



Hydrogen and Its Utilization via Fuel Cells and Other Alternative Fuels/Energies: Environmental Implications

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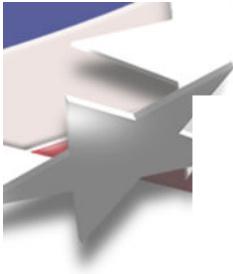
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Motivation

- Gasoline price has gone up dramatically (affecting our pocket books).
- Worldwide petroleum-based energy resources are being depleted – onshore crude oil supply peaked decades ago but demand is going up.
- Continued US dependency on imported or foreign petroleum oil, particularly on those from the Middle East, has become an important national security issue.
- Competition for global energy supply from emerging economic powers such as China and India has added to the urgency for searching and developing alternative energy sources.
- Environmental concerns such as pollution and global warming provides further motivation to address the energy challenge that we face today.
- As we develop alternative energy sources, it is imperative that we are aware of their environmental implications.



Gasoline price arising above \$3 per gallon again!

From Albuquerque Journal, Saturday, May 5, 2007

Here We Go Again: Gas at \$3

Capacity Down, Prices Up,
And Drivers Aren't Amused

BY SUSAN STIGER
Journal Staff Writer

This might be a good time to remember that the backyard can be a wonderful vacation destination.

Average gasoline prices topped \$3 a gallon nationwide Friday, and experts are wondering — and arguing: Will prices go up? Will they go back down? Will there be enough gas?

A random drive around Albuquerque revealed surprisingly few people filling up at midafternoon. But once a few drivers noticed the \$2.99 sign at Gas-n-Save at Eubank and Candelaria, customers started to roll in.

Where does Cecil Montgomery usually fill up his Mitsubishi Mighty Max truck?

"Where it's cheap," he said, sounding annoyed. "Gas shouldn't be this way."

Next up, Paul Carter, who uses his Chevy Impala to drive to painting jobs for Three Son



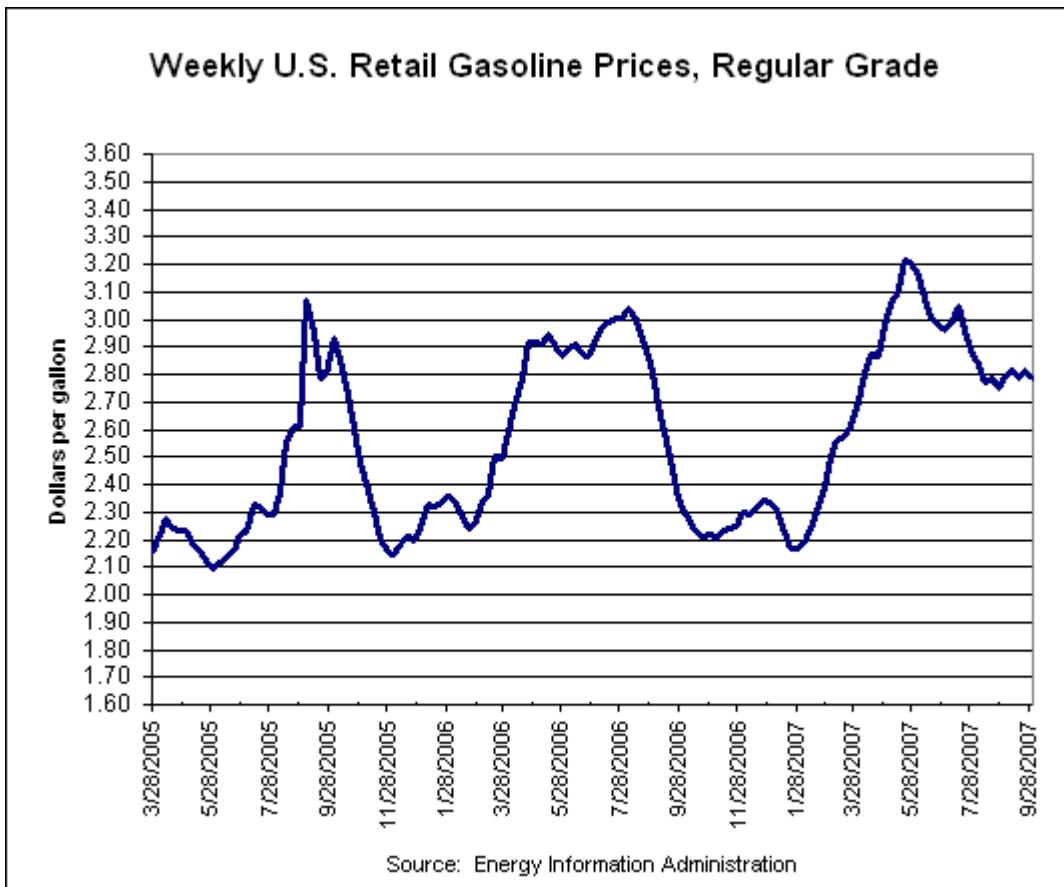
Like many other stations around Albuquerque, this Circle K listed gas at \$3.09 for regular Friday.

See GAS on PAGE A1



Average retail gasoline prices in the US (Regular grade, 3/28/2005 – 9/28/2007)

Source: Energy Information Administration



- Gasoline price has gone up dramatically in the last couple of years or so, to above \$3.00 per gallon!



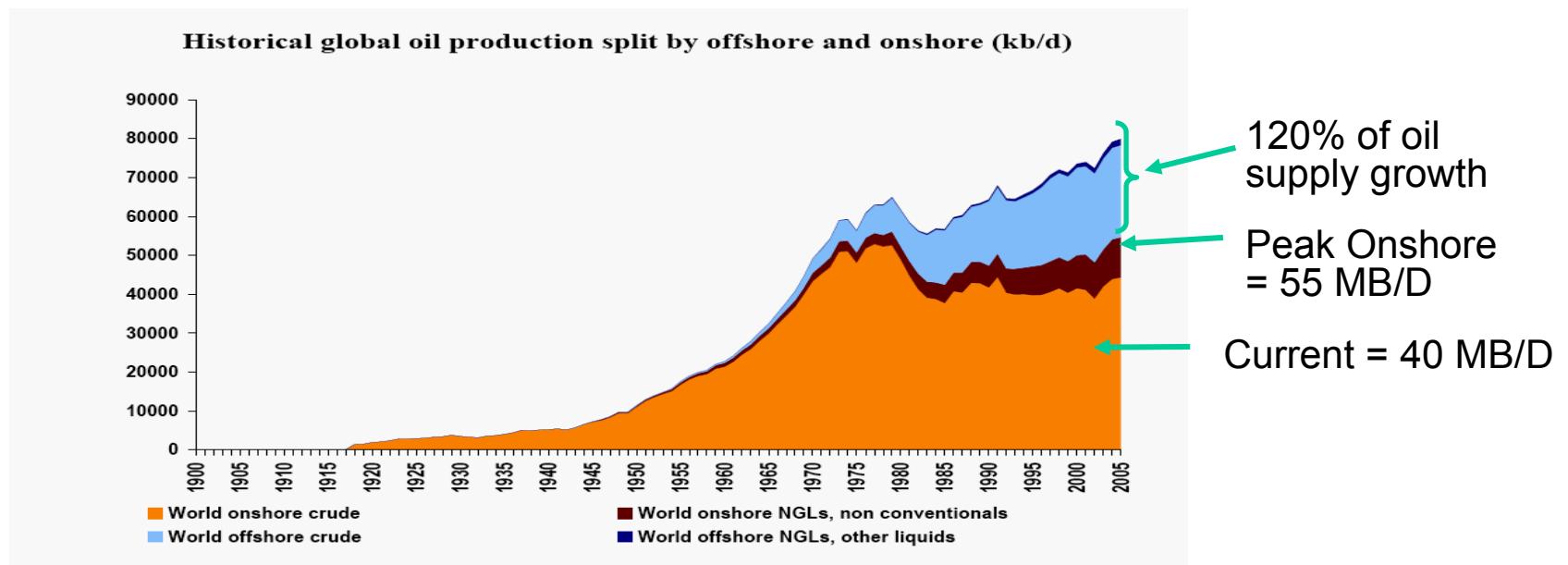
Onshore crude supply peaked decades ago

Onshore oil peaked in 1970 at 55 MB/D.

All growth since 1970/1980 has been:

- Onshore NGLs and non-conventional oil (now 10 MB/D)
- Big growth was offshore, which grew to almost 36 MB/D

Over last two decades, onshore crude has been \approx 40 MB/D.



Source: Ivan Sandrea (OPEC) and Rafael Sandrea (IPC)
(Accepted for publication in Oil and Gas Journal, 1Q 2007)

Reference: Matthew Simmons, Simmons and Company International.

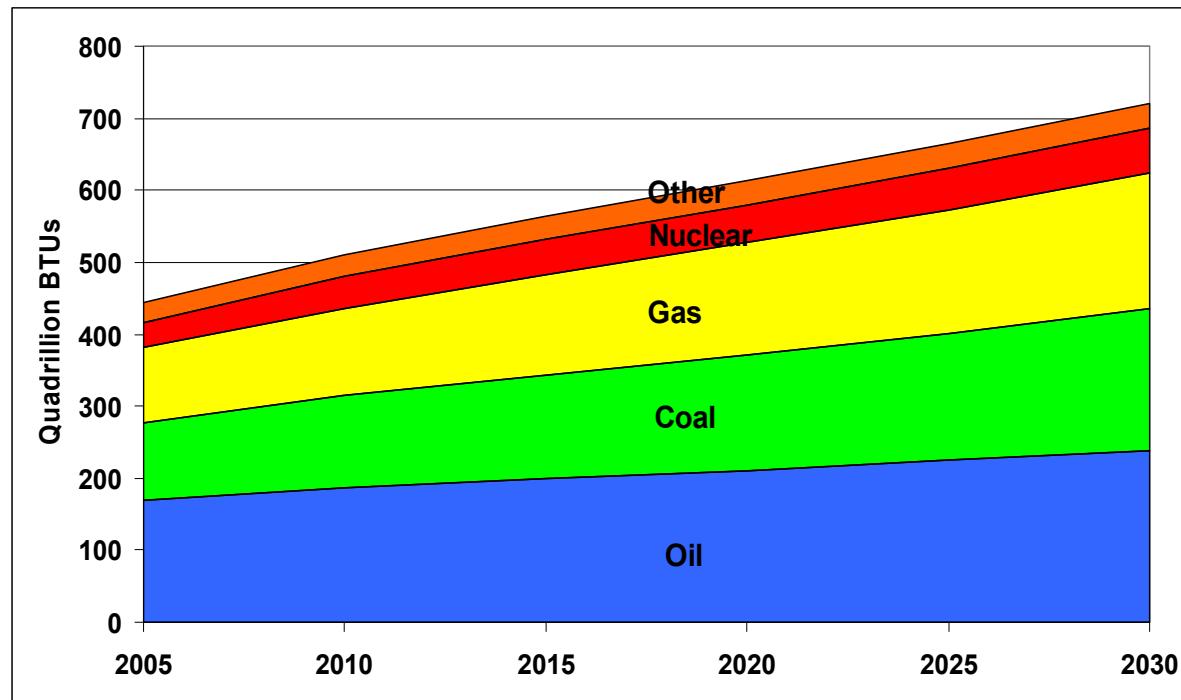


Global energy demand

Between now and 2030, world energy demand will grow by 65%

and developing countries will account for 75% of the increase

Energy demand

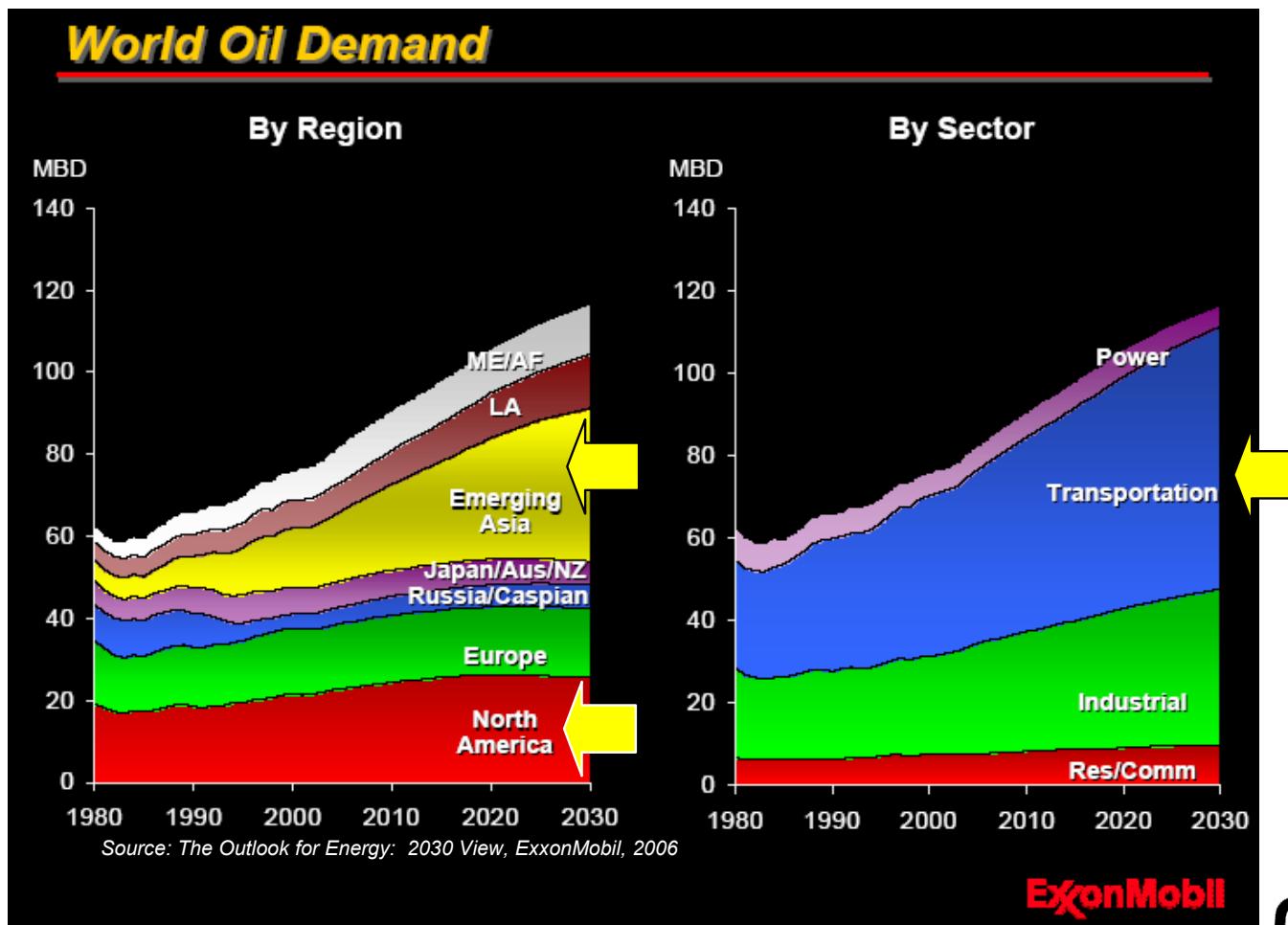


Source: USDOE EIA IEO 2006 Reference Case



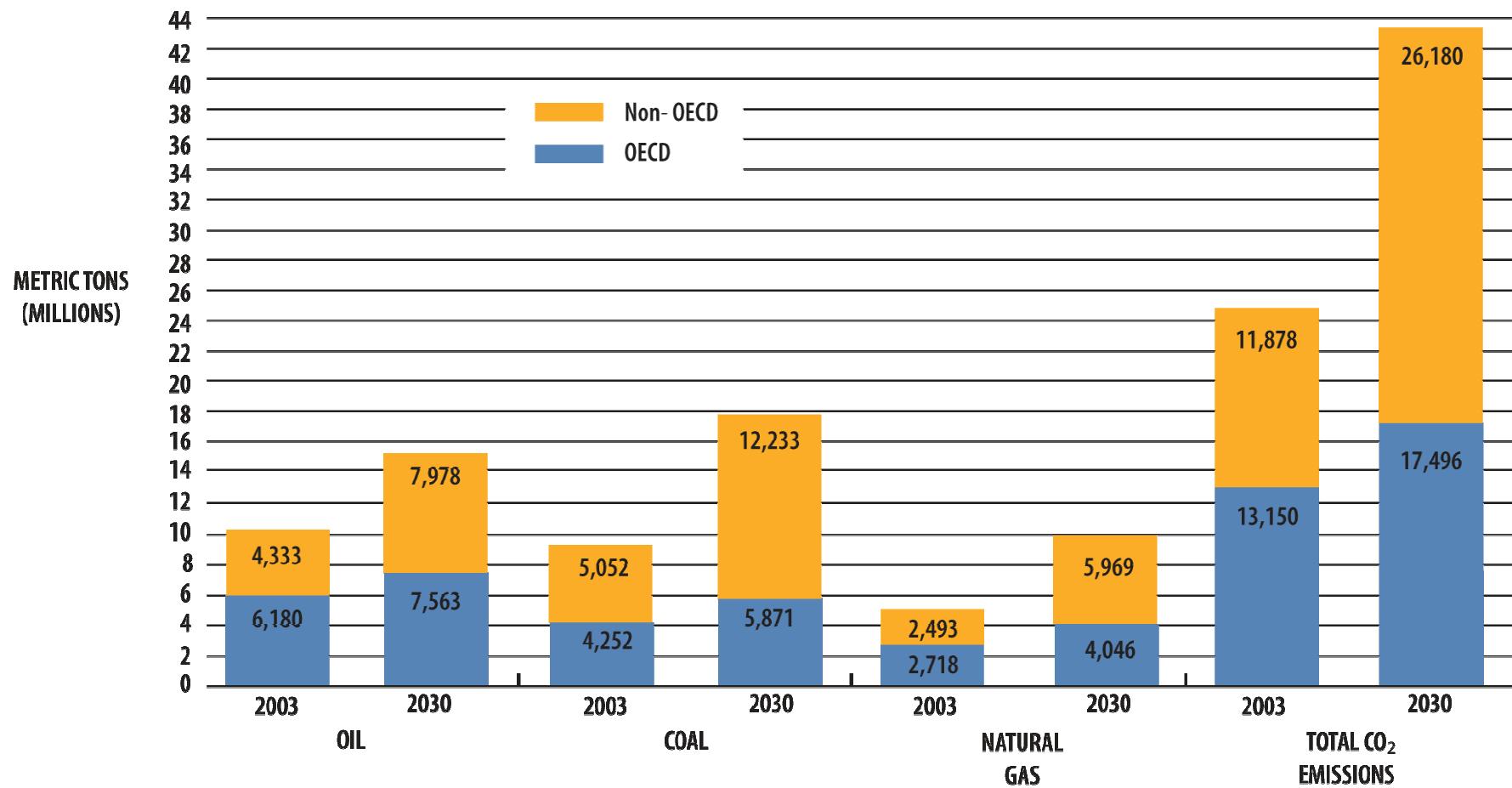
Petroleum oil demand

Globally, oil demand is driven by growth in transportation in Asia and America



Carbon emissions

WORLD CARBON DIOXIDE EMISSIONS



Source: Energy Information Administration, International Energy Outlook 2006

OECD: Organisation for Economic Co-operation and Development



Alternatives to petroleum oil

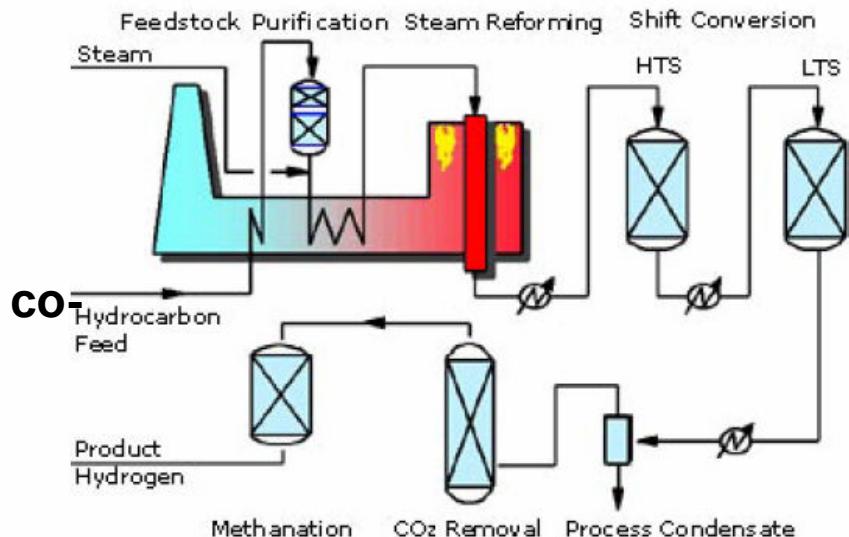
- Hydrogen (on which the “Hydrogen Economy” is based)
- Biofuels (ethanol, biodiesel, ...)
- Electricity and fuel generation using clean coal technologies
- Nuclear energy
- ...
- Savings via regulation changes and conservation
 - (“One BTU saved, one BTU produced”.
BTU refers to British thermal unit. 1 BTU = 1055.06 joules)



Hydrogen production via steam methane reforming (SMR)

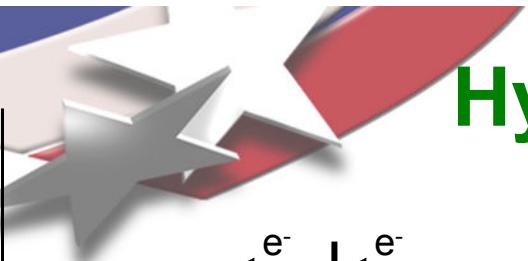
- SMR is the workhorse or dominant technology for hydrogen production in large centralized industrial plants.
- Advantages of SMR include its maturity and high efficiency, being widely use and relatively economical.
- The main challenge of SMR is the production of greenhouse gas CO₂.
- CO₂ can be concentrated, captured, and sequestered. CO₂ sequestration concepts and technologies are relatively new and still under active R&D.

Flow diagram of steam methane reforming

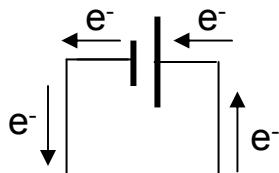


Chemistry of steam methane reforming (carried out at 700 - 1100°C):





Hydrogen production via electrolysis

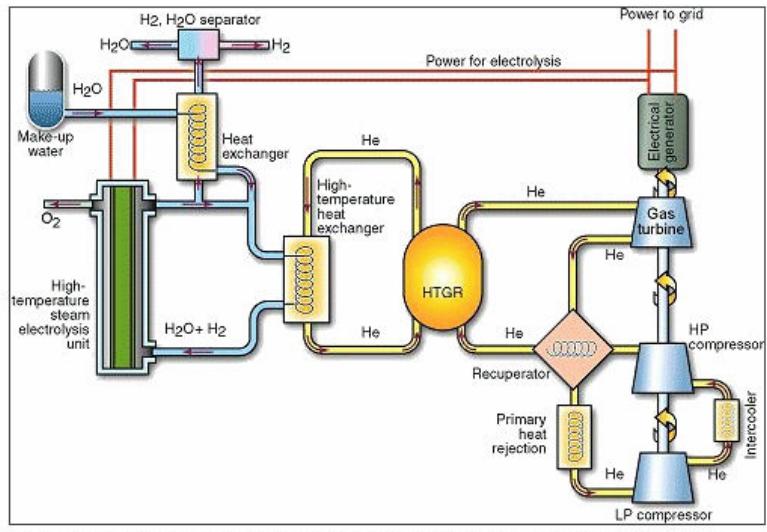


- Advantages of hydrogen production via electrolysis include extremely pure H_2 as product and zero greenhouse gas emissions.
- The main disadvantage of hydrogen production via electrolysis is its requirement for electricity.
- Renewal or other non-greenhouse gas emitting electricity production (e.g., generating electricity at a wind farm or using photovoltaics) are being pursued by US Department of Energy and others.

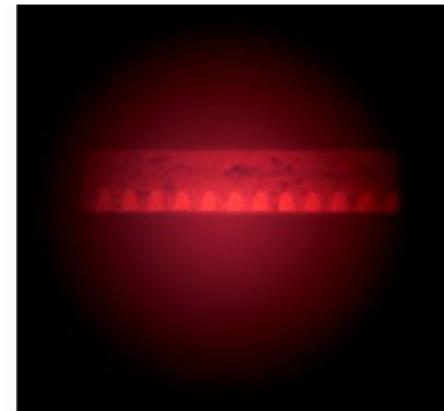


Hydrogen production from water using *high-temperature electrolysis* and *high-temperature steam* generated from nuclear reactors (source: Idaho National Lab)

Flow diagram of Idaho National Lab's high-temperature electrolysis system



View of the edge of one high-temperature electrolysis cell while operating at 830°C



- High-temperature electrolysis (15 – 20% increase in efficiency).
- Generating heat using advanced nuclear reactors.



Why Hydrogen from Nuclear Plants?

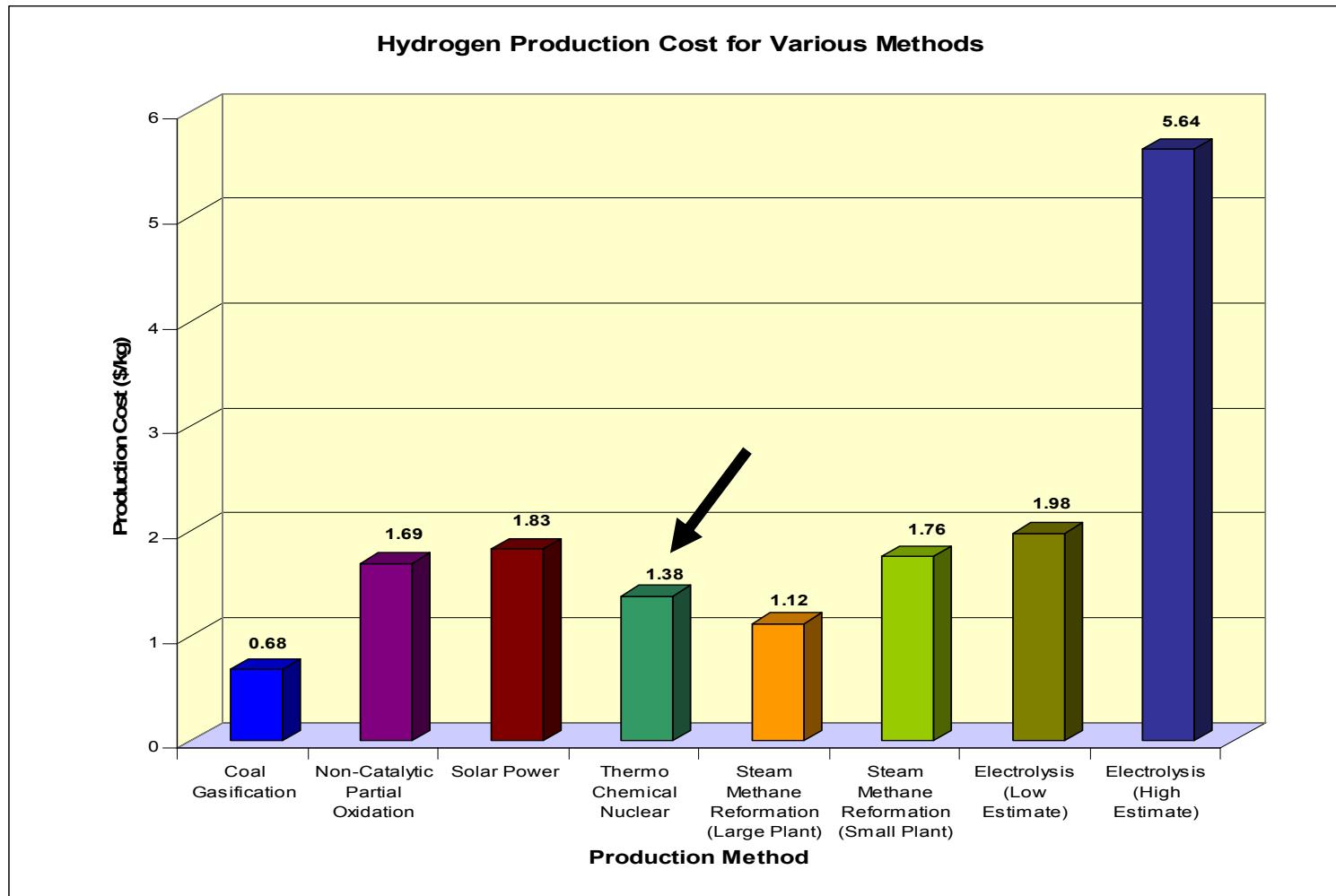
- One nuclear reactor can produce 300 million kg of H₂/year plus 390 MW of electricity.
- One kg H₂ has the same energy equivalence as 1 gallon of gasoline.
- According to H2Sim, it costs about \$1.38 to produce 1 kg H₂.
- No greenhouse gases are produced.
- H₂ production by nuclear plants is a key component of the strategic set of technologies whereby US dependence on foreign oil will be eliminated permanently.
- California already has 24 H₂ refueling stations, and plans to build 15 more in the near future.
- GM, Ford, and others are already building H₂ powered vehicles.



According to Ford, Model U is a model for change. © Ford

Source: Rodriguez et al., presentation at the 7th Tri-Lab Engineering Conference, Albuquerque, NM, May 7 – 10, 2007.

Why Hydrogen from Nuclear Plants?



Cost of Hydrogen Production, as Computed by H2Sim.

Source: Rodriguez et al., presentation at the 7th Tri-Lab Engineering Conference, Albuquerque, NM, May 7 – 10, 2007.

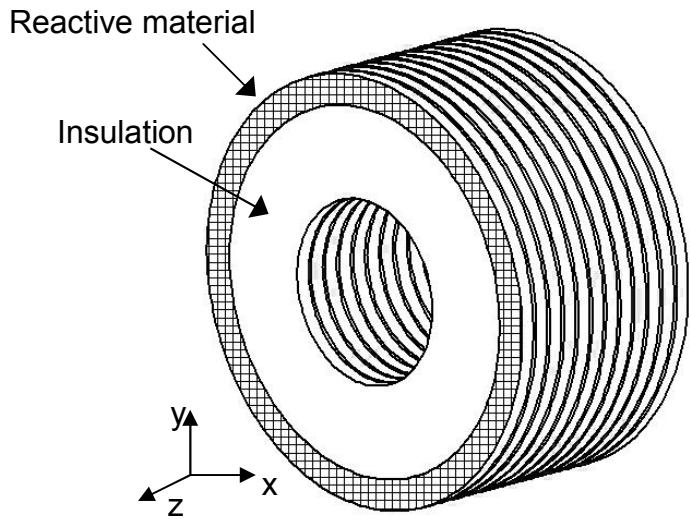


Hydrogen production with concentrated solar energy (source: SNL)

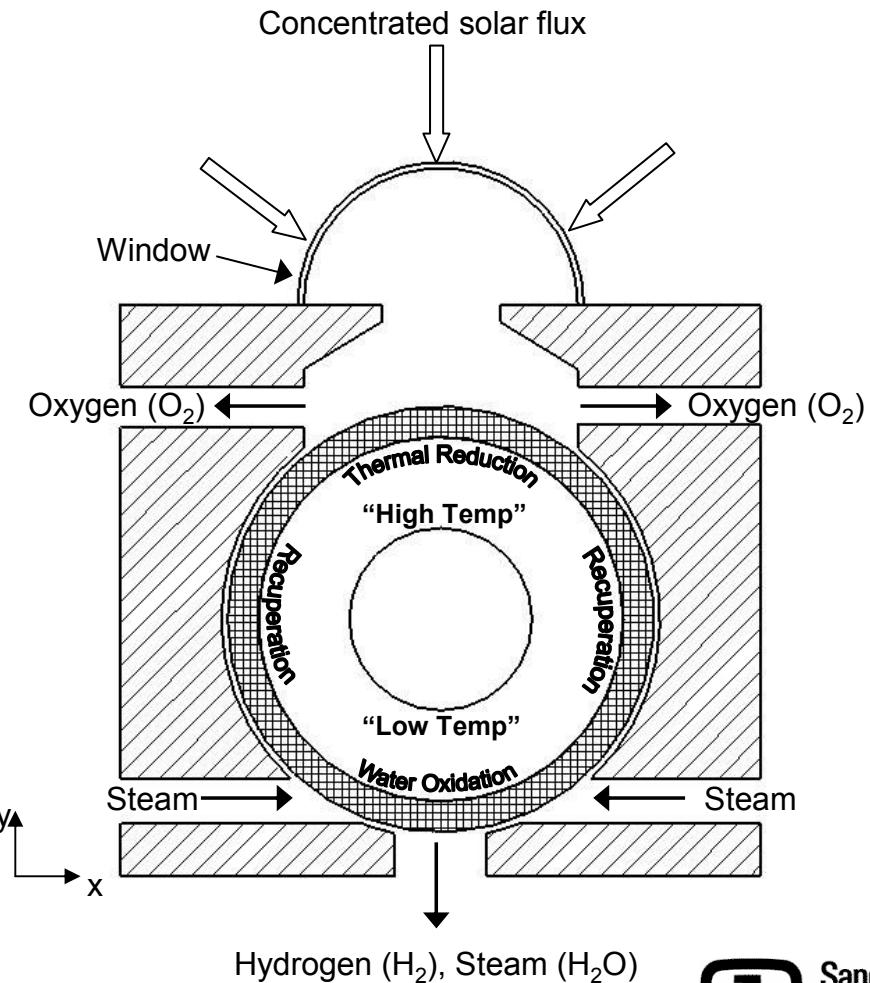
Sandia-Invented device uses a two step solar-thermochemical process based on iron-oxide to split water:



Set of Counter-Rotating Rings



Cross-Section Illustration



Contact: Rich Diver (rbdiver@sandia.gov), Nate Siegel (npsiegel@sandia.gov)



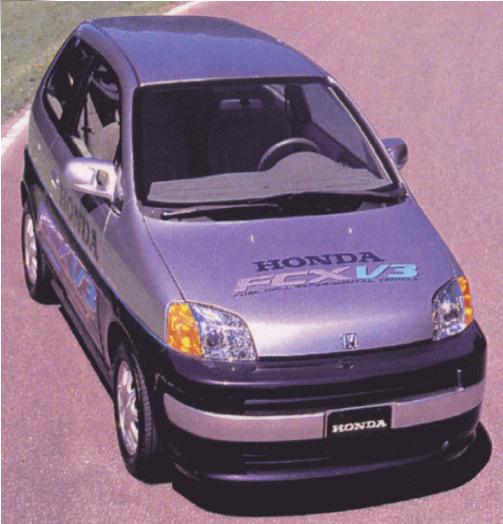
One of DaimlerChrysler *fuel-cell buses*
on a Beijing street as of 2005
(to help Beijing to have more blue skies
during the 2008 Olympic Games)



Source: <http://www.daimlerchrysler.com>



Fuel cell vehicles by various automakers



Honda FCX-V3



Toyota FCHV-4



Ford Demo IIa (Focus)



GM Hydrogen 1 (Zafira)



DaimlerChrysler NeCar4a



Nissan Xterra FCV



VW Bora HyMotion



Hyundai Santa Fe FCV



Honda delivered fuel cell vehicles to individual customers



← June 30, 2005: Jon and Sandy Spallino of Redondo Beach, CA became the world's first individual customer to lease a 2005 Honda FCX power by a fuel cell stack



March 7, 2007: 17-year old Q'orianka Kilcher became the world's Youngest fuel cell vehicle customer



Source: <http://www.hondanews.com>



Latest news on fuel-cell cars (9/28/2007): Toyota Fuel-Cell Hybrid Vehicle makes a 348-mile Osaka-Tokyo trip without refueling

Source: <http://www.toyota.co.jp/en/news/07/0928.html>





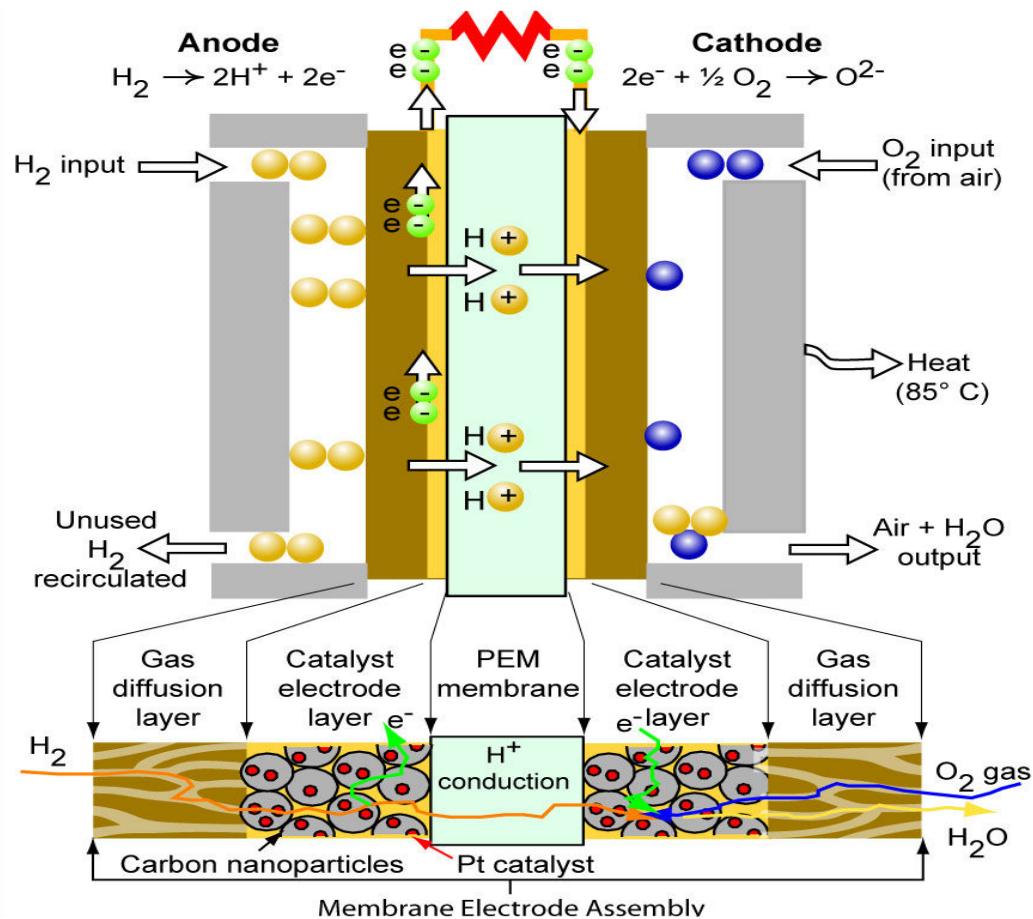
Comparison on various types of fuel cells

Fuel Cell	Electrolyte	Operating Temperature (°C)	Electrochemical Reactions
Polymer Electrolyte membrane (PEM)	Solid organic polymer poly-perfluorosulfonic acid	60 ~ 100	Anode: $H_2 \rightarrow 2H^+ + 2e^-$ Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 ~ 100	Anode: $H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$ Cathode: $\frac{1}{2} O_2 + 2H_2O + 2e^- \rightarrow 2(OH)^-$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	175 ~ 200	Anode: $H_2 \rightarrow 2H^+ + 2e^-$ Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium and/or potassium carbonates, soaked in a matrix	600 ~ 1000	Anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ Cathode: $\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ Cell: $H_2 + \frac{1}{2} O_2 + CO_2 \rightarrow H_2O + CO_2$
Solid Oxide	Solid zirconium oxide with yttria doped	600 ~ 1000	Anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$ Cathode: $\frac{1}{2} O_2 + 2e^- \rightarrow O^{2-}$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

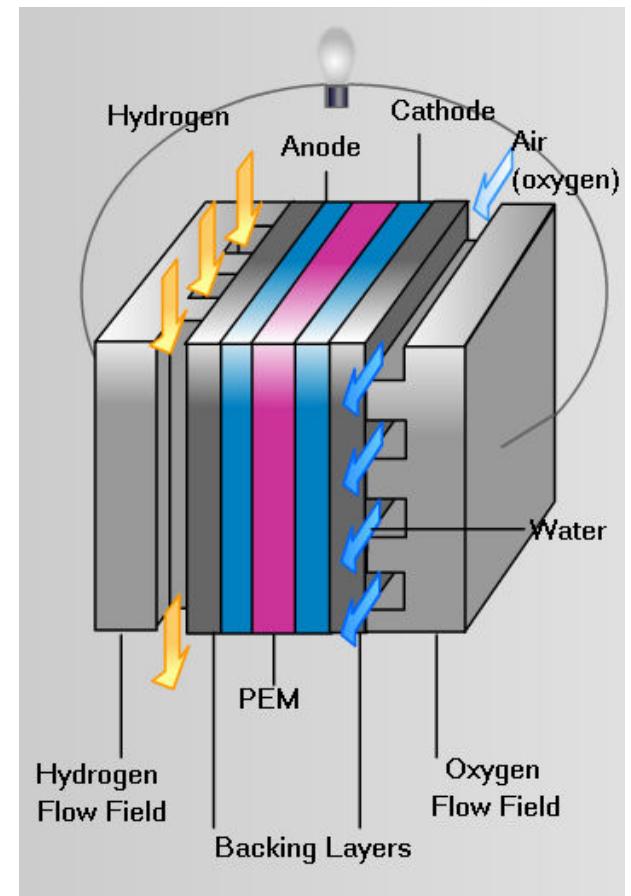
How does a PEM fuel cell work?

- Humidified H₂ and air are simultaneously forced down anode and cathode channels.
- H₂ is oxidized in the anode catalyst layer to produce protons (H⁺) and electrons (e⁻).
- O₂ is reduced in the cathode catalyst layer to consume H⁺ and e⁻ and produce H₂O.

Two-dimensional sectional view of a PEM fuel cell



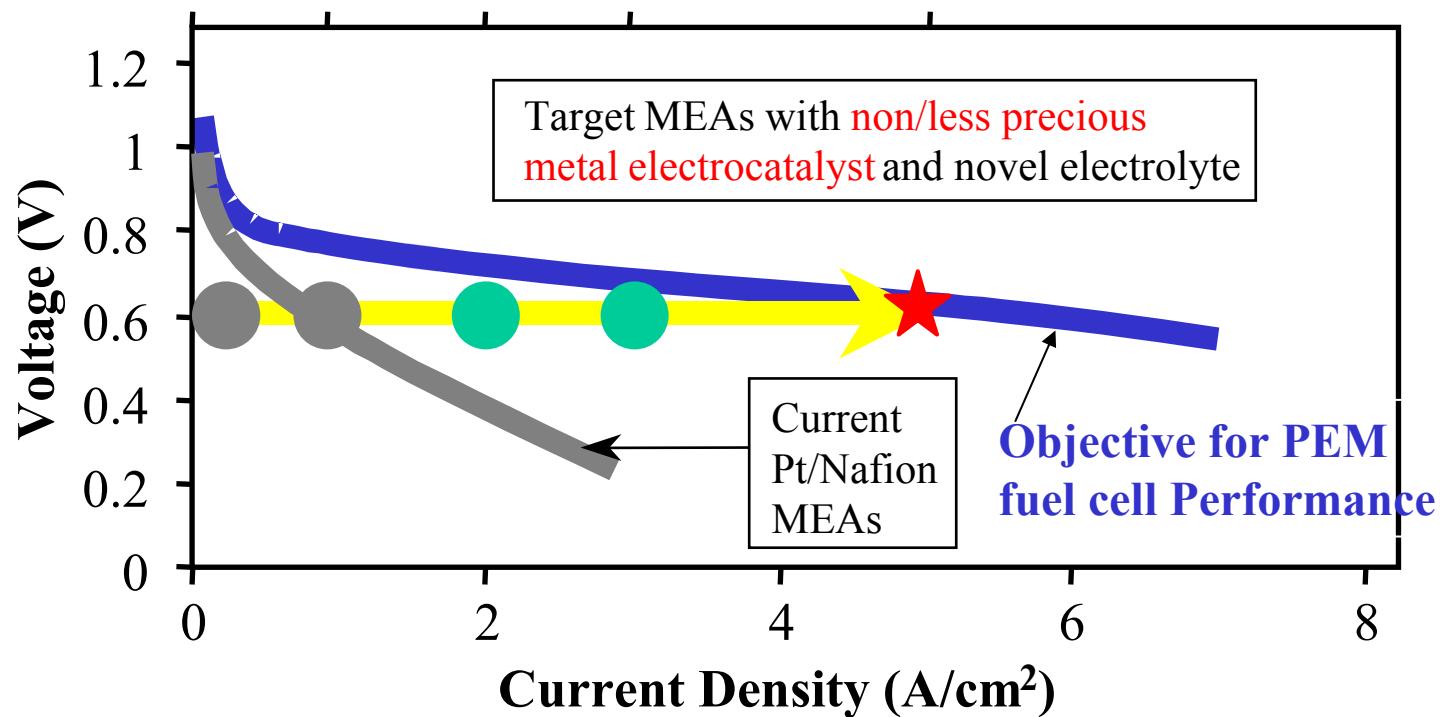
Three-dimensional schematic of a PEM fuel cell



- Protons and H₂O are transported through the membrane whereas electrons are conducted through carbon support and external wires.



We still have some way to go in terms of meeting PEM fuel-cell performance target for automotive applications



- Need research breakthroughs in high-performance membrane electrode assembly or MEA (catalyst and electrolyte).
- DOE target for MEA performance at rated power: 1.28 W/cm².



Other key challenges in PEM fuel cell technology development

- **Water management**

- Polymer membrane needs to be sufficiently hydrated in order to achieve high proton conductivity and thus high fuel cell performance.
- Water needs to be removed efficiently from cathode gas diffusion layers and flow channels in order to prevent “flooding”, which hinders oxygen transport from flow channels to the catalyst layers.

- **Improve durability** (DOE's automotive target by 2010: **5000 hrs** with cycling)

- MEA degradation due to membrane breakdown via chemical decomposing & stress-induced cracking, carbon corrosion, catalyst-layer disintegration, ...

- **Reduce costs** (DOE's automotive target by 2010: **\$45/kW**; by 2015: **\$30/kW**)

- Platinum catalyst, membrane, MEA and flow-field fabrication, ...

- **Meet cold-start and operation under freezing conditions**

(DOE targets: **50%** rated power in **30 sec** from **-20°C**; **survivability to -40°C**, i.e., being able to endure a cold soak at **- 40°C** without damage)



Environmental implications in utilizing hydrogen as fuel via fuel cells

- Utilizing hydrogen as fuel via fuel cells to produce energy is environmentally friendly – only electricity & water are produced.
- Processes for hydrogen production are a different matter:
 - Steam methane reforming or SMR, the workhorse technology for hydrogen production, generates CO₂.
 - SMR can be carried out in large centralized industrial plants located in remote areas.
 - CO₂ can be concentrated, captured, and sequestered.
 - CO₂ sequestration concepts and technologies are relatively new and still under active R&D.
 - Electrolysis is environmentally friendly but this process is costly.
 - Water splitting with heat supplied by solar concentrators is environmentally friendly but this technology is not yet matured.
 - High temperature electrolysis with heat generated using advanced nuclear reactors appears to be promising but this technology involves nuclear reactors and thus nuclear wastes.



Biofuels from biomass – definitions

Biomass – **Biomass is any organic material made from plants or animals.**

Examples of biomass include *corn, palm oil, soybeans, sugar cane, algae, animal fats, wood chips*, etc.

Biofuel – **any fuel derived from biomass.**

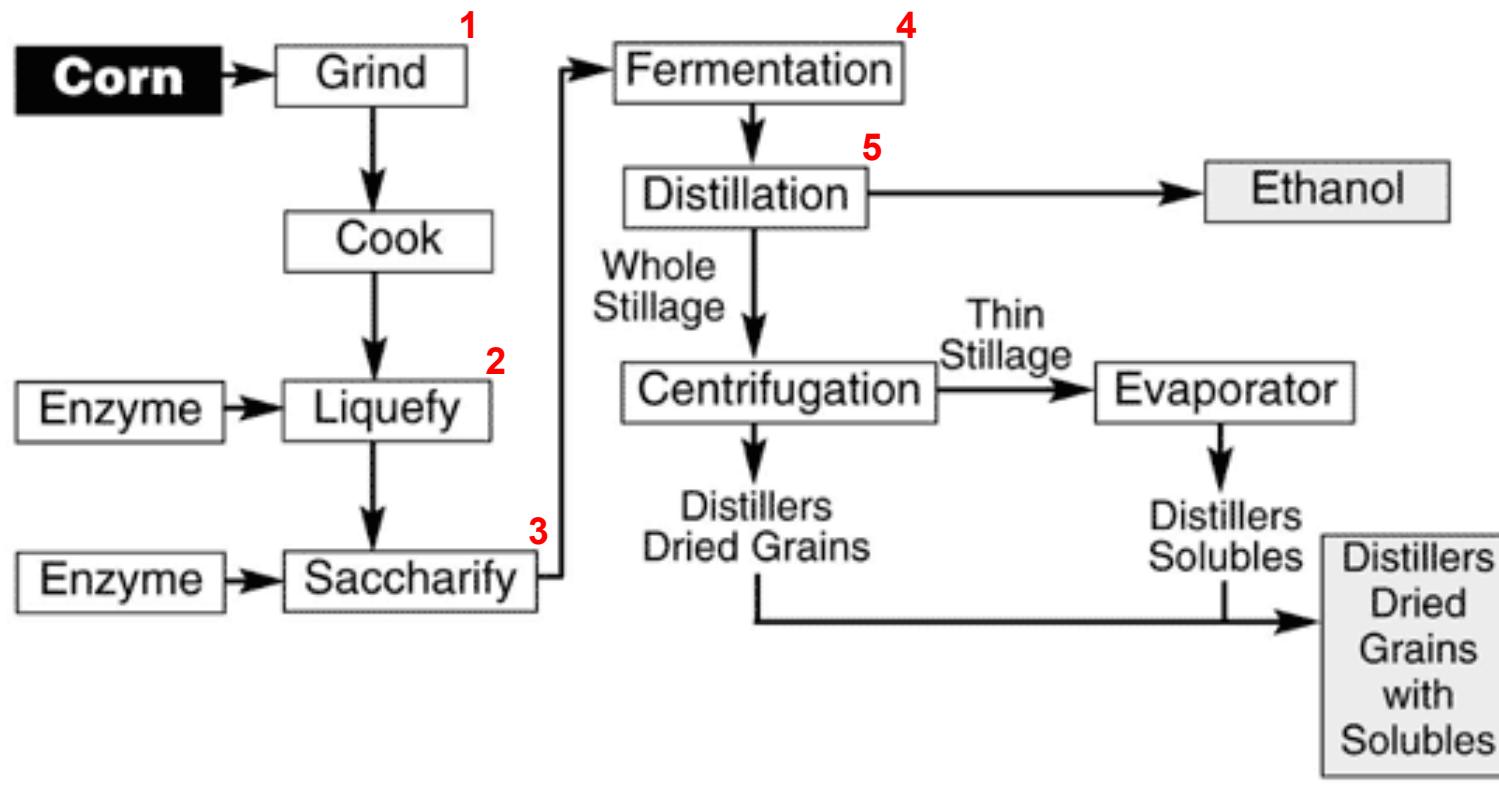
Examples of biofuels include *ethanol, methanol, biodiesel, biocrude, methane*, etc.



Ethanol from corns via the dry grind process



Flow Diagram for Dry Grind Ethanol Production



- There are about five key steps in the dry grind process.



Sandia
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Laboratories

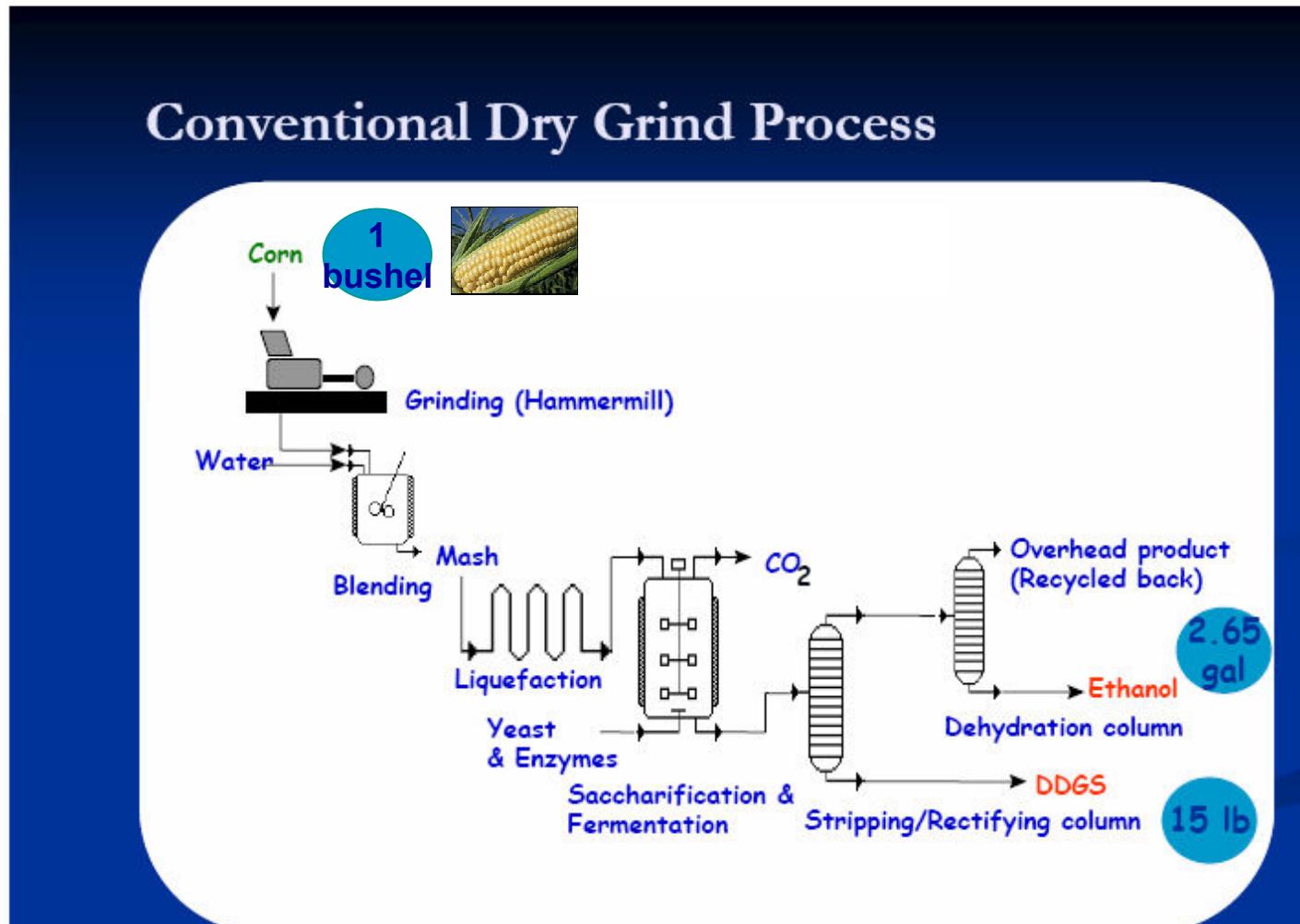


How much ethanol can we get from a bushel of corn?



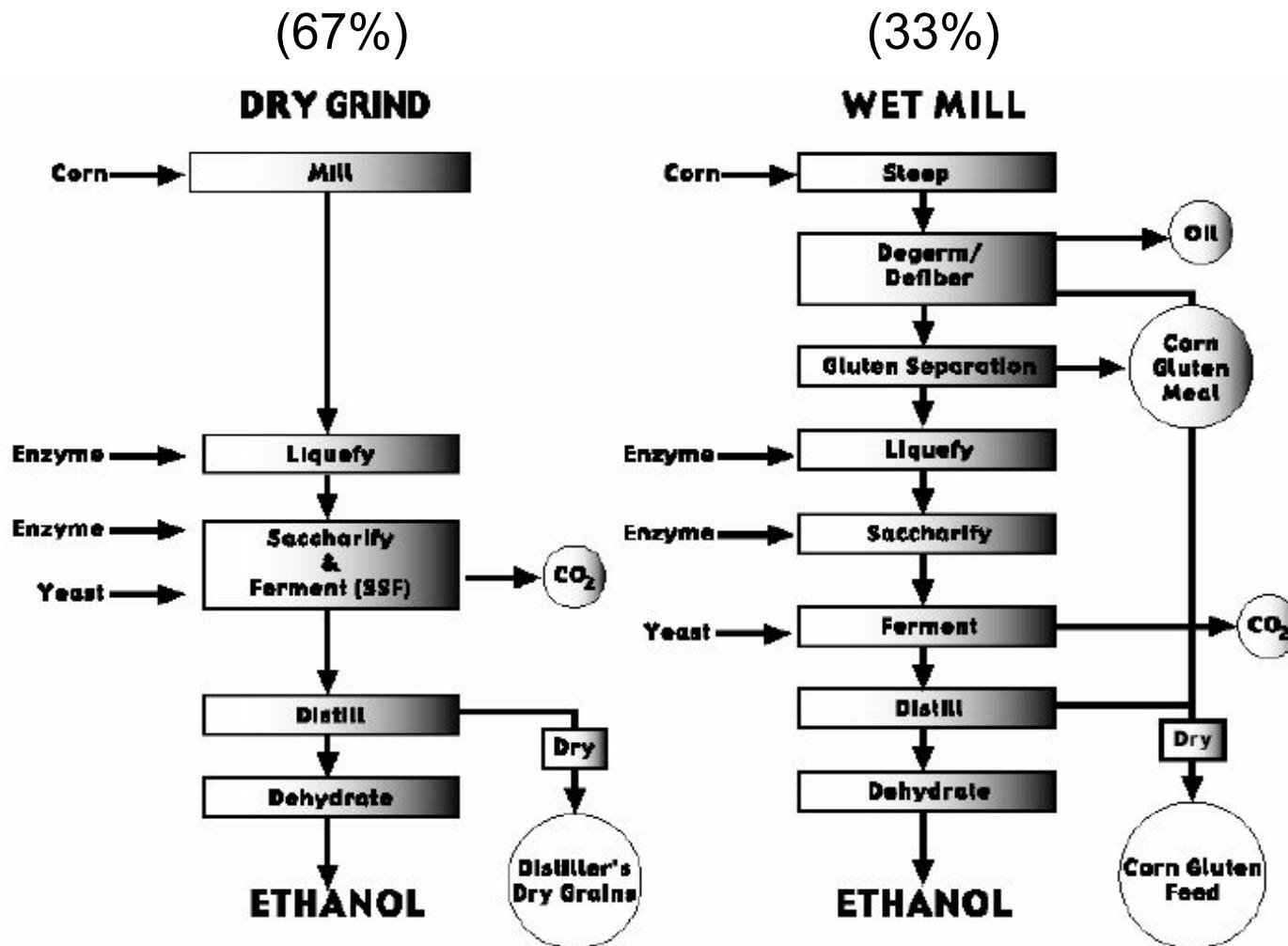
1 bushel (56 lbs) of corn \Rightarrow 2.65 gal ethanol + 15 lbs DDGS

DDGS = Distillers, Dried Grains with Solubles





Ethanol can also be produced from corn via the more complex *Wet Mill* process





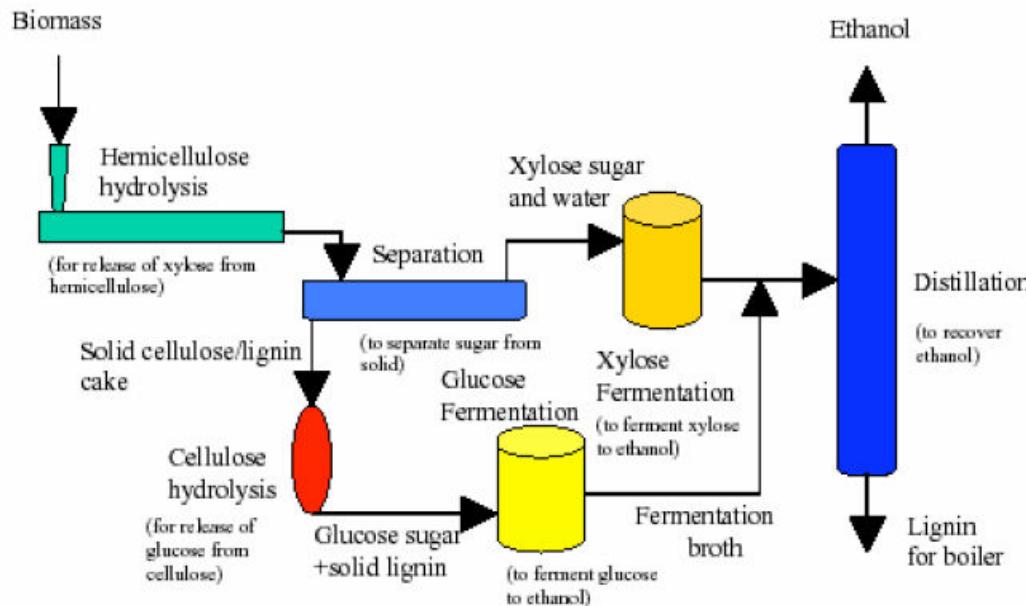
Ethanol production from corn – challenges

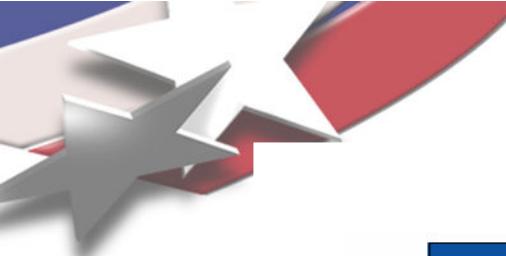
- Corn needs to be grown in large quantities, and growing corn needs lots of land – this can potentially take land away from food production. So, we may have a *fuel vs. food* problem.
- The cost of ethanol produced from corn strongly depends on the price of corn since corn is the raw material.
- Research needs to be carried out in key areas in order to produce ethanol more cost effectively:
 - high fermentable hybrids
 - recovery of new and high-value ethanol coproducts
 - new processes and enzyme technology
 - conversion of fiber (biomass) component of the kernel to ethanol.



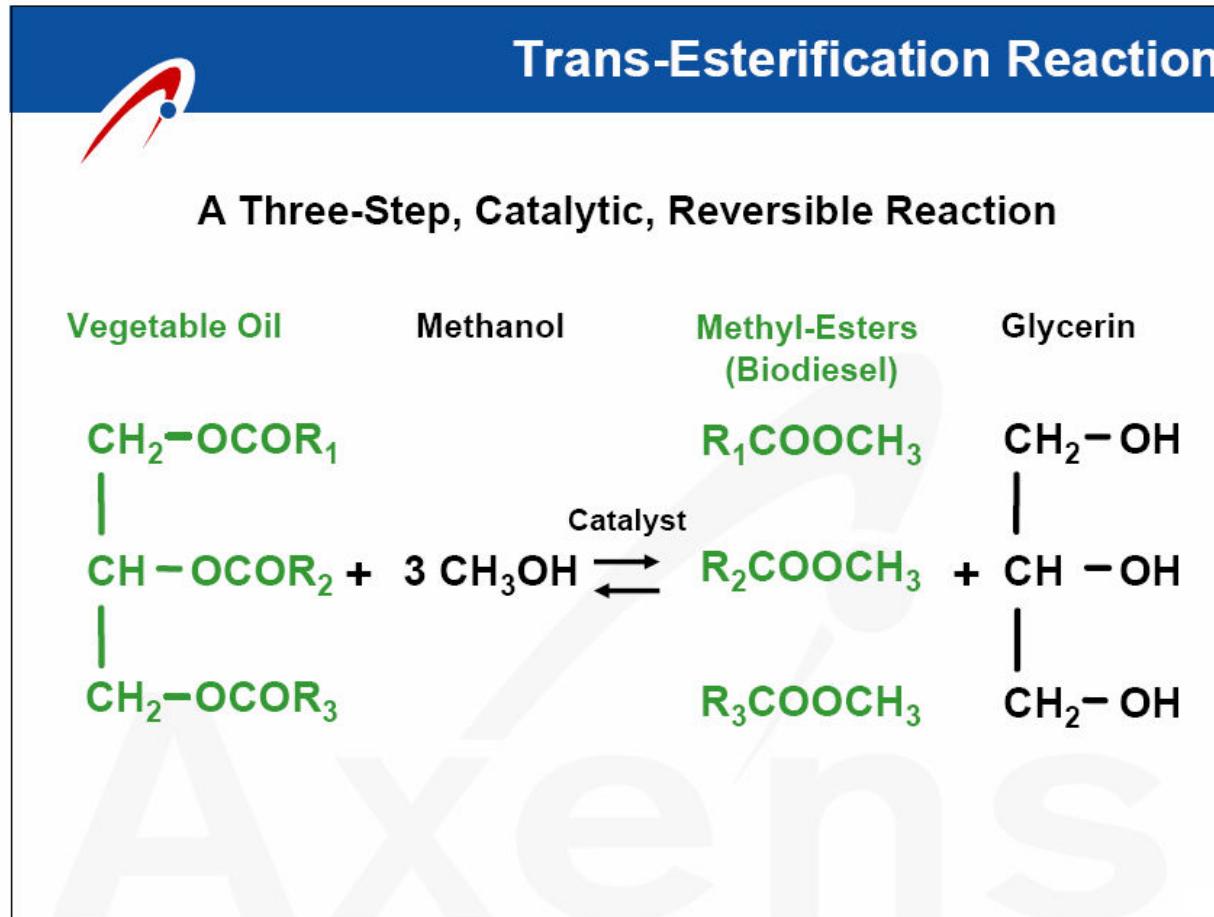
Ethanol from cellulose (*cellulosic ethanol*)

- Cellulose, $(C_6H_{10}O_5)_n$, is a naturally occurring complex carbohydrate polymer commonly found in plant cell walls. Cellulose occurs in almost pure form in cotton fiber, and it is the major constituent of paper and textiles made of cotton, linen and other plant fibers.
- **Cellulosic ethanol is chemically identical to ethanol from other sources, such as corn or sugar, and is available in a great diversity of biomass including waste from urban, agricultural, and forestry sources. However, it differs in that it requires an extra hydrolysis processing step to break cellulose down into sugars.**





Converting triglycerides to biodiesel: the transesterification reaction

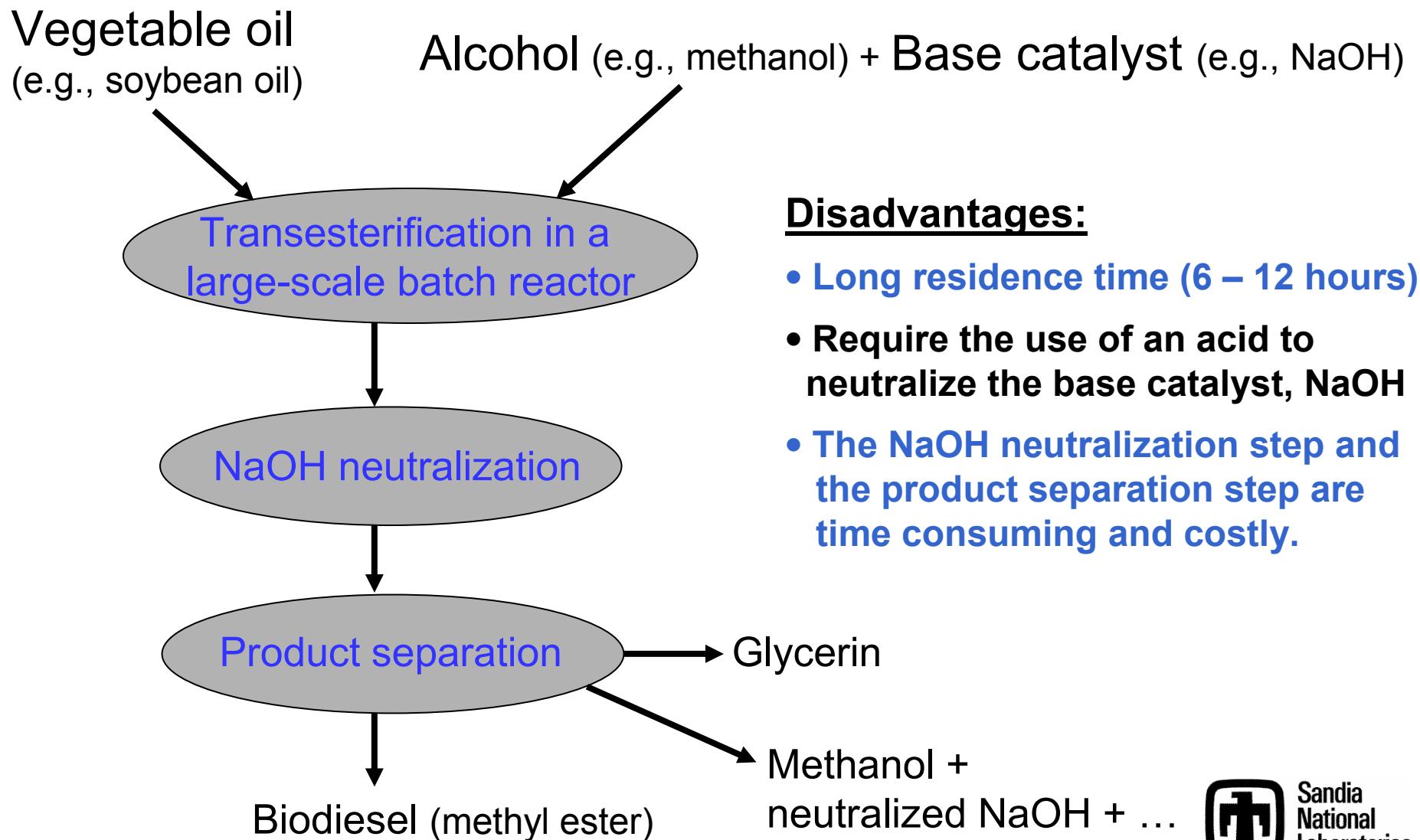


Sources of triglycerides:

- **vegetable oils** produced from oil-rich farm crops such as soybean and cottonseeds,
- **spent cooking oils from restaurants and homes,**
- **animal fats, micro-algae oils**, etc.



Converting Vegetable oils to biodiesel: the conventional process



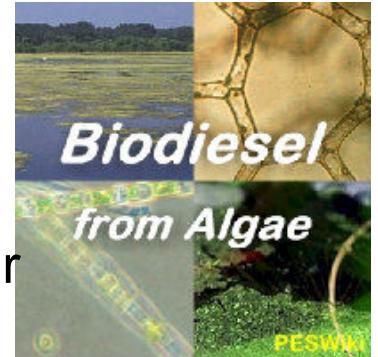


Improving the vegetable-oil-to-biodiesel conversion process

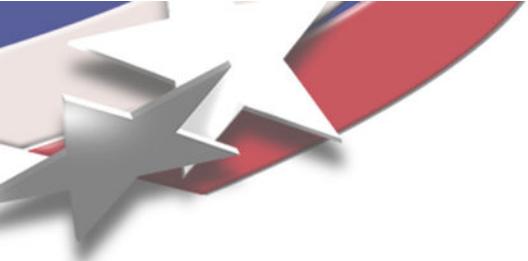
- Carry out the transesterification reaction in continuous slit-channel reactors instead of the conventional batch reactors – this will increase production throughput.
- Replace the liquid NaOH or KOH catalyst used in the conventional process with recyclable solid catalyst – this will eliminate the need for neutralizing the NaOH or KOH basic catalyst after conversion, which is time-consuming and costly.
- Deposit the solid catalyst on the surfaces of slit-channel reactors so as to further eliminate the need for catalyst handling, and precisely control the extent of vegetable-oil-to-biodiesel conversion.



Biobiesel from algae



- Algae range from small, single-celled organisms to multi-cellular organisms, some with fairly complex differentiated form.
- Algae are usually found in damp places or bodies of water and thus are common in terrestrial as well as aquatic environments.
- Like plants, algae require primarily three components to grow: sunlight, carbon-di-oxide & water. Photosynthesis is an important biochemical process in which plants, algae, and some bacteria convert the energy of sunlight to chemical energy.
- The existing large-scale natural sources of algae are: Bogs, marshes and swamps - Salt marshes and salt lakes.
- Microalgae contain lipids and fatty acids as membrane components, storage products, metabolites and sources of energy. Algae contain anywhere between 2% and 40% of lipids/oils by weight.
- There are three well-known methods to extract the oil from oilseeds, and these methods should apply equally well for algae too:
 - 1) expeller/press; 2) hexane solvent oil extraction; and
 - 3) supercritical fluid extraction.



Biofuels and the environment

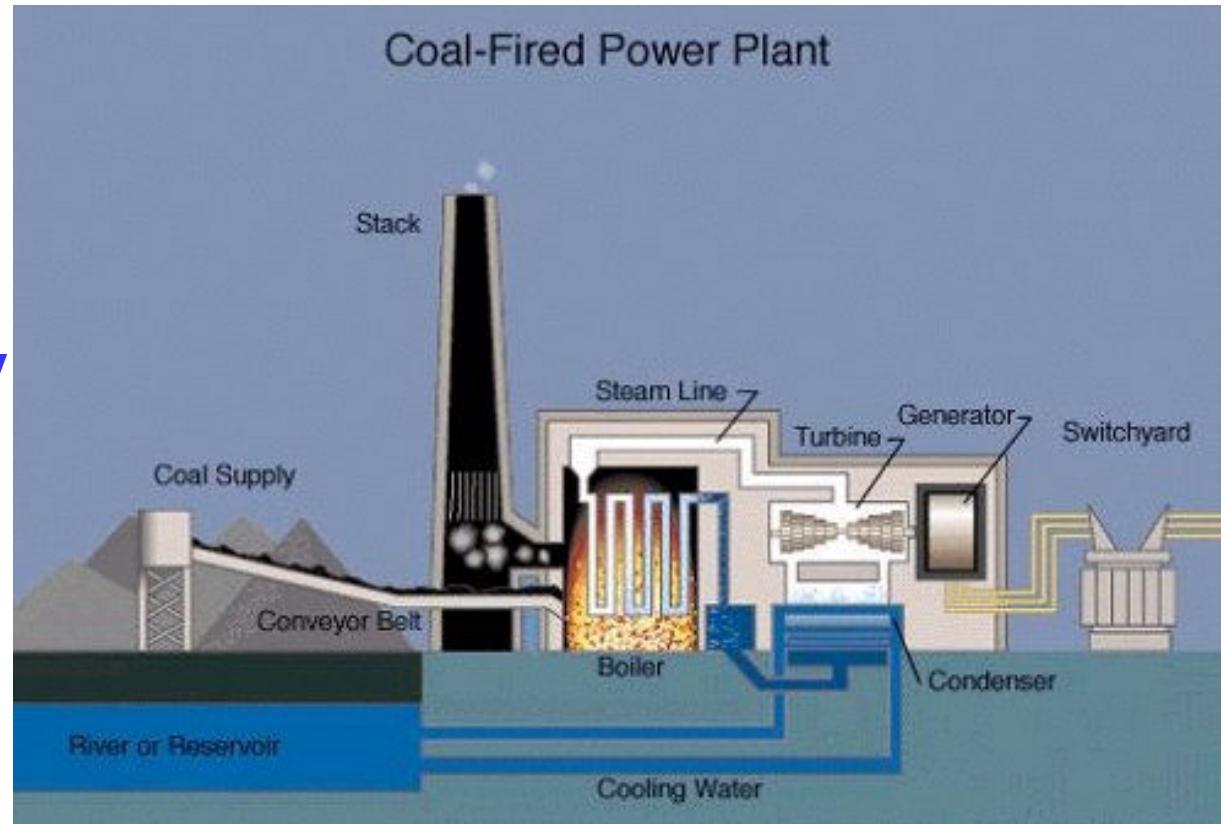
- Energy obtained from biomass do not add to *global warming*. All fuel combustion , including biofuels, releases CO₂ into the atmosphere. But, because plants use CO₂ from the atmosphere to grow (photosynthesis), the CO₂ formed during combustion is balanced by that absorbed during the annual growth of the plants used as the biomass feedstock.
- Using biofuels as an additive to petroleum-based transportation fuels can reduce the harmful emissions of carbon monoxide, nitrogen oxides, sulfur oxides and particulates, etc. Both bioethanol and biodiesel are used as fuel oxygenates to improve combustion characteristics. Adding oxygen results in more complete combustion, which reduces carbon monoxide emissions.
- There exists controversy regarding the “greenness” of biofuels.



Electricity and fuel generation using clean coal technologies

Why coal?

- Coal is abundant in US – enough to last 250 years at current rate of use.
- Coal is relatively cheap and thus affordable.
- Coal is a versatile energy resource that can be used in solid, liquid or gaseous form.
- Coal has traditionally been the largest single source of US electricity generation, currently providing more than 50% of US's total electricity.

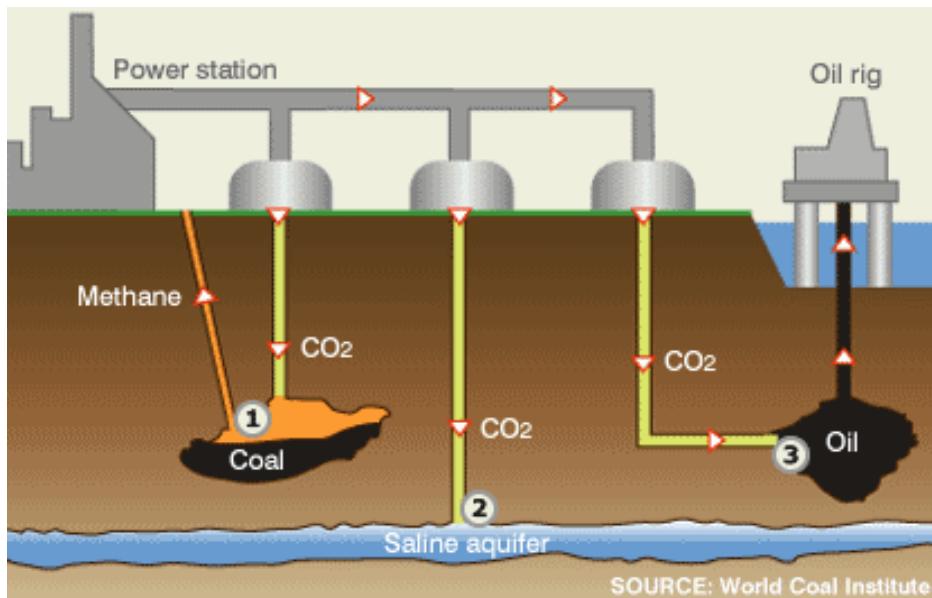




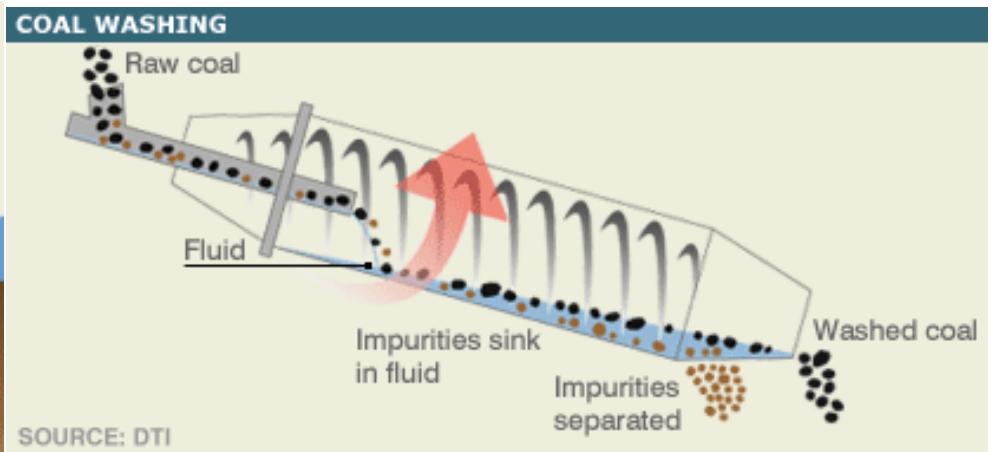
What are clean coal technologies?

- Clean coal technologies (CCTs) refers to a new generation of processes for the production of electricity and fuels from coal. CCTs are designed to increase the energy production efficiency and to reduce air emissions, waste products and other pollutants as compared to conventional coal technologies.

CO₂ capture and storage

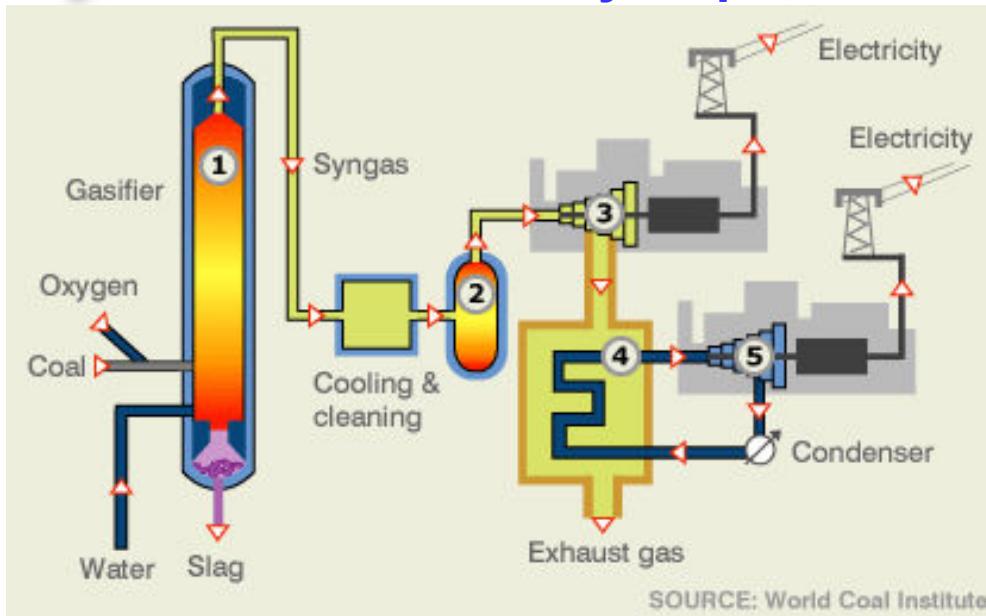


Coal preparation – coal washing

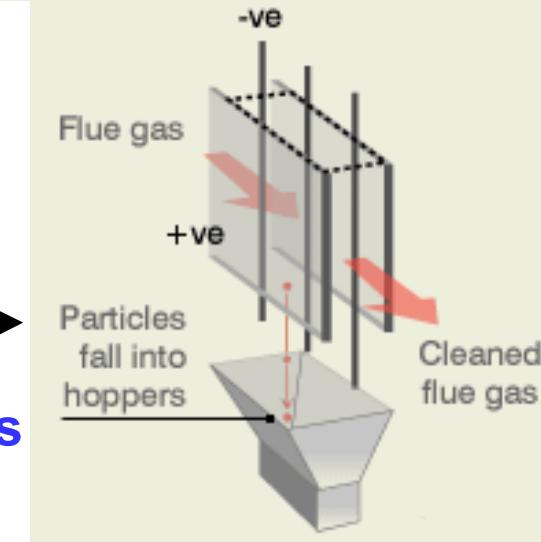


What are clean coal technologies?

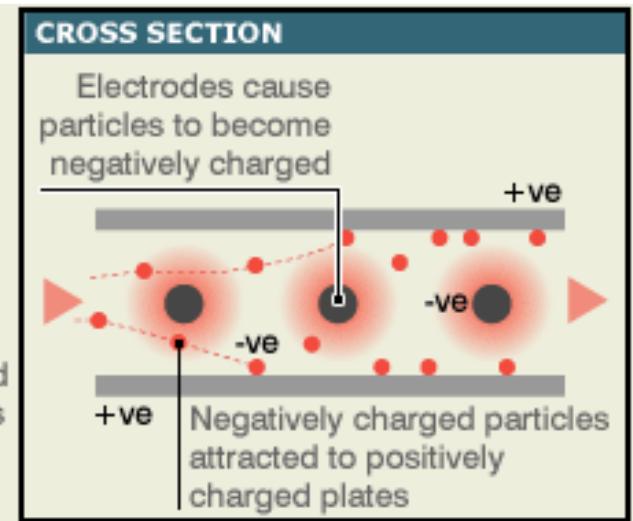
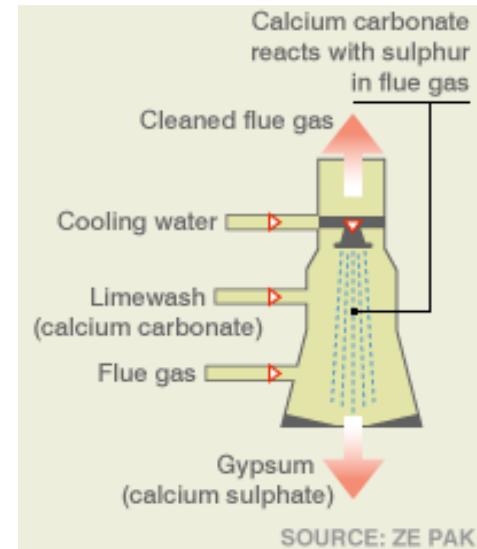
Integrated coal gasification combined cycle plant



Electrostatic precipitation to remove particulates emissions (electrostatic precipitators can remove more than 99% of particulates from the flue gas)



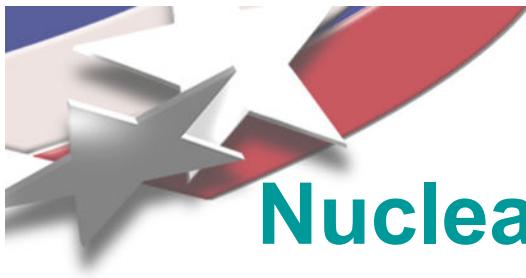
Removing SO₂ pollutant





Environmental implications in producing electricity from coal

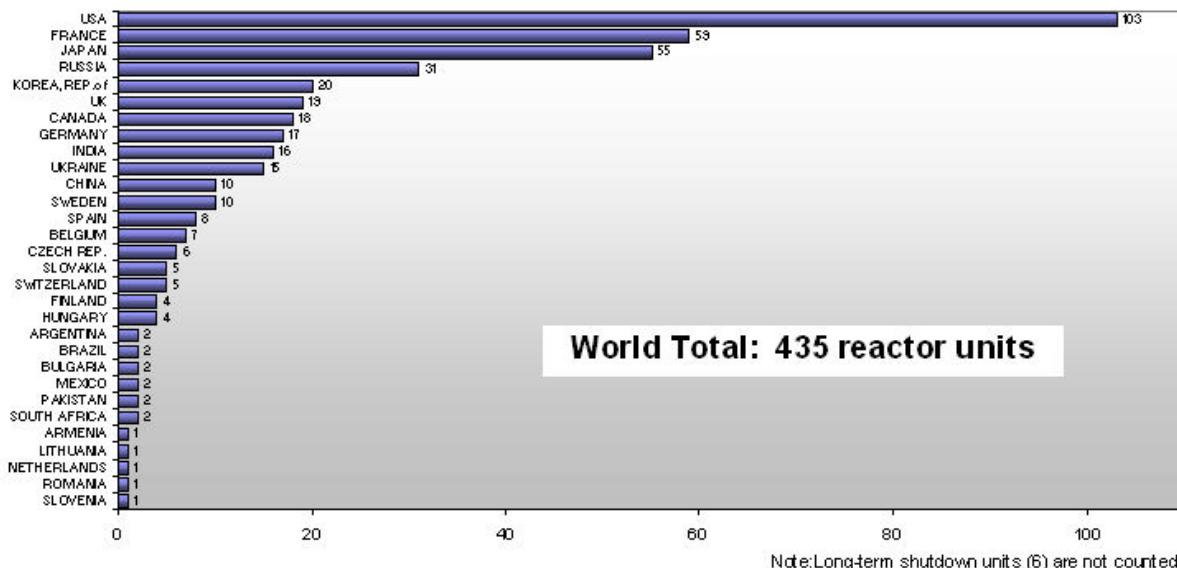
- Coal has been known as a big polluter – currently about 40% of CO₂ emissions comes from coal.
- CO₂ emissions can be reduced significantly by employing clean coal technologies:
 - CO₂ capture and storage,
 - Coal preparation – coal washing,
 - Integrated coal gasification,
 - Removing SO₂ pollutant.



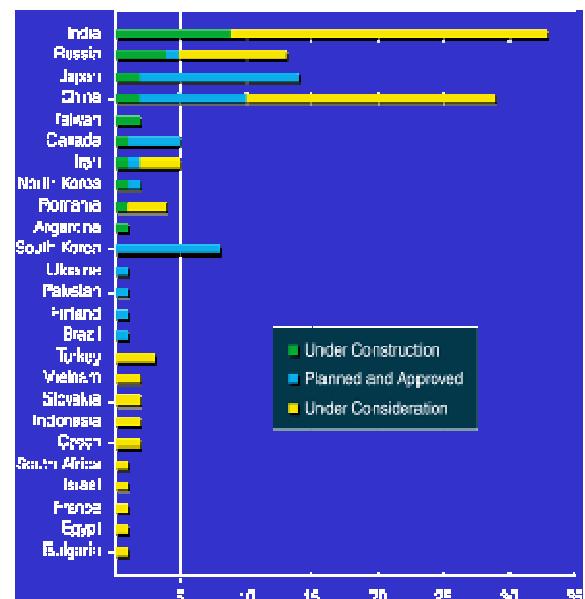
Nuclear Energy — Nuclear Power Plants

Number of Reactors in Operation Worldwide

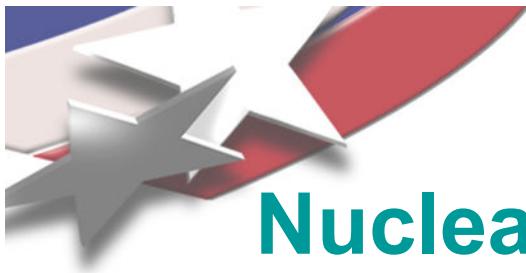
(as of 3 of January 2007)



Planned Expansion of Nuclear Energy



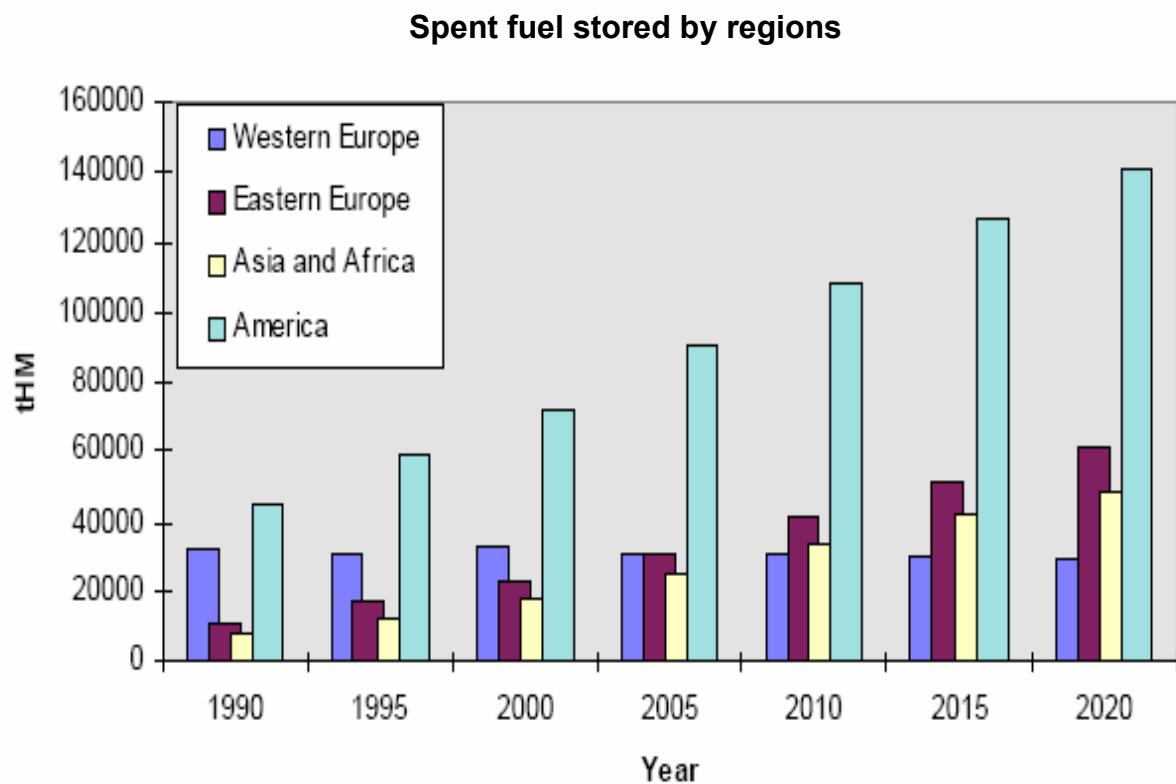
Source: To compile these graphs, information was derived from International Atomic Energy Agency, World Nuclear Association, and Nuclear Energy Institute reports and websites.



Nuclear Energy — Worldwide Spent Fuel

Region	Amount
West Europe	36 100
East Europe	27 700
America	83 300
Asia & Africa	23 900
World	171 000

Status 1 January 2003



IAEA Overview of global spent fuel storage, IAEA-CN-102/60
<http://www.iaea.org/NewsCenter/Features/UndergroundLabs/Grimsel/storageoverview.pdf>



Global Nuclear Energy Partnership (GNEP)

- The new initiative, GNEP, is a comprehensive strategy to enable the expansion of emission-free nuclear energy worldwide by demonstrating and deploying new technologies to recycle nuclear fuel, minimize waste, and improve our ability to keep nuclear technologies and materials out of the hands of terrorists.
- GNEP was launched by DOE in 2007 with an initial funding of \$250M.
- GNEP has four goals:
 1. Reduce America's dependence on foreign oil and encourage economic growth.
 2. Recycle nuclear fuel using new proliferation-resistant technologies to recover more energy and reduce waste.
 3. Encourage prosperity growth and clean development around the world.
 4. Utilize the latest technologies to reduce the risk of nuclear proliferation worldwide.



GNEP Includes Seven Elements

1. **Building of a new generation of nuclear power plants in the United States.**
2. **Developing and deploying new nuclear recycling technologies.**
3. **Working to effectively manage and eventually store spent nuclear fuel in the United States.**
4. **Designing Advance Burner Reactors that would produce energy from recycled nuclear fuel.**
5. **Establishing a fuel services program that would allow developing nations to acquire and use nuclear energy economically while minimizing the risk of nuclear proliferation.**
6. **Developing and constructing small scale reactors designed for the needs of developing countries.**
7. **Improving nuclear safeguards to enhance the proliferation-resistance and safety of expanded nuclear power.**



Environmental implications in producing energy from nuclear power plants

- No CO₂ or other greenhouse gases are emitted. So, the use of nuclear power plants to generate electricity can help reduce global warming.
- Impact of nuclear waste can be greatly reduced by developing and deploying new nuclear recycling technologies. Hydrogen can be produced in nuclear power plants by recycling used nuclear fuel.



Saving Petroleum-based Energy via Regulation Changes and Conservation

(“One BTU saved, one BTU produced”.)

- In his 2007 state-of-the-union address, President Bush said that
 - by tightening the regulations that deal with fuel standards for cars, the nation could save up to 8.5 billion gallons of gasoline by 2017.
 - new regulations that focus on supporting renewable and alternative fuels could replace up to 35 billion gallons of oil.
 - these measures would reduce gasoline usage in the United States by 20 percent in the next 10 years.
- Drive only when necessary, drive less (e.g., by carpooling, bicycling, etc.), and drive fuel-efficient vehicles, etc.
- Use energy wisely – turn off unnecessary lights, equipment, appliances, etc.
- ...



Summary

- A combination of factors have created an energy challenge:
 - Petroleum oil supply has peaked and energy demand is up.
 - Continued US dependency on foreign or imported petroleum oil.
 - Competition for global energy supply from China, India & others.
 - Environmental concerns such as pollution and global warming.
- Meeting the energy challenge requires multiple solutions:
 - Reduce petroleum-based energy usage via regulation changes and encourage energy conservation in general (e.g., drive less).
 - Transition from an energy supply dominated by hydrocarbon to one based on hydrogen – *this means that we need to develop new technologies for hydrogen production and utilization.*
 - Employ renewable energies such as solar, wind, and biofuels.
 - Use clean coal technologies to generate electricity and fuels.
 - Develop new technologies to generate nuclear energy so as to recycle used nuclear fuel and minimize waste.
- Environmental impact in meeting the energy challenge can be mitigated by developing and deploying new technologies that can reduce and control CO₂ and other greenhouse gas emissions (e.g., hydrogen production with concentrated solar energy, clean coal technologies), by employing renewable energies, and by recycling used nuclear fuel.