FOSSIL FUELS’ ENERGY
AND THEIR ENVIRONMENTAL IMPACT

Ahmed F. Ghoniem
Department of Mechanical Engineering

April 12, 2005
FOSSIL FUELS:
We love to hate …

- The Big Picture, Revisited, why do we care?
- Types, amounts, how long and what are the trends?
- Combustion and reforming, why some chemistry headache?
- Combustion phenomena, where do they fit?
- Burners and Combustors, some hardware?
- Power Cycles, conventional and advanced, what are the trends?
- Emissions and their control, successes or failures?
- Fuel Cell; what do they have to do with fossil?
- Biomass, what is the connection?
The Terawatt Challenge
R. Smalley*
Rice University

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

12 Terawatts World wide
(3.3 TW in US)
~ 80% fossil, ~ 90% with biomass
2003

Source: International Energy Agency
Energy Sources and Demand


Graph removed for copyright reasons.

Wigley, Richels and Edmonds, ppmv of CO2, pre-industrial concentration is 280 ppmv
CO2 emissions and Global Temperature!

![Graph showing atmospheric CO2 concentrations and global mean temperature over time.](image)

*Figure 1b* Increased CO2 Emissions Causing a Rise in Atmospheric CO2 Associated with a Rise in Global Temperature (Sources: CO2 data from Ethridge et al. 2001, Keeling and Whorf 2002; temperature data from Jones et al. 1998, Peterson and Vose 1997)


*Predictions are always wrong! But it is good to have a plan ...*
THE DOMESTIC PICTURE
(Quadrillion Btu)

- Includes lease condensate.
- Natural gas plant liquids.
- Conventional hydroelectric power, wood, waste, ethanol blended into motor gasoline, geothermal, solar, and wind.
- Includes -0.09 quadrillion Btu hydroelectric pumped storage.
- Natural gas, coal, coke, and electricity.
- Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.
- Crude oil, petroleum products, natural gas, electricity, and coal coke.
- Includes supplemental gaseous fuels.

* Petroleum products, including natural gas plant liquids.
† Includes 0.05 quadrillion Btu of coal coke net imports.
‡ Includes, in quadrillion Btu, -0.09 hydroelectric pumped storage, -0.24 ethanol blended into motor gasoline, which is accounted for in both fossil fuels and renewable energy but counted only once in total consumption; and 0.02 electricity net imports.
§ Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See note at end of Section 2.
Notes: • Data are preliminary. • Totals may not equal sum of components due to independent rounding.
Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

Energy Information Administration / Annual Energy Review 2003
Total $98.2 \times 10^{15}$ BTU = $103.6 \times 10^{18}$ J

By Source, 2003

- Petroleum: 39
- Coal: 23
- Natural Gas: 23
- Nuclear Electric Power: 8
- Domestic production: 12
- Geo: 0.314
- Wind: 0.106
- Solar: 0.063

Energy Information Administration / Annual Energy Review 2003
U.S. 2002 Carbon Dioxide Emissions from Energy Consumption — 5,682* Million Metric Tons of CO₂**


*Includes adjustments for domestic and international fugitive emissions.

**Previous versions of this chart showed emissions in metric tons of carbon, not of CO₂.

Note: Numbers may not equal sum of components because of independent rounding.
87-89% fossil based …..

Levelized Cost Comparison for Electricity

Source: John Weyant, Stanford Energy Modeling Forum
Edwards, C., ME Seminar, December, 2004
FOSSIL FUEL TYPES
FOSSIL/ORGANIC FUELS

COAL, OIL, NATURAL GAS.
OIL SHALE, TAR SAND, PEAT.
“BIOMASS” .. Young, “renewable”.

• Formed due to the fossilization of organic matter, under ground (although evidence of earth mantel inorganic methane is rising).

• All formed of carbon and hydrogen, some with little oxygen, plus sulfur, mercury and other minerals, and non combustibles.

• Most require some form of processing: sulfur removal, grinding and washing, oil refining, gas desulfurization.
COAL
(fossilized vegetations)
lignite, subbituminous, bituminous, anthracite.

- Coal is carbon + hydrogen \((\text{CH}_m, m < 1)\) + sulfur (up to 10% by weight) + nitrogen + ash (non combustibles).

- Some sulfur can be washed away before combustion, but mostly is scrubbed from combustion products using limestone.

- In fluidized bed combustors, pulverized coal is mixed with limestone and burned at lower temperature in blowing air.

- In gasification, rich burning in oxygen and water forms syngas \((\text{CO}+\text{H}_2)\), desulfurization before combustion or gas separation.
OIL
(or petroleum, liquid rock, fossilized marine life, algae)

• Made up of many organic compounds + hydrogen + nitrogen + sulfur. Sweet and sour refer to the amount of sulfur. CH\textsubscript{m}, 1 < m < 2.

• “Light oil” is generally composed of three hydrocarbon families:
  
  • Saturated hydrocarbons: paraffins (or normal alkanes), C\textsubscript{n}H\textsubscript{2n+2}, with gas, n = 1-4, liquid, n = 5-15, and solids, n > 15.
  • Unsaturated hydrocarbons, or aromatics, like benzene, C\textsubscript{6}H\textsubscript{6}, toluene, C\textsubscript{7}H\textsubscript{8} and nephthalene, C\textsubscript{10}H\textsubscript{8}.
  • Resin and asphaltenes, heavier hydrocarbons rich in nitrogen, oxygen, sulfur and vanadium.

• Refining: distillation (separation of lighter components), catalytic cracking (heating) and reforming (with steam or hydrogen). Products are typically refinery gas, LPG, gasoline (mostly octane C\textsubscript{8}H\textsubscript{18}), aviation fuels (JPx) diesels, heating and lube oils ....
A Large Demand for Hydrogen is due to the Declining Quality of Available Crude Oil

Past

Current Transition

Near Future

Future

Input

Light Sweet Crude Oil

(CH_{1.5+})_n

Dirty (sulfur, etc.):

(CH_{1.5+})_n

Refinery

Heavy Sour Crude Oil

(CH_{0.8})_n

Clean: (CH_2)_n

Transport Fuel

Natural Gas

Hydrogen Plant

Heavy Sour Crude Oil

(CH_{0.8})_n

Clean: (CH_{2+})_n

Nonfossil Hydrogen

HTE

INL
Idaho National Laboratory

ORNL DWG 2001-107R2
Non-Conventional “Heavy” Oil
(all require intensive processing)

Oil Shale:
impermeable hard rock containing (organic, non petroleum) kerogen (pre-oil), which pyrolyzes into oil + (organic, petroleum) bitumen that liquifies with heating.

Tar and Tar Sand:
a mixture of sand and bitumen (coal-like) can be reformed into oil components.

Peat:
“Duff” material in forests and woodland ..
NATURAL GAS

• Mostly methane, CH$_4$, ethane C$_2$H$_6$, some propane, C$_3$H$_8$, and little butane, C$_4$H$_8$, with small fractions of higher hydrocarbons, may contain sulfur, oxygen, CO$_2$ at small quantities.

• Requires least processing.

• Biogenic Gas: near surface, difficult to exploit.

• Methane hydrides/hydrates, found in deep oceans, and permafrost, encapsulated in water (estimated to exceed 2 orders of magnitude of proven gas reserves) in ice like structures.
One way to classify fuels is through their heating value, in this table it is the *LHV*, in MJ/kg fuel.

<table>
<thead>
<tr>
<th>Commercial Fuels</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>36-42</td>
</tr>
<tr>
<td>Gasoline</td>
<td>47.4</td>
</tr>
<tr>
<td>Kerosene</td>
<td>46.4</td>
</tr>
<tr>
<td>No. 2 oil</td>
<td>45.5</td>
</tr>
<tr>
<td>No. 6 oil</td>
<td>42.5</td>
</tr>
<tr>
<td>Anthracite coal</td>
<td>32-34</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>28-36</td>
</tr>
<tr>
<td>Subbituminous coal</td>
<td>20-25</td>
</tr>
<tr>
<td>Lignite</td>
<td>14-18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biomass Fuels</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (fir)</td>
<td>21</td>
</tr>
<tr>
<td>Grain</td>
<td>14</td>
</tr>
<tr>
<td>Manure</td>
<td>13</td>
</tr>
</tbody>
</table>
Some Combustion Fundamentals: Chemical Thermodynamic

“Classical Thermodynamics is the only physical theory of universal content which …. within the framework of its basic notions, will never be toppled.”  Albert Einstein.
HYDROCARBON COMBUSTION IN AIR

\[ C_nH_m + \left( n + \frac{m}{4} \right)(O_2 + 3.76N_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + 3.76\left( n + \frac{m}{4} \right)N_2 \]

• Hydrocarbons store energy in their chemical bonds. Highest energy storage per unit mass or unit volume (in liquid form).

• Chemical Energy is converted into thermal energy during combustion, or other chemical energy in refining and reforming (processes that require energy).

• In complete, *stoichiometric* combustion of hydrocarbons, the products are water and carbon dioxide.
Ragone plot of Energy Storage
• *Oxyfuel combustion*, that is burning in pure oxygen, is also used to further raise the products temperature, in gasifiers (reformers), or to avoid the formation of nitric oxides.

\[
C_nH_m + \left(n + \frac{m}{4}\right)O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O
\]

• Even with stoichiometric combustion, carbon monoxide and nitric oxides form, as well very small amounts of hydrocarbons and their fragments (PAH).

• The amount of CO, NOx and “CH” in the products depend on the fuel, combustion conditions, nature of the combustion process, and how fast the products are cooled.
The amount of heat transferred out this reaction, when burning at constant pressure is known as the enthalpy of reaction.

\[ H_2 + \frac{1}{2} (O_2 + 3.76N_2) \rightarrow H_2O + \frac{3.76}{2} N_2 \quad \| + \Delta \hat{h}^o_{H_2O} \|

For most hydrocarbon the enthalpy or reaction per unit mass of fuel is 45 - 50 MJ/kg, for hydrogen it is 123 MJ/kg.
This is also the *Higher Heating Value*, if water in the products is in the liquid phase, or the *Lower Heating Value*, if it is in the gaseous phase (getting either depends on T and p of the process).
### Thermodynamic Properties of Fuel Combustion at 25°C and One Atmosphere Pressure

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Symbol</th>
<th>Molecular Weight (g/mol)</th>
<th>$FHV^b$ (MJ/kg fuel)$^c$</th>
<th>$(h_f-h_p)^b$ (MJ/kg product)</th>
<th>$\Delta_f$ (MJ/kg fuel)</th>
<th>$FHV^b$ (MJ/kg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pure Compounds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>$\text{H}_2$</td>
<td>2.016</td>
<td>119.96</td>
<td>34.28</td>
<td>3.400</td>
<td>117.63</td>
</tr>
<tr>
<td>Carbon (graphite)</td>
<td>$\text{C}_{\text{solid}}$</td>
<td>12.01</td>
<td>32.764</td>
<td>11.51</td>
<td>2.619</td>
<td>32.834</td>
</tr>
<tr>
<td>Methane</td>
<td>$\text{CH}_4$</td>
<td>16.04</td>
<td>50.040</td>
<td>17.23</td>
<td>2.745</td>
<td>51.016</td>
</tr>
<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>
</tr>
<tr>
<td>Ethane</td>
<td>$\text{C}_2\text{H}_6$</td>
<td>30.07</td>
<td>47.513</td>
<td>16.09</td>
<td>2.780</td>
<td>48.822</td>
</tr>
<tr>
<td>Methanol</td>
<td>$\text{CH}_4\text{O}$</td>
<td>32.04</td>
<td>20.142</td>
<td>6.470</td>
<td>2.696</td>
<td>22.034</td>
</tr>
<tr>
<td>Propane</td>
<td>$\text{C}_3\text{H}_8$</td>
<td>44.10</td>
<td>46.334</td>
<td>15.67</td>
<td>2.779</td>
<td>47.795</td>
</tr>
<tr>
<td>Ethanol</td>
<td>$\text{C}_2\text{H}_5\text{O}$</td>
<td>46.07</td>
<td>27.728</td>
<td>9.000</td>
<td>2.773</td>
<td>28.903</td>
</tr>
<tr>
<td>Isobutane</td>
<td>$\text{C}<em>4\text{H}</em>{10}$</td>
<td>58.12</td>
<td>45.576</td>
<td>15.46</td>
<td>2.769</td>
<td>53.142</td>
</tr>
<tr>
<td>Hexane</td>
<td>$\text{C}<em>6\text{H}</em>{14}$</td>
<td>86.18</td>
<td>46.093</td>
<td>15.24</td>
<td>2.838</td>
<td>54.013</td>
</tr>
<tr>
<td>Octane</td>
<td>$\text{C}<em>8\text{H}</em>{18}$</td>
<td>114.2</td>
<td>44.785</td>
<td>15.12</td>
<td>2.778</td>
<td>53.246</td>
</tr>
<tr>
<td>Decane</td>
<td>$\text{C}<em>{10}\text{H}</em>{22}$</td>
<td>142.3</td>
<td>44.599</td>
<td>15.06</td>
<td>2.778</td>
<td>52.838</td>
</tr>
<tr>
<td>Dodecane</td>
<td>$\text{C}<em>{12}\text{H}</em>{26}$</td>
<td>170.3</td>
<td>44.479</td>
<td>15.01</td>
<td>2.778</td>
<td>52.567</td>
</tr>
<tr>
<td>Hexadecane</td>
<td>$\text{C}<em>{16}\text{H}</em>{34}$</td>
<td>226.4</td>
<td>44.303</td>
<td>14.95</td>
<td>2.778</td>
<td>52.208</td>
</tr>
<tr>
<td>Octadecane</td>
<td>$\text{C}<em>{18}\text{H}</em>{38}$</td>
<td>254.5</td>
<td>44.257</td>
<td>14.93</td>
<td>2.778</td>
<td>52.102</td>
</tr>
</tbody>
</table>
Under adiabatic conditions, the products’ temperature is high ~ 2000°C (depending on the initial temperature and the process). It is called the *Adiabatic Flame Temperature*. 
Products Composition in Equilibrium Combustion

There is no complete combustion!

\[ C_nH_m + \left( n + \frac{m}{4} \right) \left( O_2 + 3.76N_2 \right) \rightarrow \]

\[ (n - \alpha)CO_2 + \left( \frac{m}{2} - \beta \right)H_2O + \left( 3.76 \left( n + \frac{m}{4} \right) - \frac{\gamma}{2} \right)N_2 \]

\[ + \alpha CO + \beta H_2 + \gamma NO_x + someO_2 \]

equilibrium dissociation and NOx formation
Impact of Equivalence Ratio and Initial Temperature On Flame Temperature

• COMBUSTION PROCESSES
• COMBUSTION DEVICES
• COMBUSTORS
• BURNERS
Power, what is it and what controls it..

Two photos removed for copyright reasons. Donkeys pulling cart and a fuel cell car.
Power Density in Combustion Processes

Coal: pulverized fluidized bed 0.01 GW/m³ 0.04
SI engine 0.1
Gas boiler 0.2
Aero engine (overall) 2.0 (primary) 4.0
Vehicle brakes 5
Premixed flame (peak) 6
Spark 10
WSR (at T*) 10-50
Hydrocarbon Oxidation Mechanisms …..

- **Methane** (CH₄)
- **Ethane** (C₂H₆)
- **Ethylene** (C₂H₄)
- **Acetylene** (C₂H₂)

**Steps:**
- From CH₄ to CH₃O
- From CH₃O to CH₂O
- From CH₂O to CHO
- From CHO to CO
- From C₂H₆ to C₂H₅
- From C₂H₅ to C₂H₄O
- From C₂H₄O to C₂H₃O
- From C₂H₃O to CO
- From C₂H₄ to C₂H₃
- From C₂H₃ to C₂H₂O
- From C₂H₂O to CO
- From C₂H₂ to C₂H

**Symbols:**
- CARBON
- OXYGEN
- HYDROGEN

Figure by MIT OCW.
Practical Combustion Processes

Premixed ...
- Flames
- SI engines
- Detonation
- Recirculating flows
- WSR
- Swirling flow

Non premixed
- Single phase
- Gas jet flames
- Most burners
- Catalytic combustion

Partially premixed
- Multi phase
- droplets:
- Diesels
- Gas turbine
- Coal

Piloted combustion
- Flameless combustion
Flame Types

A rich, long, sooty, jet diffusion flame, heavy HC or coal, strong radiation, typical in boiler burners

A well mixed (swirling) compact flame of a lighter HC, typical of modern burners, gas turbines, etc.
FOSSIL BASE ENERGY CONVERSION: ADVANCED POWER SYSTEMS

The fuel does not matter much!!

Do we have an Energy or an *Entropy Crisis*?
\[ \eta_{\text{carnot}} = 1 - \frac{T_L}{T_H} \]

“Nature, in providing us with combustibles on all sides, has given us the power to produce, at all times and in all places, heat and the impelling power which is the result of it. To develop this power, to appropriate it to our uses, is the object of heat engines. The study of these engines is of greatest interest, their importance is enormous, their use is continually increasing, and they seem destined to produce a great revolution in the civilized world.”

Sadi Carnot, Reflection On The Motive Power Of Heat And On Machines Fitted To Develop That Power, 1824.
Gas turbine Open (Brayton) Cycles

Figure 1. The components and states in a Brayton combustion gas turbine cycle.

\[
\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \\
\frac{T_3}{T_{4s}} = \left(\frac{p_3}{p_4}\right)^{\frac{k-1}{k}} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}
\]

\[
\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1} \\
\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}}
\]

\[
Q_{in} = h_3 - h_2 = c_p(T_3 - T_2)
\]

\[
W_{net} = (h_3 - h_4) - (h_2 - h_1)
= c_p\left[(T_3 - T_4) - (T_2 - T_1)\right]
\]

\[
\eta_{cycle} = \frac{\text{net mechanical work out}}{\text{heat transfer in}}
\]
Gas turbines have advantages in electric power generation:

1. They operate at high temperatures.
2. They can are capable of meeting peak load demands.
3. They are compact and easy to operate, and take advantage of aerospace propulsion applications.
4. They operate at relatively low pressures.
5. Many installations burn natural gas, or in dual fuel mode burning NG and/or oil.
6. They do not handle wet gases, and are not as vulnerable to corrosion as steam turbines.
7. Combustion gas turbines do not require heat transfer equipment on the low-temperature side, and no coolant either.
However, gas turbines suffer from several limitations:

1. They have relatively low efficiency since their maximum temperature is limited by material.
2. Their efficiency is low because of the high compressor work, and low efficiency of compressors.
3. Open cycle turbines are limited by the high exhaust temperature, which limits the turbine work.
4. They cannot be used with “dirty” fuels, such as coal, since sulfur oxides can damage their blades.

Steam, or vapor Rankine cycles overcome some of these limitations, and hence have been very popular in electric power generation.
Rankine (Vapor) Cycles:

![Figure 12. The T-s diagram of an open Rankine cycle, 1p-2p-3-4p, and a closed Rankine cycle, 1-2-3-4, with subatmospheric pressure.]

Critical point: $T_c = 374 \, ^\circ C$, $P_c = 22.088 \, MPa$

Cooling available at: $T = 15 \, ^\circ C$, where $P_{sat} = 5.63 \, kPa$
Rankine cycles:

1. Fuel flexible, works well with coal (closed cycle).
2. High efficiency, low pumping power.
3. Lower flow rate (latent enthalpy).
4. Run at low T (works with geothermal and solar), but high p.
5. Works well with nuclear energy:
   - Pressurized WR: T = 350 C
   - Boiling WR: T = 400-500 C
   - Gas Cooled R: T = 600-800 C
   - High Temperature GR T > 800 C

BUT
1. High inertia, good for base load but not for load following.
2. Require cooling, big condensers, .. Water …
COMBINED CYCLES:

Figure 18. A supercritical steam cycle, and a “matching” gas turbine cycle for use in a combined cycle plant.

Combined cycles take advantage of high T gas turbine exhaust.

Combined cycle efficiency:  \[ \eta_{\text{com}} = \eta_{\text{top}} + \eta_{\text{bot}} \left(1 - \eta_{\text{top}}\right). \]

For:  \( \eta_{\text{top}} = 0.25 \) and  \( \eta_{\text{bot}} = 0.4 \),  \( \eta_{\text{com}} = 0.55 \)
Table 2.1: Efficiency of current power plant types and efficiency potential stemming from possibilities for improvement and for future power plant cycles [22]^{4}

<table>
<thead>
<tr>
<th>Year of Initial Operation</th>
<th>Example</th>
<th>Operating Characteristics</th>
<th>Efficiency in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas-Fired Power Plant Cycles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>Gas turbine simple cycle</td>
<td>TIT approx. 1190°C (ISO 2314)^{5}</td>
<td>approx. 38-40</td>
</tr>
<tr>
<td>1997</td>
<td>GT with reheat</td>
<td></td>
<td>approx. 38</td>
</tr>
<tr>
<td>1998</td>
<td>GT with recuperation</td>
<td></td>
<td>approx. 40</td>
</tr>
<tr>
<td>1997</td>
<td>GT with steam injection (STIG/Cheng)</td>
<td></td>
<td>&lt;45</td>
</tr>
<tr>
<td>&gt;1998</td>
<td>Humid Air GT (HAT)</td>
<td></td>
<td>approx. 58-59</td>
</tr>
<tr>
<td>&gt;&gt;=2000</td>
<td>GT with chemical recuperation (CRGT)</td>
<td></td>
<td>55-62</td>
</tr>
<tr>
<td>1998</td>
<td>Gas / steam turbine combined cycle power plants</td>
<td>TIT approx. 1190°C (ISO 2314)^{5}</td>
<td>58-59</td>
</tr>
<tr>
<td>1995 / &gt;=2000</td>
<td>Fuel cells, natural gas-fired:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000 / &gt;=2005</td>
<td>MCFC / SOFC combined cycle plant</td>
<td>[23, 24, 25]</td>
<td>55 ... &gt;60</td>
</tr>
</tbody>
</table>

Courtesy of U.S. DOE.
## Coal-Fired Steam Power Plants

<table>
<thead>
<tr>
<th>Operational since 1998</th>
<th>Coal-fired steam power plant (seawater cooling system) Nordjyllandsværket [26]</th>
<th>Steam: 285 bar/580°C/580°C/580°C Feedwater preheating: 300°C Condenser pressure: 0.023 bar 10 feedwater preheating stages</th>
<th>47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned for 1999 (adjusted)</td>
<td>Coal-fired steam power plant (wet cooling tower system) Gelsenkirchen-Heßler[27]</td>
<td>Steam: 275 bar/580°C/600°C Feedwater preheating: 300°C Condenser pressure: 0.037 bar 9 feedwater preheating stages</td>
<td>45 to 45.5</td>
</tr>
<tr>
<td>Planned for 2001-2005</td>
<td>Coal-fired steam power plant (seawater cooling system) Avedøre 2 [28, 29]</td>
<td>Steam: 300 bar/580°C/600°C Condenser pressure: 0.023 bar</td>
<td>50</td>
</tr>
</tbody>
</table>

Courtesy of U.S. DOE.
## Coal-Fired Combined Cycle

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Temperature</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Pressurized Fluidized Bed Combustion (PFBC) combined cycle</td>
<td>Gas turbine: 860°C/12 bar</td>
<td>36-40 (1999: &gt;45)</td>
</tr>
<tr>
<td>&gt;2010</td>
<td>Pressurized Pulverized Coal-Fired combined cycle power plant (with hot gas clean up or warm gas clean up according to heat exchanger)</td>
<td>&gt;50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Magneto Hydro Dynamic generator (MHD) + steam cycle</td>
<td>50-60</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>IGCC Power plant</td>
<td>TIT 1050°C (ISO 2314)</td>
<td>43.2</td>
</tr>
<tr>
<td>1998</td>
<td>Buggenum (NL)</td>
<td>TIT 1120°C</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Puertollano (E)</td>
<td>TIT &gt;1190°C</td>
<td></td>
</tr>
<tr>
<td>≥1998</td>
<td>IGFC (IGCC with fuel cells):</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PAFC (split fuel stream) / GT combined cycle plant</td>
<td>[31]</td>
<td>approx. 50</td>
</tr>
<tr>
<td>&gt;2000</td>
<td>MCFC combined cycle plant</td>
<td>[32]</td>
<td>&gt;55</td>
</tr>
<tr>
<td>&gt;2005</td>
<td>SOFC combined cycle plant</td>
<td>[32]</td>
<td>&gt;55</td>
</tr>
<tr>
<td></td>
<td>Multiple steam cycles</td>
<td></td>
<td>50-51</td>
</tr>
<tr>
<td></td>
<td>Kalina cycle</td>
<td></td>
<td>&gt;47</td>
</tr>
</tbody>
</table>

Courtesy of U.S. DOE.

TEMPA ELECTRIC POLK IGCC POWER PLANT

250 MW, 35.3 % efficiency, 2500 TPD coal, 200 TPD sulfuric acid, built 1996, $600M

Facility schematic diagram removed for copyright reasons.
- Tampa Electric 250 MW, Florida
- PSI energy (Cinergy) 262 MW, Indiana
- Dow Chemical 160 MW, Louisiana
- S. Cal Edison 100 MW, California

- MHI built 250MW in Japan, 56.5%
- They are building a 500 MW coal.
- China market..
- India..

Environmental assessment of IGCC Power, Ratafia et al, SAIC and DOE/NETL, 2002
Reforming, Gasification & Synthesis

From Fossil: Coal/Tar Sand/Biomass

In Gasifier: \[ 3C + O_2 + H_2O \xrightarrow{\text{catalysis}} 3CO + H_2 \]

Gas-shift \[ CO + H_2O \xrightarrow{\text{catalysis}} CO_2 + H_2 \]

Synthesis
methanation \[ CO + 3H_2 \xrightarrow{\text{400C+catalysis}} CH_4 + H_2O \]

Synthesis+Liquefaction
Methanol production \[ CO + 2H_2 \longrightarrow CH_3OH \]
Fischer-Tropsch: \[ CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O \]

Probstein and Hicks, Synthetic Fuels, 1990.
## Thermal Efficiencies of Synthetic Fuel Production

<table>
<thead>
<tr>
<th>FUEL</th>
<th>PRODUCT</th>
<th>EFFICIENCY* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Synthesis</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>
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<tr>
<td>Methanol</td>
<td>Oil and Gas</td>
<td>86</td>
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<tr>
<td>Wood</td>
<td>Gas</td>
<td>90</td>
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<tr>
<td>Corn</td>
<td>Ethanol</td>
<td>46</td>
</tr>
<tr>
<td>Manure</td>
<td>Gas</td>
<td>90</td>
</tr>
</tbody>
</table>

*Thermal efficiency is the ratio of the heating value of the synthetic product divided by the heating value of the parent fuel.