

# Financial and Sustainability Metrics of Aviation Biofuels

**2017 UTIAS National Symposium on  
Sustainable Aviation**



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# Outline

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- About Us
- Key Drivers
- Options to replace petroleum-derived jet fuels
- Production Technologies and Feedstocks
- Potential Supply and GHG Impacts
- Financial Assessment
- Conclusions

# About Our Research Group

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- Collaboration with Heather MacLean (UofT Civil Engineering)
- Focus on process design, development and evaluation for renewable fuels technologies
- Life cycle assessment, including GHG emissions, feedstock assessments, land use, air quality
- Technoeconomic assessment of various process and feedstock options

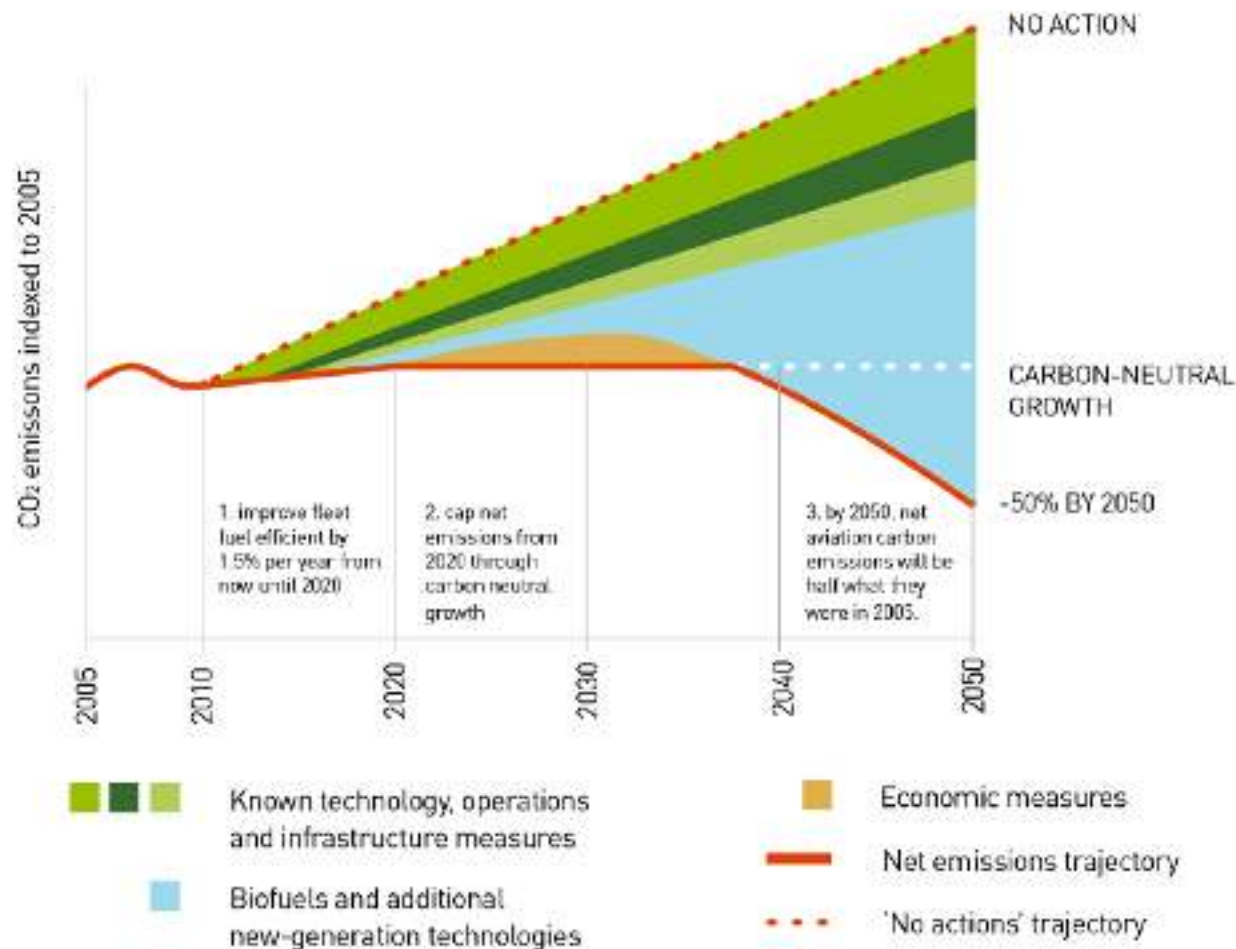
# Key Drivers and Constraints

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- GHG Emissions Targets
- Fuel Properties and Fuel Transport
- Availability of Feedstocks and Land Requirements
- Production Cost!

# Targets for Carbon-Neutral Growth

## Renewable Fuels Needed to Meet Industry Goals



# Lift-Off Requires Key Developments Along Entire Value Chain

The road to biojet fuel requires a value chain approach



**Feedstock  
Production**



**Feedstock  
Logistics**



**Bio Jet Fuel  
Production**



**Bio Jet Fuel  
Trading**



**Bio Jet Fuel  
Logistics**



**Bio Jet Fuel  
End Users**

## **SUPPLY CHAIN DEVELOPMENT**

- No silver bullet, explore multiple feedstock/technology pathways;
- From demonstration to commercial plants;
- Feed government policy & incentives;
  - Secure Investments;
  - Secure certification;
- Secure economic, social and ecological sustainability.

## **CREATE DEMAND**

- Operate demonstration flights (series);
- Aggregate demand from customers;
- Aggregate airline & airport demand;
  - Green government travel.



# TECHNOLOGY OPTIONS



# Proposed Options to Replace Jet Fuels

- **Bio-SPK:** Alkanes produced by hydrogenation of vegetable oils and tallow
  - Isomerization needed for cold-flow
- **FT-SPK:** Alkanes produced by gasification followed by Fischer-Tropsch reaction
- **ATJ - Alcohols to Jet Fuels**
  - Produce ethanol or butanol first, then catalytically convert to Jet Fuels
- **SIP - Sugars to Paraffins**
  - Production of farnesene/farnesane from sugars via fermentation and hydrogenation



# Potential Feedstocks

## Feedstock Oils Carbohydrates

Soybean      Sugar Cane, Beets

Corn          Grains

Canola/Rapeseed Lignocellulosic Feedstocks

Camelina/Carinata

Palm Oil Others

Beef tallow      MSW

Pork lard

Used cooking oils

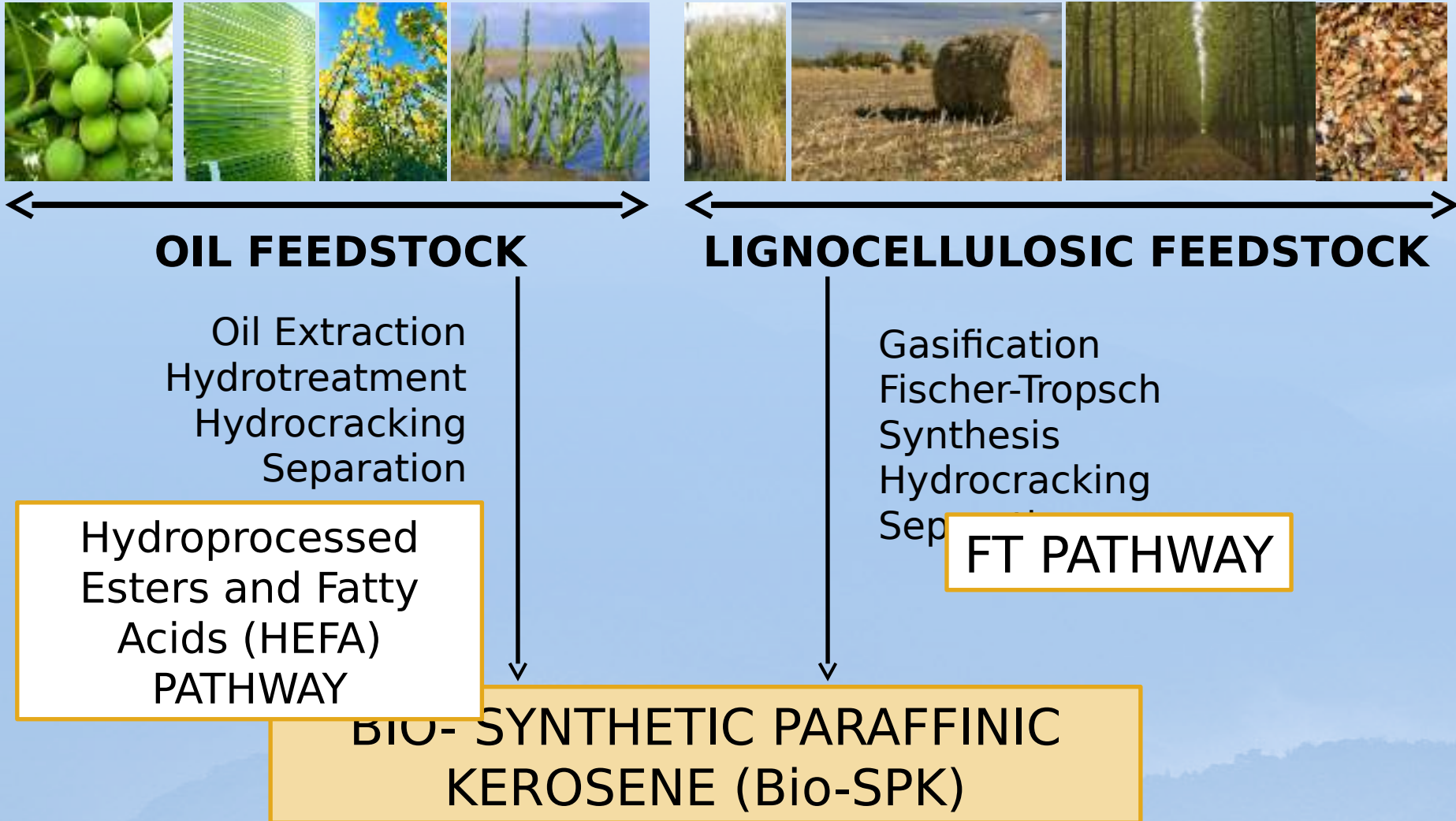
Algae

Jatropha

Cottonseed

Sunflower

# Pathways to Aviation Biofuels



# Pathways to Aviation Biofuels



## LIGNOCELLULOSIC FEEDSTOCK

Hydrolysis  
Fermentation to  
Alcohols  
Catalytic Processing

ALCOHOL TO JET  
(ATJ) PATHWAY

Hydrolysis or sugar  
production  
Fermentation/Catalysis to  
Alkanes

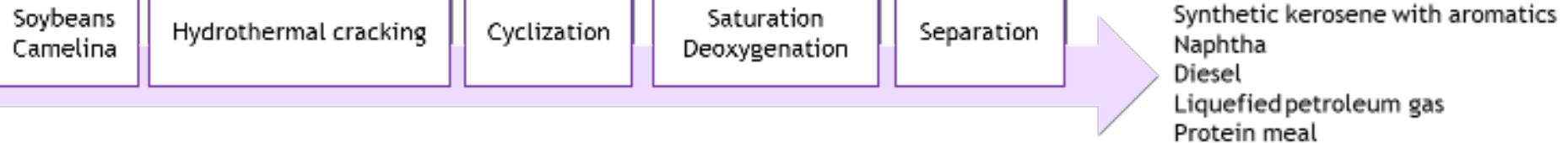
Hyd  
Aron  
Sepa

LIGNOCELLULOSE  
TO ALKANE  
PATHWAY

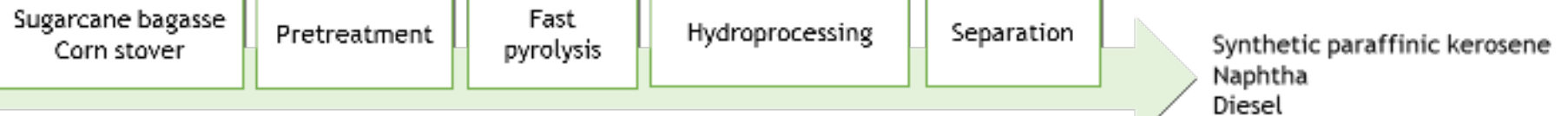
RENEWABLE JET FUELS

# Comparison of Different Pathways

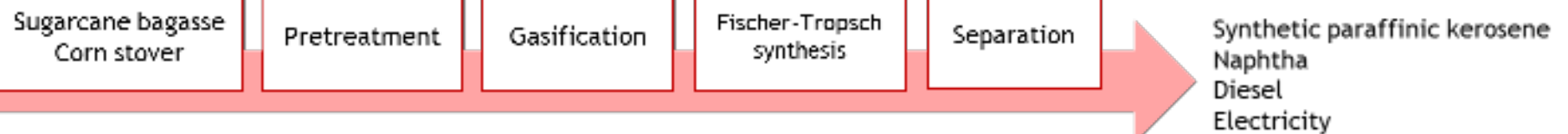
## Catalytic hydrothermolysis



## Pyrolysis to jet

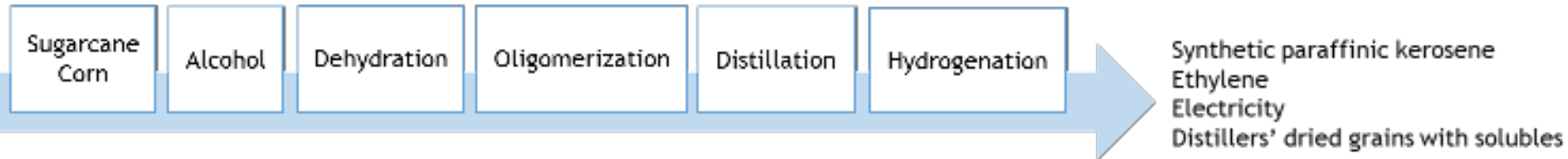


## Gasification with Fischer-Tropsch synthesis

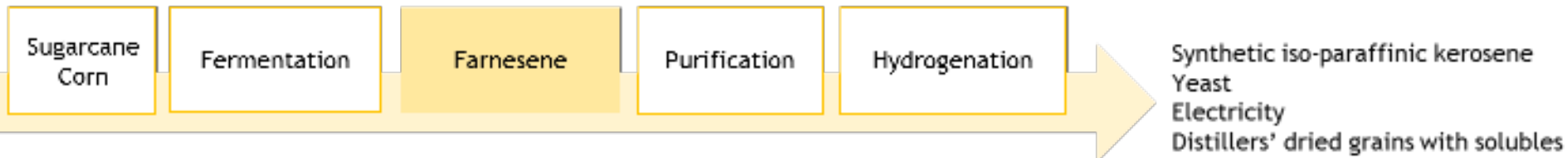


# Comparison of Different Pathways

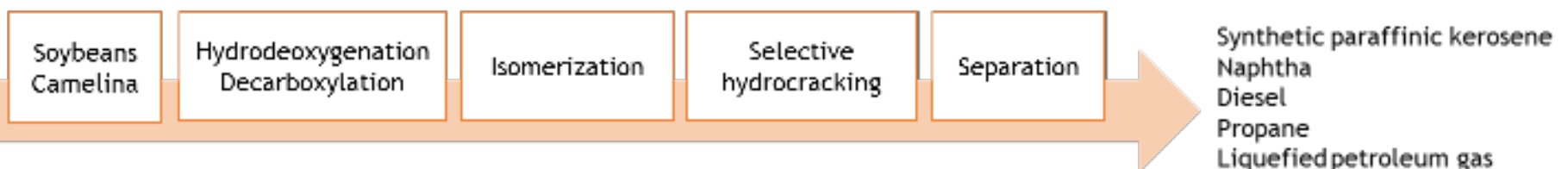
## Alcohol to jet



## Direct fermentation to jet



## Hydroprocessed esters and fatty acids

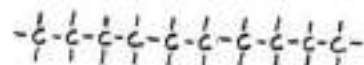
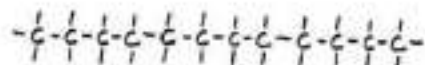
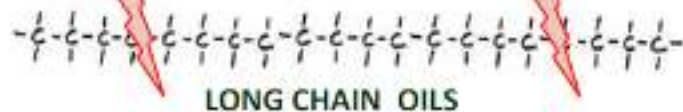


# Comparison of Oils vs CHOs

## Aviation Fuel : Technology

### Bio-Oils : Hydrocracking

(Breaking Down - Cracked)



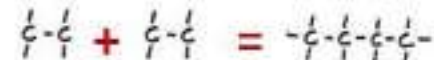
### Breaking Down From Long Chains

- High Pressure
- High Temperature
- External Hydrogen
- No Aromatics

### Alcohols : Oligomerizing (Building Up)




SHORT CHAIN OLEFINS : ETHYLENE



### Building Of From Short Chains

- Low Pressure
- Low Temperature
- No External Hydrogen
- Full Aromatics

# Production Processes Using Lipids

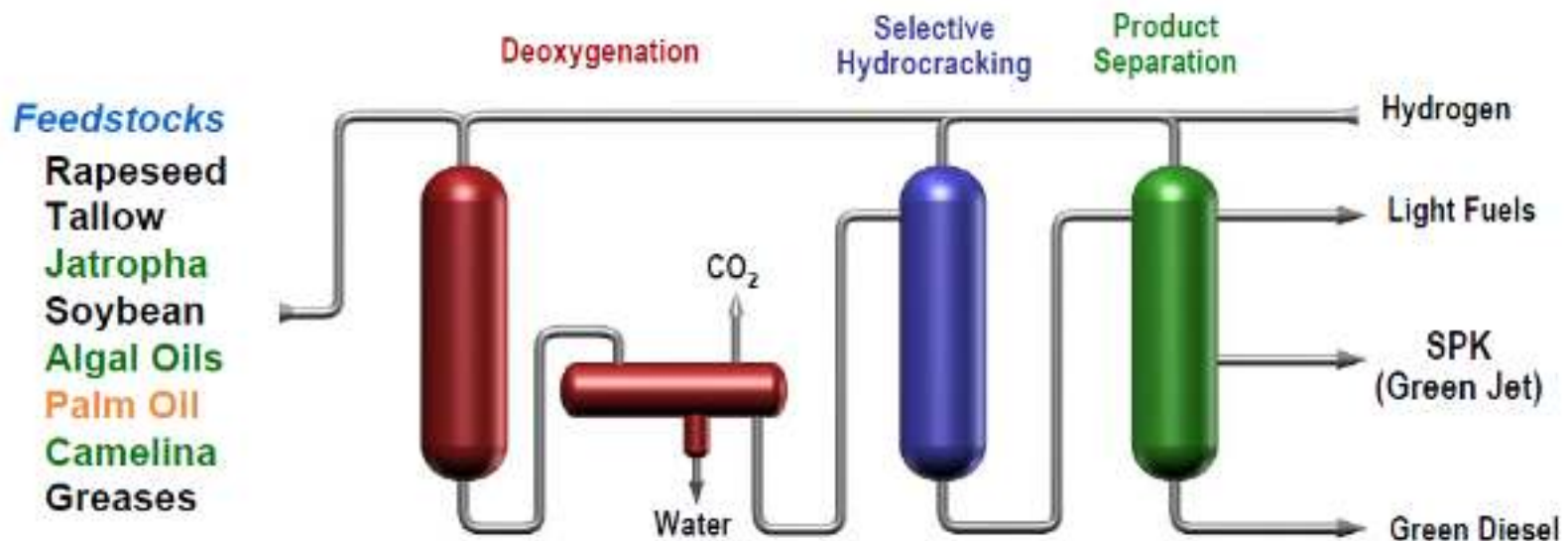
A horizontal decorative bar spanning the width of the slide, divided into five colored segments: dark blue, light blue, green, orange, and dark blue.



# Bio-SPK Process Units

## UOP's Renewable Jet & Green Diesel Process

**UOP**  
A Honeywell Company



Green diesel,  
light HC,  $\text{CO}_2$ ,  
 $\text{H}_2\text{O}$

# Challenges with Bio-SPK

- High cost of feedstock oils
  - More costly to produce than renewable diesel, which, in turn, is more costly to produce than biodiesel, which requires subsidies to be competitive with petrodiesel
- Need source of hydrogen
- No aromatics
  - Limited GHG reduction

# Algal Feedstock Players

## Algae: Multiple Sources for Fuels

**uop**  
A Honeywell Company

**aquaflow**



**Wild Algae**

Low Production Costs

High Pre-Treatment Costs

**Sapphire**  
Energy



**Enhanced Algae Strains**

Moderate Production Cost  
Moderate Pre-Treatment Costs

**solazyme**



**Heterotrophically Grown Algae**

Moderate Production Costs

Low Pre-Treatment Costs

**Ecofining™**

**Green Fuels**  
Jet, Diesel

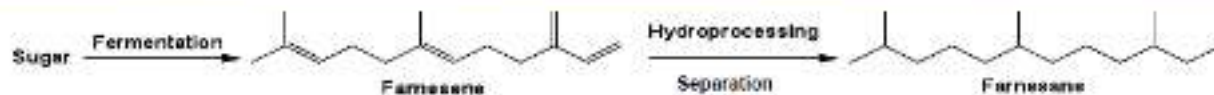


# **OTHER OPTIONS USING SUGARS**

# Amyris

## Farnesane from Biomass-derived Sugars

### Technology based on common industrial steps



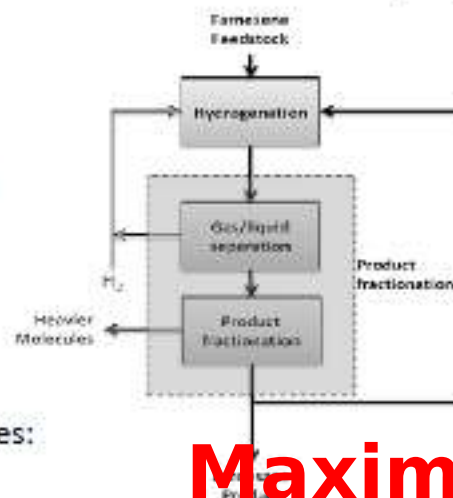
#### ❑ Fermentation



- Microbe-catalyzed conversion of sugar: key is the development of a farnesene producing yeast which is sugar agnostic
- Farnesene production to date: ~5 million liters in multiple sites
- Brotas, Brazil could reach 50 million liters per year at target efficiency

#### ❑ Downstream Processing

- Combination of hydroprocessing and separation operations
- Farnesane diesel grade production to date: ~2 million liters
- Using diesel process with greater purification, farnesane aviation grade production to date for ASTM test purposes: ~30,000 liters



**Maximum 10% Blend**



# Byogy and Gevo Alcohol to Jet Platform

## The Byogy Ethanol Bio-Refinery

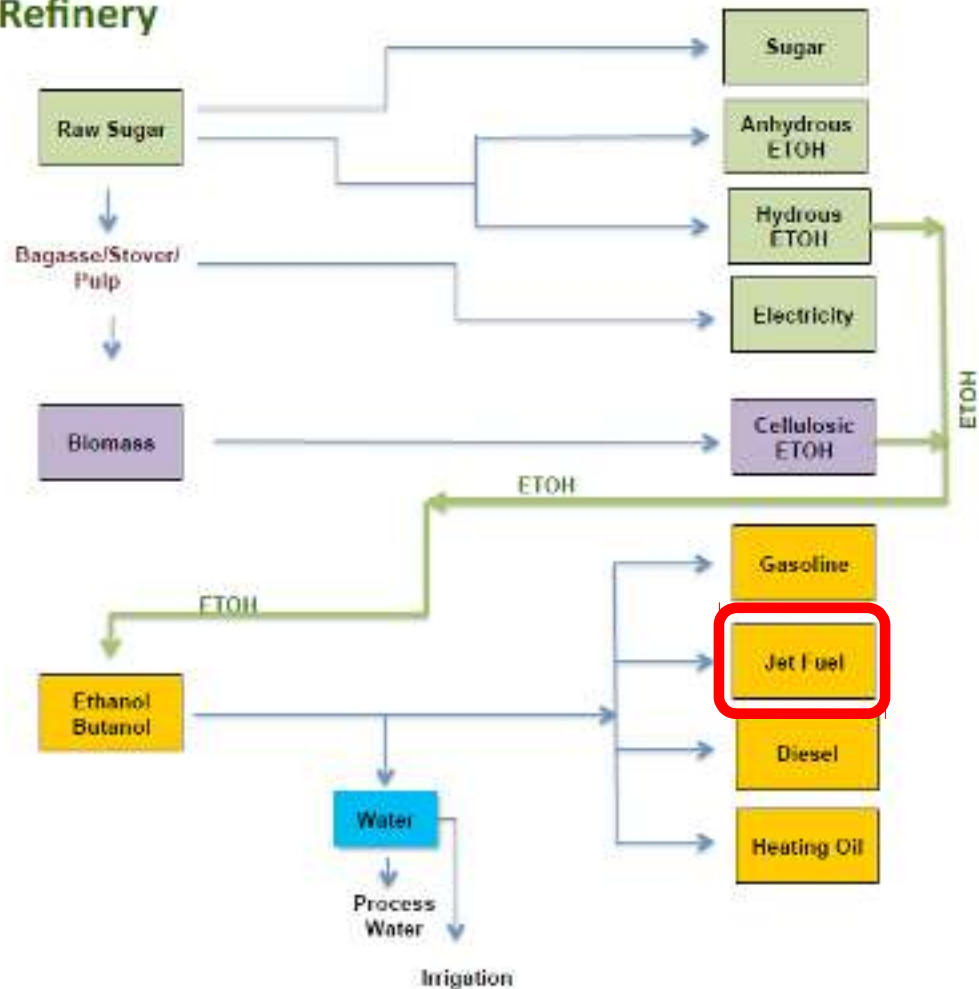
**Conventional**  
(Sugar Cane/Corn/Beets)



**Cellulosic**  
(Bagasse, Eucalyptus)



**Advanced**  
(Byogy)



# Challenges with Platforms Using Sugars

- Need inexpensive sugar source
- To get significant GHG reductions, need cellulosic biomass – but conversion technology is still being developed
- Will be more costly than making alcohols from same sugars

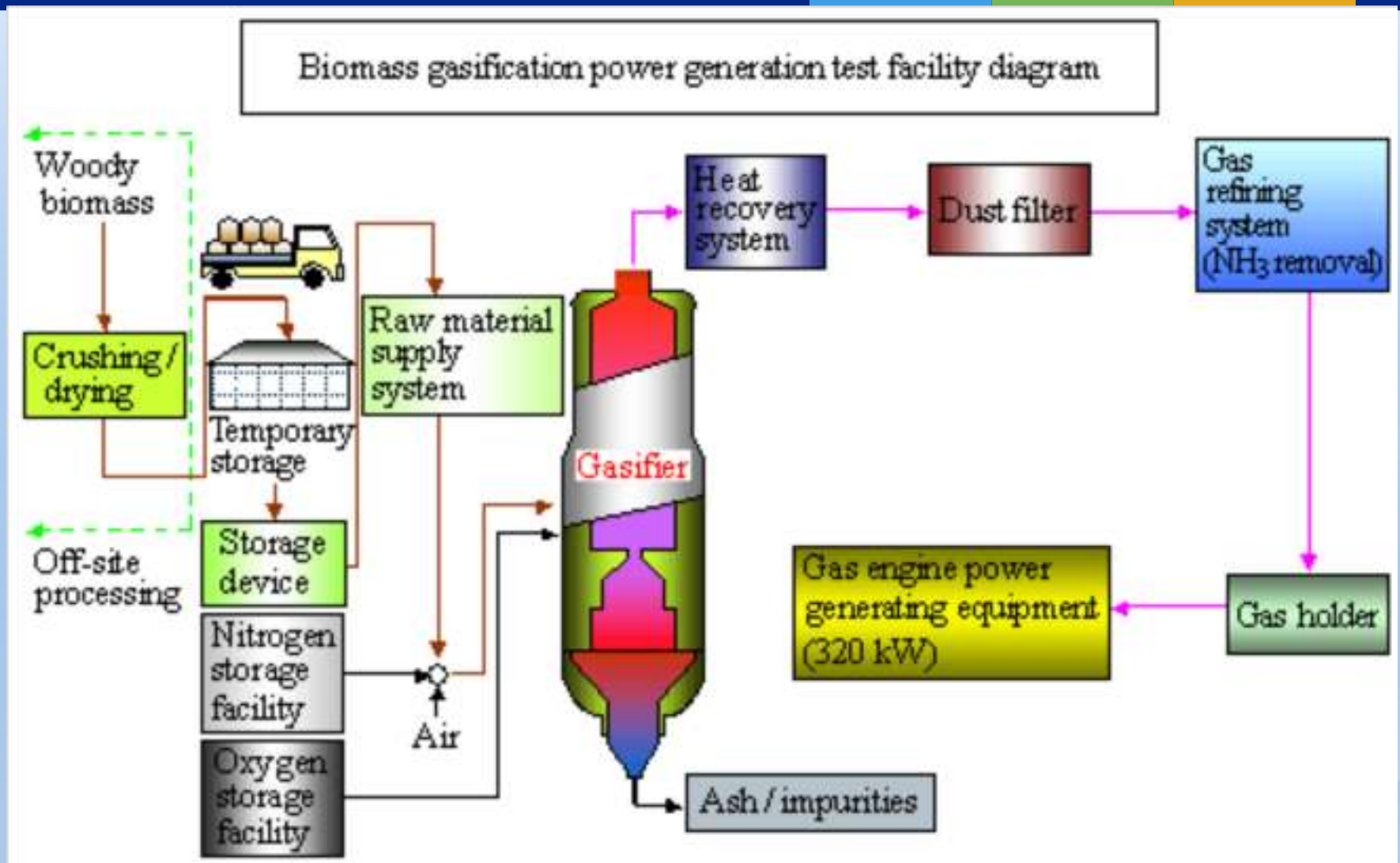




# OPTIONS FROM SYNGAS

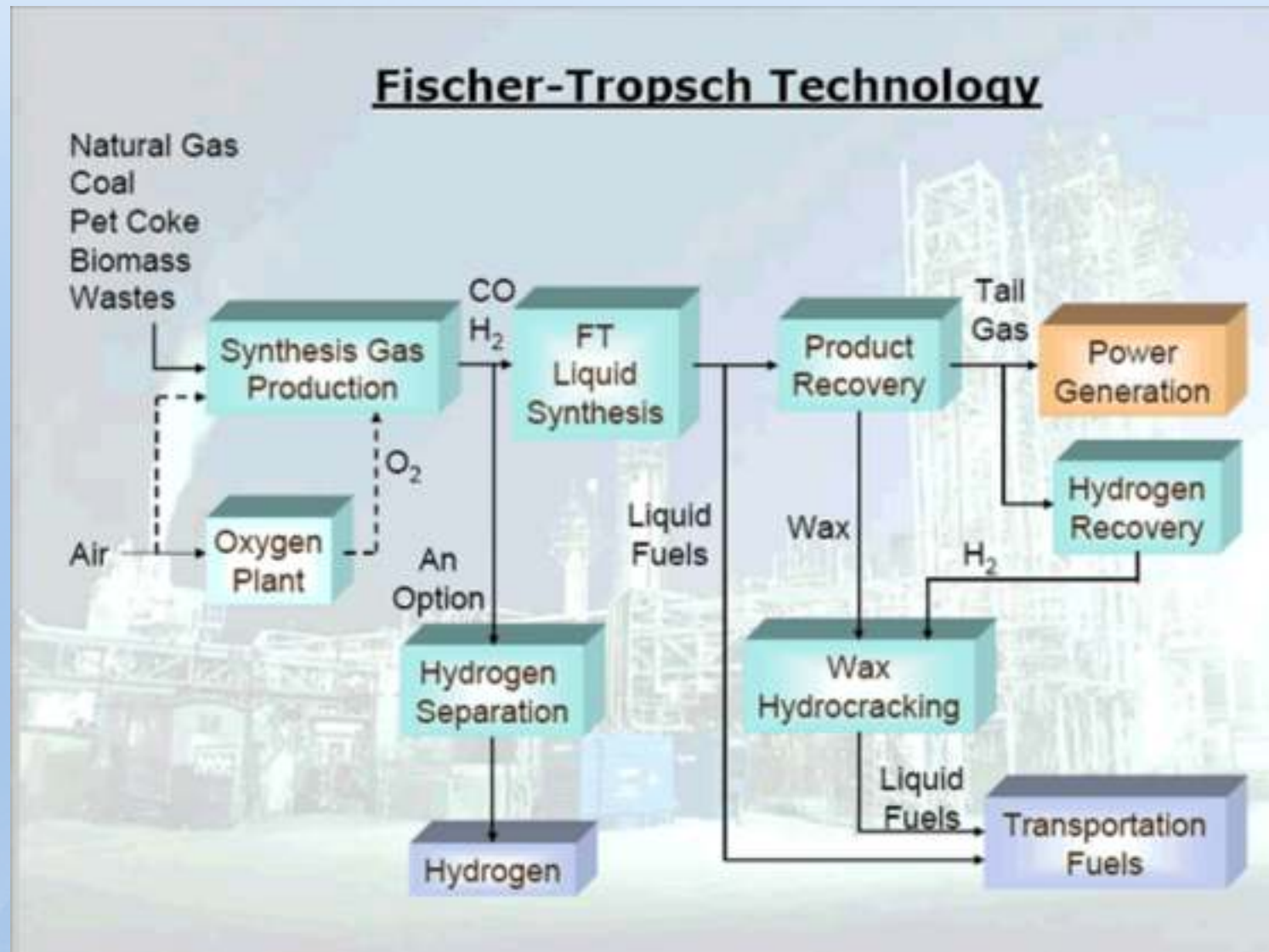
# Step 1

## Syngas Production from Biomass Gasification



# FT Process Step 2

## Convert Syngas into Alkanes



# LanzaTech

## Thermo/bio-catalysis of Platform Chemicals

### LanzaTech Gas to Liquid Platform



Resources

CO

Industrial

CO

Syngas: Biomass, Coal, Methane

H<sub>2</sub>

H<sub>2</sub>

COG, Chemical

CO<sub>2</sub>

CO<sub>2</sub>

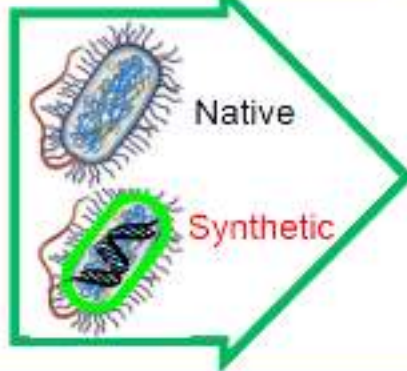
CO<sub>2</sub>

Power

CH<sub>4</sub>

Natural Gas

Customized Catalysts



Native

Synthetic

Engineering Control Chemistry

Product Suite

C<sub>2</sub>

- Ethanol
- Acetic acid

C<sub>3</sub>

- *i*-propanol
- acetone

C<sub>4</sub>

- BDO
- *n*-Butanol
- *i*-Butanol
- Succinic

C<sub>8</sub>

- Isoprene

Other

- PHB
- .....

Product Suite

Hydrocarbon Fuels  
(diesel, jet,  
gasoline)

Thermochemical Approaches

Chemical  
Intermediates

Olefins

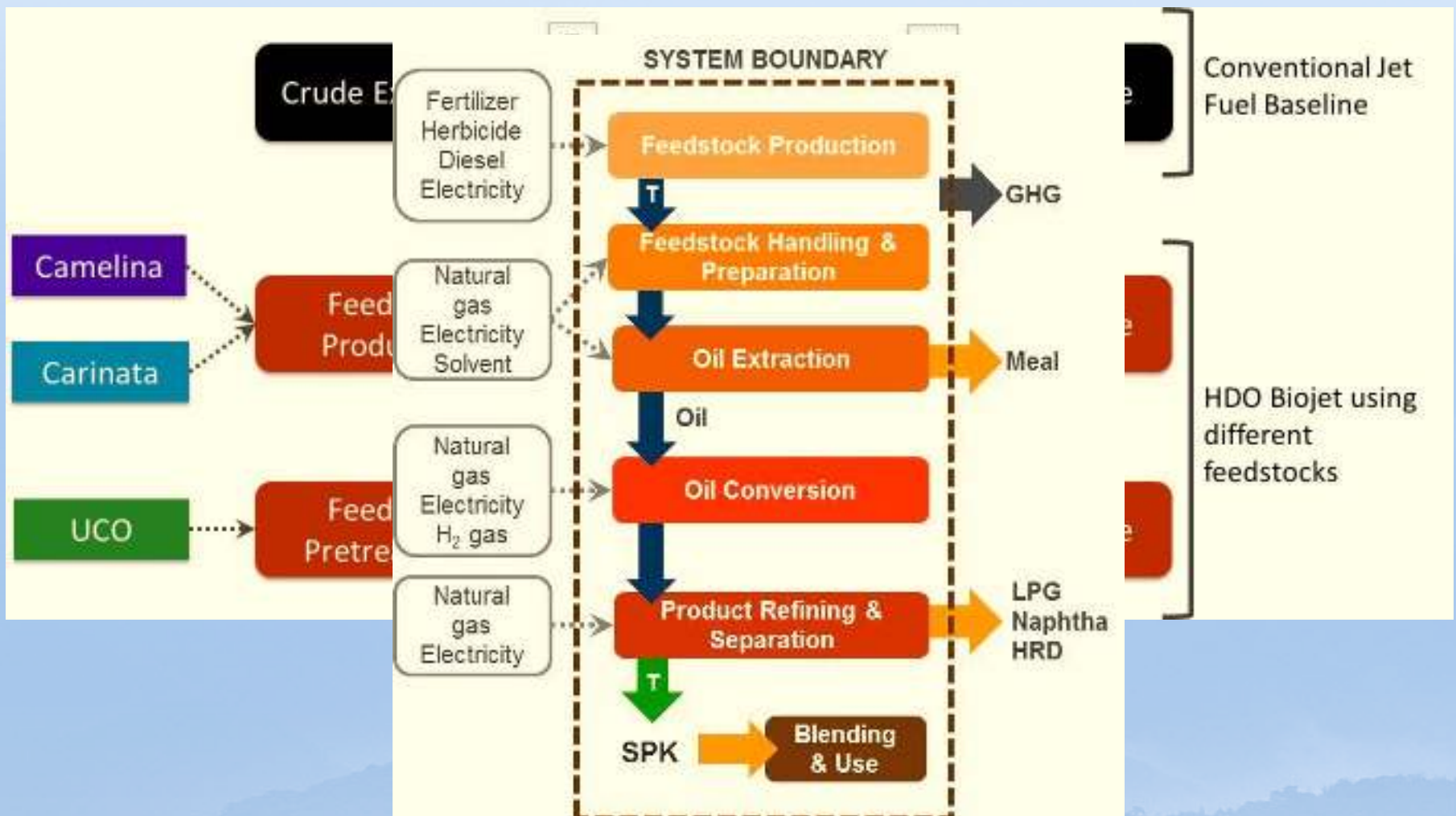
Chemicals



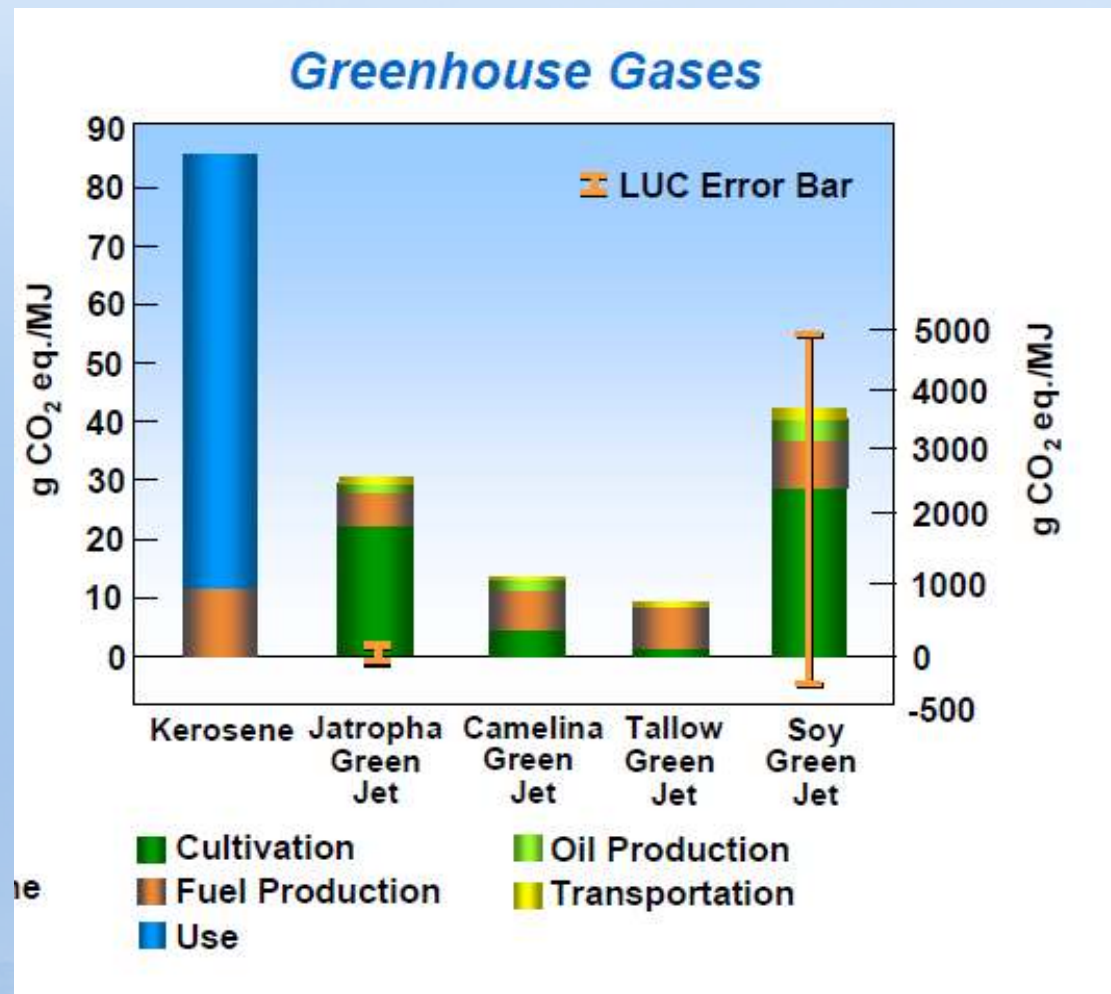
# **GHGS, LAND USE, SUPPLY/DEMAND METRICS**



# LCA Boundaries

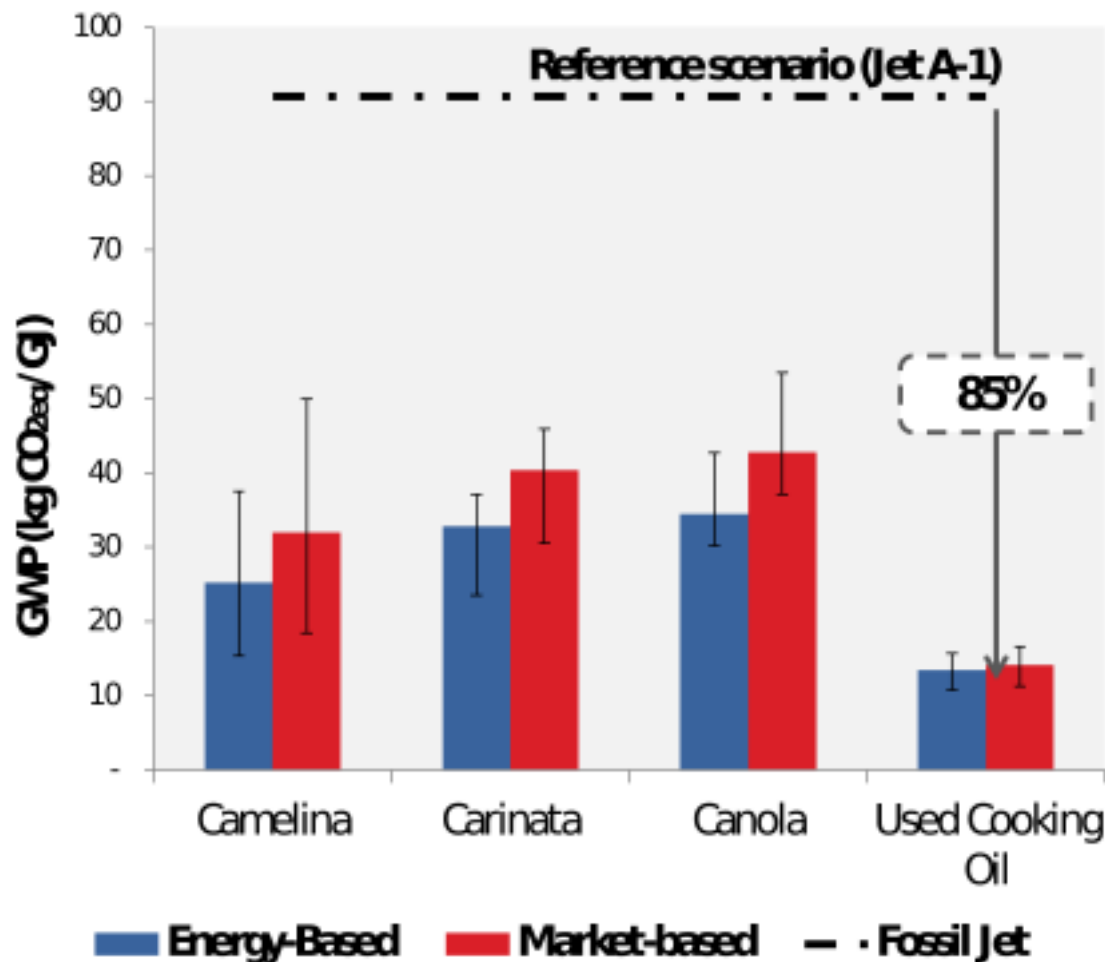


# GHG Emissions of Renewable Jet Fuel





# GHG Profile for Bio-SPK from Camelina, Carinata, UCO



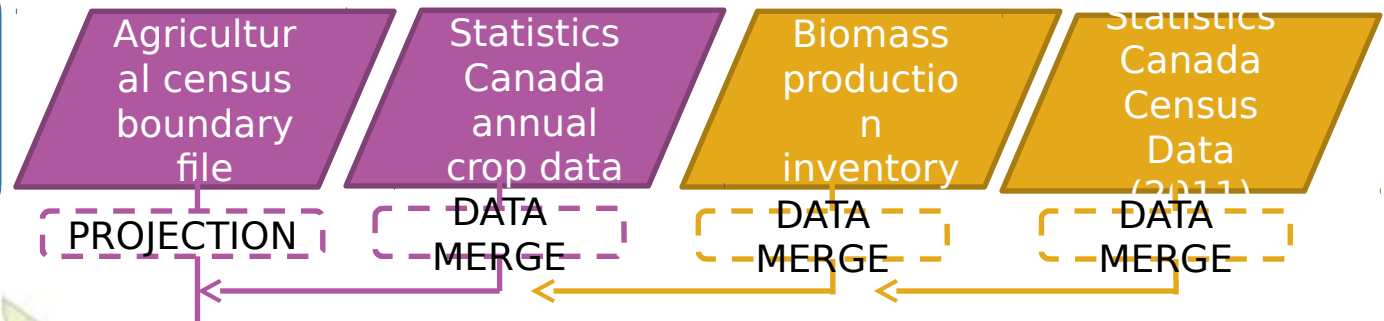
See also poster from Jon Obnamia on GHG emissions profile of canola-based jet fuel

# Land Use Implications

- Highly dependent upon productivity of feedstock
  - Oilseeds: 2 – 3 tonnes/Ha, with 20 – 45% useable oil
  - Crop Residues: 2 – 4 dry tonnes/Ha, with 60 – 95% useable content
  - Dedicated Energy Crops: 5 – 35 dry tonnes/Ha, with 60 – 95% useable content
  - Sugarcane: 15 – 20 dry tonnes/Ha, with 15 – 25% useable content

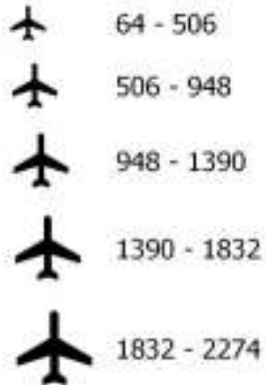
# SUPPLY/DEMAND ASSESSMENT

**Biomass  
production  
on available  
land &  
population**

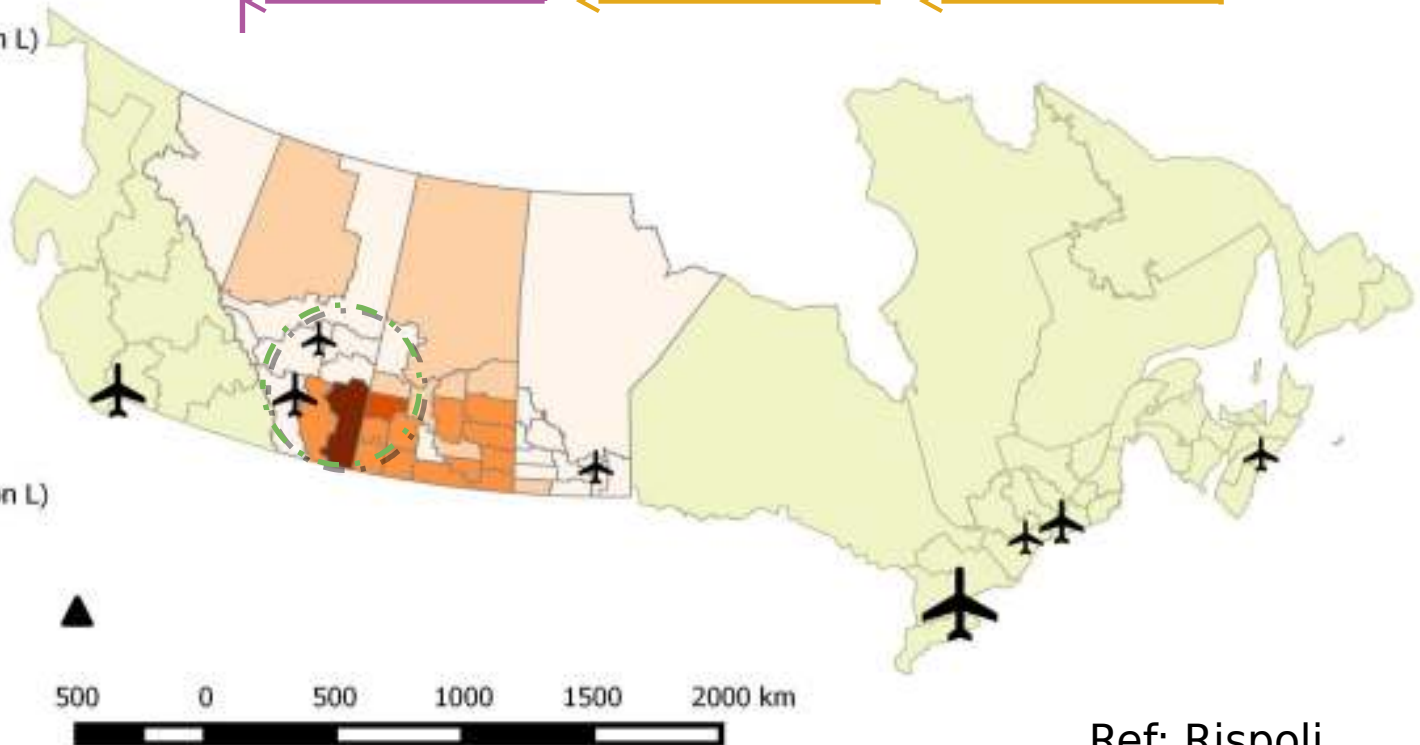
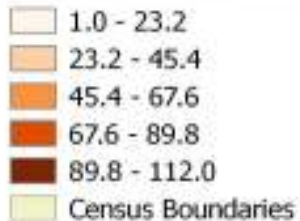


Legend

Major Airports (fuel use - million L)



Cameline SPK Production (million L)



Ref: Rispoli,  
2015

# SUPPLY/DEMAND ASSESSMENT

## Potential jet fuel displacement & emission reduction



### EXCEL LCA MODEL

- *average values*
- *energy-based allocation*

	Amount produced	% Fuel Displaced	% Fuel Displaced	Potential Emission reduction	
	Million L	All Major Airports	Calgary Airport	From SPK Production in MT CO2	% of Canada's aviation emissions
<b>Carinata SPK</b>	2,158	38%	416%	2.5	29%
<b>Cameline SPK</b>	1,295	23%	250%	1.3	16%
<b>UCO SPK</b>	52	1%	10%	0.1	1%

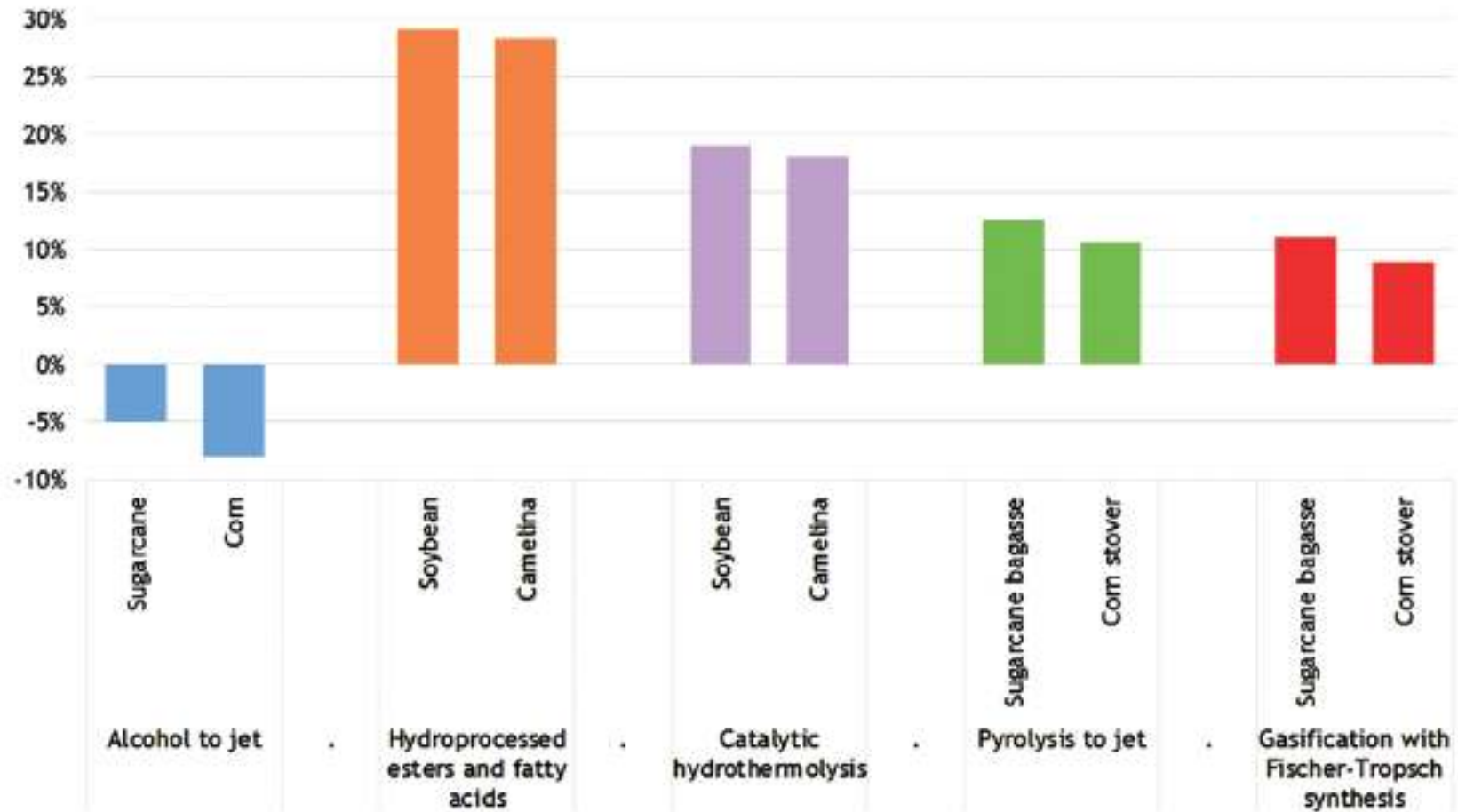


# FINANCIAL METRICS

# Key Financial Issues

- Cost-competitiveness largely relies upon high crude oil prices
- Feedstock represents 70 to 90% of the overall production cost
  - Low-cost feedstocks are key – benefit for MSW and FT/ ATJ processes
- Low cost sugar platform
  - Amyris, Virent, Solazyme, Byogy
- Intermediates (alcohols, etc.) already expensive
  - High value co-products and lower cost feedstocks may help financial viability
- High capital for gasification + FT
  - Interesting biological alternatives – will they prove out?

# IRR For Select Renewable Jet Fuel Pathways



Ref: Pereira et al., BIOFPR, 2017



# Financial Metrics: Renewable Jet vs. Renewable Diesel

	HRJ	HRJ	HRJ	HDRD	HDRD	HDRD
	Camelina	Carinata	UCO	Camelina	Carinata	UCO
Feedstock price \$/tonne oilseed	314	346	–	314	346	–
Feedstock price \$/tonne oil	897	786	449	897	786	449
CAPEX (\$MM)	411	411	387	246	246	205
OPEX (\$MM)	331	292	179	323	286	172
Total Revenue (\$MM)	440	382	263	439	380	260
Fuels	259	262	264	259	259	260
Meal	181	121	–	181	121	–
IRR (%)	17	14	14	28	23	25
NPV (\$MM) (15% MARR)	35	–29	–26	195	121	123

Ref: Chu et al. Applied Energy 2017

# Underlying Challenge

- Using crude oil as feedstock, production of jet fuel is no more expensive than producing diesel or gasoline
- By comparison, using the same renewable oil feedstock, producing renewable jet fuels is (and may always be) more expensive than producing renewable fuels that displace gasoline or diesel
  - Near-term: Biojet as co-product of renewable diesel refinery
  - Growth in production likely requires direct investment from end users

# Summary

- Various platforms for conversion of biomass-derived oils, sugars, and biomass
  - Most are technically viable
  - GHG reductions on the order of 50 to 80%
- Feedstock supply is limiting
- Financial feasibility uncertain
  - Camelina and carinata show promise
  - Algae, used cooking oil have limited potential

# What does the Future Hold?



- Current feedstocks are expensive or limited supply
- Need new, low cost oil-rich feedstocks, and low cost sugars
- Financial metrics will dictate path

# Acknowledgements

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- Collaborators, Students, PDFs
  - Heather MacLean
  - Pei Lin Chu, Katherine Rispoli, Hajar PourBafrani, Jon Obnamia, Lucas Pereira
- Funding
  - NSERC CREATE
  - BiofuelNet
  - ASCENT





# Cost of Biojet from Previous Techno-Economic Studies

Publication	Pathway	Feedstock	Price, US\$/L
Pearlson	HDO	Soybean oil	1.00-1.16
Agusdinata et al, 2011	HDO	Camelina	0.91
		Algae	4.61
	Gasification-FT	Corn stover	0.77
		Switchgrass	1.20
		SRWC*	1.49
Klein et al., 2013	HDO	Algae	8.45
		Pongamia pinnata	2.35
	Advanced fermentation	Sugarcane molasses	1.89
Staples et al., 2014	Advanced fermentation	Sugarcane	0.61-2.63
		Corn grain	0.84-3.65
		Switchgrass	1.09-6.30
Seber et al., 2014	HDO	Waste oil	0.84-0.97
		Tallow	1.02-1.14
		Soybean oil	1.15-1.27

**Free Fatty Acid**  
MW=200-300

$\text{HO}-\text{C}(=\text{O})-\text{CH}_2(\text{CH}_2)_n-\text{CH}_3 + \text{H}_2 \rightarrow \text{CO}_2 + \text{H}_3\text{C}(\text{CH}_2)_n-\text{CH}_3$

**Triglyceride**  
MW=700-900

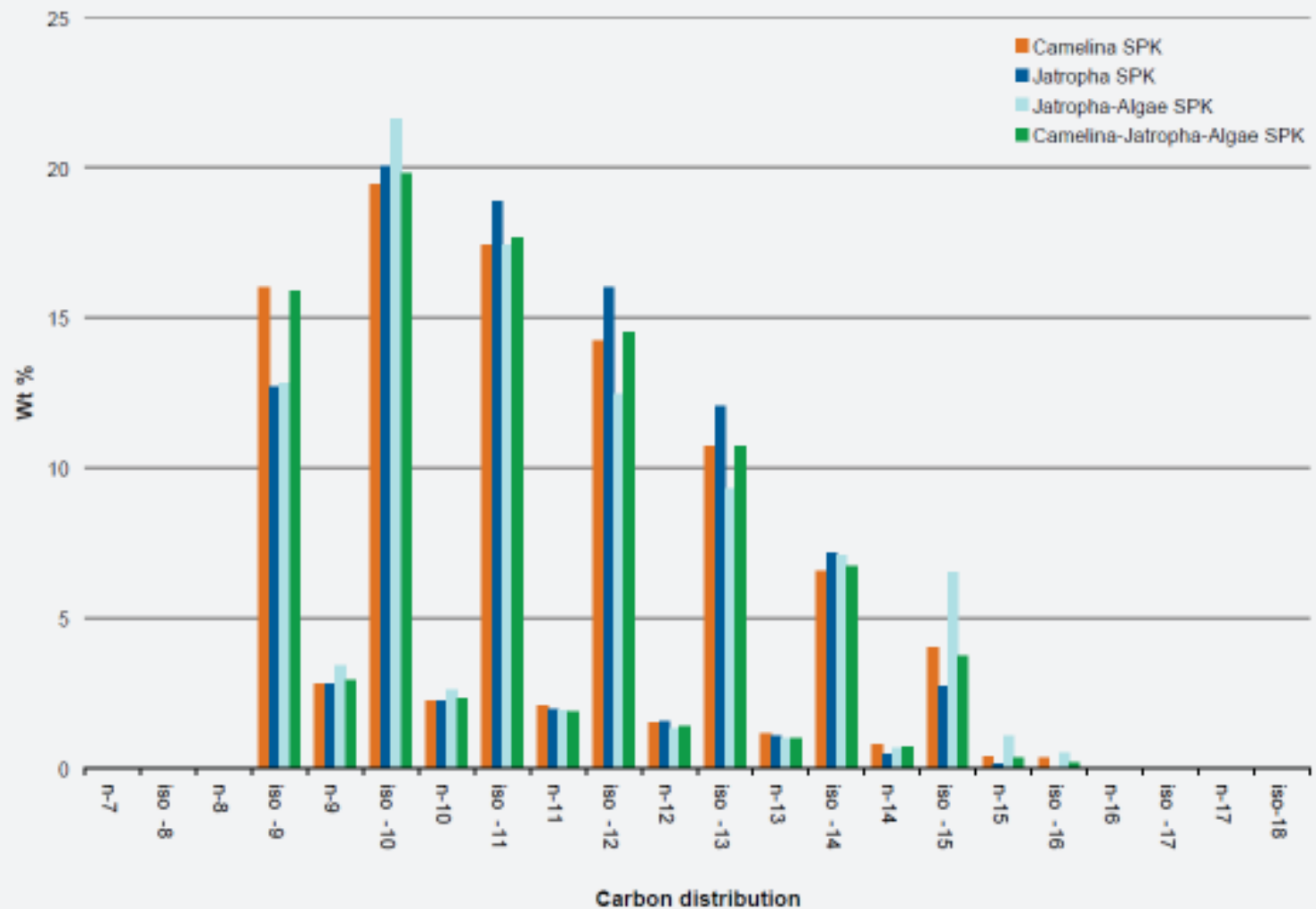
$\text{HC}(\text{O}-\text{C}(=\text{O})-\text{CH}_2(\text{CH}_2)_n-\text{CH}_3)_3 + \text{H}_2 \xrightarrow{\text{UOP Catalyst}} \text{CO}_2 + \text{H}_2\text{O} + \text{H}_3\text{C}(\text{CH}_2)_n-\text{CH}_3$

**Straight Chain Paraffins**

**Synthetic Paraffinic Kerosene**

- Natural oils contain oxygen, have high molecular weight
- 1st reaction removes oxygen – product is diesel range waxy paraffins
- 2nd reaction “cracks” diesel paraffins to smaller, highly branched molecules
- End product is same as molecules already present in aviation fuel
- End product is independent of starting oil

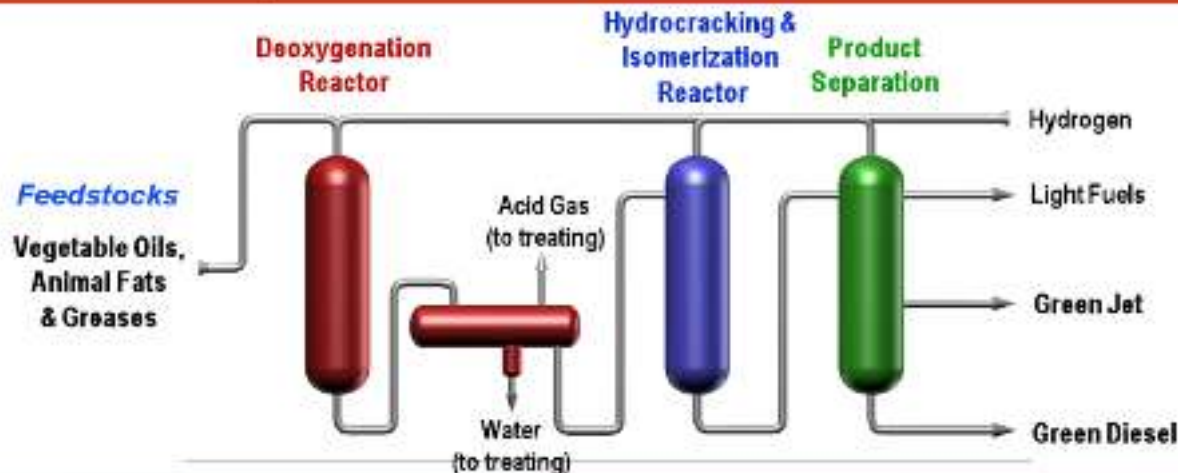
# Feedstock Affects Carbon Profile of Bio-SPK Product



# AltAir

## Commercial Biorefinery Using UOP Technology

### The AltAir Project



#### Project Summary

- Retrofit part of an existing petroleum refinery to become a 30 million gallon per year, advanced biofuel refinery near Los Angeles, California.
- Utilizes Honeywell UOP Renewable Jet Fuel Process technology.
- Will produce low-carbon, renewable jet fuel and other renewable products.
- United has agreed to buy 15 million gallons of lower-carbon, renewable jet fuel over a three-year period, with the option to purchase more.
- AltAir expects to begin delivering five million gallons of renewable jet fuel per year to United starting in 2014.

*First full-scale plant dedicated to producing renewable jet fuel  
for commercial and military use*

# Solazyme

## Biomass CHOs to Algal Lipids to Alkanes

Solazyme utilizes **plant sugars** to manufacture tailored algae for a variety of applications

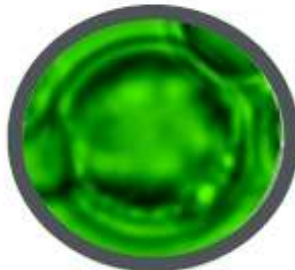
### FLEXIBLE INPUT



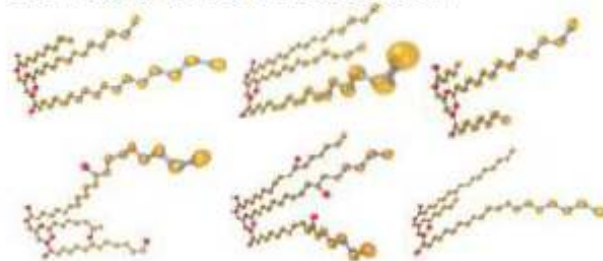
### MULTIPLE HIGH-VALUE MARKETS



### HIGHLY PRODUCTIVE MICROALGAE

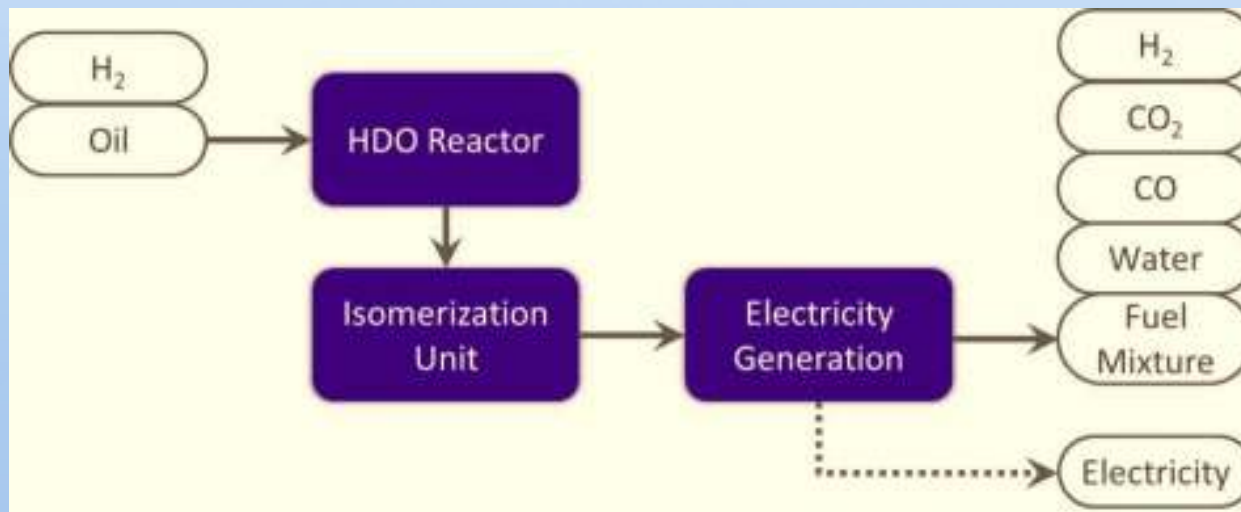


### OIL DESIGNED TO SPECIFICATION



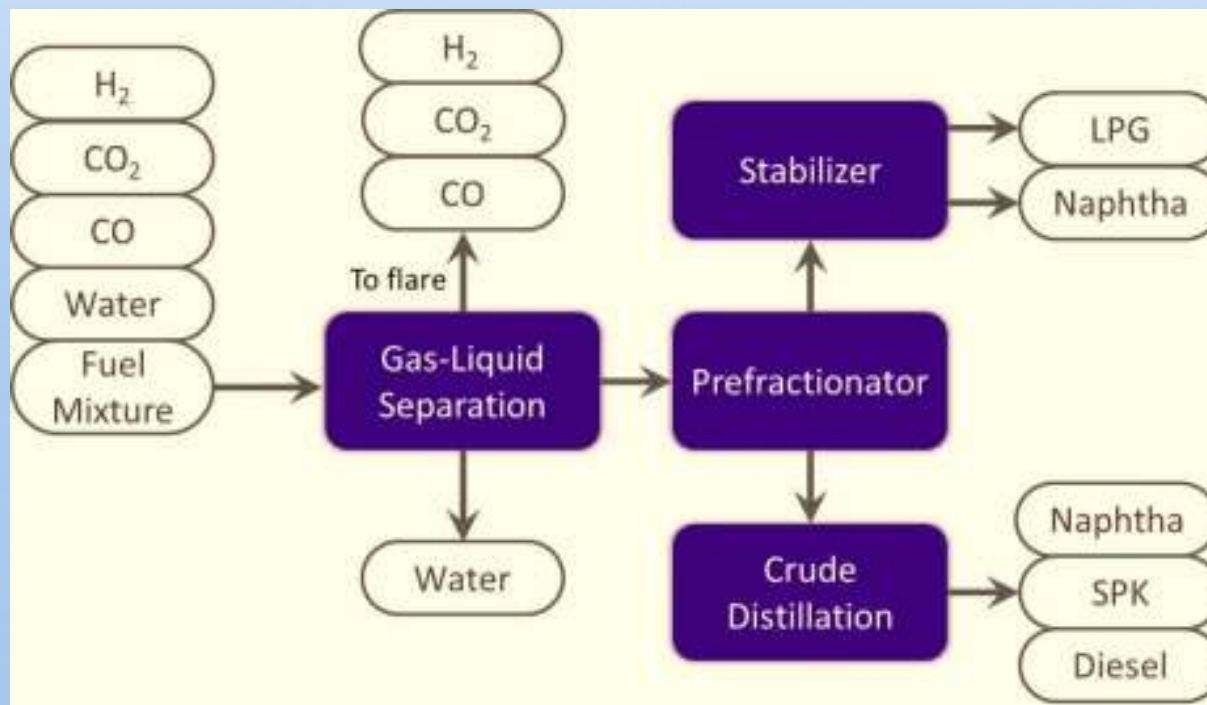


# Oil Conversion





# Product Purification



# Product Distributions

	Camelina	Carinata	UCO	Pearlson Soyoil	Han et al. Soybean	Han et al. Palm	Han et al. Rapeseed	Han et al. Jatrophia	Han et al. Camelina
<b>Input</b>									
<b>Oil</b>	1000	1000	1000	1000	1000	1000	1000	1000	1000
<b>H<sub>2</sub> gas</b>	30.0	25.8	26.3	40	50	40	46	45	53
<b>Output</b>									
<b>CO<sub>2</sub></b>	101	95	104	54	N/R	N/R	N/R	N/R	N/R
<b>CO</b>	2.7	2.5	2.7	N/R	N/R	N/R	N/R	N/R	N/R
<b>Water</b>	36	34	37	87	N/R	N/R	N/R	N/R	N/R
<b>LPG</b>	88	79	69	102	146	130	109	145	140
<b>Naphtha</b>	127	145	147	70	113	125	136	114	110
<b>Kerosene</b>	535	537	529	494	740	740	760	740	750
<b>Diesel</b>	140	132	138	233	N/R	N/R	N/R	N/R	N/R

# Utility Summary

Total Process Energy	Thermal energy, MJ/tonne oil	Electricity, kWh/tonne oil
Camelina	5715	227
Carinata	5185	170
UCO	2835	73
Pearlson, Soyoil	10843	88
Han et al., Soybean	13693	67
Han et al., Palm	9311	67
Han et al., Rapeseed	12718	64
Han et al., Jatropha	11346	66
Han et al., Camelina	13693	67

# Did you find the common thread?

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- Most (all?) renewable jet fuels have another renewable fuel as an intermediate
  - Additional processing
  - Yield losses
  - No additional product value