Coal Conversion Technology

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Timeline of Coal Conversion Technologies

Late 1800s/ early 1900s: Coal-derived "town gas" used in the United States

1912: Sabatier and Senderens win Nobel Prize in Chemistry for work on catalytic conversion of hydrogen and carbon monoxide

1920s: German scientists Fischer and Tropsch pass coal-derived syngas over catalyst to produce hydrocarbons

1944: Germany produces 124,000 bpd of liquids from coal

1950s: Sasol of South Africa begins using F-T process to convert coal to fuels and chemicals

1970s/1980s: U.S., UK, Japan, and Germany respond to oil supply and price shocks by initiating major CTL development efforts

1984: Great Plains Synfuels Plant commences operation

2008: Environmental Focus on R&D for improved coal conversion processes

Today, Sasol produces 150,000 bpd of fuels from coal

. . . 1900 . . . . 1910 . . . . 1920 . . . . 1930 . . . . 1940 . . . . 1950 . . . . 1960 . . . . 1970 . . . . 1980 . . . . 1990 . . . . 2000 . . . . 2010 . . .

Coal Conversion Processes

- Carbonation and Pyrolysis
  - Low severity (mild gasification)
  - High temperature
- Direct Liquefaction
  - One-stage reactor technology
  - Two-stage reactor technology
  - Co-processing
  - Hybrid
- Indirect Liquefaction
  - Gas reactors
  - Slurry reactors

Coal Liquefaction Technologies

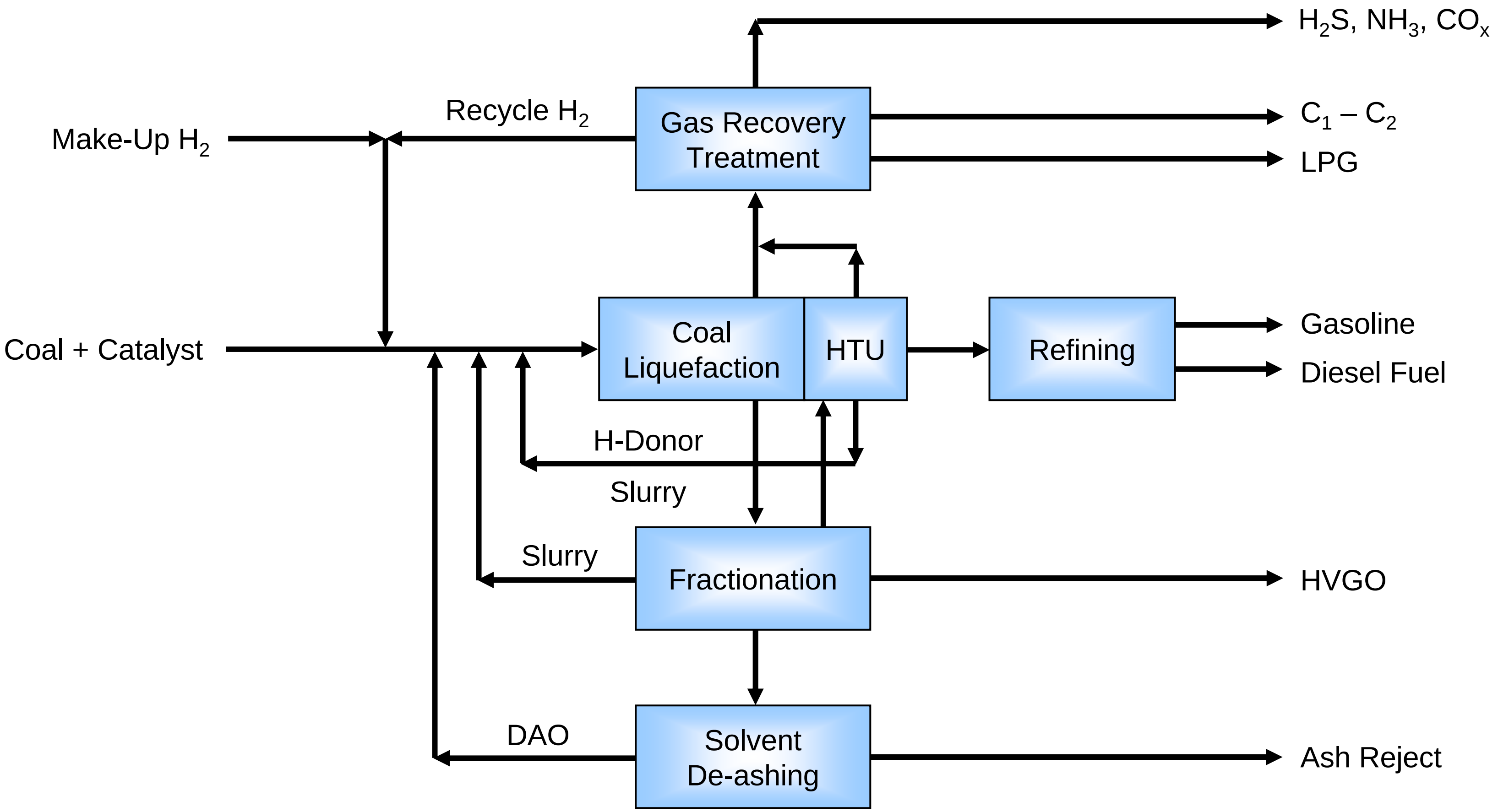
Mild Pyrolysis	Single-Stage Direct Liquefaction	Two-Stage Direct Liquefaction	Co-Processing and Dry Hydrogenation	Indirect Liquefaction
• Liquids from Coal (LFC) Process – Encoal • Coal Technology Corporation • Univ. of North Dakota Energy and Environmental Center (EERC)/AMAX R&D Process • Institute of Gas Technology • Char, Oil Energy Development (COED)	• Solvent Refined Coal Processes (SRC-I and SRC-II) – Gulf Oil • Exxon Donor Solvent (EDS) Process • H-Coal Process – HRI • Imhausen High-Pressure Process • Conoco Zinc Chloride Process • Kohleoel Process – Ruhrkohle • NEDO Process	• Consol Synthetic Fuel (CSF) Process • Lummus ITSL Process • Chevron Coal Liquefaction Process (CCLP) • Kerr-McGee ITSL Work • Mitsubishi Solvolysis Process • Pyrosol Process – Saarbergwerke • Catalytic Two-Stage Liquefaction Process – DOE and HRI • Liquid Solvent Extraction (LSE) Process – British Coal • Brown Coal Liquefaction (BCL) Process – NEDO • Amoco CC-TSL Process • Supercritical Gas Extraction (SGE) Process – British Coal	• MITI Mark I and Mark II Co-Processing • Cherry P Process – Osaka Gas Co. • Solvolysis Co-Processing – Mitsubishi • Mobil Co-Processing • Pyrosol Co-Processing – Saabergwerke • Chevron Co-Processing • Lummus Crest Co-Processing • Alberta Research Council Co-Processing • CANMET Co-Processing • Rheinbraun Co-Processing • TUC Co-Processing • UOP Slurry-Catalysed Co-Processing • HTI Co-Processing	• Sasol • Rentech • Syntroleum • Mobil Methanol-to-Gasoline (MTG) Process • Mobil Methanol-to-Olefins (MTO) Process • Shell Middle Distillate Synthesis (SMOS)

Source: "Coal Conversion – A Rising Star," 23rd Int'l Pittsburgh Coal Conference, September 25-28, 2006.

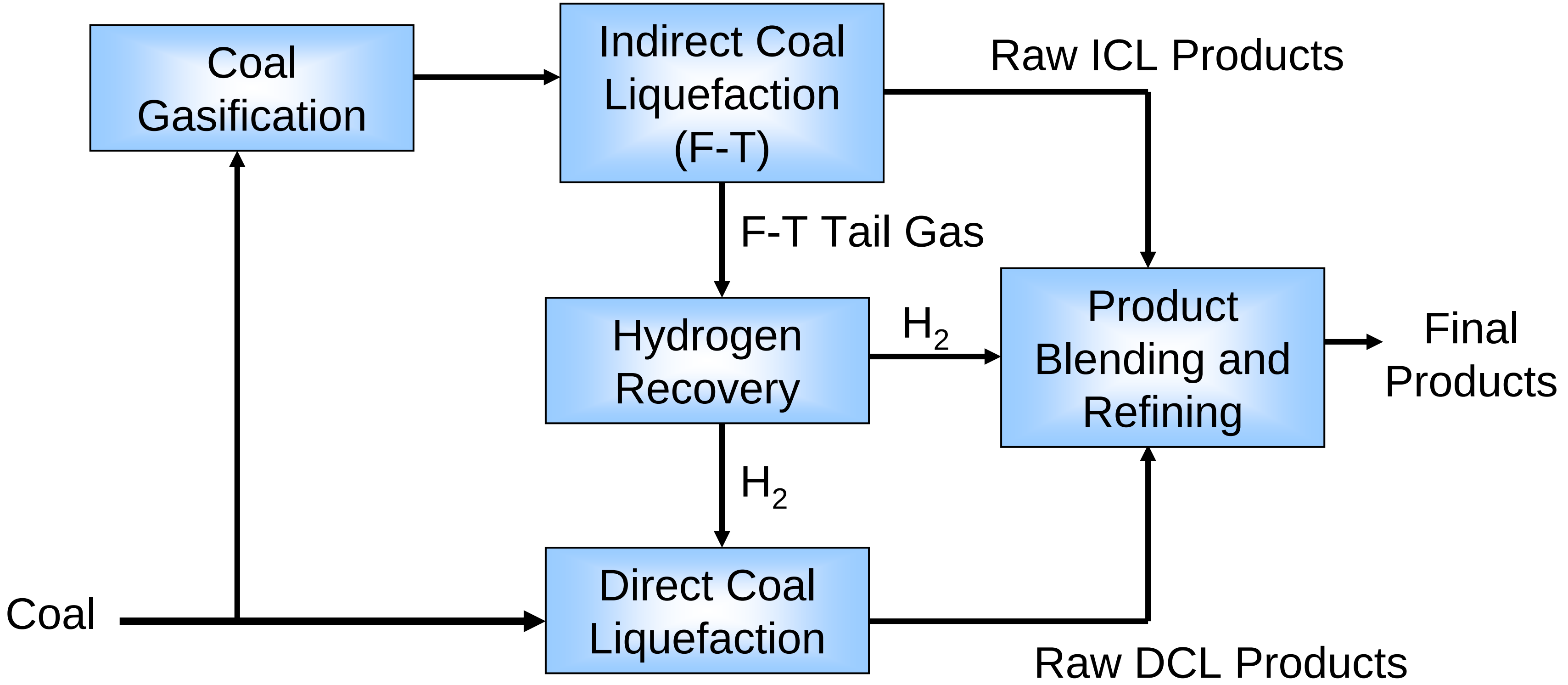
Two Liquefaction Technologies

- Indirect Liquefaction
  - Coal is gasified with oxygen to produce a synthesis gas consisting of carbon monoxide and hydrogen. This gas is cleaned of all impurities, and the clean synthesis gas is sent to a Fischer-Tropsch (F-T) reactor where most of the clean gas is catalytically converted into zero-sulfur liquid hydrocarbon fuels. Carbon dioxide in the tail gas can be captured for subsequent storage, and the unconverted synthesis gas combusted in a gas turbine combined-cycle power plant to generate electric power.
- Direct Liquefaction
  - Coal is reacted under high temperature and pressure with hydrogen and coal-derived solvent to produce a synthetic crude oil. This synthetic crude, or syncrude, then must undergo substantial upgrading by direct hydrocracking and hydrotreating, to produce acceptable transportation fuels.

Direct Coal Liquefaction Process



Hybrid DCL/ICL Plant Concept



Maturing Direct Coal Conversion

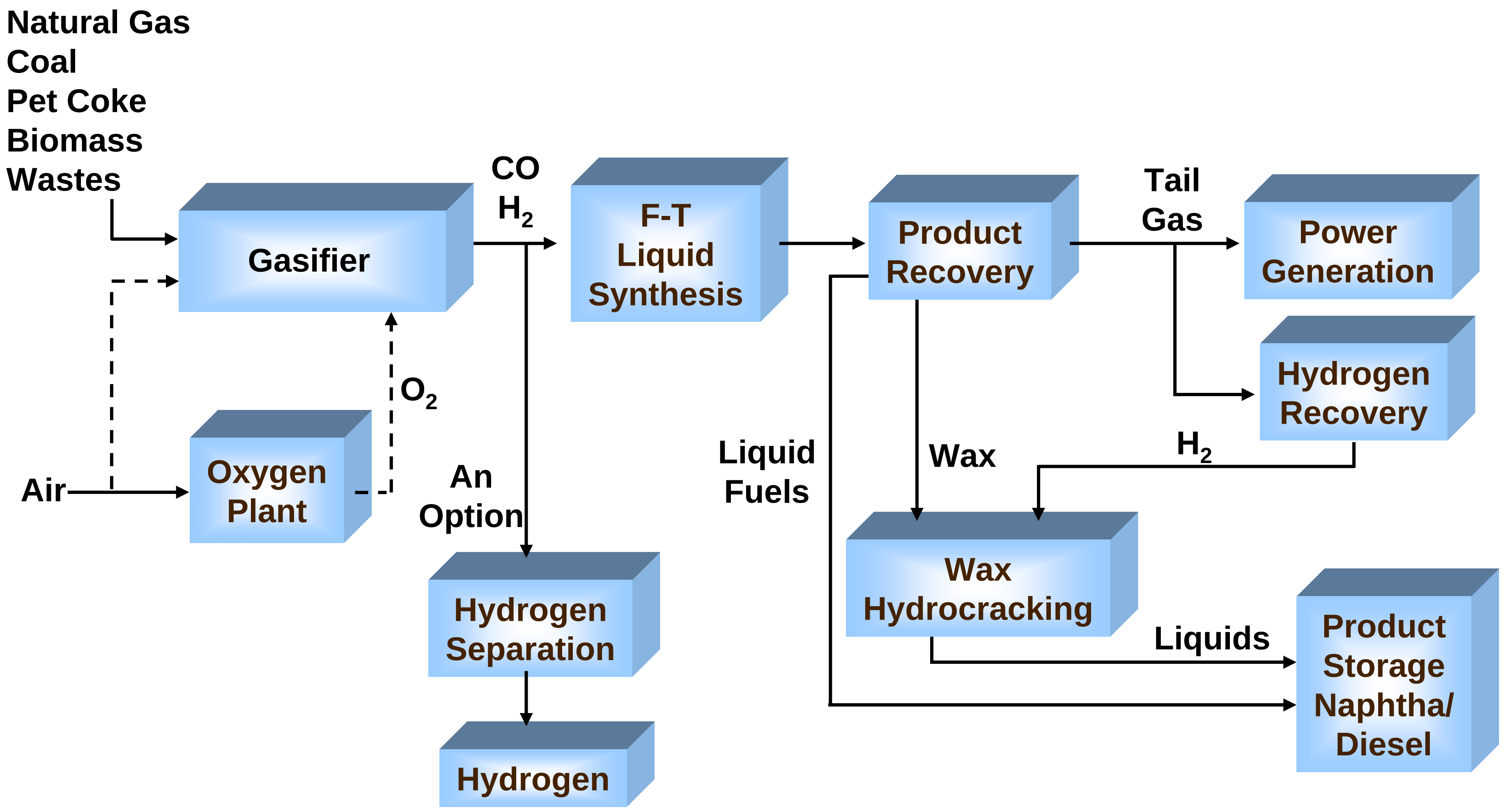
- Originally developed in Germany in early 1900s
- Used to produce military fuel in WWII
- US spent $3.6 billion on DCL from 1975-2000
- Technologies licensed to China in 2002

Lawrenceville, NJ
3 TPD

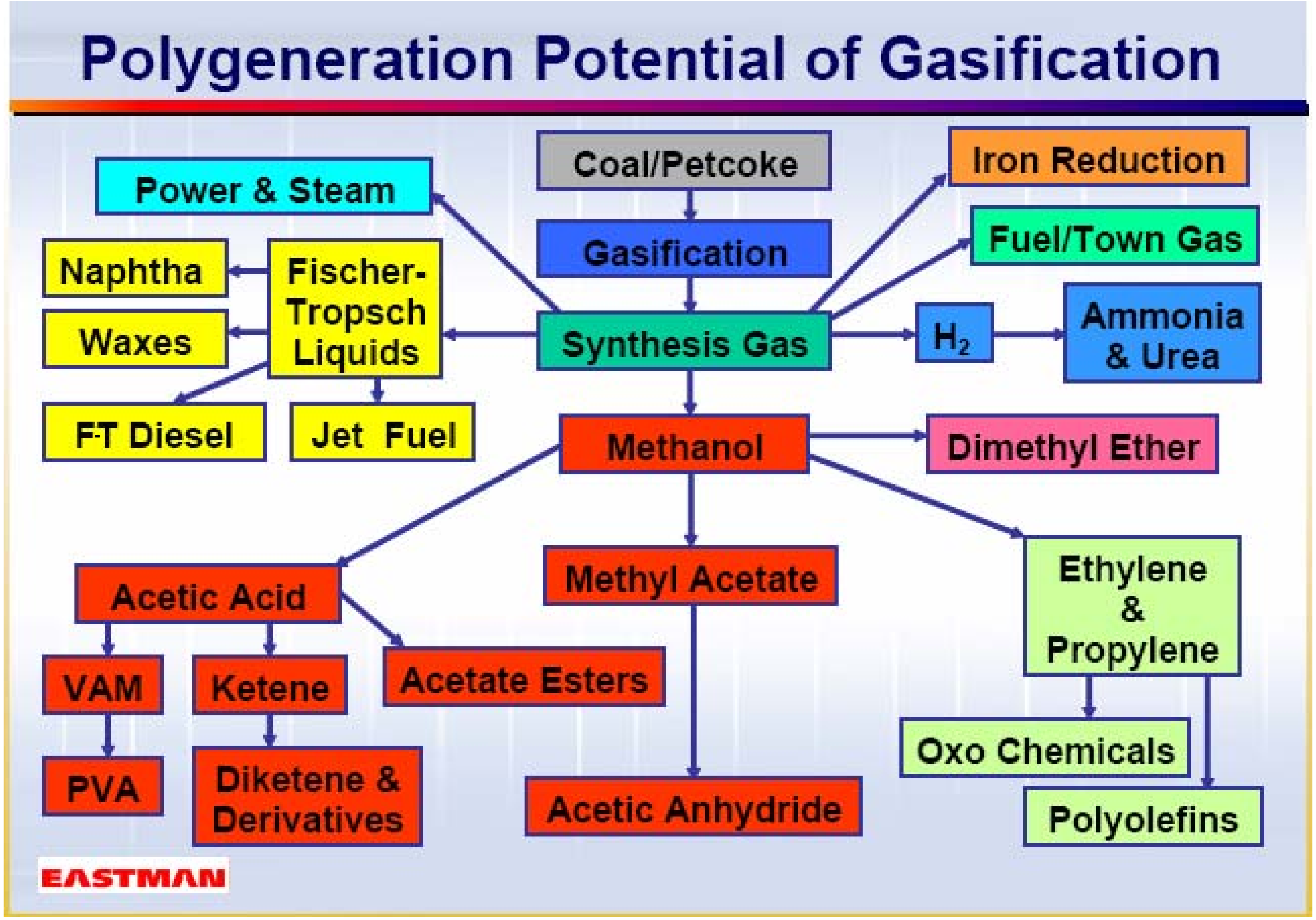
Catlettsburg, KY
250 – 600 TPD

Inner Mongolia, China
4,200 TPD

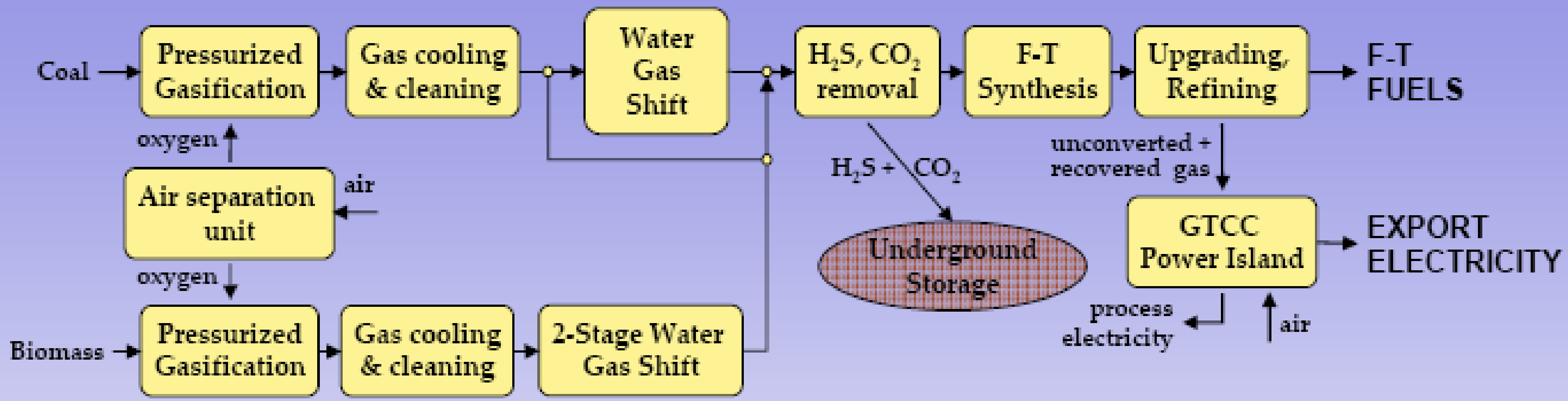
Indirect Coal Liquefaction Overview



Many Possible Products from Syngas



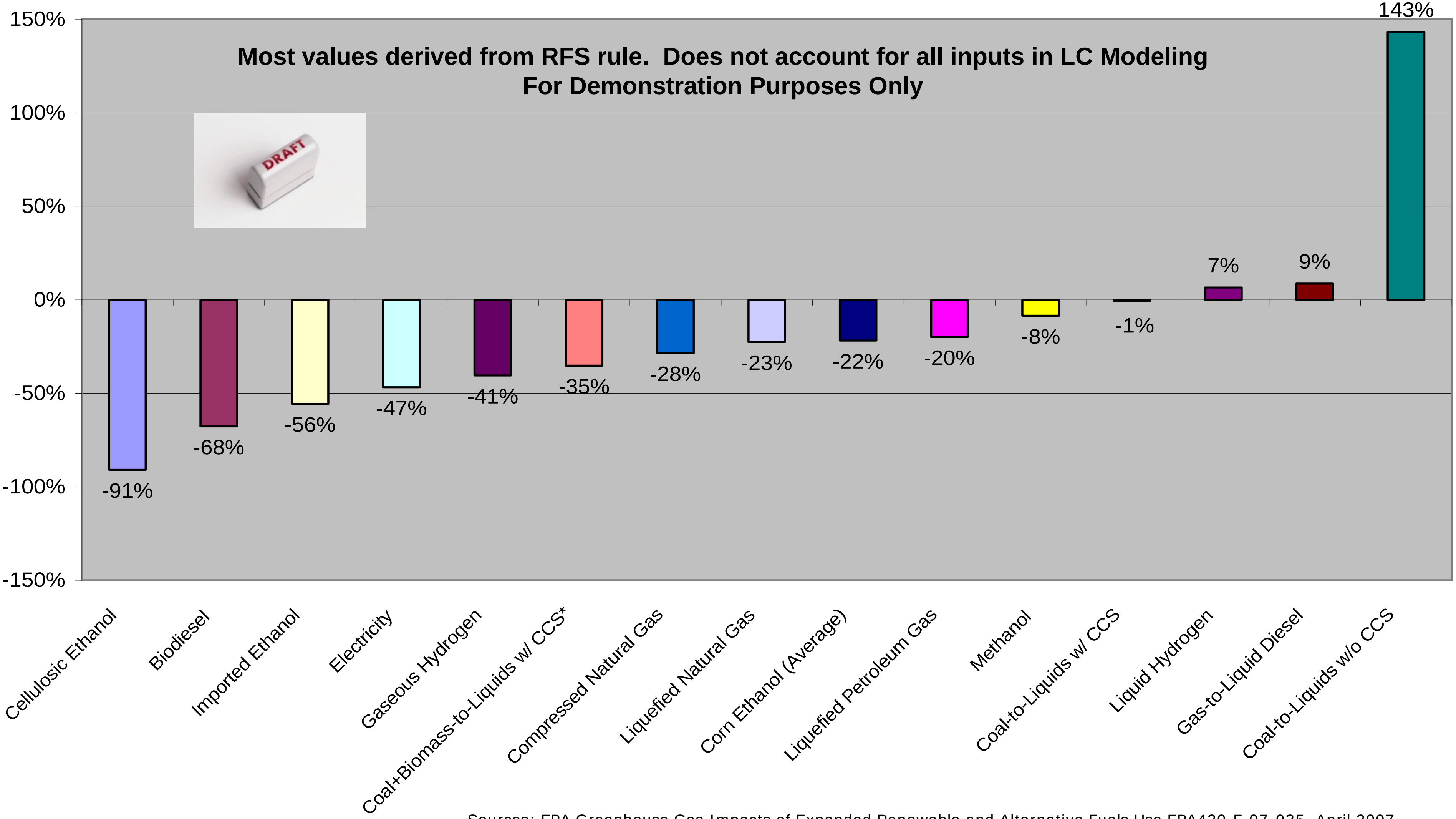
FTL + Electricity from Coal + Biomass with CCS – Separate Parallel Gasifiers



Source: Robert H. Williams, Princeton Environmental Institute, Princeton University – Washington Coal Club Presentation, July 2007

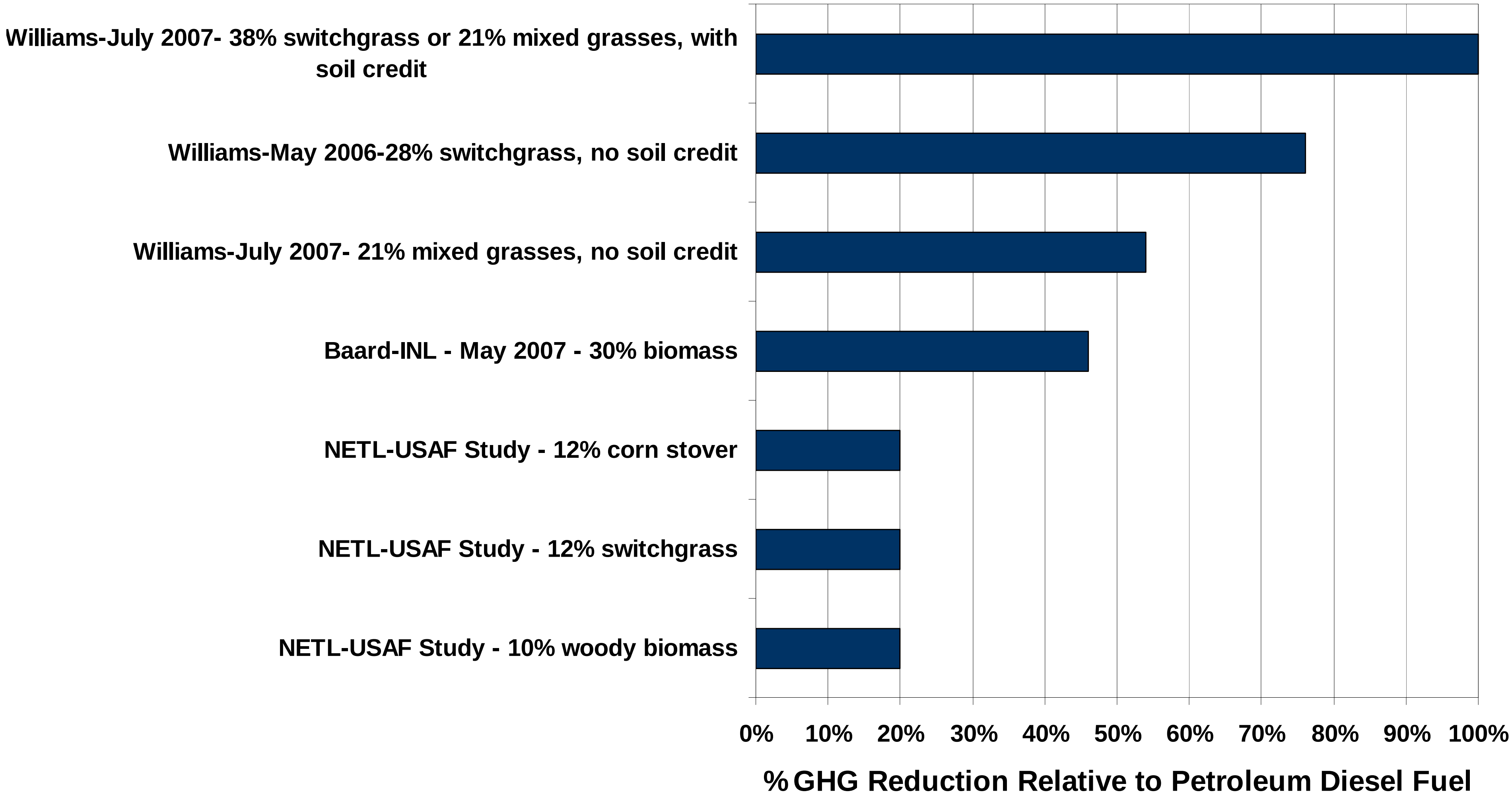
- In this configuration, hydrogen (H_2) is made from biomass via gasification to compensate for the H2 deficit in coal-derived synthesis gas for manufacturing FTL
- Co-processing biomass and coal in this manner exploits simultaneously
  1. The scale economies of coal energy conversion systems
  2. The low cost of coal as a feedstock
  3. The negative CO_2 emissions of photosynthetic CO2 storage

Differentiating Between Fuels on a GHG Basis
Percent Change in GHG Emissions



Sources: EPA Greenhouse Gas Impacts of Expanded Renewable and Alternative Fuels Use EPA420-F-07-035, April 2007
*Preliminary results from National Energy Technology Laboratory (NETL) 10% biomass by energy

Percent Reduction of GHG Emissions on a Well-to-Wheels Basis through Domestic CBTL Production Compared to Petroleum Diesel Fuel (Various Studies)



Notes: Percent of biomass incorporated into plant is shown on a weight basis except for the Williams data which is on an energy basis. All data shown also include carbon capture and storage.

Environmental Considerations

- Air
  - Criteria Emissions
    - » Sulfur
    - » Nitrogen
    - » Particulates
    - » Mercury

    } Control Technology Exists

    Currently used to meet all existing performance criteria
  - Global Warming
    - » Carbon Dioxide – Control Technology Currently Exists through Carbon Capture and Storage Systems

      Advanced technology being developed in major RD&D effort; CBTL
- Water
  - System Design – Maximum Air Cooling
  - Recycle to Extinction
  - Zero Discharge

CTL Technology – Economics Remain Key Issue

- Conceptual plant designs estimate $3.5–6.0 billion required for initial 50,000-bpd plants (Capital cost = $70–120K/daily barrel)
- Plants may be profitable with crude oil price between $45–70/bbl with carbon storage (carbon storage estimated to account for $4/barrel of the required selling price)
- Higher unit investment costs for pioneer demonstration plants (10,000- to 20,000-bpd plants)
- Difficult to accurately estimate costs since no plants have been built worldwide since the 1980s

Barriers to Coal-To-Liquids

- Technical
  - Integrated operations of advanced CTL technologies have never been demonstrated
- Economic
  - Uncertainties about future world oil production
  - High capital and operations costs
  - Investment risks
  - Energy price volatility
- Environmental
  - CO_2 and criteria pollutant emissions
  - Expansion of coal production and requisite infrastructure (railroads, railcars, etc.)
  - Water use
- Commercial Deployment
  - Competition for critical process equipment, engineering, and skilled labor
  - Who would take the lead in commercial deployment? Part power part liquid fuels
- Social
  - NIMBY and public resistance to coal use