National Renewable Energy Laboratory
Innovation for Our Energy Future

Biofuels Beyond Ethanol

Public Meeting of the Biomass Research and Development Technical Advisory Committee

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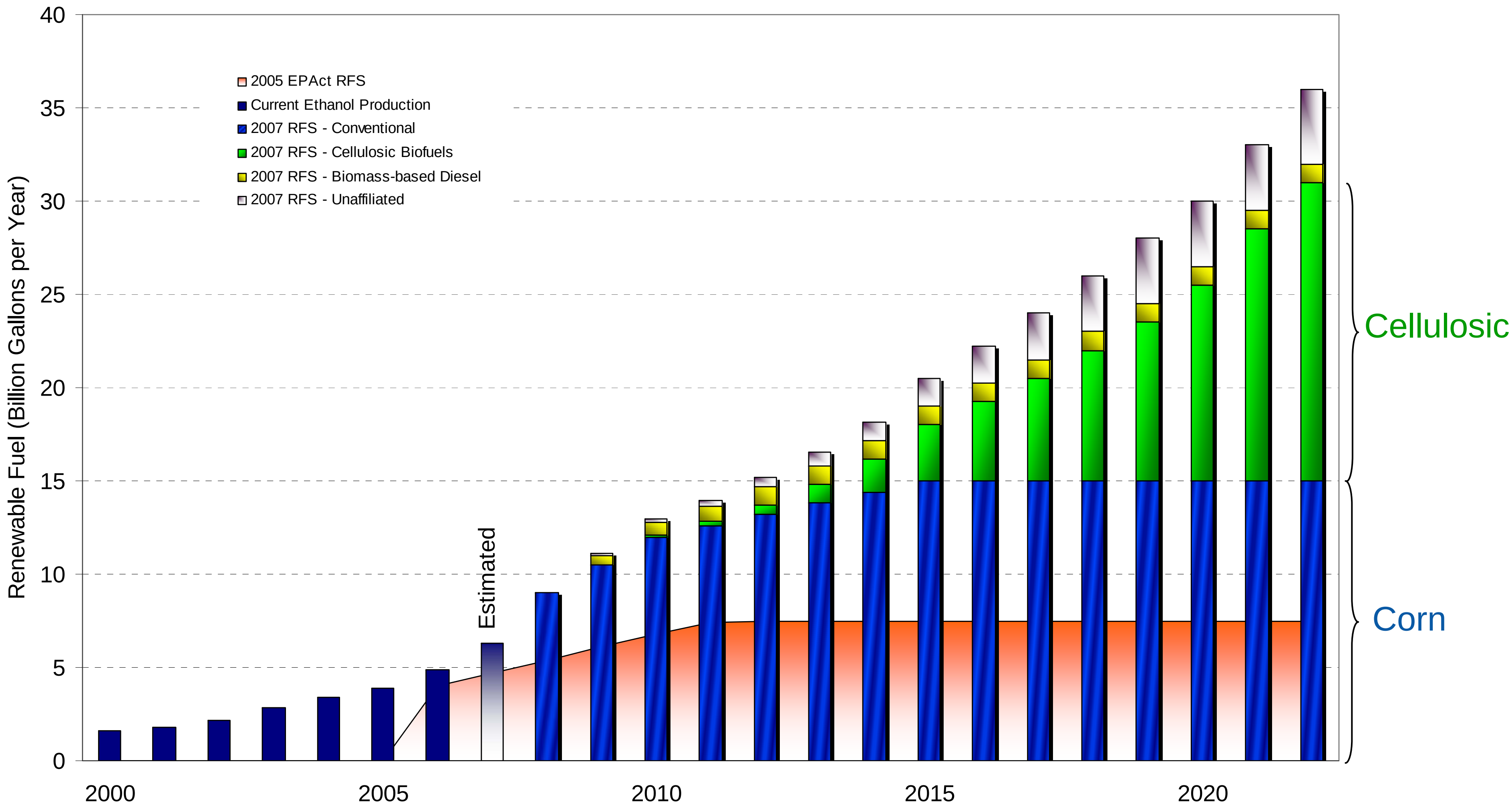
Energy Independence and Security Act 2007



Cellulosic Biofuels do not specifically say ethanol

Beyond Ethanol

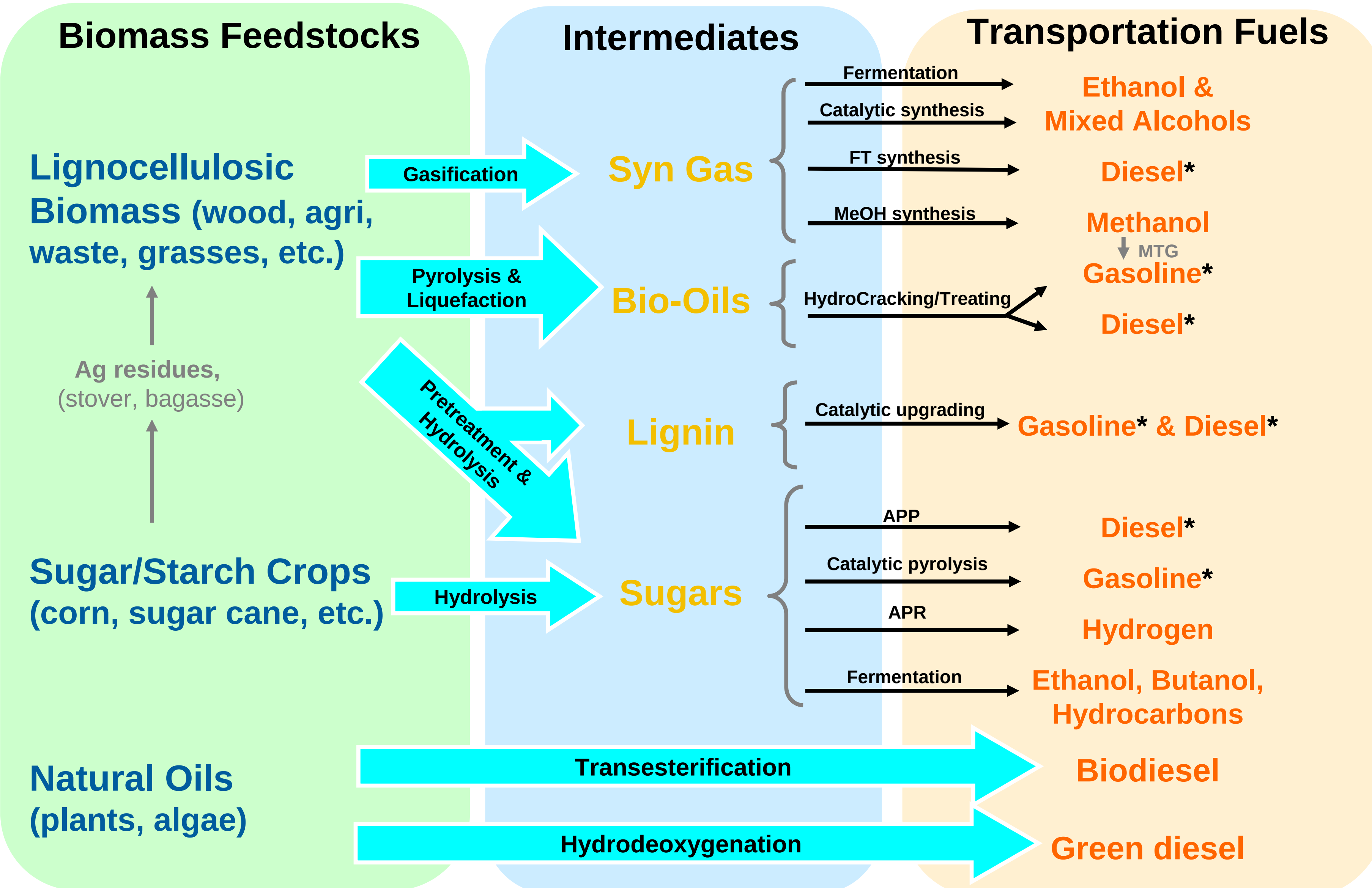
Advantages of ethanol

- Corn and sugar cane ethanol are commercial today
- Greenhouse gas savings
- Energy security
- Years of cellulosic ethanol research
- Oxygenate, blends with gasoline at low concentrations

Limitations of ethanol

- Lower energy density
- Corrosive
- Mixes with water
- Only partially compatible with existing infrastructure

Biofuels Transportation Options

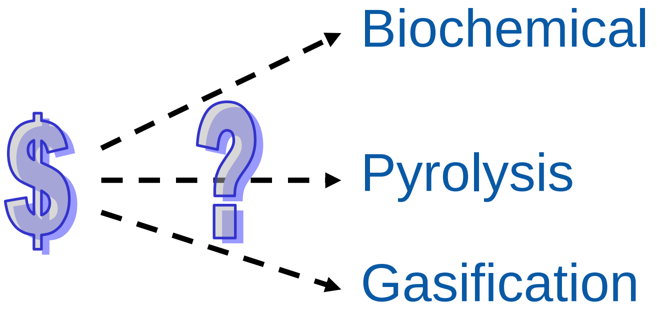


* Blending Products

Academic/Industrial/Government Lab Study

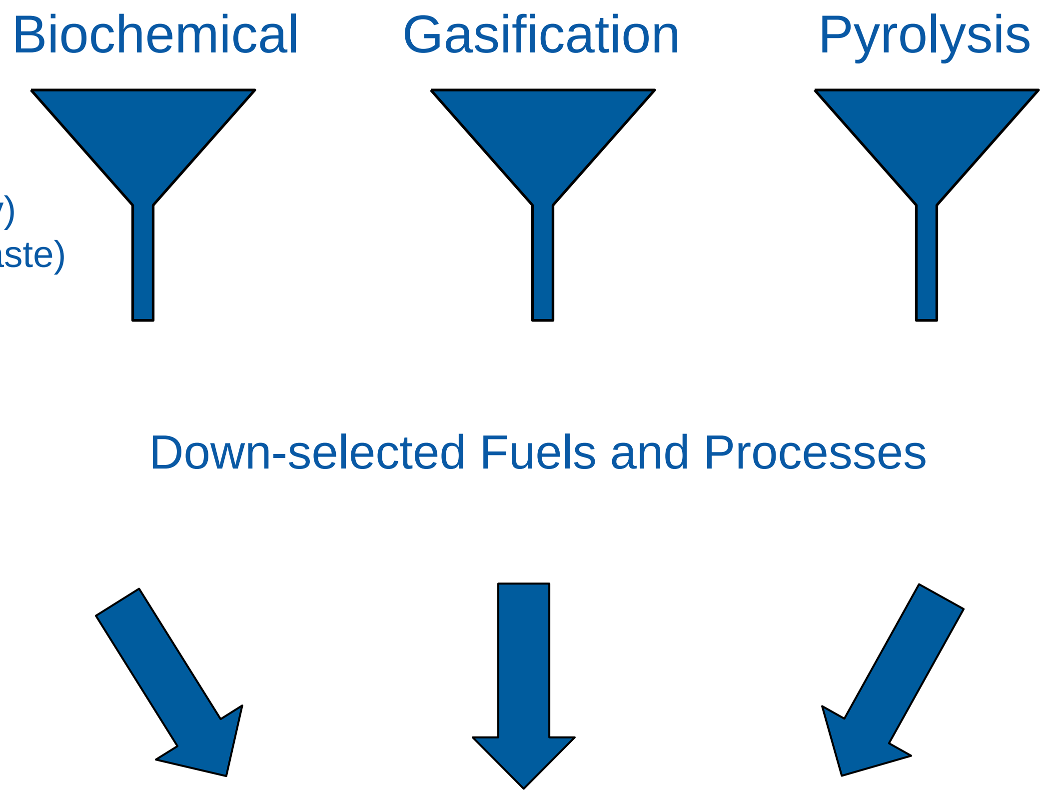
NREL ConocoPhillips IOWA STATE UNIVERSITY

ConocoPhillips



- 5-8 year timeframe
- What technologies?
- What fuels?
- Use common basis/assumptions to compare

Methodology

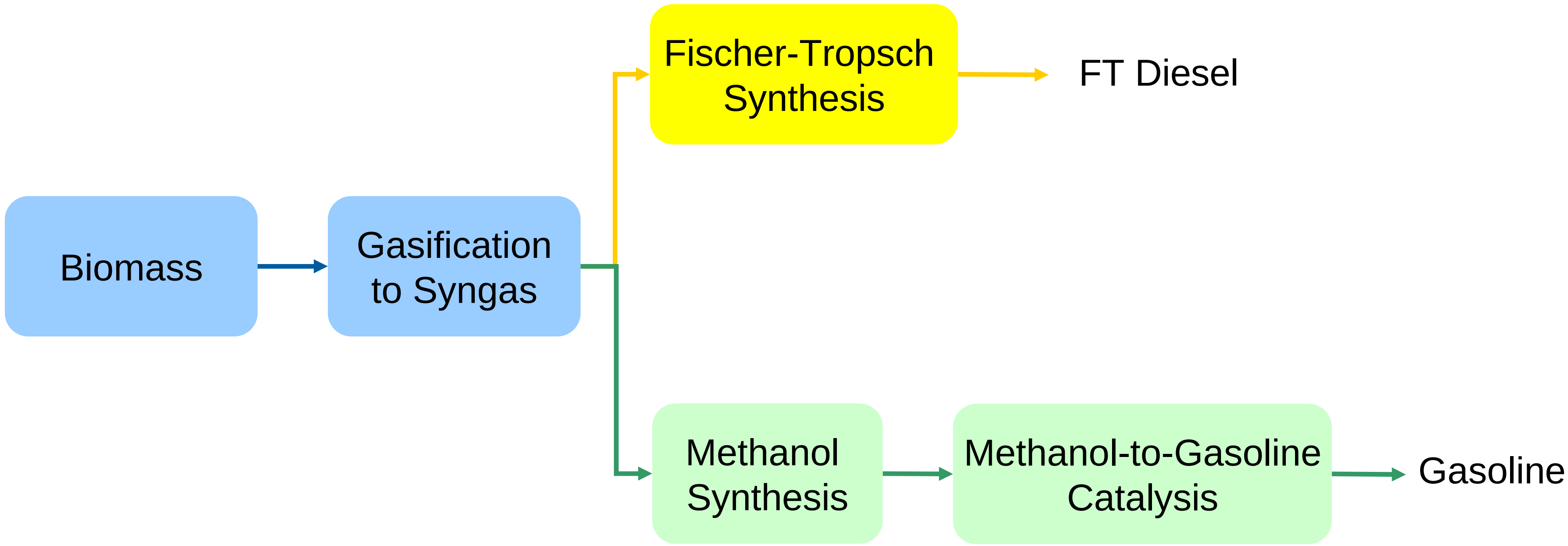


Step 1: Down select Matrix
Economic (costs, risk, return)
Technology (yield, maturity, complexity)
Sustainability (GHG, water, toxicity, waste)
Fuel quality (compatibility, emissions)

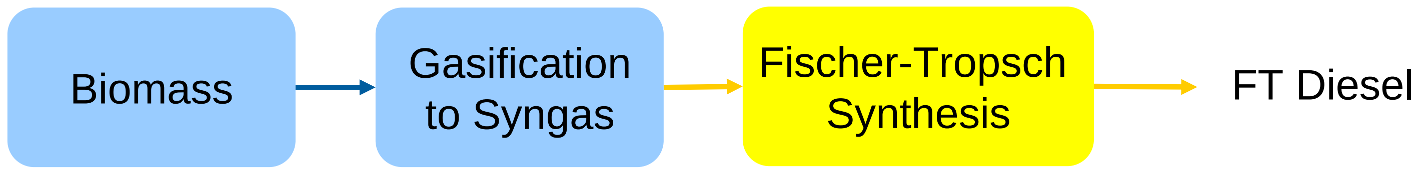
Step 2: Models
Develop mass/energy balance models and financial models based on **common** assumptions

Step 3: Evaluation
Using models, evaluate down-selected technologies based on economic, sustainability, other metrics

Gasification Fuels



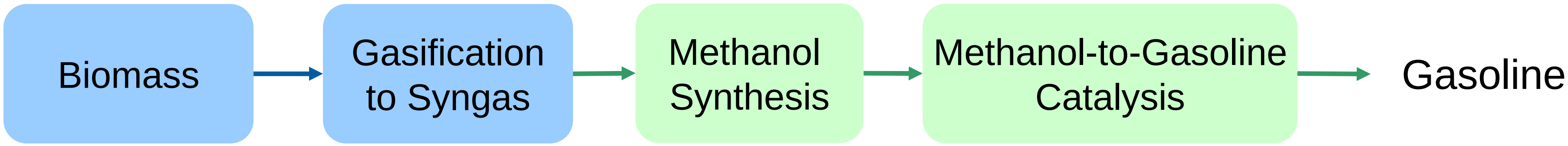
Fischer-Tropsch (FT) Diesel



	Rank	Comments
Fuel compatibility	Good	Compatible with infrastructure, engines
Level of Technology	Demo	•Proven for natural gas (Shell), coal (Sasol). •Economics more challenging with biomass
Techno-economic Analysis	In progress	•COP/ISU/NREL-Early 2009 •Challenges include gas cleanup, scale-up
Sustainability	Good	•50-85% GHG savings over gasoline[1,2,3] •Electricity displacement

1. GREET 1.8b
2. Marano and Ciferno, *Life-cycle greenhouse-gas emissions inventory for Fischer-Tropsch Fuels.* 2001
3. Gielen and Unander. *Alternative fuels: An energy technology perspective.* 2005. Use GREET value of 4,125 BTU/mile

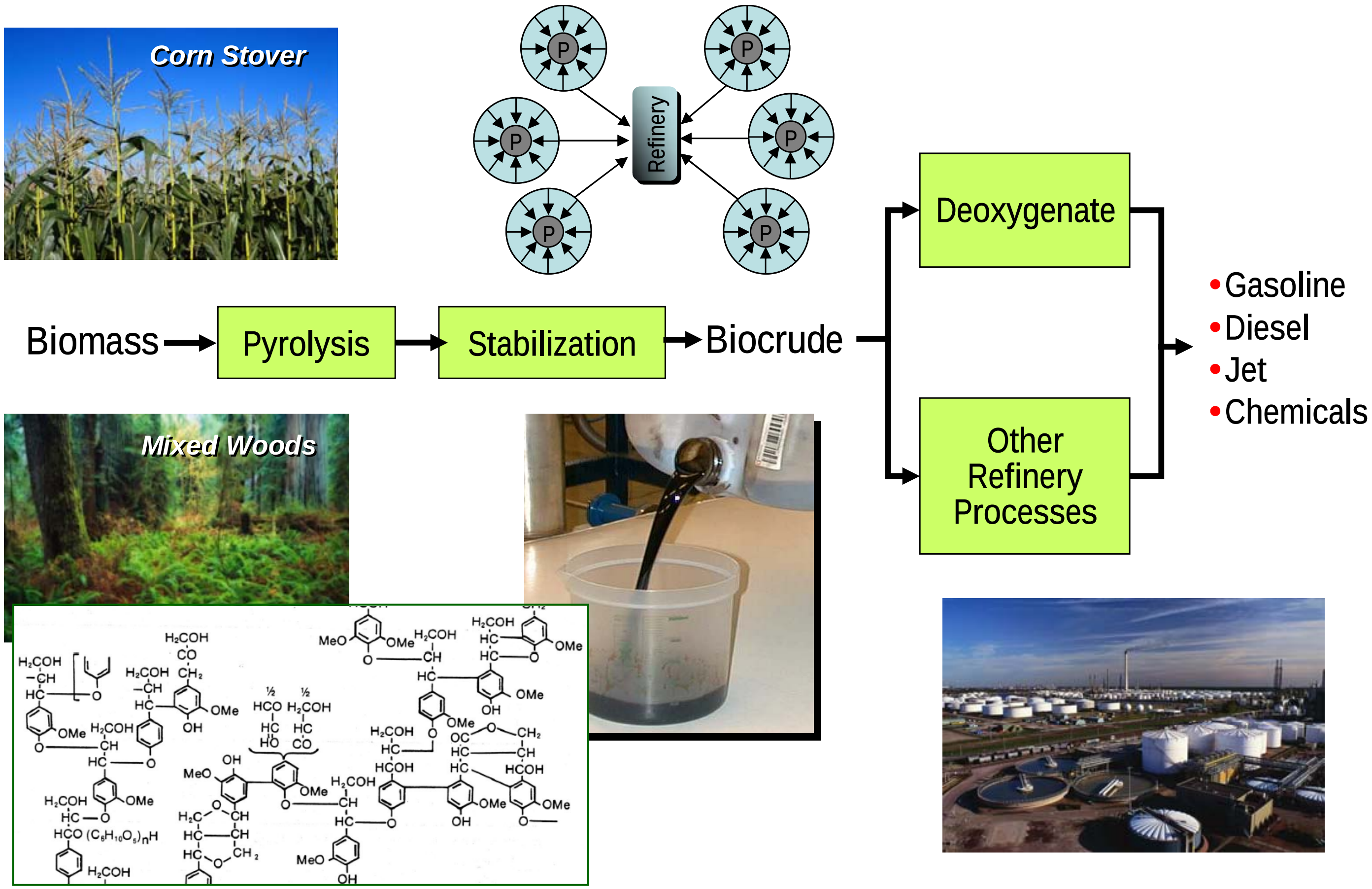
Methanol to Gasoline (MTG)



	Rank	Comments
Fuel compatibility	Good	•Compatible with infrastructure, engines •Aromatic hydrocarbon may be too high
Level of Technology	Demo	•Process developed in 1970s (Mobil) •Natural gas MTG plant in New Zealand in 1985. Produced gasoline until 1997. Switch to methanol.
Techno-economic Analysis	In progress	•COP/ISU/NREL-Early 2009 •NREL process model forthcoming
Sustainability	Good	75% GHG reduction over gasoline[1]

1. GREET 1.8b. MTG LCA data based on scaling methanol processes by energy content of output fuels in MTG process. Source: Probstein and Hicks. *Synthetic Fuels*

Pyrolysis



Holmgren et al. *Converting Pyrolysis Oils to Renewable Transport Fuels: Processing Challenges and Opportunities.* January 2008.

Pyrolysis Bio-Oil as Refinery Feed

Bio-oil is composed of many oxygenated organic chemicals with water-miscible and oil-miscible fractions.

- Dark brown, mobile liquid
- Combustible
- Not 100% miscible with hydrocarbons
- Modest heating value ~17 MJ/kg
- High density ~1.2 kg/l
- Acidic, pH ~2.5
- Pungent odor
- "Ages," viscosity increases with time

Based on research performed at NREL (1990–2000).

Pyrolysis

	Rank	Comments
Fuel compatibility	Good	Pyrolysis oil can be upgraded to produce diesel and gasoline
Level of Technology	Lab	•Pyrolysis oil production is well-established. •Challenges are reducing char, oil standards, cheap stabilization of oil •UOP, ConocoPhillips interested
Techno-economic Analysis	Several done, in progress	•UOP/PNNL/NREL: ($1.70-$1.90/gal gasoline equivalent) •NREL (Wood) •Pacific Northwest National Labs •COP/ISU/NREL-Early 2009
Sustainability	Fair	•40-50% GHG reduction over gasoline (NREL/UOP) •Pyrolysis oil is carcinogenic, acidic

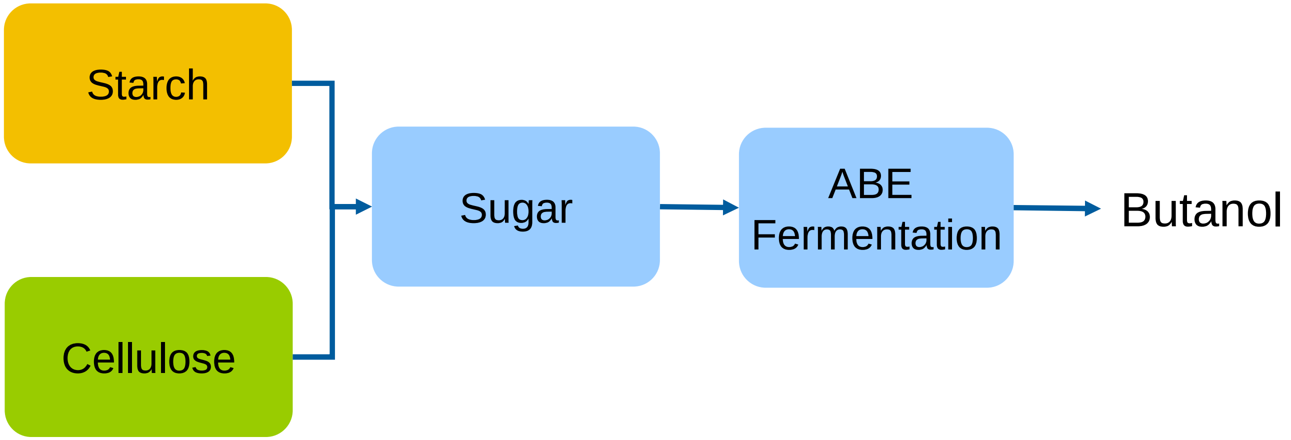
COP/ISU/NREL Plans

- Also looking at cellulosic ethanol
- Reports submit for publication in early 2009
- Currently at technical process modeling stage, moving toward economic analysis

- Selected fuels/technologies based on
  - 5-8 year timeframe
  - Organization background/expertise
  - Publicly available information

- Other fuels not in COP/ISU/NREL study

Butanol



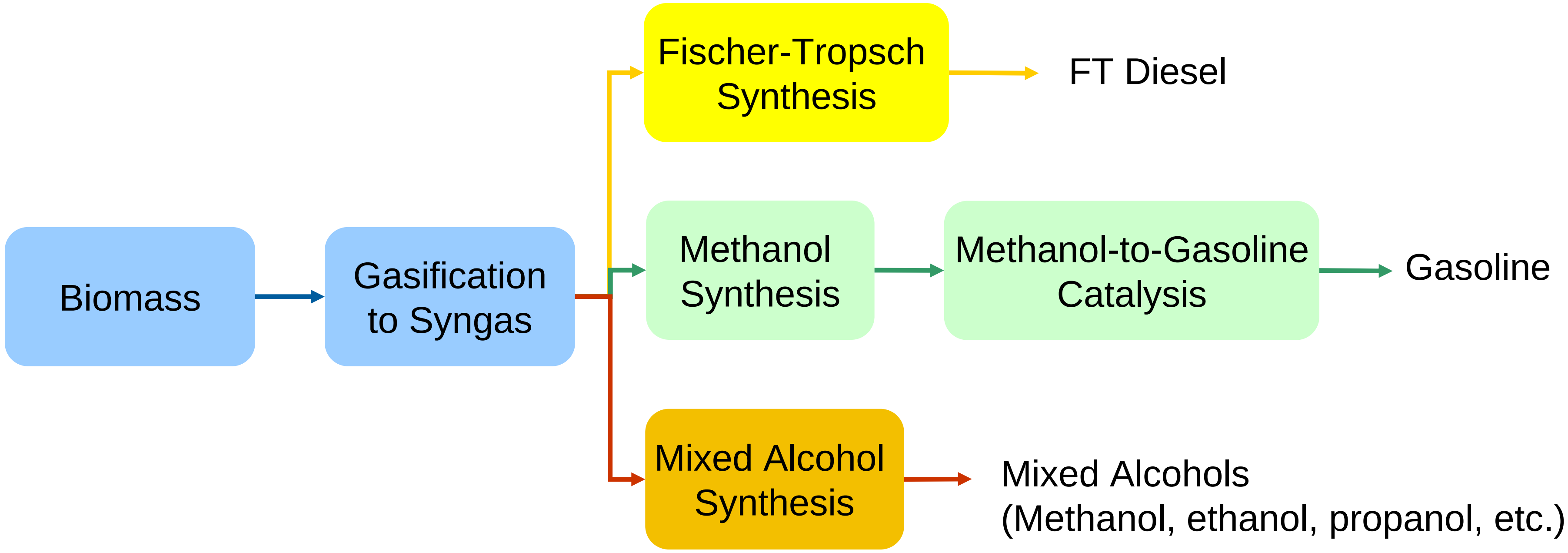
- Butanol
  - Higher energy content than ethanol
  - Claims that existing vehicles could run with little modification
    - Limited testing of claim
  - Does not mix with water. Pipeline compatibility
  - Can be produced in ethanol facilities
  - Can be blended with gasoline or diesel

Butanol

	Rank	Comments
Fuel compatibility	Fair	•Better than ethanol •Claims of being compatible with existing vehicles
Level of Technology	Lab	•BP and DuPont to produce •BP expects butanol faster than cellulosic ethanol •Smaller companies (Gevo, ChemLac Inc.) working on butanol
Techno-economic Analysis	In progress	•NREL Aspen model and economic analysis on butanol from corn starch almost complete. Cellulosic will follow. •Cost, yield issues
Sustainability	Fair	•20-60% GHG reduction over gasoline, depending on allocation for acetone[1] •Corn butanol expected to be similar to corn ethanol

1. Wu, M. et al. *Fuel cycle assessment of corn-based butanol.* 2007.

Mixed Alcohols



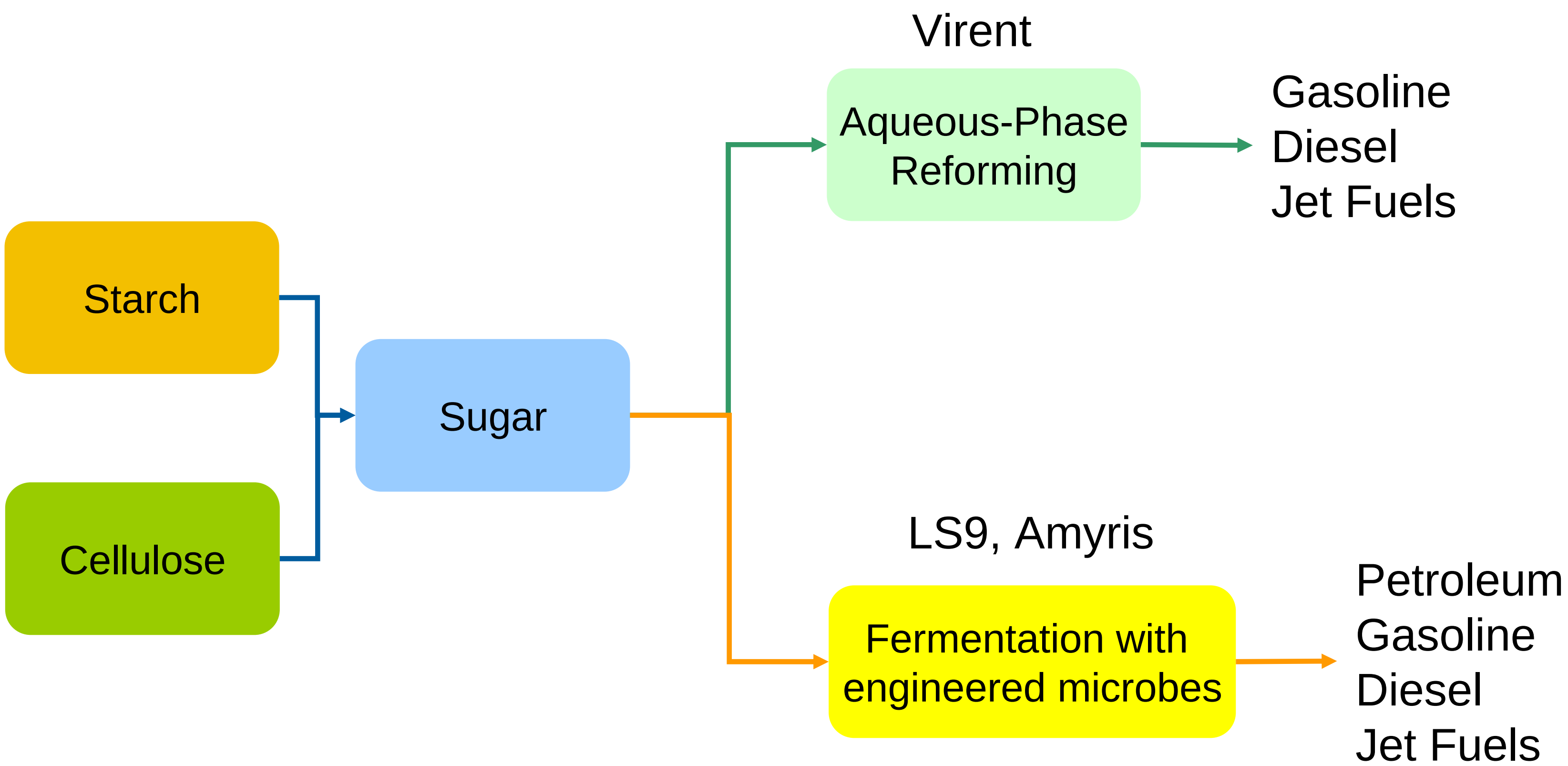
- Mixed Alcohols
  - Higher energy content than just ethanol
  - No distillation (no need to separate out ethanol)
  - Can blend with gasoline

Mixed Alcohols

	Rank	Comments
Fuel compatibility	Poor	Blends with gasoline
Level of Technology	Pilot	•Range Fuels 932 plant is an ethanol from mixed alcohols plant. 20 MGY. (2009 completion) •Abengoa 932 plant (11.4 MGY ethanol)
Techno-economic Analysis	Partly done	•NREL 2007 Thermochemical design report is ethanol from a mixed alcohol design[1] •High catalyst cost
Sustainability	TBD, likely Good	•Thermochemical ethanol being done. •Expect mixed alcohols to be better because of elimination of distillation

1. *http://www.nrel.gov/docs/fy07osti/41168.pdf*

Renewable Alkanes



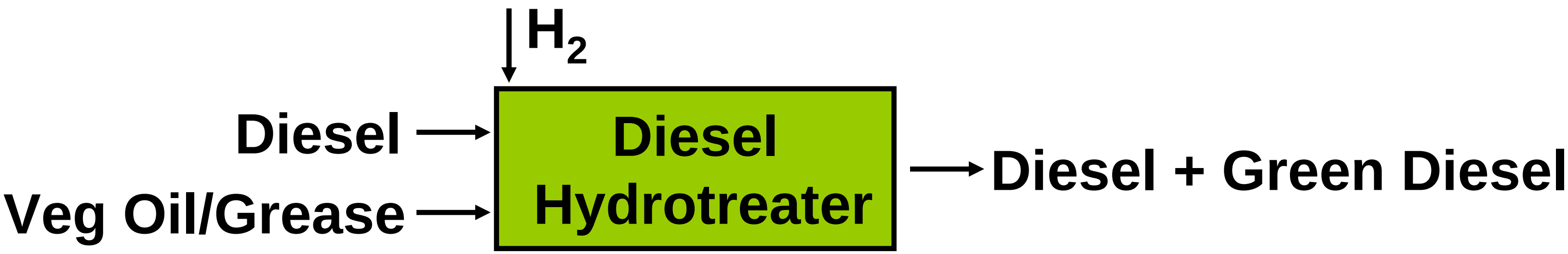
Aqueous-Phase Reforming references:

- Huber et al., *Angew. Chem. Int. Ed.* (2004).
- Huber et al., *Science* (2005).

Renewable Alkanes

	Rank	Comments
Fuel compatibility	Good	Goal of alkanes is to produce gasoline, diesel, and jet fuels
Level of Technology	Lab/Pilot	•LS9 plans pilot facility in 2008. •Amyris plans pilot facilities, has contracts with Brazilian sugar cane/ethanol companies
Techno-economic Analysis	None	•Internal data make external analysis difficult. •Claims in the press are often optimistic: LS9 expects competitive with $40-50/bbl crude oil.
Sustainability	No external	Claims of better yield and utilization than corn ethanol, but not verified

Hydrogenation-Derived Renewable Diesel

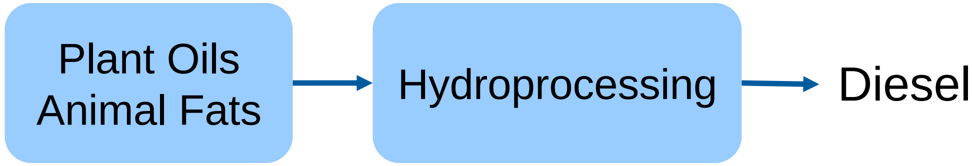


- Hydro-treating of biorenewable oils in existing refinery units
- Lower capital costs than biodiesel
- Excellent fuel properties

Feed	
% Oil or Grease	100
% H_2	1.5–3.8
Products	
% Water, CO_2	12–16
% Lt HC	2–5
% Diesel	83–89
Cetane Number	80–100
ppm S	<10

Source: U.O.P. Corp.
First International Biorefinery Conference, August 2005

Hydrogenation-Derived Renewable Diesel



	Rank	Comments
Fuel compatibility	Good	Should be compatible with refineries, vehicles
Level of Technology	Demo	•ConocoPhillips and Tyson Foods work to make diesel from fat •Neste Oil, Petrobas, Syntroleum, UOP-Eni •Feedstock availability is issue
Techno-economic Analysis	Not public	•Animal fat and plant oil prices can be obtained •Refining costs are often proprietary •Commercial trials suggest that economics may be favorable
Sustainability	In progress	ConocoPhillips has LCA on HDRD from tallow. Will be presented at AIChE conference in November.

Microalgae as a Source of Biofuels

DOE's Aquatic Species Program at NREL (1978–1996) provided the technical foundation for producing biodiesel from algae.

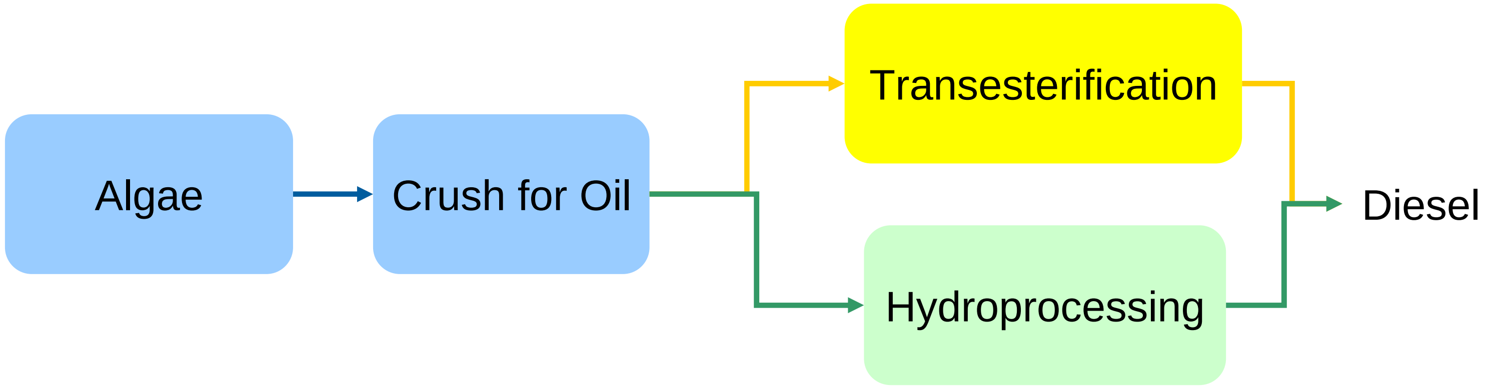
The concept involves:

- Sunlight
- CO_2 in fuel gases and/or vent gases
- Unproductive land
- Brackish or saline water.

Productivity per-acre potential (~10,000 gal/acre/yr) far exceeds that of terrestrial plants. *R&D is needed to reach this potential.*

NREL and Chevron are in a collaborate research and development agreement to study liquid fuels using algae.

Algal Biodiesel



	Rank	Comments
Fuel compatibility	Good	Diesel
Level of Technology	Lab	•Very early stage •Several companies exploring algae: Livefuels, Greenfuels, PetroSun, Chevron, Boeing, Air Force
Techno-economic Analysis	Spreadsheet level	•Biological, rather than engineering, factors influencing cost •Aggressive assumptions still lead to 2x conventional diesel fuel costs (1998)
Sustainability	None	•No competition for arable land •Water use an issue

Fuel Summary Table

	Fuel Compatibility	Level of Technology	Techno-economic Analysis	Sustainability
Fischer-Tropsch Diesel	Good	Demo	In Progress	Good
Methanol-to-Gasoline	Good	Demo	In Progress	Good
Pyrolysis	Good	Lab	Several done	Fair
Butanol	Fair	Lab	In Progress	Fair
Mixed Alcohols	Poor	Pilot	Partly done	Likely good
Renewable Alkanes	Good	Lab/Pilot	None	None
HD Renewable Diesel	Good	Demo	Not public	In Progress
Algal Biodiesel	Good	Lab	Spreadsheet	None