Fossil, Biomass, and Synthetic Fuels
Why do we care about heat engines?

Global energy consumption 2014

- Fossil Fuels = 86%
- Coal: 30%
- Oil: 32%
- Gas: 24%
- Nuclear: 7%
- Hydro: 4%
- Wind: 1%
- Solar: 0%
- Geothermal & biomass: 1%
- Biofuels: 0%

Energy Matters
euanmearns.com
BP 2015 data
Waste heat

U. S. electricity generation = $1.3 \times 10^{19}$ J/y
Assuming 40% efficiency = $8 \times 10^{18}$ J/y waste heat
Volume Lake Superior = 12,100 km$^3$

$T = \frac{\Delta H}{cm} = \frac{8 \times 10^{18}}{(1.2 \times 10^{16})(4.2 \times 10^3)} = 0.16 \, ^\circ C$

**Fuel (Thermal) Efficiencies of Current Power Technologies**

<table>
<thead>
<tr>
<th>Type</th>
<th>Efficiency (%)</th>
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</thead>
<tbody>
<tr>
<td>Steam electric power plant</td>
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<tr>
<td>Steam at 62 bar, 480°C</td>
<td>30</td>
</tr>
<tr>
<td>Steam at 310 bar, 560°C</td>
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</tr>
<tr>
<td>Nuclear Power plant</td>
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<tr>
<td>Steam at 70 bar, 286°C</td>
<td>33</td>
</tr>
<tr>
<td>Automotive gasoline engine</td>
<td>25</td>
</tr>
<tr>
<td>Automotive diesel engine</td>
<td>35</td>
</tr>
</tbody>
</table>
| Gas turbine electric power plant |        | 30
| Combined cycle electric power plant |     | 43
| Fuel cell electric power    | 45             |
Coal reserves for select countries. Relationship between industrialization, politics, and coal.
Formation of coal
- Time
- Temperature
- Pressure
Higher rank coals have higher heating value – more carbon, less water
Various coal mining methods and environmental impacts
Coal

- Environmental impacts of coal mining:
  - Substantial effects on the environment
  - Topsoil loss (from erosion or removal during mining) prevents restoration of site
  - Landslides occur due to loss of soil-stabilizing vegetation
Coal

- Environmental impacts of coal mining:
  - Acid and toxic mineral drainage leaches from minerals exposed in mine waste
    - Acid mine drainage—sulfuric acid and dangerous dissolved materials, such as lead, arsenic, and cadmium, wash from coal and metal mines into nearby lakes and streams
  - Streams become polluted with silt runoff and acid mine drainage
Chemistry of AMD

General equations for this process are:

- \(2\text{FeS}_2 + 7\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{Fe}^{2+} + 4\text{SO}_4^{2-} + 4\text{H}^+\)
- \(4\text{Fe}^{2+} + \text{O}_2 + 4\text{H}^+ \rightarrow 4\text{Fe}^{3+} + 2\text{H}_2\text{O}\)
- \(4\text{Fe}^{3+} + 12\text{H}_2\text{O} \rightarrow 4\text{Fe(OH)}_3 + 12\text{H}^+\)
- \(\text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+\)

The net effect of these reactions is to release \(\text{H}^+\), which lowers the pH, produces sulphate ions.

Effect scenarios in some places

- About half of the coal mine discharges in Pennsylvania have pH under 5.
- In US >12,000 miles of river and 180,000 acres of lakes/reservoirs are adversely affected.
- US companies now spend >$1million/day to treat CMD prior to discharging;
- In the coal belt around the south Wales valleys in the UK highly acidic nickel-rich discharges from coal stocking sites have proved to be particularly troublesome.
## Acid Mine Drainage

### Chemical
- Increased acidity
- Increase in soluble metal concentrations & particulate metals
- Destruction of bicarbonate buffering system

### Physical
- Sedimentation
- Increase in stream velocity
- Increased turbidity
- Decrease in light penetration

### Biological
- Affects reproductive patterns of organism
- Acute and Chronic toxicity
- Death of sensitive species
- Migration of species

### Ecological
- Habitat modification
- Bio-accumulation
- Reduction in primary production
- Increased instability of food chain
AMD Control Strategies

- Containment and isolation
  - Soil covers - by imported materials e.g. clay, soil
    - low sulphide waste-rock if compactable
    - Geo-textile fabrics
  - Water cover - creation of a permanent lake or swamp
    - use of an existing lake
    - flooding of underground tunnels
    - submarine disposal
  - Blending - mixing of acid and non acid forming waste rock

- Treatment - Using AMD remediation technologies
Coal

- Environmental impacts of coal mining
  - Mountaintop removal
    - One of most destructive mining methods
    - Has leveled 15–25% of mountains in southern West Virginia
      - Half the peaks in that area will be gone by 2020
    - Valleys and streams between mountains are obliterated; filled in with tailings and debris
    - Also in Kentucky, Pennsylvania, Tennessee, Virginia
    - [http://earthobservatory.nasa.gov/Features/WorldOfChange/hobet.php](http://earthobservatory.nasa.gov/Features/WorldOfChange/hobet.php)
  - Surface Mining Control and Reclamation Act
    - 1977—controlled abandoned surface mines
    - Set standards for mines to follow during operation and reclamation
Oil Reserves
(billion barrels)

Data presented are for countries with 4 billion barrels of reserves or greater.
Hubbert curve

The prototypical Hubbert curve is a probability density function of a logistic distribution curve. It is not a gaussian function (which is used to plot normal distributions), but the two have a similar appearance. The density of a Hubbert curve approaches zero more slowly than a gaussian function.

The graph of a Hubbert curve consists of three key elements:
1. a gradual rise from zero resource production that then increases quickly
2. a "Hubbert peak", representing the maximum production level
3. a drop from the peak that then follows a steep production decline.

The actual shape of a graph of real world production trends is determined by various factors, such as development of enhanced production techniques, availability of competing resources, and government regulations on production or consumption. Because of such factors, real world Hubbert curves are often not symmetrical.
Formation of petroleum

- Source rock
- Reservoir rock
- Trap
Drilling oil wells
Oil refining

Diagram showing the refining process, with various fractions of oil refined into different products at different temperatures:
- C₁ to C₄ gases
- C₅ to C₉ naphtha
- C₅ to C₁₀ petrol (gasoline)
- C₉ to C₁₂ kerosine (paraffin oil)
- C₁₀ to C₁₆ kerosine
- C₁₄ to C₂₀ diesel oils
- C₂₀ to C₅₀ lubricating oil
- C₂₀ to C₇₀ fuel oil
- >C₇₀ residue

Products include:
- Liquefied petroleum gas
- Chemicals
- Petrol for vehicles
- Jet fuel, paraffin for lighting and heating
- Diesel fuels
- Lubricating oils, waxes, polishes
- Fuels for ships, factories and central heating
- Bitumen for roads and roofing

Images show different aspects of an oil refinery.
15 countries hold 87% of the world's proved reserves. 2012 natural gas consumption worldwide was 114 tcf.
3) NATURAL GAS

- Natural Gas:
  - is a mixture of 50-90% methane (CH₄) by volume; contains smaller amounts of ethane, propane, butane and toxic hydrogen sulfide.
  - Either Conventional natural gas or Unconventional deposits.

- Gas Hydrates: an ice-like material that occurs in underground deposits (globally).

- Liquefied Petroleum Gas (LPG): propane and butane are liquefied and removed from natural gas fields. Stored in pressurized tanks.

<table>
<thead>
<tr>
<th>Conventional gas</th>
<th>Unconventional gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulations in medium to highly porous reservoirs with sufficient permeability to allow gas to flow to producing well.</td>
<td>Deposits of natural gas found in relatively impermeable rock formations—Tight sand and coal beds.</td>
</tr>
<tr>
<td>lies above most reservoirs of crude oil</td>
<td>Include coal beds, shale rock, deep deposits of tight sands and deep zones that contain natural gas dissolved in hot water.</td>
</tr>
<tr>
<td>Pressure regime tends to moves gas toward producing well (i.e., natural flow).</td>
<td>To get resources out of the ground, artificial pathways (fractures) have to be created.</td>
</tr>
<tr>
<td></td>
<td>Key technologies are horizontal drilling and hydraulic fracturing techniques.</td>
</tr>
<tr>
<td></td>
<td>Need much higher number of extracting well</td>
</tr>
</tbody>
</table>

© Hassan Harraz 2016
Shale Gas Basins In The United States

Total Resources: Potential of 500 – 1000 tcf
Hydraulic fracturing - how it works

**THE PROCESS**

Hydraulic fracturing, commonly known as fracking, is the creation of fractures in rock formations in the earth using pressurised fluid, generally for the purpose of extracting natural gas.

**Common Fracturing Equipment**

- Data monitoring van
- Chemical storage trucks
- Frac tanks - stimulation fluid storage
- Frac pumps
- Sand storage units
- Frac blender
- Wellhead

**Aquifer**

- Waste water pit
- Municipal water well (over 300 m)
- Private well
- Cemented well casing protects aquifer
- Waste cuttings generated during drilling are brought to a plastic-lined pit at the surface

**“Kickoff” point**

Drillers begin arc that levels off horizontally when shale layer is reached

**Horizontal Drilling**

1. Well drilled horizontally at 914-1,524 m
2. Production casing inserted into borehole, then surrounded with cement
3. Charges then detonated inside a perforating gun, blasting small holes into the shale
4. Pressurised mixture of water, sand and chemicals then pumped into the well at 15,900 litres a minute
5. The fluid generates numerous small fissures in the shale, freeing trapped gas that flows to the surface

**RISKS**

- **Air emissions**
  - Methane gas associated with natural gas extraction can leak into air
- **Drinking water**
  - Chemicals used in fracking process have the potential to contaminate aquifers
- **Earthquakes**
  - The disposal of waste fluid from the fracking process is cited as a cause of earth-quakes. Disposed fluids migrate below the injection area, destabilising the natural fractures in the rock formation

Sources: National Geographic, Chesapeake Energy, EIA, USGS

Staff, 24/12/2012
Oil shale reserves

1. United States
   3,706 billion barrels*
   *Oil in Place
   (800-1,200 billion barrels estimated recoverable)

2. China
   354 billion barrels

3. Russia
   248 billion barrels

4. Brazil
   82 billion barrels

5. Morocco
   54 billion barrels

6. Jordan
   34 billion barrels

7. Australia
   31 billion barrels
Oil shale – extraction (mining or wells) and processing

1 BORE IN
In a 30-by-20-foot field, a series of 600-foot-deep holes are drilled to reach oil shale — sedimentary rock containing hydrocarbons. The holes are spaced 5 feet apart around the perimeter and within the field.

2 FIRE UP
Specialized heating tubes placed in the holes warm the rock to 700 degrees Fahrenheit, a process that can take anywhere from eight months to four years.

3 SPLIT OFF
At the molecular level, the heat separates carbon — oil and gas from the rock.

4 LIFT OUT
The oil and gas are then sucked from the ground through holes equipped with pumps at the top.

LUMPS OF OIL SHALE ROCKS FROM CONVEYOR INTO TOP OF RETORT VIA NON-RETURN VALVE

DRAWN BY WILLY SCOTT 8/7/2010
Tar Sands

- Contain Bitumen
  - Semi solid; doesn’t “flow”
- Mined – strip mined
  - Steamed in place
- 5% sulfur content
- Most reserves in Canada & Venezuela
- Net energy yield – moderate
- Problems:
  - Acid rain, air pollution, global warming
1. Soil is removed to expose sand containing semi-solid petroleum bitumen.

2. The oil sand is loaded into trucks and poured into a crusher to break up lumps and remove rocks.

3. The oil sand is then mixed with warm water to create a slurry mixture and transported by pipeline to an extraction plant.

4. At the plant, the slurry enters a separation vessel. Sand settles to the bottom and bitumen and tiny air bubbles form a froth at the top.

5. The bitumen froth is skimmed off, later mixed with solvent and spun in a centrifuge to remove water and clay solids. The bitumen then is processed into crude oil.

Some key points:

- It takes 3 barrels of water to extract one barrel of oil from sand.
- Toxic tailing ponds are left behind that can leak and are big enough to see from space.
- Oil sands extraction produces 14 to 20 percent more greenhouse gases than conventional drilling.
Combustion of fossil fuel

\[ C_nH_m + (n + \frac{m}{4})O_2 \xrightarrow{\text{yields}} nCO_2 + (\frac{m}{2})H_2O \]

where \( C_nH_m \) is a hydrocarbon fuel molecule

Stoichiometric ratio – the number of oxygen molecules to the number of fuel molecules required to produce \( CO_2 \) and \( H_2O \) (complete combustion)

Stoichiometric ratio in terms of air mass to fuel mass

\[ \frac{\text{air mass}}{\text{fuel mass}} = 4.319\left(\frac{32n + 8m}{12n + 1.008m}\right) \]

Rich mixture – less air than stoichiometric proportion not all the carbon or hydrogen is fully oxidized (e.g. CO, solid C, or \( H_2 \))

Lean mixture – more air than stoichiometric proportion not all the oxygen is used but all the fuel’s chemical energy has been released during the combustion process.
### TABLE 4.1  Thermodynamic Properties of Fuel Combustion in Air at 25°C and One Atmosphere Pressure

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Symbol</th>
<th>Mol wt (g/mol)</th>
<th>( \text{FHV}^b ) (MJ/kg fuel)(^c)</th>
<th>((\text{A/F})_{st} )</th>
<th>((h_r - h_p)^b ) (MJ/kg product)</th>
<th>( \Delta f ) (MJ/kg fuel)</th>
<th>FHV(^b) (MJ/kg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure compounds(^d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Hydrogen</td>
<td>H(_2)</td>
<td>2.016</td>
<td>119.96</td>
<td>34.28</td>
<td>3.400</td>
<td>117.63</td>
<td>na</td>
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<tr>
<td>Carbon (graphite)</td>
<td>C(_{\text{solid}})</td>
<td>12.01</td>
<td>32.764</td>
<td>11.51</td>
<td>2.619</td>
<td>32.834</td>
<td>32.764</td>
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<tr>
<td>Methane</td>
<td>CH(_4)</td>
<td>16.04</td>
<td>50.040</td>
<td>17.23</td>
<td>2.745</td>
<td>51.016</td>
<td>66.844</td>
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<tr>
<td>Carbon monoxide</td>
<td>CO</td>
<td>28.01</td>
<td>10.104</td>
<td>2.467</td>
<td>2.914</td>
<td>9.1835</td>
<td>23.564</td>
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<tr>
<td>Ethane</td>
<td>C(_2)H(_6)</td>
<td>30.07</td>
<td>47.513</td>
<td>16.09</td>
<td>2.780</td>
<td>48.822</td>
<td>59.480</td>
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<tr>
<td>Methanol</td>
<td>CH(_2)O</td>
<td>32.04</td>
<td>20.142</td>
<td>6.470</td>
<td>2.696</td>
<td>22.034</td>
<td>53.739</td>
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<tr>
<td>Propane</td>
<td>C(_3)H(_8)</td>
<td>44.10</td>
<td>46.334</td>
<td>15.67</td>
<td>2.779</td>
<td>47.795</td>
<td>56.708</td>
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<tr>
<td>Ethanol</td>
<td>C(_2)H(_6)O</td>
<td>46.07</td>
<td>27.728</td>
<td>9.000</td>
<td>2.773</td>
<td>28.903</td>
<td>53.181</td>
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<tr>
<td>Isobutane</td>
<td>C(_4)H(_10)</td>
<td>58.12</td>
<td>45.576</td>
<td>15.46</td>
<td>2.769</td>
<td>53.142</td>
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<tr>
<td>Hexane</td>
<td>C(_6)H(_14)</td>
<td>86.18</td>
<td>46.093</td>
<td>15.24</td>
<td>2.838</td>
<td>54.013</td>
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<td>Octane</td>
<td>C(_8)H(_18)</td>
<td>114.2</td>
<td>44.785</td>
<td>15.12</td>
<td>2.778</td>
<td>53.246</td>
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<tr>
<td>Decane</td>
<td>C(_{10})H(_22)</td>
<td>142.3</td>
<td>44.599</td>
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<td>Dodecane</td>
<td>C(_{12})H(_26)</td>
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<td>Hexadecane</td>
<td>C(_{16})H(_34)</td>
<td>226.4</td>
<td>44.303</td>
<td>14.95</td>
<td>2.778</td>
<td>52.208</td>
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<td>Octadecane</td>
<td>C(_{18})H(_38)</td>
<td>254.5</td>
<td>44.257</td>
<td>14.93</td>
<td>2.778</td>
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<td>Commercial fuels</td>
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<td>Bituminous coal</td>
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<td>Subbituminous coal</td>
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<td>Grain</td>
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<tr>
<td>Manure</td>
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</tbody>
</table>


\(^b\) H\(_2\)O product in vapor phase; heating value is the lower heating value (LHV).

\(^c\) 1 MJ/kg = 429.9 Btu/lb mass.

\(^d\) Gas phase, except carbon.
Biomass burning is considered to be carbon neutral, but not always
Synthetic Fuels – manufactured from raw fuel to enhance its usefulness

- Oil, natural gas, alcohols, hydrogen produced from coal, oil shale, tar sands biomass, etc.
- Enhanced ease of transport and storage
- Removal of base fuel constituents such as sulfur, nitrogen, and ash, i.e. a cleaner fuel
- Major disadvantage is cost and reduction in Fuel Heating Value

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Product</th>
<th>Efficiency(^a) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Synthesis gas</td>
<td>72–87</td>
</tr>
<tr>
<td>Coal</td>
<td>Methane</td>
<td>61–78</td>
</tr>
<tr>
<td>Coal</td>
<td>Methanol</td>
<td>51–59</td>
</tr>
<tr>
<td>Coal</td>
<td>Hydrogen</td>
<td>62</td>
</tr>
<tr>
<td>Oil</td>
<td>Hydrogen</td>
<td>77</td>
</tr>
<tr>
<td>Methane</td>
<td>Hydrogen</td>
<td>70–79</td>
</tr>
<tr>
<td>Coal, oil, or gas</td>
<td>Hydrogen (electrolytic)</td>
<td>20–30</td>
</tr>
<tr>
<td>Oil shale</td>
<td>Oil and gas</td>
<td>56–72</td>
</tr>
<tr>
<td>Methanol</td>
<td>Oil and gas</td>
<td>86</td>
</tr>
<tr>
<td>Wood</td>
<td>Gas</td>
<td>90</td>
</tr>
<tr>
<td>Corn</td>
<td>Ethanol</td>
<td>46</td>
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<tr>
<td>Manure</td>
<td>Gas</td>
<td>90</td>
</tr>
</tbody>
</table>

\(^a\) Thermal efficiency is the ratio of the heating value of the synthetic product divided by the heating value of the parent fuel.
Fossil fuel synthesis

\[
\begin{align*}
C + O_2 & \rightarrow CO_2; \quad \Delta h = 8.941 \text{ MJ/kg r/p}; \quad \Delta f = 8.960 \text{ MJ/kg r/p} \\
CO + \frac{1}{2} O_2 & \rightarrow CO_2; \quad \Delta h = 6.431 \text{ MJ/kg r/p}; \quad \Delta f = 5.845 \text{ MJ/kg r/p} \\
H_2 + \frac{1}{2} O_2 & \rightarrow H_2O; \quad \Delta h = 13.424 \text{ MJ/kg r/p}; \quad \Delta f = 13.163 \text{ MJ/kg r/p} \\
CH_4 + 2O_2 & \rightarrow CO_2 + 2H_2O; \quad \Delta h = 10.01 \text{ MJ/kg r/p}; \quad \Delta f = 10.203 \text{ MJ/kg r/p}
\end{align*}
\]

As written, these are oxidation reactions (exothermic) and energy is transferred to the environment.

If we reverse the reactions they become reduction reactions and are endothermic. Energy must be transferred from the environment.
Coal to gas

Hydrogen is often the fuel of choice for fuel cells. It may be formed from coal:

\[
C + 1.664 \text{H}_2\text{O} + 0.168 \text{O}_2 \rightarrow \text{CO}_2 + 1.664 \text{H}_2; \quad \Delta h = 0; \quad \Delta f = 0,
\]

A common example of a biosynthetic process is the generation of methane by anaerobic bacteria in bogs or municipal solid or liquid organic waste facilities and by enteric fermentation in the digestive tracts of animals. In this process carbohydrate fragments (CH\text{2}O\text{)}\text{17} are reconfigured into methane and carbon dioxide:

\[
\text{CH}_2\text{O} \rightarrow \frac{1}{2} \text{CH}_4 + \frac{1}{2} \text{CO}_2; \quad \Delta h = 1.34 \text{MJ/kg fuel}; \quad \Delta f = 1.258 \text{MJ/kg fuel},
\]

A more important biochemical process is the fermentation of carbohydrate sugars to form ethanol (\text{C}_2\text{H}_6\text{O}):

\[
\text{CH}_2\text{O} \rightarrow \frac{1}{3} \text{C}_2\text{H}_6\text{O} + \frac{1}{3} \text{CO}_2; \quad \Delta h = 3.351 \text{MJ/kg fuel}; \quad \Delta f = 3.258 \text{MJ/kg fuel}.
\]
Biochemical production of ethanol from biomass
- Only fermentable biomass converted to ethanol
- Thermodynamic costs involving crop production and transportation
- Uses arable land which is no longer available for food production
- Utilizing food crops for biofuel may threaten food supply
### Table 2-1 Electrochemical Reactions in Fuel Cells

<table>
<thead>
<tr>
<th>Fuel Cell</th>
<th>Anode Reaction</th>
<th>Cathode Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Exchange Membrane and Phosphoric Acid</td>
<td>H₂ → 2H⁺ + 2e⁻</td>
<td>½ O₂ + 2H⁺ + 2e⁻ → H₂O</td>
</tr>
<tr>
<td>Alkaline</td>
<td>H₂ + 2(OH)⁻ → 2H₂O + 2e⁻</td>
<td>½ O₂ + H₂O + 2e⁻ → 2(OH)⁻</td>
</tr>
<tr>
<td>Molten Carbonate</td>
<td>H₂ + CO₃⁻ → H₂O + CO₂ + 2e⁻</td>
<td>½ O₂ + CO₂ + 2e⁻ → CO₃⁻</td>
</tr>
<tr>
<td></td>
<td>CO + CO₃⁻ → 2CO₂ + 2e⁻</td>
<td></td>
</tr>
<tr>
<td>Solid Oxide</td>
<td>H₂ + O²⁻ → H₂O + 2e⁻</td>
<td>½ O₂ + 2e⁻ → O²⁻</td>
</tr>
<tr>
<td></td>
<td>CO + O²⁻ → CO₂ + 2e⁻</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH₄ + 4O²⁻ → 2H₂O + CO₂ + 8e⁻</td>
<td></td>
</tr>
</tbody>
</table>

CO - carbon monoxide  
CO₂ - carbon dioxide  
CO₃⁻ - carbonate ion  
e⁻ - electron  
H₂O - water  
H⁺ - hydrogen ion  
O₂ - oxygen  
OH⁻ - hydroxyl ion

### Nernst Potential:

\[
E_{\text{ner}} = E_o + \frac{RT_{\text{sol}}}{2F} \ln \left( \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \right)
\]
H₂

- Natural gas
  - Steam reforming (with CO₂ capture)
  - Pyrolysis
  - Plasma reforming

- Coal, oil
  - Gasification
  - Partial oxidation (with CO₂ capture)

- Solar energy
  - Electrolysis of water
  - Photolytic splitting of water
  - Thermal splitting of water

- Wind, hydro, wave
  - Electrolysis of water

- Fission/fusion
  - Electrolysis of water
  - Thermal splitting of water

- Biomass
  - Fermentation
  - Gasification
  - Pyrolysis

- Transport applications
  - Stationary/domestic electricity/heat generation
  - Locally stored energy
  - Balancing of renewable electricity production
  - Portable electronics

- (Sustainable) hydrogen production
- Hydrogen storage
- Hydrogen utilization
Hydrogen gas can be produced by various processes. Two examples, coal gasification and electrolysis are shown below.

Hydrogen gas is stored either as a compressed gas or a liquid (cryogenic, must be stored at \(-253^\circ C\) or 20K).

Hydrogen is highly explosive.