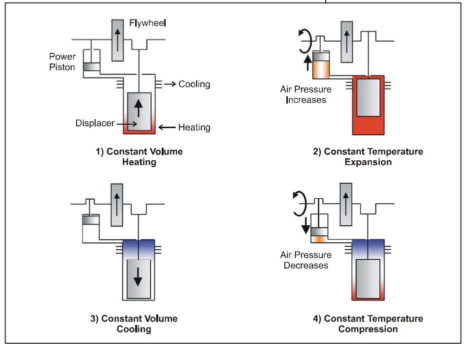


Figure 8-9 Stirling Engine Operation

8.2.2.5 Gas Turbines

Gas turbines, one of the oldest forms of combustion engines, are composed of a turbine, a combustion chamber and an air compressor.

The turbine has a rotor that is turned by moving fluid such as water, steam, gas or wind. It changes kinetic energy (energy of movement) into mechanical energy (energy in form of mechanical power). The mechanical energy is transmitted by the turbine through the spinning motion of the rotor's axle.

Williams Gas Turbine Engine

A gas turbine burns fuels such as oil, natural gas or kerosene. Gas turbines are small, lightweight, smooth running, have good power-to-weight ratios and low emissions. The fundamental problem with them, however, is their expense, poor efficiency at part load and their high operating tempera-

Key Points & Notes

ture. Gas turbines engines are used on jet aircraft and burn jet fuel, which is a kind of kerosene.

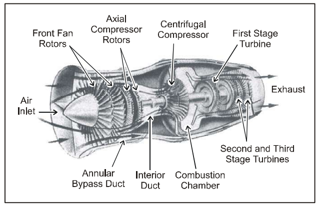


Figure 8-10 Gas Turbine Engine Major Components

8.2.2.6 Fuel Cells

Fuel cells are discussed in detail in other modules of this course. Fuel cells are convenient in electrical hybrid applications since they can be used in tandem with other electricity generating devices.

8.2.3 Generators

All the power systems described above, except for the fuel cell, require a generator to convert the mechanical power into electrical power when used in a series hybrid. Generators, like electrical motors, are either AC or DC.

8.2.3.1 AC Generators

An AC generator (or alternator) produces an electric current that reverses direction many times per second. It is also called a synchronous generator because it generates a voltage containing a high frequency proportional to, or synchronous with, the speed of the rotor.

A simple AC generator has each end of its wire loop, or armature, attached to a slip ring. A carbon brush connected to the outside circuit rests against each of the slip rings. As the armature rotates, the current moves in the direction of the arrows. The brush at the first slip ring conducts the current out of the armature, and the brush at the second slip ring brings it back in.

Key Points & Notes

When the armature rotates parallel to the magnetic field, no current is generated for a moment. When the armature rotates into the magnetic field again, the current reverses direction. It then flows out of the armature through the second slip ring and back into the armature at the first slip ring.

8.2.3.2 DC Generators

A DC generator produces an electric current that always flows in the same direction. It is different from the AC generator in both the way it is built and how it is used.

The commutator rotates with a loop of wire just as the slip rings do with the rotor of an AC generator. Each half of the commutator ring is called the commutator segment and is insulated from the other half. Each end of the rotating loop of wire is connected to a commutator segment. Two carbon brushes connected to the outside circuit rest against the rotating commutator. One brush conducts the current out of the generator and the other brush feeds the current back in.

The commutator is designed so that no matter how current in the loop alternates, the commutator segment containing outward-going current is always against the "out" brush at the proper time.

8.2.4 Energy Storage Systems

The peak power required in hybrid vehicles is met by devices like batteries, capacitors or a flywheel. These devices store energy and readily release it when needed.

8.2.4.1 Batteries

Batteries are one of the most important parts of a hybrid vehicle. A battery produces electricity by means of chemical action. It consists of one or more electric cells. Each cell has all the chemicals and parts needed to produce an electric current.

There are two types of batteries: primary and secondary (or storage) batteries. Primary batteries discharge and must be discarded after one or more of the chemicals is used up. Secondary batteries, on the other hand, can be recharged after they have delivered their electrical energy. Consequently, secondary batteries are ideal for hybrid application. They are able to supply power to the vehicle and be re-used.

The criteria used for battery selection are: temperature, energy density, power density, service life, shelf life, cost, reliability, cell configuration, charge/discharge cycle, safety,

Key Points & Notes

operating environment, recycling, minimal memory effect and efficiency.

8.2.4.2 Capacitors

A capacitor is a device that stores electrical energy in the form of an electrical charge.

A capacitor consists of two metal plates with an insulating material called a dielectric between them. Wires usually connect the plates to a source of electric current such as a battery. When an electric charge flows through the wires from one plate of the capacitor to the other, both plates become charged — one with a positive charge, and the other with a negative charge. The two plates then have potential difference in energy — a voltage — between them.

Capacitors

The plates release their charge when their wires are disconnected from the source and touched together. The ability of the capacitor to store electric energy is its capacitance. The main difference between a battery and a capacitor is that a capacitor can be rapidly charged and discharged.

8.2.4.3 Flywheels

The flywheel is an alternative energy storage system that is capable of replacing chemical batteries in conventional electric vehicles.

A flywheel is a balanced mass spinning around a constant axis that stores energy as rotational kinetic energy. Simply put, a flywheel is a mechanical battery that is capable of delivering multi-kilowatt-hours of energy to the drive system of an electric vehicle.

Flywheel energy storage (FES) systems have been researched for many decades, but their application has been limited due to the high cost of inefficient materials. However, recent advancement in fiber-composite materials, control electronics, and frictionless magnetic bearings have led researchers to believe that modern FES systems could be used to power efficient non-polluting electric vehicles.

The FES systems have been shown to theoretically rival chemical batteries in terms of power, energy density, cycle life, charge time, operating temperature range, environmental friendliness and maintenance needs.

The FES systems are now a viable technology for regenerative braking, for averaging peak power demands, and for storing energy on electric and hybrid vehicles. In hybrids, for example, FES systems can replace expensive ultra-

Key Points & Notes

capacitors for energy storage energy and to average out power demands.

8.2.5 Regenerative Braking

Brakes are devices that slow or stop the movement of a wheel, engine or entire vehicle. Most brakes have a fixed part called a brake shoe or block that presses against a turning wheel to create friction (heat) that causes the wheel to stop or slow down.

In regenerative (or dynamic) braking, some of the energy is converted into electrical energy and stored. Pressing on the brake pedal first activates the regenerative braking system, and then the conventional friction brake. The rotational energy of the braking mechanism generates electrical power and stores it in the batteries.

Electric and hybrid vehicles are well suited to use regenerative braking, as the captured electricity can power the drive motor. This electricity can be used in place of, or to supplement the APU, further reducing fuel use and improving fuel economy.

8.2.6 Control Systems

The electronic control system regulates the high-intensity current, helping it work with the APU counterparts. It controls the power flow between the battery and the motor as well as regenerative braking. A control system contains two main components, namely the command and power components. The command component manages and processes the driver's instructions. The power component chops power flows to control the motor's power intake.

There are two choppers to manage this power flow. The primary chopper is the startup phase and works at low motor speeds. The excitation chopper regulates the motor at medium and high motor speeds.

FUEL CELLS

What is a fuel cell?

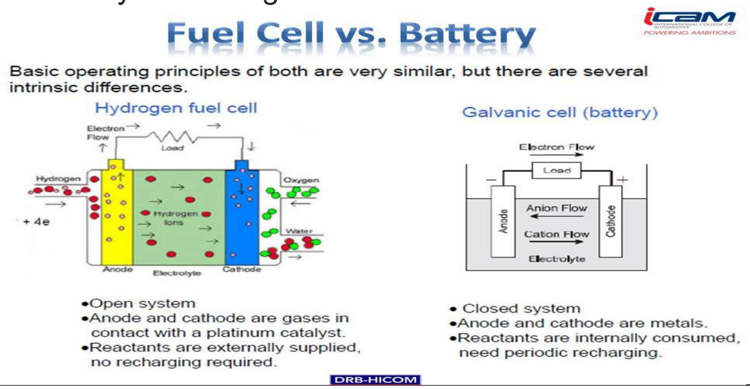
- A fuel cell is a galvanic cell in which the chemical energy of a fuel is converted directly into electrical energy by means of electrochemical processes.
- The fuel and oxidizing agents are continuously and separately supplied to the two electrodes of the cell, where they undergo a reaction.
- An electrolyte is necessary to conduct the ions from one electrode to the other.
- The fuel is supplied to the anode or positive electrode, where electrons are released from the fuel under catalyst.
- Principally To convert the chemicals hydrogen and oxygen into water, and in the process it produces electricity

Difference from a Battery

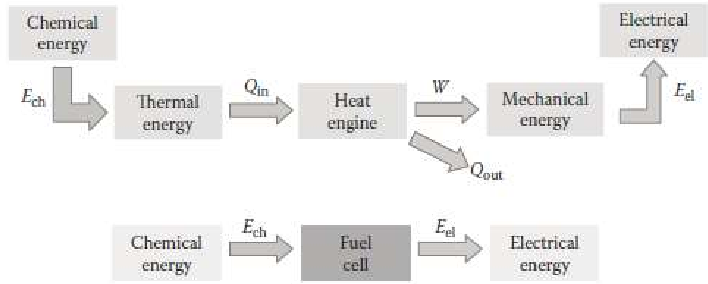
- Battery the other electrochemical device that we are all familiar.

⇨A battery has all of its chemicals stored inside, and it converts those chemicals into electricity too.

⇨This means that a battery eventually "goes dead" and you either throw it away or recharge it



Difference from an Engin



In a fuel cell

- Chemicals constantly flow into the cell so it never goes dead.

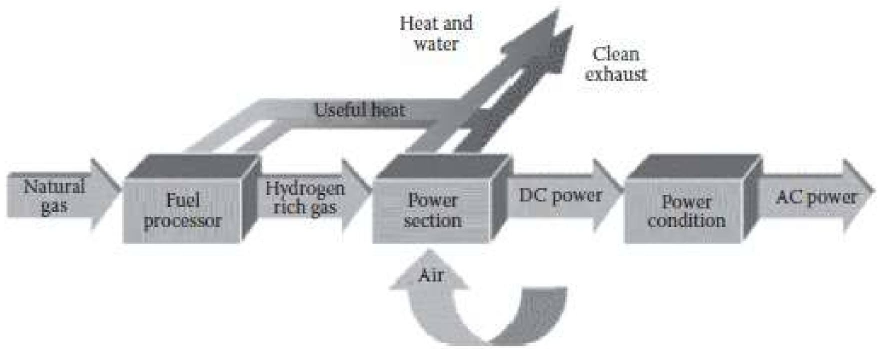
As long as there is a flow of chemicals into the cell, the electricity flows out of the cell.

- Most fuel cells in use today use hydrogen and oxygen as the chemicals
- Fuel Cells generate electricity through an electrochemical process

⇨In which the energy stored in a fuel is converted directly into DC electricity.

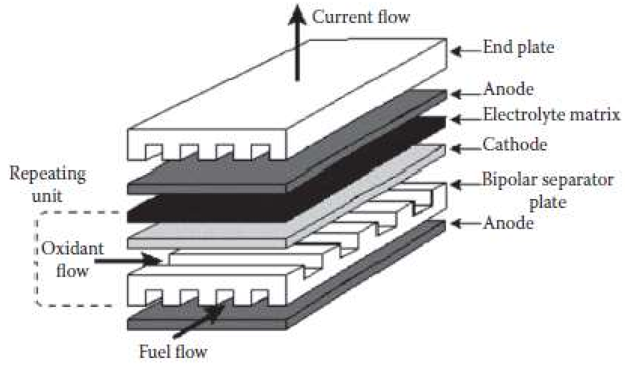
- Because electrical energy is generated without combusting fuel,

⇨Fuel cells are extremely attractive from an environmental stand point

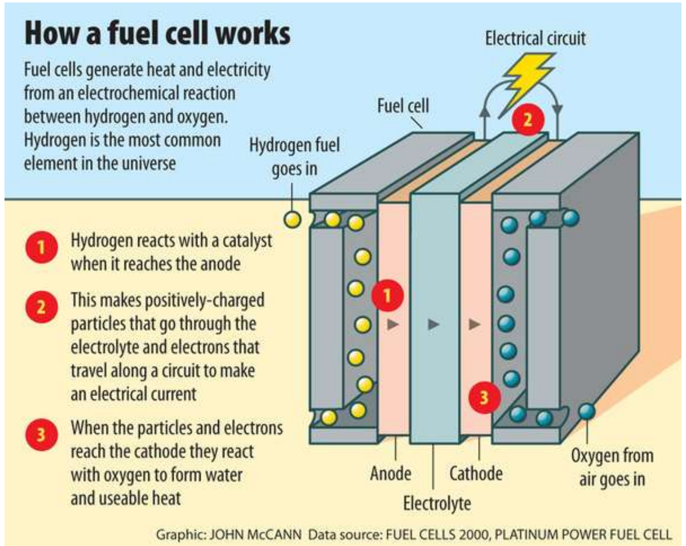


Parts of a Fuel cell

- Anode- Negative post of the fuel cell, Conducts electrons freed from hydrogen molecules to be used in external circuits. Etched channels disperse hydrogen gas over the surface of the catalyst
- Cathode- Positive post of the fuel cell, etched channels distribute oxygen to the surface of the catalyst. Recombine with hydrogen ions to form water
- Electrolyte- Exchange membrane, specially treated material
- Catalyst- Facilitates the reaction, usually platinum powder

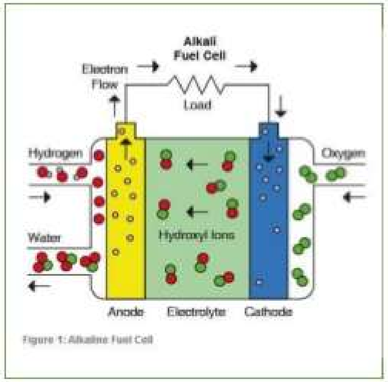


How does it work?



working:

- Hydrogen atom enter fuel cell at anode where a platinum catalyst causes the Hydrogen to split into positive Hydrogen ions (protons)and negatively charge electrons.
- The positively charge Hydrogen ions react with Hydroxyl (OH-)ions in the electrolyte to form water.
- The negatively charge electrons can not flow through the electrolyte to reach the positively charge cathode, so they must flow through an external circuit, forming an electrical current.
- Oxygen enter the fuel cell at cathode and picks up electrons and then travel through electrolytes to The anode , where it combines with hydrogen atom.
- Oxygen with electron combine hydrogen at anode and form water which drains from the cell.



The attractive option- Why?

- High energy conversion efficiency
- Modular design
- Very low chemical and acoustical pollution
- Fuel flexibility
- Cogeneration capability
- Rapid load response

Types of Fuel cell

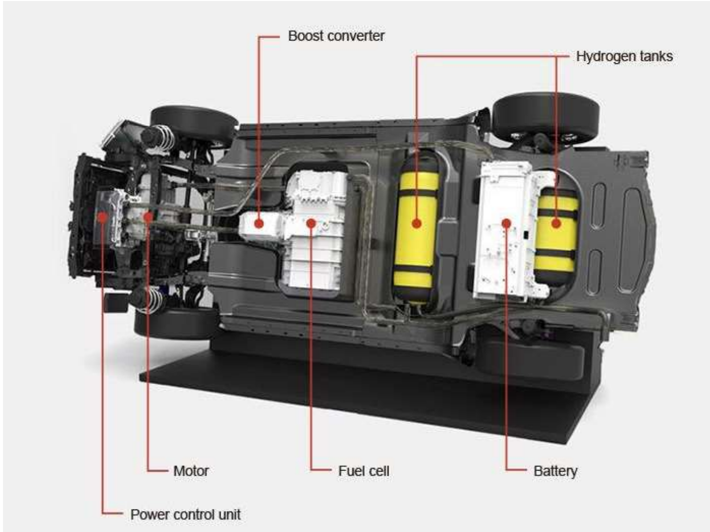
- Polymer electrolyte membrane fuel cells
- Direct methanol fuel cells
- Alkaline fuel cells
- Phosphoric acid fuel cells
- Molten carbonate fuel cells
- Solid oxide fuel cells
- Reversible fuel cells

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)*	Perfluoro sulfonic acid	50-100°C 122-212°F	1 kW–250 kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 19-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • S sensitivity
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW–3 MW 300 kW module	50-60%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	600-1000°C 1112-1832°F	1 kW–2 MW	50-60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • HT operation requires long start up time and limits shutdowns

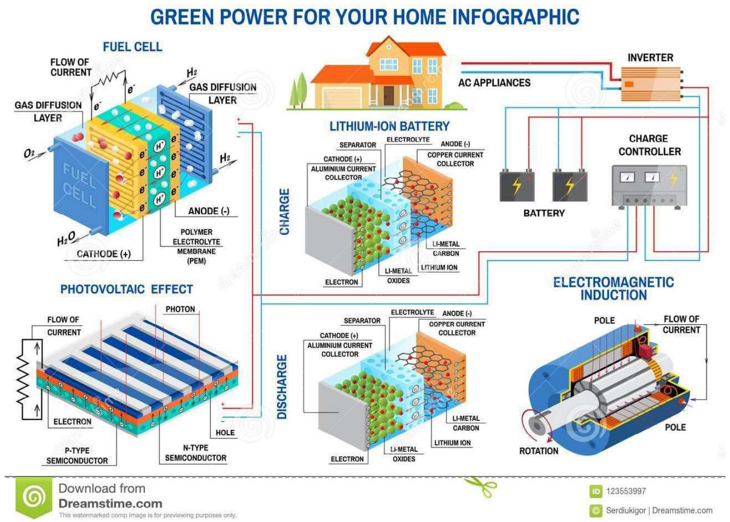
*Direct Methanol Fuel Cells (DMFC) are a subset of PEM typically used for small portable power applications with a size range of about a subwatt to 250 W and operating at 60-90°C.

COMMERCIAL FUEL CELL USE

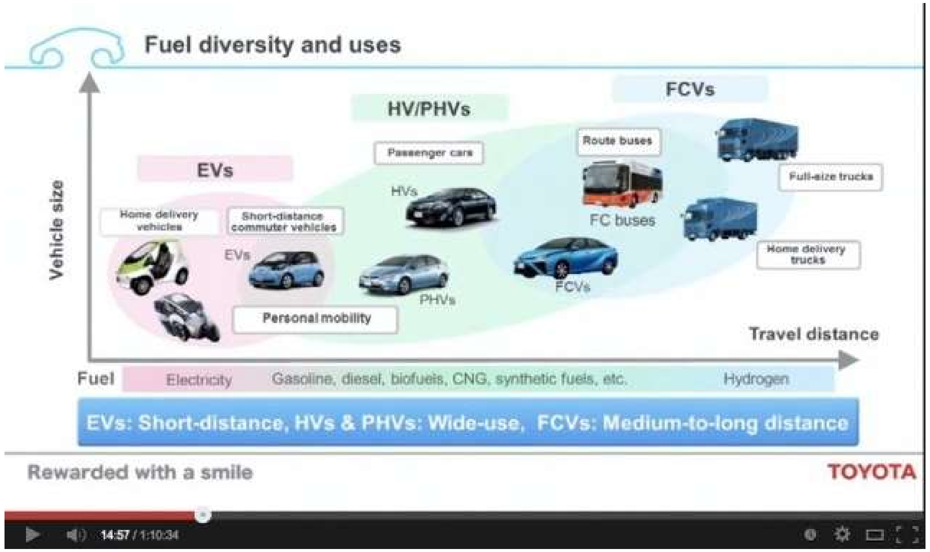
COMMERICAL FUEL CELL USE

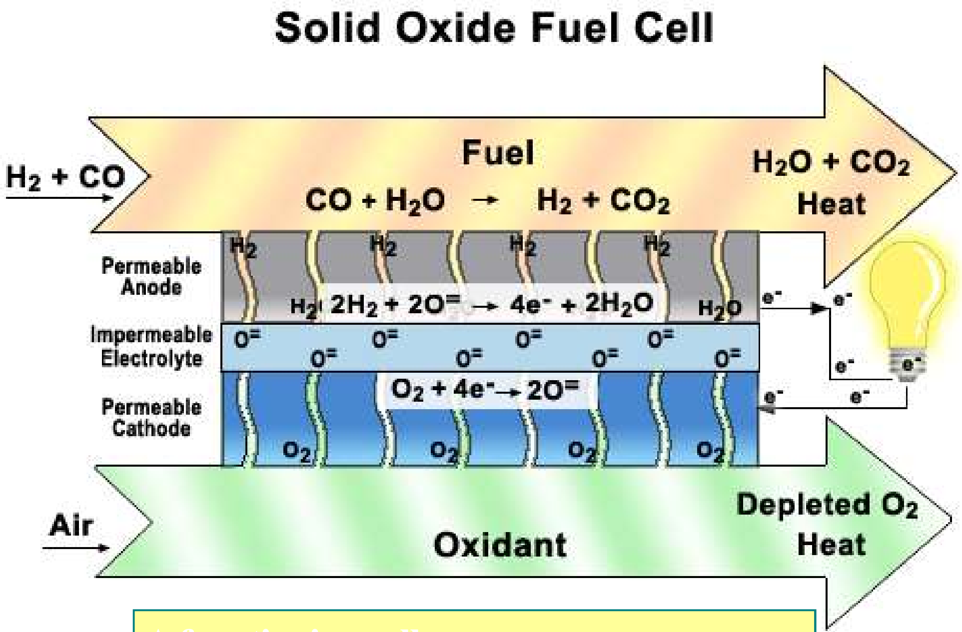


INTEGRATED HOME BASED ENERGY SYSTEM



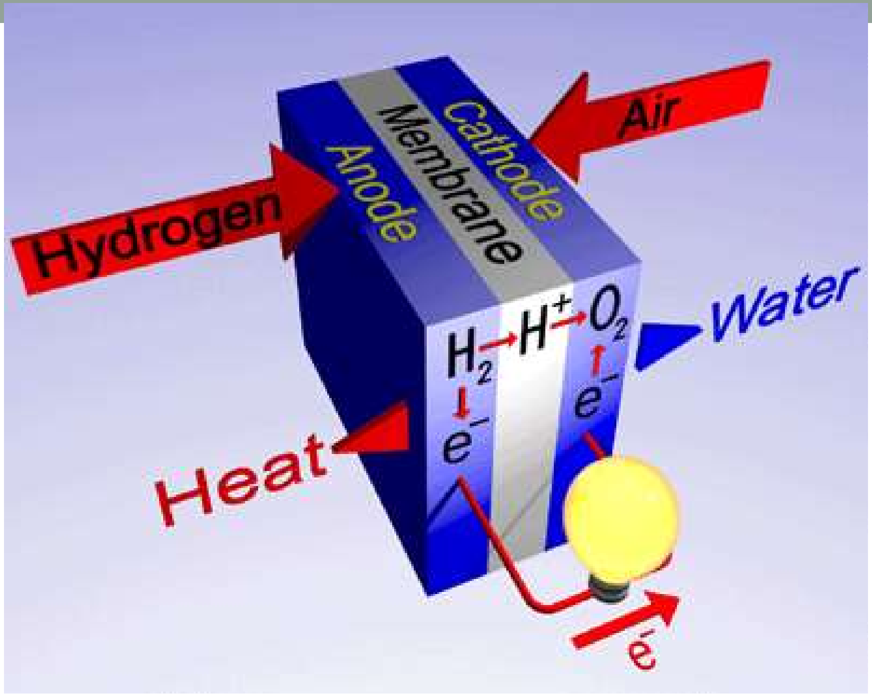
Fuel cell for transportation





A functioning cell

in a Solid Oxide Fuel Cell stack



How SOFC works?

- It consists of three components - a cathode, an anode, and an electrolyte sandwiched between the two.
- Oxygen from the air flows through the cathode
- A fuel gas containing hydrogen, such as methane, flows past the anode.

⇨Negatively charged oxygen ions migrate through the electrolyte membrane react with the hydrogen to form water,

- The reacts with

  the methane fuel

  to form hydrogen (H_2) &

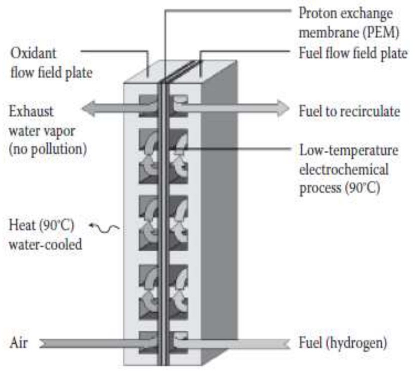
  carbon dioxide (CO_2).

- This electrochemical reaction generates electrons, which flow from the anode to an external load and back to the cathode,

⇨a final step that both completes the circuit and supplies electric power.

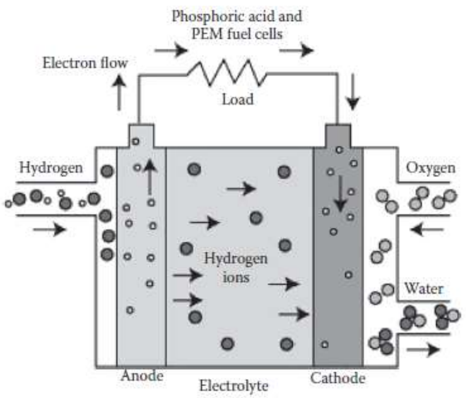
- To increase voltage output, several fuel cells are stacked together to form the heart of a clean power generator.

PEMFC



Developed in US by NASA for space exploration.
Contains proton conducting membrane sandwiched between 2 platinum impregnated porous electrodes.
Teflon gaskets and current collectors are added to complete the fuel cell structure.
Membranes are basically fluorocarbon polymer based structure to which sulphonic acid groups are attached.
Protons are free to travel

PEMFC Working



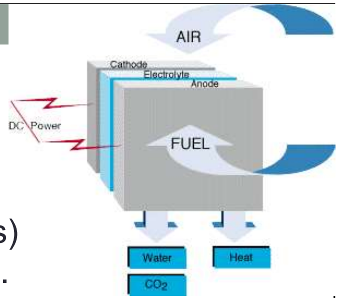
Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Cell reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Hydrogen gas is supplied to the anode where it dissassociates into Hydrogen atoms in the presence of platinum catalyst.
The atoms further splits to protons and electrons which travel in separate ways from the anode to cathode.
Protons are conducted through the electrolyte membrane, the electrons are forced to go via, the external circuit to the cathode to produce electricity
Oxygen is supplied to the cathode where a reduction process occurs and water and heat are created as by-products.

All fuel cells have the same basic operating principle.



- An input fuel is catalytically reacted (electrons removed from the fuel elements) in the fuel cell to create an electric current.
- Fuel cells consist of an electrolyte material which is sandwiched in between two thin electrodes (porous anode and cathode).
- The input fuel passes over the anode (and oxygen over the cathode) where it catalytically splits into ions and electrons.
- The electrons go through an external circuit to serve an electric load while the ions move through the electrolyte toward the oppositely charged electrode.
- At the electrode, ions combine to create by-products, primarily water and CO_2. Depending on the input fuel and electrolyte, different chemical reactions will occur.