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Using the Best of Biology and Chemistry for Sustainable Solutions
Feb 28, 2017

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Introduction

Growth in Bio-Products

CO2

Government mandates and incentives favor low carbon routes. Consumer driven interest in sustainable products.

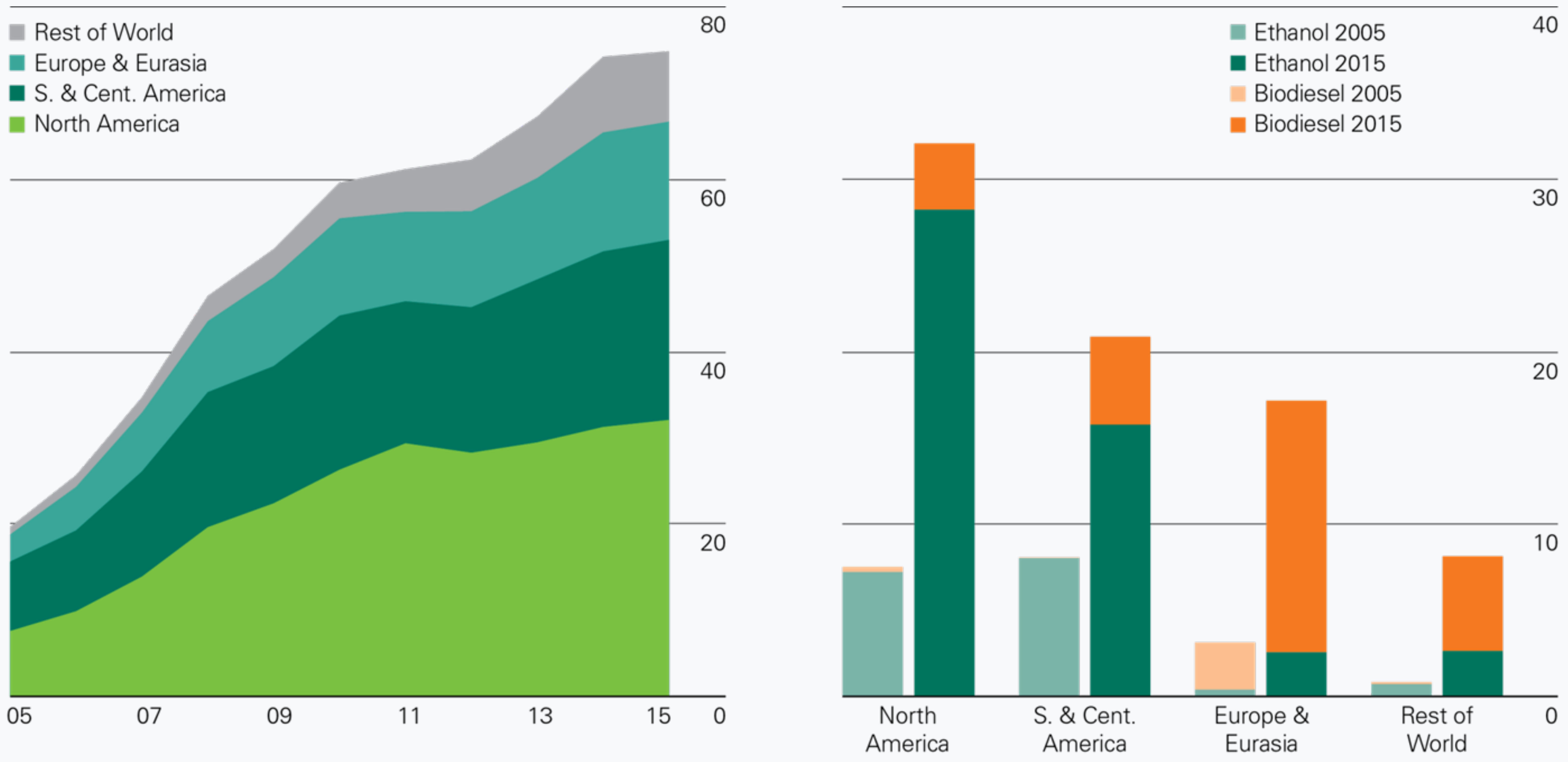
Advantaged Carbon

Low cost carbon source

Better Product, Lower Cost

Cheaper, safer processing route. Performance benefits over traditional materials

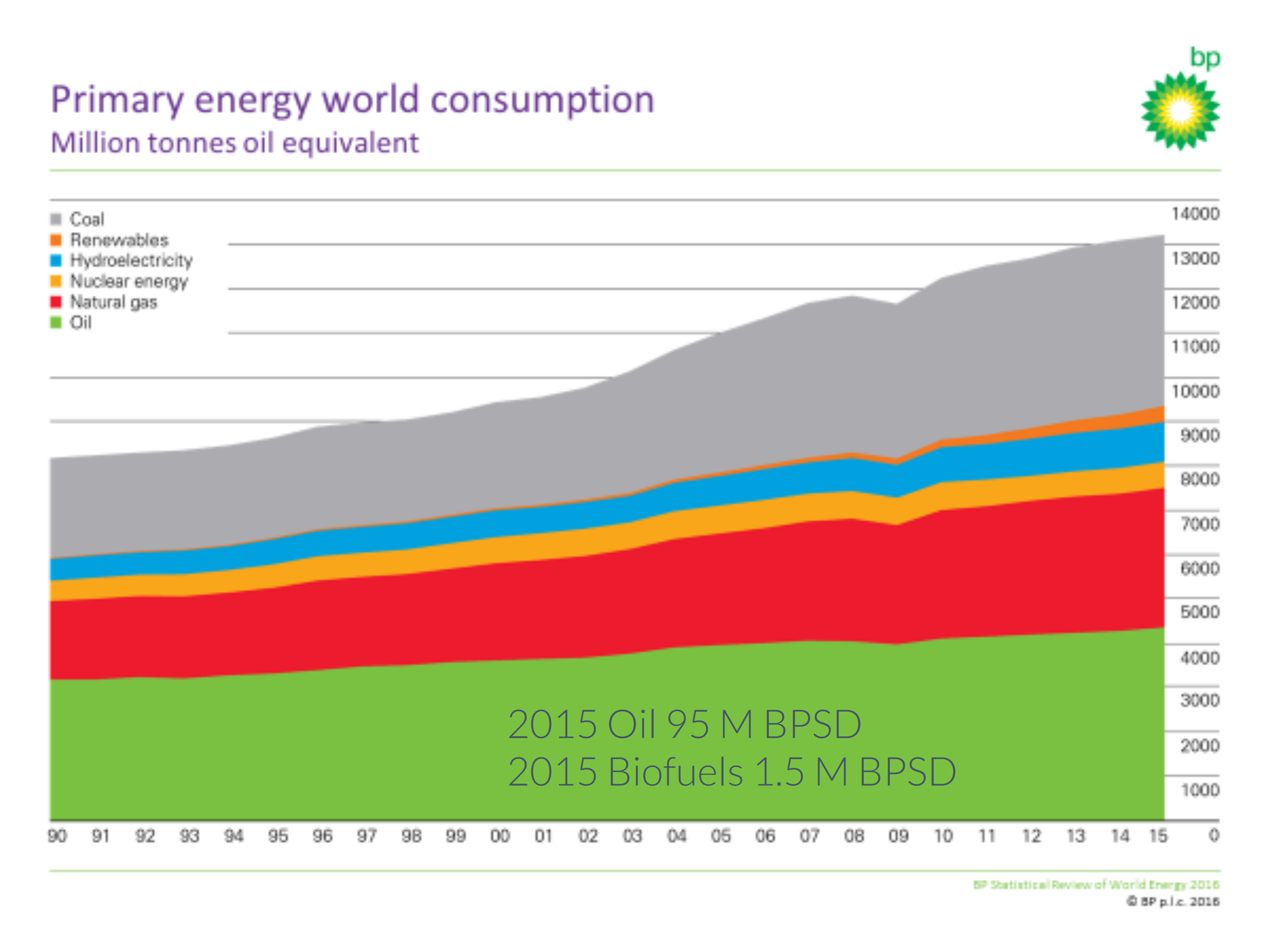
Million Tons Oil Equiv.



BP Statistical Review of World Energy 2016

2015 Bioproducts = 74 M TOE (BP 2016)

Conversion of Fossil Fuels Still Dominates



Million
Tons Oil Equiv.

Reducing Fossil Fuel Dominance
Bioprocessing: a key piece of the puzzle

§ Growth in installed capacity

Production of biodiesel and ethanol is increasing dramatically. Markets, supply chains, equipment manufacture, technology knowhow in this space are following suit.

§ Emergence of tools to support industrial bioprocessing

Advanced tools are emerging, mirroring the past advances in thermochemistry: advanced analytics, high throughput screening, and genetic tools for custom microbes.

§ Scale-up methodologies

Scale-up methodologies are critical to advancing existing technologies and developing the next generation

To truly transform the market, we need to continue to push the boundaries of what is possible

A Brief History of Thermochemical Processing

Technology Development Enabled Growth in the Oil Industry

Economies of Scale

Larger equipment -- cheaper per unit volume.
Large equipment no longer first of its kind

Learning Curve

Process optimization, operational procedures, and supply chain development contribute to reduced cost of production

Operational Experience

Operating experienced is leveraged to inform process design. Rules of thumb, design equations, and other design tools develop to encapsulate operating experience

REFINING TECHNOLOGY DATES

1861	Batch still in Titusville, Pa., U.S.
1893	"Horseless carriage" invented by Duryea brothers
1908	General Motors established
1911	Continuous pipestill & 600,000 cars in operation
1914	Continuous thermal cracking
1930	Delayed coking; Standard Oil Co. (Indiana)
1936	Catalytic Cracking; Eugene Houdry
1940	Hydrogen reforming
1949	Catalytic reforming
1961	Resid fluid catalytic cracking
1962	Vacuum gas oil hydrocracking
1963	Vacuum residue hydrocracking (H-Oil)
1969	Atmospheric residue desulfurization
1977	Vacuum residue desulfurization
1984	High conversion vacuum residue hydrocracking

Source: Oil & Gas Journal, 2/9/98, Cleaner fuels shift refineries to increased resid hydroprocessing

It took time to get where we are today

Using Operational Knowledge to Drive Process Design

- Design rules dominate design of thermochemical processes, such as:
  - Coking Rates
  - Space velocity rules to set reactor volume
  - Tray efficiencies for distillation and absorber columns
  - Heat exchanger fouling factors and approach temperatures
- We use these in process design to support, and often replace rigorous experimentation and scale-up

Encapsulate operational knowledge to enable rapid scale-up

Bioprocessing

Signs of maturity

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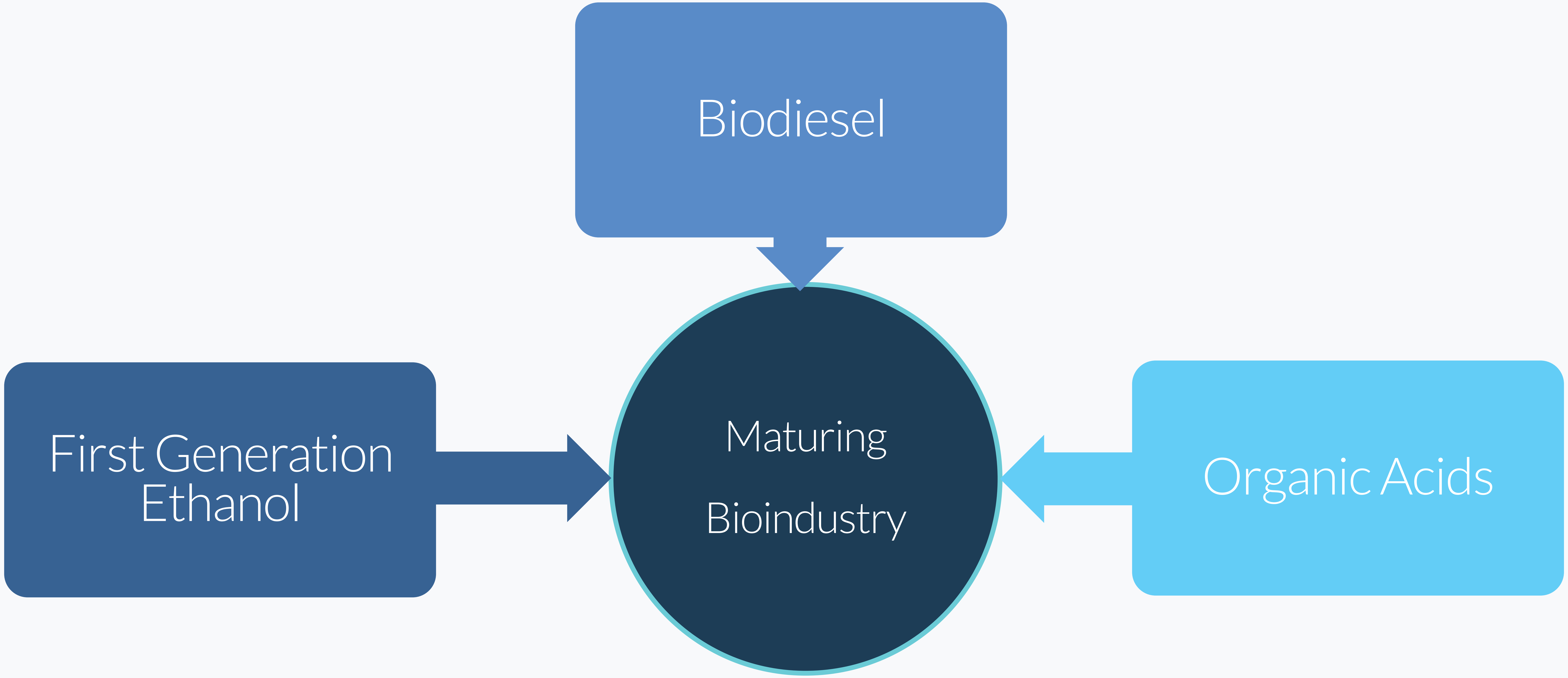
Industrial Biotech Maturity

Larger facilities, robust supply chains, reduced production costs, integrated multi-product plants

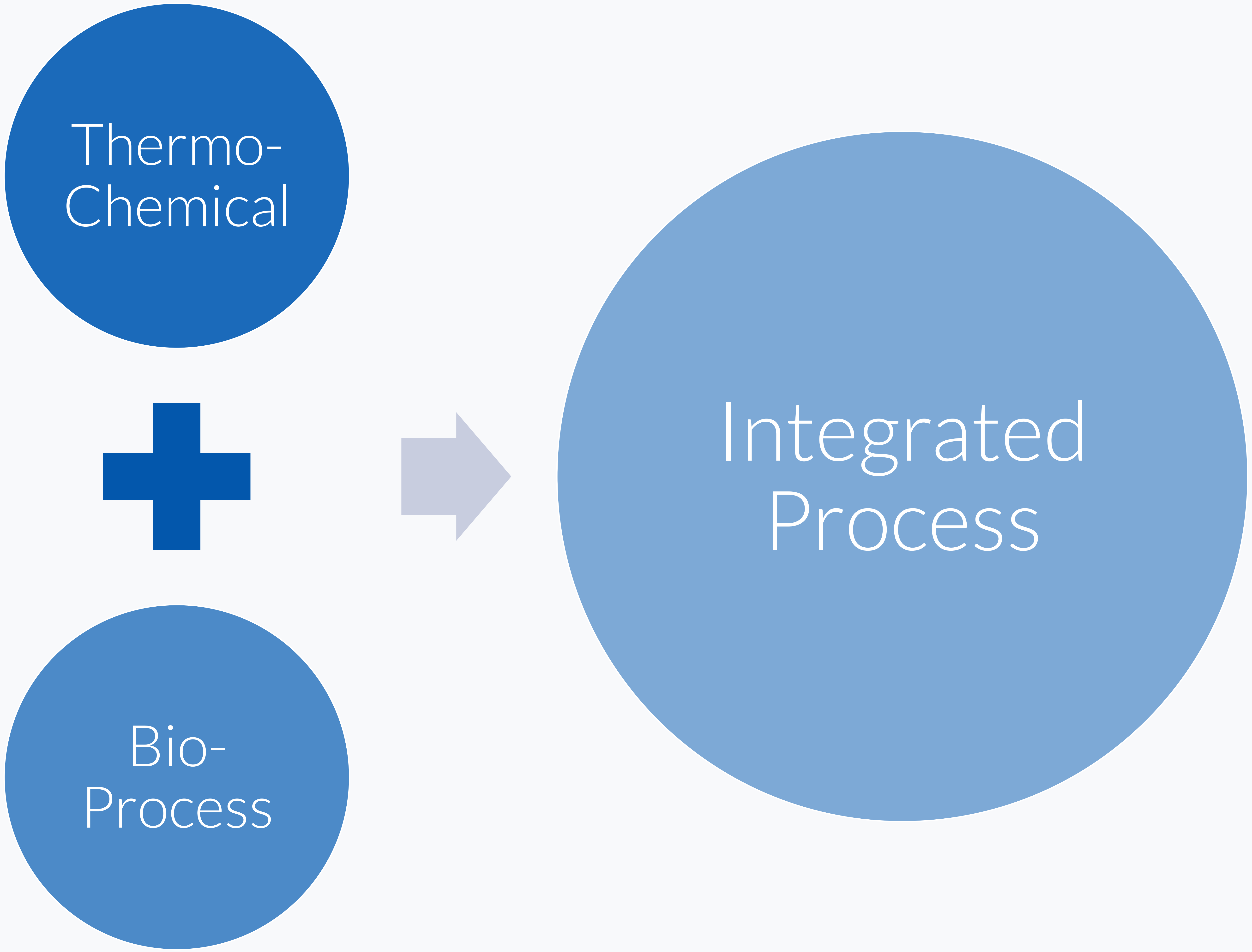


Bioprocessing Pros and Cons

+	−
--Mild Temperature and Pressure	--Low Reaction Rate
--Contaminant Tolerance	--Low Titre
--Feedstock Flexibility	--Limited in Scale

Enabling a New Paradigm

- Thermo-chemical Process: *Centuries of experience*
- Bio-process: *Novel feedstock, products, and processing routes*
- Integrated process: *Couple advantages of each to optimize production of low carbon, profitable products*



Integrated Processing Schemes

Maturity

Thermo-Chemical Conversion of Bio-Based Feedstock	Thermo-Chemical Conversion of Bio-Based Products
Renewable Diesel and Jet Fuel: Hydroprocessing of oils and fats to drop-in product	Conversion of ethanol to ethylene and subsequent downstream products (polyethylene, ethylene oxide, ethylene glycol, etc)
Catalytic conversion of bio-based feedstocks and intermediates to form oxygenated chemicals such as adipic acid, succinic acid, and propylene glycol	Fuel blendstocks from fermentation metabolites such as ethanol and iso-butanol
Aqueous phase catalysis of sugars to drop-in fuel and chemical products	Dehydrogenation of bio-based 13-BDO to butadiene
In-situ and ex-situ catalytic deoxygenation of pyrolysis oil	Conversion of ethanol to ethyl acetate

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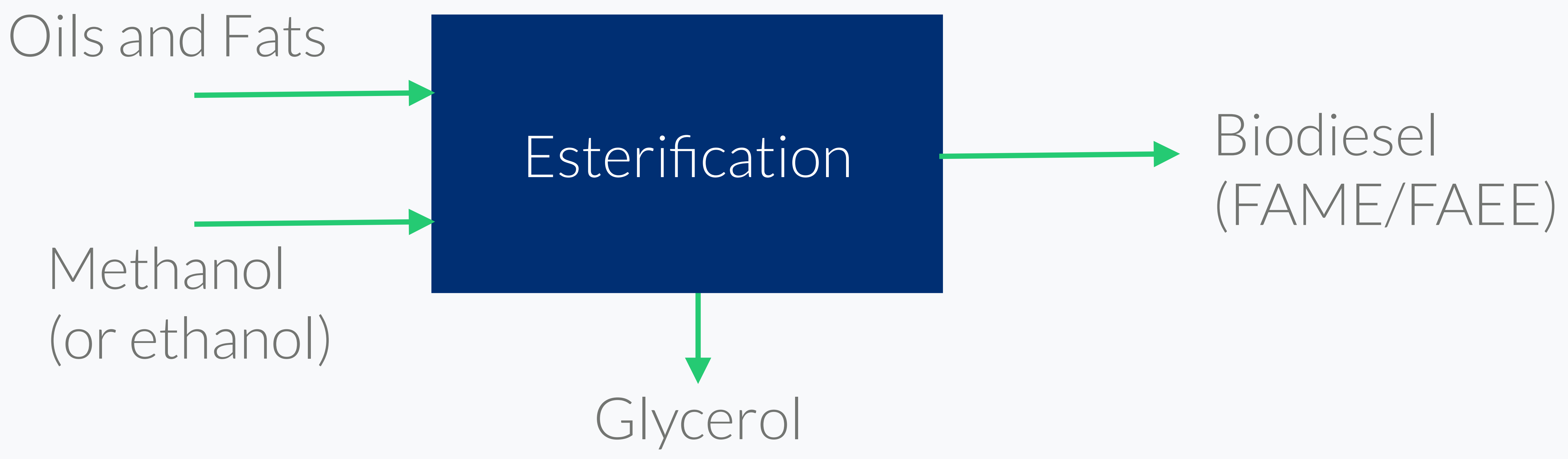
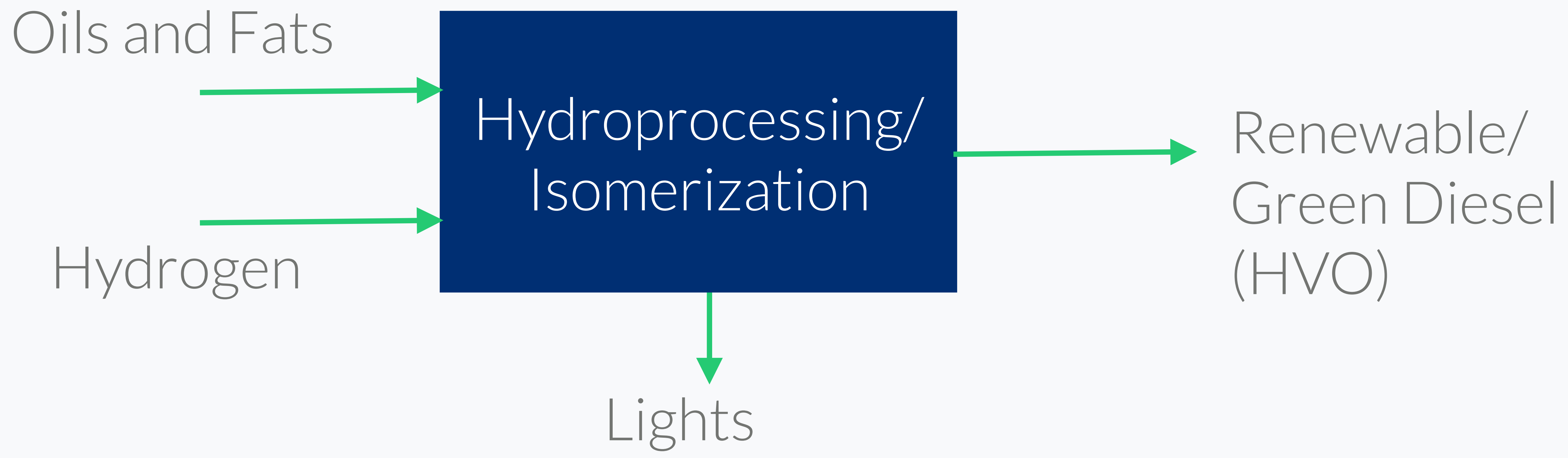
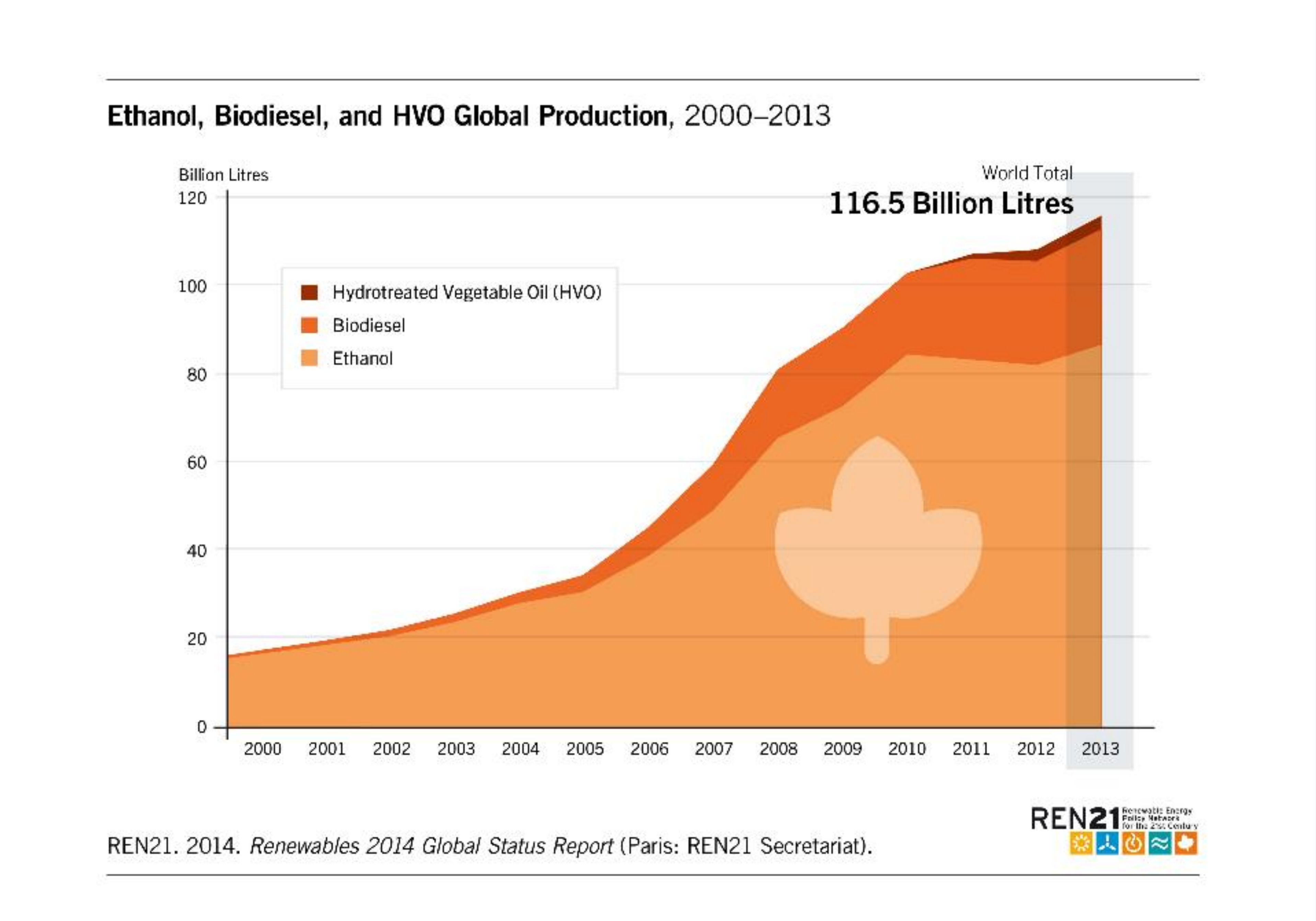
Renewable Diesel





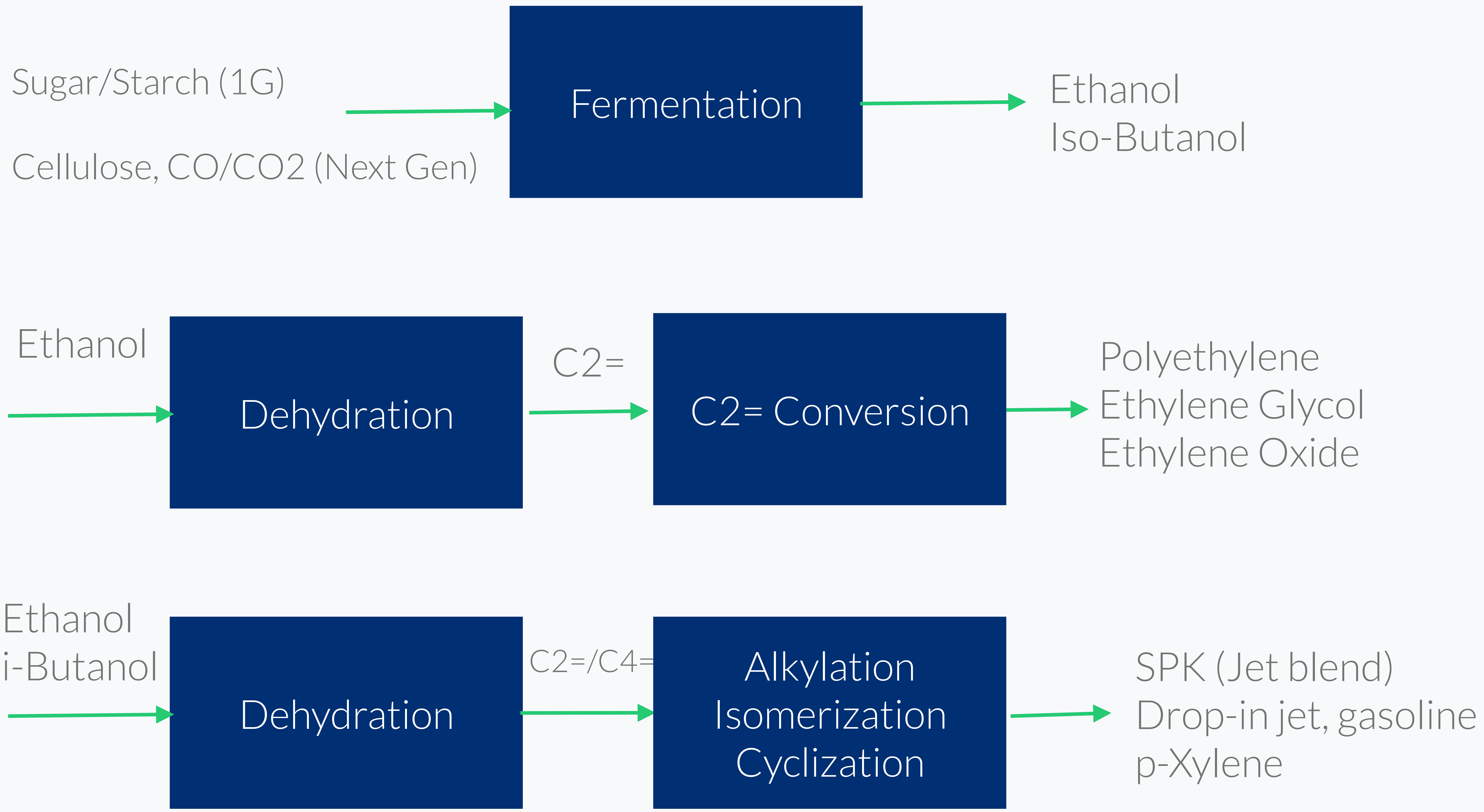
Thermo-chem Leverages Maturing Feedstock Supply Chain to Produce a Better Product



	Petroleum ULSD	FAME Biodiesel	Green Diesel
Oxygen, %	0	11	0
Cetane	40-55	50-65	75-90
Energy Density, MJ/kg	43	38	44
Sulfur, ppm	<10	<2	<2
Cold Flow	Baseline	Poor	Excellent
Oxidative Stability	Baseline	Poor	Excellent

Source: Honeywell Green Diesel ™ Literature

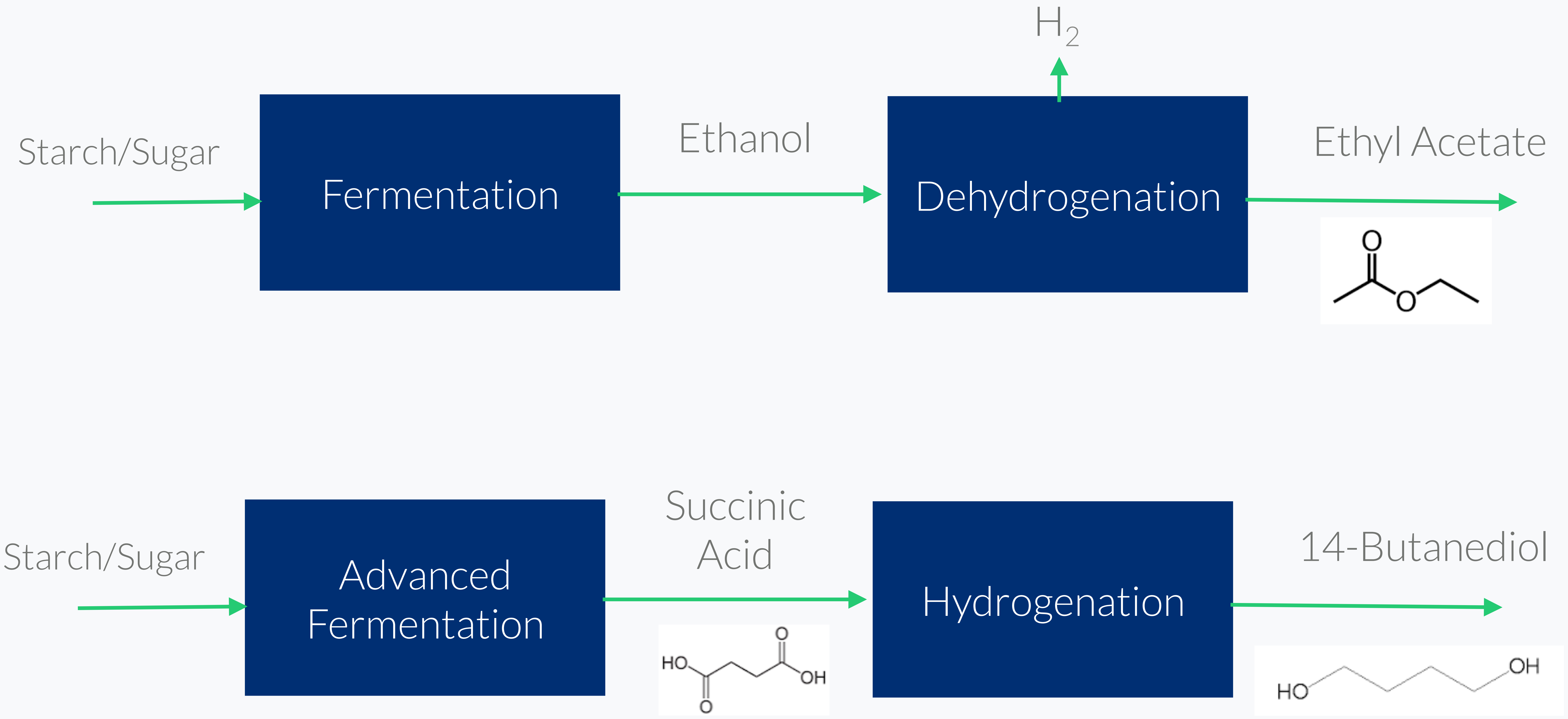
Alcohol Conversion to Drop-in Products



- Make use of established ethanol infrastructure
- Use thermochem to produce drop-in products
- Economic Challenges:
  - Ethanol is a fungible product
  - Overcome yield loss (e.g. 2 $/gal Ethanol = 1100 $/MT ethylene + cost of dehydration/purification)
- Can we get away from purified ethylene intermediate?

Thermo-chem Creates Drop-In Products and Expands the Market

Retaining the Oxygen



Bioprocessing + Thermochemical Conversion Eliminates the Need for Oxidation

Cav eats

§ Scale

Largest ethanol plant, Jilin Fuel Ethanol Co., (14,000 BPSD) << smaller than largest refinery complex, Reliance Jamnagar (1.2 M BPSD across two refineries).

§ Value Destruction and Yield Loss

Economics challenging in certain circumstances.

§ Water

Bioprocesses often require 90% water, so management and conservation is key. Some focus now on 'nexus' between water, energy, and sometimes food/land

These Challenges are Not Insurmountable and Should Not Stand in the Way of a Robust Bioeconomy

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Wrap-up and Conclusions

§ Biology + chemistry is a powerful combination

Opportunities to leverage another tool in the toolbox to get to a bio-based economy that has a significant impact on carbon reduction and added economic value

§ Ethylene intermediate is a challenge

Routes through ethylene intermediates will struggle to compete except in isolated circumstance. Conversion of ethanol to products, or sugars/oils

§ Let's Take the Mystery out of Bioprocessing

Make use of operational knowledge to develop scale-up rules and tools in order to accelerate the next generation of biotechnologies.