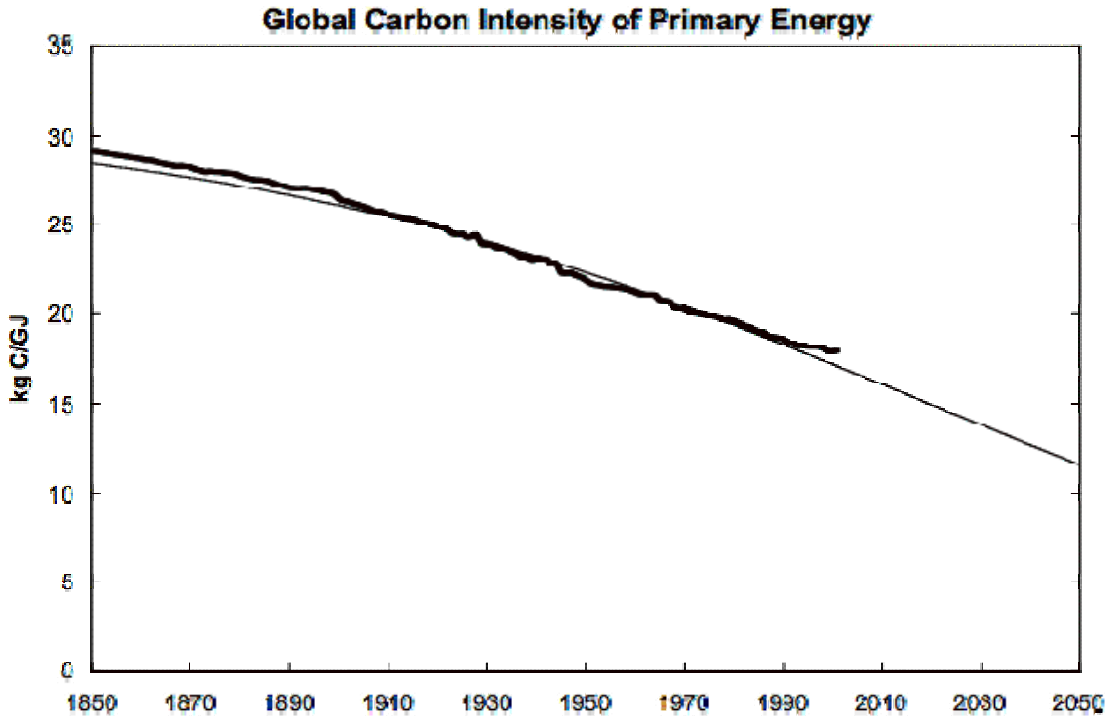
- **STRATEGIC PERSPECTIVE** – Decarbonization over centuries



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Decarbonization or the changing carbon intensity of primary energy for the world. Carbon intensity is calculated as the ratio of the sum of the carbon content of all fuels to the sum of the energy content of all primary energy sources. Figure prepared by N. M. Victor, Program for the Human Environment, The Rockefeller University, 2003.

- The most important and surprising fact to emerge from energy studies during the past two decades is that, for the last 200 years, the world has progressively pursued a path of decarbonization, a decreasing relative reliance on carbon

- Think of decarbonization as the course over time in the ratio of tons of carbon in the energy supply to the total energy supply, for example, tons of carbon per tons of oil equivalent encompassing all energy supplies.

- Wood is made of much cellulose and some lignin. Heated cellulose leaves charcoal, almost pure carbon. Lignin is a hydrocarbon with a complex benzenic structure. Wood effectively burns about ten carbons for each hydrogen atom.

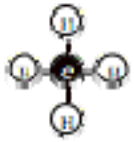
- Coal approaches parity with one or two C's per H, depending on the

- Oils are lighter yet, with, for example, with two H's per C, in kerosene or jet fuel.

- A molecule of methane, the typical natural gas, is a carbon-trim ($CH_{4)}$ that is one carbon for four molecules of hydrogen.

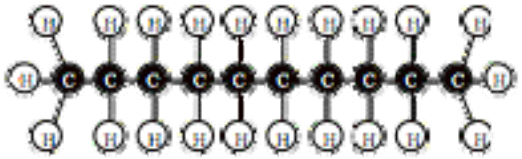
Hydrogen-Carbon Ratios of Fuels

Methane Gas



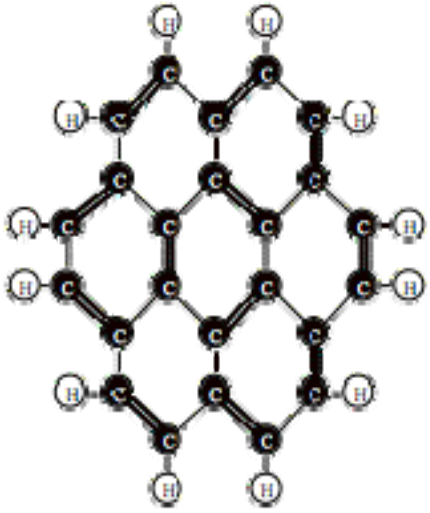
H:C = 4:1

Typical Oil

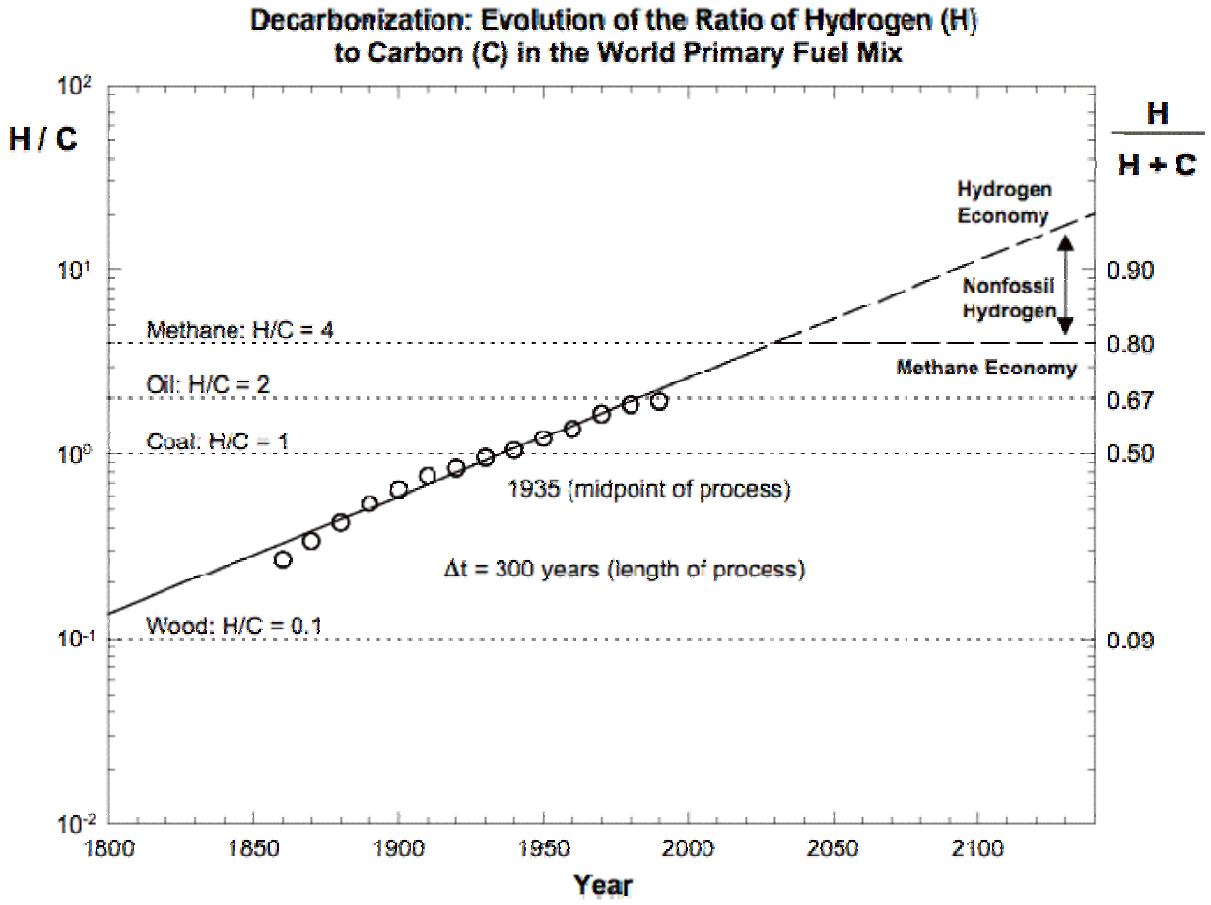


H:C = 2:1

Typical Coal



H:C = 0.5:1



Competition between hydrogen and carbon in primary energy sources. The evolution is seen in the ratio of hydrogen (H) to carbon (C) in the world fuel mix, graphed on a logarithmic scale, analyzed as a logistic growth process and plotted in the linear transform of the logistic (S) curve. Progression of the ratio above natural gas (methane, CH_4) requires production of large amounts of hydrogen fuel with non-fossil energy. Source: J. H. Ausubel, Can Technology Spare the Earth? American Scientist 84(2):166-178, 1996.

- In 1800 carbon had 90% of the market. In 1935 the elements tied. *With business as usual and the rising Pacific Rim economies not considered*, hydrogen will garner 90% of the market by 2100.

- Carbon becomes soot or the feared greenhouse gas CO_2, and hydrogen becomes only water when combusted, carbon depending on the combustion process combines with nitrogen and oxygen in the air to generate pollutants like CO2, CO, NOX and hydrogen generates water.

- Decarbonization towards a hydrogen economy is only a question of when not if. This transition provides a convergence not conflict between energy and environment.

- **The driving force in evolution of the energy system is the increasing spatial density of energy consumption at the level of the end user.**

- The British experience demonstrates that, when energy consumption per unit of area rises, the energy sources with higher economies of scale gain an advantage.

- Coal had a long run at the top of the energy heap. Coal-powered automobiles, however, never had much appeal. The weight and volume of the fuel were hard problems, especially for a highly distributed transport system.

- Oil had a higher energy density than coal—and the advantage of flowing through pipelines and into tanks. It is easy to understand why oil gained ascendancy over coal by 1950 as the world's leading energy source.

- Nevertheless, the share of primary energy used to make electricity has grown steadily in all countries over the past 75 years and now approaches 40%. The Internet economy demands further electrification, with perfect reliability

- **The stable dynamics of the energy system permit reliable forecasts. Decarbonization essentially defines the future of energy supply.**

- Globally we are destined to use about 50-80 billion tons more coal. This is about one-third what humans have mined in all our earlier history, and about 30 years at present levels of production.

- Coal companies R/D and commercialization is focused on extracting methane from coal seams and sink CO_2 there, staying in business without coal extraction. Using CO_2 to displace methane (CH_4) adsorbed in coal beds provides a two for one bargain

- Globally, drivers and others will consume close to 300 billion tons more oil, before the fleet runs entirely on H_2 separated from methane or water. This amount is almost double the petroleum that has so far been extracted, and about 50 years at present production, so oil companies it is business as usual for a while.

- For gas, the next decades will bring enormous growth, matching rising estimates of the gas resource base, which have more than doubled over the past 20 years;

- Between its uses to fuel turbines to make electric power and for fuel cells for transport, Natural gas will dominate the primary energy picture for the next few decades.

- It is expected that methane will provide perhaps 70% of primary energy soon after the year 2030 and to reach a peak absolute use in 2060 of about 30 x 10^{12} m^3, ten times present annual use.

Conclusion

Evolution is a series of replacements. Replacements also mark the evolution of the energy system. Between about 1910 and 1930 cars replaced horses in the United States.

Earlier steam engines had replaced water wheels and later electric drives replaced steam engines. **These replacements required about 50 years in the marketplace**.

It required about the same amount of time for railways to replace canals as the lead mode of transport and longer for roads to overtake railways and for air to overtake roads.

- GLOBAL OVERVIEW OF ENERGY
  - Increased competition between strategic players for energy
  - Energy shortfall in USA
  - Increasing Energy demands of Pacific Rim Nations
  - Major oil producing countries oil production is on a plateau or peaked
  - Increasing dependence on Middle Eastern oil.
  - The oil markets do not work well without safety net
  - Oil price will rise

Greatest Oil Reserves by Country, 2003

2002 rank	Country	2003 proved reserves (billion barrels)
1.	Saudi Arabia	261.7
2.	Iraq	115.0
3.	Iran	100.1
4.	Kuwait	98.9
5.	United Arab Emirates	63.0
6.	Russia	58.8
7.	Venezuela	53.1
8.	Nigeria	32.0
9.	Libya	30.0
10.	China	23.7

NOTES: Figures for Russia are “explored reserves,” which are understood to be proved plus some probable. All other figures are proved reserves recoverable with present technology and prices.
Source: World Oil, Vol. 224, No. 8 (Aug. 2003). From: U.S. Energy Information Administration, *International Energy Annual 2002* (March–June 2004).