Personal Transportation in the 21st Century (and Beyond)

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Saginaw Valley Torch Club
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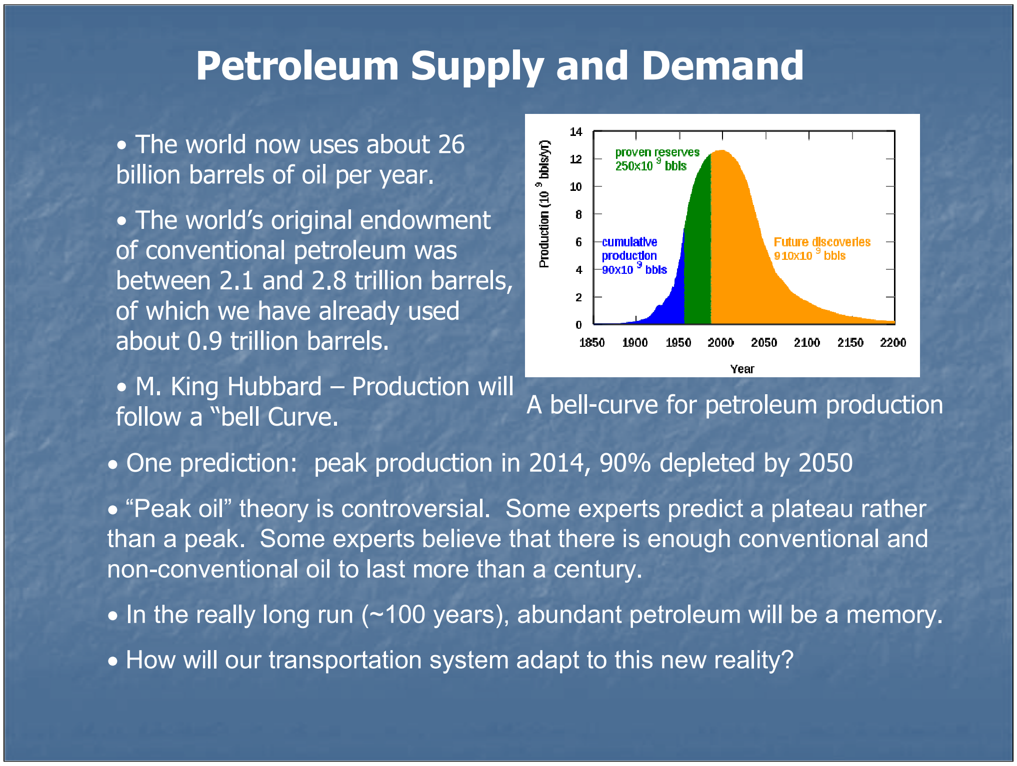
In order to avoid negative effects on the economy and social structure of the US we must change the transportation infrastructure of our country, particularly the types of private automobiles that we drive.



World consumption of petroleum now stands at about 26 billion barrels per year. The original world endowment of conventional petroleum (including estimates of what we have not discovered yet), is generally estimated to be less than three trillion barrels. About a third of that original resource has already been pumped. Simple math indicates that about 75 years worth of conventional oil left in the ground. Getting the last trillion barrels out of the ground will be a lot harder than getting the first trillion barrels.

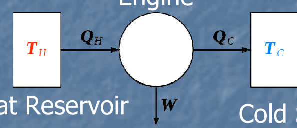
A recent study concluded that oil production will peak in 2014 and that by the year 2050 ninety percent of the recoverable oil on the planet will have been pumped*. More optimistic studies forecast a gradual global decline by 2020 or later. A term has evolved for this idea. It is called "peak oil" although "peak easy oil" is a more appropriate term. Many believe that oil from shale, tar sands, and heavy crude can provide additional petroleum to last well into the 22nd century albeit at increasingly higher prices, and greater environmental peril.

The oil depletion models might not have everything right, but it is certainly true that petroleum is a finite resource and that conventional production will peak or plateau sometime in the 21st century. It is disservice to future generations for us to only think in terms of the next few decades. This talk is an attempt to look ahead to see how our transportation system must change to adjust to the realities steadily declining petroleum production.

Another problem with our reliance on petroleum for transportation is economic. The $440 billion in oil payments by the US in 2008 was the largest transfer of wealth in human history. Currently the US imports about 12.2 million barrels of crude oil daily. At 80 $/barrel, that amounts to 355 billion dollars annually or 2.4 percent of our GDP and about one third of our balance of payments deficit. Added to these costs, we must also consider the cost of our military posture and actions in the middle East

Not All Energy is Equal

Nicolas Léonard Sadi Carnot



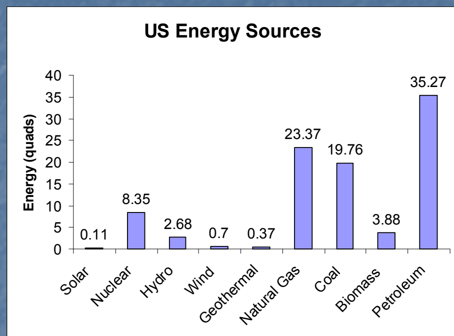
W = useful energy

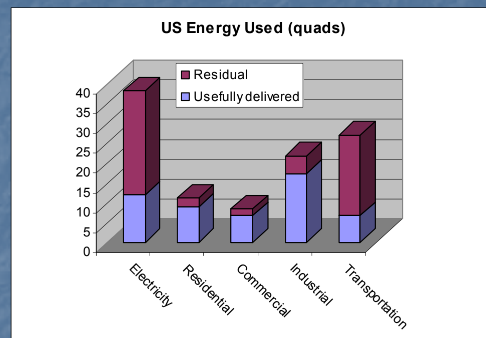
Maximum Efficiency = $(1 - T_C/T_H) \times 100\%$
Also called the Carnot Efficiency

- Transportation requires mechanical energy (work energy)
- Converting chemical energy to work is the job of the engine.
- Gasoline engines ~20% efficient (37% is theoretical max)
- Electric motors - ~90% efficient.

We like to talk about energy as if it were simple commodity like grapefruit or soy beans. Energy actually comes in many forms, some more useful than others for transportation purposes. When we say that a liter of gasoline has 32 mega-joules of energy, we mean that 32 mega-joules of heat can be had by burning that liter of gasoline. Only a fraction of that heat energy can be converted to mechanical energy for running a vehicle. Physics says that the fraction of chemical energy that an engine is able convert to mechanical energy has a limit called the "Carnot efficiency". The Carnot limit for a gasoline internal combustion engine is about 37%. Actual gasoline engines are about 20% efficient. Electric motors can have efficiencies close to 90%. Therefore the amount of energy that must be stored by a fuel cell vehicle or battery-powered vehicle is about a factor of four less than the energy that would be required for an internal combustion engine vehicle.

US Energy Sources and Uses





- Petroleum supplies about 97% of our transportation energy of which about 75% becomes residual heat in our engines.
- The total mechanical energy used in transport is less than half the useful energy delivered by our electric utilities.
- We don't have an energy problem as much as we have a transportation fuel problem. It is transportation needs that drive our need for imported petroleum.

These charts show where America's energy comes from and where it goes. Transportation consumes a large percentage of our petroleum and petroleum supplies about 97% of our transportation energy, but the total energy derived from petroleum is somewhat less than the energy that we derive from coal and natural gas. Note that the mechanical energy necessary for our transportation sector is less than half the useful energy delivered by electric utilities to customers. The reason for our reliance on petroleum is that it is the least expensive way to derive liquid fuels appropriate for transportation. We in the US don't have an energy problem so much as a transportation fuel problem.

Some Transportation Fuels

Fuel	Energy Volume Density (MJ/liter)	Energy Mass Density (MJ/kilo-gram)
Gasoline	32	44.4
Ethanol	23.5	31.1
Methanol	17.9	19.9
Diesel Fuel	38.6	45.4
LPG (Autogas)	26.8	46
Ammonia (-33°C)	15.3	22.5
Hydrogen (5,000 psi)	2.76	143
Natural Gas (5,000 psi)	12.5	53.6
Electricity (Li-ion battery*)	~4	2.16

* Electrical estimate is based on 150 w-hr/kg with a factor of four scaling to account for the greater efficiency of electric motors relative to gasoline engines.

= liquid fuels = gaseous fuels (compressed storage)

In the 20th century, energy and petroleum fuels were virtually one and the same. No other fuels come close in terms of ease of supply and distribution. Access and control of petroleum resources was essential to the Allies in World War II and has continued to be of paramount importance to strategic planning. This slide lists the common fuels used for transportation and some possible alternatives. The right two columns show the amount of energy stored per liter of volume and kilogram of mass respectively. Those parameters are important because low density implies that a larger percentage of the vehicle's mass and size must be dedicated to fuel storage. In general, liquid fuels are preferable to gaseous fuels because liquids are about a thousand times more dense than gases. Chemical fuels store much more energy than batteries, even when allowance is made for the higher efficiency of electric motors relative to internal combustion engines.

Burning, or oxidizing, petroleum fuels recovers energy stored millions of years ago by photosynthesis of carbon dioxide from the atmosphere.

Gasoline is the primary fuel for cars and light trucks in the US. Diesel fuel is the primary fuel for heavy transport (semi-trucks, buses, trains). Liquified Petroleum Gas (LPG), also known as autogas in Europe, is a mixture of propane and butane. It does liquify at room temperature and reasonable pressures. Unfortunately, LPG is a by-product of crude oil production and plagued by the same long term supply issues as gasoline and diesel fuel.

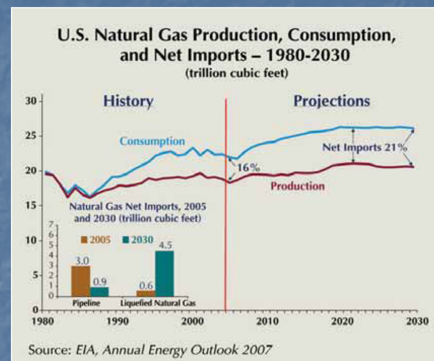
Alternatives to Petroleum for Transportation

- Natural Gas
- Synthetic Fuels
  - Synthesis from coal, tar, or shale
  - Biofuels
  - Hydrogen
  - Ammonia
- Electrical energy

What will follow is a discussion of alternatives to gasoline and diesel as fuel for transportation. Despite the fact that natural gas is itself a finite resource, it deserves serious consideration as a bridge to renewable technologies. The other fuels are synthetic fuels, in the sense that they must be manufactured biologically or chemically.

Natural Gas (methane)

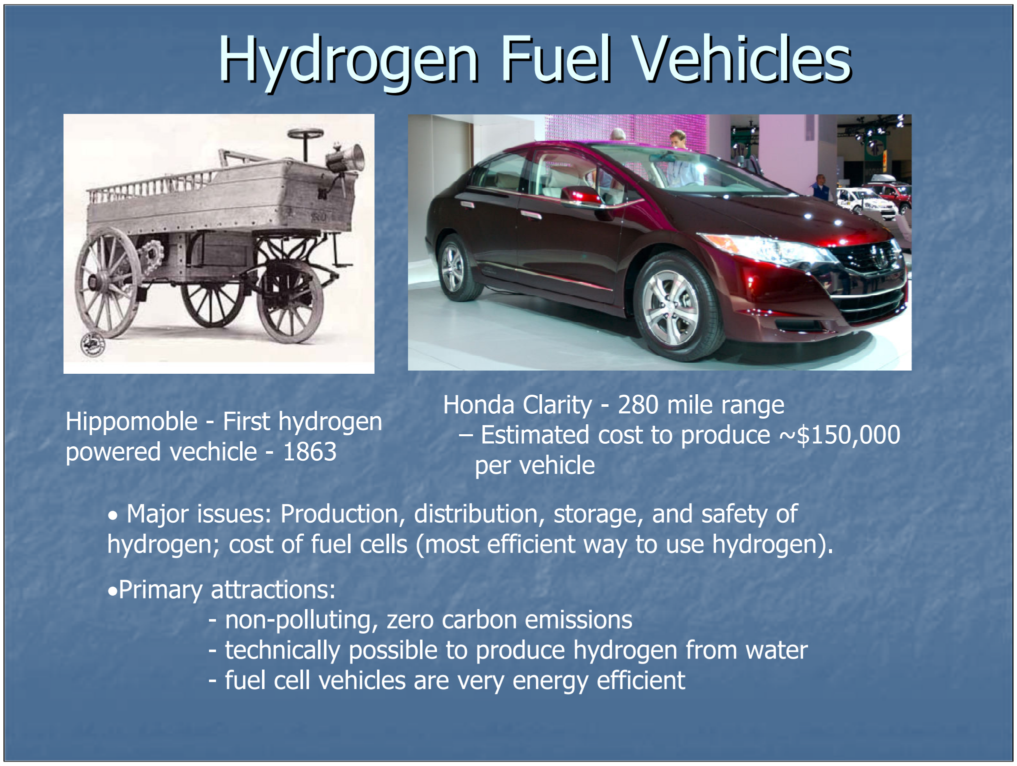
Experimental Methane Hydrate Well in Alaska



- Pro's: Good storage density for a gaseous fuel. Existing vehicles easily converted to compressed natural gas. Low(er) greenhouse emissions. Some of the distribution system already in place.
- Con's: Domestic reserves limited. Expensive and dangerous to import as liquid natural gas. Useful for other purposes, i.e. heating and electricity generation.

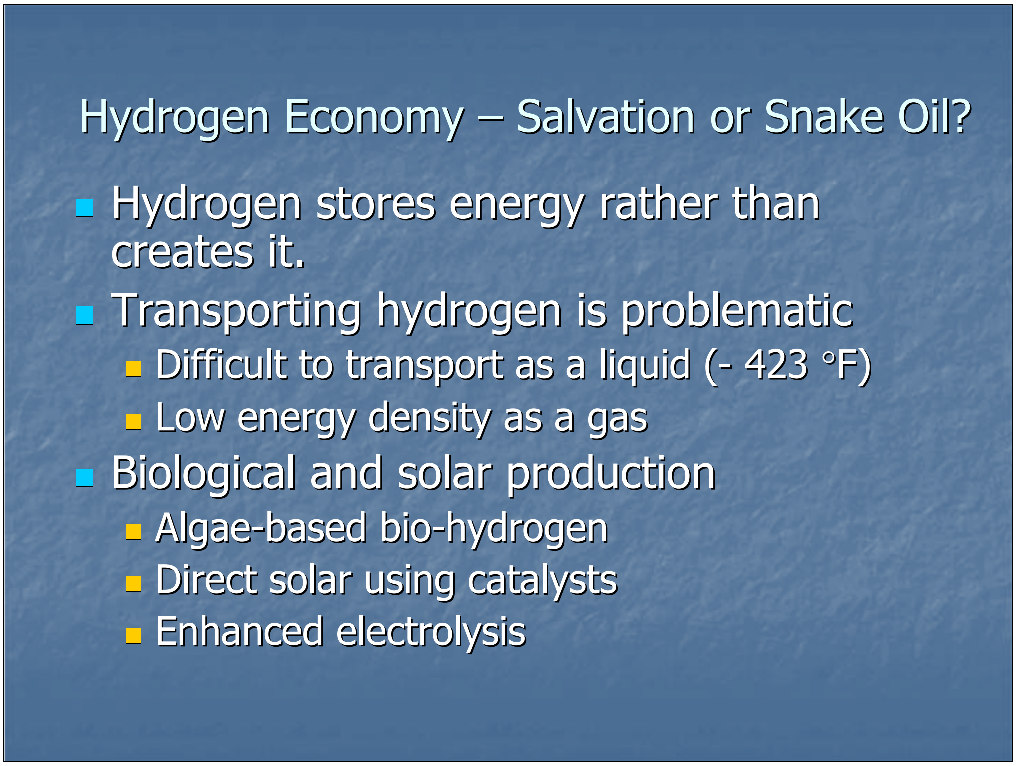
Natural gas is predominantly methane, the simplest hydrocarbon. Natural gas is an excellent fuel, readily burned in internal combustion engines. In terms cost per unit of energy, natural gas is about three times cheaper than gasoline, roughly equivalent to having gasoline cost $1.20 per gallon. Natural gas can be liquified (LNG) in bulk for international shipment via cryogenic tanker vessels. There are several terminals in the US for receiving LNG. Unfortunately, the low condensation temperature natural gas, makes fueling and storage of liquified natural gas for vehicle use problematic. Compressed natural gas is easier to handle but more bulky. I have personal experience of driving a CNG car on a 300 mile round trip without having to use the gasoline backup tank. Some public figures, among them T. Bone Pickens, advocate much more use of natural gas in US transportation. US natural gas reserves are estimated at 2074 trillion cubic feet. The US currently uses about 23 trillion cubic feet of natural gas annually. About 19% of US natural gas is imported via pipeline and about 1% is imported in liquified natural gas tanker ships. I calculate that it would take about 18 trillion cubic feet of natural gas to completely replace the gasoline consumed annually in the US. Shifting all gasoline driven vehicles to natural gas would mean that rather than having a 90 year domestic reserve of natural gas, we would have a 50 year domestic reserve.

Another potential source of methane exists in the world's oceans and permafrost regions. At the high pressures of the ocean floor and cold temperatures of the permafrost, methane is trapped in ice. The estimated quantity of methane is quite high, possibly greater than all the other reserves of fossil fuels. The department of energy has done evaluation of methane hydrate deposits in Alaska and the gulf of Mexico, but extracting methane from hydrate deposits remains an elusive goal. . Other potential sources of methane are from biomass and waste processing.



Hydrogen has received a great deal of attention as a potential alternative fuel. It can fuel internal combustion engines directly or power fuel cells to make electricity for electric motors. Hydrogen can be produced from water using electricity via a process called electrolysis. When the hydrogen is burned in an engine or utilized in a fuel cell, the product is water, thus reversing the electrolysis reaction. The electrolysis process is currently too costly as a method for hydrogen production. Hydrogen is currently produced commercially from natural gas. It hardly seems useful to use natural gas, which is itself a viable transportation fuel to manufacture hydrogen. Technical improvements to the electrolysis process are being developed, as are biological and solar/catalytic approaches that could also enable hydrogen production from water. One attraction of using hydrogen as a fuel is that no pollution or green house gases are produced in its utilization on the vehicle.

There is considerable allure to the prospect of a "hydrogen economy". Honda will lease 200 hydrogen-fuel-cell vehicles to California residents for $600 per month. Honda has also developed home refueling stations that plug into domestic natural gas lines for individual consumers. The Honda vehicle stores its hydrogen in 5000 psi tanks and has an advertised range or 200 miles.



All this sounds good, but there are significant problems with the manufacture, storage, and bulk distribution of hydrogen. For starters, hydrogen does not occur naturally on earth. It must be manufactured using other energy sources, such as electricity, solar energy, or natural gas. Essentially, hydrogen is not an energy source, but rather a means of storing and transporting energy. Hydrogen does not liquify at reasonable temperatures, so bulk distribution would need to be in the gaseous state. Distribution via tanker trucks or pipelines would be problematic due to the low volumetric energy content and high reactivity of hydrogen. There have been proposals to distribute hydrogen as methane, ammonia, or methanol, and then generate hydrogen on-site using “reformers”. Reforming methanol on-board the vehicle to drive fuel cells has been considered but no practical system has been developed.

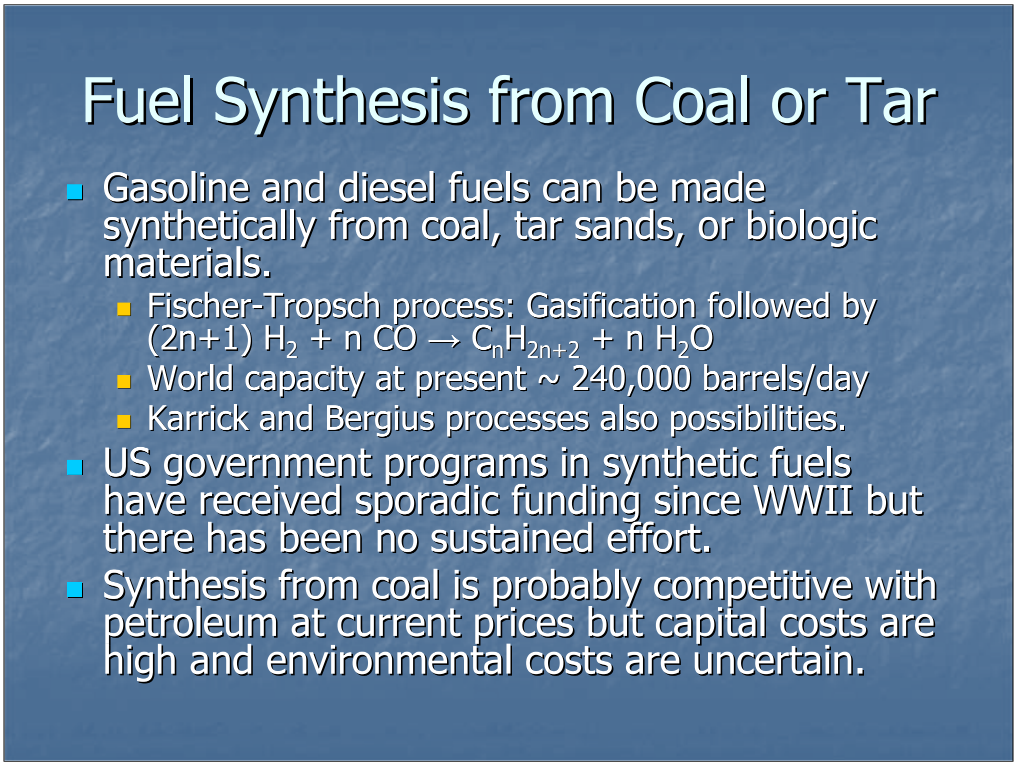
No alternative method of producing hydrogen has yet been shown to be practical. One method takes advantage of the fact that some algae produce hydrogen directly. Another method uses direct exposure to sunlight in the presence of certain chemical catalysts to produce hydrogen from water. Methods for enhancing the efficiency of electrolysis are also under study.

Ammonia (NH_3)

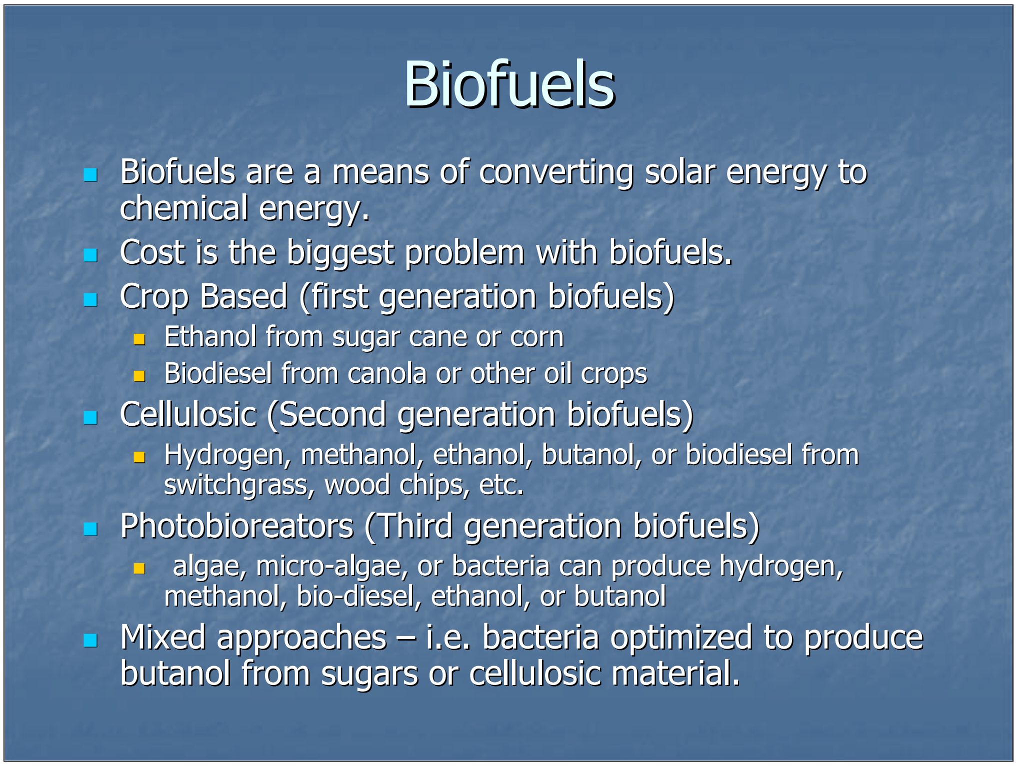
Anhydrous-ammonia-powered bus used in Belgium during WWII

- Ammonia has several attractive properties:
  - liquefies fairly easily, high energy content
  - fuel cell vehicles or conventional (ICE) vehicles
  - No greenhouse emissions (but possible NO_x emissions)
- Problems with ammonia:
  - Safety - hazardous at the levels greater than 35 ppm
  - Energy intensive to manufacture (unless reformed from methane)

Using ammonia as a fuel has attracted some adherents in the scientific and engineering communities. Complete combustion of ammonia yields only water and nitrogen, so in principle ammonia engines could be non-polluting. Production methods for ammonia either require methane or large inputs of electrical energy. Another problem with ammonia is its toxicity. The permissible exposure limit is 35 parts per million. Extremely high levels of exposure can result in death. One study has concluded that the risks of ammonia transport and storage are no greater than the risks of transporting and storing gasoline or LPG.

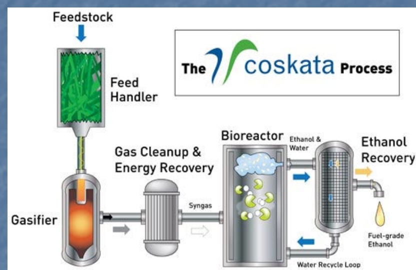


Chemical methods of manufacturing liquid fuels from coal have been known since the 1920's. The Fischer-Tropsch process, or similar methods, can be used to synthesize liquid fuels from coal, tar sands, or biomass. The current worldwide production capacity of synthetic fuels is about 240,000 barrels per day which compares to the world demand (for crude oil) of about 70 million barrels per day. Canada produces about 14% of its crude oil synthetically from tar sands. More famously, Germany produced up to 120,000 barrels per day of synthetic fuel during World War II. The US had an active synthetic fuels program in the early 1950's with a hydrogenation plant in St. Louis, Missouri, producing 1.5 million gallons of synthetic gasoline from coal between 1949 and 1953. The program was de-funded by Congress in 1953, partly as a result of lobbying by the National Petroleum Council. An attractive feature of the Fischer-Tropsch process is that fuels equivalent to gasoline and diesel fuel can be manufactured. Therefore little change is required in the distribution system or vehicles. A recent study concluded that a 50,000 barrel per day, coal-to-synthetic-diesel plant could produce a return on investment of almost 20%. A drawback to these processes is that they consume other finite resources like coal or tar sands. I suspect another the reason that a ventures have not attracted investment are environmental concerns and high financial risk.



In a sense, biofuel technology converts solar energy into fuel using biological processes. In fact, all non-nuclear fuels come from solar energy; it's just a matter of when the photo-synthesis occurred. There is enough solar energy falling on an area 40 miles by 40 miles to substitute for the energy expended by all the cars in the US, so it is not totally crazy to search for practical biofuel technologies. In principal, biofuels are renewable resources. Biofuel technology has the additional advantage that it need not contribute to greenhouse gas emissions and may actually serve to reduce them. Biofuel technology can be lumped into three general approaches: (1) crop based, which uses only the kernel from the plant; (2) cellulosic, which uses the whole plant; and (3) photo-bioreactor, which grows simple organisms in ponds. The best developed biofuel is ethanol, which has reduced the Brazilian need for gasoline by an approximate factor of two. The US ethanol program, which is based on ethanol production from corn, produced about 10 billion gallons in 2009, or about 2.6% of the US consumption of gasoline. Although this program has many detractors, it has reduced importation of crude oil to some extent. Both the US Navy and Air Force have aggressive programs to develop biofuel mixtures for jet aircraft and ships.

Cellulosic Ethanol



- Various approaches are in development
- Shown above is a process that gasifies organic material for a bioreactor.
- The company claims to have micro-organisms optimized for ethanol and proprietary membrane technology for separation of ethanol from water.
- Problems: using large volumes of feedstock could damage soil, scaling to US requirements takes a lot of feedstock, and large capital investment.

The technology for producing large quantities of ethanol or methanol from cellulosic materials like switch grass or wood chips is not mature. One approach involves breaking the cellulose down into glucose with mild acids, enzymes, or fungi; followed by fermentation. One company in Canada produced about 150,000 gallons of ethanol from straw using an enzyme process in 2009. Another approach involves breaking cellulose down chemically into methane at high temperatures, followed by alcohol production from methane. Still another approach involves breaking down the cellulose thermally to a gaseous mixture followed by fermentation in a bioreactor to form ethanol. Despite significant funding from the Department of Energy and private investors, a project to synthesize ethanol from wood chips in Georgia has fallen well short of its initial goal of 20 million gallons per year (~1300 barrels per day).

Biodiesel from Microalgae

Open raceway paddle wheel mixed ponds now used by 98% commercial microalgae production. Products are pharmaceuticals not fuels. From J. R. Breneman at NREL-AFOSR Workshop, Arlington VA (2008).

Microalgae biodiesel

- Theoretical yield: 22,000 gallons/acre/year
- Several attempts at commercializing biodiesel production have failed due to low yields and cost of harvesting.

The production of liquid fuels from micro-algae has attracted some adherents, chiefly because the processes appear to be scalable. The Department of Energy estimates that the US requirement for liquid fuels could be satisfied by dedicating 15,000 square miles of land to micro-algae farming, which is less than one-seventh the land currently dedicated to corn production. Unfortunately, production of fuel from micro-algae is not cost competitive with current technology. The ponds or bioreactors are difficult to keep clean and harvesting is problematic. There have been several pilot plants built to produce fuel from micro-algae, however none have been able to achieve the necessary cost reductions. Another approach is to let the photosynthesis occur in normal plants, like sugar cane, and then use genetically engineered bacteria or yeast to produce the desired fuels.

Hybrid Vehicles

Toyota Prius: 51/48 mpg
Msrp $22,800

Honda Civic Hybrid: 40/45 mpg
Msrp $23,800

- Improved fuel economy through:
  - Reduced gasoline engine size enabled by power boost from electric motors
  - Regenerative braking
- Nickel-metal-hydride batteries
  - Better developed and cheaper than lithium-ion, but lower performing.

We now turn our attention to the use of “electric fuel”. Most of the power requirement in cars and light trucks comes from the need for acceleration. Driving at constant velocity on a level surface requires only enough power to overcome the drag resistance from the air passing around the vehicle, the rolling resistance of the tires, and frictional forces in the drive train. I calculate that my Honda Civic uses about 20 horsepower to maintain a constant speed of 70 miles per hour on level roadway. So why does it have a 140 horsepower engine? The other 120 horsepower is there for acceleration and hill climbing. Much of the energy expended in acceleration and hill climbing eventually ends up being dissipated in as heat in the brake linings. Hybrids provide a way to recapture some of the energy that is normally dissipated in braking by using that energy to re-charge an on-board battery. That power can then applied to an electric motor to help achieve the next cycle of acceleration or hill climbing. Some hybrids actually have better fuel economy in city driving than highway driving. Because of the power boost provided by the electric motor for acceleration, the gasoline engine can be smaller than it would otherwise need to be, and a smaller gasoline engine requires less fuel. The Prius and some other hybrids have a patented drive system that allows the electric motors to contribute power over a wide range of vehicle speeds. Other hybrids use a simpler, but less beneficial scheme which utilizes the electric motor only at low speeds. The current generation of hybrid vehicles generally use nickel-metal-hydride batteries, which are better developed and less expensive than lithium ion batteries. On the other hand, lithium ion batteries store much more energy per kilogram of battery weight.

Plug-in hybrids allow some energy to be stored in the battery from a charging station or normal household plugs. Electric "fuel" acquired in this way is about four times less costly than gasoline, on a per mile basis. This might seem to be a really good idea, and after-market kits for adapting the Toyota Prius for plug-in operation are available. After-market kits that simply add on more nickel metal hydride batteries have limitations. Vehicle speeds are limited during EV-mode operation and the extra batteries add greatly to the weight. One company offers an aftermarket kit for the Toyata Prius that uses lithium-ion batteries. The cost of the installed kit is $10,000 to achieve about 40 miles of EV mode operation. The battery installs in the spare tire location and operates in parallel with the stock nickel-metal-hydride battery.

Plug-in Hybrids and Extended Range Electric Vehicles

GM Volt – 10,000 units to be produced in 2011. Price is $41,000 before $7500 tax rebate. Lease $350/month.

BYD f3DM – Only produced in small numbers in China. Not available in US. Price is about 150,000 Yuan ($22,000)

- After-market kit for Toyota Prius with lithium-ion battery for $10,000
- Lithium ion batteries
- 40 miles range in electric mode for Volt, 62 mile range for f3DM
- When battery drains to ~25% of maximum charge, the vehicles operate as hybrids with hybrid-like fuel efficiencies.

The "game changer" for electric vehicles has been the development of lithium ion batteries. The weight of the batteries has traditionally been a problem for electric vehicles. For instance, the original EV1 built by GM and Honda in the 1990's had 1200 pounds of lead acid batteries, which was almost half the weight of the vehicle. Lead acid batteries store only 35 watt-hours per kilogram. Currently, Lithium-ion batteries achieve about 150 watt-hours (0.54 mega-Joules) per kilogram at the cell level. The GM Volt uses about 400 pounds of lithium ion batteries to achieve its 40 mile (electric only) range. Other battery technologies, such as lithium-air and lithium-sulfur are theoretically capable of storing up to 5000 watt-hours per kilogram. But those batteries are either not rechargeable or have some other drawback. It is likely that greatly improved battery technology will be available for cars in the future. Even at current gasoline prices the cost of operation for an electric vehicle figures to be about three to five times cheaper than a gasoline powered vehicle with similar characteristics. In principle, the electrical generating capability of the US would not have to undergo a drastic expansion to accommodate electric cars and light trucks. The entire transportation sector annually consumes about 6×10^{18} Joules of usenful energy (after allowing for the distribution losses and the inefficiency of internal combustion engines) while the electric companies now deliver about 12×10^{18} Joules of useful energy to consumers.

The GM Volt and BYD's F3-DM are examples of extended range electric vehicles, also called series hybrids. The distinction between “series hybrids” and “plug-in” hybrids is somewhat obscure. These vehicles differ from other hybids in that their electric motors and the batteries are sufficiently large to support electric-only operation for some distance. Diesel electric locomotives, which use an all-electric drive train, have been around for over 60 years. Series hybrids have all the efficiency advantages of other hybrid vehicles and are capable of electric-only operation at cruising speeds. In gasoline-only mode the Volt achieves 37 miles per gallon average fuel economy. For owners who only occasionally take more than short trips, the effective gas mileage could be over 200 miles per gallon. The keys to success for these vehicles in the market place will be reliability and acquisition costs.

Electric Vehicles

Nissan Leaf
Five passenger
Base Price: $25,280
Range: ~100 miles
Performance: 0-60 ~ 9 sec., 90 mph max

Tesla Roadster
Two seater sports car
Base Price: $101,500
Range: ~244 miles
Performance: 0-60 ~ 3.7 sec., 125 mph (electronic governor)

Issues: (1) range not adequate for long trips, (2) recharge time, (3) battery costs, (4) initial costs, (5) battery life, (6) battery disposal/recycling, (7) not practical for heavy transport

Advantages: (1) fuel cost much less than gasoline, (2) no emissions, (3) fuel distribution system already in place, (4) potentially carbon neutral

If the motor-generator system in the extended range electric vehicle is replaced with additional batteries, the range that the vehicle can travel in electric-only mode is extended, and one then has an all-electric vehicle. Of course there is no back-up mode, so range and recharging times become important. A few companies have been producing road worthy electric vehicles. Notably, Tesla Motors in California has been producing a high performance all-electric sports car since 2008. That vehicle is one of the fastest accelerating production cars in the world - zero to 60 mph in 3.9 seconds. It has a range of 236 miles and costs about $101,500, mainly due to the high cost of its lithium-ion batteries. In 2011 Tesla will introduce a sedan that will cost around $50,000 and have a range of 300 miles. A Chinese company, BYD, will introduce an electric sedan with 200 mile range and projected cost of $40,000. Nissan is introducing an all-electric vehicle called the Leaf that will cost about $25,000 after a $7,500 federal subsidy is deducted from the cost. The Leaf has an advertised range of 100 miles. At this point in time, all-electric vehicles like the Tesla, Nissan Leaf, and BYD sedans do not make a lot of economic sense. Even hybrid owners are not likely to recoup the difference in initial cost from fuel savings, at current prices. With improvements in battery performance, reductions in battery cost, and likely rises in the cost of gasoline, all-electric vehicles will soon become cost competitive for cars and light trucks.

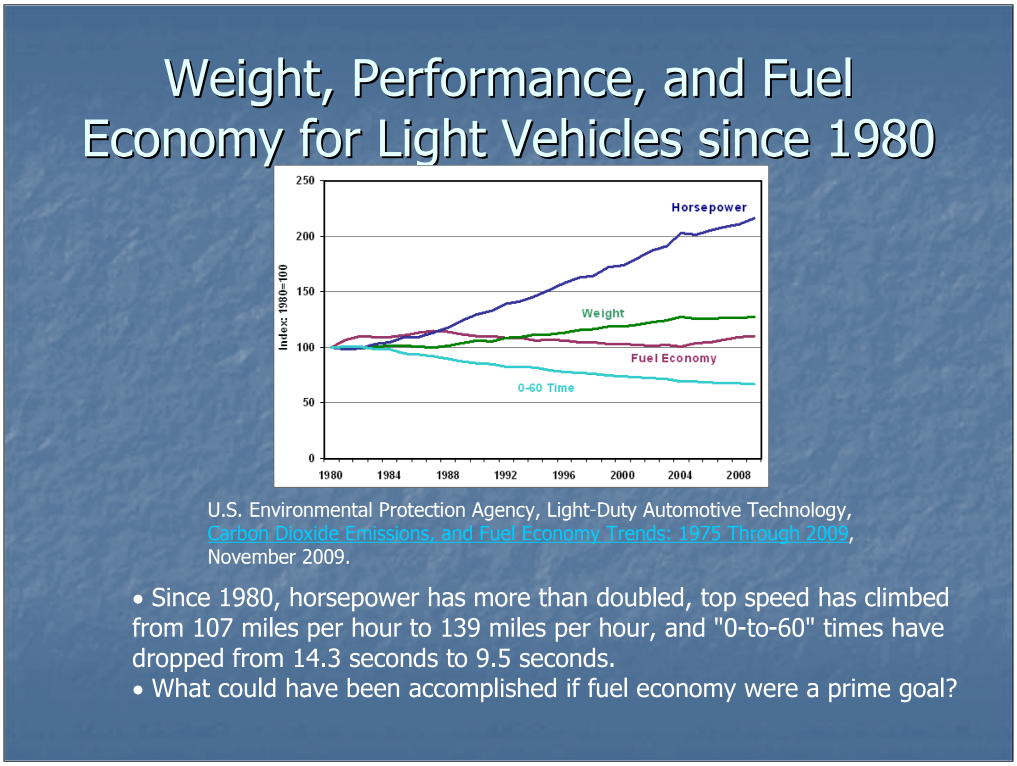
As previously stated, my Honda Civic going 70 mph on level road uses about 20 horsepower (~15 kW) from its 140 horsepower engine. A normal household circuit only provides about 2.2 kW of power. Therefore recharging an electric car from a household plug requires about 6.8 hours of charging time for each hour of vehicle operation. My electric dryer plug provides about 6.6 kW of power, so recharging from that circuit would require a little more than two hours recharging time for each hour of vehicle operation. Most battery types can be recharged much more rapidly than can be accomplished with household circuits provided the charging station is "beefy" enough. Conceivably the "gas station" of the future could provide beefy charging stations for rapid recharging of electric vehicles, or battery exchange. But that is an infrastructure change that will be slow in coming as long as liquid fuels are relatively cheap.

Electric/Hybrid Vehicle Comparison

Vehicle	Gas Engine Power (HP)	Electric Motor Power (HP)	Usable Battery Storage Energy (MJ)	Fuel Economy	Curb Weight (pounds)
Prius	98	36	4.7	51/48/50	3042
Civic Hybrid	110	20	3.1	40/45/42	2877
Ford Fusion Hybrid	136	55	4.7	41/36	3720
GM Volt	71	141	28.8	~200/37*	3500
Nissan Leaf	N/A	110	86.4	N/A	3500
Mitsubishi MiEV	N/A	64	57	N/A	2400
Tesla Roadster	N/A	288	~160	N/A	2723

* First number is based on average mix of EV and gasoline only operation. Second number is for gasoline operation only.

This figure shows a comparison of various hybrid, extended range electrics, and electric vehicles. It is not a complete list. Note the quantum leap in battery storage energy for vehicles using lithium-ion battery technology. Note also the that the ratio of electric motor power to gas engine power on the Prius is by far the greatest and that the Prius has the best fuel economy of any hybrid vehicle. Some hybrids do not achieve significantly better fuel economy than the gasoline-only version of the same model.



The one thing that we can most readily do to reduce petroleum imports is something for which we have a poor track record - conservation. In particular, the Corporate Average Fuel Economy (CAFE) standards have been ineffective in improving the fuel economy of the vehicle fleet in America. Since 1980 the average horsepower of American light vehicles has doubled and the fuel economy has remained relatively constant. While this is a remarkable engineering achievement, one must ask what improvements in fuel economy would have been possible if the average horsepower had not doubled.

Where Does this Leave Us?

- A total technical solution to the loss of cheap petroleum is unlikely. Society will have to adapt.
- Hybrids, range extended electrics, and natural gas vehicles are the best near-term options for long trips.
- Electric vehicles are likely to subsume the vehicle market for commuters and city dwellers.
- Biofuels or synthetic fuels (from coal) will be necessary for heavy transport and air travel.

I am cautiously optimistic that synthetic fuels and electric vehicles will help us to avoid the worst consequences of diminishing oil supplies. The availability of petroleum from tar sands or oil shale may allow us some "breathing room". Coal-to-liquid fuel processes are well understood and could be brought into play if necessary. Natural gas could also provide some relief from petroleum shortfalls, but domestic supplies are finite and probably should be preserved for other uses. In fact, all fossil fuels are finite resources. Only renewable resources will suffice for time frames on the order of centuries.

The technical alternatives to petroleum fuels are all problematic, and it is not clear when or whether the hoped-for breakthroughs, i.e. improved batteries, cellulosic ethanol, and advanced biofuels, will occur. The executive summary of a report by the Council on Foreign Relations states:

"A popular response to the steep rise in energy prices in recent years is the false expectation that policies to lower imports will automatically lead to a decline in prices. The public's continuing expectation of the availability of cheap energy alternatives will almost surely be disappointed. . . . . Moreover, the political system of the United States has so far proved unable to sustain the policies that would be needed to manage dependence on imported fuels. As history since 1973 shows, the call for policy action recedes as prices abate.[1]"

Petroleum exporters have an incentive to keep prices high enough to make large profits but not so high as to cause developed countries to switch to alternative sources. If petroleum were not a finite resource deserving of conservation, allowing the marketplace to set supply and demand would be ideal. As things are, however, moderate petroleum prices, only prevent us from taking steps that must be taken in the long run.

Certainly the faster that we diversify our transportation sector, the better. Shifting to a hydrogen-based transportation system is unlikely. I believe that there are too many issues with hydrogen for it to be a viable fuel in the 21st century. Production, distribution, on-board storage, fuel cell costs, and safety are all problematic.

Despite the advances in battery technology, those already made and those anticipated in the future, hydrocarbon fuels will continue to be necessary for heavy transport. The power and energy requirements for trucks and locomotives are too great to contemplate replacement with battery technology. The higher efficiency (and possible electrification) of rail transport may serve to replace long-haul trucking. One hopes that synthetic fuels can eventually be available for heavy transport and air travel. Biofuels from micro-algae, genetically modified bacteria, or normal crops are attractive possibilities, but the costs will be high and the past failures in this area have been many. Whatever approach is taken, synthetic fuels will certainly be more expensive than petroleum fuels.

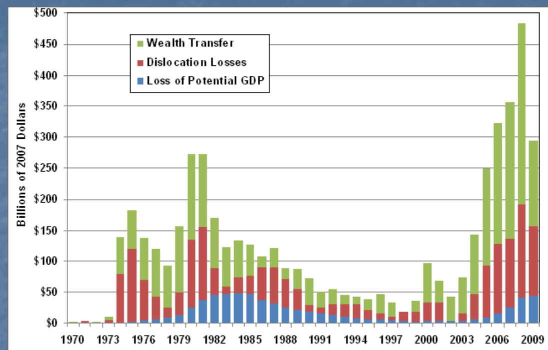
A lot that can be done to reduce oil imports by conservation and improving gasoline driven vehicles. The Corporate Average Fuel Economy (CAFE) standards for cars and light trucks have been tightened in 2007 and 2009. The 2011 standards will apply, for the first time, to vehicles over 8000 pounds in vehicle weight. As much as many of us prefer large, comfortable, vehicles like SUV's, we need to appreciate the cost of those vehicles to ourselves and our economy. In my opinion, automobile manufacturers have been too aggressive in lobbying for CAFE standards more to their liking and the result has been a glut of super-sized, overpowered vehicles. There are a number of options for improving the fuel economy of gasoline driven vehicles at reasonable costs. These options include cylinder deactivation, turbo-charging, and start/stop systems. But vehicle manufacturers are unlikely to promote these options, and buyers are unlikely to demand them, as long as fuel is relatively cheap.

There is the temptation to put off serious research, pilot programs, and infrastructure changes until crude oil prices become really onerous. That would be a mistake because changing the system will take decades, not years. Vehicle manufacturers have been active in developing electric and hybrid vehicles; and investing in key technologies like high performance batteries and more efficient gasoline engines. The vehicle manufacturers have done less well in the area of conservation, building and promoting overpowered, supersized vehicles because higher profits are attainable with larger vehicles. Many petroleum companies have active programs in biofuel technology, methane hydrate extraction, and battery technology.

The Department of Energy seems to be doing mostly the right things by funding some promising technologies. They have bought into some costly unsuccessful projects. It is difficult, however, predict technical breakthroughs (and blind alleys) in advance. Whenever large amounts research money is available, one must be suspicious of claims of facile solutions. Agencies and private investors need to critically assess proposals so that valuable research funds are used to best advantage.

BACKUP SLIDES

Cost of Petroleum Dependence to US



Source: Greene, David L., and Janet L. Hopson, "The Costs of Oil Dependence 2009," Oak Ridge National Laboratory Memorandum, 2010

Does not include cost of:

- 130,000 troops in Iraq and Afghanistan
- Billions of $ worth of war material pre-positioned in the gulf.
- 3 wars since 1990

This chart plots our annual cost of imported petroleum in three categories: (1) direct wealth transfer, (2) temporary losses of productivity due to price shocks, and (3) loss of potential GDP due to the cost of petroleum relative to fair market price. These costs do not include the cost of maintaining a strong military presence in the middle East.

Backup information:

Wealth Transfer is the product of total U.S. oil imports and the difference between the actual market price of oil (influenced by market power) and what the price would have been in a competitive market.
Dislocation Losses are temporary reductions in GDP as a result of oil price shocks.
Loss of Potential Gross Domestic Product (GDP) results because a basic resource used by the economy to produce output has become more expensive. As a consequence, with the same endowment of labor, capital, and other resources, our economy cannot produce quite as much as it could have at a lower oil price.

Gasoline and Diesel Fuel

- Gasoline (petrol)
  - Mixture of hydrocarbons with 6 to 12 carbon atoms per molecule
  - 42 gallon barrel of crude -> 18.5 gallons of gasoline
- Diesel fuel
  - Mixture of hydrocarbons with 8 to 21 carbon atoms per molecule
  - 42 gallon barrel of crude -> 10.3 gallons of diesel
  - Also used as a heating fuel (No. 2 heating oil)
- Jet fuels (JP-A, JP4, JP8)
  - Mixtures of kerosene and gasoline with properties similar to diesel fuel

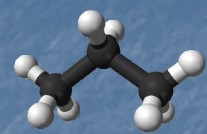
Gasoline is the primary fuel for cars and light trucks in the US. Diesel fuel is the primary fuel for heavy transport (semi-trucks, buses, trains) in the US. In recent years, engineers have developed diesel engines that have significantly higher efficiencies than gasoline engines. As a result, the mileage of diesel cars and light trucks is approximately 50% higher than gasoline vehicles. Europe has embraced efficient diesel. US manufacturers have leaned more toward gas-electric hybrids for improved efficiency.

Liquified Petroleum Gas (LPG)

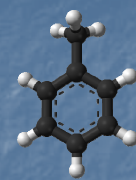
- Mixture of propane (C_3H_8) and butane (C_4H_{10})
- Liquid at room temperature and reasonable pressures
- By-product of petroleum refining
- Not a viable alternative to gasoline or diesel

Liquified Petroleum Gas (LPG), also known as autogas in Europe, is a mixture of propane (C_3H_8) and butane (C_4H_{10}). It does liquify at room temperature and reasonable pressures. Unfortunately, LPG is a by-product of crude oil production and plagued by the same long term supply issues as gasoline and diesel fuel.

A (Very) Little Chemistry



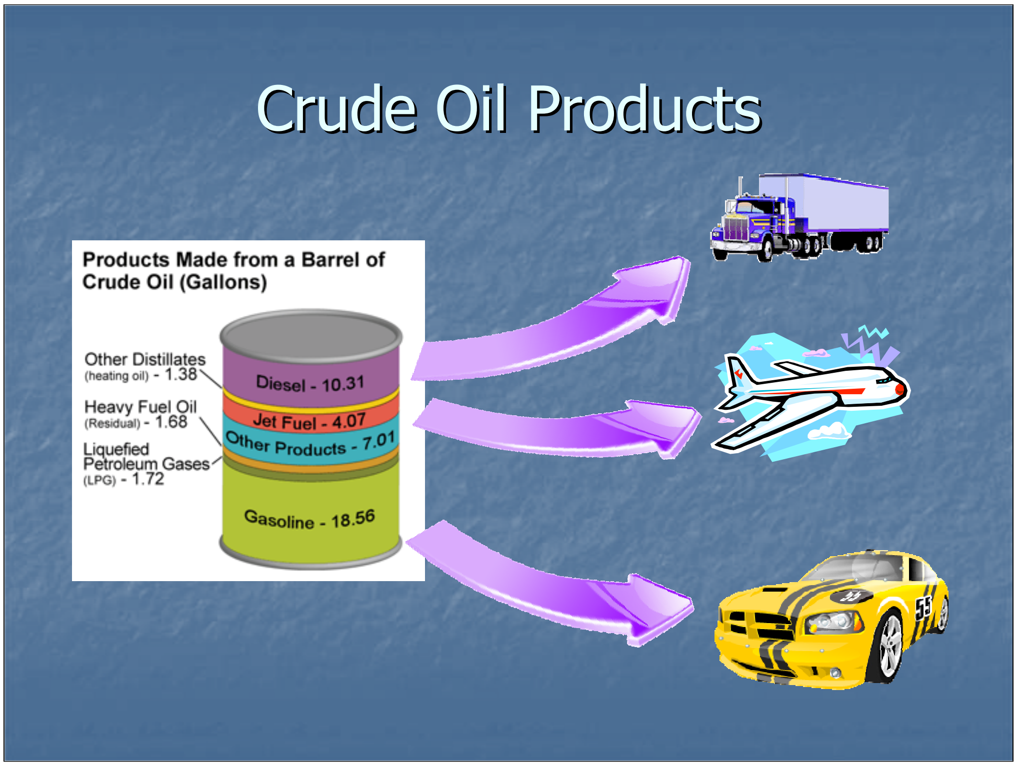
Propane C_3H_8



Toluene $C_6H_5CH_3$

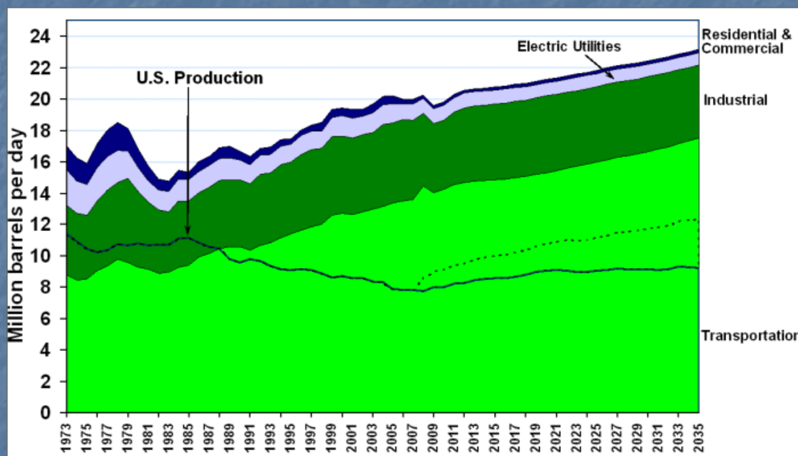
- Many good fuels are hydrocarbons
  - Alkane, or paraffin, hydrocarbons (C_nH_{2n+2}) like methane (CH_4) , ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10})
  - Other hydrocarbons like benzene (C_6H_6) and toluene ($C_6H_5CH_3$) have a ring structure and are more hazardous to health.
  - Alcohols like methanol (CH_3OH) and ethanol (C_2H_5OH) replace one hydrogen atom from an alkane hydrocarbon with an OH “radical”.
- Petroleum fuels recover solar energy stored over millions of years.
- Ammonia (NH_3) and hydrogen (H_2) are potential inorganic fuels.

Many fuels are some type of hydrocarbon, which is to say that the molecules contain hydrogen and carbon. The alkane hydrocarbons, like methane, ethane, butane, propane, etc. follow the chemical recipe of having 'n' carbon atoms surrounded by 2n+2 hydrogen atoms. Energy is released by breaking the weak carbon-hydrogen and carbon-carbon bonds and replacing them with strong carbon-oxygen bonds and hydrogen-oxygen bonds. Oxidizing "fossil" fuels recovers energy stored millions of years ago by photosynthesis of carbon dioxide, generally during the carboniferous period. Alcohols, like ethanol, methanol, and butanol have one of their hydrogen atoms replaced by a hydroxol radical (O-H), somewhat diminishing the energy stored per molecule, but producing a liquid fuel for even the lightest molecules.



The use of petroleum for private transportation is only one of many uses for petro-chemicals. Other products include fertilizers, plastics, lubricants, jet fuels, and fuels for freight carriers. Eliminating gasoline and diesel fuel from private vehicles would not eliminate the need petroleum derived products, but it would greatly reduce our need for crude oil. Since the refining process is essentially one of "cracking" long chain hydrocarbons into shorter ones, it seems to me that adjustments could be made to produce less gasoline and more diesel fuel, chemicals, fertilizer, and asphalt.

US Oil History and Future



Dotted line represents contributions from ethanol and other synthetic fuels.