Alternative Hydrogen Futures

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Presentation for DOE Hydrogen Program
U.S. Department Of Energy
Washington D.C.
August, 2001

File name: hydrogen.NCTWG.March.2000

Basic Thesis

- **There are many possible hydrogen futures**
- **The future is uncertain**
  - **Technology**
  - **Economics**
  - **Safety and public acceptance**
- **For success, the hydrogen program should not assume a single hydrogen future**

Characteristics of Hydrogen Futures

- **Each future requires massive quantities of hydrogen**
- **One future may be a stepping stone to a second future**
- **Example futures**
  - **Hydrogen-fueled (baseline)**
  - **Ammonia (vehicles)**
  - **No-greenhouse liquid fuels (vehicles)**

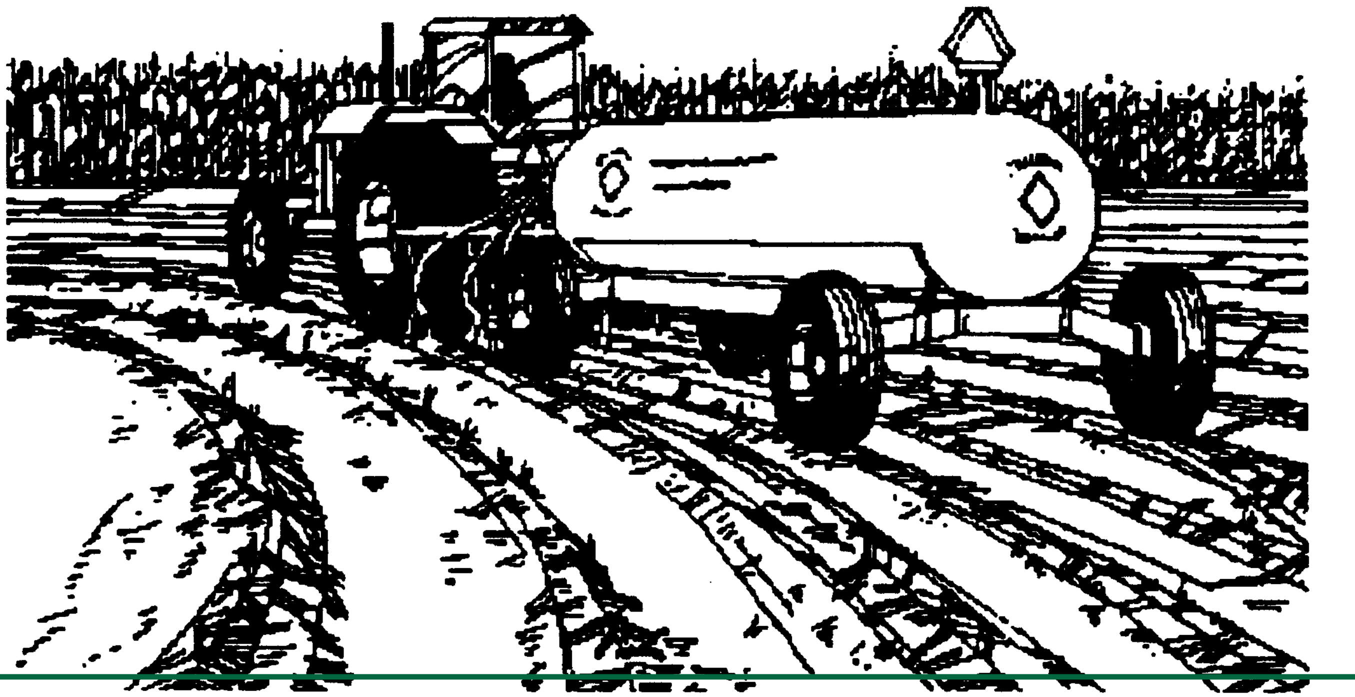
Ammonia-Fueled Vehicles

Ammonia (NH_3) is a hydrogen carrier

Ammonia can be converted to hydrogen in the vehicle

Ammonia is a cheap commodity chemical

Today, Ammonia (NH_3) Is Primarily Used As A Fertilizer



DOE Hydrogen Program Goals

- **Use: Transportation fuel**
- **Vehicle Storage: 8.5% by weight hydrogen**
- **Cost: $10–15/million Btu**
- **Distribution: Same as gasoline**

Comparison of Hydrogen Carriers

% Hydrogen by Weight

	Hydride	Bucky Balls	Nanotubes	Pressurized	Ammonia	Gasoline
Storage	1.2	5	5	7.5–8.5	14.1	89
	$/million Btu Hydrogen					
	Electrolysis	Reforming	Solar	Bioprocess	Ammonia	Gasoline
Manufacture	5.5	11–44	13–16	8.4	7.45	8.07

Different units for gasoline: % fuel and $/million Btu total

Benefits Of Ammonia As An Efficient Hydrogen Chemical Storage System

- **Established production methods**
  - **Nitrogen (from air) and hydrogen**
  - **Natural gas and air**
- **Price competitive with gasoline**
- **Distribution system in place**
- **Widely used by consumers**
- **Storage technology developed**
- **Safety rules and standards in place**

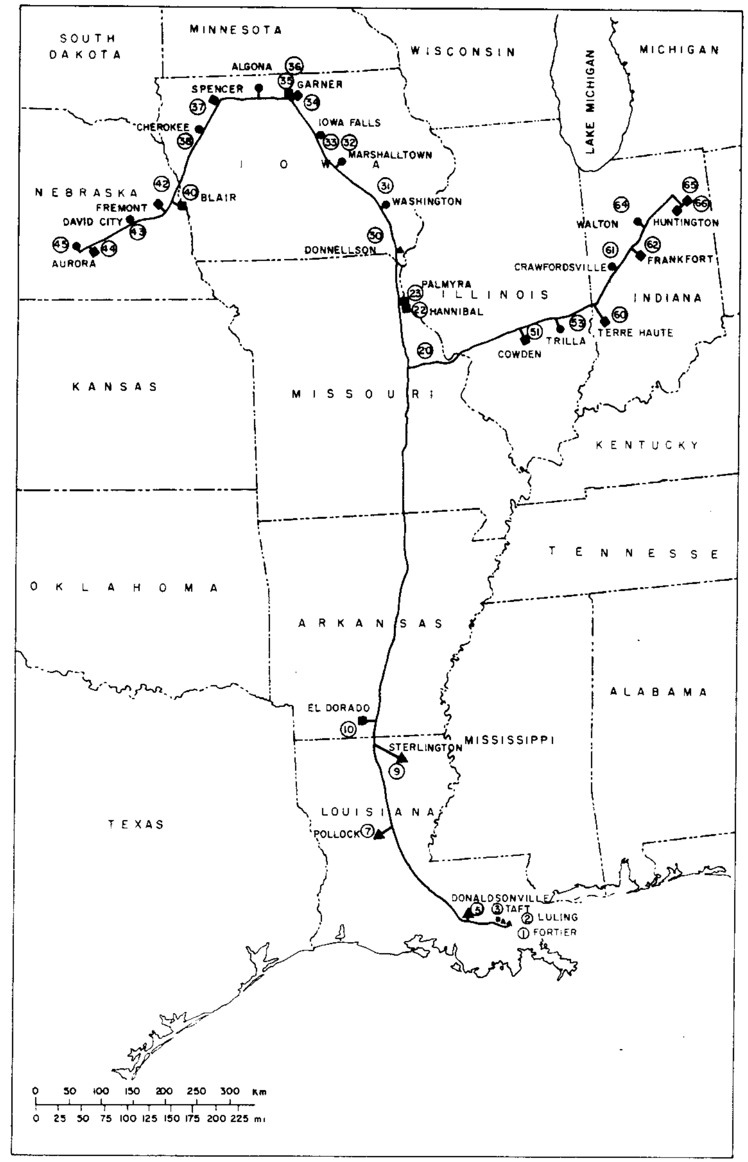
Ammonia Distribution

Ammonia Storage

-14.1 wt% Hydrogen

-15.5 psia at –27°F

-215 psia at 86°F



Hydrocarbon Liquid Transport Fuels Without Greenhouse Effects

Large carbon fluxes to the atmosphere

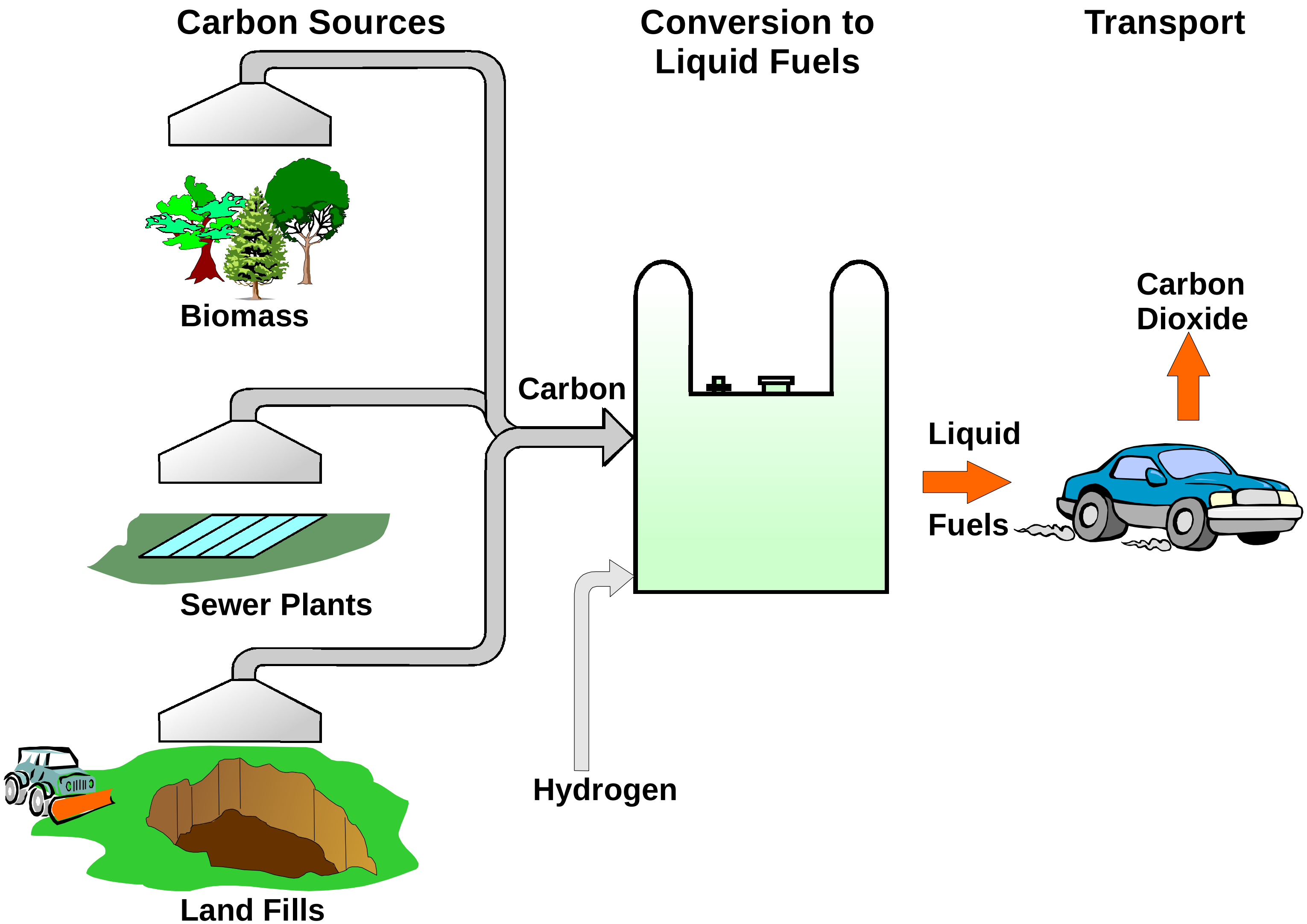
Intercept fluxes to atmosphere and add hydrogen to yield liquid fuels

No change in the carbon flux to atmosphere

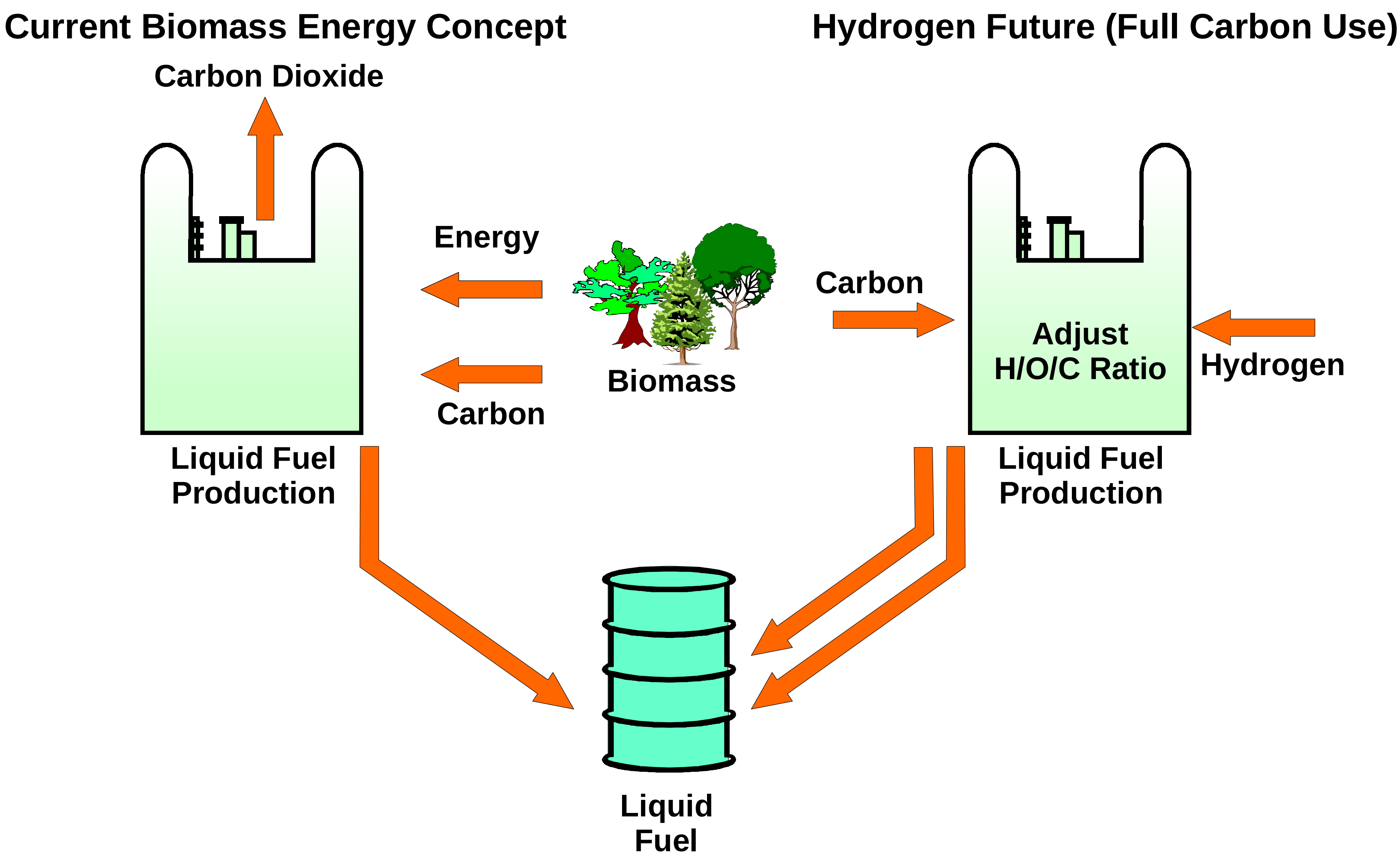
Liquid Hydrocarbon Fuels Have Advantages and Liabilities

- **Liquid fuels are easy to store and transport; but there are liabilities**
  - **Greenhouse effect**
  - **Dependence on foreign supplies**
- **Solution—produce custom liquid fuel**
  - **Intercept carbon flux to atmosphere**
    - **Carbon used to make fuels**
    - **Existing carbon flux to the atmosphere routed through vehicles to atmosphere**
  - **Combine carbon with hydrogen to make clean liquid fuels**

Intercept Carbon Fluxes for Liquid Fuels – An Alternative To Carbon Sequestration



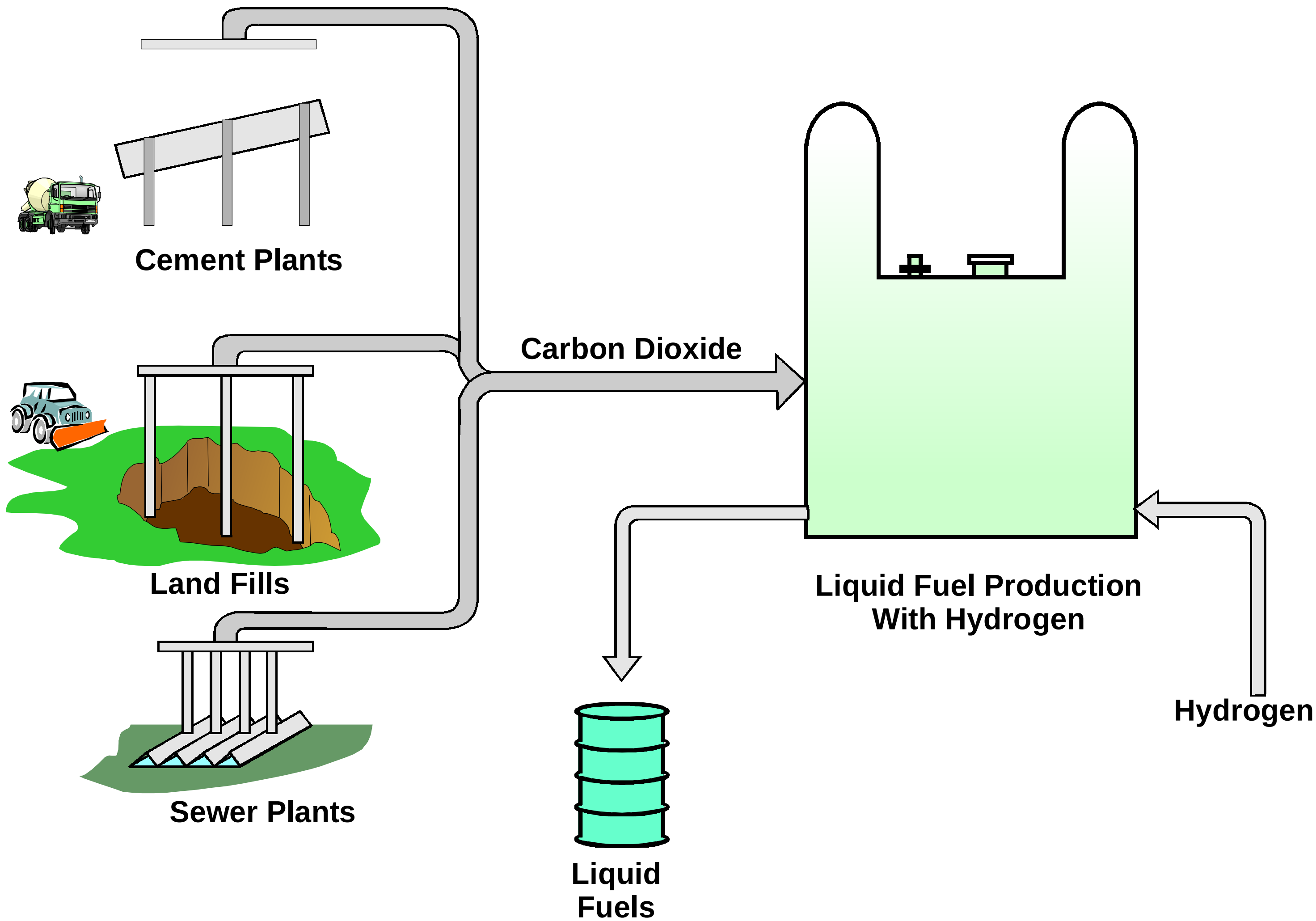
Liquid Fuels From Biomass



Liquid Fuels From Biomass

- **Current biomass fuels approach**
  - **Biomass used for two purposes in fuels plants**
    - **Carbon and hydrogen source**
    - **Energy source**
  - **Two exit streams from biomass fuel plant**
    - **Liquid fuel (product)**
    - **Carbon dioxide (waste)**
- **Hydrogen biomass approach**
  - **Biomass: carbon source first, energy second**
  - **Biomass and hydrogen→liquid fuels**
  - **Increase the fuel produced per unit of biomass**

Hydrogen-Rich Liquid Fuels From Intercepted Carbon Dioxide: "Unlimited" But Higher Energy Cost



Liquid Fuels From Carbon Dioxide

- **Intercept carbon dioxide fluxes going to the atmosphere**
  - **Sewer plants**
  - **Incinerators**
  - **Municipal land fill**
- **Carbon dioxide plus hydrogen → liquid fuel**
  - **Many production options (Some methanol produced by this route)**
  - **No added carbon dioxide to atmosphere (Carbon–dioxide flux routed through vehicles)**
  - **Higher energy cost than biomass-hydrogen route**

Conclusions

- **A hydrogen economy can be in many forms**
  - **Hydrogen-fueled (baseline)**
  - **Ammonia (vehicles)**
  - **No-greenhouse liquid fuels (vehicles)**
- **The future is uncertain—it is risky to bet that all barriers to one hydrogen future will disappear**
- **A portfolio of hydrogen futures are needed to assure program success**

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HYDROCARBON LIQUID TRANSPORT FUELS WITHOUT GREENHOUSE EFFECTS
(An alternative hydrogen future)

An alternative path for the world is proposed that allows full use of liquid hydrocarbon fuels for transportation but does not alter atmospheric carbon dioxide (CO_2) levels. Hydrogen (H_2) from solar, nuclear, and other nonfossil sources is used to create H_2-rich hydrocarbon transportation fuels. The carbon for these fuels comes from intercepting large carbon streams that will ultimately reach the atmosphere as CO_2. Because these CO_2 fluxes are going to be released to the atmosphere under any circumstances, the process of capturing the carbon, converting it to fuel, and then cycling the resultant fuel through transportation vehicles does not increase atmospheric CO_2 levels.

This approach is an alternative H_2 future for transport vehicles. It requires improvements in H_2 production techniques and massive increases in H_2 production; however, it does not require breakthroughs in H_2 storage technology for the vehicle. A transition pathway and two carbon sources have been identified.

Carbon-saver fuels (near term and transition; low net carbon-dioxide emissions). With this approach, H_2 is added to crude oil to maximize the H_2-to-carbon ratio of the fuel. Some crude oils have H_2-to-carbon ratios as low as 0.8. This must be increased to >1.5 to produce gasoline. The H_2-to-carbon ratio could be increased to >2 with more gasoline per barrel of oil. Currently, lower-value fractions of the oil are used to make H_2 for the conversion process. This produces large CO_2 releases at the refinery.

Augmented biomass (zero net carbon dioxide emissions). Hydrogen is added to biomass to produce a liquid fuel with the maximum H_2-to-carbon ratio. Current approaches to producing liquid fuels from biomass use the biomass as a source of carbon and a source of energy. For example, when biomass is used to make liquid fuels such as alcohol, the alcohol contains less than half of the initial carbon. Of the carbon in the initial biomass, half or more is released as CO_2 or indirectly as CO_2 with decay of the biomass (dead bugs) at the end of the conversion process. If biomass is considered first as a carbon source and second as an energy source, H_2 and biomass can be converted to liquid fuels with far larger quantities of liquid fuels per unit of biomass. In a world that may have 10 billion people by the end of the century, biomass may become a scarce resource. Therefore, the output of liquid fuels per unit of biomass should be maximized.

Carbon dioxide fuels (zero net carbon dioxide emissions). Concentrated CO_2 streams are intercepted as they go to the atmosphere (from sewer plants, incinerators, cement plants, etc.) and converted to liquid fuels with a maximum H_2-to-carbon ratio. In this context, Iran is currently constructing a world-class methanol plant where H_2 from natural gas and CO_2 will be combined to produce methanol, a potential liquid fuel. In this particular case, combining available CO_2 from other operations and H_2 reduces plant size compared with producing methanol from the traditional process (H_2 and carbon monoxide). Other technical options exist with different fuel products.

These alternative H_2 futures should be investigated. They provide a backup to the mainline concept of an H_2 future that does not require (1) as great a leap in technology or (2) as many changes to the transport system. A portfolio of H_2 options provides a higher assurance of program success. These alternative systems would provide stepping-stones to build an H_2 infrastructure that enables ultimate deployment of a transport system that directly uses H_2.