Nuclear Energy and Sustainability

Can a Nuclear-Assisted Biofuels System Enable Liquid Biofuels as the Economic Low-carbon Replacement for All Liquid Fossil Fuels and Hydrocarbon Feedstocks and Enable Negative Carbon Emissions?

C. Forsberg*, and B. Dale[1],

*Massachusetts Institute of Technology, Cambridge, MA, cforsber@mit.edu
[1]Michigan State University, East Lansing, MI, bdale@egr.msu.edu

MIT-NES-TR-023A
Combined Appendix
April 2022

For Public Distribution

CENTER FOR
ADVANCED NUCLEAR
ENERGY SYSTEMS

Massachusetts Institute of Technology
77 Massachusetts Avenue, 24-215
Cambridge, MA 02139-4307

(617) 452-2660
canes@mit.edu
canes.mit.edu

Massachusetts Institute of Technology
MICHIGAN STATE UNIVERSITY

Appendix A: Workshop Agenda

Can a Nuclear Biofuels System Enable Liquid Biofuels as the Economic Low-carbon Replacement for All Liquid Fossil Fuels and Hydrocarbon Feedstocks and Enable Negative Carbon Emissions?

Three Wednesday Webinars: 10:00 am-1:30 pm EST; August 4, 11 and 18

C. Forsberg*, B. Dale[1], D. Jones[2] and L. M. Wendt[3]

*Massachusetts Institute of Technology, Cambridge, MA, 02139, cforsber@mit.edu
[1]Michigan State University, East Lansing, MI, bdale@egr.msu.edu
[2]North Carolina State University, Raleigh, NC 27695, dsjones5@ncsu.edu
[3]Idaho National Laboratory, Idaho Falls, ID, lynn.wendt@inl.gov

System Design (Webinar 1: August 4, 2021: 10 am to 1:30 pm EST)

Welcome (10:00 am): Charles Forsberg (Massachusetts Institute of Technology) and Bruce Dale (Michigan State University): Modern civilization exists because of the remarkable properties of liquid fossil fuels—affordable, easily stored, dense energy source that are easy to transport. It is the chemical form of liquid fossil fuels [$(CH_2)_x$] that creates these properties. The problem is that the burning of fossil fuels adds carbon dioxide to the atmosphere that drives climate change. Biomass can provide an alternative source of carbon. Because plants remove carbon dioxide from the air, burning biomass does not change the carbon dioxide content of the atmosphere. The question is: Can we fully replace fossil hydrocarbons using carbon from biomass? If we can accomplish this, the proposed nuclear-assisted biofuels system provides a fast route to decarbonization because we do not have to rebuild the entire energy infrastructure.

1. ***Replacing Liquid Fossil Fuels and Chemical Plant Feedstocks with a Low-Carbon Nuclear Biofuels System Including Negative Carbon Emissions (10:10 am)***. Charles Forsberg (Massachusetts Institute of Technology)

2. ***Availability of Biomass as a Carbon Source for Biofuels (10:40 am)***. Bruce Dale (Michigan State University)

3. ***Carbon Dioxide Sequestration and Negative Carbon Emissions (11:10 am)***. Howard Herzog (Massachusetts Institute of Technology)

   Break: 11:40 am – 12:00

4. ***Feedstocks and Utilities Supply and Quality for the Biorefinery (12:00 am)*** Richard Boardman (Idaho National Laboratory)

5. ***Roeslein Alternative Energy's Vision for Conversion of Biomass to Digestate, Methane and Carbon Dioxide (12:30 am).*** Hassan Loutfi (Roeslein Alternative Energy)

6. ***Roundtable Discussion with Audience Participation (1:00-1:30)***

Biomass Supply Chain to the Refinery (Webinar 2: August 11, 2021; 10 am to 1:30 pm EST)

Welcome (10:00 am). Lynn Wendt (Idaho National Laboratory) The biomass supply chain is from the farm/forest to the nuclear-assisted biorefinery front gate. The depot converts low-density biomass into a high-density, storable, shippable product. However, it has other impacts. Depot processes generate secondary streams that in many cases enable recycle of nutrients back to farm and forest to improve long-term sustainability and soils.

7. ***The U.S. Refinery Decarbonization Potential and Cost Analysis (10:10 am)***. Pingping Sun (Argonne National Laboratory)

8. ***Depot Processing Options: Managing Variability through Fractionation, Merchandising, Formulation (10:40 am)***. Richard Hess (Idaho National Laboratory)

9. ***Wet versus Dry Biomass Intermediate Products and Associated Logistics Systems (11:10 am).*** Lynn Wendt (Idaho National Laboratory)

Break: 11:40 am – 12:00 pm

10. ***Carbon-Negative Electrobiofuels from Regional Pyrolysis Depots (12:00 pm).*** Christopher Saffron (Michigan State University)

11. ***Biomass Supply Chain to the Refinery Transportation from Depot to Biorefinery (12:30).*** Daniela Jones (North Carolina State University)

12. ***Roundtable Discussion with Audience Participation (1:00 pm)***

Nuclear Biorefinery Options (Webinar 3: August 18, 2021: 10 am to 1:30 pm EST)

Welcome (10:00 am). Charles Forsberg (Massachusetts Institute of Technology): The nuclear-assisted biorefinery converts biomass feedstocks to hydrocarbon fuels with massive inputs of heat and hydrogen. What are the options—both inputs (heat and hydrogen) and the refinery?

13. ***Nuclear Hydrogen for Biofuels (10:10 am)***. Eric Ingersoll (LucidCatalyst)

14. ***Low-Carbon Intensity Hydrogen Production (10:35 am)***. Addison Cruz (Honeywell UOP)

15. ***Conversion of Biomass to Hydrocarbon Fuels and Chemicals*** *[Ethanol to Hydrocarbon Fuel Blendstocks]* ***(11:00 am)***. John Hannon (Vertimass)

16. ***Direct Hydrodeoxygenation of Lignocellulosic Biomass into Hydrocarbons (11:25 am)***. Ana Rita C. Morais (University of Kansas)

    Break: 11:50 am – 12:10 am

17. ***Shell's Gas-to-Liquids (Fisher-Tropsch) Technology and Opportunities in the Energy Transitions (12:10 pm)***. Svetlana van Bavel (Shell Global Solutions International B.V.)

18. ***Matching Nuclear Reactors to Nuclear Biomass Systems (12:35 pm)***. Charles Forsberg (Massachusetts Institute of Technology)

19. **Roundtable Discussion with Audience Participation (1:00 pm)**

.

Appendix B: Workshop Participants

Appendix B: Workshop Participants

The workshop had a highly diverse set of participants as shown in Fig. B.1. There were 174 participants including 65 from industry, 40 from national laboratories, 39 from universities, 22 other and 8 from government.

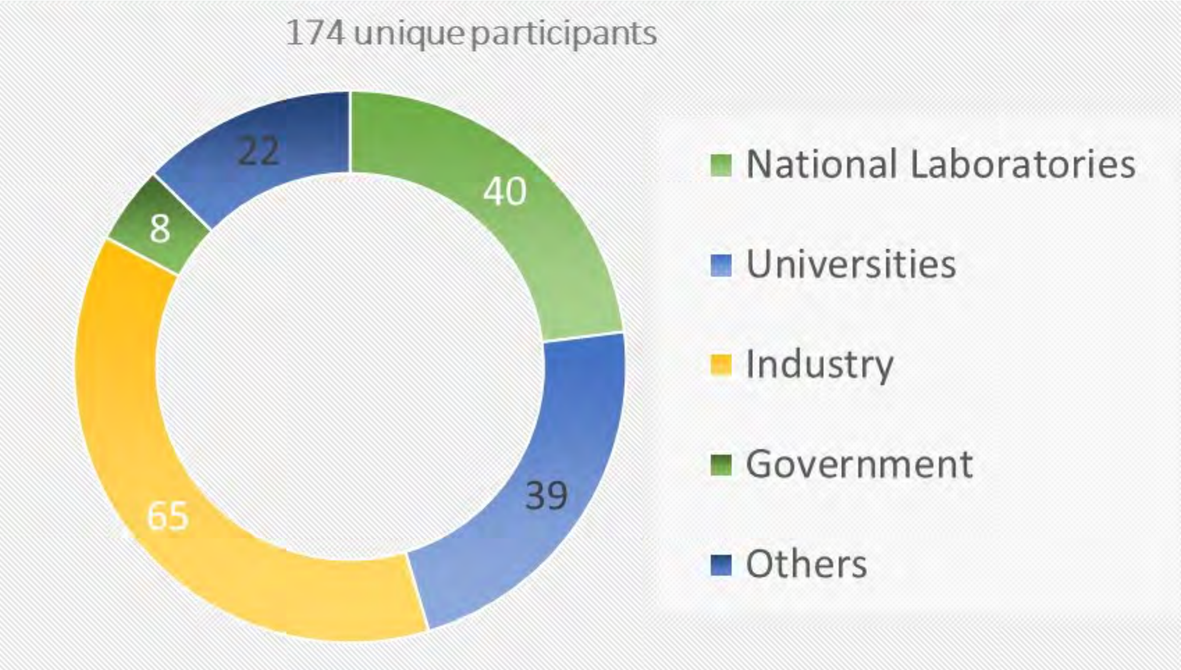


Fig. B.1. Workshop Participants

Appendix C: Speaker Presentations

Appendix C: Presentation Table of Contents

	Presentation	Speaker	Page
1-1	Replacing Liquid Fossil Fuels and Chemical Plant Feedstocks with a Low-Carbon Nuclear Biofuels System Including Negative Carbon Emissions.	Charles Forsberg (Massachusetts Institute of Technology)	1
1-2	Availability of Biomass as a Carbon Source for Biofuels.	Bruce Dale (Michigan State University)	17
1-3	Carbon Dioxide Sequestration and Negative Carbon Emissions.	Howard Herzog (Massachusetts Institute of Technology)	30
1-4	Feedstocks and Utilities Supply and Quality for the Biorefinery	Richard Boardman (Idaho National Laboratory)	37
1-5	Roeslein Alternative Energy's Vision for Conversion of Biomass to Digestate, Methane and Carbon Dioxide.	Hassan Loutfi (Roeslein Alternative Energy)	46
2-1	Depot Processing Options: Managing Variability through Fractionation, Merchandising, Formulation.	Richard Hess (Idaho National Laboratory)	51
2-2	Wet versus Dry Biomass Intermediate Products and Associated Logistics Systems.	Lynn Wendt (Idaho National Laboratory)	74
2-3	Carbon-Negative Electrobiofuels from Regional Pyrolysis Depots.	Christopher Saffron (Michigan State University)	99
2-4	Biomass Supply Chain to the Refinery Transportation from Depot to Biorefinery.	Daniela Jones (North Carolina State University)	129
3-1	Nuclear Hydrogen for Biofuels.	Eric Ingersoll (LucidCatalyst)	142
3-2	Low-Carbon Intensity Hydrogen Production.	Addison Cruz (Honeywell UOP)	150
3-3	Conversion of Biomass to Hydrocarbon Fuels and Chemicals.	John Hannon (Vertimass)	156
3-4	Direct Hydrodeoxygenation of Lignocellulosic Biomass into Hydrocarbons.	Ana Rita C. Morais (University of Kansas)	168
3-5	Shell's Gas-to-Liquids (Fisher-Tropsch) Technology and Opportunities in the Energy Transitions.	Svetlana van Bavel (Shell Global Solutions International B.V.)	176
3-6	Matching Nuclear Reactors to Nuclear Biomass Systems.	Charles Forsberg (Massachusetts Institute of Technology)	181

Replacing Liquid Fossil Fuels and Chemical Plant Feedstocks with a Low-Carbon Nuclear Biofuels System Including Negative Carbon Emissions

Charles Forsberg (*cforsber@mit.edu*)
Massachusetts Institute of Technology
Cambridge, MA

Workshop: Can a Nuclear Biofuels System Enable Liquid Biofuels as the
Economic Low-carbon Replacement for All Liquid Fossil Fuels and
Hydrocarbon Feedstocks with Negative Carbon Emissions
August 4, 2021: 10:00-1:30 Eastern
Webinar Series: 10:00-1:30 Eastern; August 4, 11 and 18

Presentation Outline

- Why a Nuclear Biomass System?
- System Design (Webinar 1)
- Nuclear Bio-refinery and Implications on Biomass Supply Chain (Webinar 3)
- Biomass Supply Chain (Webinar 2)

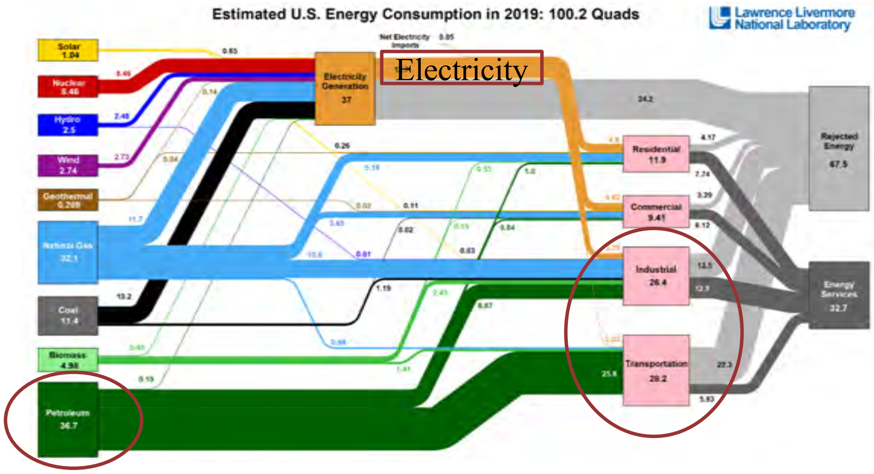
Acknowledgement: We would like to thank for their support the Idaho National Laboratory and the INL National Universities Consortium (NUC) Program under DOE Idaho Operations Contract DE-AC07-05ID14517.

Why a Nuclear Biomass System?

Massachusetts Institute of Technology

Liquid Fuels Are Central to the U.S. Economy

- Electricity: 37% input; 17% to Customer
- Oil: 36.7% input; 48% to Customer



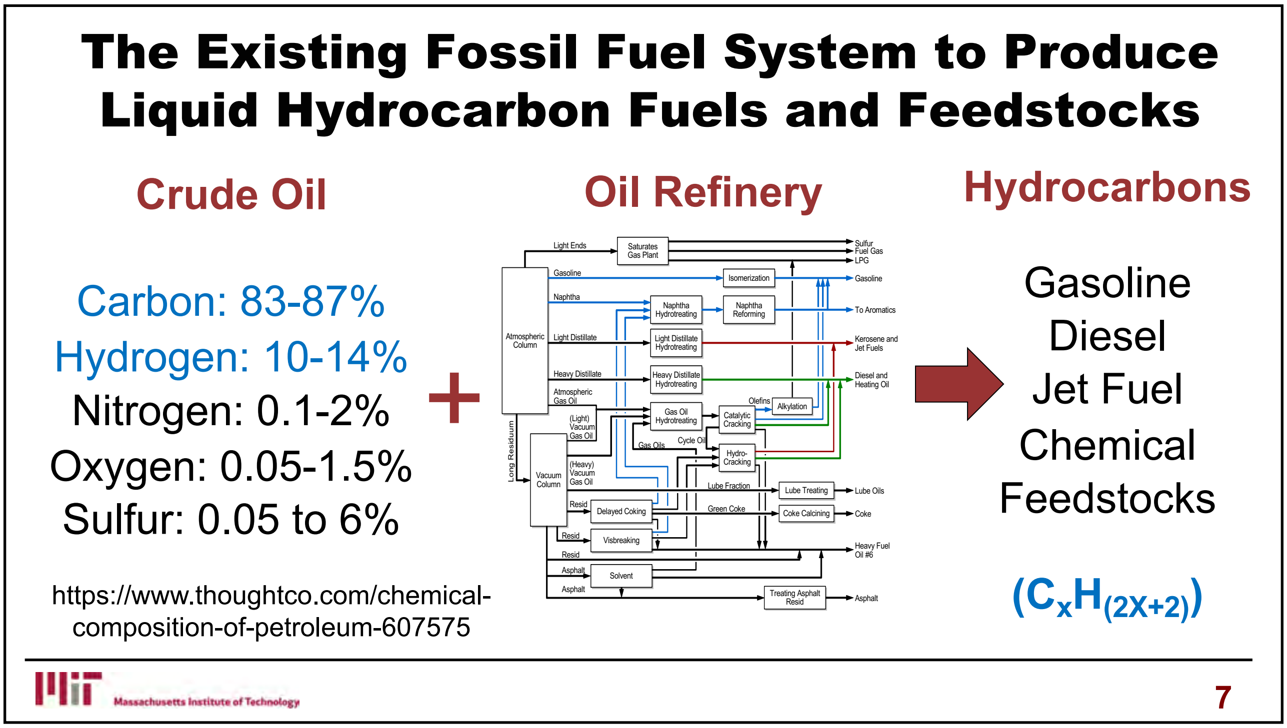
The Webinar Deals with about One-Half of the Energy System

Massachusetts Institute of Technology

Replacing Liquid Hydrocarbon Fuels and Chemical Feedstocks is Difficult

- Transportation from cars to airplanes with different fuels
- Chemical industry (thousands of processes and products)
- Peak winter heating demands that are many times existing peak electricity demands—X times larger grid if electrify?
- **The workshop examines whether nuclear biofuels can fully & economically replace oil in a low-carbon world; not biofuels as a niche fuel for limited applications**

Nuclear Biomass System Design



The Existing Fossil Fuel System to Produce Liquid Hydrocarbon Fuels and Feedstocks

Crude Oil

Carbon: 83-87%
Hydrogen: 10-14%
Nitrogen: 0.1-2%
Oxygen: 0.05-1.5%
Sulfur: 0.05 to 6%

https://www.thoughtco.com/chemical-composition-of-petroleum-607575

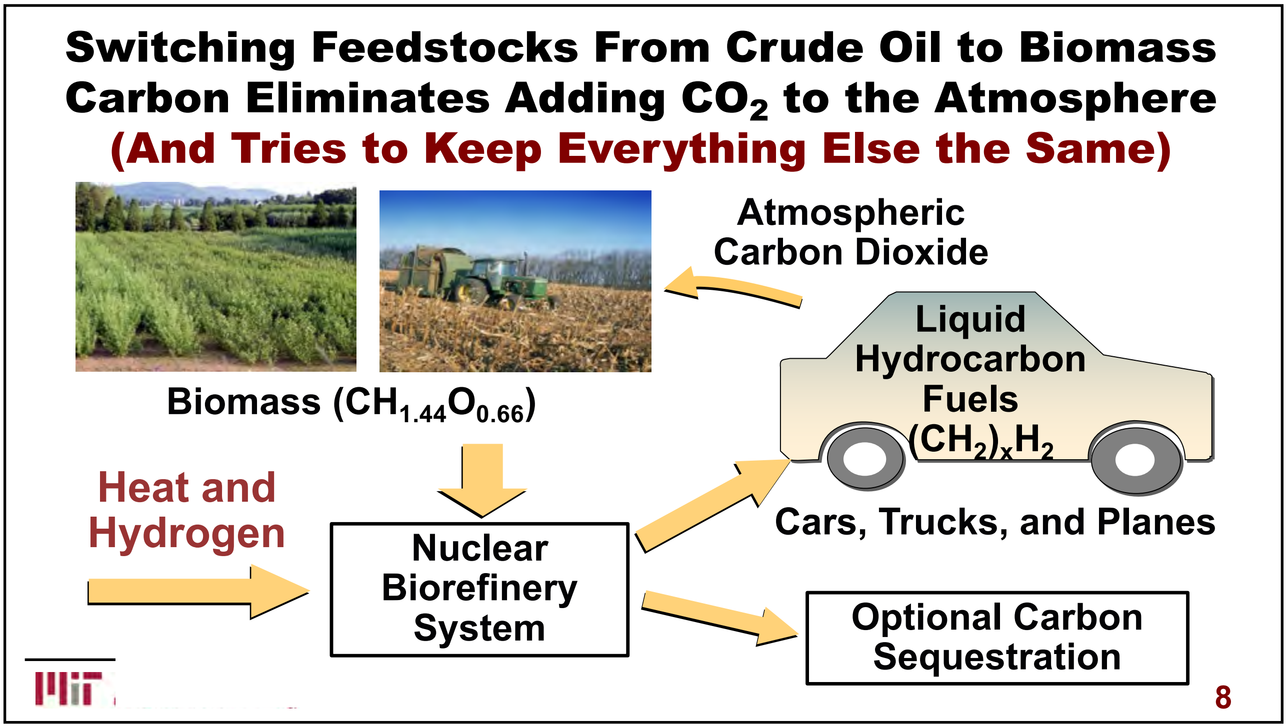
\+

Oil Refinery

Hydrocarbons

Gasoline
Diesel
Jet Fuel
Chemical
Feedstocks

$(C_xH_{(2X+2)})$



Switching Feedstocks From Crude Oil to Biomass Carbon Eliminates Adding CO_2 to the Atmosphere (And Tries to Keep Everything Else the Same)

Biomass $(CH_{1.44}O_{0.66})$

Atmospheric Carbon Dioxide

Liquid Hydrocarbon Fuels $(CH_2)_xH_2$

Cars, Trucks, and Planes

Heat and Hydrogen

Nuclear Biorefinery System

Optional Carbon Sequestration

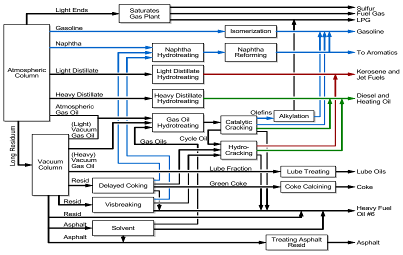
Strategy Implies Massive Change in Feedstocks, Large Changes in Refineries, No Change in Hydrocarbon Products

Biomass
Supply Chain

$CH_{1.44}O_{0.66}$
Wide Variability

+

Nuclear Biorefinery



Hydrocarbons

Gasoline
Diesel
Jet Fuel
Chemical
Feedstocks

No Change

Sequestered Carbon from Atmosphere

Traditional Versus Nuclear Biofuels

Biomass + Oxygen → Hydrocarbons + Carbon Dioxide

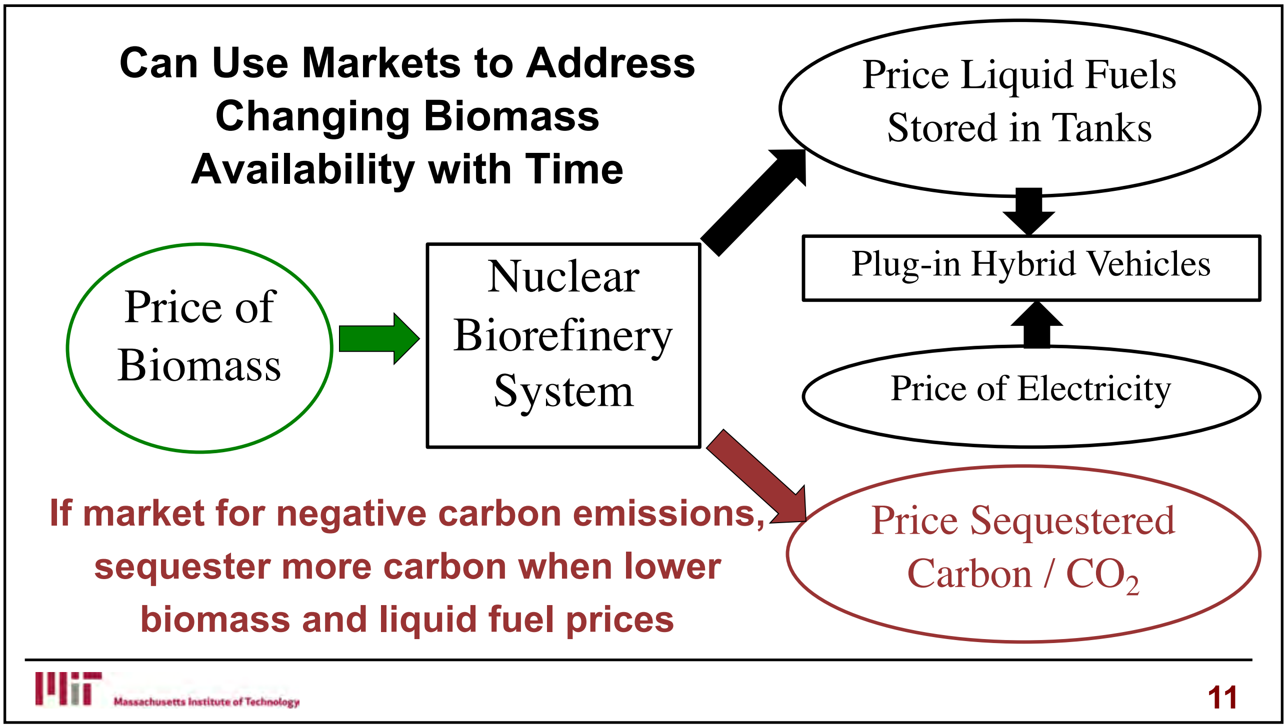
$\underline{C}H_{1.44}O_{0.66}$ + O_2 → $(\underline{C}H_2)_xH_2$ + $\underline{C}O_2$

- – Carbon used to make hydrocarbon fuels (gasoline, diesel and jet fuel)
- – Carbon oxidation (1) removes oxygen and (2) provides energy for the process

Biomass + Hydrogen + Nuclear → Hydrocarbons + Water

$\underline{C}H_{1.44}O_{0.66}$ + H_2 + Heat → $(\underline{C}H_2)_xH_2$ + H_2O

- – **External H_2 and heat doubles energy of hydrocarbon fuel per unit feedstock**
- – **Enables use of low-energy-value high-carbon-content biomass feedstocks**
- – **Potentially sufficient biomass to replace all crude oil for liquid fuels and chemical feedstock production**



Can Use Markets to Address Changing Biomass Availability with Time

Price of Biomass

Nuclear Biorefinery System

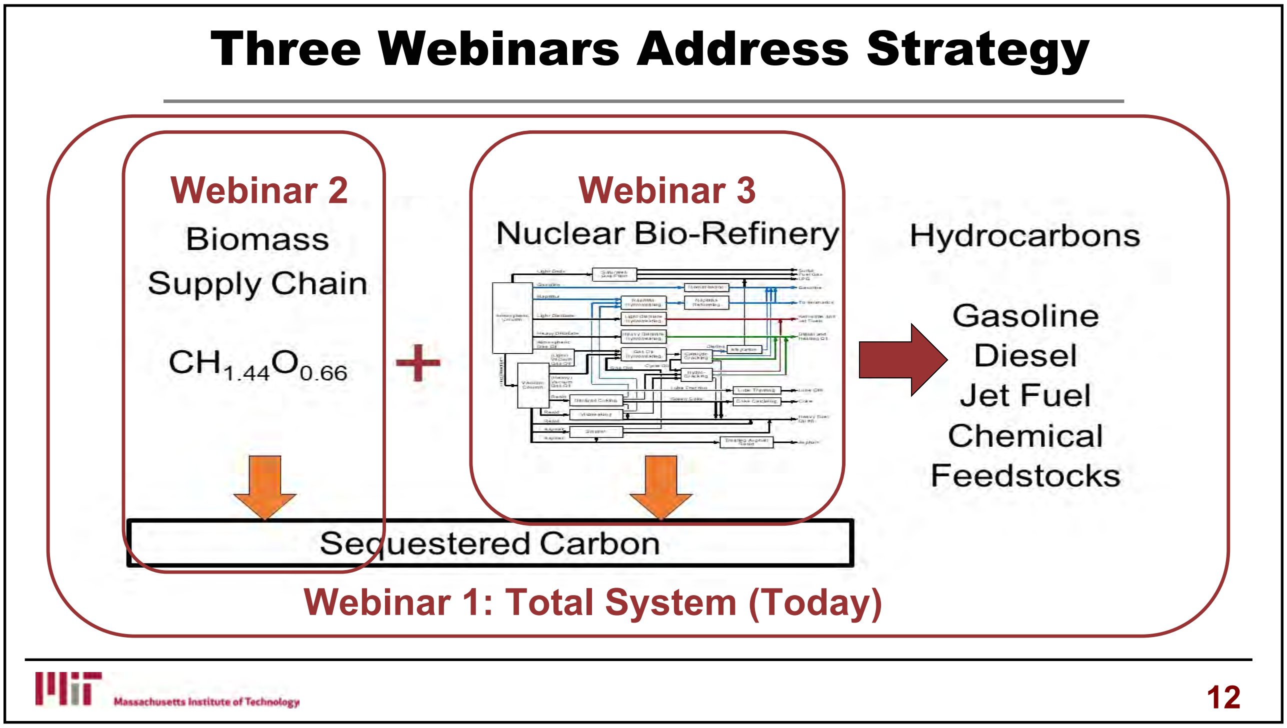
Price Liquid Fuels Stored in Tanks

Plug-in Hybrid Vehicles

Price of Electricity

Price Sequestered Carbon / CO_2

If market for negative carbon emissions, sequester more carbon when lower biomass and liquid fuel prices



Three Webinars Address Strategy

Webinar 2

Biomass Supply Chain

$CH_{1.44}O_{0.66}$

+

Webinar 3

Nuclear Bio-Refinery

Hydrocarbons

Gasoline
Diesel
Jet Fuel
Chemical Feedstocks

Sequestered Carbon

Webinar 1: Total System (Today)

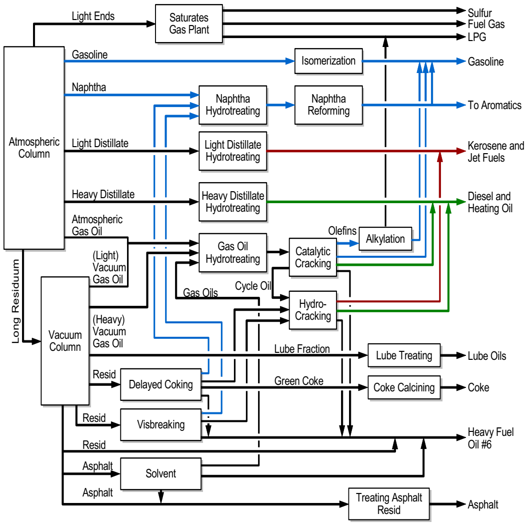
Nuclear Biorefinery

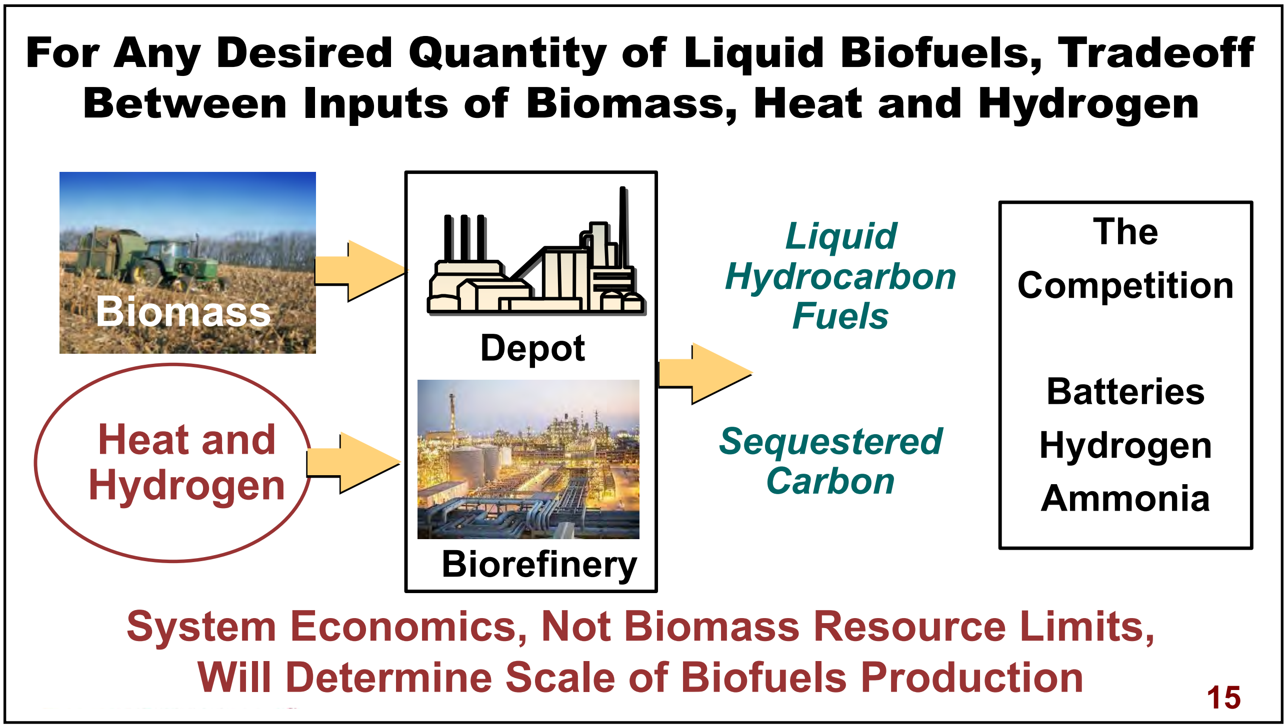
Drives System Design

(Webinar 3)

Nuclear Biorefinery Is a Variant of an Oil Refinery

- Need to remove impurities
  - Crude Oil: Up to 6% Sulfur and 1.5% Oxygen by weight
  - Biomass: 44% Oxygen, some N, P, K, S and water.
- Adjust hydrogen-to-carbon ratio
- Rearrange molecules to get hydrocarbon products
- Oil & biomass feedstocks both vary considerably in composition





For Any Desired Quantity of Liquid Biofuels, Tradeoff Between Inputs of Biomass, Heat and Hydrogen

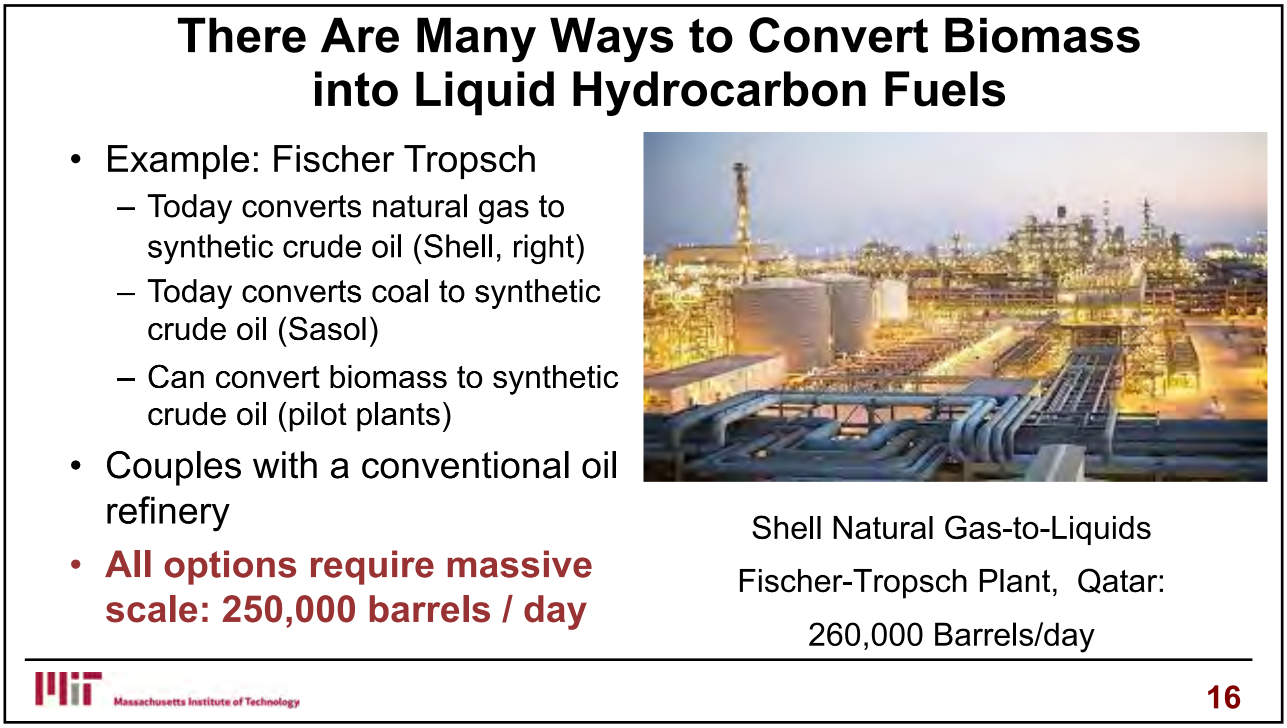
Liquid Hydrocarbon Fuels

Sequestered Carbon

The Competition

Batteries
Hydrogen
Ammonia

System Economics, Not Biomass Resource Limits, Will Determine Scale of Biofuels Production



There Are Many Ways to Convert Biomass into Liquid Hydrocarbon Fuels

- Example: Fischer Tropsch
  - Today converts natural gas to synthetic crude oil (Shell, right)
  - Today converts coal to synthetic crude oil (Sasol)
  - Can convert biomass to synthetic crude oil (pilot plants)
- Couples with a conventional oil refinery
- **All options require massive scale: 250,000 barrels / day**

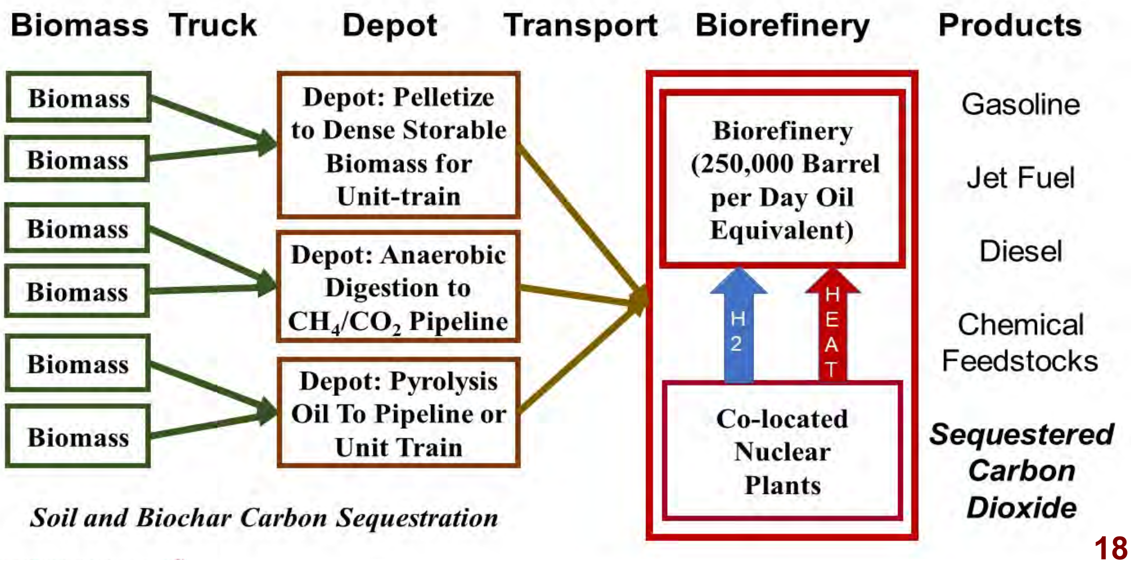
Shell Natural Gas-to-Liquids
Fischer-Tropsch Plant, Qatar:
260,000 Barrels/day

Implications of Large Biorefineries

- Require concentrated heat sources that can only be provided by nuclear or fossil fuels with carbon capture and sequestration
- Require massive amounts of biomass feedstocks
  - ~60,000 tons per day per biorefinery (250,000 barrel/day)
  - Low-density biomass can be economically shipped 30 to 50 miles. Insufficient biomass to support nuclear biorefinery
  - Require depots to consolidate biomass near the farm or forest into dense, storable economically-shippable intermediate biomass products
- **Three different kinds of depots producing solid, liquid and/or gaseous intermediate products**

Massachusetts Institute of Technology

Depots Convert Biomass Into Economically-Shippable Storable Intermediate Product for Nuclear Biorefinery



Biomass Truck **Depot** **Transport** **Biorefinery** **Products**

Biomass

Biomass

Biomass

Biomass

Biomass

Biomass

Depot: Pelletize to Dense Storable Biomass for Unit-train

Depot: Anaerobic Digestion to CH_4/CO_2 Pipeline

Depot: Pyrolysis Oil To Pipeline or Unit Train

Biorefinery (250,000 Barrel per Day Oil Equivalent)

H_2

HEAT

Co-located Nuclear Plants

Gasoline

Jet Fuel

Diesel

Chemical Feedstocks

Sequestered Carbon Dioxide

Soil and Biochar Carbon Sequestration

Processes Enable Variable Fuel and Sequestered Carbon Production Based on Market Prices

- Carbon sequestration
  - At depot level, e.g., as biochar or digestate from anaerobic digestion
  - At refinery level, sequestering CO_2 is cheap if right geology (Webinar 1)
- Carbon capture economics
  - Expensive at power plants because cost of separating CO_2 from stack gas
  - Zero cost with digestate or pyrolysis depot options
  - Low cost at nuclear biorefinery where nearly pure CO_2 streams

Sequestration Site Map

https://www.usgs.gov/media/images/co2-sequestration-assessment-interactive-map

The Hydrogen Requirements are Massive

Steam Methane Reforming with CCS of Natural Gas

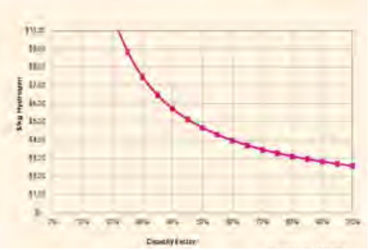
- SMR produces most hydrogen today
- Process can produce pure CO_2 as byproduct at low cost
- Economic where cheap natural gas and local carbon sequestration sites

Nuclear High-Temperature Electrolysis of Steam

- Most efficient
- Nuclear H_2 Gigafactory
- Potentially competitive

Wind / Solar PV Electrolysis of Water

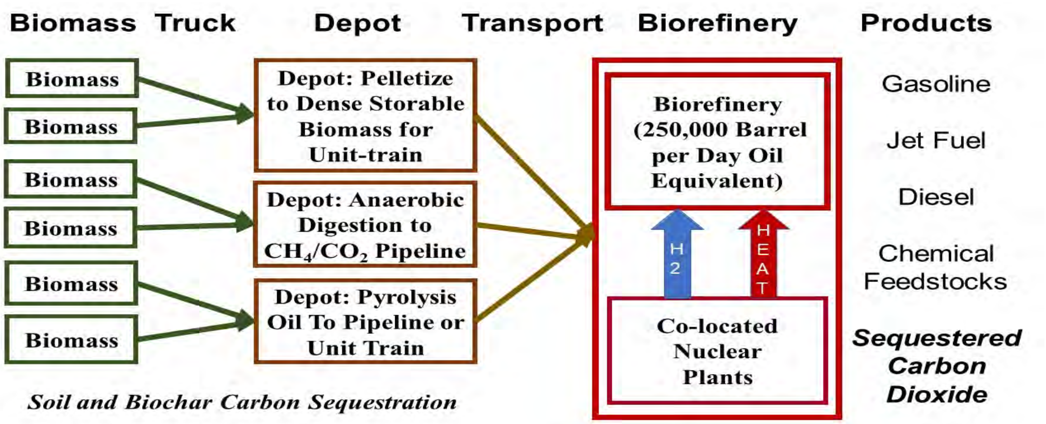
- Low-capacity-factor electrolysis plants yields expensive H_2
- Is there any solution?



For U.S., ~100 Million Tons per Year

Massive Heat / H_2 / Electricity Input: 10 - 20% U.S. Energy

Oil Today Provides Almost Half Energy Input to Final Users



Biomass Truck Depot Transport Biorefinery Products

Biomass

Biomass

Biomass

Biomass

Biomass

Biomass

Depot: Pelletize to Dense Storable Biomass for Unit-train

Depot: Anaerobic Digestion to CH_4/CO_2 Pipeline

Depot: Pyrolysis Oil To Pipeline or Unit Train

Biorefinery (250,000 Barrel per Day Oil Equivalent)

H_2

HEAT

Co-located Nuclear Plants

Gasoline

Jet Fuel

Diesel

Chemical Feedstocks

Sequestered Carbon Dioxide

Soil and Biochar Carbon Sequestration

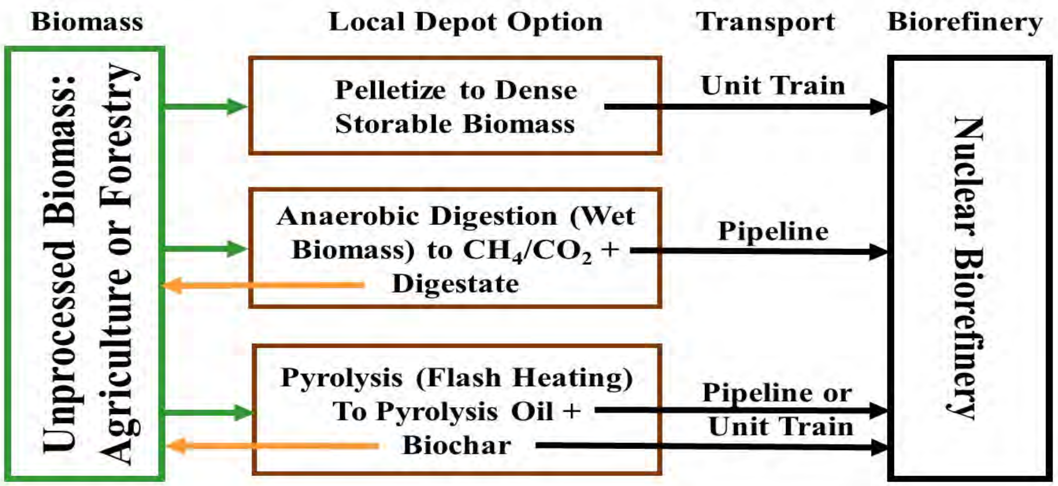
Co-Generation or Fission Batteries

Larger Reactors

Biomass Supply Chain

(Webinar 2)

We Have Three Depot Options To Convert Biomass into Storeable, Economically-Shippable Feedstock for the Biorefinery



Biomass

Local Depot Option

Transport

Biorefinery

Unprocessed Biomass: Agriculture or Forestry

Pelletize to Dense Storable Biomass

Unit Train

Anaerobic Digestion (Wet Biomass) to CH_4/CO_2 + Digestate

Pipeline

Pyrolysis (Flash Heating) To Pyrolysis Oil + Biochar

Pipeline or Unit Train

Nuclear Biorefinery

Some Depot Options Produce Added Products: Animal Feed, etc.

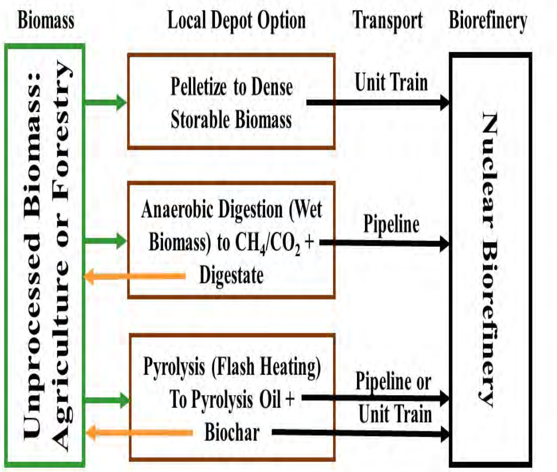
Depots Enable Economic Shipping to Biorefinery

- Dense pelletized biomass by unit train and barge
  - Today corn (dense and stable) is shipped worldwide
  - ~60,000 tons biomass / day for 250,000 b/d biorefinery
- Ship anaerobic CO_2/CH_4 by pipeline and store like natural gas
- Pyrolysis liquids by unit train

Archer Daniels:
Corn wet mill in Decatur, IL
15,000 tons per day

We Can Recycle Nutrients, Sequester Carbon in Soil and Improve Soil Productivity

- Food, paper and timber remove soil nutrients because need them in the final product
- **We only want carbon and hydrogen (no P, K, others)**
  - Can recycle nutrients back to agriculture and forests
  - Can recycle carbon char or digestate to sequester carbon & improve soil properties

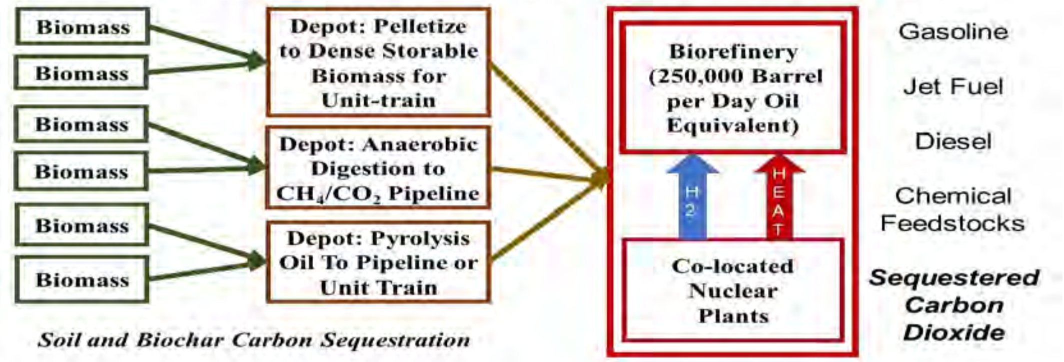


Initial Studies Indicate Sufficient Biomass Without Major Impacts on Food and Fiber Prices

- Most biomass studies view biomass as an *energy source*
- **Nuclear biofuels views biomass first as a carbon source, including low-energy biomass (kelp, double crops, sewage sludge, garbage, etc.)**
- Basis for sustainable biomass carbon production levels
  - Extraordinary growth in yields: Example: corn yields have increased from 20 to 180 bushels per acre
  - Expand biomass production such as two crops per year
  - Harvesting carbon, not energy (Different definition of crop)

Summary and Conclusions

- A Nuclear Biofuels System May Enable Liquid Biofuels as the Economic Low-carbon Replacement for All Liquid Fossil Fuels and Hydrocarbon Feedstocks with Negative Carbon Emissions
- **Workshop is a starting point to understand the options**



Biomass

Biomass

Biomass

Biomass

Biomass

Biomass

Depot: Pelletize to Dense Storable Biomass for Unit-train

Depot: Anaerobic Digestion to CH_4/CO_2 Pipeline

Depot: Pyrolysis Oil To Pipeline or Unit Train

Biorefinery (250,000 Barrel per Day Oil Equivalent)

Co-located Nuclear Plants

Gasoline

Jet Fuel

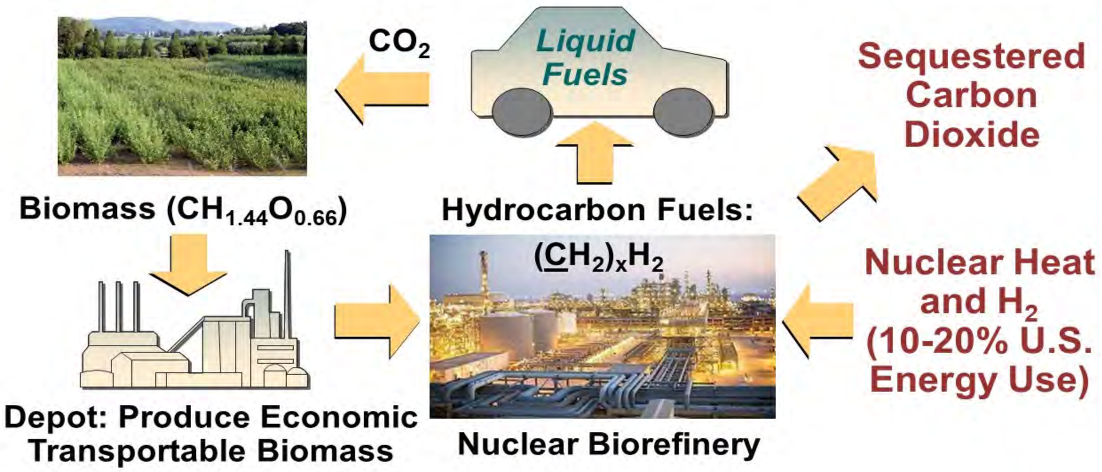
Diesel

Chemical Feedstocks

Sequestered Carbon Dioxide

Soil and Biochar Carbon Sequestration

Questions?



CO_2

Liquid Fuels

Sequestered Carbon Dioxide

Biomass ($CH_{1.44}O_{0.66}$)

Hydrocarbon Fuels: $(\underline{C}H_2)_xH_2$

Nuclear Heat and H_2 (10-20% U.S. Energy Use)

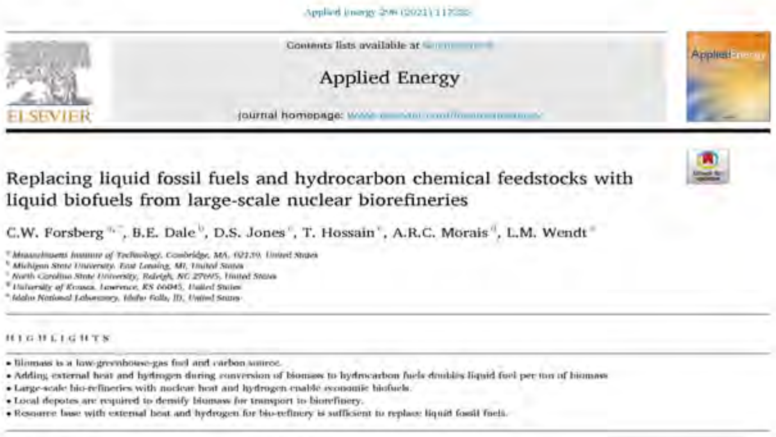
Depot: Produce Economic Transportable Biomass

Nuclear Biorefinery

Massachusetts Institute of Technology

Added Resources

- Prepared paper (right and web address below) as basis for organizing workshop that provides much added detail
- Workshop proceedings will be prepared and sent to all participants



Applied Energy 298 (2021) 117225

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

ELSEVIER

Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries

C.W. Forsberg[a,*], B.E. Dale[b], D.S. Jones[c], T. Hossain[e], A.R.C. Morais[d], L.M. Wendt[e]

[a] Massachusetts Institute of Technology, Cambridge, MA, 02139, United States
[b] Michigan State University, East Lansing, MI, United States
[c] North Carolina State University, Raleigh, NC 27695, United States
[d] University of Kansas, Lawrence, KS 66045, United States
[e] Idaho National Laboratory, Idaho Falls, ID, United States

HIGHLIGHTS

- Biomass is a low-greenhouse-gas fuel and carbon source.
- Adding external heat and hydrogen during conversion of biomass to hydrocarbon fuels doubles liquid fuel per ton of biomass
- Large-scale bio-refineries with nuclear heat and hydrogen enable economic biofuels.
- Local depotes are required to densify biomass for transport to biorefinery.
- Resource base with external heat and hydrogen for bio-refinery is sufficient to replace liquid fossil fuels.

Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries - ScienceDirect

Massachusetts Institute of Technology

CO_2 Sequestration Is Inexpensive at Scale In Good Locations

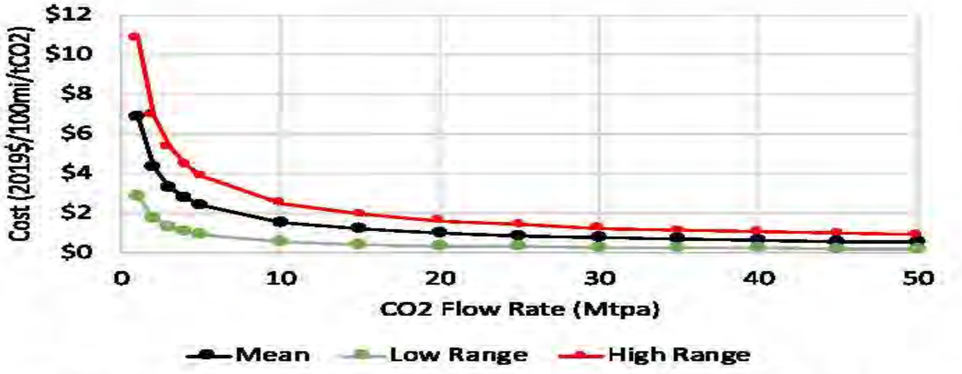


Fig. 1. Total CO_2 transport costs for a 100-mile onshore pipeline in the United States in 2019 current dollars. Low and high cost range reflect two standard deviations away from the mean and are based on the capital cost factors updated from Heddle et al. (2003) as visible in Table 1.

E. Smith et. al, "The Cost of CO_2 Transport and Storage in Global Integrated Assessment Modelling", International Journal of Greenhouse Gas Control, 109 (2021) 103367. https://doi.org/10.1016/j.ijggc.2021.103367

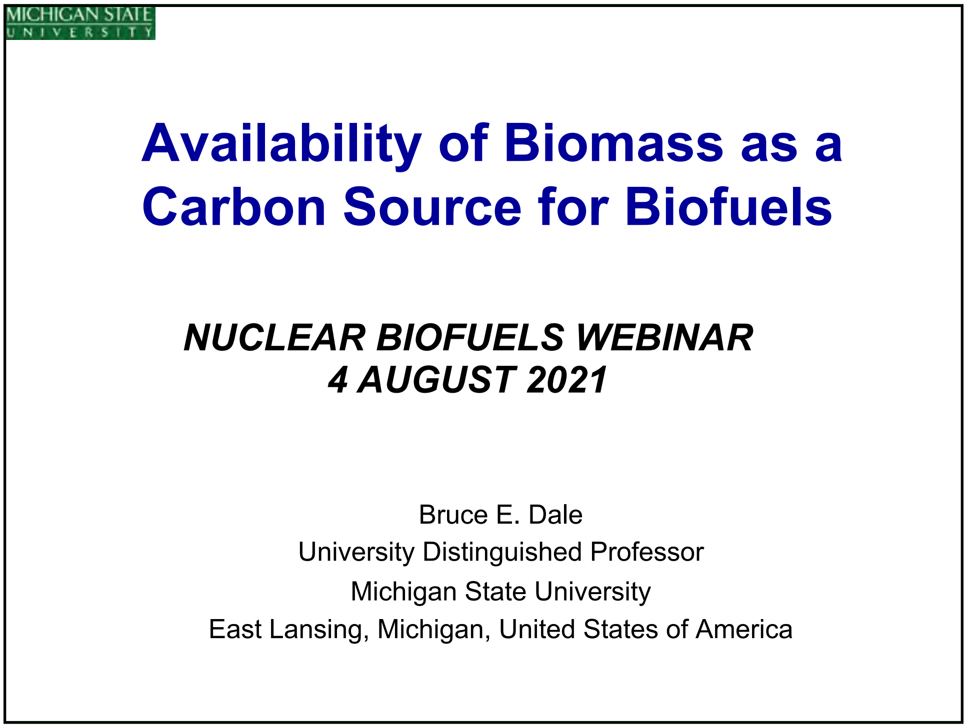
Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include (1) Fluoride-salt-cooled High-Temperature Reactors (FHRs), (2) utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh Crushed Rock Ultra-Large Stored Heat (CRUSH) systems and (3) nuclear hybrid systems including nuclear biofuels. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.

Massachusetts Institute of Technology

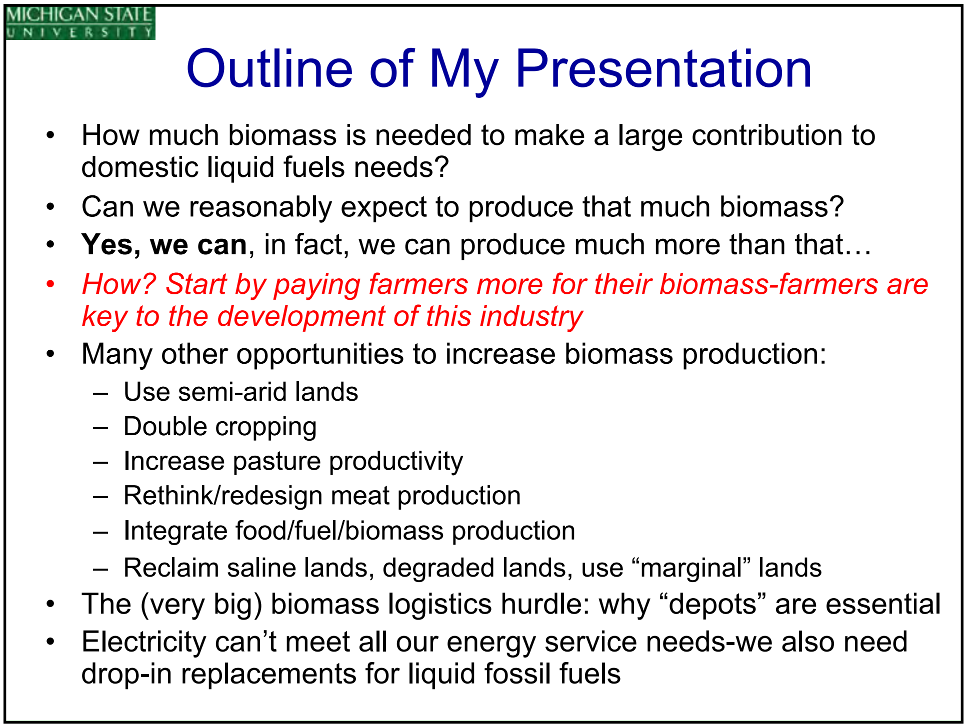
http://web.mit.edu/nse/people/research/forsberg.html



Availability of Biomass as a Carbon Source for Biofuels

NUCLEAR BIOFUELS WEBINAR
4 AUGUST 2021

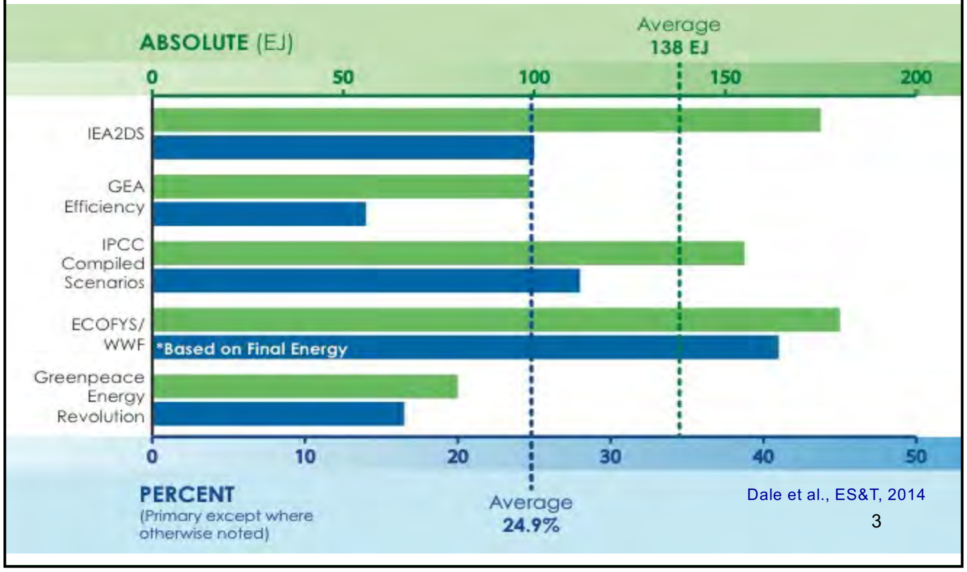
Bruce E. Dale
University Distinguished Professor
Michigan State University
East Lansing, Michigan, United States of America



Outline of My Presentation

- How much biomass is needed to make a large contribution to domestic liquid fuels needs?
- Can we reasonably expect to produce that much biomass?
- **Yes, we can**, in fact, we can produce much more than that…
- *How? Start by paying farmers more for their biomass-farmers are key to the development of this industry*
- Many other opportunities to increase biomass production:
  - Use semi-arid lands
  - Double cropping
  - Increase pasture productivity
  - Rethink/redesign meat production
  - Integrate food/fuel/biomass production
  - Reclaim saline lands, degraded lands, use “marginal” lands
- The (very big) biomass logistics hurdle: why “depots” are essential
- Electricity can’t meet all our energy service needs-we also need drop-in replacements for liquid fossil fuels

If GHG Levels are to be Controlled:
Bioenergy/biofuels are NOT optional



Dale et al., ES&T, 2014

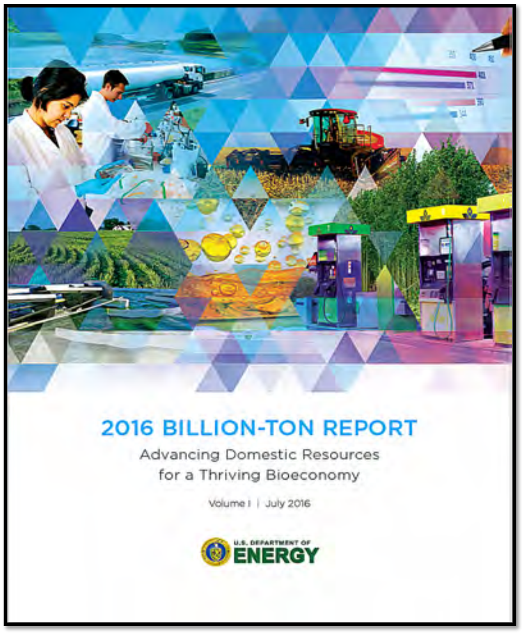
How Much Biomass is Needed?

- Assume 10 million barrels of diesel fuel per day…how much carbon is that?
  - Assume $C_{14}H_{30}$ = MW of 198, or 168/198 = 85% C by mass
  - 10 x 10^6 barrels/day x 300 lb oil/barrel x 365 days/yr x 0.85 lb C/lb oil = 9.3 x 10^{11} lb C/year = <u>4.63 x 10^8 tons carbon/year</u>
- How much biomass is required to produce this much carbon?
  - Biomass is about 40% carbon by weight
  - 4.63 x 10^8 tons carbon/year x 1.0 ton biomass /0.4 ton carbon ~
  - <u>1.2 x 10^9 tons biomass per year</u>
- In round numbers, this is <u>one billion tons</u> of biomass per year…*can we produce this much biomass?*
- *The DOE and the USDA say: Yes, we can produce about 1.4 billion tons per year.*
- I think the DOE/USDA number is low: it could be increased substantially and with greater <u>sustainability</u>...

DOE-USDA BILLION TON REPORT

https://www.energy.gov/sites/default/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf

The report is driven by modeling assumptions that strongly influence the results—we will see what happens if we *change some of these assumptions*



2016 BILLION-TON REPORT
Advancing Domestic Resources for a Thriving Bioeconomy
Volume I | July 2016
U.S. DEPARTMENT OF ENERGY

Billion Ton Report: *where is the biomass?*

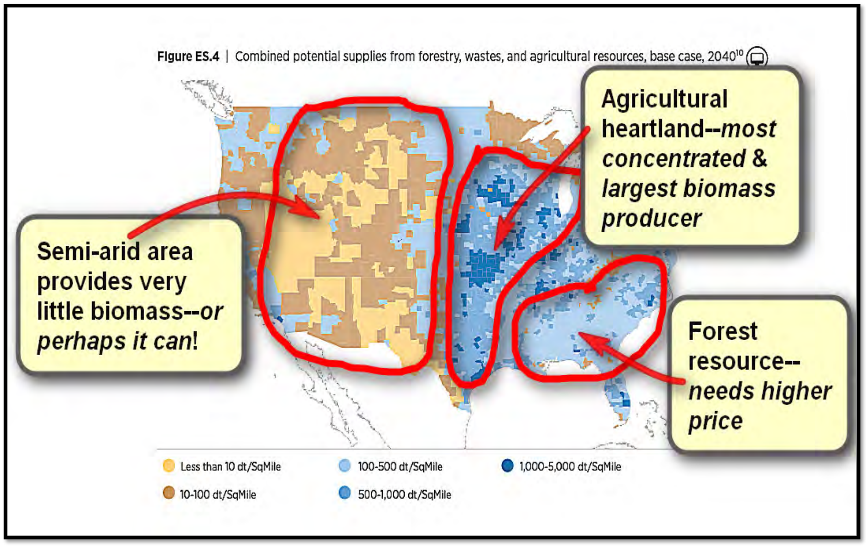


Figure ES.4 | Combined potential supplies from forestry, wastes, and agricultural resources, base case, 2040[10]

Agricultural heartland--*most concentrated & largest biomass producer*

Semi-arid area provides very little biomass--*or perhaps it can*!

Forest resource--*needs higher price*

Billion Ton Report: *agriculture is the big dog*

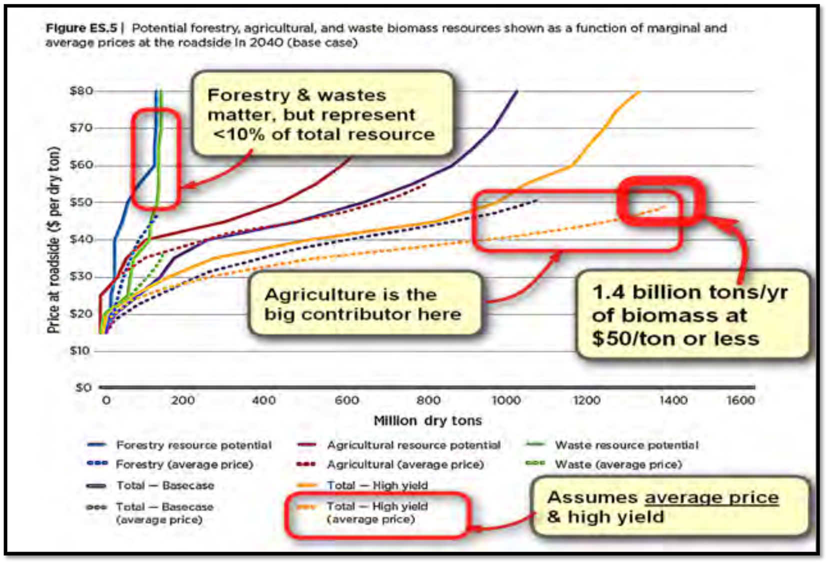


Figure ES.5 | Potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside in 2040 (base case)

Forestry & wastes matter, but represent <10% of total resource

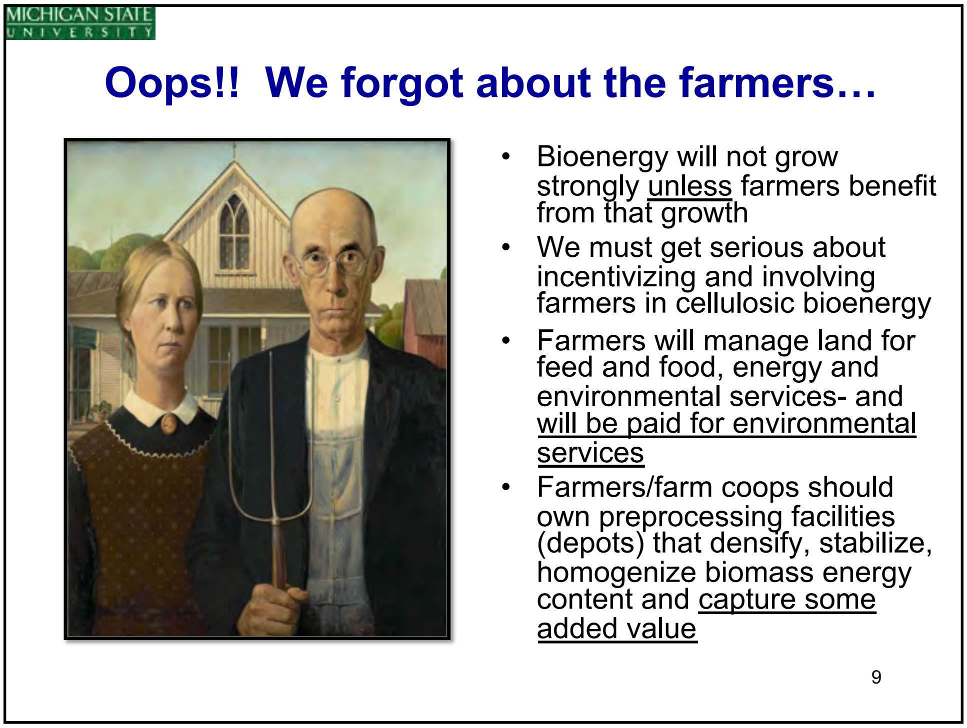
Agriculture is the big contributor here

1.4 billion tons/yr of biomass at $50/ton or less

Assumes average price & high yield

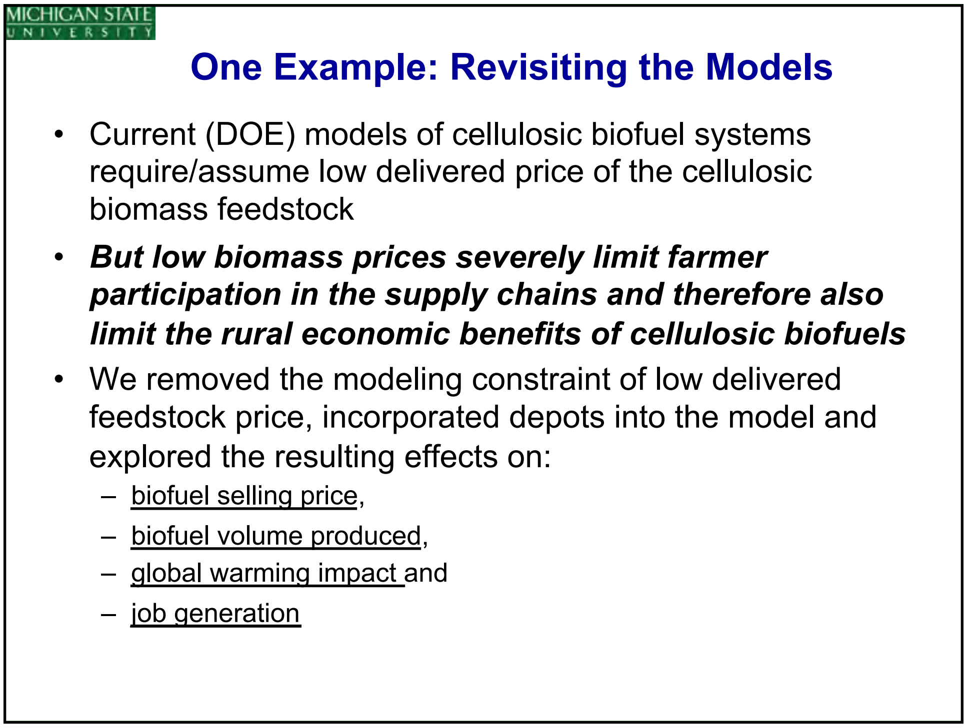
How to Sustainably Increase Biomass Production: a Few Approaches

1. Pay farmers/forest owners more (for their sustainably-produced biomass)
2. Use much more double cropping (sequential cropping)
3. Rethink meat production-*increase pasture productivity*
4. Involve semi-arid lands in biomass production
5. Integrate food/feed/fuel production
6. Reclaim saline and otherwise degraded lands (from past practices and naturally saline/degraded lands)
7. Fund plant breeding for total biomass production (not just grain or food oil production)
8. Use regenerative (carbon-fixing) agricultural practices much more widely: biomass yields will also increase
9. *These approaches overlap and synergize: we should change our agriculture/food/bioenergy policies to reward sustainable biomass production for bioenergy*



Oops!! We forgot about the farmers…

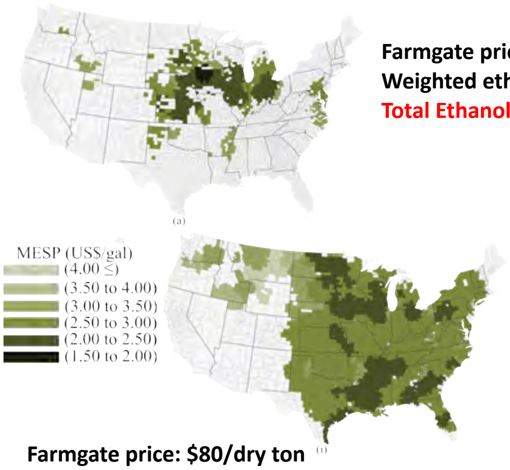
- Bioenergy will not grow strongly unless farmers benefit from that growth
- We must get serious about incentivizing and involving farmers in cellulosic bioenergy
- Farmers will manage land for feed and food, energy and environmental services- and will be paid for environmental services
- Farmers/farm coops should own preprocessing facilities (depots) that densify, stabilize, homogenize biomass energy content and capture some added value



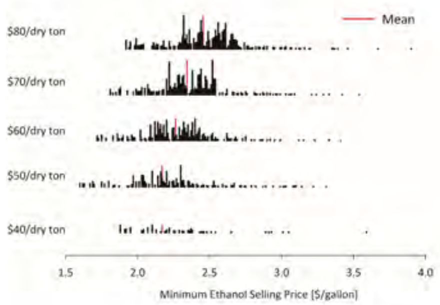
One Example: Revisiting the Models

- Current (DOE) models of cellulosic biofuel systems require/assume low delivered price of the cellulosic biomass feedstock
- ***But low biomass prices severely limit farmer participation in the supply chains and therefore also limit the rural economic benefits of cellulosic biofuels***
- We removed the modeling constraint of low delivered feedstock price, incorporated depots into the model and explored the resulting effects on:
  - biofuel selling price,
  - biofuel volume produced,
  - global warming impact and
  - job generation

Effect of Doubling Biomass Price on Amount of Biomass Grown



Farmgate price: $40/dry ton
Weighted ethanol selling price: **$2.18/gal**
Total Ethanol Produced: 4.5 billion gal/yr



Farmgate price: $80/dry ton
Weighted ethanol selling price: **$2.46/gal**
Total Ethanol Produced: 42 billion gal/yr

All biomass is local: "average" values do not provide much useful information

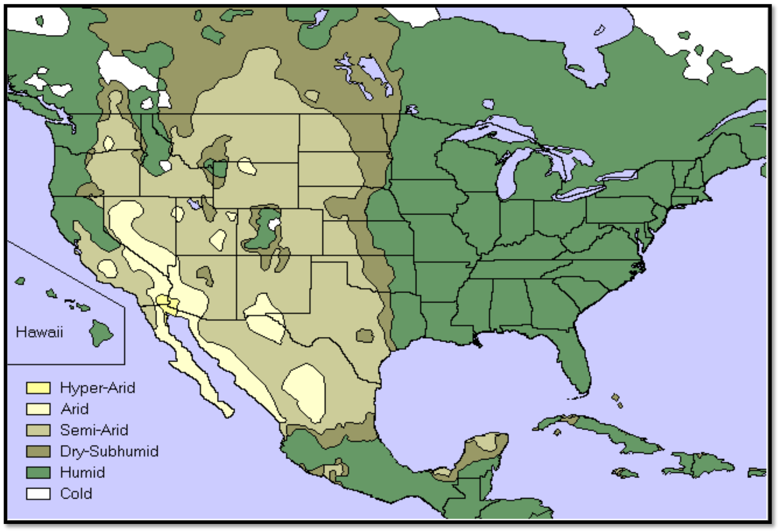
Sustainable Agriculture by Double Cropping: Utilize "Wasted" (Unplanted) Land

- Grow biomass energy crop during fall/winter while **still** growing food crops
- Does **not** require new land- no "food vs. fuel", soil is covered year round
- Provides important environmental services: *reduces erosion, nutrient losses & N2O emissions, improve water quality, increase biodiversity, sequester carbon in soil*
- ***Can farmers monetize some of these environmental services?***

Double crop of winter rye grass

Same day-adjacent field-nothing planted yet- *WASTE* of solar energy, fertilizer, land potential

US semi-arid lands: *total ~600 million acres vs. ~300 million acres of harvested croplands*

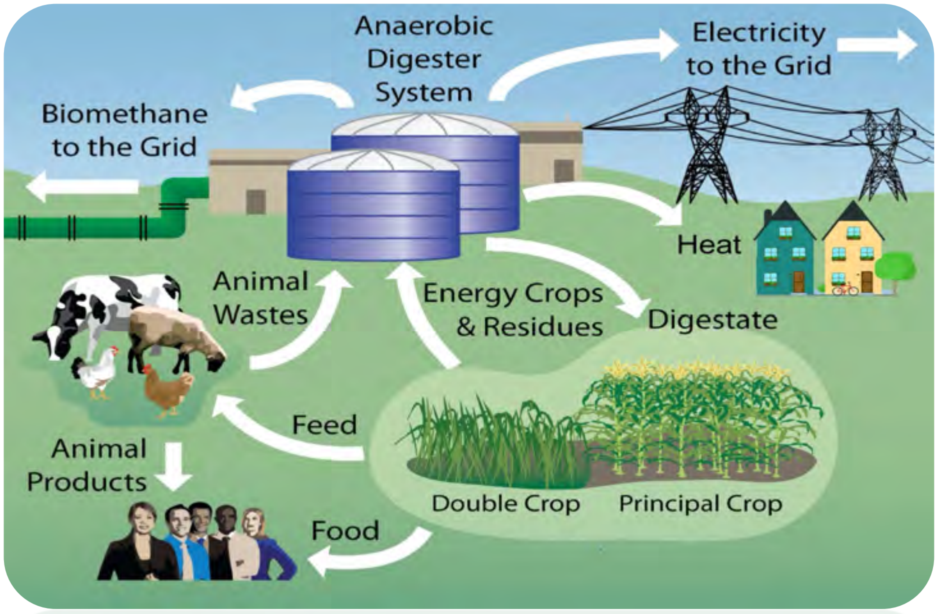


CAM plants for semi-arid areas: *these plants accumulate water in their tissues*

- *Opuntia* averages 15% dry matter with 4 tons of dry matter/acre/year given 16 inches of rainfall/year.
- Assuming 60 million acres (10% of US semi-arid lands) we could produce ~240 million dry tons biomass/yr
- *More than any other single source of biomass in 2016 Billion Ton Study*
- High water content probably rules out pyrolysis or pelleting ⟹ *use wet processing by anaerobic digestion*

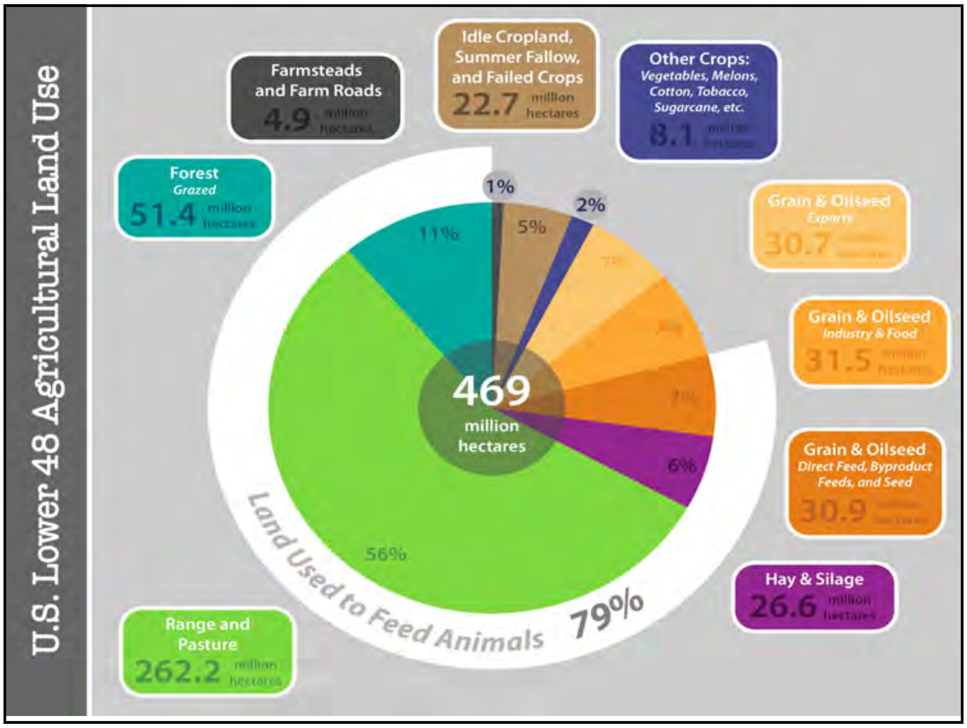
Field of Opuntia (prickly pear) in Brazil

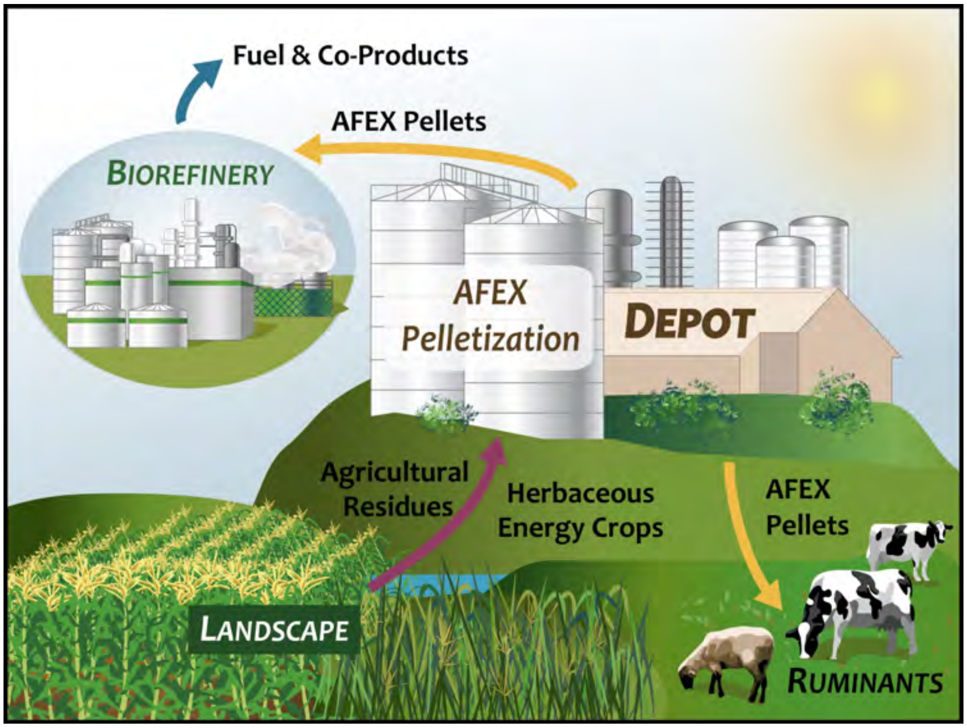
The Biogasdoneright™ System in Italy:
A Farm Level "Depot" Bioenergy System



We Don't "Grow Food"

- About 80% of US arable land produces animal feed, not food directly…globally the percentage is even higher
- We can coproduce, quite easily, animal feeds and cellulosic biofuels to their mutual benefit, for example:
  - Silage for animal feed and/or anaerobic digesters
  - Increase pasture productivity by crop breeding & better management
  - Highly digestible ruminant (cattle) feeds via biomass pretreatment--replace some hay, corn and silage
- We must <u>reimagine, rethink and redesign</u> agriculture to accommodate large scale cellulosic biofuel production, improve sustainability and increase <u>the wealth of farmers</u>
- We don't lack land for biofuels, as long as our brains, imagination and commitment are up to the challenge
- *For example, at local "depots" produce pretreated, pelleted biomass as both improved animal feed & also biorefinery feedstock*


U.S. Lower 48 Agricultural Land Use
Farmsteads and Farm Roads
4.9 million hectares
Idle Cropland, Summer Fallow, and Failed Crops
22.7 million hectares
Other Crops: Vegetables, Melons, Cotton, Tobacco, Sugarcane, etc.
8.1 million hectares
Forest Grazed
51.4 million hectares
Grain & Oilseed Exports
30.7 million hectares
Grain & Oilseed Industry & Food
31.5 million hectares
Grain & Oilseed Direct Feed, Byproduct Feeds, and Seed
30.9 million hectares
Hay & Silage
26.6 million hectares
Range and Pasture
262.2 million hectares
1%
2%
5%
11%
7%
7%
6%
56%
469 million hectares
Land Used to Feed Animals 79%


Fuel & Co-Products
AFEX Pellets
BIOREFINERY
AFEX Pelletization
DEPOT
Agricultural Residues
Herbaceous Energy Crops
AFEX Pellets
LANDSCAPE
RUMINANTS

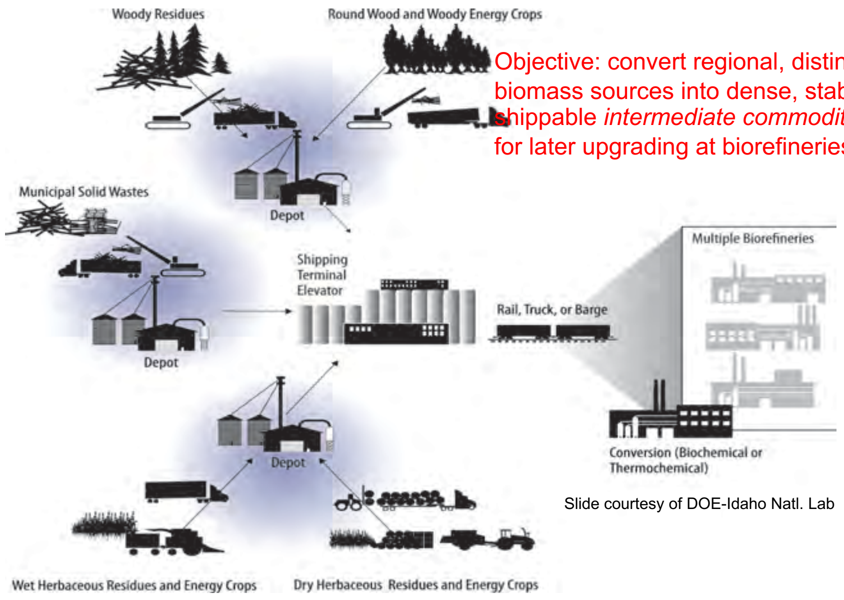
How much biomass can the US produce?

- Billion Ton Report: 1,400 million tons/yr
- Pay farmers more: +600 million tons/yr
- Use 10% of semi-arid lands for *Opuntia*: +240 million tons/yr
- Use double cropping extensively: +150 million tons/yr
- Integrate food/feed/fuel production: +300 million tons/yr (?)
- Improve pasture/energy crop productivity: +200 million tons/yr
- Rehabilitate saline, retired & degraded lands: +100 million tons/yr
- *Total biomass ~ 3,000 million tons/yr (at least)*

*Yes, we can produce plenty of biomass— **but how can we move 3 billion tons/yr of biomass from the fields & forests to the biorefineries???***

Attacking Biomass Logistics Challenges:

Regional Biomass Processing Depots (RPBDs)



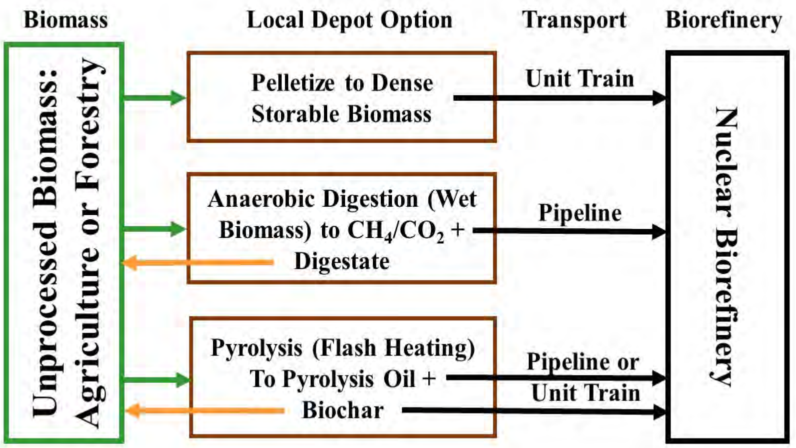
Objective: convert regional, distinct biomass sources into dense, stable, shippable *intermediate commodities* for later upgrading at biorefineries

Slide courtesy of DOE-Idaho Natl. Lab

Advantages/Properties of Depots

- Manage and greatly reduce biomass variability near point of production
- Produce energy dense, stable, shippable *intermediate commodities* for biofuel producers (the “biorefineries”)
- Reduce transaction costs & capital risks for biorefineries
- Benefit rural communities through job creation & depot ownership
- Address sustainability issues more directly/effectively by focusing on the local level

Three Depot Options to Convert Biomass into Storable, Economically-Shippable Biorefinery Feedstocks



Biomass | **Local Depot Option** | **Transport** | **Biorefinery**

Unprocessed Biomass: Agriculture or Forestry

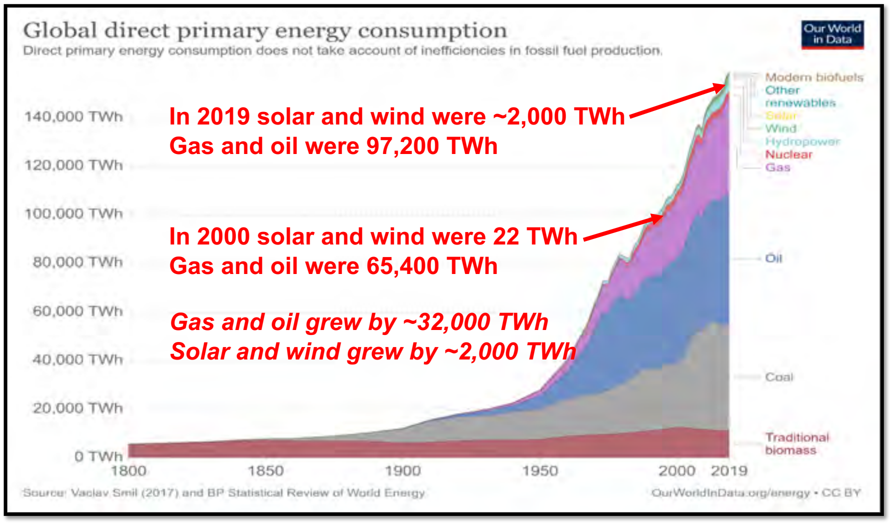
Pelletize to Dense Storable Biomass → **Unit Train** → **Nuclear Biorefinery**

Anaerobic Digestion (Wet Biomass) to CH_4/CO_2 + Digestate → **Pipeline** → **Nuclear Biorefinery**

Pyrolysis (Flash Heating) To Pyrolysis Oil + Biochar → **Pipeline or Unit Train** → **Nuclear Biorefinery**

MICHIGAN STATE
UNIVERSITY

World Energy Use: Fossil Fuels Still Dominate: *and Have **Grown 16x Faster** than Solar & Wind*


Global direct primary energy consumption
Direct primary energy consumption does not take account of inefficiencies in fossil fuel production.

In 2019 solar and wind were ~2,000 TWh
Gas and oil were 97,200 TWh

In 2000 solar and wind were 22 TWh
Gas and oil were 65,400 TWh

Gas and oil grew by ~32,000 TWh
Solar and wind grew by ~2,000 TWh

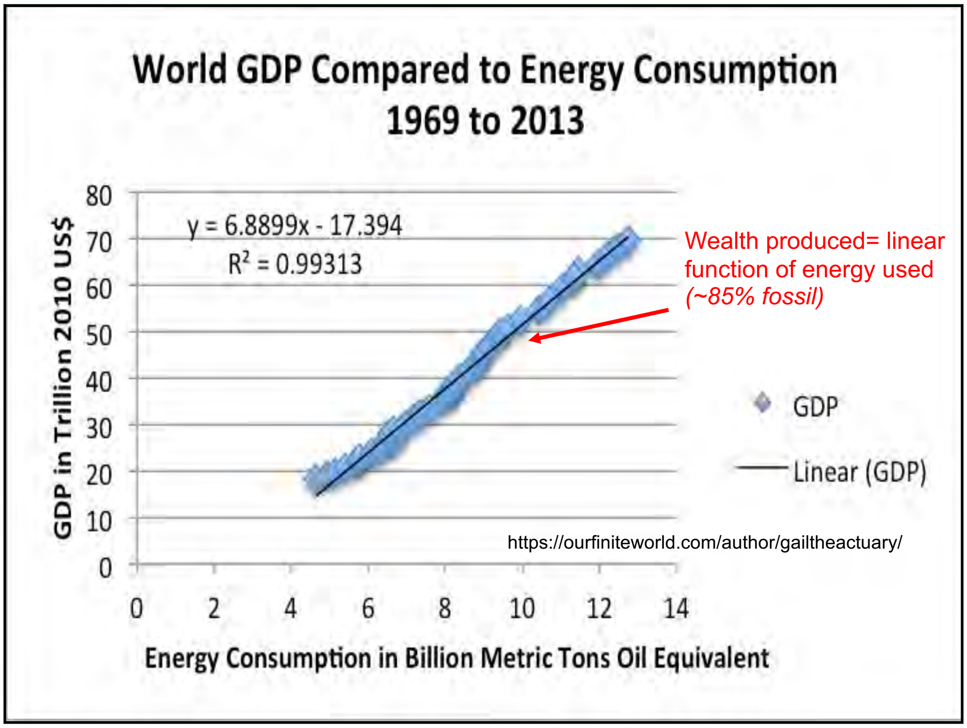
Source: Vaclav Smil (2017) and BP Statistical Review of World Energy
OurWorldInData.org/energy • CC BY

23

MICHIGAN STATE
UNIVERSITY

Support Provided by Michigan State University
AgBioResearch Office and by the USDA/NIFA Program

24



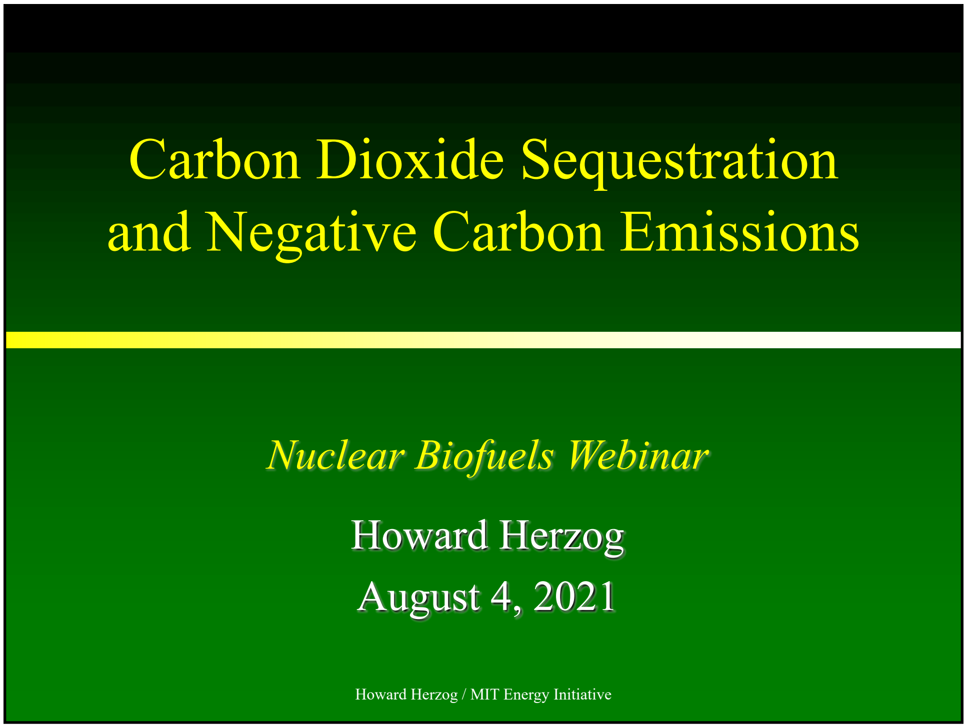
Wealth produced= linear function of energy used *(~85% fossil)*

https://ourfiniteworld.com/author/gailtheactuary/

MICHIGAN STATE UNIVERSITY

The Realities of a Finite World: rethinking (very soon) our obsession with "growth"

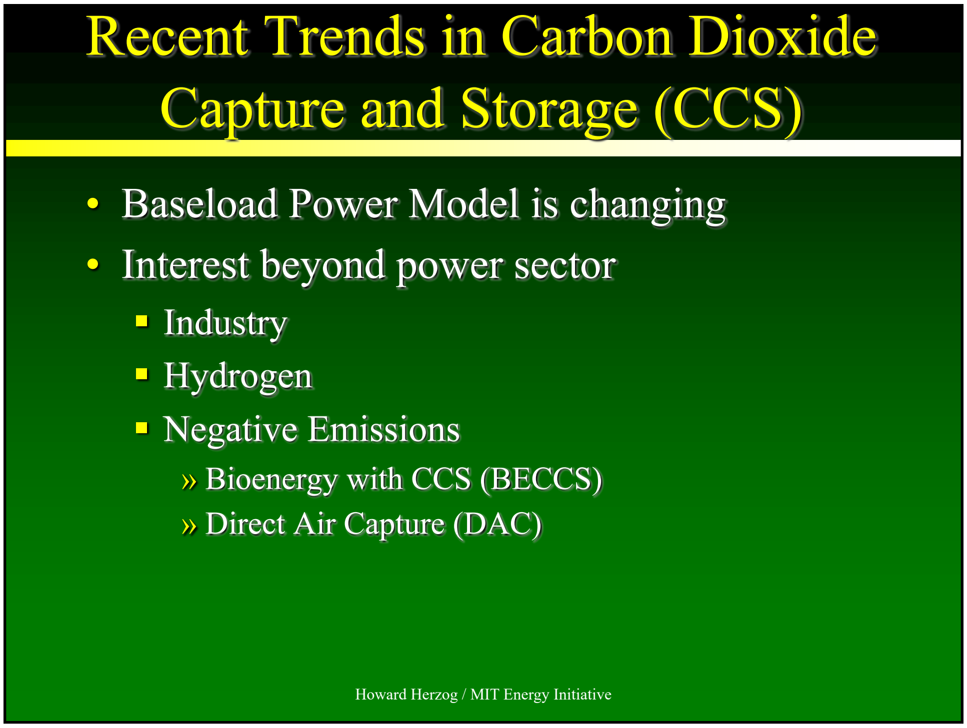
- Globally, the "energy have nots" (aka "the poor") are much more numerous than the "energy haves" (aka "the rich")
- *Can we achieve a more just, more humane world by more equitable access to energy?*
- *Can we change our culture and our hard-wired "need" to consume more and more and more—without limit?*
- Energy use determines the size of the human economy
- The culture we choose determines how the economy impacts both humankind and the natural world
- *Regardless of these choices, continuous growth on a finite planet is both impossible and absurd…we will have to deal with that issue whether we want to or not, probably sooner rather than later*



Carbon Dioxide Sequestration and Negative Carbon Emissions

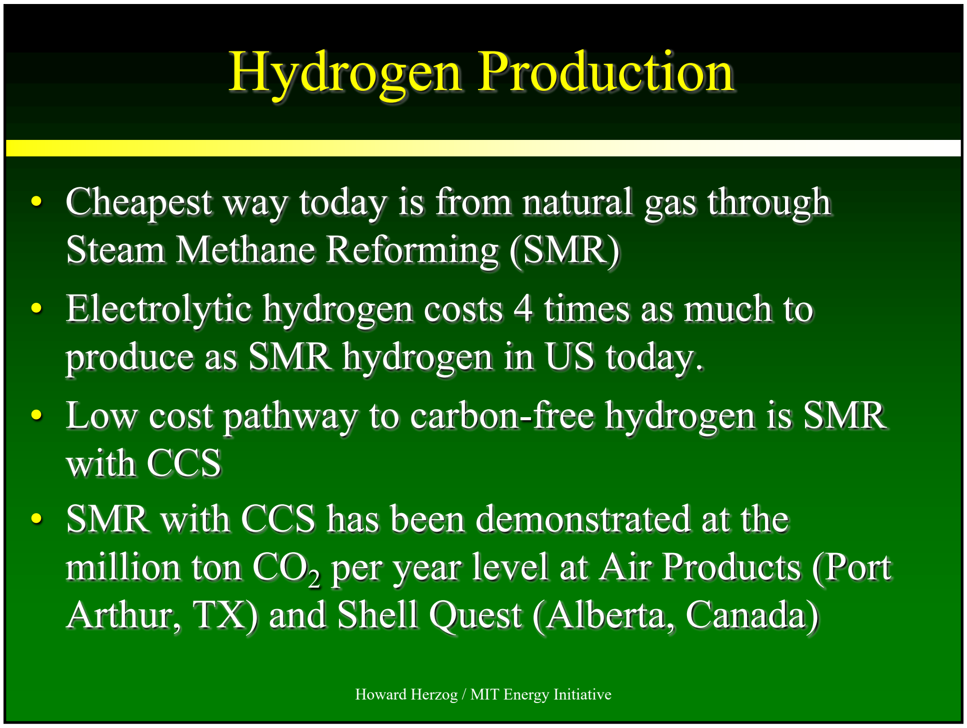
Nuclear Biofuels Webinar

Howard Herzog
August 4, 2021



Recent Trends in Carbon Dioxide Capture and Storage (CCS)

- Baseload Power Model is changing
- Interest beyond power sector
  - Industry
  - Hydrogen
  - Negative Emissions
    - » Bioenergy with CCS (BECCS)
    - » Direct Air Capture (DAC)



Hydrogen Production

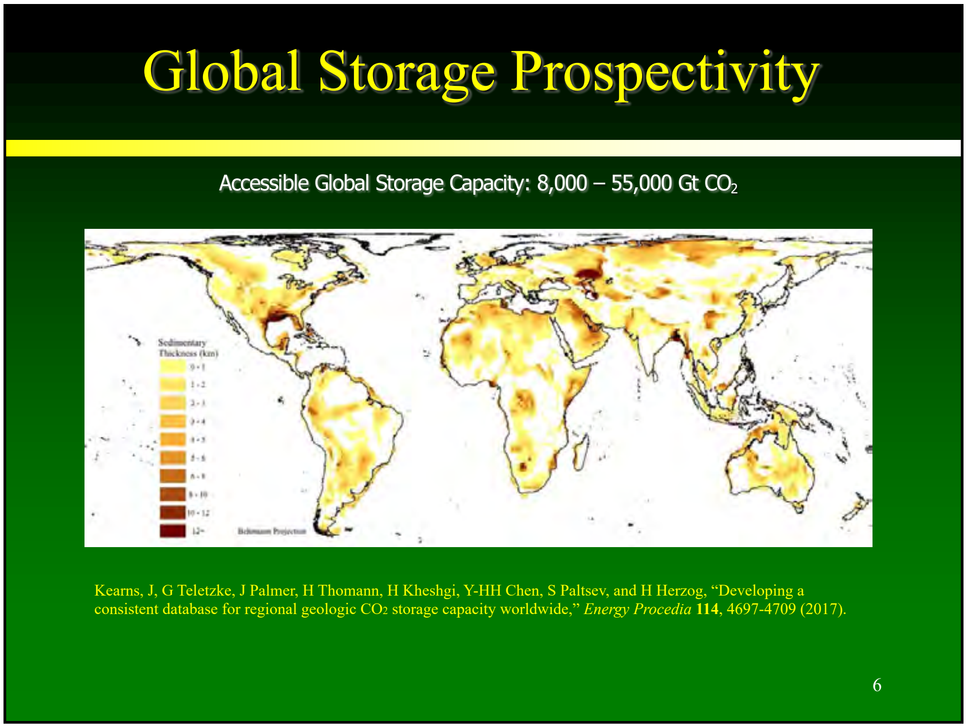
- Cheapest way today is from natural gas through Steam Methane Reforming (SMR)
- Electrolytic hydrogen costs 4 times as much to produce as SMR hydrogen in US today.
- Low cost pathway to carbon-free hydrogen is SMR with CCS
- SMR with CCS has been demonstrated at the million ton CO_2 per year level at Air Products (Port Arthur, TX) and Shell Quest (Alberta, Canada)

Air Products SMR w/CCS

Source: Air Products and Chemicals, Inc., http://prphotolibrary.airproducts.com/

Geologic Storage

- Commercial Today
  - Target Formations
    - » Deep saline formations
    - » Depleted oil and gas reservoirs
    - » Enhanced oil recovery (EOR)
  - Below 800 m
  - CO_2 injected as a supercritical fluid
- Others being investigated
  - Mafic Rocks
  - Offshore Sedimentary Sequences



Global Storage Prospectivity

Accessible Global Storage Capacity: 8,000 – 55,000 Gt CO_2

Kearns, J, G Teletzke, J Palmer, H Thomann, H Kheshgi, Y-HH Chen, S Paltsev, and H Herzog, “Developing a consistent database for regional geologic CO_2 storage capacity worldwide,” *Energy Procedia* **114**, 4697-4709 (2017).

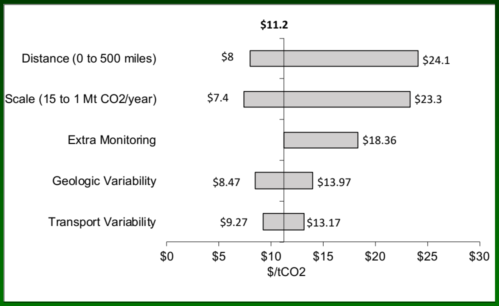
CCS Cost Estimates

- Capture (gross) vs. avoided (net) costs
  - Avoided is consistent with a carbon price
- <$50/$tCO_2$ avoided – high purity or high pressure sources
- $50-100/$tCO_2$ avoided – dilute sources (first mover costs higher)
- ~$240/$tCO_2$ avoided – BECCS (electricity production with negative emissions)
- ~1000/tCO_2 avoided - DAC

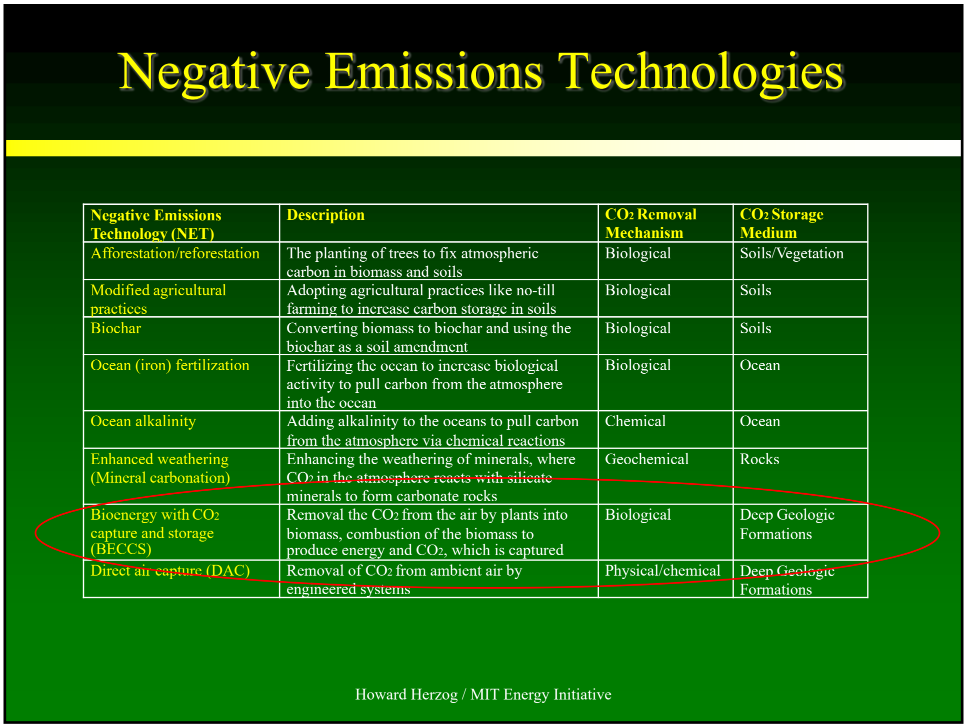
Howard Herzog / MIT Energy Initiative

Combined CO_2 Transport and Storage Cost Range

Sensitivity of CO_2 transport and storage costs around the Base Case of 3.2 $MtCO_2$/year being transported 100 miles.



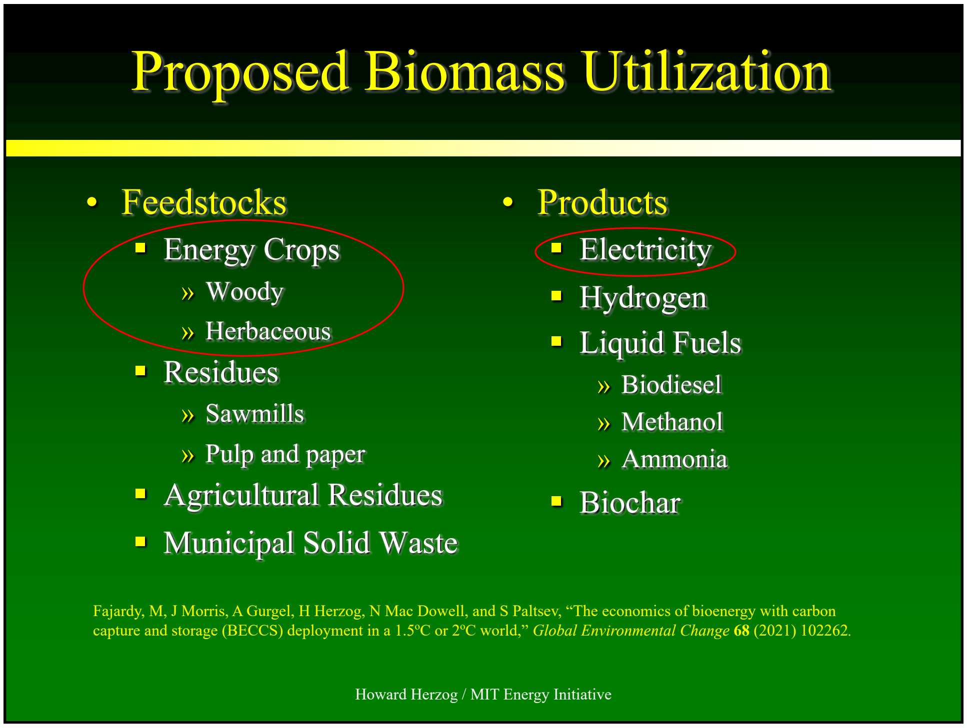
Smith, E, J Morris, H Kheshgi, G Teletzke, H Herzog, and S Paltsev, "The cost of CO_2 transport and storage in global integrated assessment modeling," *International Journal of Greenhouse Gas Control* **109** (2021) 103367.



Negative Emissions Technologies

Negative Emissions Technology (NET)	**Description**	**CO_2 Removal Mechanism**	**CO_2 Storage Medium**
Afforestation/reforestation	The planting of trees to fix atmospheric carbon in biomass and soils	Biological	Soils/Vegetation
Modified agricultural practices	Adopting agricultural practices like no-till farming to increase carbon storage in soils	Biological	Soils
Biochar	Converting biomass to biochar and using the biochar as a soil amendment	Biological	Soils
Ocean (iron) fertilization	Fertilizing the ocean to increase biological activity to pull carbon from the atmosphere into the ocean	Biological	Ocean
Ocean alkalinity	Adding alkalinity to the oceans to pull carbon from the atmosphere via chemical reactions	Chemical	Ocean
Enhanced weathering (Mineral carbonation)	Enhancing the weathering of minerals, where CO_2 in the atmosphere reacts with silicate minerals to form carbonate rocks	Geochemical	Rocks
Bioenergy with CO_2 capture and storage (BECCS)	Removal the CO_2 from the air by plants into biomass, combustion of the biomass to produce energy and CO_2, which is captured	Biological	Deep Geologic Formations
Direct air capture (DAC)	Removal of CO_2 from ambient air by engineered systems	Physical/chemical	Deep Geologic Formations

Howard Herzog / MIT Energy Initiative



Proposed Biomass Utilization

- Feedstocks
  - Energy Crops
    - Woody
    - Herbaceous
  - Residues
    - Sawmills
    - Pulp and paper
  - Agricultural Residues
  - Municipal Solid Waste
- Products
  - Electricity
  - Hydrogen
  - Liquid Fuels
    - Biodiesel
    - Methanol
    - Ammonia
  - Biochar

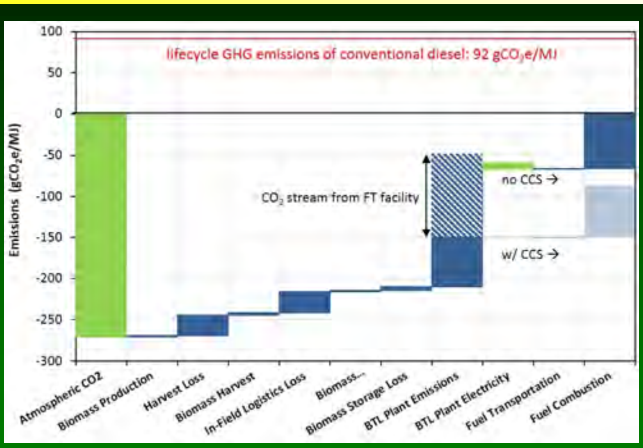
Fajardy, M, J Morris, A Gurgel, H Herzog, N Mac Dowell, and S Paltsev, "The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5°C or 2°C world," *Global Environmental Change* **68** (2021) 102262.

Howard Herzog / MIT Energy Initiative

Many BECCS Concepts

- Concept 1 (this webinar)
  - Biomass → Liquid Fuels + Negative Emissions
  - Liquid biofuels fuels replace conventional liquid fuels
- Concept 2 (Fajardy et al., 2021)
  - Biomass → Electricity + Negative Emissions
  - Negative emissions offset emissions from conventional liquid fuels
- Comparison
  - Concept 1 - more costly, less negative emissions, but more valuable product
- Warning – Today there is no way to monetize negative emissions

BTL Lifecycle Emissions



Techno-Economic-Environmental Evaluation of Alternative Fuels Production Pathways

Final Report

Final Points

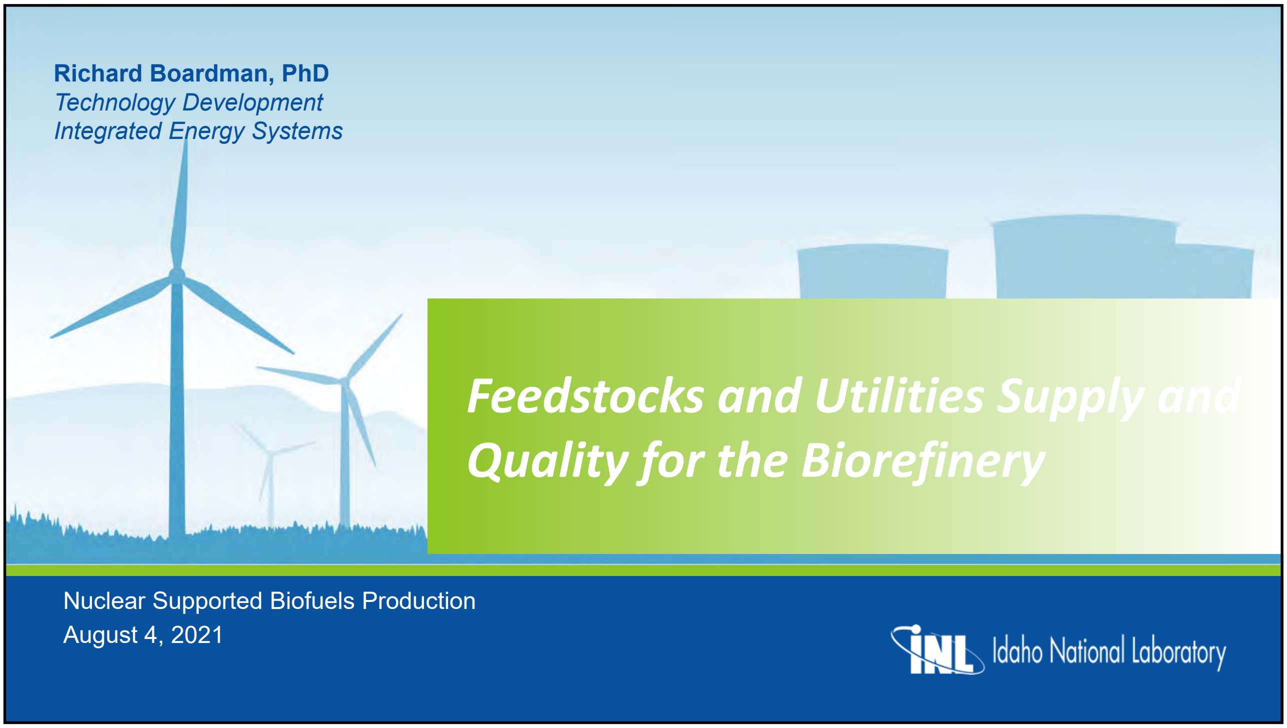
- Large-scale biomass gasification is not a mature technology
- Operational Flexibility - Not so easy in practice; there are costs as well as benefits (tail wagging the dog)

Contact Information

Howard Herzog
Senior Research Engineer

Massachusetts Institute of Technology (MIT)
Energy Initiative
Room E19-370L
Cambridge, MA 02139

Phone: 617-253-0688
E-mail: hjherzog@mit.edu
Web Site: sequestration.mit.edu

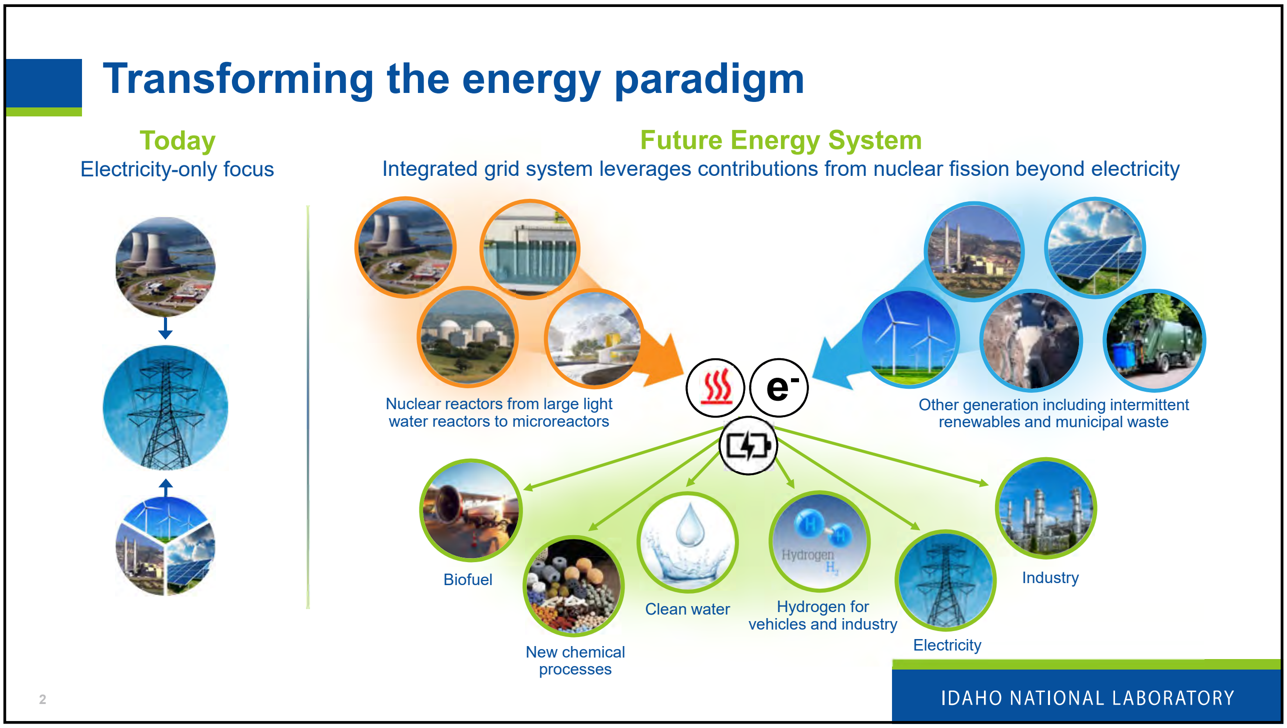


Richard Boardman, PhD
Technology Development
Integrated Energy Systems

Feedstocks and Utilities Supply and Quality for the Biorefinery

Nuclear Supported Biofuels Production
August 4, 2021

Idaho National Laboratory



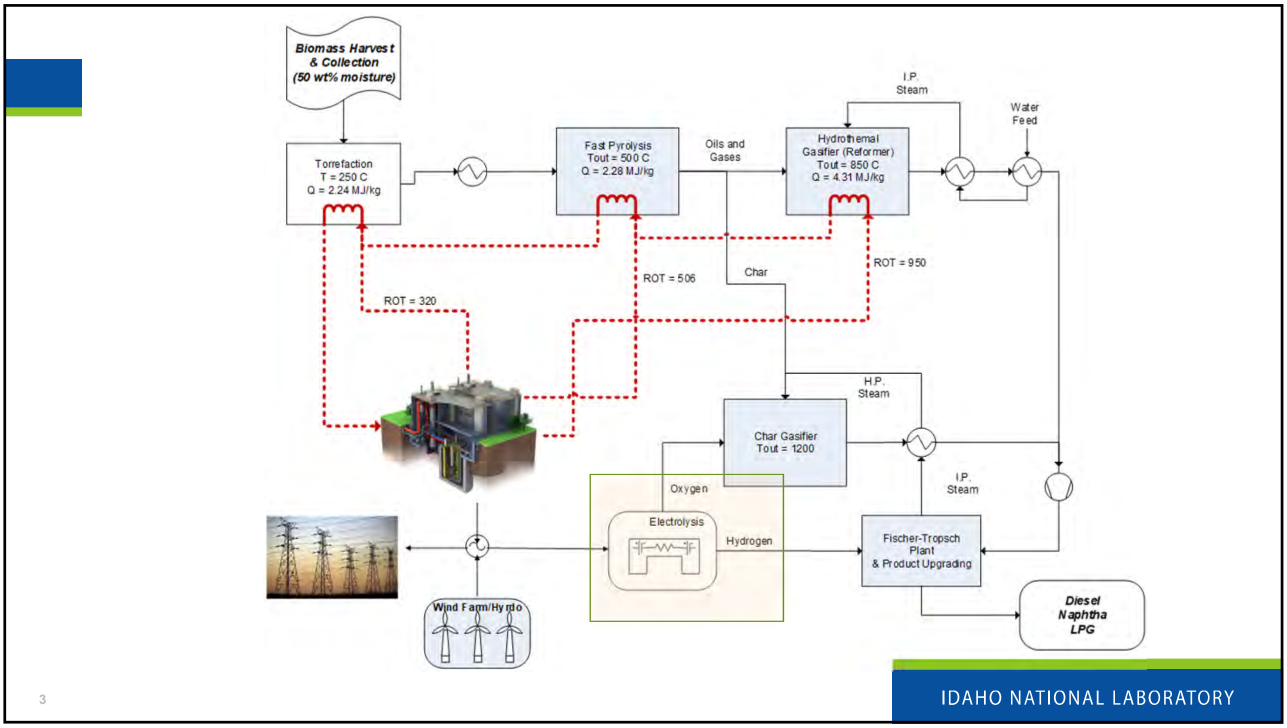
Transforming the energy paradigm

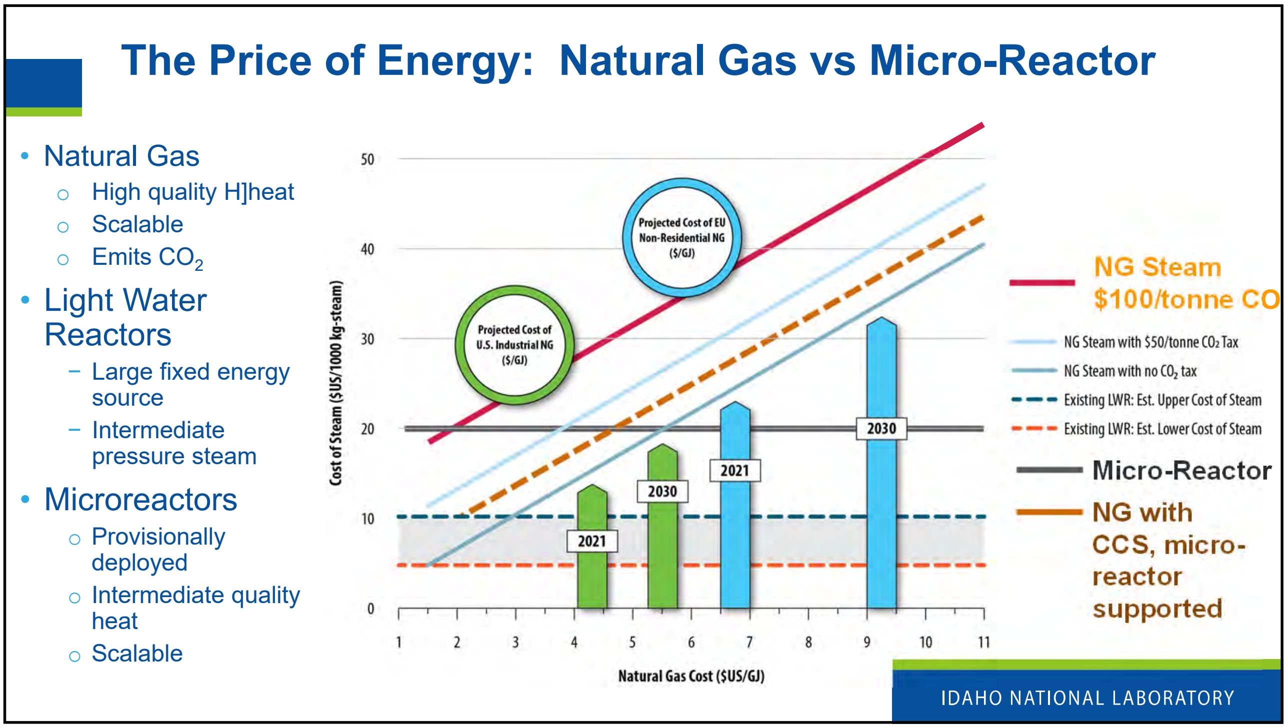
Today
Electricity-only focus

Future Energy System
Integrated grid system leverages contributions from nuclear fission beyond electricity

2

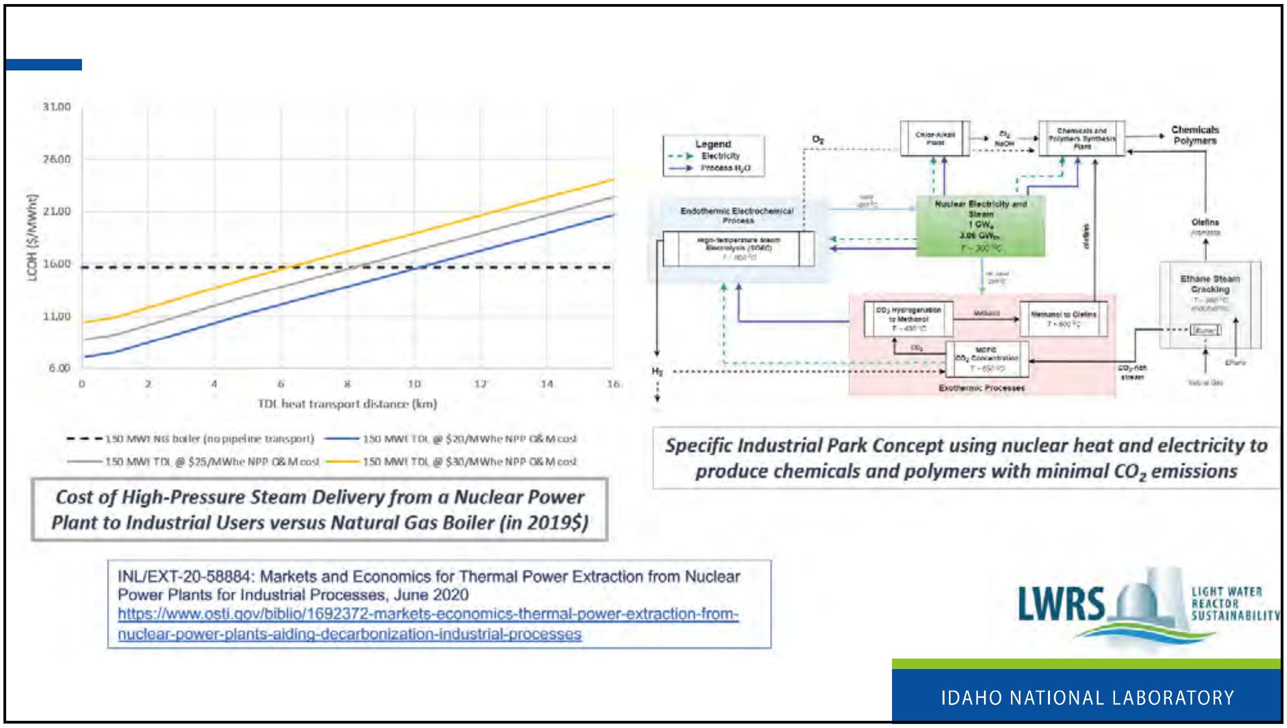
IDAHO NATIONAL LABORATORY





The Price of Energy: Natural Gas vs Micro-Reactor

- Natural Gas
  - High quality H]heat
  - Scalable
  - Emits CO_2
- Light Water Reactors
  - Large fixed energy source
  - Intermediate pressure steam
- Microreactors
  - Provisionally deployed
  - Intermediate quality heat
  - Scalable



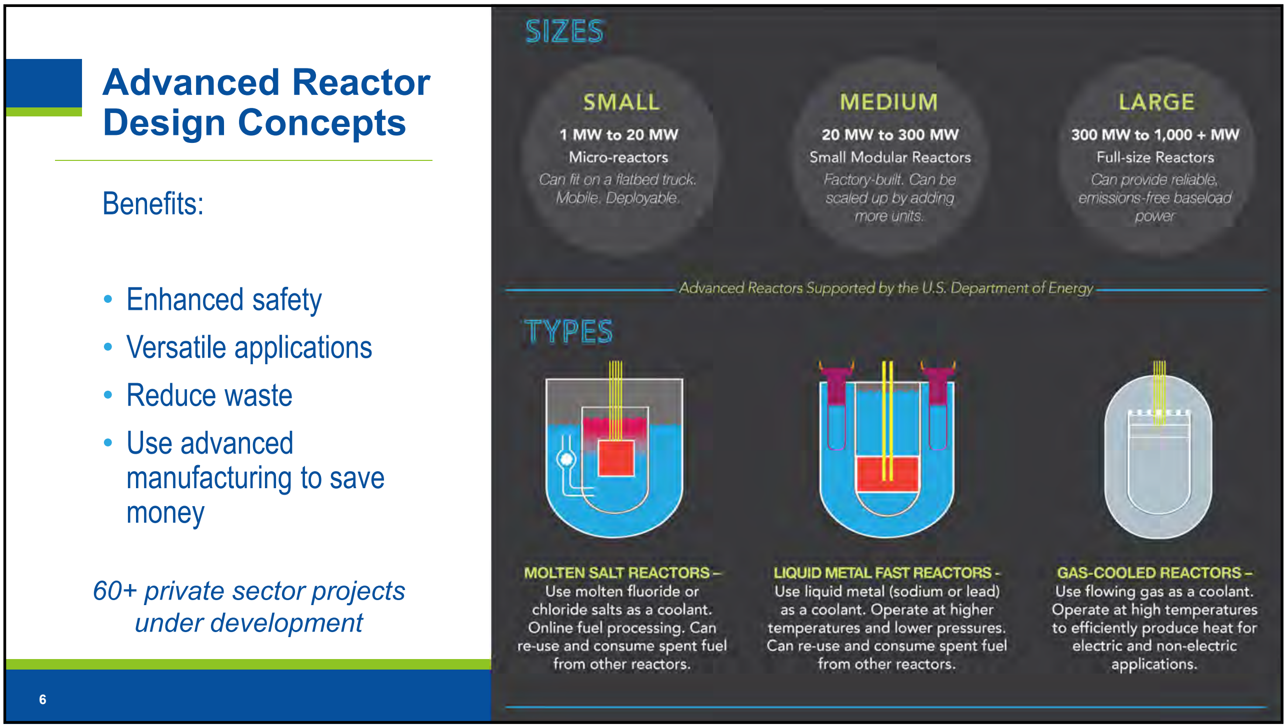
Cost of High-Pressure Steam Delivery from a Nuclear Power Plant to Industrial Users versus Natural Gas Boiler (in 2019$)

Specific Industrial Park Concept using nuclear heat and electricity to produce chemicals and polymers with minimal CO_2 emissions

INL/EXT-20-58884: Markets and Economics for Thermal Power Extraction from Nuclear Power Plants for Industrial Processes, June 2020
https://www.osti.gov/biblio/1692372-markets-economics-thermal-power-extraction-from-nuclear-power-plants-aiding-decarbonization-industrial-processes

LWRS LIGHT WATER REACTOR SUSTAINABILITY

IDAHO NATIONAL LABORATORY



Advanced Reactor Design Concepts

Benefits:

- Enhanced safety
- Versatile applications
- Reduce waste
- Use advanced manufacturing to save money

60+ private sector projects under development

SIZES

SMALL
1 MW to 20 MW
Micro-reactors
Can fit on a flatbed truck. Mobile. Deployable.

MEDIUM
20 MW to 300 MW
Small Modular Reactors
Factory-built. Can be scaled up by adding more units.

LARGE
300 MW to 1,000 + MW
Full-size Reactors
Can provide reliable, emissions-free baseload power

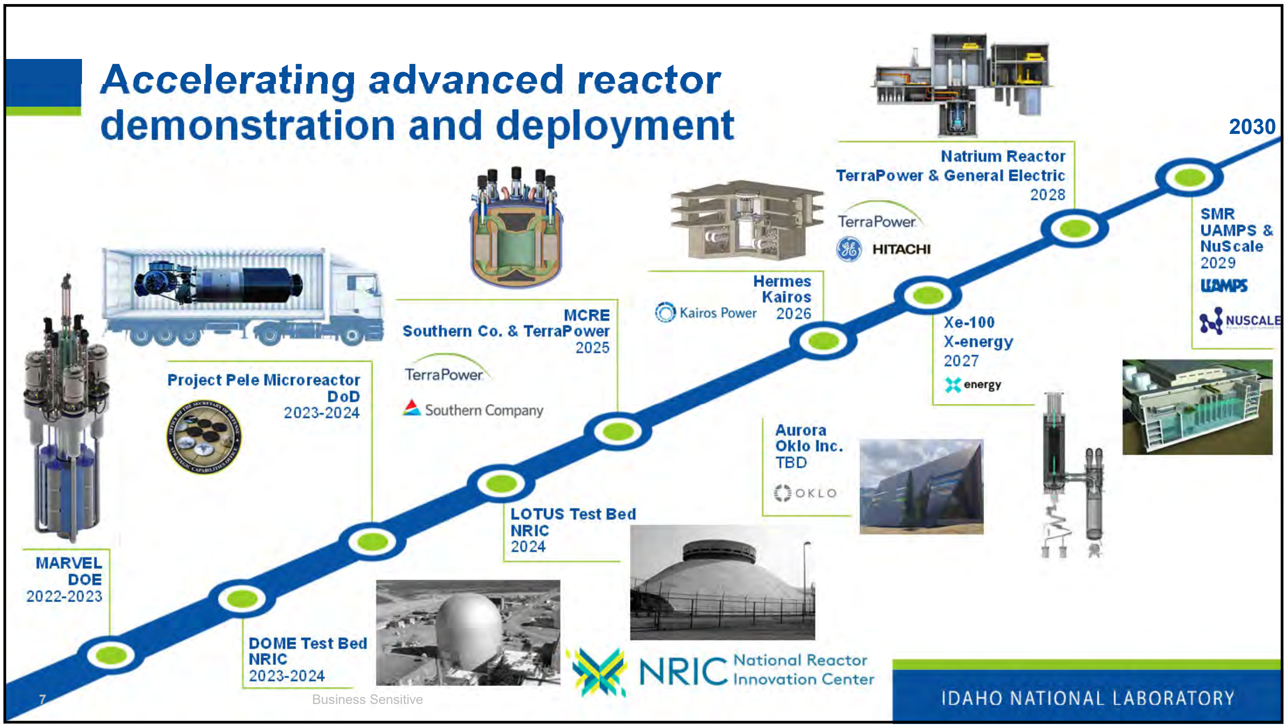
Advanced Reactors Supported by the U.S. Department of Energy

TYPES

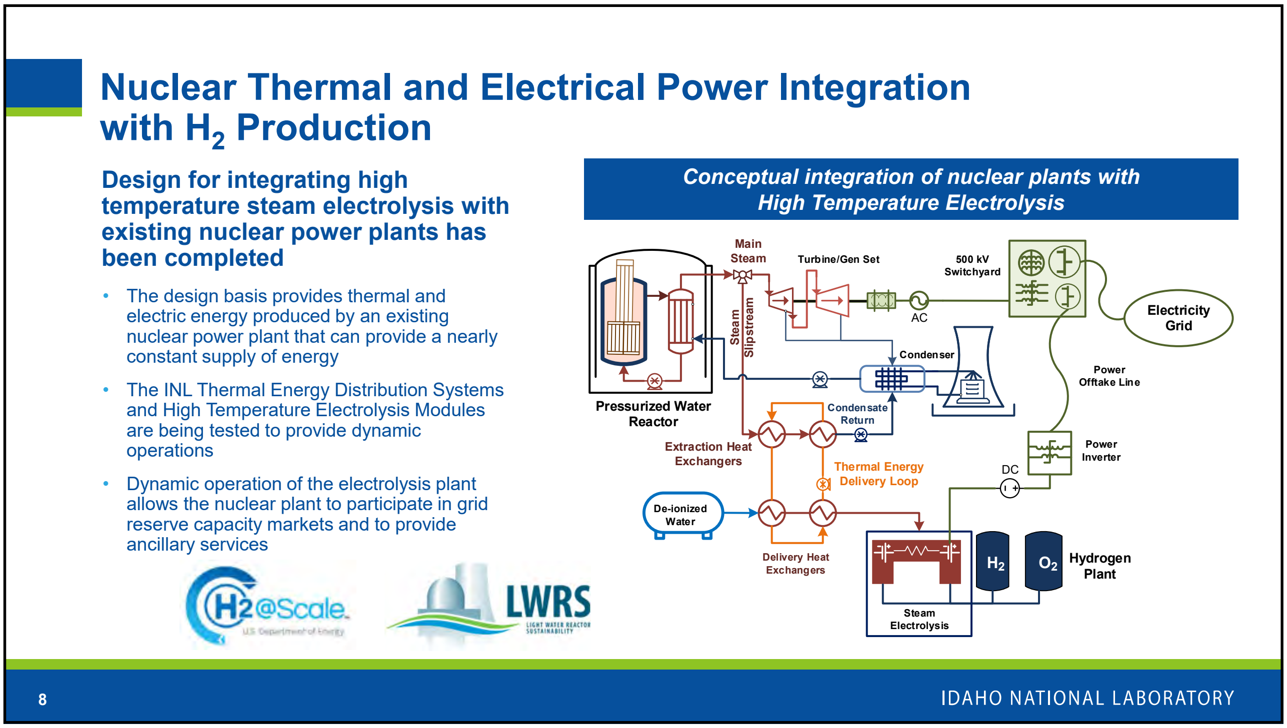
MOLTEN SALT REACTORS – Use molten fluoride or chloride salts as a coolant. Online fuel processing. Can re-use and consume spent fuel from other reactors.

LIQUID METAL FAST REACTORS - Use liquid metal (sodium or lead) as a coolant. Operate at higher temperatures and lower pressures. Can re-use and consume spent fuel from other reactors.

GAS-COOLED REACTORS – Use flowing gas as a coolant. Operate at high temperatures to efficiently produce heat for electric and non-electric applications.



Accelerating advanced reactor demonstration and deployment

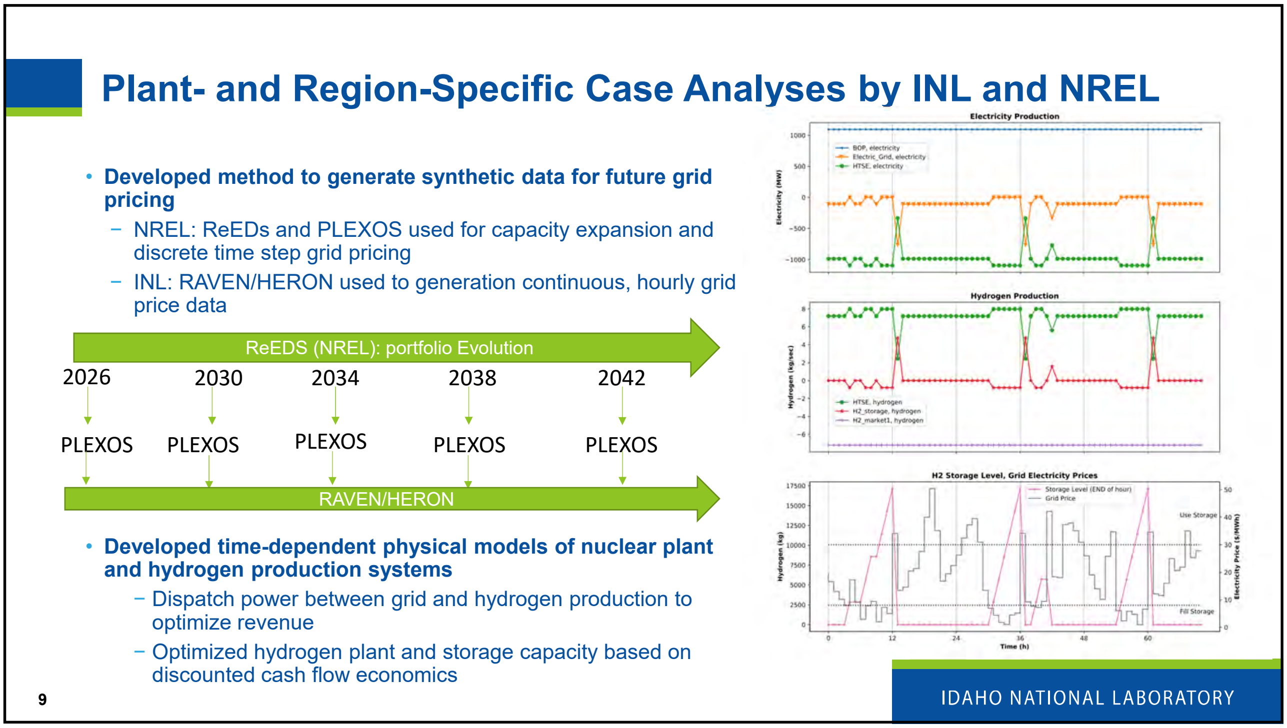


Nuclear Thermal and Electrical Power Integration with H_2 Production

Design for integrating high temperature steam electrolysis with existing nuclear power plants has been completed

- The design basis provides thermal and electric energy produced by an existing nuclear power plant that can provide a nearly constant supply of energy
- The INL Thermal Energy Distribution Systems and High Temperature Electrolysis Modules are being tested to provide dynamic operations
- Dynamic operation of the electrolysis plant allows the nuclear plant to participate in grid reserve capacity markets and to provide ancillary services

Conceptual integration of nuclear plants with High Temperature Electrolysis



Plant- and Region-Specific Case Analyses by INL and NREL

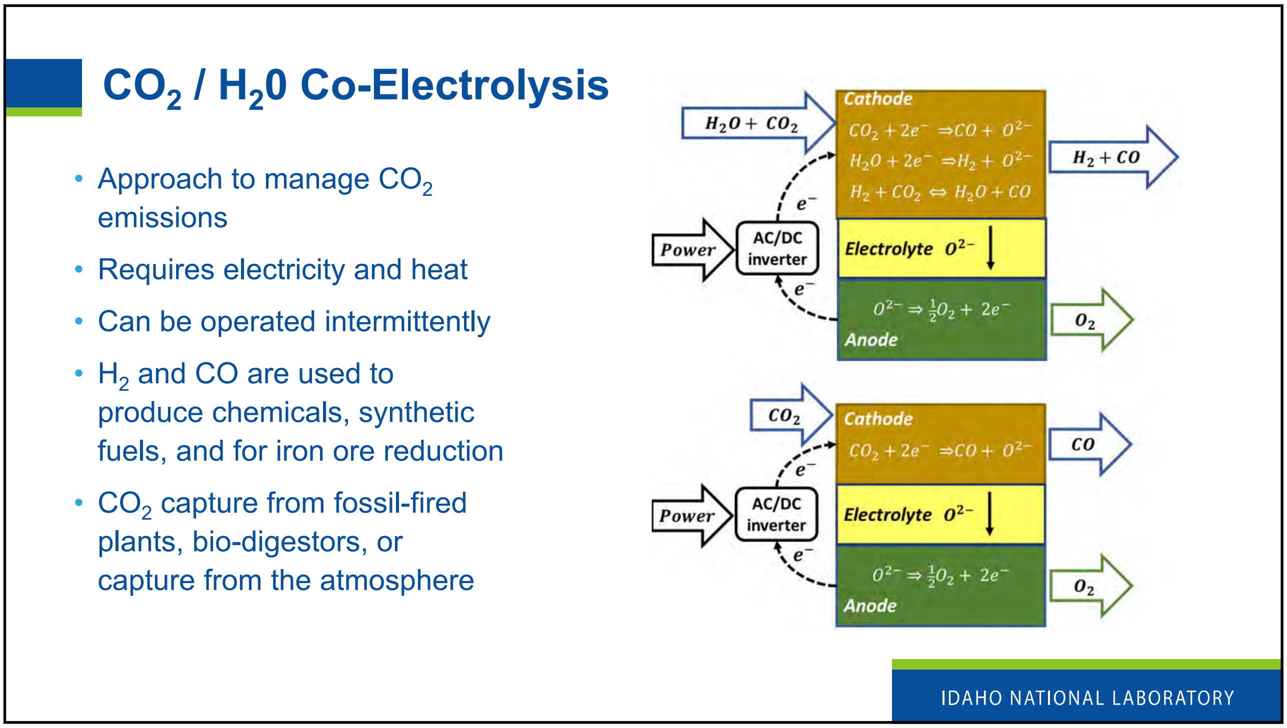
- **Developed method to generate synthetic data for future grid pricing**
  - NREL: ReEDs and PLEXOS used for capacity expansion and discrete time step grid pricing
  - INL: RAVEN/HERON used to generation continuous, hourly grid price data

ReEDS (NREL): portfolio Evolution

2026 → PLEXOS
2030 → PLEXOS
2034 → PLEXOS
2038 → PLEXOS
2042 → PLEXOS

RAVEN/HERON

- **Developed time-dependent physical models of nuclear plant and hydrogen production systems**
  - Dispatch power between grid and hydrogen production to optimize revenue
  - Optimized hydrogen plant and storage capacity based on discounted cash flow economics



CO_2 / H_20 Co-Electrolysis

- Approach to manage CO_2 emissions
- Requires electricity and heat
- Can be operated intermittently
- H_2 and CO are used to produce chemicals, synthetic fuels, and for iron ore reduction
- CO_2 capture from fossil-fired plants, bio-digestors, or capture from the atmosphere

$H_2O + CO_2$

Cathode

$CO_2 + 2e^- \Rightarrow CO + O^{2-}$

$H_2O + 2e^- \Rightarrow H_2 + O^{2-}$

$H_2 + CO_2 \Leftrightarrow H_2O + CO$

$H_2 + CO$

Power

AC/DC inverter

e^-

e^-

Electrolyte O^{2-}

$O^{2-} \Rightarrow \frac{1}{2}O_2 + 2e^-$

Anode

O_2

CO_2

Cathode

$CO_2 + 2e^- \Rightarrow CO + O^{2-}$

CO

Power

AC/DC inverter

e^-

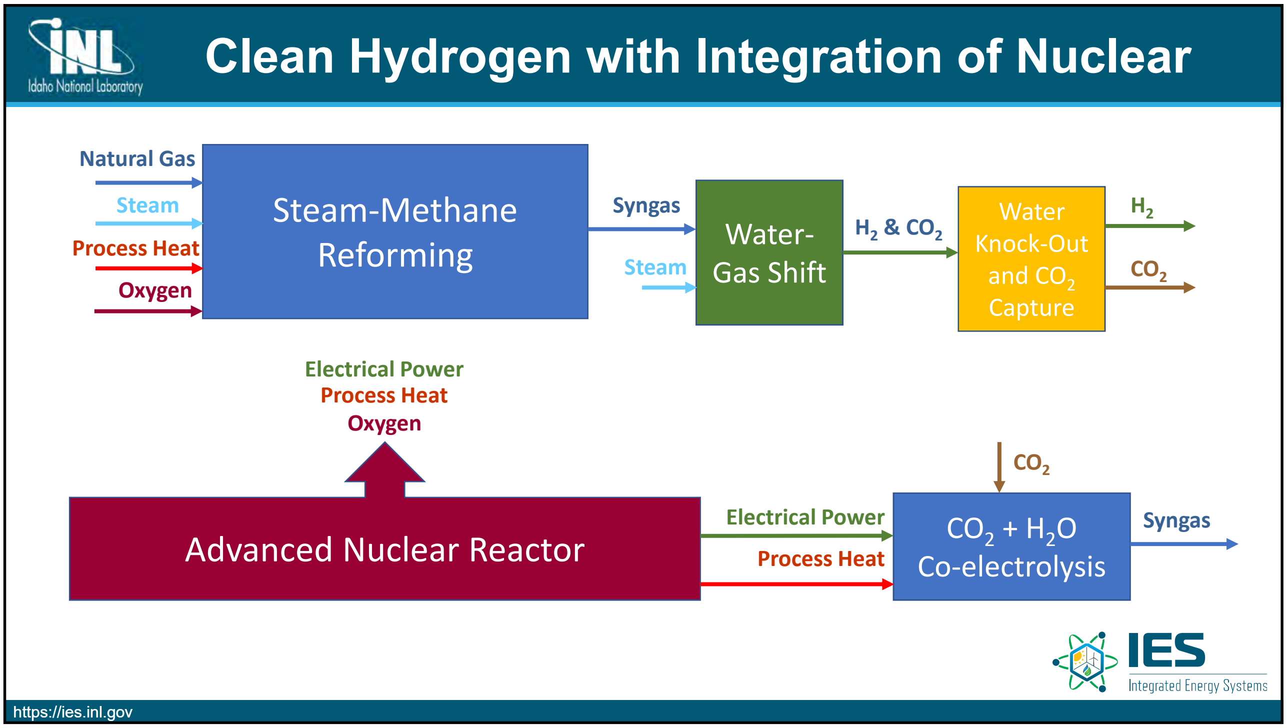
e^-

Electrolyte O^{2-}

$O^{2-} \Rightarrow \frac{1}{2}O_2 + 2e^-$

Anode

O_2



Clean Hydrogen with Integration of Nuclear

Natural Gas
Steam
Process Heat
Oxygen

Steam-Methane Reforming

Syngas
Steam

Water-Gas Shift

H_2 & CO_2

Water Knock-Out and CO_2 Capture

H_2
CO_2

Electrical Power
Process Heat
Oxygen

Advanced Nuclear Reactor

Electrical Power
Process Heat

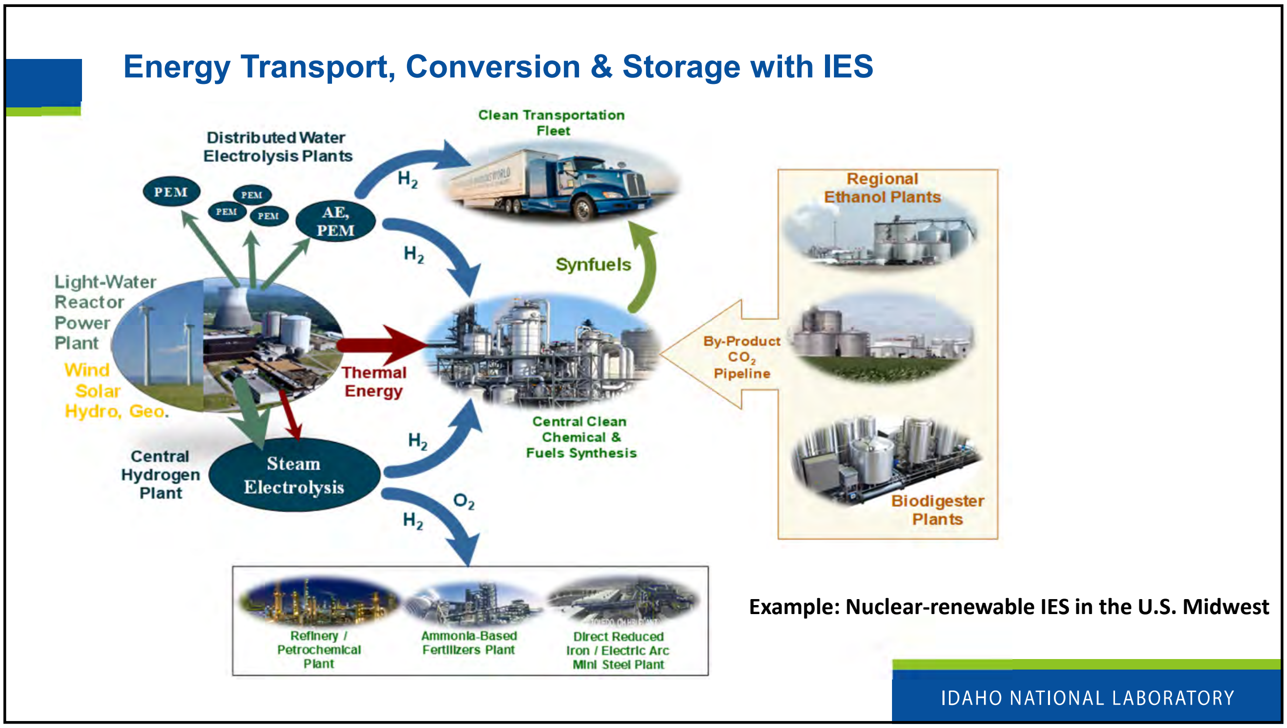
CO_2

$CO_2 + H_2O$ Co-electrolysis

Syngas

IES Integrated Energy Systems

https://ies.inl.gov



Energy Transport, Conversion & Storage with IES

Example: Nuclear-renewable IES in the U.S. Midwest

IDAHO NATIONAL LABORATORY

Joint EERE-NE H_2 Production Demonstration Projects

Three projects have been announced for demonstration of hydrogen production at nuclear power plants

- Demonstrate hydrogen production using direct electrical power offtake from a nuclear power plant
- Develop monitoring and controls procedures for scaleup to large commercial-scale hydrogen plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce hydrogen for captive use by NPPs and first movers of clean hydrogen

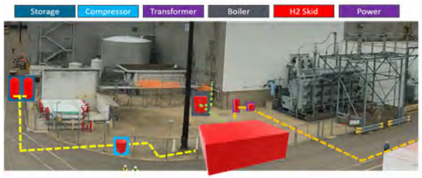
Schedule:

- Exelon: Nine-Mile Point NPP; LTE/PEM Vendor 1; using “house load” power; PEM skid testing is underway at NREL; H2 production beginning ~Jan. 2022
- Energy Harbor; LTE/PEM Vendor 2; power provided by completing plant upgrade with new switch gear at the plant transmission station; installation to be made at next plant outage; contract start anticipate by Oct. 2022
- Xcel Energy: HTE/SOEC Vendor 1; Project negotiations are being finalized. Tie into plant thermal line engineering has been completed; official project start anticipated by Jan. 2022.

Davis-Besse Nuclear Power Plant LTE-PEM Vendor 1

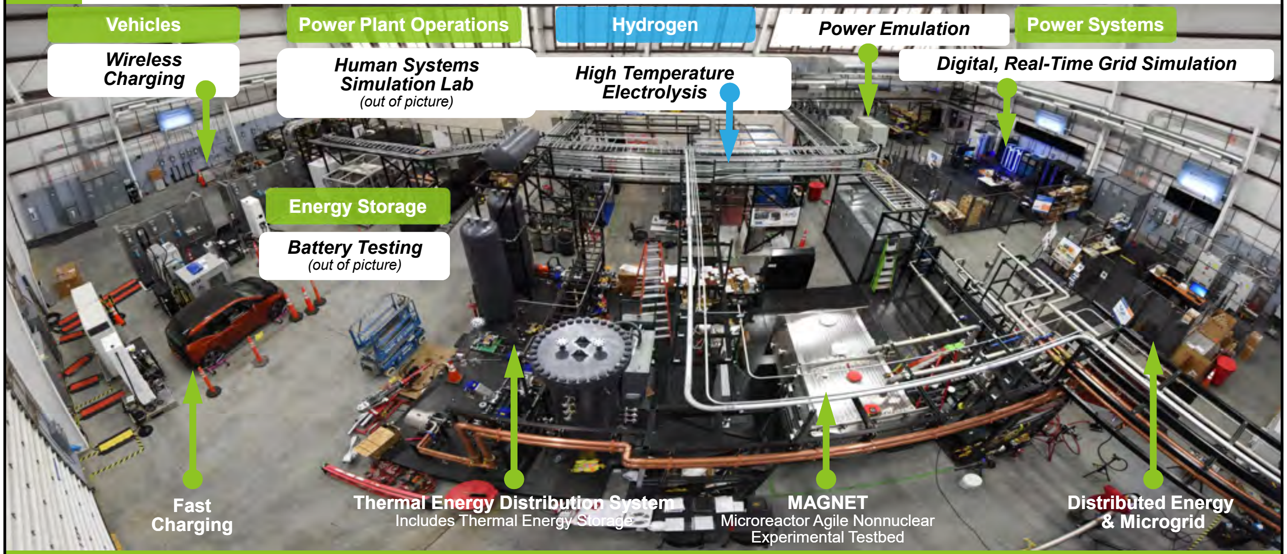
Nine Mile Point Nuclear Power Plant LTE/PEM Vendor 2

Thermal & Electrical Integration at Xcel Energy Nuclear Power Plant HTE/Vendor 1



HTE/SOEC efficiency is 20-30% higher than LTE/PEM

Integrating systems for the nation’s net-zero future



Vehicles

Wireless Charging

Fast Charging

Power Plant Operations

Human Systems Simulation Lab
(out of picture)

Energy Storage

Battery Testing
(out of picture)

Thermal Energy Distribution System
Includes Thermal Energy Storage

Hydrogen

High Temperature Electrolysis

Power Emulation

MAGNET
Microreactor Agile Nonnuclear Experimental Testbed

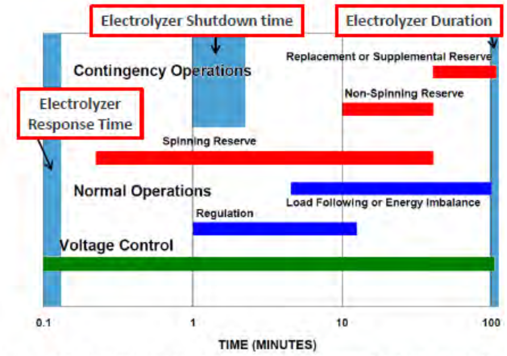
Power Systems

Digital, Real-Time Grid Simulation

Distributed Energy & Microgrid

Nuclear-Supported Hydrogen Production

- ❑ High Temperature Hydrogen Production Development Concepts
  - Couple thermal & electrical power to H_2 production
  - Develop heat recuperation
  - Increase performance and materials longevity
  - Produce hydrogen at >10,000 psi
  - Develop transient operations for grid demand response and regulation



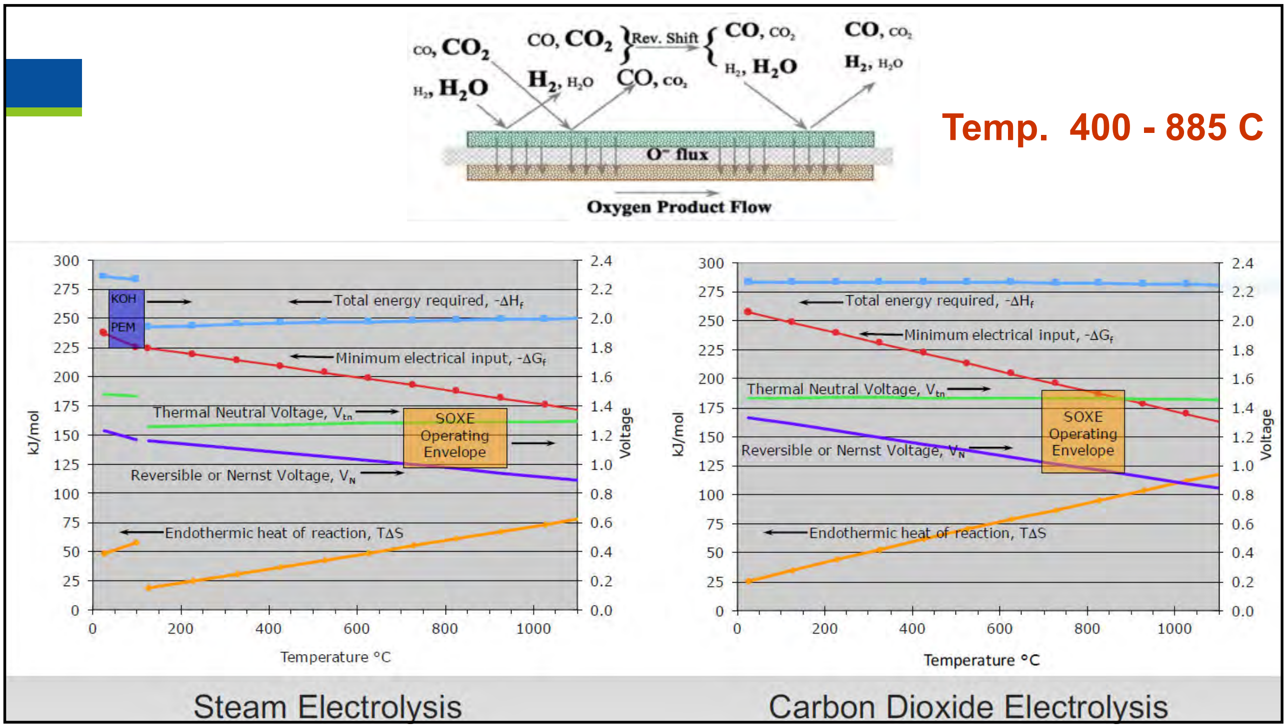
Source: Kirby, B.J. 2006. Demand Response for Power Systems Reliability: FAQ. ORNL
Source: Eichman, J.D.; Harrison, K.; Peters, M. (Forthcoming). Novel Electrolyzer Applications: Providing more than just Hydrogen. NREL/TP-5400-61758

• **PEM and Alkaline Electrolyzers** **100% electrical**	**Electrical**
• **Steam Electrolysis** **85% Electrical, 15% Thermal**	**Thermal-Electrical**
• **Hybrid Sulfur Acid** **50% Electrical, 50% Thermal**	**Electro-Chemical**
• **Sulfur-Iodine** **15% Electrical, 85% Thermal**	**Thermal-Chemical**
• **Steam Methane Reforming** **5% Electrical, 95% Thermal**	**Thermal**

Understanding the efficiency, cost, and operational flexibility of hydrogen technologies is critical to assessing their ability to integrate with the grid

---

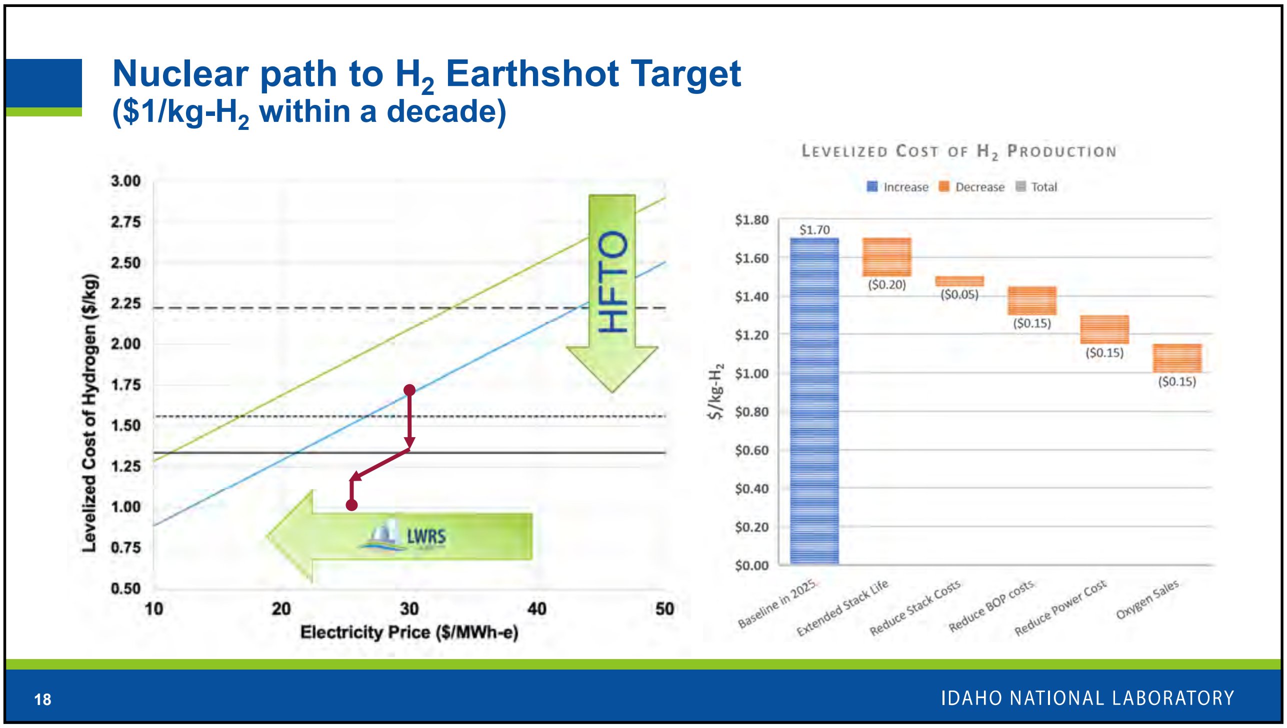
Idaho National Laboratory



Temp. 400 - 885 C

Steam Electrolysis

Carbon Dioxide Electrolysis



Nuclear path to H_2 Earthshot Target ($1/kg-$H_2$ within a decade)

Roeslein Alternative Energy's Vision for Conversion of Biomass to Digestate, Methane and Carbon Dioxide

Hassan Loutfi
Research & Development Program Manager
August 4, 2021

Roeslein Alternative Energy (RAE)

Rudi Roeslein founded RAE in 2012 as an operator and developer of renewable energy production facilities that convert animal wastes, along with restored native prairie biomass feedstocks, into renewable natural gas and sustainable co-products.

Mission and Vision

- Provide sustainable solutions for livestock production and renewable energy generation
- Using residues for bio-energy production and nutrient replenishment
- Incorporates native prairie restoration
- Substantial decrease in carbon footprint
- Provide ecological services for people, wildlife, and the environment

Vertically Integrated Business Model

- RAE is a full solution developer of business, finance, and technical / regulatory solutions
- Design, build, own, and operate (DBO) facilities

The Challenge of Population Growth to 9.6 B by 2050

- CAFO use for hogs and dairy cows' production
  - Manure disposal
    - Decomposition in open fields impacts methane emission
    - Environmental impact on water and natural resources

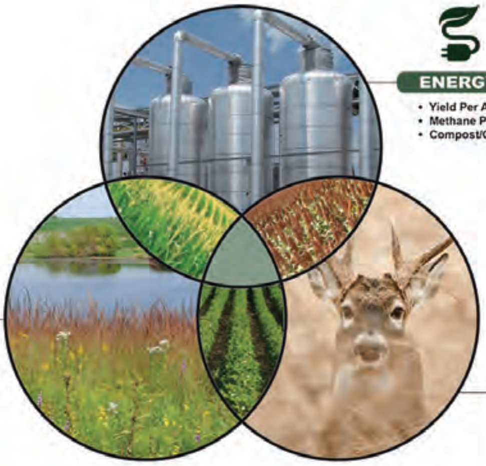
- Atmospheric GHG and climate change
  - Impact= increased frequency and severity of weather events

- Competing demands and increasing stress on landscape
  - Soil erosion and soil quality deterioration
  - Water contamination
  - Loss of wildlife and pollinators habitat

- Economic impacts on agriculture, outdoor recreation, consumer spending, jobs and tax revenue

SUSTAINABLE SOLUTIONS // RENEWABLE ENERGY

Energy, Ecosystem, and Wildlife Objectives in Balance



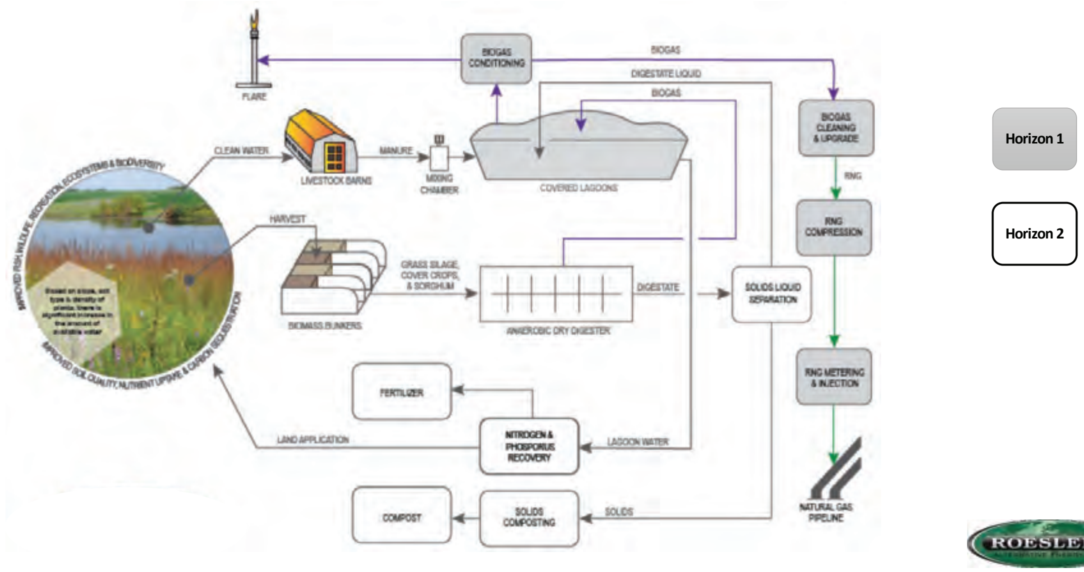
ENERGY
- Yield Per Acre
- Methane Production
- Compost/Organic Fertilizer

ECOSYSTEM
- Clean Water
- Water Storage
- Soil Health
- CO2 Sequestration
- Carbon Rebuilding

WILDLIFE
- Pollinators
- Grassland Birds
- Food & Shelter

SUSTAINABLE SOLUTIONS // RENEWABLE ENERGY

RAE Facilities Conceptual Block Flow Diagram



SUSTAINABLE SOLUTIONS // RENEWABLE ENERGY

Horizon 1 – AD of Manure Biomass

Feedstock:

- Swine Manure

Infrastructures:

- Covered Lagoon AD,
- Biogas handling,
- Upgrade to RNG, and
- Tie-in to National Grid

Co-Products:

- RNG, Water, Nutrients, Solids, and CO_2


Covered Swine Manure Lagoon AD near Albany, MO

Advantages of Manure Treatment by Covered Lagoons AD include:

- Low capital and operating cost
- Alleviate GHG and odor emissions
- Mitigate open lagoon vulnerability to flooding
- Protect animal and human health by reducing pathogens
- Convert nutrients in manure into more accessible forms for plants

SUSTAINABLE SOLUTIONS // RENEWABLE ENERGY

Horizon 2 – AD of Grassy Biomass

Feedstock:

- Prairie Grasses and Cover Crops

Infrastructures:

- Grass storage areas (bunkers / piles),
- Above ground digester and facilities (CHP, Pretreatment, etc.)
- Solid/liquid separation, storage, composting, and
- Tie-in to H-1 biogas upgrade and RNG to the grid connection.

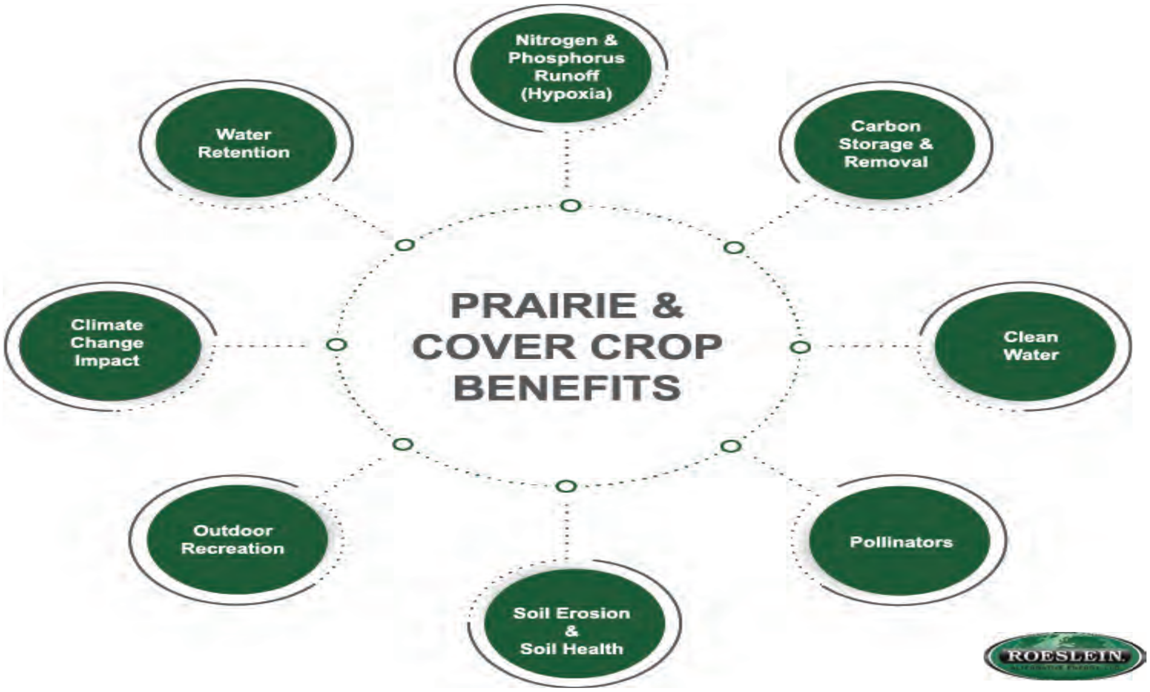
Co-Products:

- RNG, Water, Nutrients, compost, and CO_2

2021-07-07 Photo of Restored Prairie in Gentry County, MO

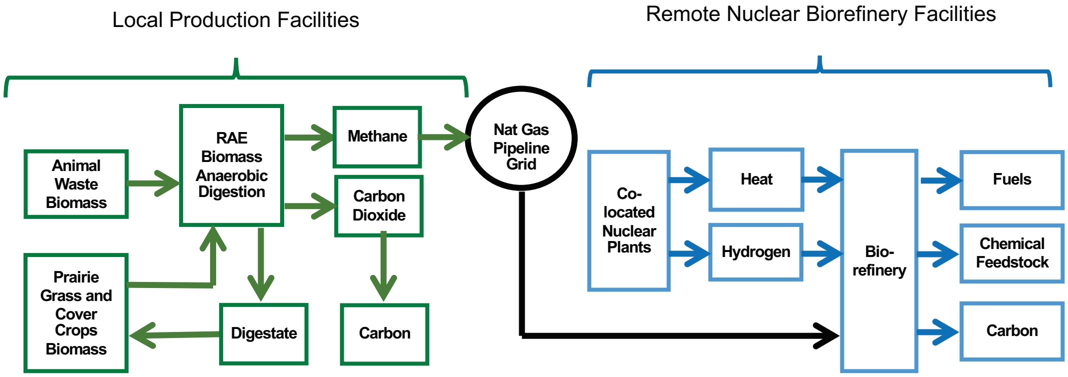
Advantages of Prairie grass and Cover Crops AD include:

- Realizing the substantial benefits from re-establishment of prairies particularly when grown on marginal land including improved wildlife and pollinators habitat, sustain soils, reduced runoff and improved water quality.
- Growing cover crops improve fields production and generate a host of ecological benefits.



RAE Integration with the Nuclear Biorefinery

SUSTAINABLE SOLUTIONS // RENEWABLE ENERGY



Local Production Facilities

Remote Nuclear Biorefinery Facilities

Animal Waste Biomass

RAE Biomass Anaerobic Digestion

Methane

Carbon Dioxide

Prairie Grass and Cover Crops Biomass

Digestate

Carbon

Nat Gas Pipeline Grid

Co-located Nuclear Plants

Heat

Hydrogen

Bio-refinery

Fuels

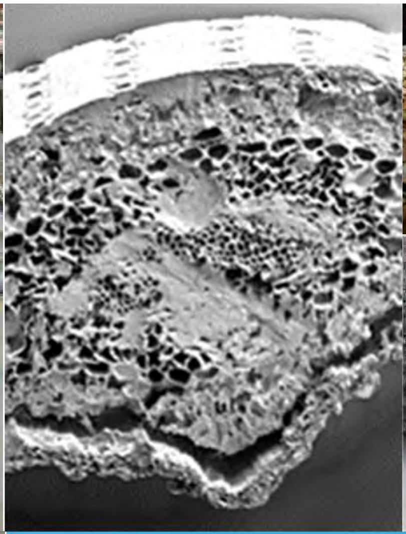
Chemical Feedstock

Carbon

ROESLEIN

Thank You

ROESLEIN



Date: August 11, 2021

Name: J. Richard Hess

Title: Director, INL Energy Efficiency Science & Technology Programs

Depot Processing Options: Managing Variability through Fractionation, Merchandising, Formulation

Idaho National Laboratory

2011 Concept: Transform Raw Biomass into High-Density, Stable, Commodity Feedstocks

The Uniform Commodity Feedstock Vision enables commodity-scale, custom-formulated feedstocks to play a critical role in producing biofuels, biopower, and other bioproducts.

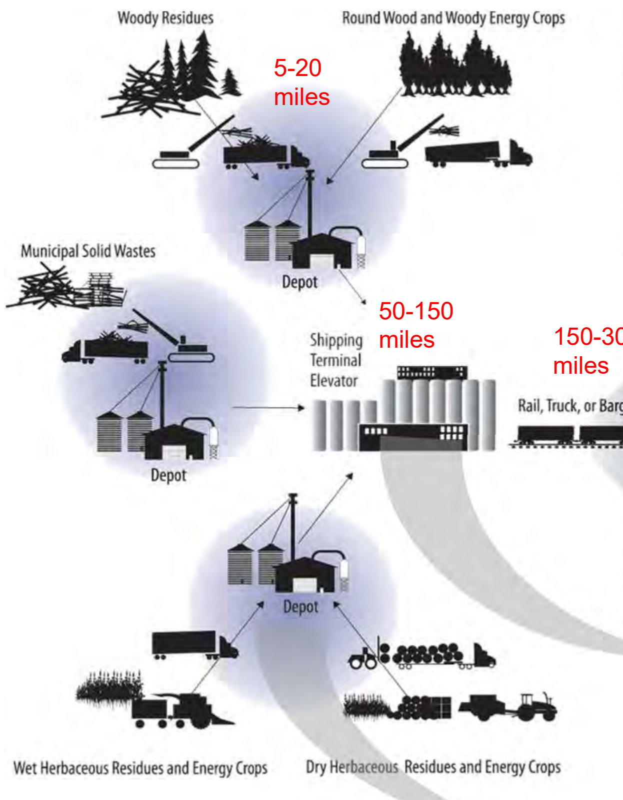
Biomass Preprocessing

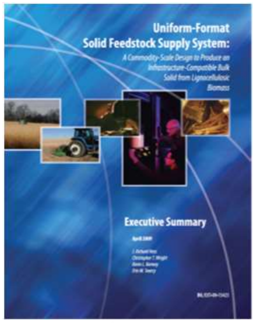
Biomass preprocessing, which [illegible] key to a commodity bioenergy vision. A [illegible] link between biomass producers and refineries. It also alows flexibility for local communities to produce bioproducts including feedstocks customized for biochemical, thermochemical, and combustion conversion facilities. It also enables

The Preprocessing Depot enables development of commodity biomass feedstock markets by managing diverse biomass, promoting increased resource access, and ensuring quality, on-spec feedstock delivery to conversion facilities.

But a preprocessing depot can do much more. It offers limitless opportunities for innovations to

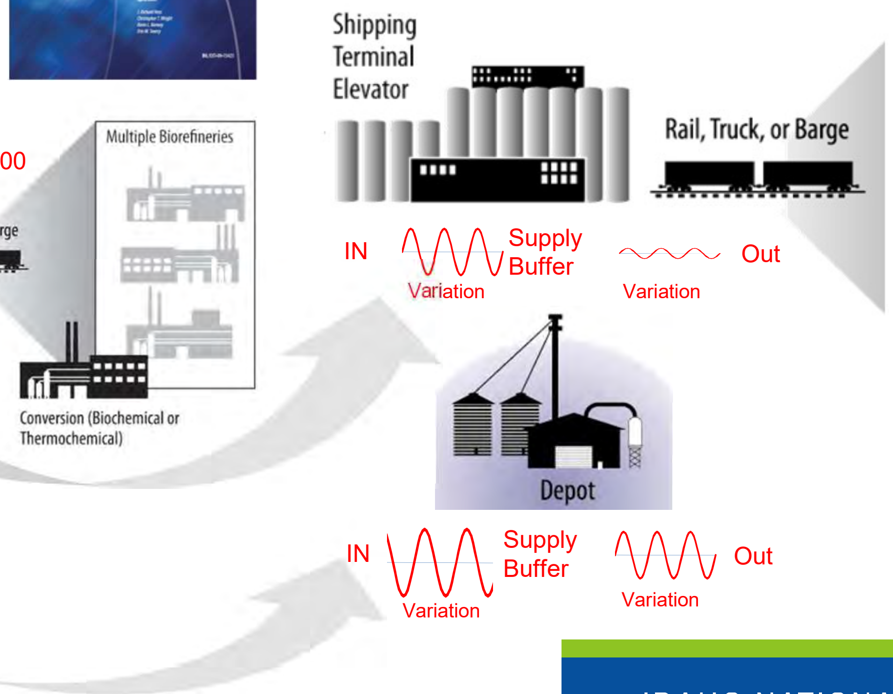
2011 Ideas: Improve Biomass Density, Stability and Infrastructure Compatibility




Uniform-Format Solid Feedstock Supply System:
A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass

Executive Summary

Commodity Attributes:
- Standardized Material/Quality
- National Market
- Biomass Exchange Market



IDAHO NATIONAL LABORATORY

2011 Objective: Improve Biomass Quality and End-use Performance

Feedstock Specifications

- **Physical properties / handling behavior**
  - Bulk and particle densities
  - Tissue structure
  - Grindability index, shear strength
  - Particle-size distribution and shape factors
  - Particle morphology (surface area, porosity)
  - Thermal conductivity, heat capacity
  - Compaction index
  - Free flow and pneumatic rheology
  - Physisorption and swelling
- **Chemical properties / reactions behavior**
  - Proximate and Ultimate analysis
  - Organic composition
  - Functional groups and bond energy
  - Heat of formation; heating value, LOD, LOI
  - Mineral matter composition
  - Mechanistic reactivity (depolymerization, devolatilization, char reactivity)
  - Chemisorption
- **Storage behavior**
  - Equilibrium moisture
  - Biodegradability
  - Phytosanitation
  - Ignitability, explosivity (K_{st})

Truck Load of Barley Straw Pellet Meal

¼ minus Stover

Stover Pellet Meal

Other Preprocessed Products:

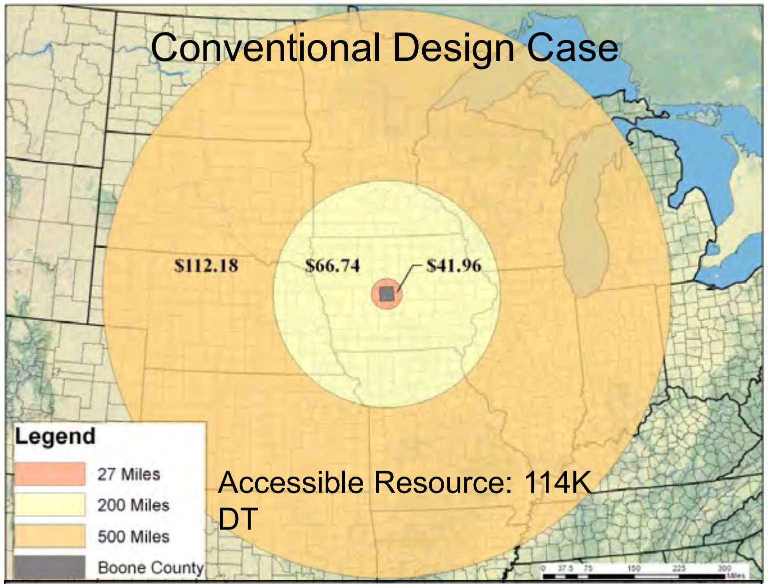
- Fractionated (Stover Fiber)

- Thermal Treated

- Various Densification Formats

- Blended

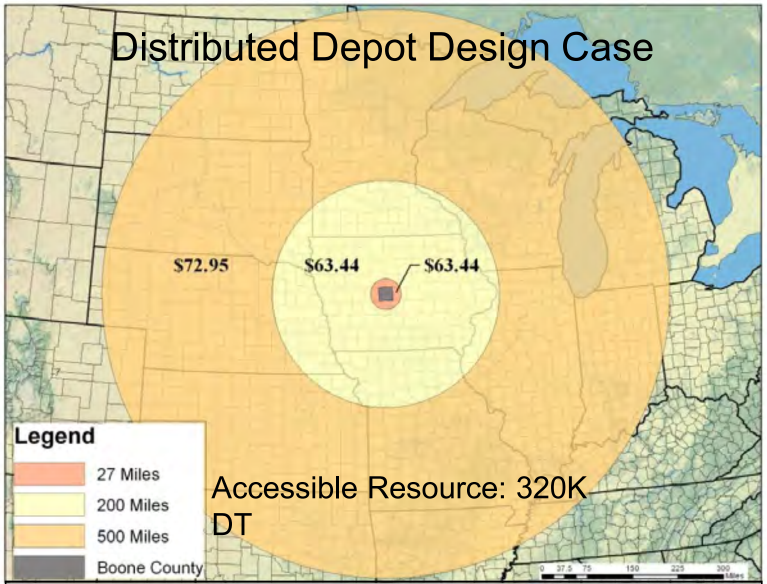
2011 Justification: Increase Accessible Biomass Quantities/Diversity and Supply Stability


Conventional Design Case

Accessible Resource: 114K DT

Elevated Risk

- Supply Risk
- Material Quality and Spec Risk
- Cost Risk


Distributed Depot Design Case

Accessible Resource: 320K DT

Stable System

- Supply and Cost Risk Mirror the Grain System
- Material Quality Standards

Raw Materials are Preprocessed to Feedstock Quality Specifications

Cotton

Cotton Gin

Corn

Drying

Cleaning

Logs

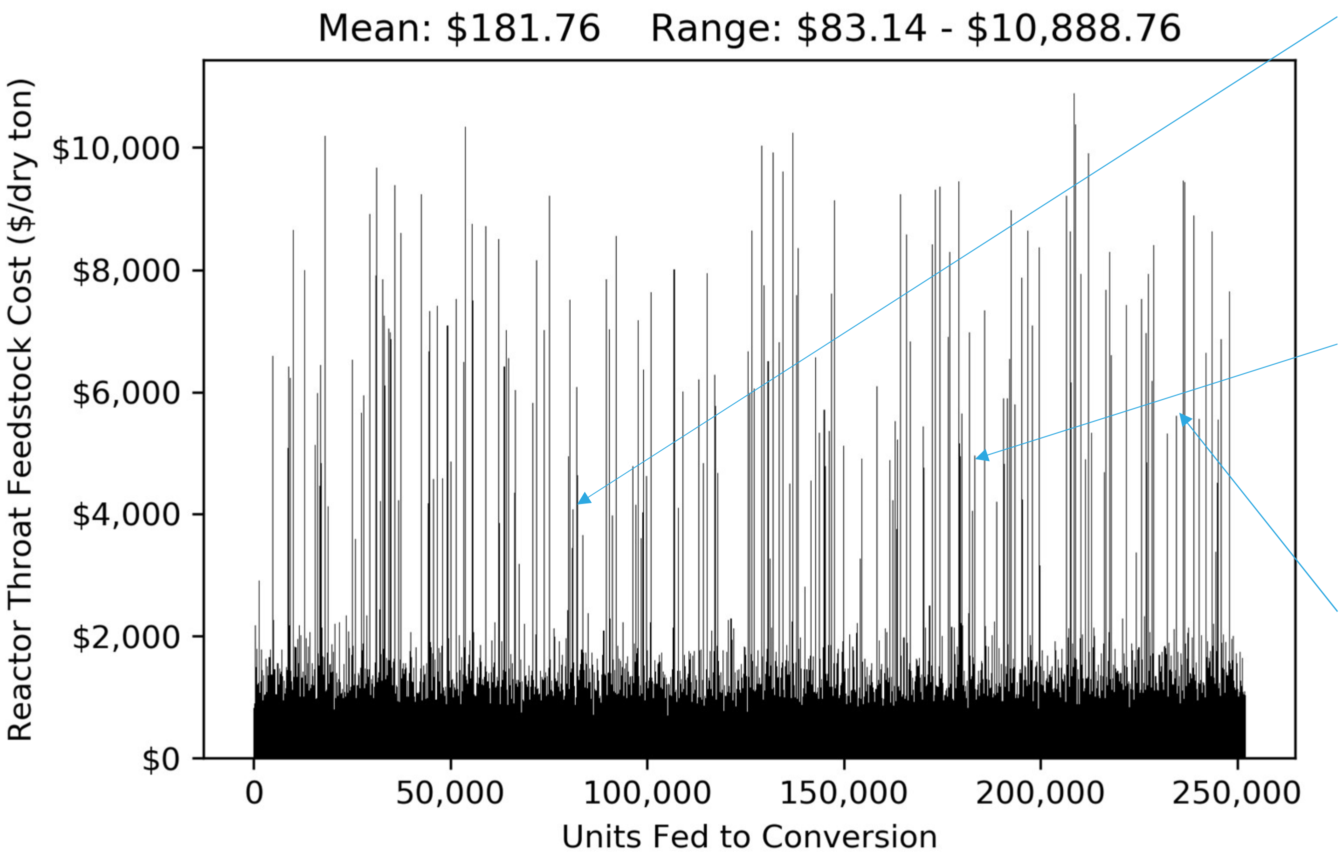
Debark/Chipping

Screening/
Sizing

Kelderman Self-Unloading Trailer Delivering Stover Bales to a Biorefinery

- Raw Stover Bales directly from the field or field side storage stack
- Stover Bales were ground and feed directly into the conversion systems.

Variability in Processing Costs of Raw “Field-Run” Corn Stover



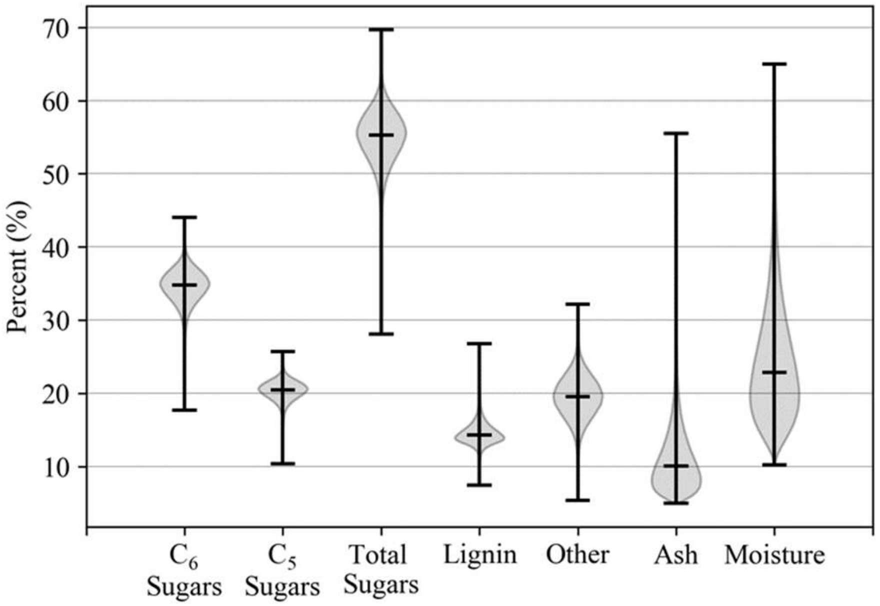
- Bridging in Even Flow Bin
- Bridging in Drop Chute
- Plugged Conveyor

Why Particle Processes are so Difficult

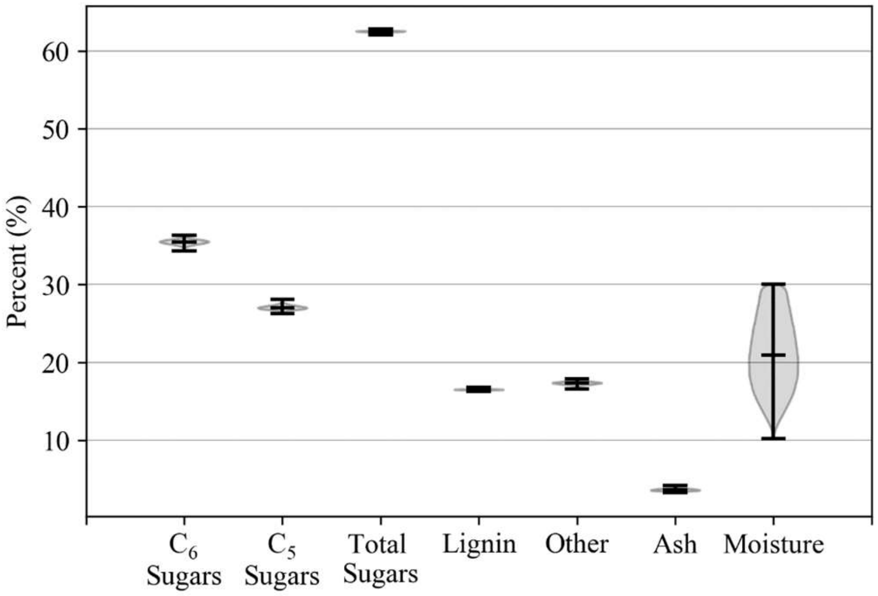
- A particle system is more likely to be inconsistent than consistent
- Particles can almost be described as a fourth state of matter
  - They can develop cohesive strength and transfer stresses like a solid
  - They can retain air and take on fluid-like properties
  - They are often compressible and elastic like a gas
  - Unlike liquids and gases, particles often remember where they have been and never forget
  - Gases and liquids do not grow, agglomerate, aggregate or suffer attrition, particles do
- Materials process differently after being aged or subjected to repetitive handling
- Particle behavior often does not scale

Less than 30% of Field-Run Corn Stover Meets Critical Biorefinery Quality Specifications

Field-Run Stover Quality Variability



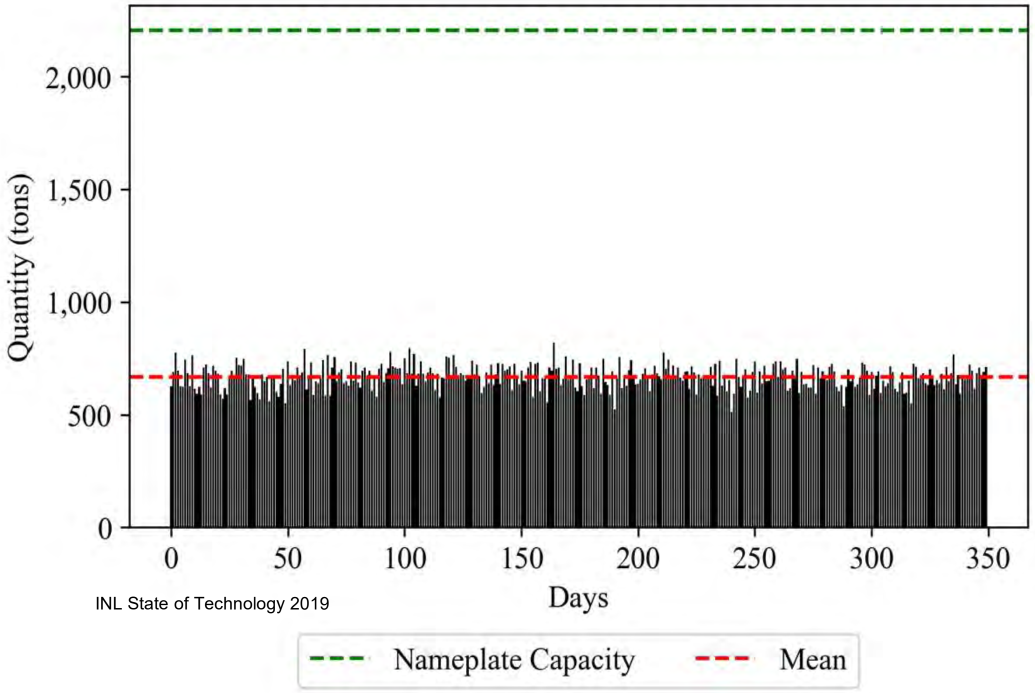
Biorefinery Feedstock Quality Specs



- Greater than 90% of Biomass Feedstock material must meet all conversion specifications

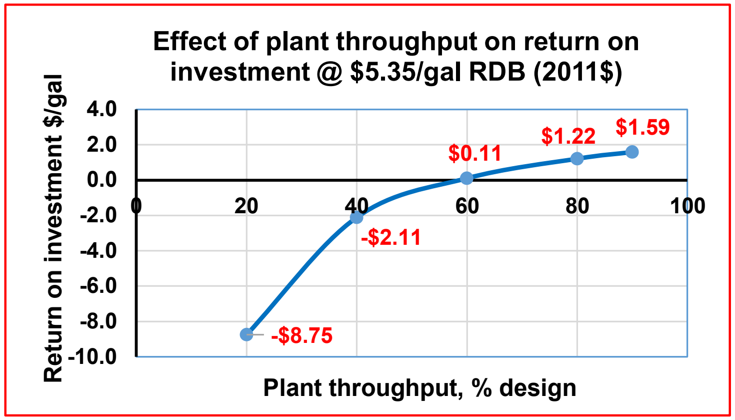
Effect of Raw Material Quality Variability on Throughput

Simulated Biorefinery Operation Using Field-Run Corn Stover Bales



INL State of Technology 2019

- Problems generally relate to an inadequate understanding of the behavior of particle systems (Bell 2005)
- Feedstock variability and the limitations of preprocessing systems to handle such variability is a significant factor
- Biorefinery simulated operation only reached 30.32% of nameplate capacity



NREL/TP-5100-60223

Quality is an Issue for all Biomass Resources

Forest Residues

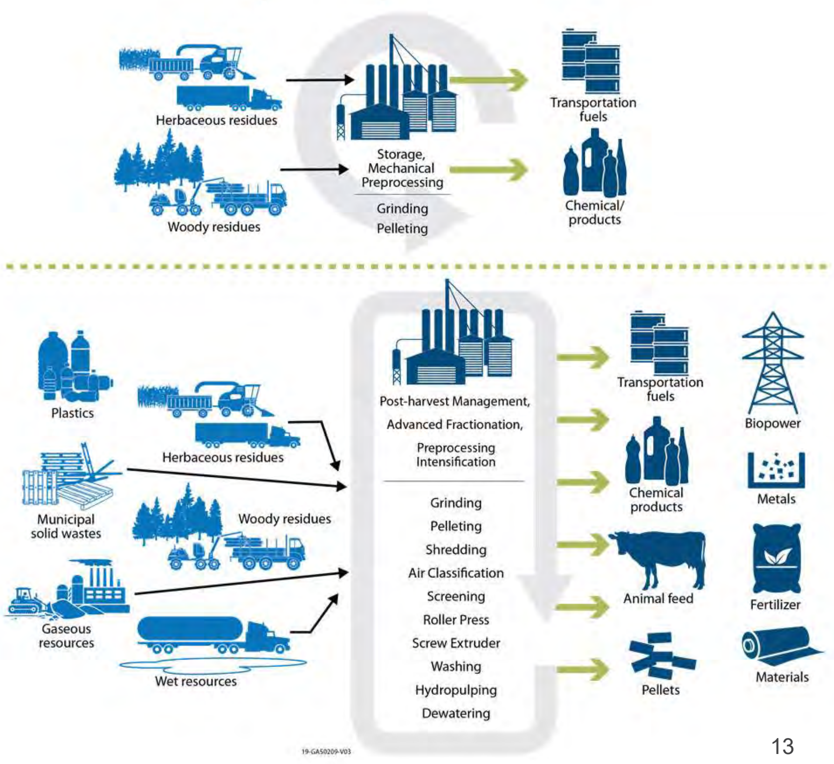
Corn Stover Bales

Municipal Solid Waste

- Raw Biomass DOES NOT meet Feedstock Specifications
- Biomass Resource Diversity and Variability Requires Preprocessing of Raw Biomass to Achieve Feedstock Specification

Updated Vision: Quality-by-Design Feedstock Supply Chain

- Develop value-add, transformative, economical and sustainable technologies to enable Quality-by-Design Feedstock Supply Systems from renewable and diverse carbon and energy sources for biofuels, bioproducts and biopower production



Uniform Format Feedstock Supply System

Stone Milling Approach

Simple supply systems that grinds, dries and densifies

Quality-by-Design Feedstock Supply System

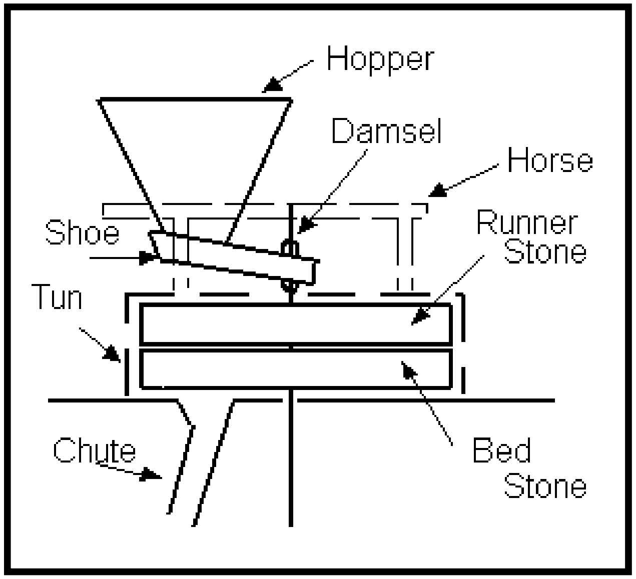
Fractional Roller Milling Approach

Expands preprocessing operations:

- Enables access to new feedstocks
- Selective pairing of feedstock fractions and conversion processes based on feedstock quality
- **Midstream** for fractionation, merchandizing, and value-add.

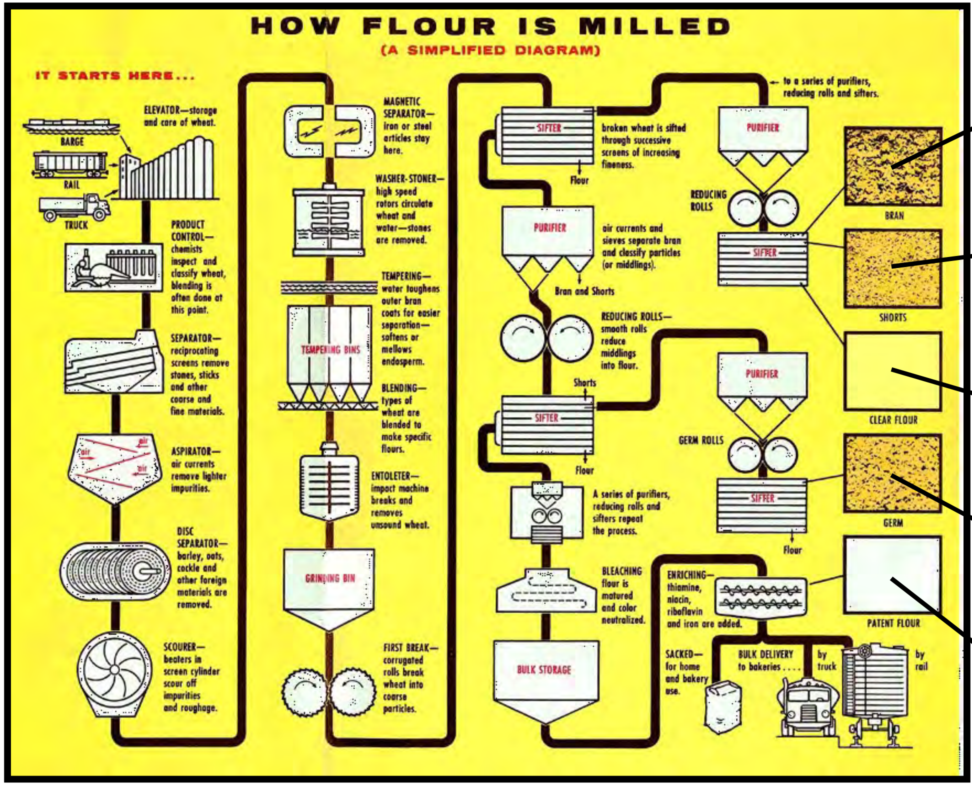
Development of the Roller Mill in the 1870's Started the Growth of the Modern Flour Milling Industry

Grist Mill Diagram




Whole Wheat Stone Milled Flour

Simplified Roller Mill Diagram




Bran


Shorts

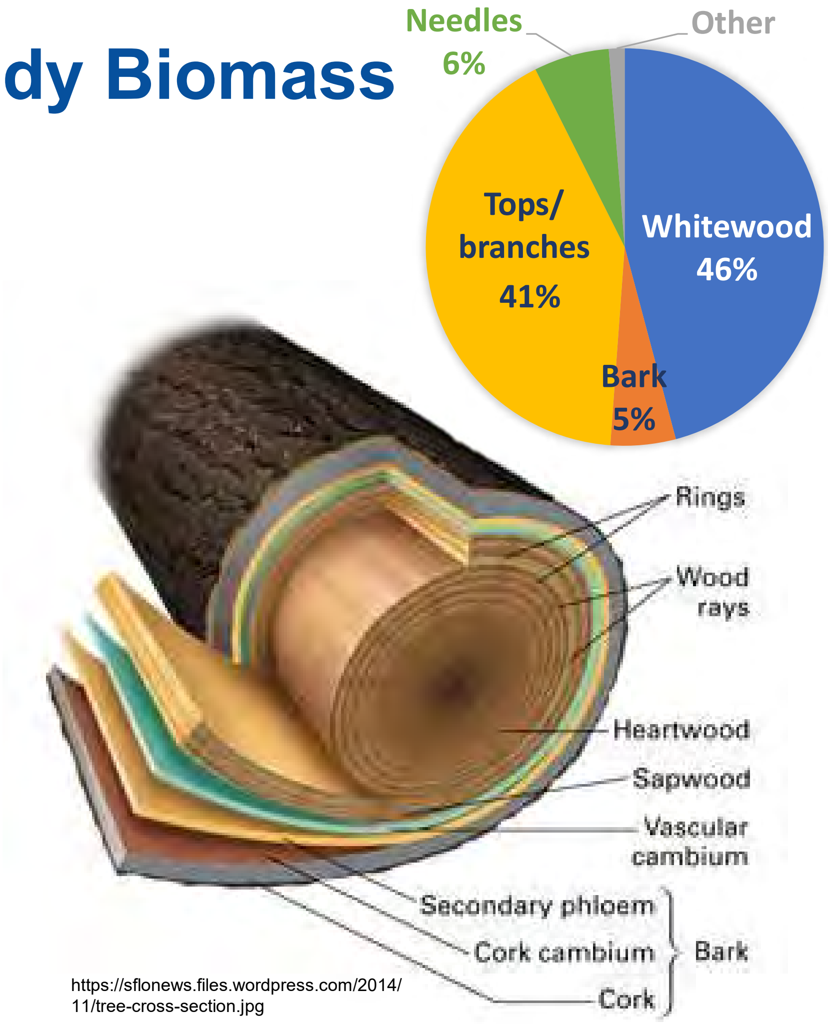

Clear Flour


Germ


Patent Flour

Compositional Variation in Woody Biomass Anatomical Fractions

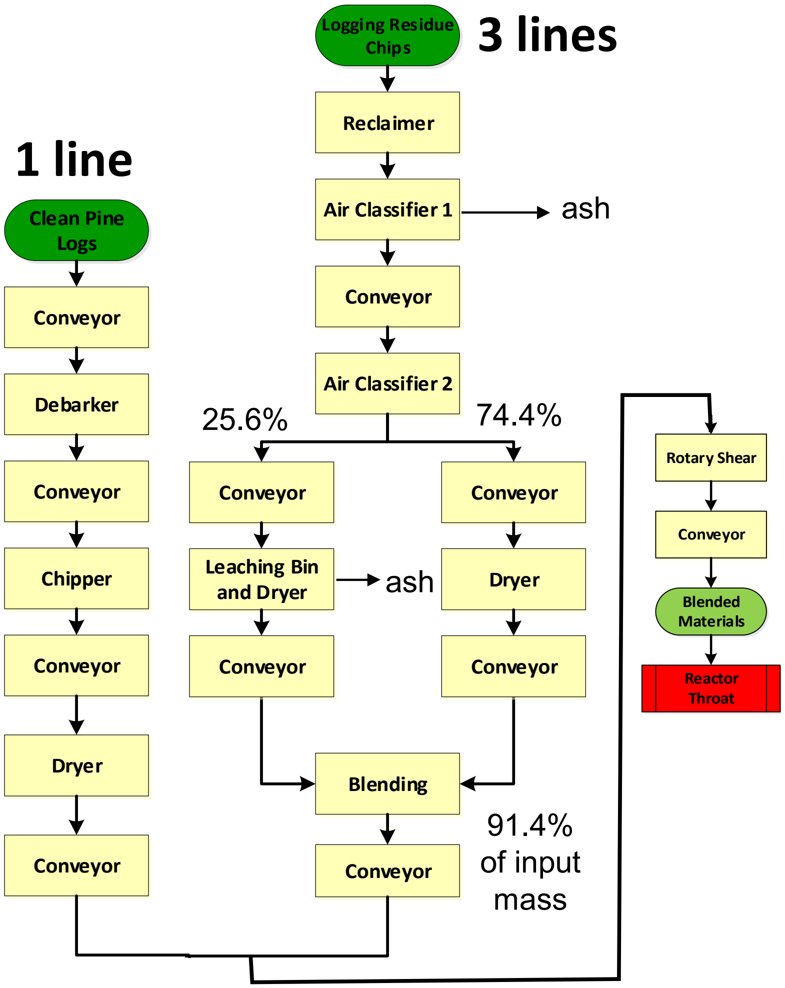
- White Wood (heartwood, sapwood) enriched in carbohydrates, lignin
- Bark enriched in lignin
  - Can trap soil due to surface roughness
- Water and nutrient transport elements contain higher concentrations of alkali and alkaline earth metals
- Photosynthesizing tissues (needles) are typically high in silicon
  - Terminal point for transpiration; water leaves and inorganics are enriched
- Variability is compounded with age, growing condition, harvest season



https://sflonews.files.wordpress.com/2014/11/tree-cross-section.jpg

Fractionation of Loblolly Pine

- Temporary residue chip storage in pile at biorefinery
- Air classification of chips to reduce ash content
- Drying to < 10% moisture prior to grinding
- Multi-stage tissue fractionation using varying technologies depending on tissue
- Minimal quantities are exposed to additional processing to improve overall quality
- Recombination of tissue fractions in different ratio to meet quality specifications



Feedstock Supply Chain Analysis, Thompson, Hartley, et al.

A Model for Advanced Fractionation is Loblolly Pine

①

Pine Plantation

②

Feller-buncher

③

Grapple skidder

④

Whole tree disc knife chipper with chain flail

Clean Pine Chips

⑤

Residue pile

⑥

Drum knife chipper

Residue Chips

Multi-Stage Comminution Combined with Separators Enables Pine Residue Fractionation

Air Classifier

Gravity Separator

As-received loblolly pine forest residues.

Air classified “Heavy” clean fraction with fan speed of 3.8 m/s air velocity.

Air classified “Light” dirty fraction with fan speed of 3.8 m/s air velocity.

- Plant-tissues have variable density, drag and morphology properties that impact separations.
- Particle drag models applied to separators enabled fractionation of anatomical pine tissues.

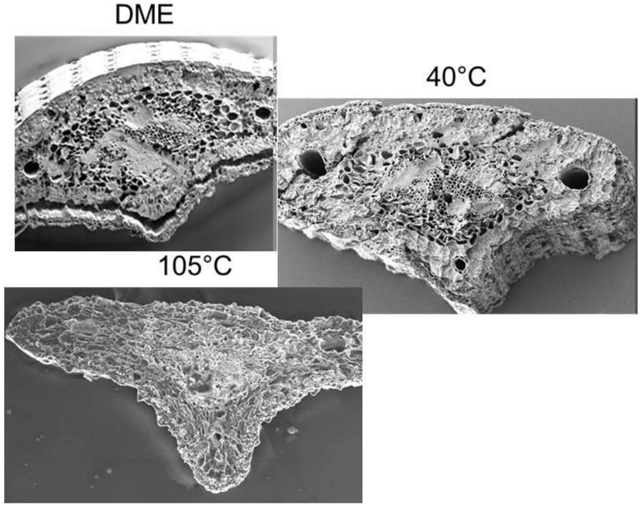
Materials Conditioning

Material state is a key factor in mechanical preprocessing. Material conditioning with moisture, heat, chemicals, and pressure facilitates deconstruction and separation of layered composite biomass materials

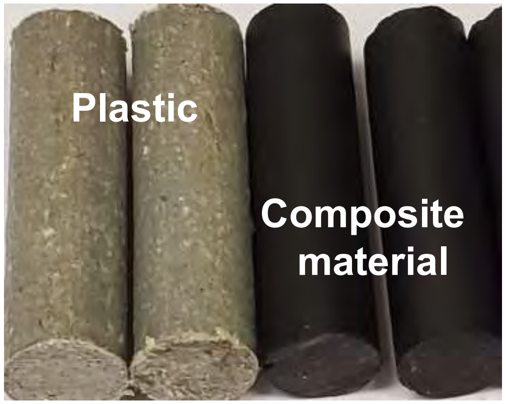
Material State and Conditioning

Environmental Storage

Moisture Modification



Tempering



Material Engineering Solutions

- Insert processes to alter biomass material properties and enable use of existing equipment
- Examples
  - Blending: variability
  - Densification: compressible, elastic behavior
  - Flow Additives: cohesiveness
  - Heat Treatment: mild deconstruction of cell structure to alter properties
- Benefits
  - Fixes the problem and keeps it from cascading
  - Scalable solution – only use it when and as much as needed

Ground
Herbaceous
Biomass

Pelleted
Herbaceous
Biomass

Forest Concepts
Stem Wood
Crumbles

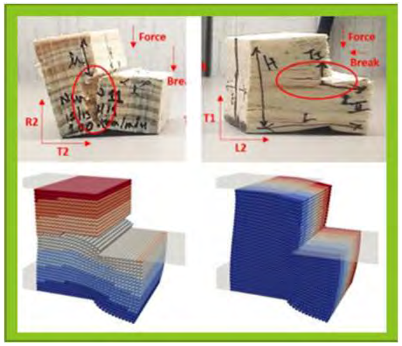
Technical Quality-by-Design Feedstock Supply System Challenges

- Separations and Sorting Raw Materials – Primarily a Technology development Challenge:
    - Vision Systems
    - A.I. control/sorting systems
    - Robotics

- Fractionation of tissues and material composites – Primarily a Material Science Challenge:
    - Interfacial chemical and biological material properties
    - Micro-mechanical material properties characterization
    - Multi-scale structure of tissues/materials and particles

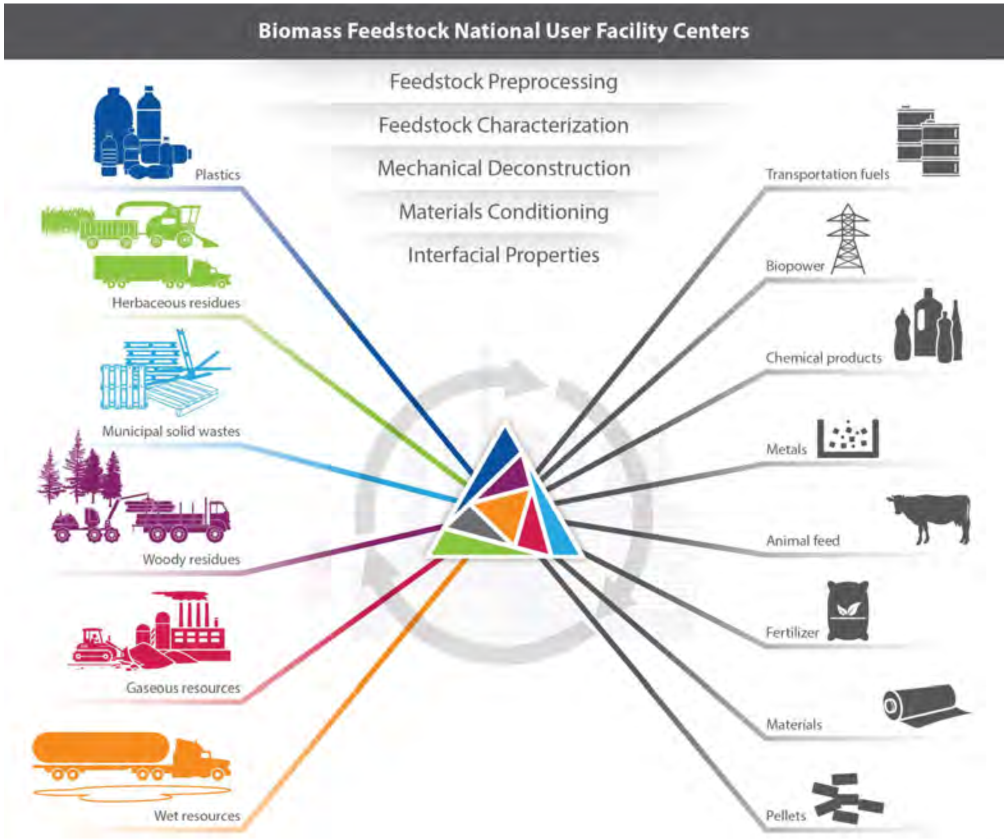
Chemical Signature Separation

Macro-Scale Shear Fracture Mechanics



Depot (or Midstream) Need for Affordable Bioenergy Fuels, Products and Power

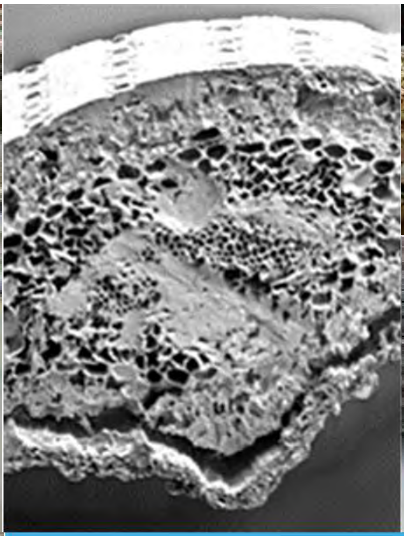
- Feedstock costs contribute to 30% of the total costs of a cellulosic-based biorefinery
- Feedstock quality specifications are critical to maximizing predictability of conversion
- As industry moves to more diverse resources such as MSW, wet wastes, and gaseous feedstocks to support a circular carbon economy, more emphasis is needed to reduce variability in:
  - Flowability and Handling
  - Fractionation (critical to maximizing revenue)
  - Stability
- Feedstock management is critical to biorefinery performance



INL

Idaho National Laboratory

WWW.INL.GOV

Date: August 11, 2021

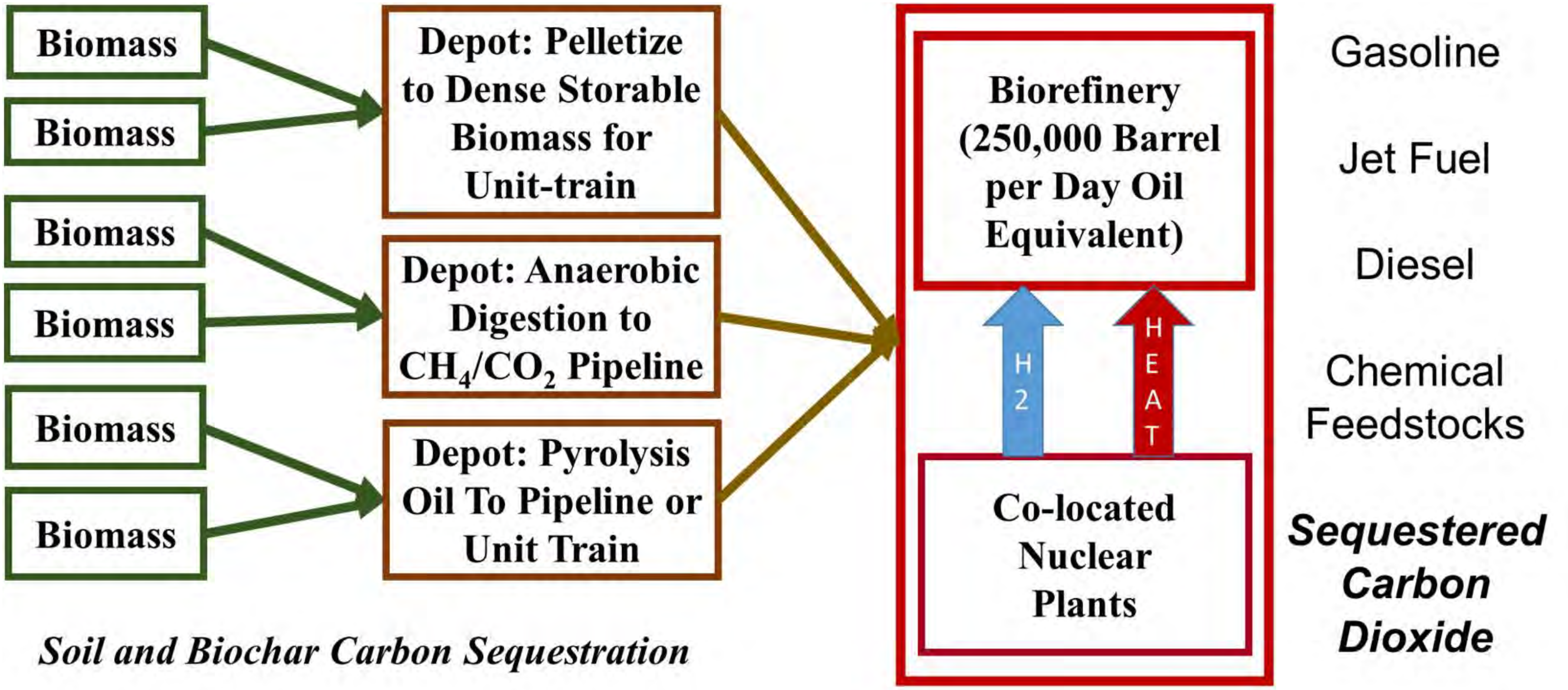
Week 2: Nuclear Biofuels Workshop

Name: Lynn Wendt, Ph.D.

Wet vs. dry biomass intermediate products and associated logistics systems

Idaho National Laboratory

Logistics Operations Along the Biomass Supply Chain



Biomass

Biomass

Biomass

Biomass

Biomass

Biomass

Depot: Pelletize to Dense Storable Biomass for Unit-train

Depot: Anaerobic Digestion to CH_4/CO_2 Pipeline

Depot: Pyrolysis Oil To Pipeline or Unit Train

Soil and Biochar Carbon Sequestration

Biorefinery (250,000 Barrel per Day Oil Equivalent)

Co-located Nuclear Plants

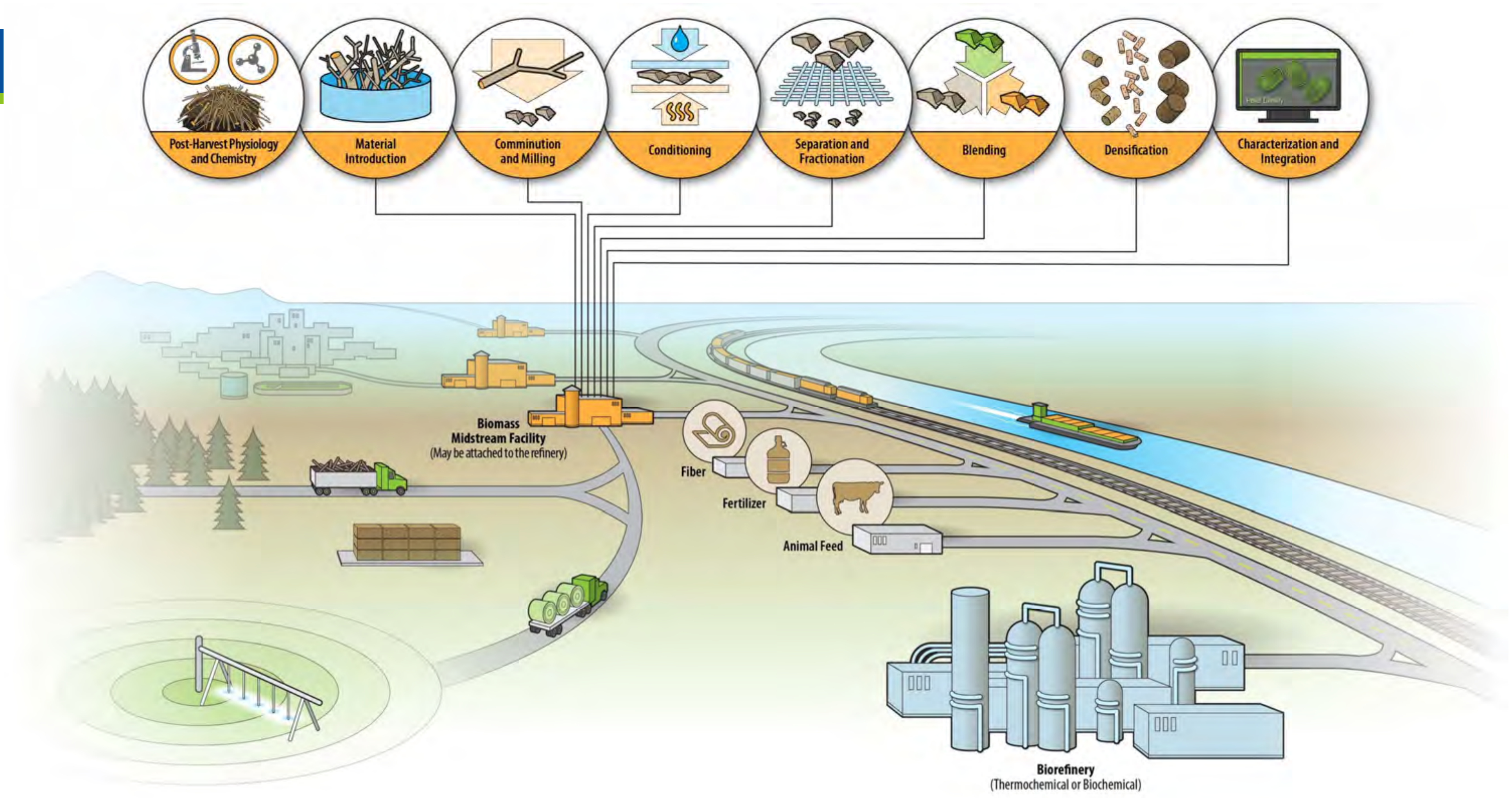
Gasoline

Jet Fuel

Diesel

Chemical Feedstocks

Sequestered Carbon Dioxide


Post-Harvest Physiology and Chemistry
Material Introduction
Comminution and Milling
Conditioning
Separation and Fractionation
Blending
Densification
Characterization and Integration
Biomass Midstream Facility
(May be attached to the refinery)
Fiber
Fertilizer
Animal Feed
Biorefinery
(Thermochemical or Biochemical)

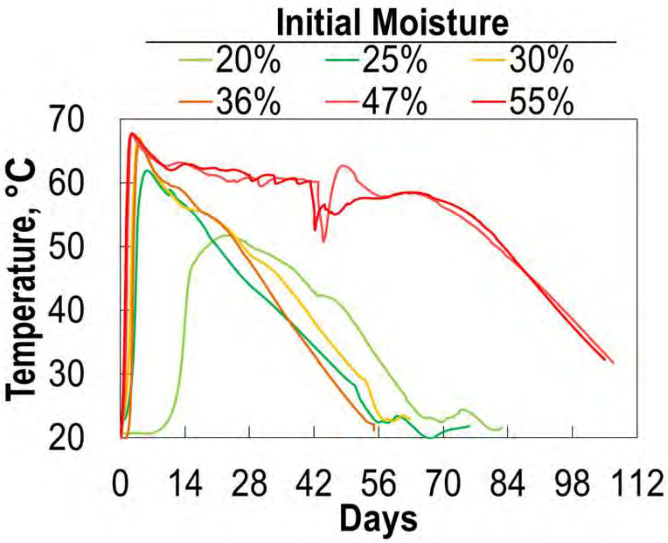
Moisture is a Failure Point for the Industry and Must be Managed

- Moisture moves during storage; biodegradation follows moisture, leading to spatial and temporal problems
  - Biological effects (microorganisms)
  - Chemical effects (hydrolysis, secondary reactions)
  - Physical effects (temperature swings, particle size, brittleness/fines generation)
- Goal: Develop technologies that reduce variability and degradation in harvested biomass to enable downstream utilization
- Every % loss in storage is estimated to cost $0.40/ton

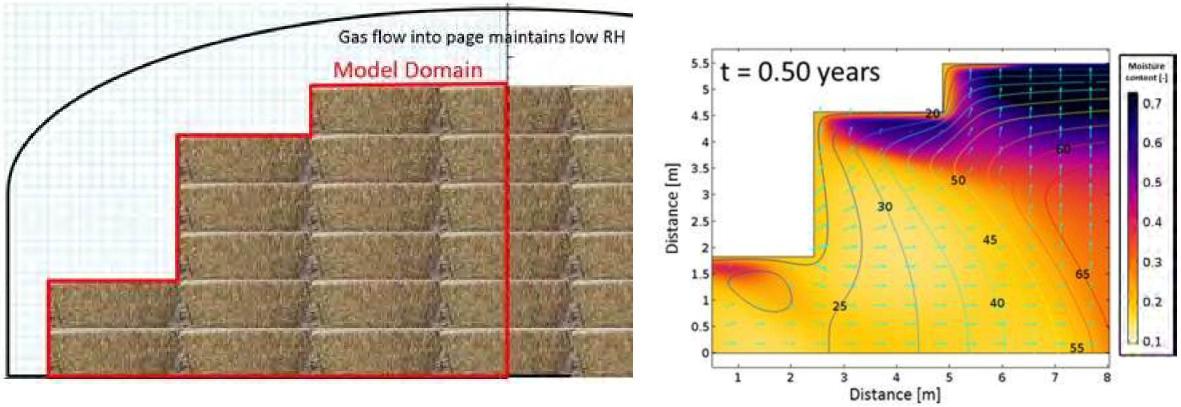
INL Technical Point of Contact: william.smith@inl.gov

Moisture Management is Possible with Dry Systems

- Goal: Capture microbially-generated heat in service of carbon retention and value-added drying supporting the needs of downstream processes
- Breakthrough: Dry matter loss was reduced from 12% to 4% when corn stover was dried from 30% to 19% (wet basis) during storage



Smith et al., 2020, Frontiers in Bioengineering and Biotechnology



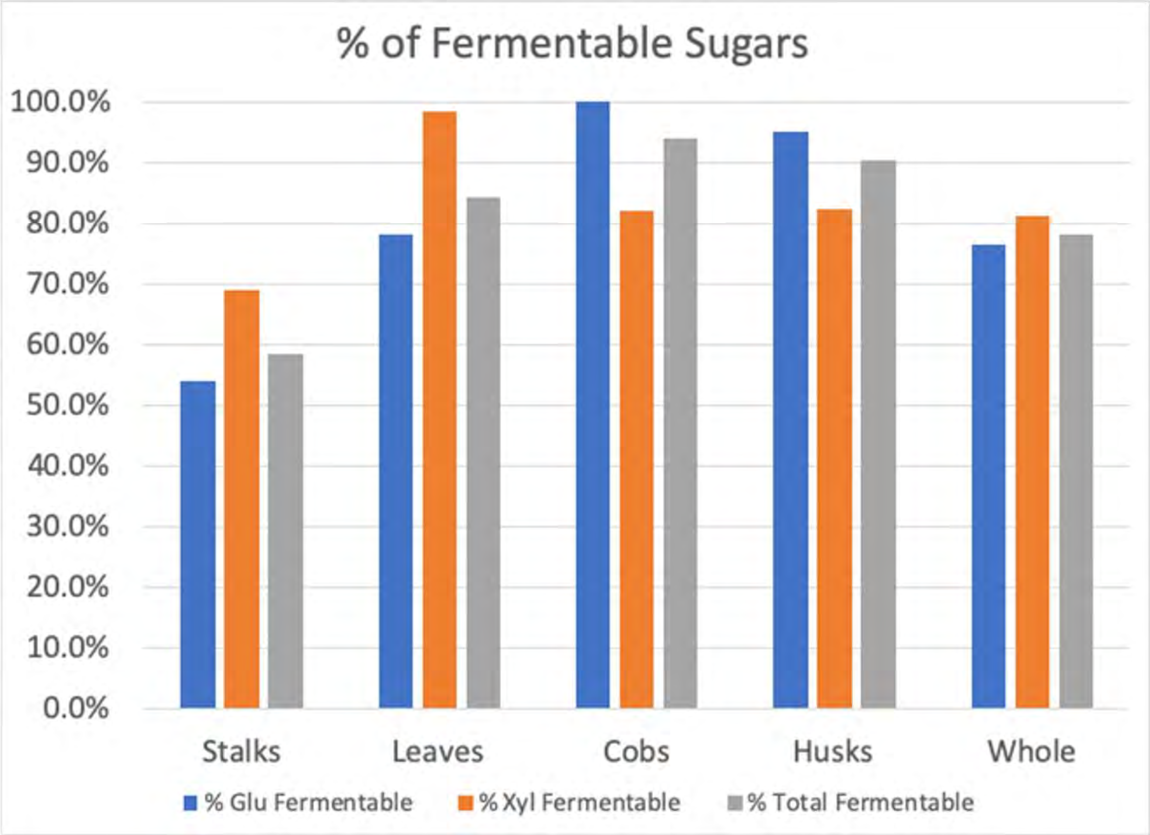
Modeling Efforts Inform Field Design for Stability

INL Technical Point of Contact: william.smith@inl.gov

Herbaceous Biomass Recalcitrance – The Case For Fractionation

- Stalks have by far the highest sugar potential in terms of glucan content
- Yet only ~50% of that glucan is fermentable in a standard treatment
- As part of the mix, stalks require more “preprocessing” or settling for reduced yields
- Tissue level fractionation of stalks will significantly increase the fermentable sugar potential

	Glucose/ tonne	Xylose/ tonne
Stalks	166.6 ± 7.3	66.6 ± 1.4
Leaves	93.2 ± 0.1	42.2 ± 0.0
Cobs	92.4 ± 2.0	67.7 ± 2.9
Husks	65.8 ± 1.0	36.6 ± 10.3
Whole stover	418.0 ± 10.0	213.2 ± 2.7



Data Adapted from Berchem et al. 2017, Biofuels, Bioprod. Bioref. 11:430–440

Herbaceous Biomass Can Be Separated Via Air Fractionation

- INL Fractionation Results (not pure, but enriched fractions)
  - Switchgrass – exogenous ash, leaves, and stems can be separated
  - Grass Clippings (MSW) – exogenous ash, tree/shrub leaves, grass
  - Corn Stover – exogenous ash, leaves, husks, cobs, stalks
  - Coppice Poplar, shrub willow – exogenous ash, leaves
- Combining air classification with other screening approaches allows us to meet quality specs
  - Low operating and capital costs
  - Minimal energy consumption

INL Technical Point of Contact: vicki.thompson@inl.gov, jeffrey.lacey@inl.gov

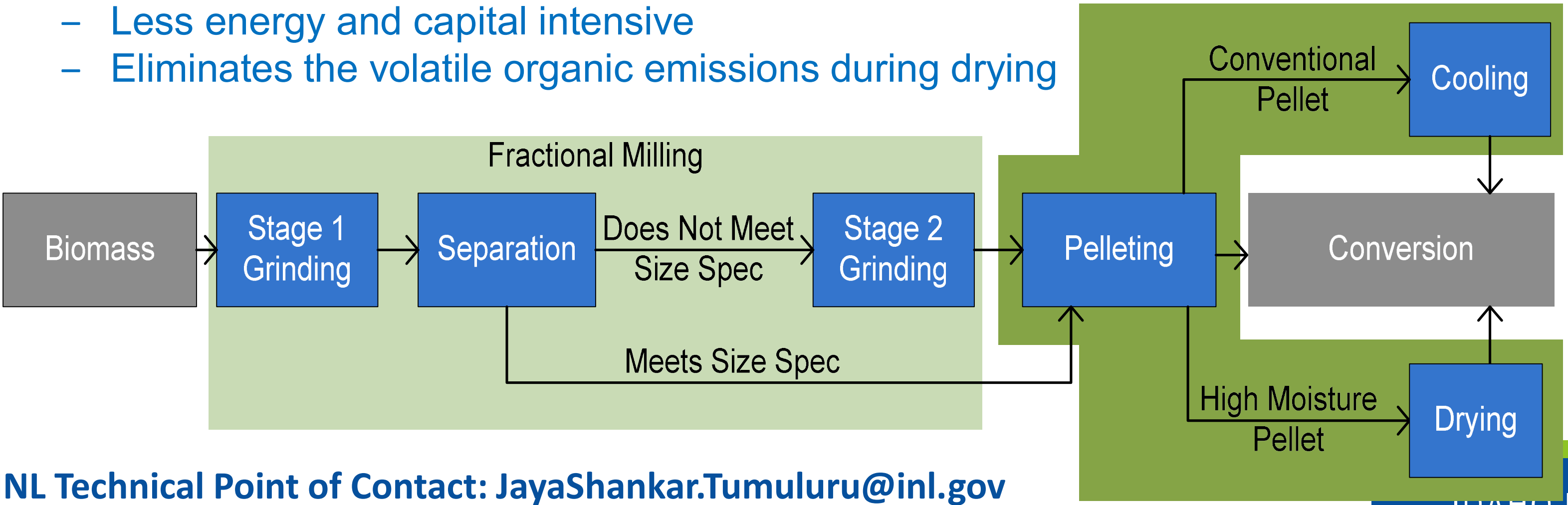
Advanced preprocessing technologies to create flowable pellets

Aim: Reduce grinding and drying energy and make biomass into a dense flowable product

Fractional milling: Increase screen size of stage-1 grinder and insert separator between stage-1 & 2 grinding operations to bypass fraction which meets stage-2 grinder specs
- Avoids redundant preprocessing and saves energy.
- Tighter particle size distribution with reduced fines.

High-moisture pelleting: Biomass is pelleted at moistures 18-30% (w.b.).
- Biomass loses moisture (5-10%, w.b.) due to preheating & frictional heat in the die
- Drying is optional (pellets can be dried only when highly durable and aerobically stable pellets are needed).

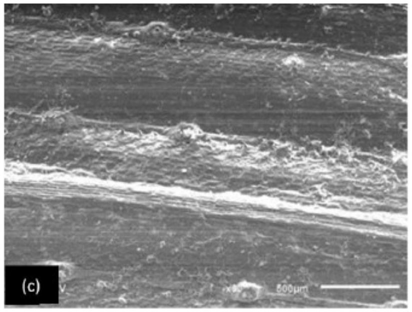
Low-temperature drying: High-moisture pellets can be dried using grain and belt dryers
- Less energy and capital intensive
- Eliminates the volatile organic emissions during drying


Fractional Milling
Biomass
Stage 1 Grinding
Separation
Does Not Meet Size Spec
Stage 2 Grinding
Meets Size Spec
Pelleting
Conventional Pellet
Cooling
Conversion
High Moisture Pellet
Drying

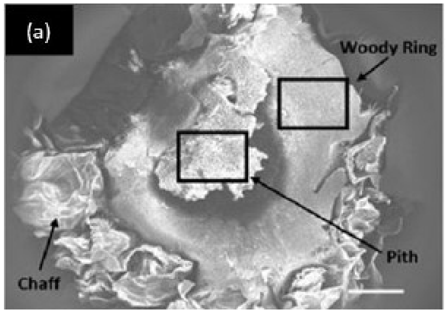
INL Technical Point of Contact: JayaShankar.Tumuluru@inl.gov

Co-products for Herbaceous Biomass

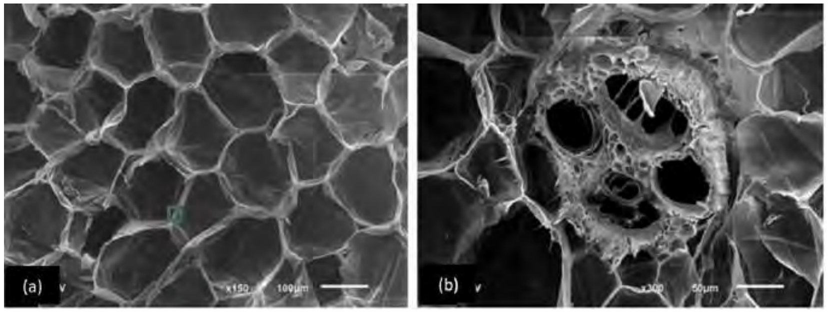
Biomass Fractions	Potential Markets	Material Attributes
Leaves	Feed supplements	Total Digestible Nutrients (TDN) 52-59%
Husks	Feed supplements	
Cobs	Animal Bedding	Materials must be non-abrasive, high absorption, small particle size (passing through ¾ inch screen)
Stalk	Cellulose insulation, Fibers	Thermal conductivity: .029- .032 W/m.K Thermal Resistance: .316 - .349 m^2.K/W



Corn stover leaves



Corn cobs



Corn stover stalks

Li et al., 2020, *ACS Sus. Chem. Eng.*

INL Technical Point of Contact: Damon.Hartley@inl.gov, Pralhad.Burli@inl.gov

Moisture is an Opportunity for the Industry and Can be Managed

Anaerobic storage, or ensiling, used historically for livestock

- Anaerobic conditions followed by acid fermentation to low pH and stabilize biomass
- Dry matter losses of <5% possible compared to losses of 12% for bales entering storage at 30% moisture
- Costs are 10% higher than dry systems

Storage can be used as a value-add (vs cost center)—exploit residence time to perform slow physical & chemical transformations

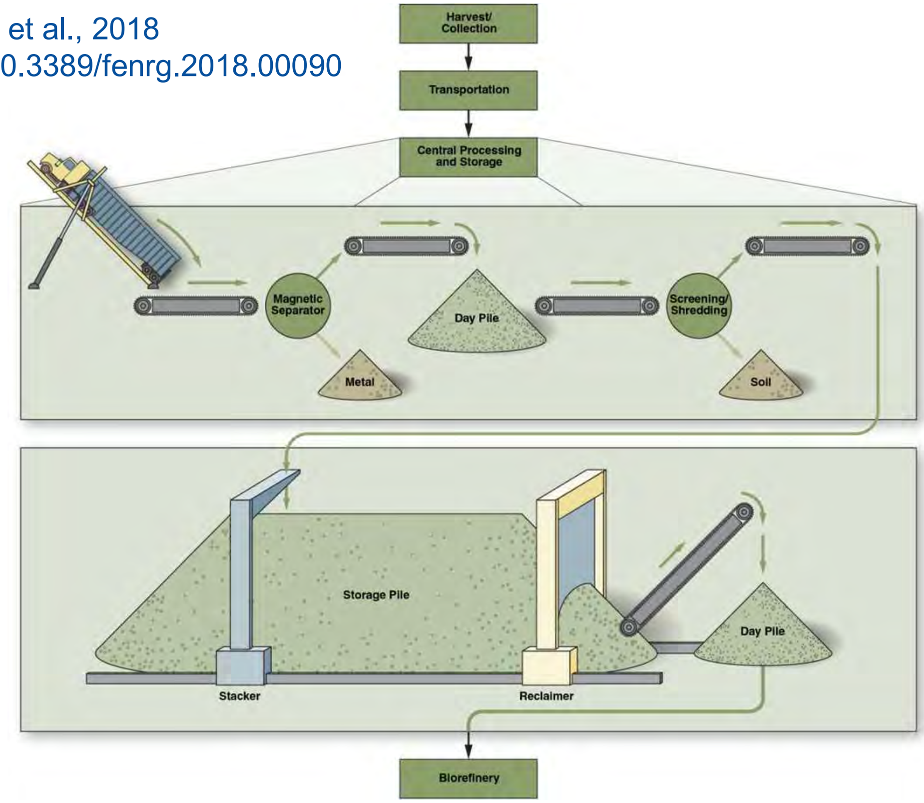
Wendt et al., 2018, Frontiers in Bioengineering and Biotechnology

INL Technical Point of Contact: Lynn.Wendt@inl.gov

Lessons Learned from Large-Scale Storage Options

- Akin to bagasse pile storage at a sugar refinery, a previous TEA design for corn stover stored at a biorefinery gate
    - Potential for combining long-term storage and queuing, eliminating a unit operation and providing a secure feedstock source protected from fire
- Costs were 10% higher than a baled logistics systems due to:
    - Low harvest yield of residues necessitates 30–50-mile transportation radius
    - Low bulk density in transportation
    - Operating preprocessing unit operations seasonally
    - Infrastructure costs

Wendt et al., 2018
DOI: 10.3389/fenrg.2018.00090



Modeled receiving of forage chopped corn stover and storage of 50,000-ton piles

A Possible Approach for Long-Term Storage

- An alternative approach explored based on previous design by U. Wisconsin collaborators (Cook et al., 2011)
- Forage chopping used to meet biorefinery size specifications and eliminate soil contamination
  - Density was increased field-side using silage tubes and maintained in transportation

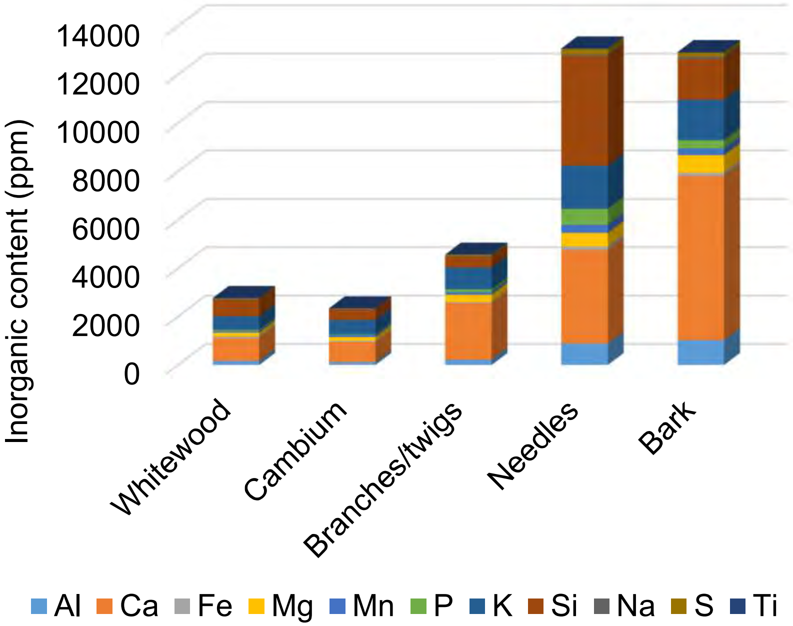
Self-propelled forage chopper and high dump wagon

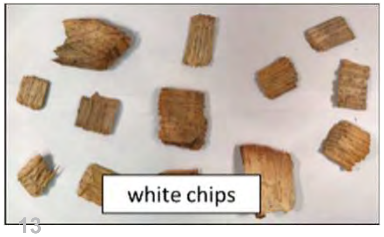
Silage tube and bagger

Walking floor trailer

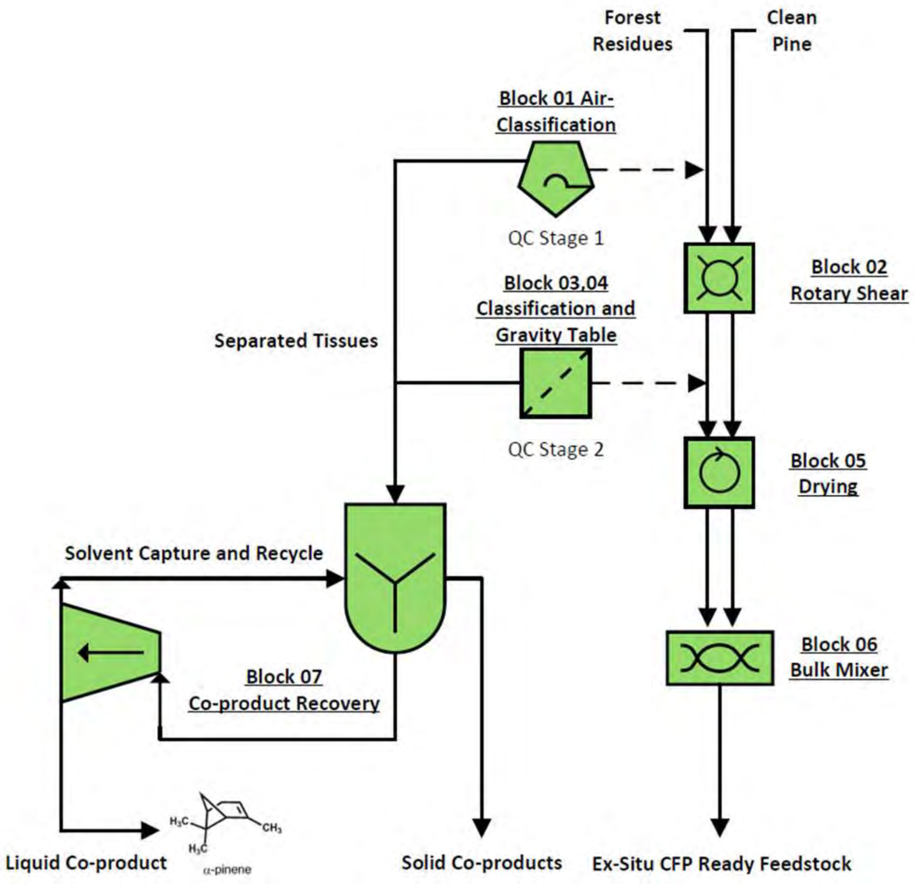
Inorganics in Loblolly Pine Anatomical Tissues

- Elemental analysis shows relative magnitude and influence of inorganic species in various fractions
- Bark high in calcium (calcium oxalate crystals) and also traps soil due to its texture (Al, Ti, Fe)
- Needles highest in silicon
    - Terminal point for transpiration
- Cambium inorganic content can be seasonal





Fractionation of forest residues to create conversion-ready feedstock



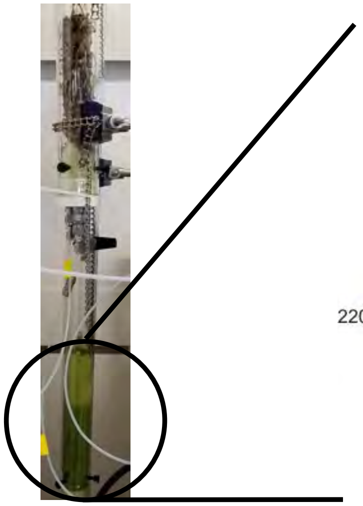
- Pine residues blended with clean pine meet cost and quality targets
- Air classification and gravity separation remove soil and needles
- Rotary shear used for comminution of chips
- Solvent capture and recycle isolate value-added co-products

Co-products for Wood residue - based products

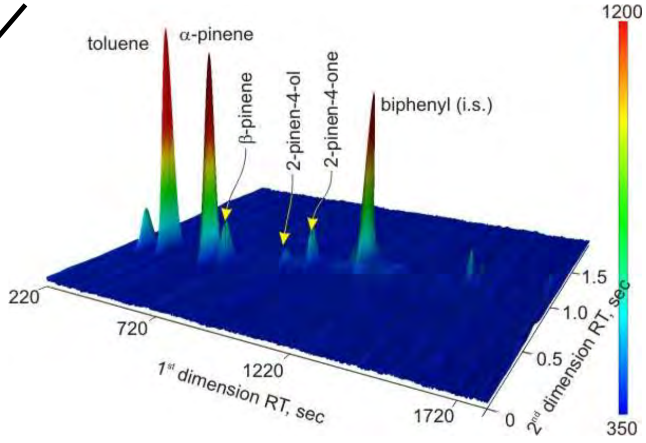
Biomass Fractions	Potential Markets	Material Attributes
Needles	Essential Oils	Extractive (~40%); Cellulose (~28%) Hemicellulose (25%) ; Lignin (7%) Inorganics
Branches	Essential Oils	Extractive (~16%) Cellulose (~32%) Hemicellulose (32%) Lignin (21%) Inorganics
Bark	Mulch	Material must be free from weeds, insects, diseases. Particle size can vary based on intended application (1/4 - 1 ½ inches)
Composite wood residues	Fiberboards	No specific data on material attributes for composite residues

Solvent Based Drying Captures Value-Added Coproducts

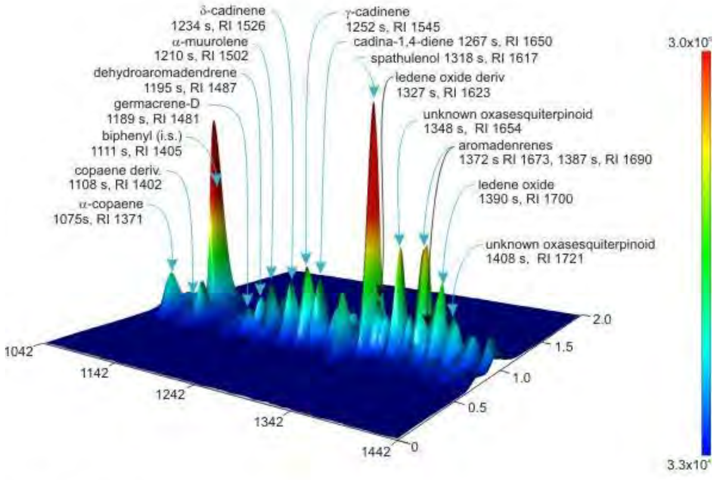
- Drying biomass with Dimethyl-ether (DME) could reduce drying energy by 50%
- Micropyrolysis 2D GC/MS utilized to characterize extracts
- α-pinene was identified as a value-added co-product from DME dried biomass



DME Dried Pine



Diterpenes from Aqueous Extracts

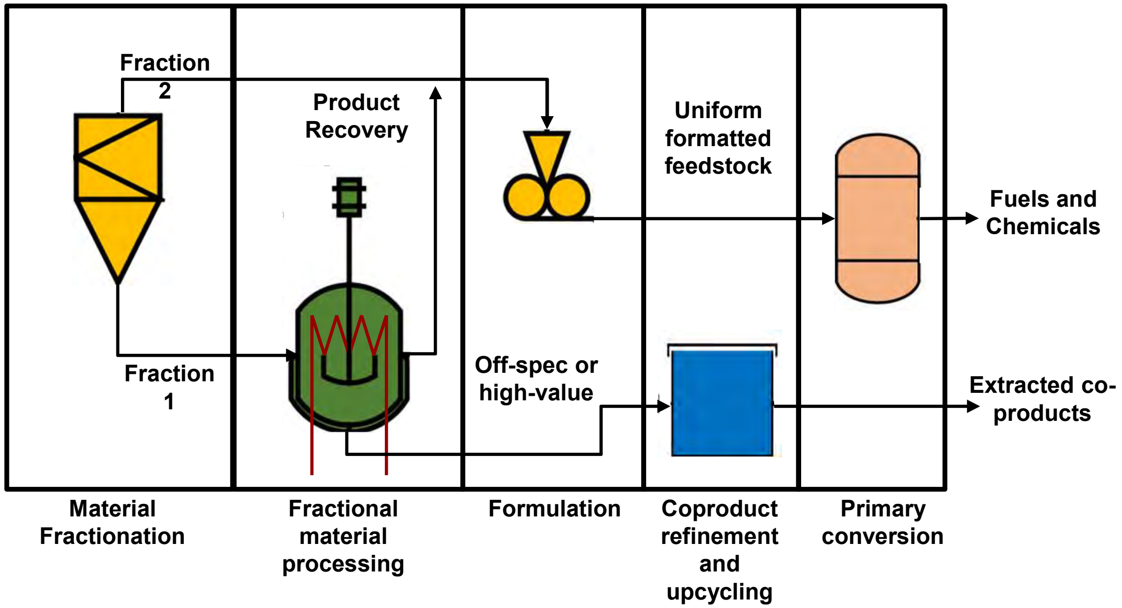


Sesquiterpenes from Insoluble Extract

INL Technical POC: Gary.Groenewold@inl.gov, Aaron.Wilson@inl.gov

Municipal Solid Waste (MSW) processing

- Following the quality paradigm increases the fundamental knowledge and control of a production process for cost advantaged feedstocks including MSW
- MSW variability is significant challenge for the industry

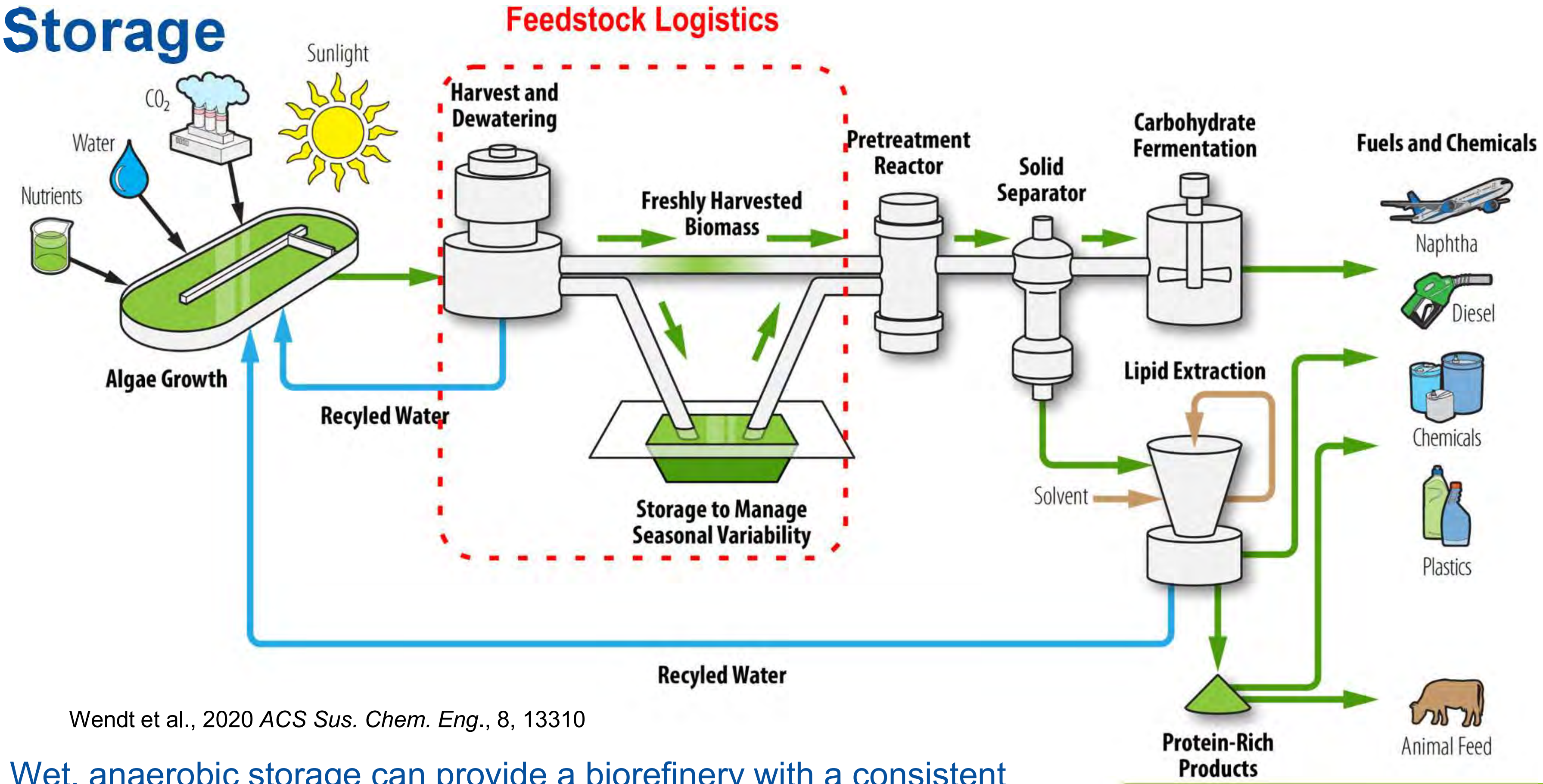


Torrefaction to Improve Quality of Wastes

- Goal: to develop a more uniform feedstock from wastes for bioenergy through torrefaction and compounding
  - Increased carbon content and energy density
  - Removal of volatile contaminants
- Improvements in processes and knowledge have:
  - Shown improvements to homogeneity
  - Demonstrated process economics and improved system throughput
  - Developed advanced models to represent the chemical kinetics of the process to inform industrial operation
- Torrefaction has been shown to positively impact downstream performance in gasification and pyrolysis

INL Technical Point of Contact:
Jordan.Klinger@inl.gov, JayaShankar.Tumuluru@inl.gov

The need for logistics in algae systems – Seasonal Storage

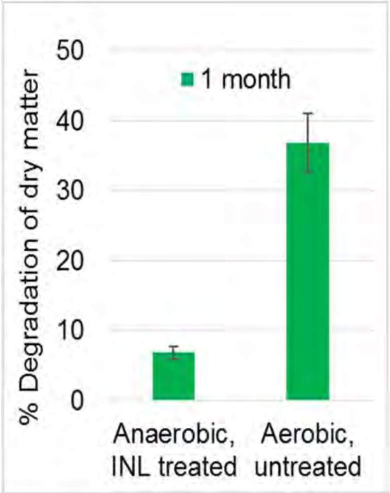


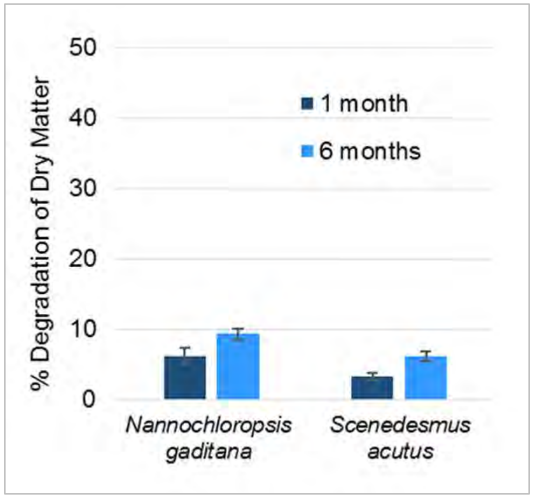
Wendt et al., 2020 *ACS Sus. Chem. Eng.*, 8, 13310

- Wet, anaerobic storage can provide a biorefinery with a consistent feed supply despite 3-5X productivity swings between summer and winter

Wet anaerobic storage for microalgae

- Stability of slurries is critical in storage and in handling and transport.
- Anaerobic storage method can preserve algae biomass over 6 month period
  - Applicable to high moisture biomass including food wastes



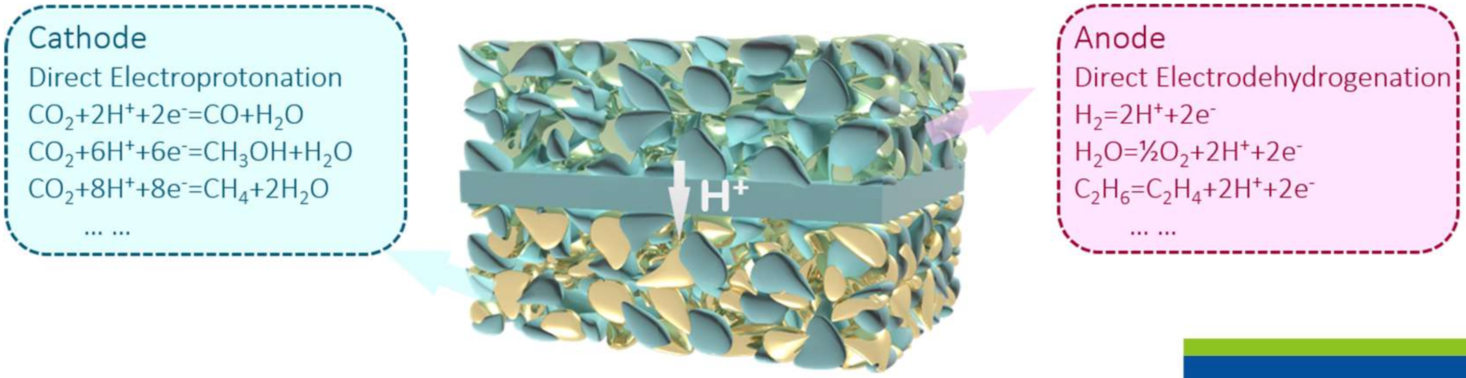


Wendt et al., 2017.
doi:10.1016/j.algal.2017.05.016

INL Technical POC: Bradley.Wahlen@inl.gov, Lynn.Wendt@inl.gov

Anaerobic Digesters and Landfill Gas

- Anaerobic Digesters can convert high moisture biomass to energy products
  - CH_4 is separated and transported in natural gas pipelines
  - Nutrients remaining serve as co-products for field application to improve soil health
- Upgrade captured CO_2 gaseous products can be further converted to product leveraging INL's electrochemical upgrading capabilities
  - Dr. Dong Ding's team has developed proton conducting electrochemical cells that can selectively produce methane from CO_2
- Integration with nuclear provides local heat and electricity for CO_2



Cathode

Direct Electroprotonation

$CO_2+2H^++2e^-=CO+H_2O$

$CO_2+6H^++6e^-=CH_3OH+H_2O$

$CO_2+8H^++8e^-=CH_4+2H_2O$

… …

Anode

Direct Electrodehydrogenation

$H_2=2H^++2e^-$

$H_2O=½O_2+2H^++2e^-$

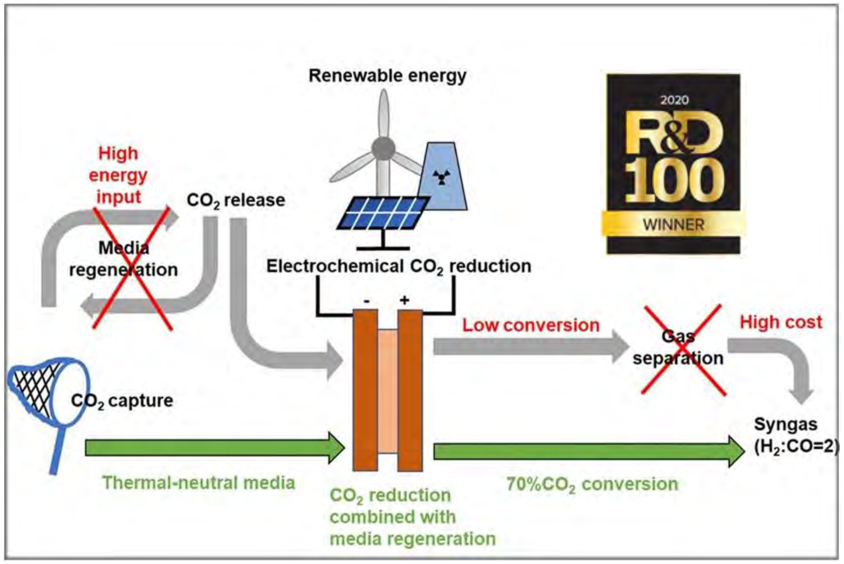
$C_2H_6=C_2H_4+2H^++2e^-$

… …

INL Technical POC: dong.ding@inl.gov

Anaerobic Digesters and Landfill Gas

- To improve performance of digesters, CO_2 can be captured & concentrated leveraging INL's membrane separation and electrochemistry expertise
  - Isothermal capture and conversion
  - Low temperature electrochemical conversion process
  - Intensified conversion/solvent regeneration
  - Reduces downstream separation
- Integration with nuclear provides local heat and electricity for upgrading
- Opportunities for creating fuel precursors from syngas including methanol, DME

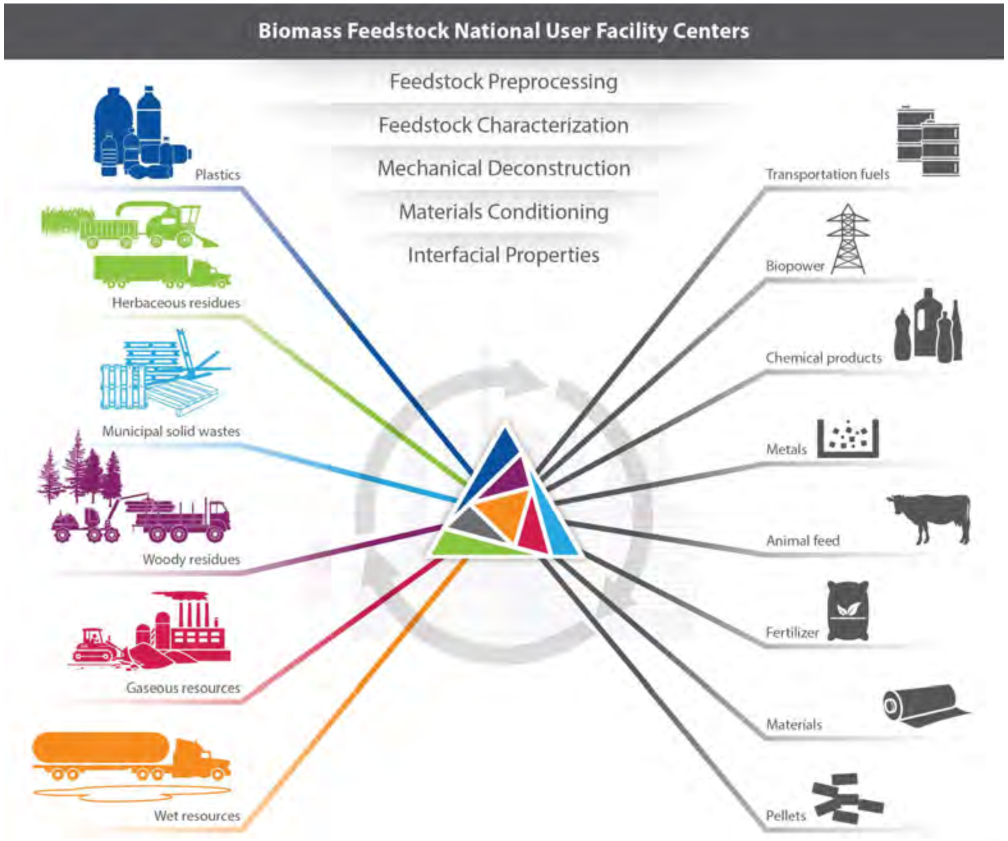


Intensified captured CO_2 co-electrolysis (ICC)

INL Technical POC: Tedd.Lister@inl.gov, luis.diazaldana@inl.gov

Depot (or Midstream) Need for Affordable Bioenergy Fuels, Products and Power

- Feedstock costs contribute to 30% of the total costs of a cellulosic-based biorefinery
- Feedstock quality specifications are critical to maximizing predictability of conversion
- As industry moves to more diverse resources such as MSW, wet wastes, and gaseous feedstocks to support a circular carbon economy, more emphasis is needed to reduce variability in:
  - Flowability and Handling
  - Fractionation (critical to maximizing revenue)
  - Stability
- Feedstock management is critical to biorefinery performance



Acknowledgments

- This work is supported by the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy, Bioenergy Technologies Office, under DOE Idaho Operations Office Contract DE-AC07-05ID14517.
- INL Bioenergy Colleagues:
  - Bradley Wahlen, William Smith, Vicki Thompson, Jaya Shankar Tumuluru, Jordan Klinger, Neal Yancey, Aaron Wilson, Luke Williams, Garold Groenewold, Brittany Hodges, Yingqian Li, Damon Hartley, Frederick Stewart, Dong Ding, Luis Diaz Aldana, and many others

Idaho National Laboratory

WWW.INL.GOV

MICHIGAN STATE
UNIVERSITY

Carbon-Negative Electrobiofuels from Regional Pyrolysis Depots

Christopher M. Saffron

Sabyasachi Das
Peyman Fasahati
Meheryar Kasad
Mahlet Garedew
Rachael Sak
Le Wu

James E. “Ned” Jackson

Department of Chemical Engineering and Materials Science
Department of Biosystems and Agricultural Engineering
Department of Chemistry
Department of Forestry

August 11th, 2021

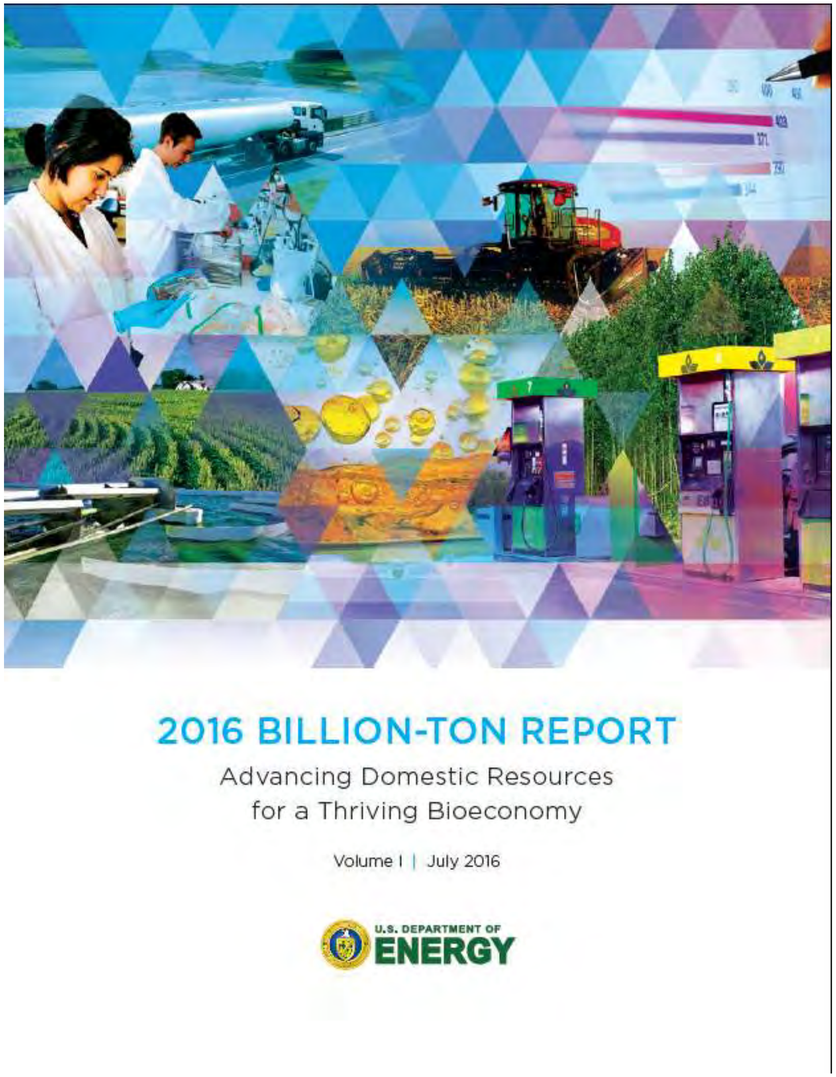
Biomass Conversion to Hydrocarbon Fuels

Rationale for displacing petroleum

- Minimize climate change impact
- Promote energy independence and security
- Slow resource depletion
    - ~300 billion gal/yr in the U.S. alone

Rationale for pyrolysis/upgrading

- First generation biodiesel and ethanol can provide short-term remedies but have significant challenges
- Industry desires “drop-in” hydrocarbon replacements for petroleum fuels
- Unbeatable energy to weight ratio
- Nature’s choice for energy storage



2016 BILLION-TON REPORT

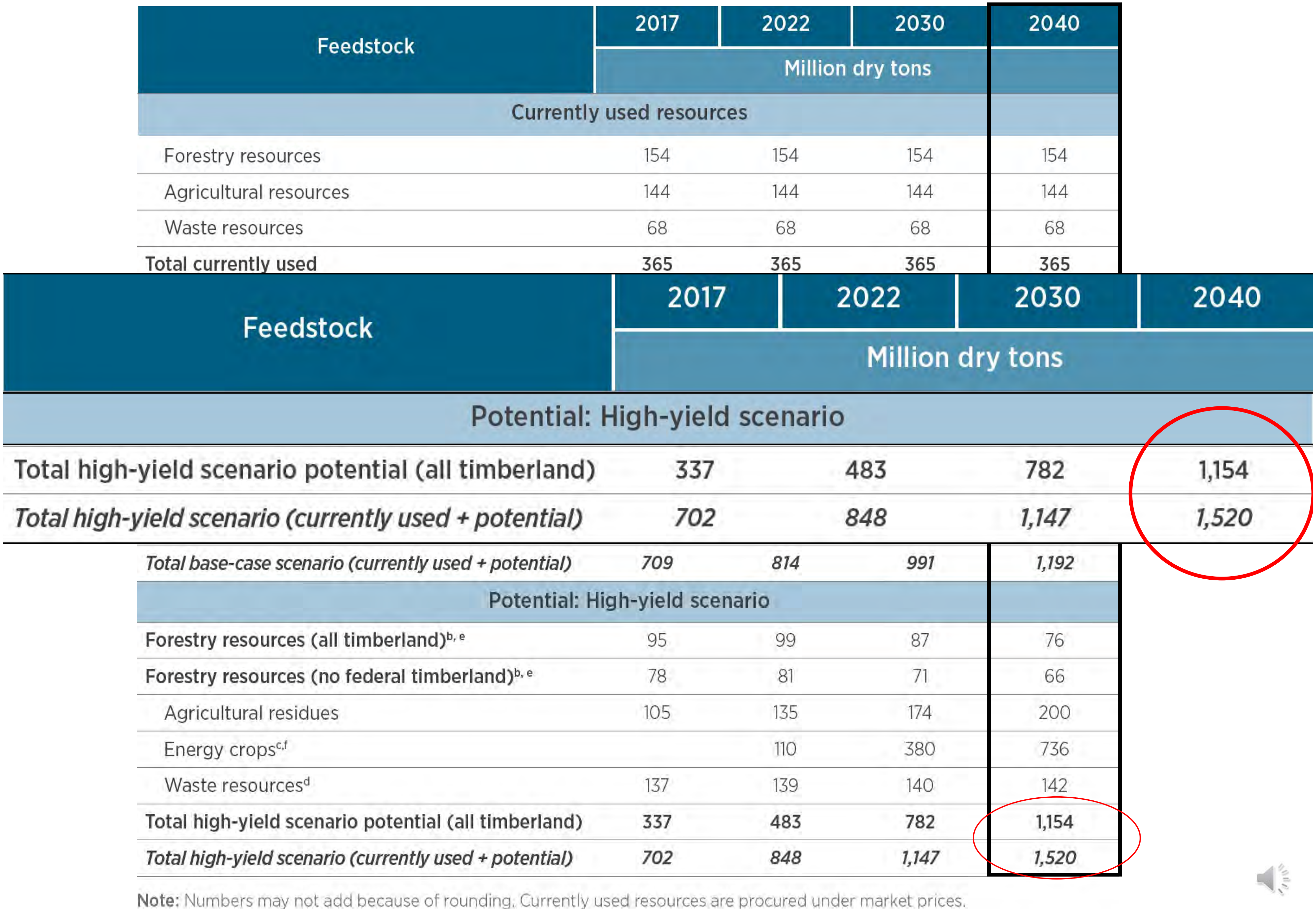
Advancing Domestic Resources
for a Thriving Bioeconomy

Volume I | July 2016

U.S. DEPARTMENT OF
ENERGY

U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651. http://energy.gov/eere/bioenergy/2016-billion-ton-report

2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy



Feedstock	2017	2022	2030	2040
	Million dry tons			
Currently used resources				
Forestry resources	154	154	154	154
Agricultural resources	144	144	144	144
Waste resources	68	68	68	68
Total currently used	**365**	**365**	**365**	**365**

Feedstock	2017	2022	2030	2040
	Million dry tons			
Potential: High-yield scenario				
Total high-yield scenario potential (all timberland)	**337**	**483**	**782**	**1,154**
Total high-yield scenario (currently used + potential)	***702***	***848***	***1,147***	***1,520***

Total base-case scenario (currently used + potential)	***709***	***814***	***991***	***1,192***
Potential: High-yield scenario				
Forestry resources (all timberland)[b, e]	95	99	87	76
Forestry resources (no federal timberland)[b, e]	78	81	71	66
Agricultural residues	105	135	174	200
Energy crops[c,f]		110	380	736
Waste resources[d]	137	139	140	142
Total high-yield scenario potential (all timberland)	**337**	**483**	**782**	**1,154**
Total high-yield scenario (currently used + potential)	***702***	***848***	***1,147***	***1,520***

Note: Numbers may not add because of rounding. Currently used resources are procured under market prices.

Comparison of Scale: Fossil Energy vs. Bioenergy

- **Oil:** 2017 U.S. consumption about 7.3 billion bbl/yr or ~1 billion tons/yr
    - C content in "CH_2" is 12/14 or 86% → 860 MM tons C/yr
    - E content: HHV = 45 MJ/kg → ~42 EJ/year

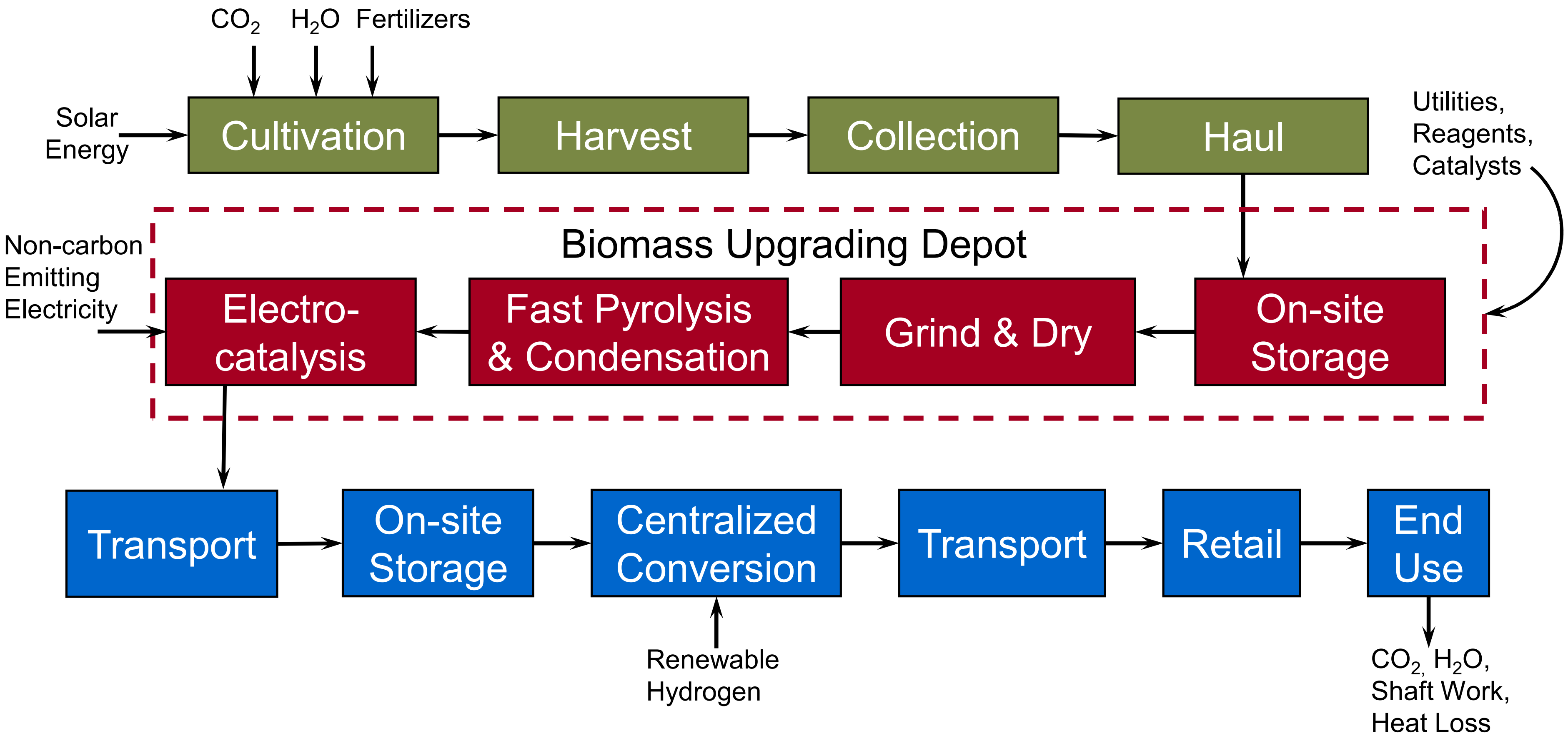
- **Biomass:** 2040 U.S. biomass 1.5 x 10^9 tons/yr (crop residues, forest wastes, and energy crops)
    - C content in "CHOH" is 12/30 or 40% → ~610 MM tons C/yr
    - E content: HHV = 15 MJ/kg → ~20 EJ/year (assuming perfect conversions)

- **Today's biofuels:** Consider ethanol production:
    - $C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH$ (MW = 46) + $2CO_2$ (MW = 44)
    - Concentrates plant-captured E into half the mass, but throws away 1/3 of the C
    - E content: Ethanol doesn't come close to a 1:1 gasoline or diesel replacement

- Carbon Efficient Bioenergy Systems Needed!
- Energy Upgrading Strategies for Bioenergy Systems Needed!

Bioenergy System Diagram using Decentralized Depots

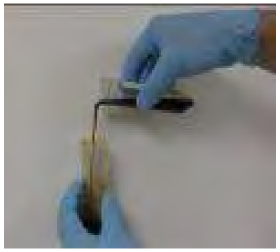
- Biomass Upgrading Depots (BUDs) are small-scale facilities used to preprocess biomass to improve its physicochemical properties

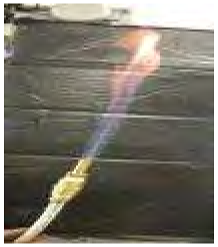


Biomass Fast Pyrolysis

Biomass → Bio-oil + Char + Gases

(100%) = (up to 70%) + (~15%) + (~15%)

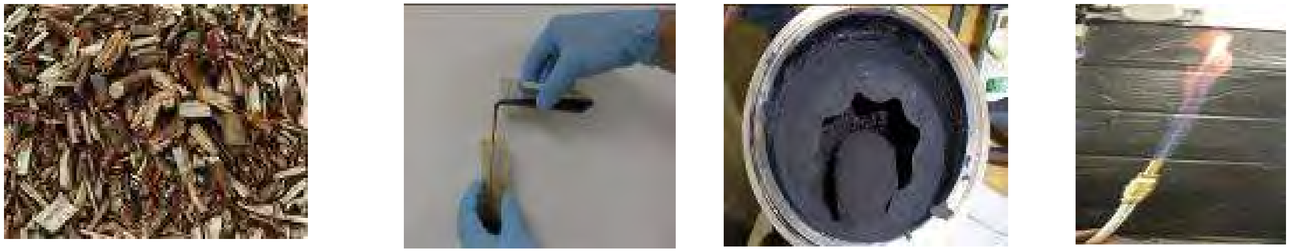


- **Pyrolysis is thermal decomposition without oxygen**
  - Low energy requirement: Nearly neutral endo- vs. exothermicity
  - Modest temperatures: Pyrolysis reaction temps. of ca. 500°C
  - Rapid throughput: Short vapor residence time in the reactor (<1s)
  - Carbon-retentive: Cellulose, hemicellulose and lignin are liquefied
  - Densification: Bio-oil specific gravity is 1.1-1.2

Biomass Fast Pyrolysis

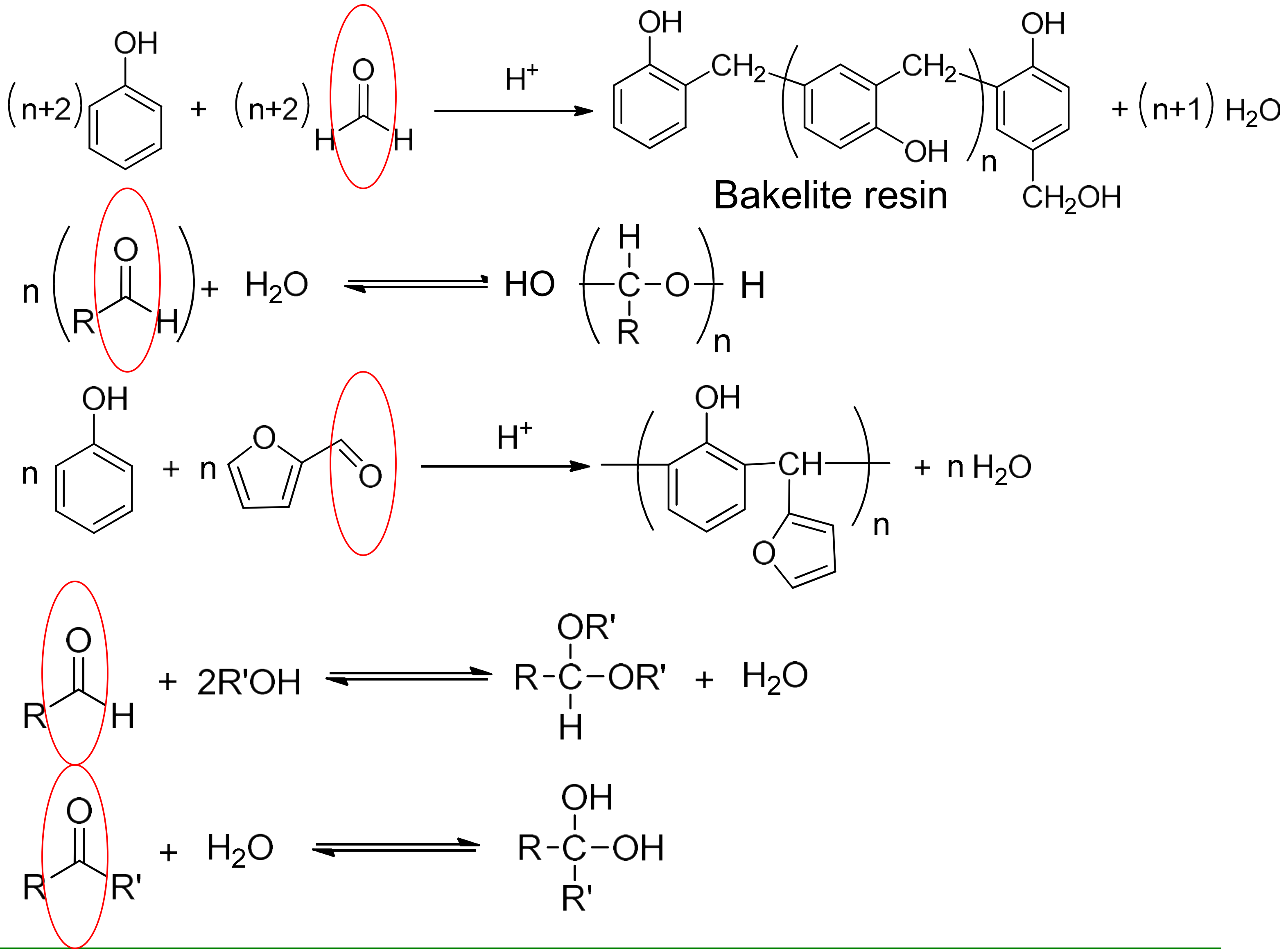
Biomass ⟶ Bio-oil + Char + Gases

(100%) = (up to 70%) + (~15%) + (~15%)



- **Pyrolysis is thermal decomposition without oxygen**
  - Low energy requirement: Nearly neutral endo- vs. exothermicity
  - Modest temperatures: Pyrolysis reaction temps. of ca. 500°C
  - Rapid throughput: Short vapor residence time in the reactor (<1s)
  - Carbon-retentive: Cellulose, hemicellulose and lignin are liquefied
  - Densification: Bio-oil specific gravity is 1.1-1.2
- **Bio-oil unwanted properties (stabilization):**
  - Reactive and unstable: aldehydes, ketones, phenols
  - Corrosive: carboxylic acids, phenols
  - Low specific energy: HHV is 15 to 19 MJ/kg

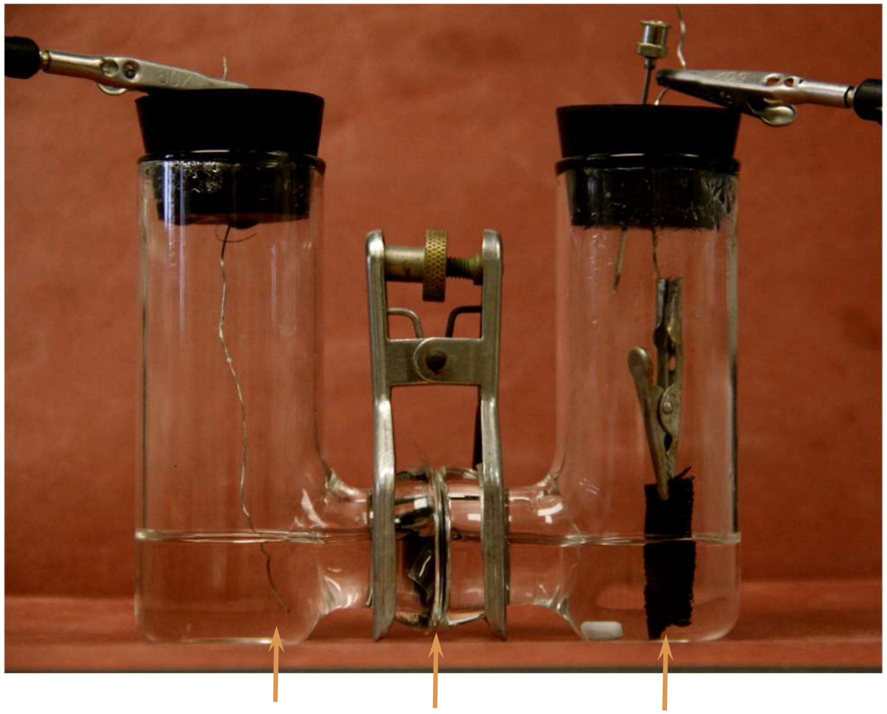
Bio-oil Reactivity and Instability



Adapted from: Diebold J.P., et al. Review. 1999.

Electrocatalytic Hydrogenation and Deoxygenation

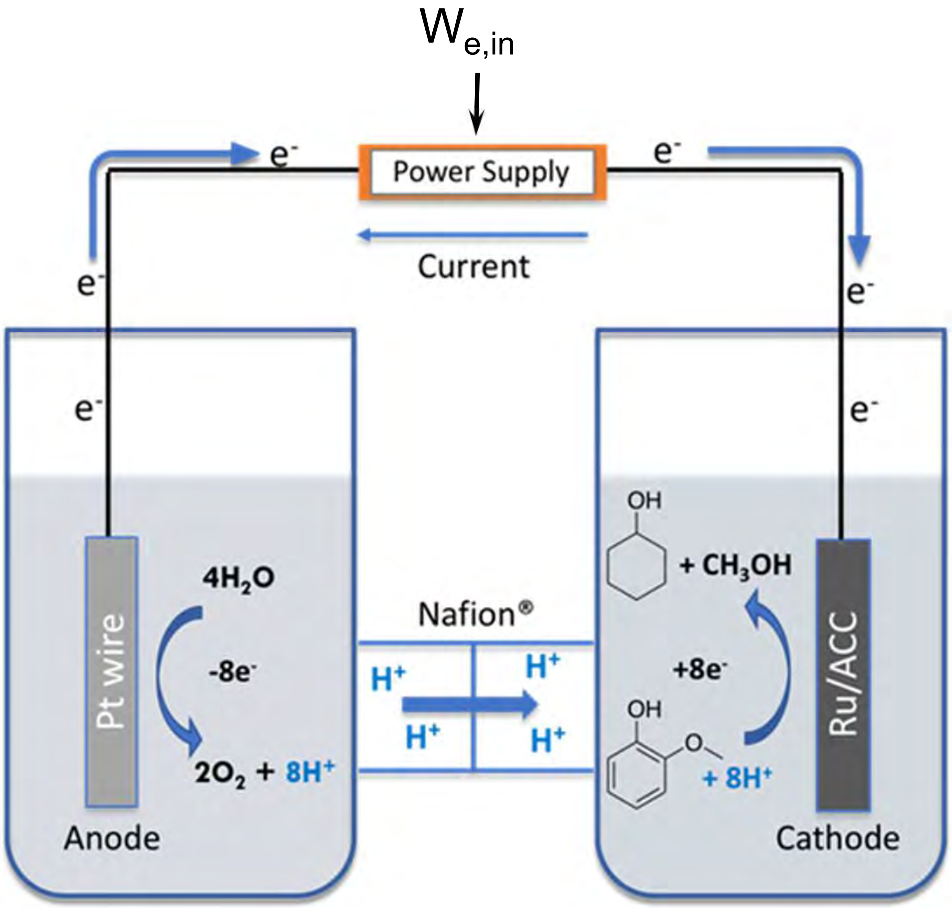
Divided batch “H-cell”



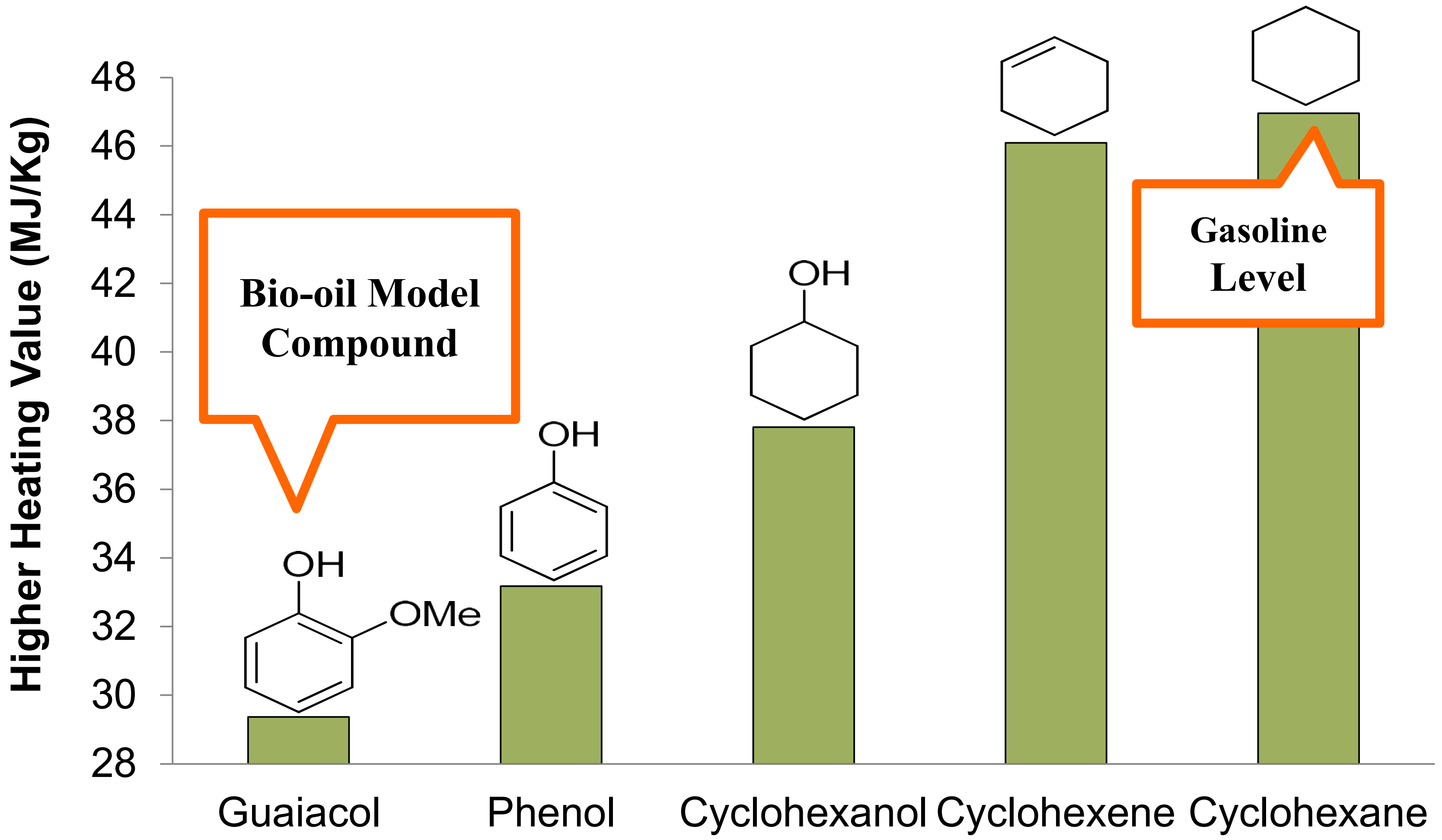
Platinum anode

Nafion membrane

Ruthenium on activated carbon cloth catalytic cathode



Upgrading to Improve Energy Content

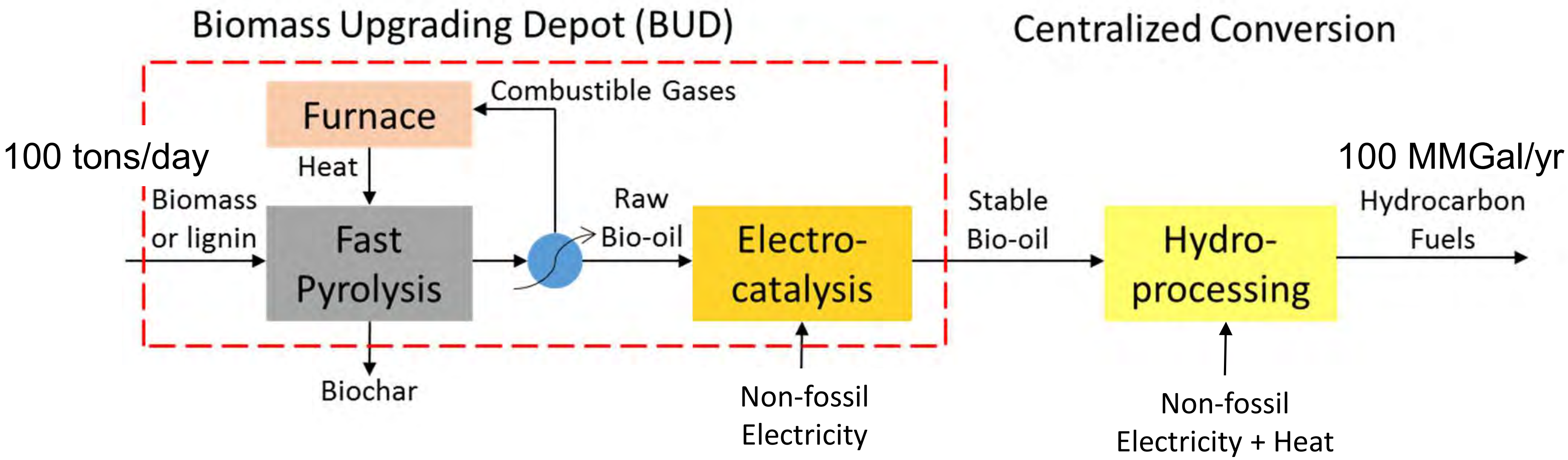


Bio-oil Model Compound

Gasoline Level

Increase in Energy Content

Production Capacities and Operating Conditions



Pyrolysis conditions:

T = 400-600 °C

P = 1 atm

Electrocatalysis conditions:

T = 50-99 °C

P = 1 atm

V = variable; currently
- 1-10 Volts in H-cells
- 5-10x less in flow cells

H_2 production must be controlled

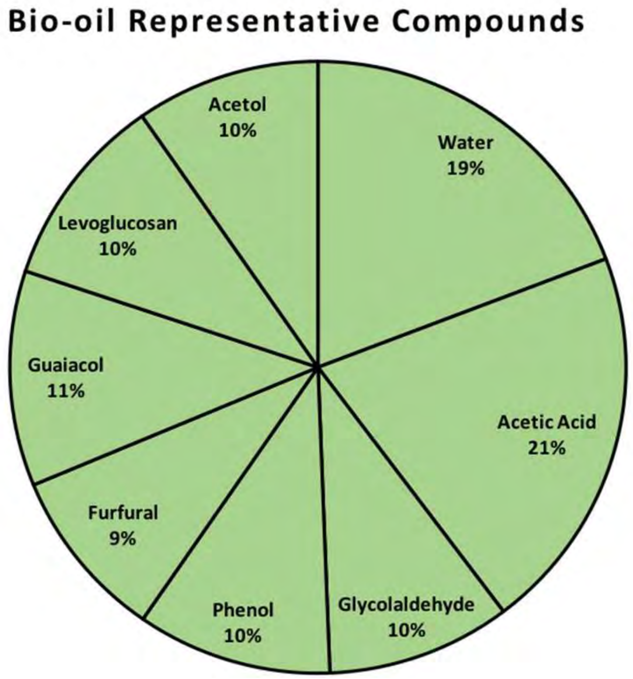
Hydroprocessing conditions:

More severe
- up to 2,000 psig H_2

Can be managed in large, centralized refineries

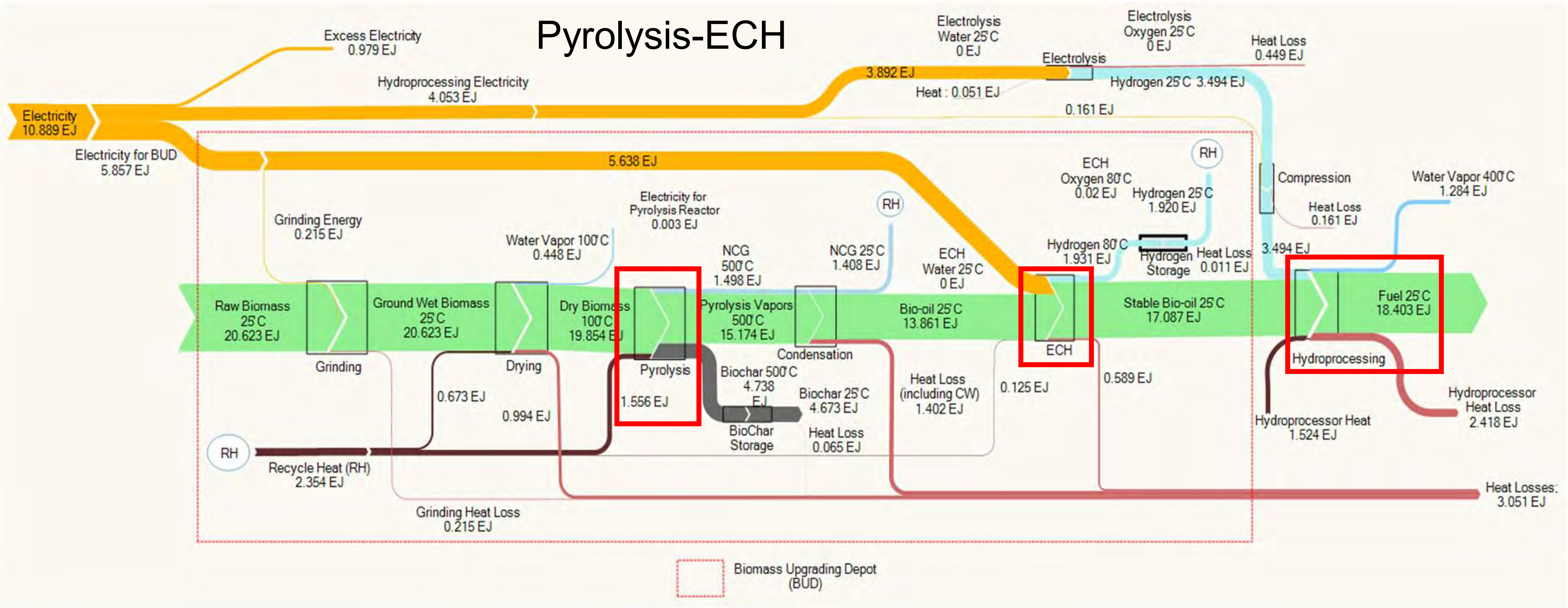
Model Assumptions

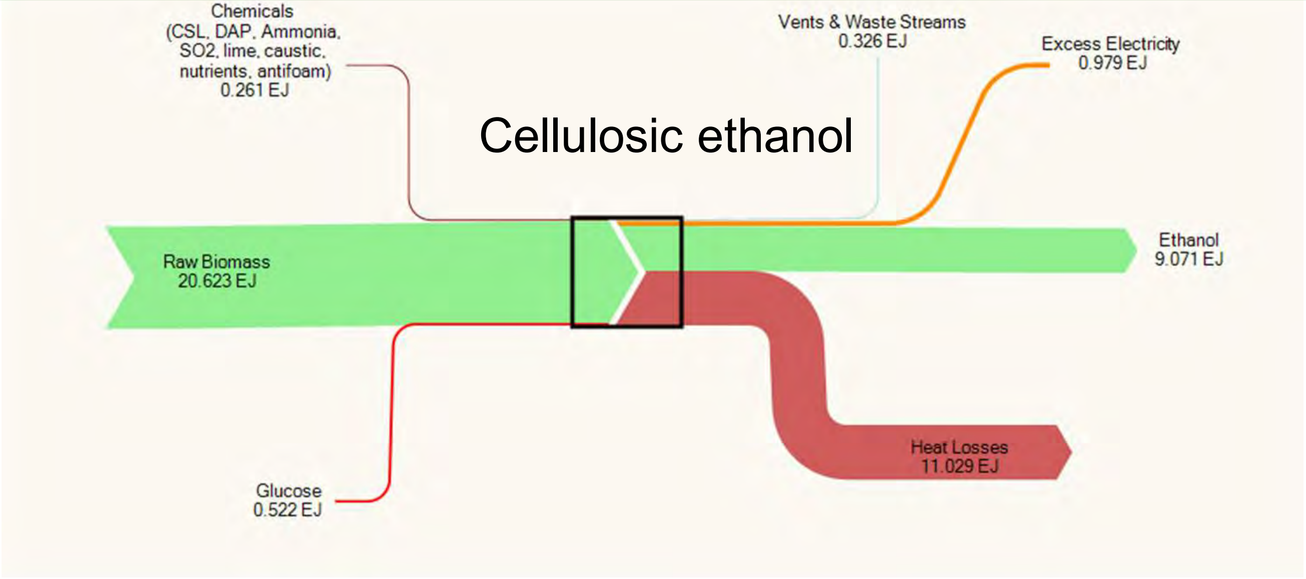
- Bio-oil is represented by a combination of eight model compounds: water, acetic acid, acetol, glycolaldehyde, furfural, levoglucosan, phenol, and guaiacol
- Biomass moisture content is 20 wt.% before drying and 5 wt.% after drying
- Grinding operation performed a size reduction from 50-200 mm to 2mm particles.
- Fast pyrolysis mass yields: 70% bio-oil, 15% biochar, and 15% non-condensable gases (NCG)
- Electrocatalytic hydrogenation operates at 75% voltage efficiency and 67% current efficiency resulting in a 50% overall efficiency



Adapted from: Bridgwater A.V., Fast Pyrolysis of Biomass: A Handbook Volume 2, CPL Press, 2008

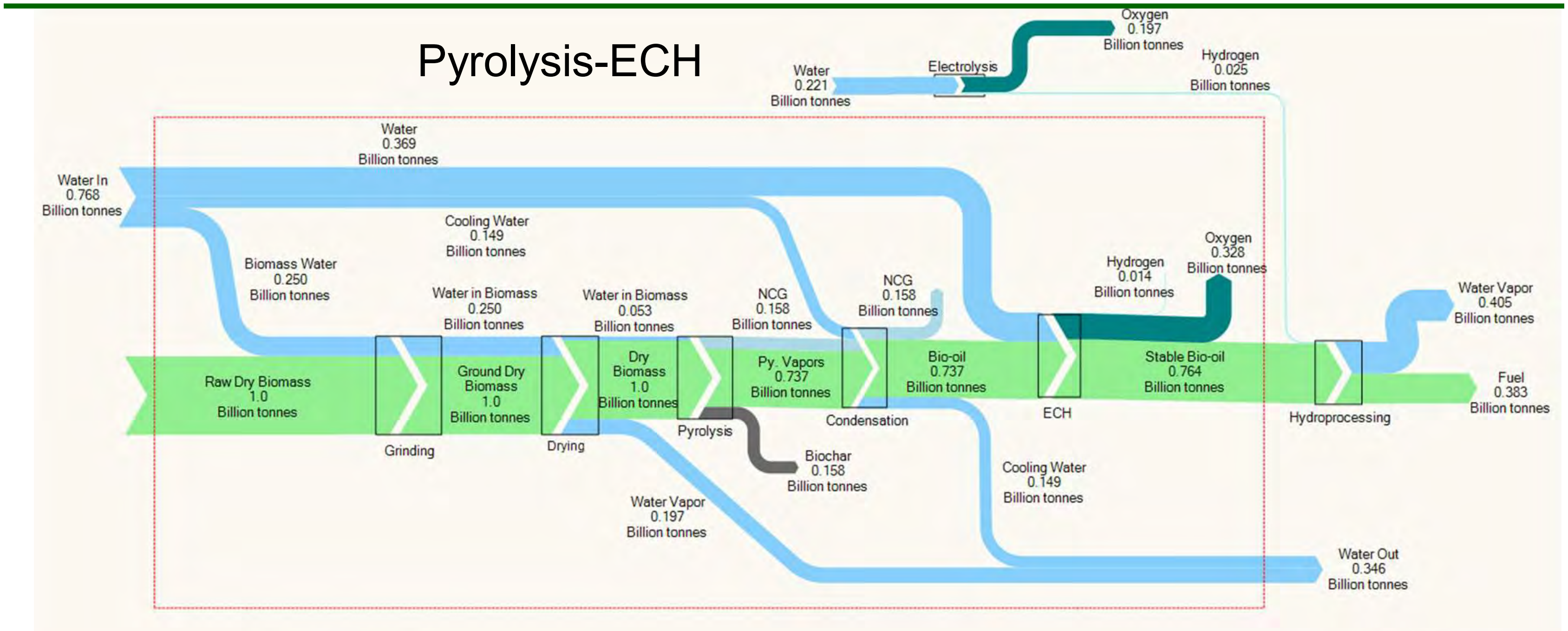
Energy Analysis

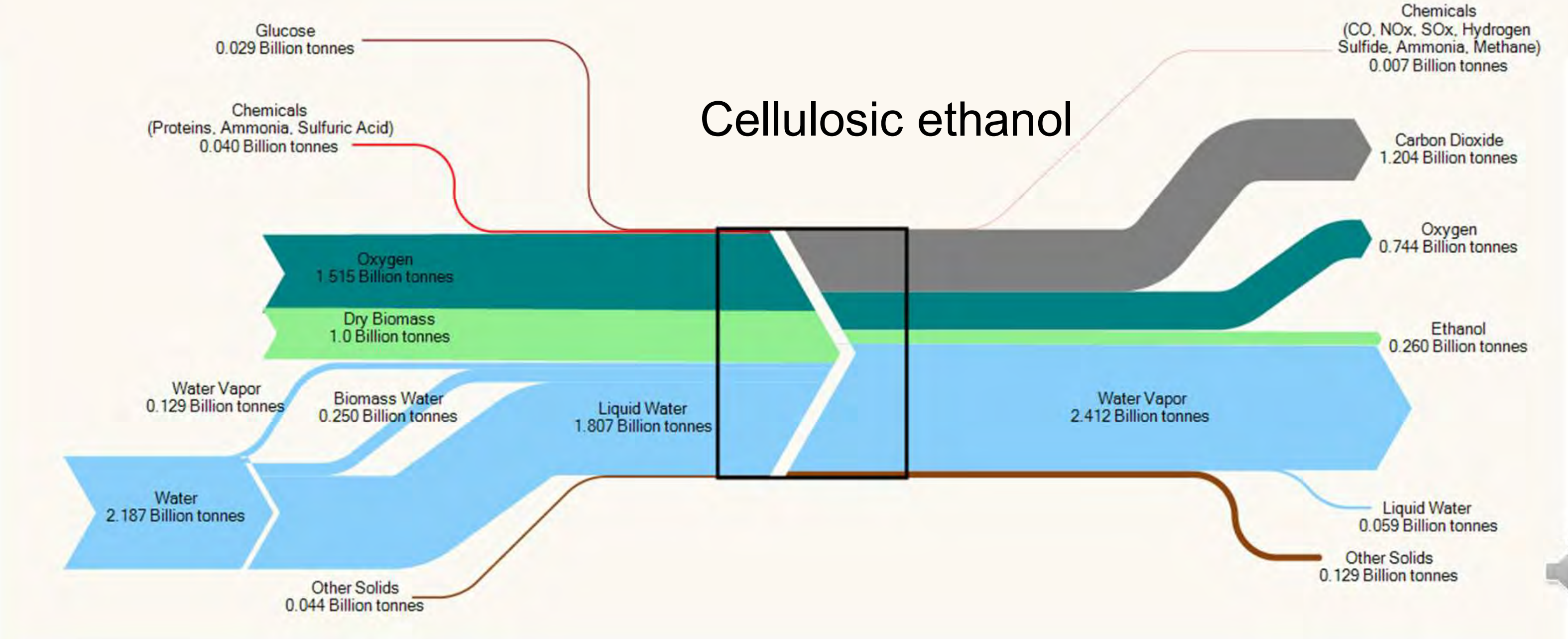

Pyrolysis-ECH


Cellulosic ethanol

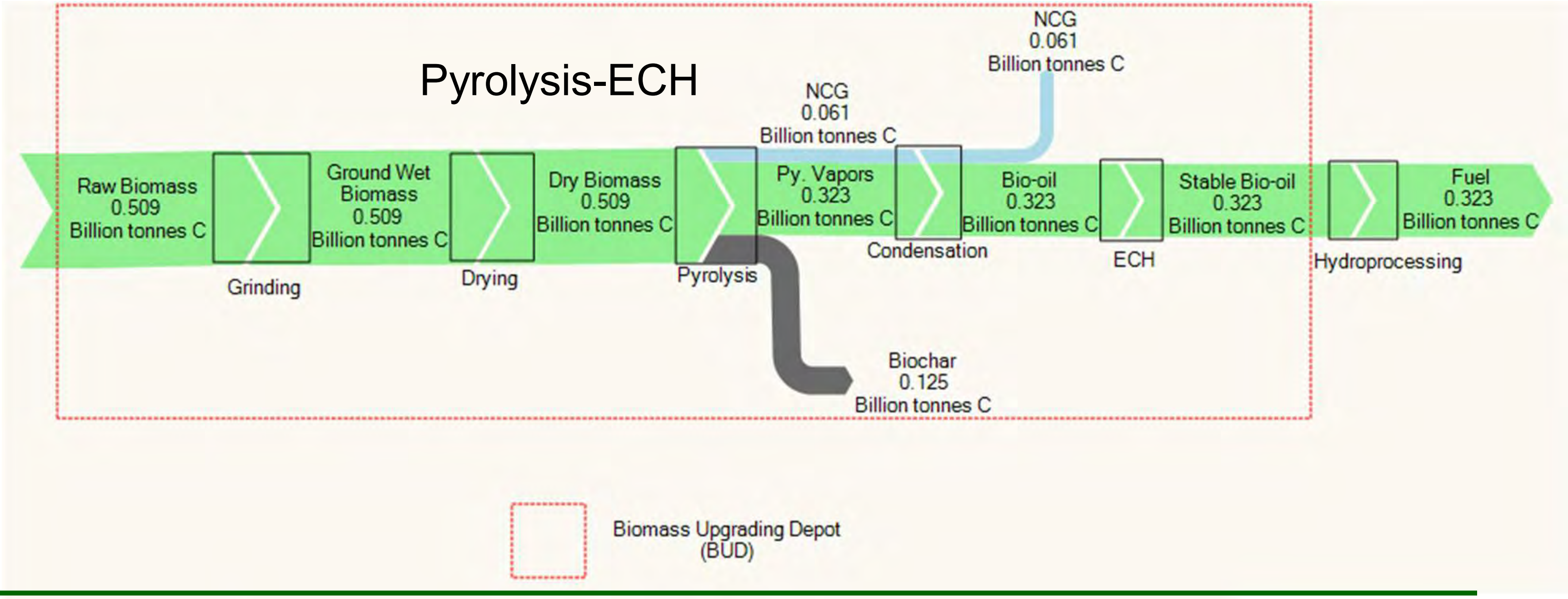
MICHIGAN STATE
UNIVERSITY

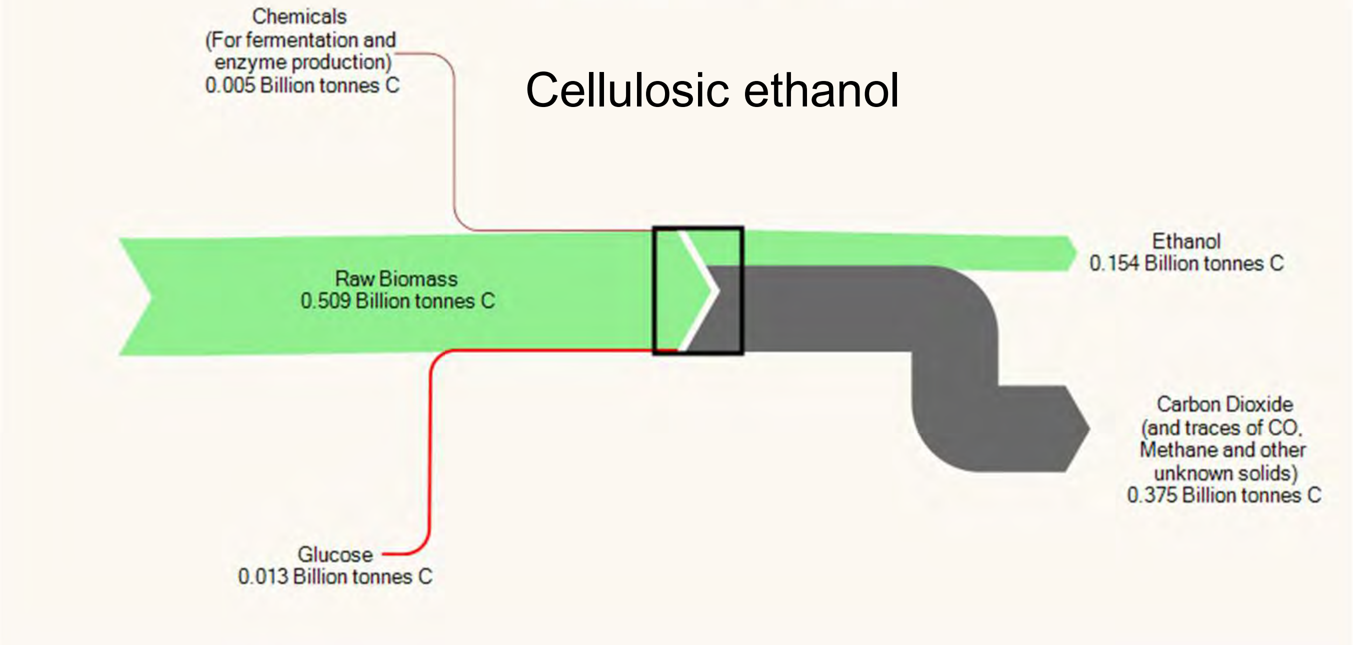
Mass Analysis


Pyrolysis-ECH


Cellulosic ethanol

Carbon Analysis


Pyrolysis-ECH


Cellulosic ethanol

Technoeconomic Model Formulation

Process economics at the depots and central refinery were evaluated at 100 dry U.S. ton/day and 100 million gal/year plant scales, respectively.

- Start-up period: 3 months
- Plant life: 30 years
- 10% internal rate of return (IRR)
- Working capital 5% of fixed capital investment (FCI)
- Tax rate: 35% per year
- Startup period:
  - Revenues during start-up: 50%
  - Variable costs incurred during start-up: 75%
  - Fixed costs incurred during start-up: 100%
- Start-up time: 0.25 year
  - Fuel production/Feedstock use (% of Normal: 50%)
  - Variable Costs (% of Normal): 75%
  - Fixed Cost (% of Normal): 100%

- Land: 1.6% of Installed Costs
- Zero salvage value
- Operating hours per period: 8,410 h/year
- Dollar value: 2011
- Equity: 40%
- Loan interest: 8%
- Loan term: 10 years
- Depreciation period
  - General Plant: 7 years
  - Steam/Electricity System: 20 years
- Construction period: 1 year

MICHIGAN STATE UNIVERSITY

Technoeconomic Model Formulation

Direct Costs	% of Installed Costs
Installed Costs	100%
Warehouse	4%
Site Development	9%
Additional Piping	4.5%
Indirect costs	**% of total Direct Costs**
Pro-rateable Costs	10%
Field Expenses	10%
Home Office and Construction Costs	20%
Project contingency	10%
Other costs	10%

Raw Material	2011 Price $/U.S. ton
Feedstock (20% moisture)	26.66
Electricity	0.0572 $/kWh
Sand	249
Boiler Chemicals	5,557
Cooling Tower Chemicals	3,330
Makeup Water	0.29
Char	20

Stabilized Bio-Oil Hauling cost*

Distance (mi)	45	5
Speed (mph)	55	35
Transportation Cost ($/hr)	42	
Weight limit (kg/axle)	7,257	
4 axle truck (kg)	29,030	

*Michigan Department of Transportation T-1 (3/07), MAXIMUM LEGAL TRUCK LOADINGS AND DIMENSIONS.

Results: Total Capital Investment

Process Area	Depot
Area 100: Feedstock handling	$ 3,100,000
Area 200: Pyrolysis and Recovery	$ 1,100,000
Area 300: Electrocatalysis	$ 2,300,000
Area 400: Boiler and Utilities	$ 2,700,000
Area 500: Storage	$ 600,000
Total Installed Costs	**$ 9,800,000**
Total Direct Costs (TDC)	$ 11,600,000
Total Indirect Costs	$ 6,900,000
Fixed Capital Investment (FCI)	**$ 18,500,000**
Land	$ 600,000
Working Capital	$ 900,000
Total Capital Investment (TCI)	**$ 20,000,000**

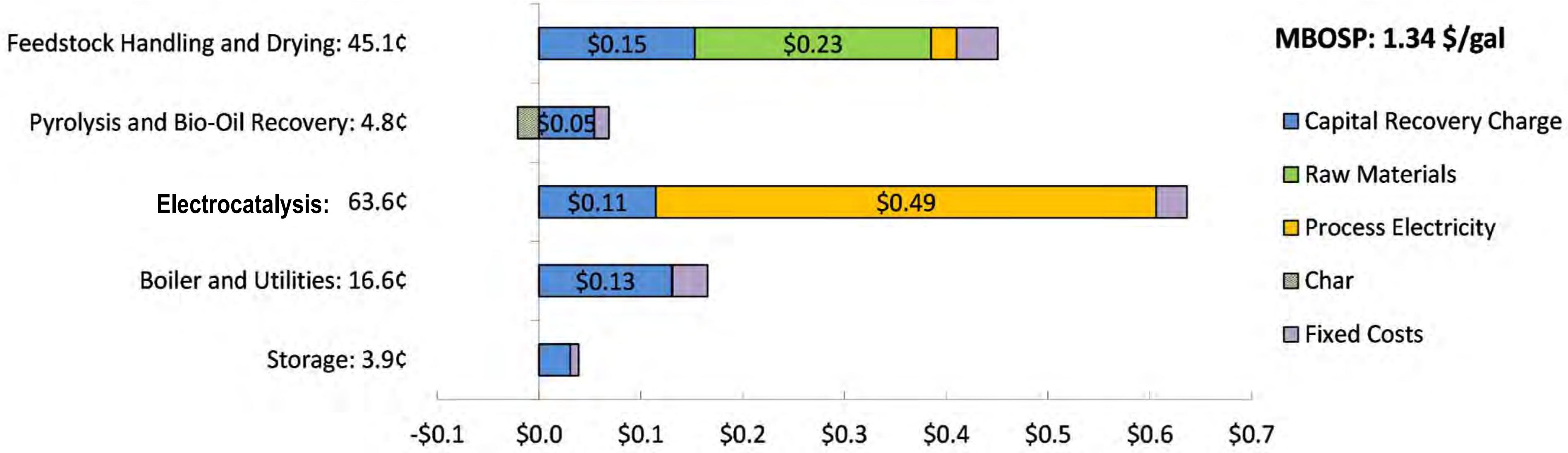
Process Area	Central Refinery
Area 100: Hydroprocessing	$ 19,700,000
Area 200: Electrolyzer & H2 Production	$ 81,200,000
Area 300: Storage	$ 11,200,000
Total Installed Costs	**$ 112,100,000**
Total Direct Costs (TDC)	$ 131,700,000
Total Indirect Costs	$ 79,000,000
Fixed Capital Investment (FCI)	**$ 210,800,000**
Land	$ 6,700,000
Working Capital	$ 10,500,000
Total Capital Investment (TCI)	**$ 228,000,000**

Results: Raw Material & Utility Costs ($MM/year)

Depot (100 U.S. ton/day)		$MM/year
Area 100: Feedstock handling	Feedstock	1.17
	Grinder & Conveyer Power	0.13
Area 200: Pyrolysis and Recovery	Fresh Sand Makeup	0.002
Area 300: Electrocatalysis	Electrical Power	2.47
Area 400: Boiler and Utilities	Boiler Chemicals	0.000
	Cooling Tower Chemicals	0.000
	Makeup Water	0.0037
Total $MM/year		**3.77**

Central Refinery (100 million gal/year)		$MM/year
Area 100: Hydroprocessing	Stable Bio-oil Transportation Cost	2.01
	Catalyst	1.30
	Stable Bio-oil	213
Area 200: Hydrogen Production	Electrolyzer Power	83.3
	Compression Power	3.03
Total $MM/year		**302**

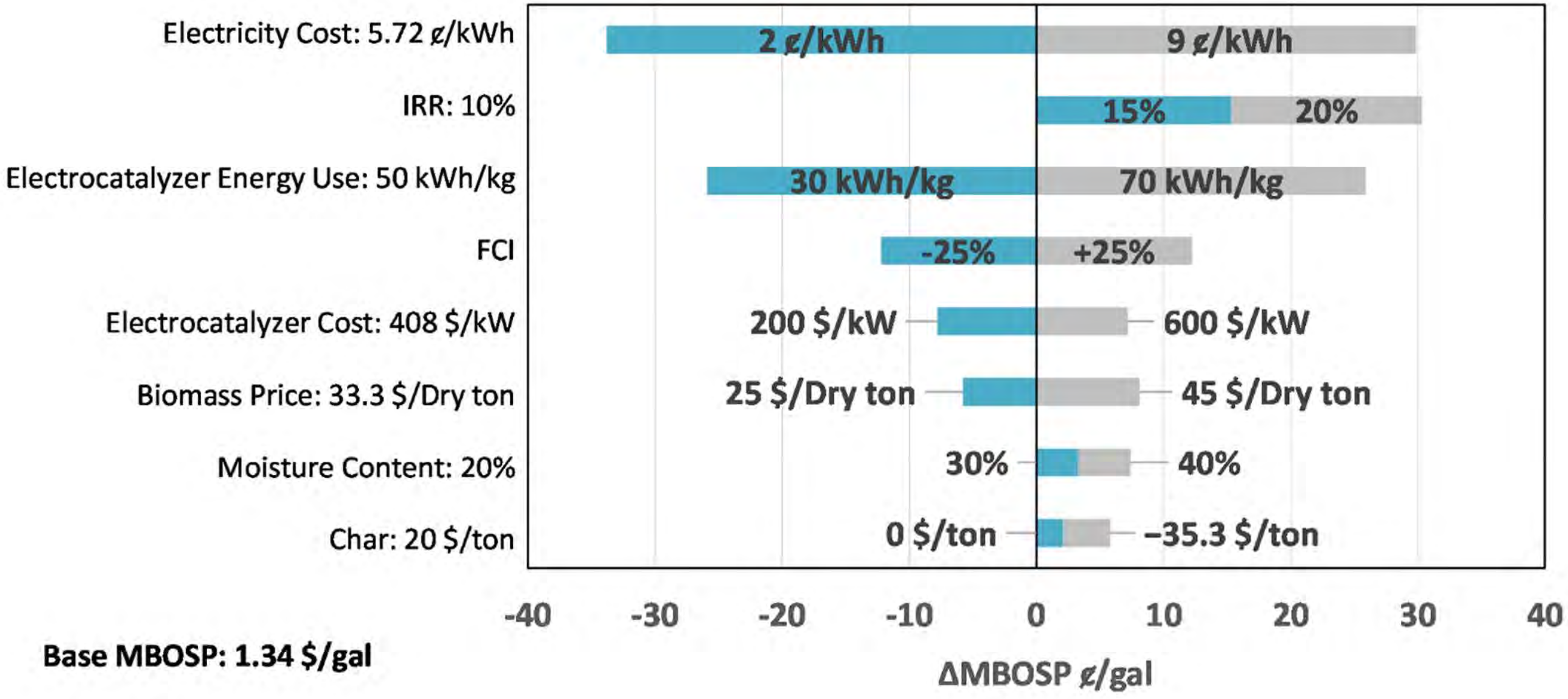
Minimum Bio-Oil Selling Price (MBOSP)



Minimum Fuel Selling Price (MFSP)

Sensitivity Analyses

- Single point sensitivity analysis on economic and process parameters performed to assess their impact on **MBOSP** at **depots**

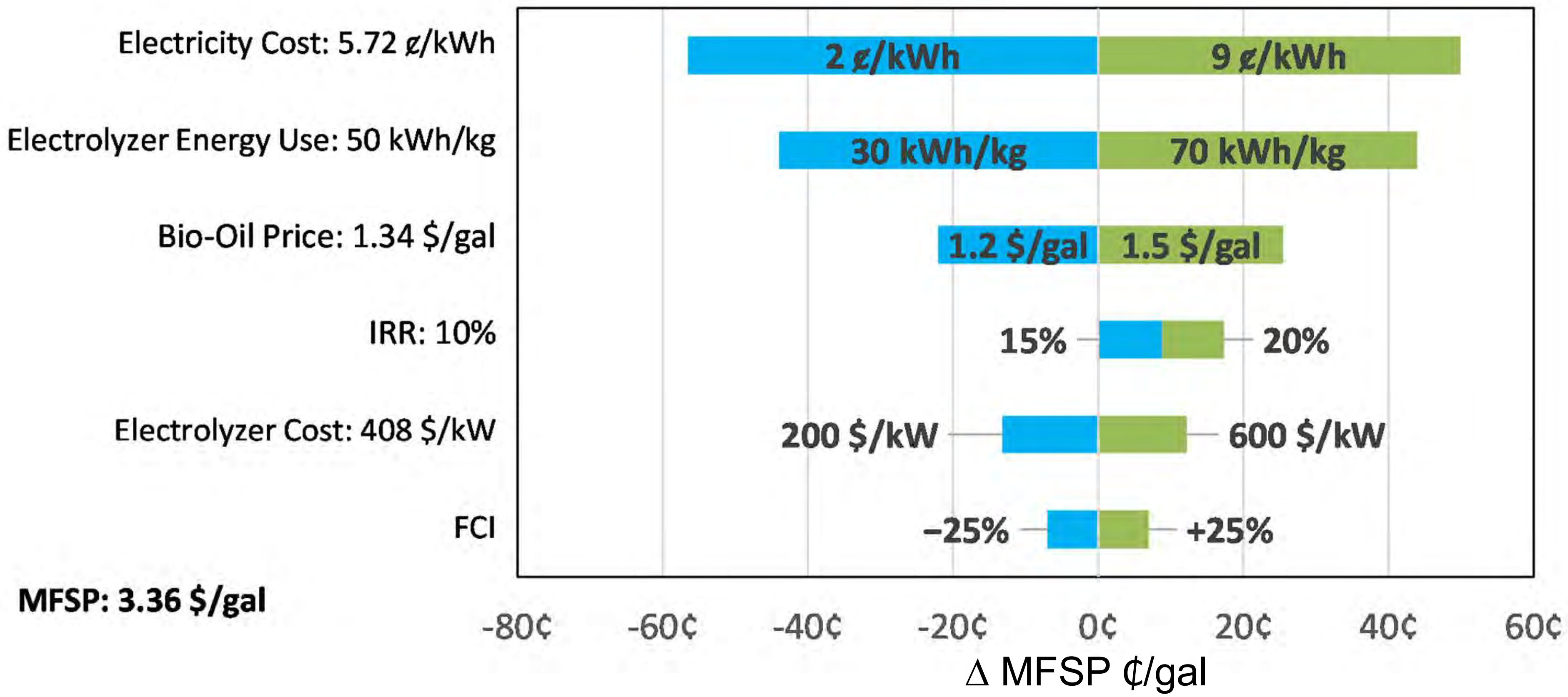


Base MBOSP: 1.34 $/gal

U.S. DOE, 2015 Wind Technologies Market Report. Energy Efficiency & Renewable Energy, 2016.

Sensitivity Analyses

- Single point sensitivity analysis on economic and process parameters performed to assess their impact on **MFSP** at **central refinery**



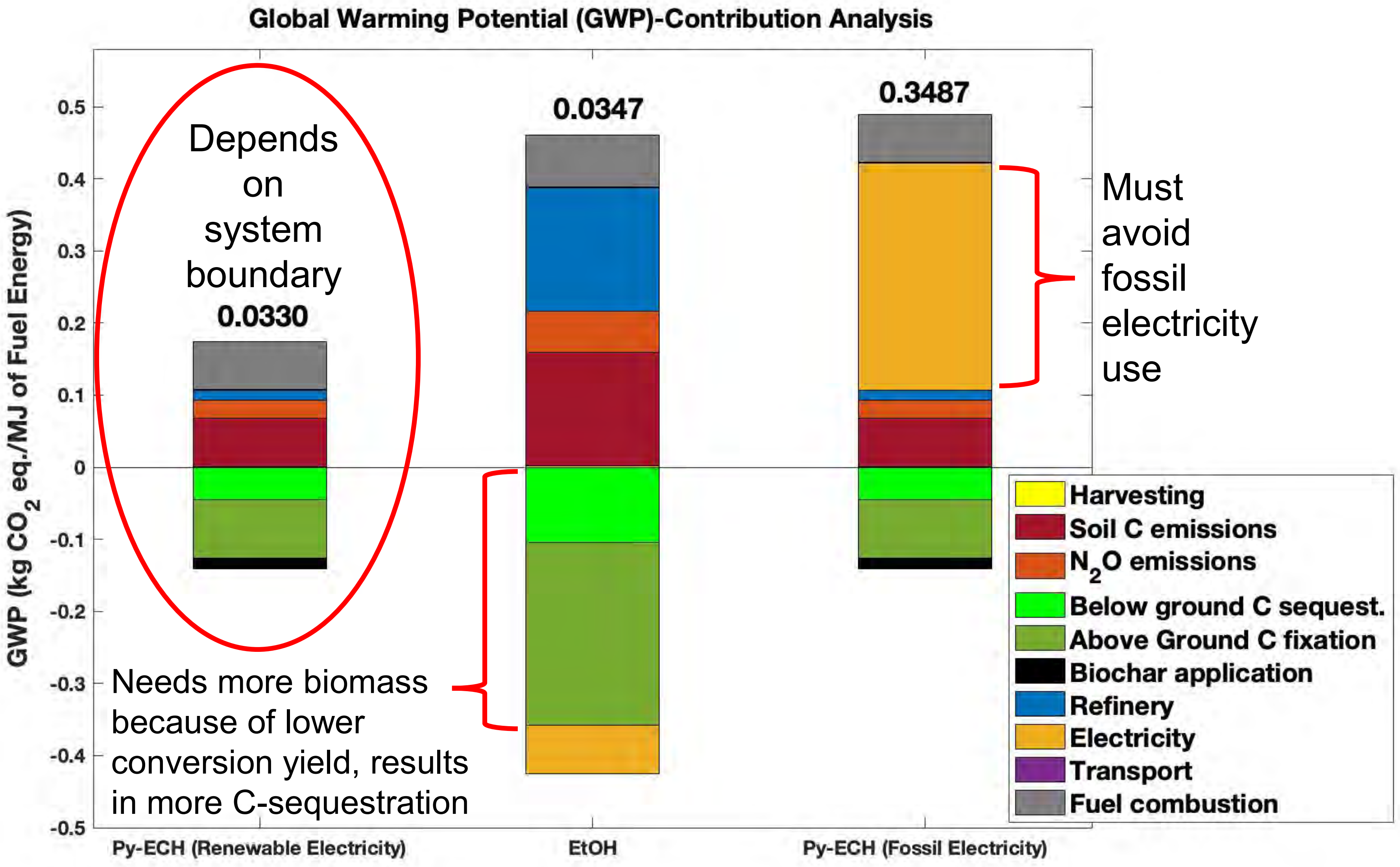
U.S. DOE, 2015 Wind Technologies Market Report. Energy Efficiency & Renewable Energy, 2016.

Preliminary Life Cycle Assessment

- Goal and Scope: Cradle-to-grave life cycle assessment
- Functional unit = 1 MJ of liquid fuel energy at refinery outlet
- Time Horizon: 20 years
- The ratio of reference flows of dry corn stover being processed for the cellulosic ethanol process to the Py-ECH process is about 2.3
- A continuous no-till corn system has been assumed
- A corn stover yield of 160 bushels ac^{-1} yr^{-1} and a N fertilization rate of about 160 kg/ha have been assumed
- Corn stover storage losses of 8.4%, transport losses of 2.4% and stover removal rate of 66% was assumed
- GHG emission values for grid electricity were derived from the RFC Michigan electrical grid
- For the cellulosic ethanol process, corn stover is transported 50 miles from farm to refinery and 110 miles from refinery to terminal by trucks using diesel fuel
- For the Py-ECH process, corn stover is transported 19.2 miles from farm to depot and 154 miles from depot to refinery by trucks using diesel fuel
- Life cycle impact assessment (LCIA): Climate Change Potential was characterized by Global Warming Potentials calculated according to the TRACI model for a 100 year time horizon

MICHIGAN STATE UNIVERSITY

GHG Emission Results

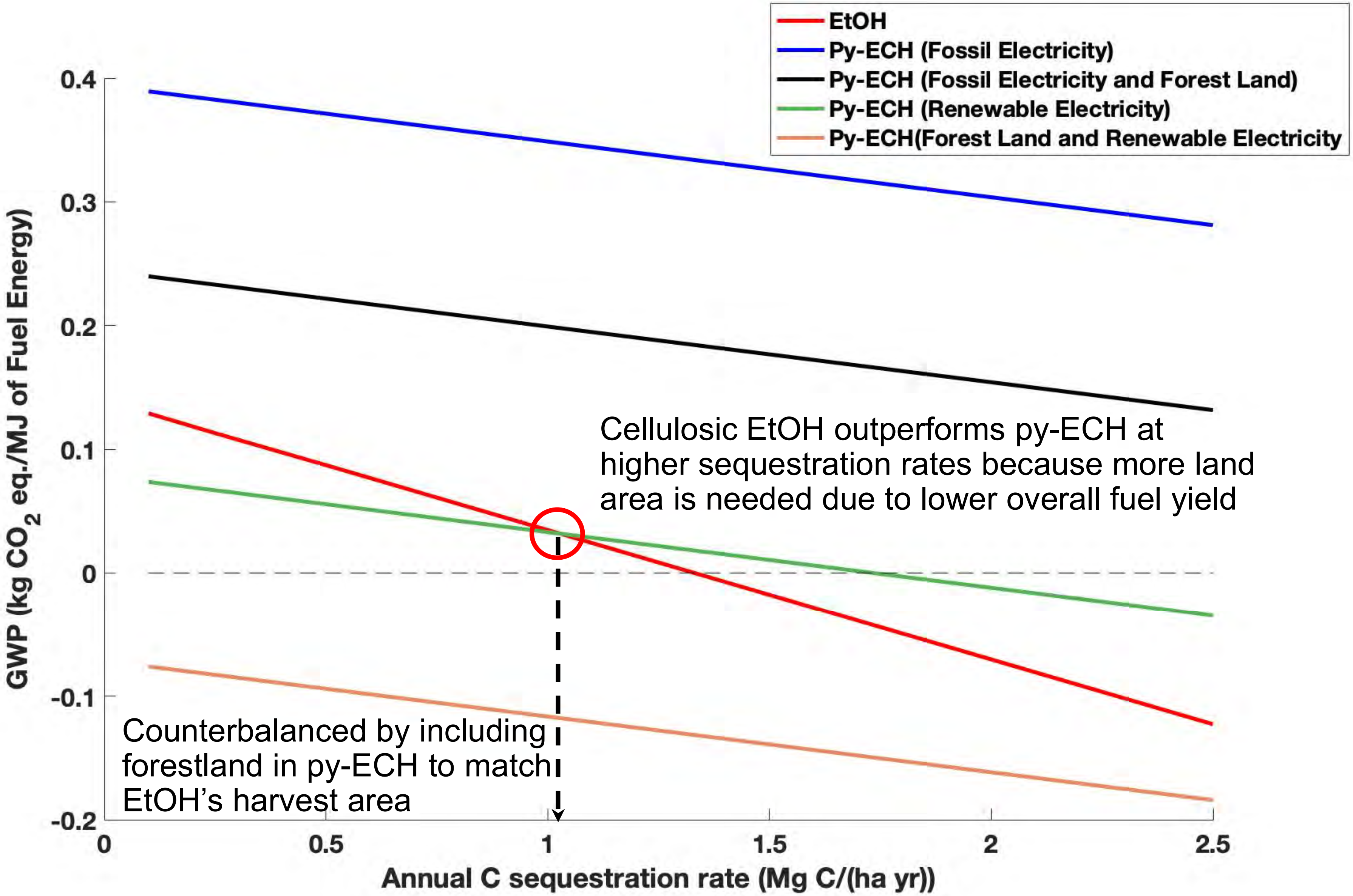


Depends on system boundary

Must avoid fossil electricity use

Needs more biomass because of lower conversion yield, results in more C-sequestration

GHG Sensitivity Analysis



Cellulosic EtOH outperforms py-ECH at higher sequestration rates because more land area is needed due to lower overall fuel yield

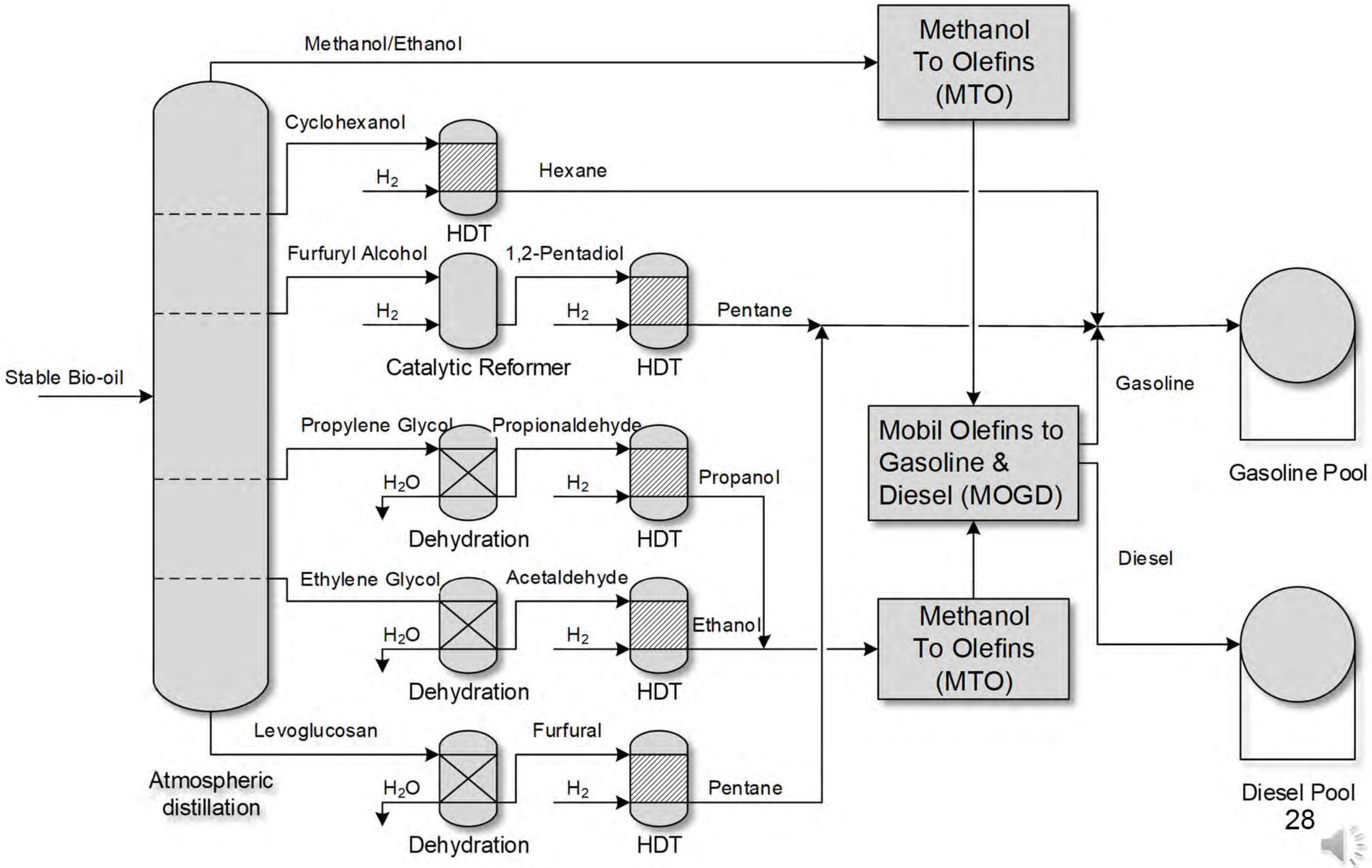
Counterbalanced by including forestland in py-ECH to match EtOH's harvest area

Ref: FENGMING YUAN , M. ALTAF ARAIN, ALAN G. BARR , T. ANDREW BLACK , CHARLES P.-A. BOURQUE, CAROLE COURSOLLE, HANK A. MARGOLIS , J. HARRY McCAUGHEY, STEVEN C. WOFSY, *Global Change Biology*, 2008, **14**, 1765-1784.

Pyrolysis-ECH Summary

1. Pyrolysis-ECH-Hydroprocessing systems compare favorably to dilute acid cellulosic ethanol in terms of carbon, mass, and energy efficiency
2. These technologies are not at the same technology readiness level (TRL), i.e. more research and development is needed to make fair comparisons
3. Pathways to MFSP < $3/gal are possible with low cost electricity and/or high electrocatalysis/electrolysis cell efficiencies
4. Proposed approach is favorable in terms of climate change potential provided renewable electricity is used
5. In addition to investigating bio-oil electrocatalysis, analysis of central refineries capable of stable bio-oil conversion to hydrocarbon fuels is a needed next step

Ongoing Work: Central Refinery Process Design



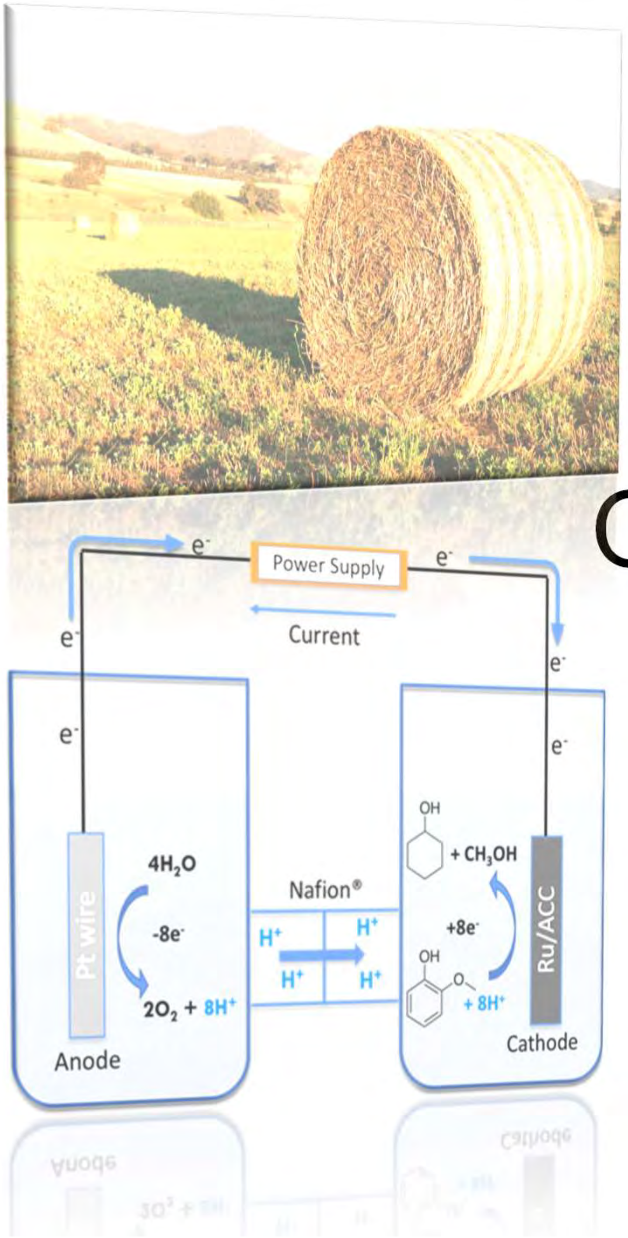
Acknowledgments

- Key faculty members:

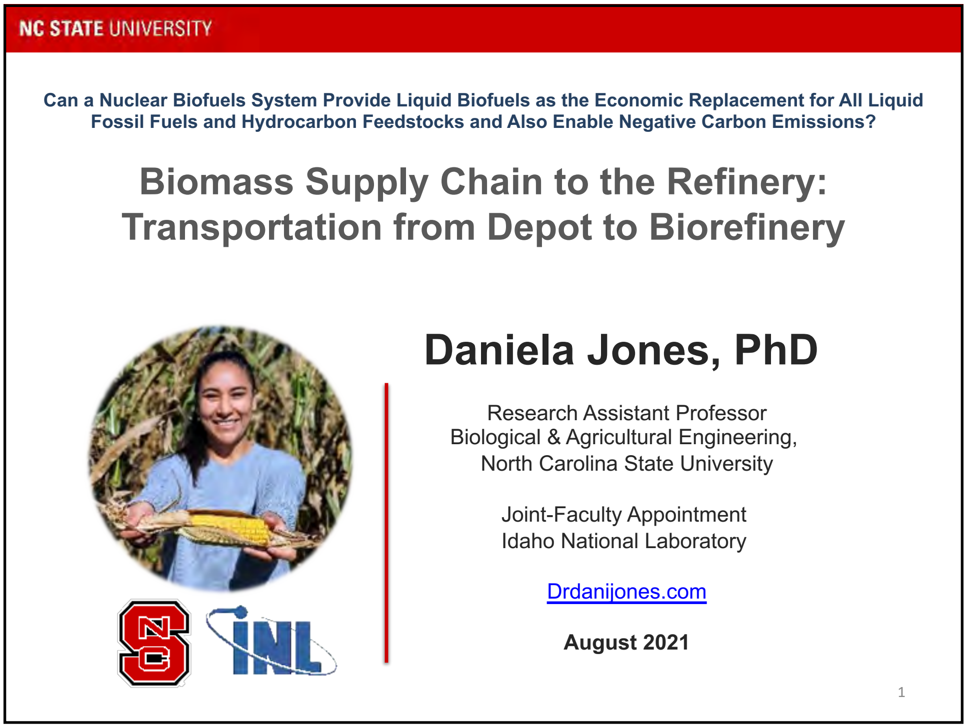
  Prof. Dennis Miller, Dr. Seungdo Kim
- Other group members:

  Dr. Zhenglong Li, Dr. Chun Ho Lam, Tom Stuecken, Dr. Li Chai, Jon Bovee, Dr. Lars Peereboom, Dr. Mikhail Redko, Souful Bhatia, Dr. Somnath Bhattacharjee, Mrs. Nichole Erickson, Dr. Leonardo Sousa, Mr. Cale Hyzer

Thank You!



Questions?



NC STATE UNIVERSITY

Can a Nuclear Biofuels System Provide Liquid Biofuels as the Economic Replacement for All Liquid Fossil Fuels and Hydrocarbon Feedstocks and Also Enable Negative Carbon Emissions?

Biomass Supply Chain to the Refinery: Transportation from Depot to Biorefinery

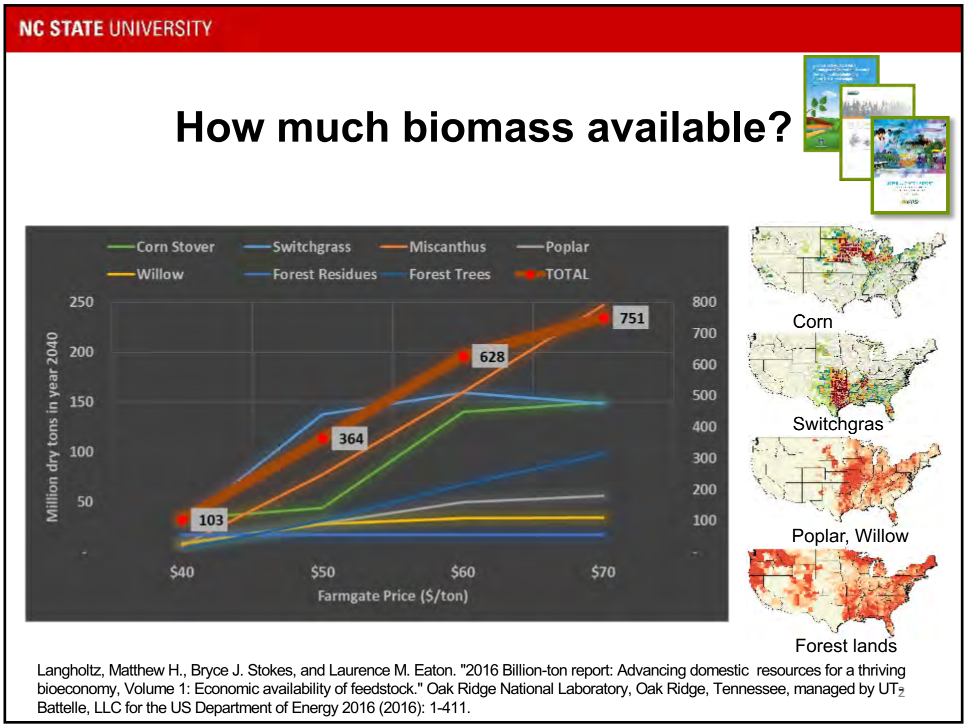
Daniela Jones, PhD

Research Assistant Professor
Biological & Agricultural Engineering,
North Carolina State University

Joint-Faculty Appointment
Idaho National Laboratory

Drdanijones.com

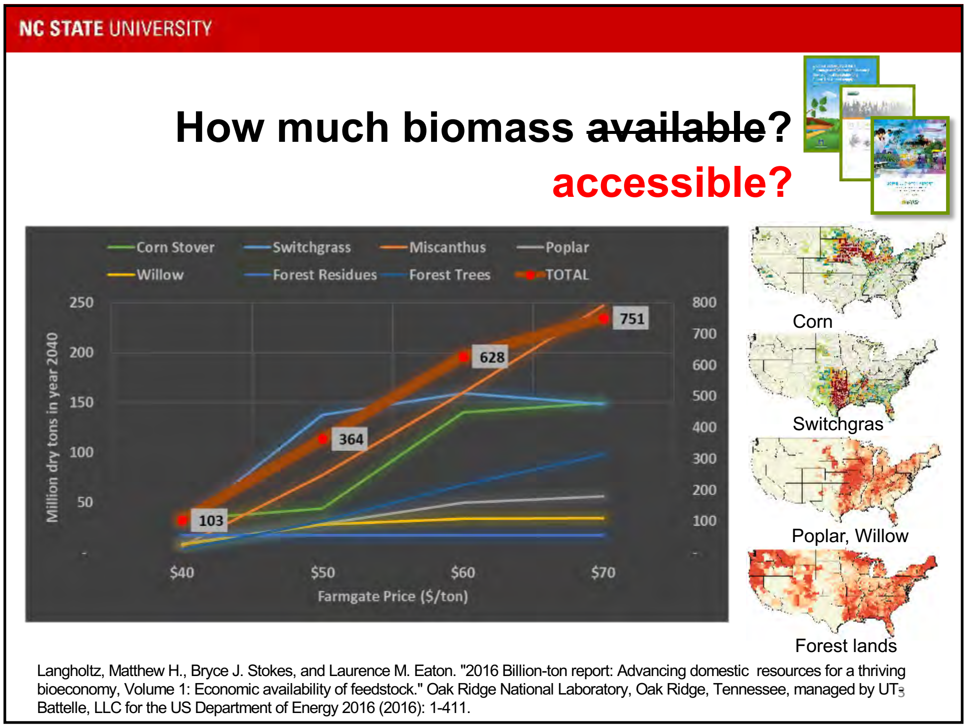
August 2021



NC STATE UNIVERSITY

How much biomass available?

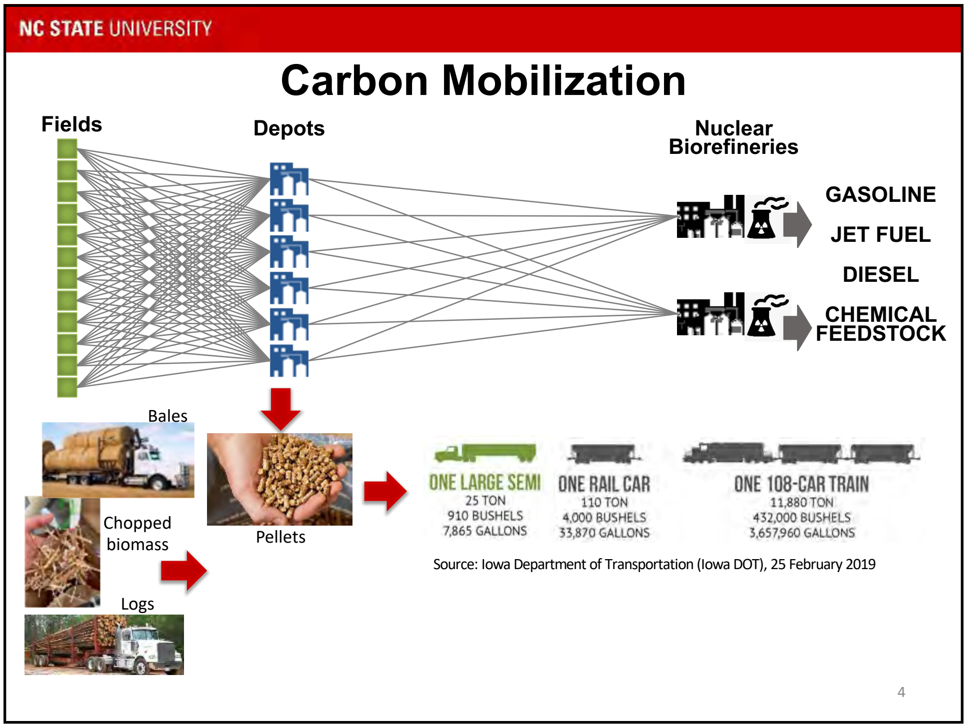
Langholtz, Matthew H., Bryce J. Stokes, and Laurence M. Eaton. "2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstock." Oak Ridge National Laboratory, Oak Ridge, Tennessee, managed by UT-Battelle, LLC for the US Department of Energy 2016 (2016): 1-411.



NC STATE UNIVERSITY

How much biomass ~~available~~? accessible?

Langholtz, Matthew H., Bryce J. Stokes, and Laurence M. Eaton. "2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstock." Oak Ridge National Laboratory, Oak Ridge, Tennessee, managed by UT-Battelle, LLC for the US Department of Energy 2016 (2016): 1-411.



NC STATE UNIVERSITY

Carbon Mobilization

Fields

Depots

Nuclear Biorefineries

GASOLINE

JET FUEL

DIESEL

CHEMICAL FEEDSTOCK

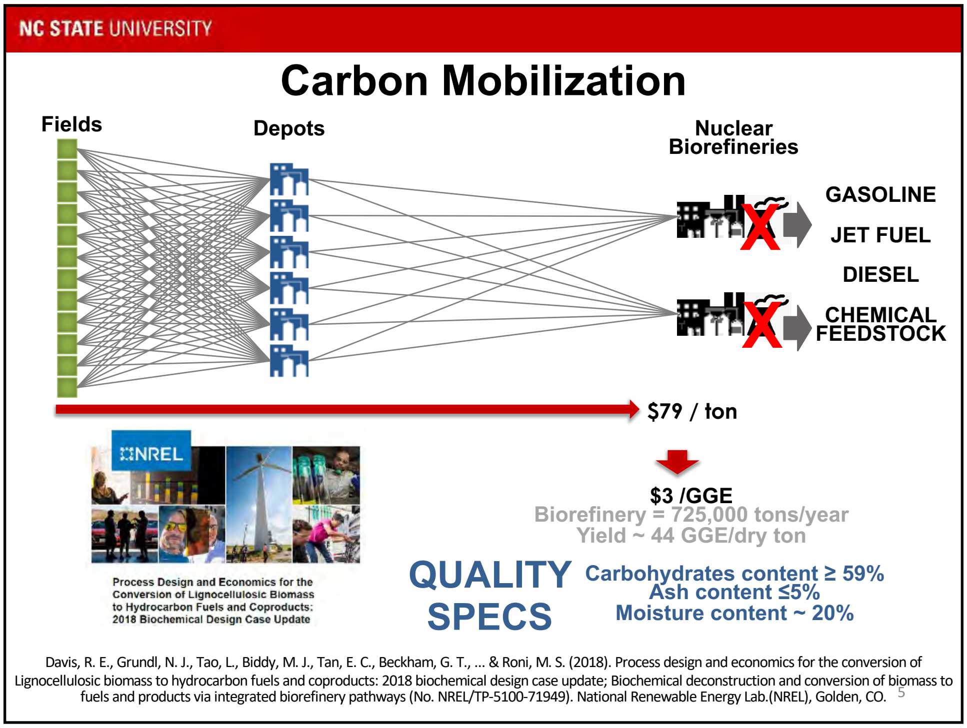
Bales

Chopped biomass

Logs

Pellets

Source: Iowa Department of Transportation (Iowa DOT), 25 February 2019



NC STATE UNIVERSITY

Carbon Mobilization

$79 / ton

$3 /GGE

Biorefinery = 725,000 tons/year

Yield ~ 44 GGE/dry ton

QUALITY SPECS

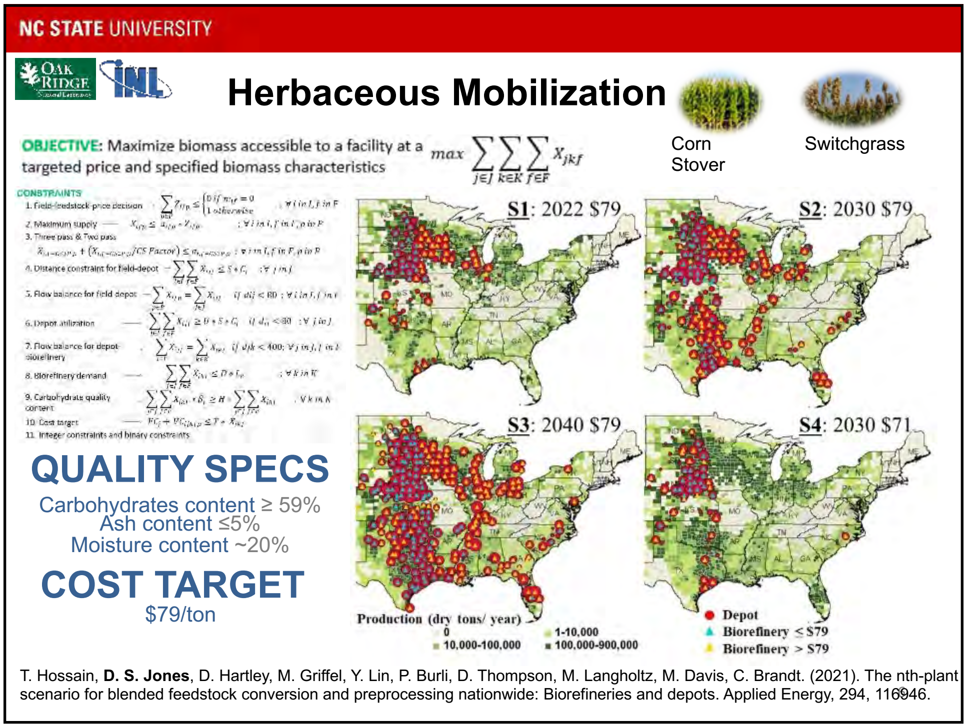
Carbohydrates content ≥ 59%

Ash content ≤5%

Moisture content ~ 20%

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels and Coproducts: 2018 Biochemical Design Case Update

Davis, R. E., Grundl, N. J., Tao, L., Biddy, M. J., Tan, E. C., Beckham, G. T., ... & Roni, M. S. (2018). Process design and economics for the conversion of Lignocellulosic biomass to hydrocarbon fuels and coproducts: 2018 biochemical design case update; Biochemical deconstruction and conversion of biomass to fuels and products via integrated biorefinery pathways (No. NREL/TP-5100-71949). National Renewable Energy Lab.(NREL), Golden, CO.



NC STATE UNIVERSITY

Herbaceous Mobilization

OBJECTIVE: Maximize biomass accessible to a facility at a targeted price and specified biomass characteristics $max \sum_{j\in J}\sum_{k\in K}\sum_{f\in F} X_{jkf}$

CONSTRAINTS

1. Field-feedstock-price decision $\sum_{p\in P} Z_{ifp} \le \begin{cases} 0 \text{ if } m_{if}=0 \\ 1 \text{ otherwise} \end{cases}$; ∀ i in I, f in F
2. Maximum supply — $X_{ifp} \le a_{ifp} * Z_{ifp}$; ∀ i in I, f in F, p in P
3. Three pass & Two pass
   $X_{if-ecorp} + (X_{if-ecorp}/CS\ Factor) \le a_{if-ecorp}$; ∀ i in I, f in F, p in P
4. Distance constraint for field-depot — $\sum_{i\in I}\sum_{f\in F} X_{ijf} \le S * G_j$; ∀ j in J
5. Flow balance for field depot — $\sum_{p\in P} X_{ifp} = \sum_{j\in J} X_{ijf}$ if $d_{ij} < 80$; ∀ i in I, f in F
6. Depot utilization — $\sum_{i\in I}\sum_{f\in F} X_{ijf} \ge D * S * G_j$ if $d_{ij} < 80$; ∀ j in J
7. Flow balance for depot-biorefinery $\sum_{i\in I} X_{ijf} = \sum_{k\in K} X_{jkf}$ if $d_{jk} < 400$; ∀ j in J, f in F
8. Biorefinery demand — $\sum_{j\in J}\sum_{f\in F} X_{jkf} \le D * L_k$; ∀ k in K
9. Carbohydrate quality content $\sum_{j\in J}\sum_{f\in F} X_{jkf} * B_f \ge H * \sum_{j\in J}\sum_{f\in F} X_{jkf}$; ∀ k in K
10. Cost target — $FC_j + VC_{(jkf)} \le T * X_{jkf}$
11. Integer constraints and binary constraints

QUALITY SPECS

Carbohydrates content ≥ 59%

Ash content ≤5%

Moisture content ~20%

COST TARGET

$79/ton

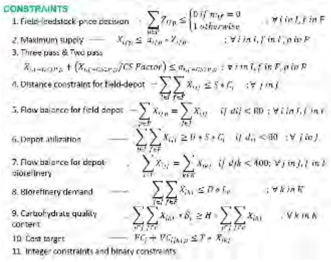
T. Hossain, **D. S. Jones**, D. Hartley, M. Griffel, Y. Lin, P. Burli, D. Thompson, M. Langholtz, M. Davis, C. Brandt. (2021). The nth-plant scenario for blended feedstock conversion and preprocessing nationwide: Biorefineries and depots. Applied Energy, 294, 116946.

Herbaceous Mobilization


Corn
Stover

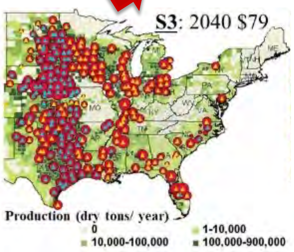

Switchgrass

OBJECTIVE: Maximize biomass accessible to a facility at a targeted price and specified biomass characteristics $\max \sum_{j \in J} \sum_{k \in K} \sum_{f \in F} x_{jkf}$


CONSTRAINTS
1. Field-feedstock-price decision
2. Maximum supply
3. Three pass & Two pass
4. Distance constraint for field-depot
5. Flow balance for field depot
6. Depot utilization
7. Flow balance for depot-biorefinery
8. Biorefinery demand
9. Carbohydrate quality content
10. Cost target
11. Integer constraints and binary constraints

NATIONWIDE

YEARLY	DAILY
168M dry tons	460K dry tons
~100M tons of carbon	~270K tons of carbons
~ 7.4B GGE	~ 20M GGE
~ 180M barrels	~ 480k barrels



QUALITY SPECS

Carbohydrates content ≥ 59%
Ash content ≤5%
Moisture content ~20%

COST TARGET

$79/ton

Biorefinery Size
= 2k barrels/day

Nuclear Biofuels Biorefinery Size
= 250k barrels/ day

T. Hossain, **D. S. Jones**, D. Hartley, M. Griffel, Y. Lin, P. Burli, D. Thompson, M. Langholtz, M. Davis, C. Brandt. (2021). The nth-plant scenario for blended feedstock conversion and preprocessing nationwide: Biorefineries and depots. Applied Energy, 294, 116946.

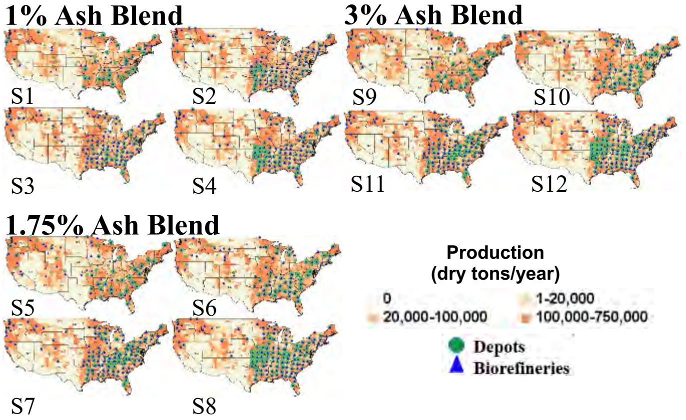
Woody Mobilization


Forest Trees
Forest Residues
Short Rotation
Woody Crops

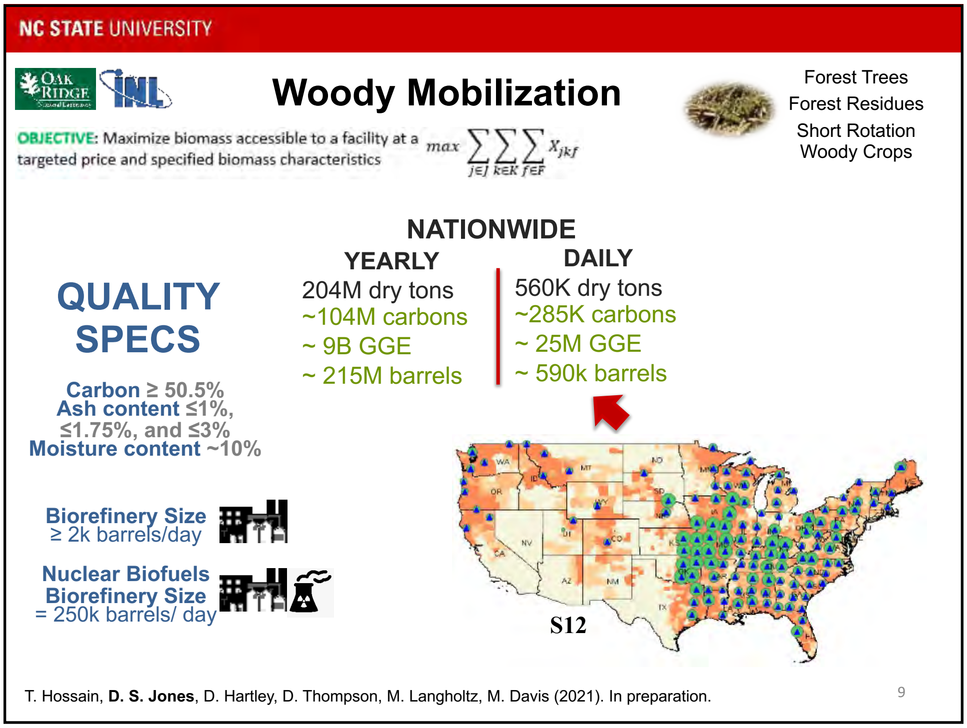
OBJECTIVE: Maximize biomass accessible to a facility at a targeted price and specified biomass characteristics $\max \sum_{j \in J} \sum_{k \in K} \sum_{f \in F} x_{jkf}$

QUALITY SPECS

Carbon ≥ 50.5%
Ash content ≤1%, ≤1.75%, and ≤3%
Moisture content ~10%



T. Hossain, **D. S. Jones**, D. Hartley, D. Thompson, M. Langholtz, M. Davis (2021). In preparation.



NC STATE UNIVERSITY

Woody Mobilization

OBJECTIVE: Maximize biomass accessible to a facility at a targeted price and specified biomass characteristics $max \sum_{j \in J} \sum_{k \in K} \sum_{f \in F} X_{jkf}$

Forest Trees
Forest Residues
Short Rotation
Woody Crops

QUALITY SPECS

Carbon ≥ 50.5%
Ash content ≤1%, ≤1.75%, and ≤3%
Moisture content ~10%

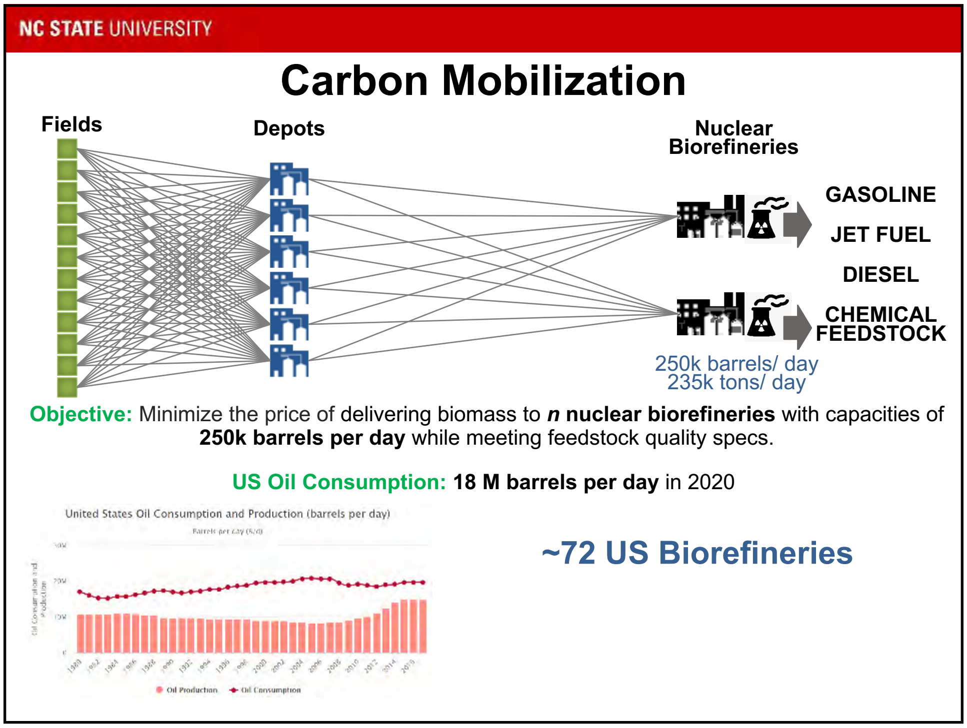
Biorefinery Size
≥ 2k barrels/day

Nuclear Biofuels Biorefinery Size
= 250k barrels/ day

NATIONWIDE

YEARLY	**DAILY**
204M dry tons	560K dry tons
~104M carbons	~285K carbons
~ 9B GGE	~ 25M GGE
~ 215M barrels	~ 590k barrels

T. Hossain, **D. S. Jones**, D. Hartley, D. Thompson, M. Langholtz, M. Davis (2021). In preparation.



NC STATE UNIVERSITY

Carbon Mobilization

GASOLINE
JET FUEL
DIESEL
CHEMICAL FEEDSTOCK

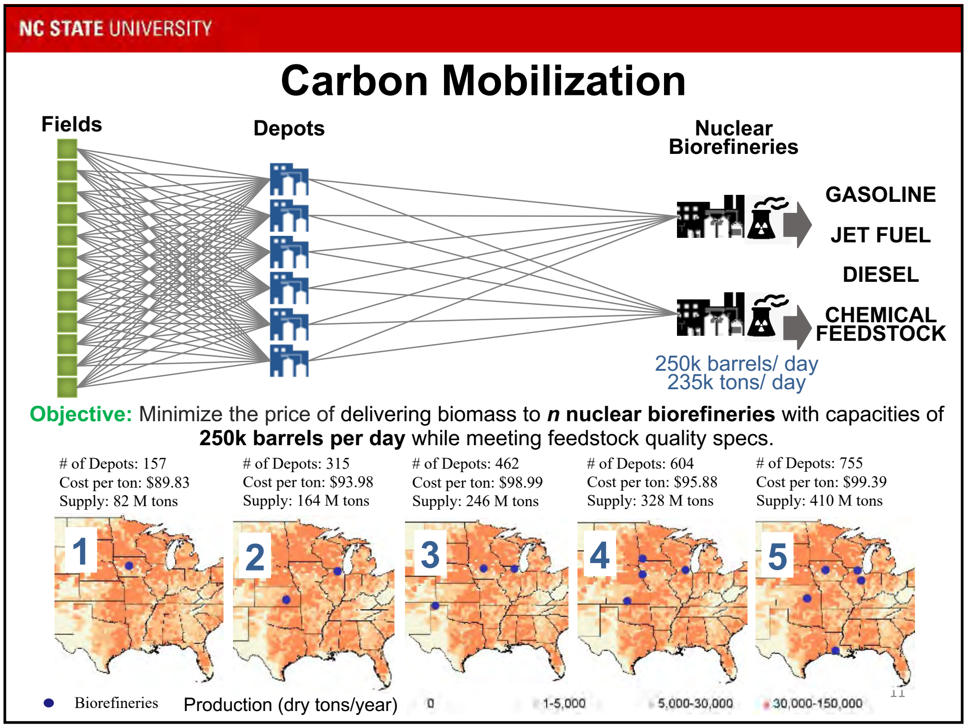
250k barrels/ day
235k tons/ day

Objective: Minimize the price of delivering biomass to ***n*** **nuclear biorefineries** with capacities of **250k barrels per day** while meeting feedstock quality specs.

US Oil Consumption: 18 M barrels per day in 2020

United States Oil Consumption and Production (barrels per day)

~72 US Biorefineries



NC STATE UNIVERSITY

Carbon Mobilization

Fields

Depots

Nuclear Biorefineries

GASOLINE

JET FUEL

DIESEL

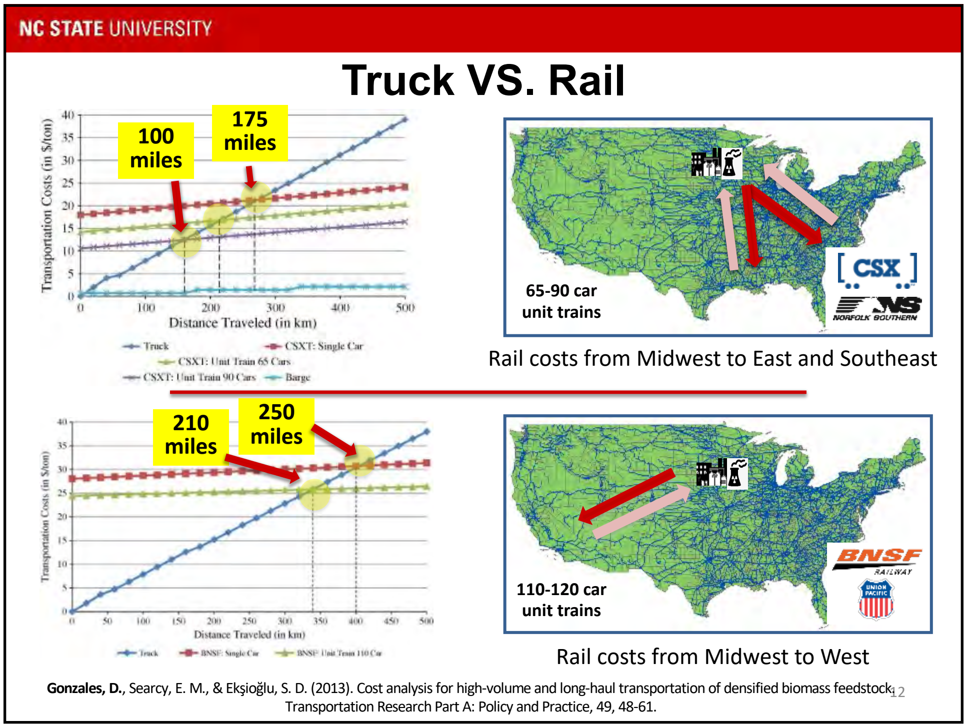
CHEMICAL FEEDSTOCK

250k barrels/ day
235k tons/ day

Objective: Minimize the price of delivering biomass to ***n* nuclear biorefineries** with capacities of **250k barrels per day** while meeting feedstock quality specs.

1	2	3	4	5
# of Depots: 157	# of Depots: 315	# of Depots: 462	# of Depots: 604	# of Depots: 755
Cost per ton: $89.83	Cost per ton: $93.98	Cost per ton: $98.99	Cost per ton: $95.88	Cost per ton: $99.39
Supply: 82 M tons	Supply: 164 M tons	Supply: 246 M tons	Supply: 328 M tons	Supply: 410 M tons

● Biorefineries Production (dry tons/year) 0 1-5,000 5,000-30,000 30,000-150,000



NC STATE UNIVERSITY

Truck VS. Rail

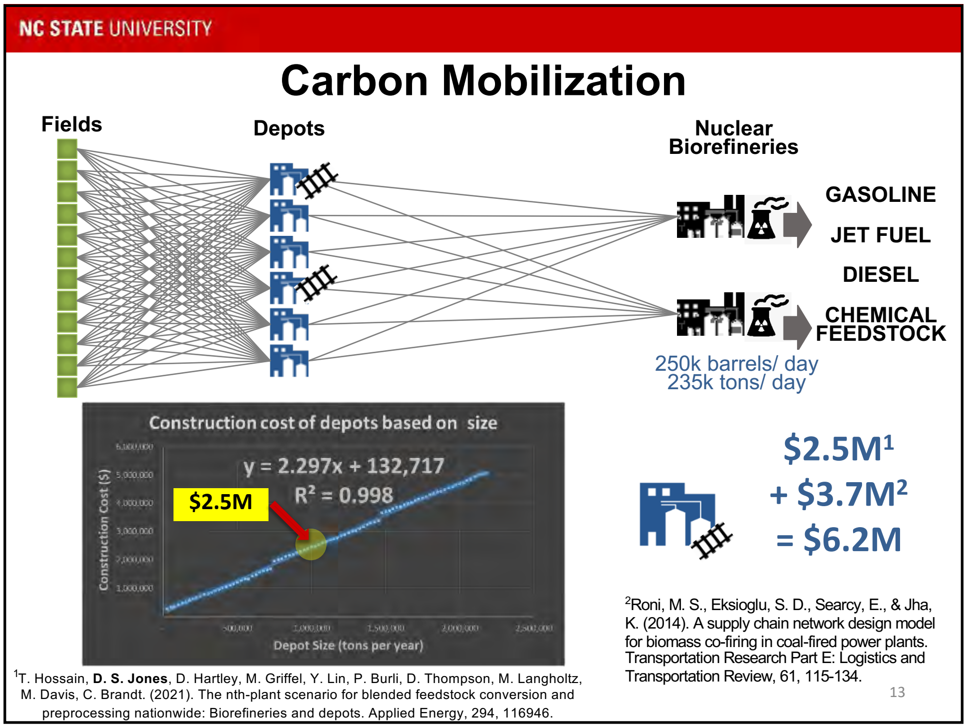
65-90 car unit trains

Rail costs from Midwest to East and Southeast

110-120 car unit trains

Rail costs from Midwest to West

Gonzales, D., Searcy, E. M., & Ekşioğlu, S. D. (2013). Cost analysis for high-volume and long-haul transportation of densified biomass feedstock. Transportation Research Part A: Policy and Practice, 49, 48-61.



NC STATE UNIVERSITY

Carbon Mobilization

Fields

Depots

Nuclear Biorefineries

GASOLINE

JET FUEL

DIESEL

CHEMICAL FEEDSTOCK

250k barrels/ day
235k tons/ day

Construction cost of depots based on size

$y = 2.297x + 132{,}717$

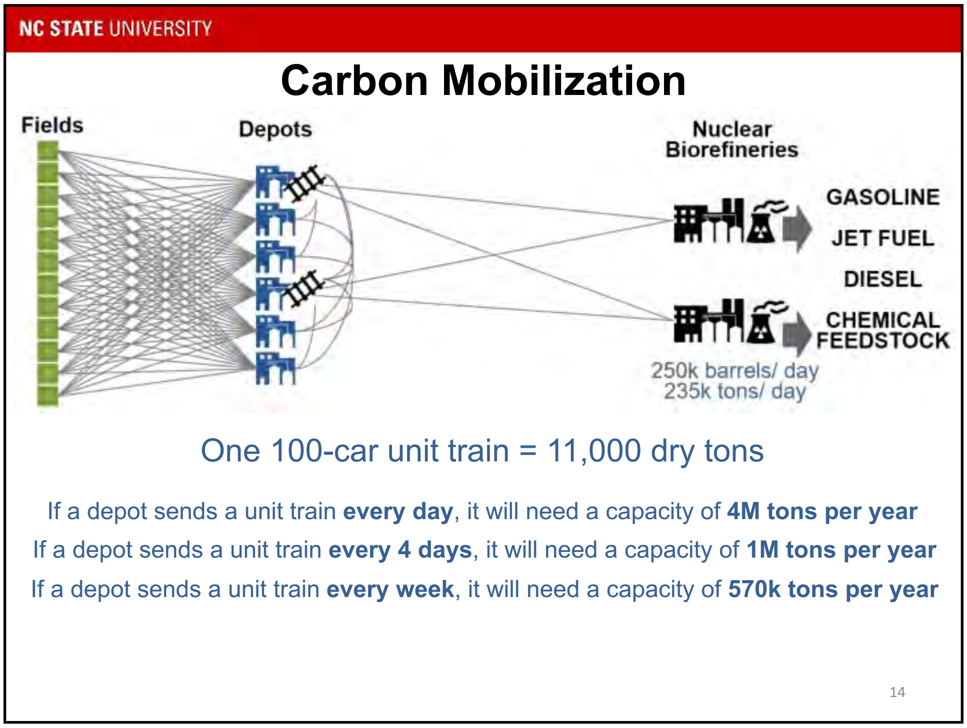
$R^2 = 0.998$

$2.5M

$2.5M[1]
+ $3.7M[2]
= $6.2M

[2] Roni, M. S., Eksioglu, S. D., Searcy, E., & Jha, K. (2014). A supply chain network design model for biomass co-firing in coal-fired power plants. Transportation Research Part E: Logistics and Transportation Review, 61, 115-134.

[1] T. Hossain, **D. S. Jones**, D. Hartley, M. Griffel, Y. Lin, P. Burli, D. Thompson, M. Langholtz, M. Davis, C. Brandt. (2021). The nth-plant scenario for blended feedstock conversion and preprocessing nationwide: Biorefineries and depots. Applied Energy, 294, 116946.



NC STATE UNIVERSITY

Carbon Mobilization

Fields

Depots

Nuclear Biorefineries

GASOLINE

JET FUEL

DIESEL

CHEMICAL FEEDSTOCK

250k barrels/ day
235k tons/ day

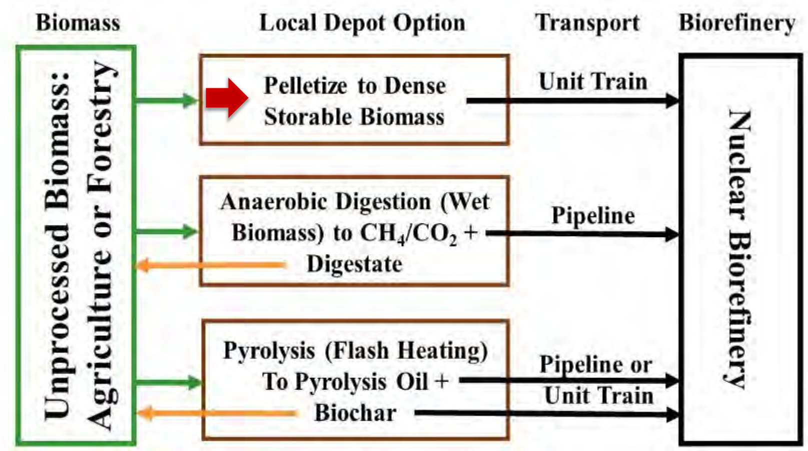
One 100-car unit train = 11,000 dry tons

If a depot sends a unit train **every day**, it will need a capacity of **4M tons per year**

If a depot sends a unit train **every 4 days**, it will need a capacity of **1M tons per year**

If a depot sends a unit train **every week**, it will need a capacity of **570k tons per year**

Nuclear Biofuels


Biomass

Local Depot Option

Transport

Biorefinery

Unprocessed Biomass: Agriculture or Forestry

Pelletize to Dense Storable Biomass

Anaerobic Digestion (Wet Biomass) to CH$_4$/CO$_2$ + Digestate

Pyrolysis (Flash Heating) To Pyrolysis Oil + Biochar

Unit Train

Pipeline

Pipeline or Unit Train

Nuclear Biorefinery

Forsberg, C. W., Dale, B. E., **Jones, D. S.**, Hossain, T., Morais, A. R. C., & Wendt, L. M. (2021). Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries. Applied Energy, 298, 117225.

Thank you for your attention!

Dr. Dani Jones
Research Assistant Professor

Biological & Agricultural Engineering
North Carolina State University

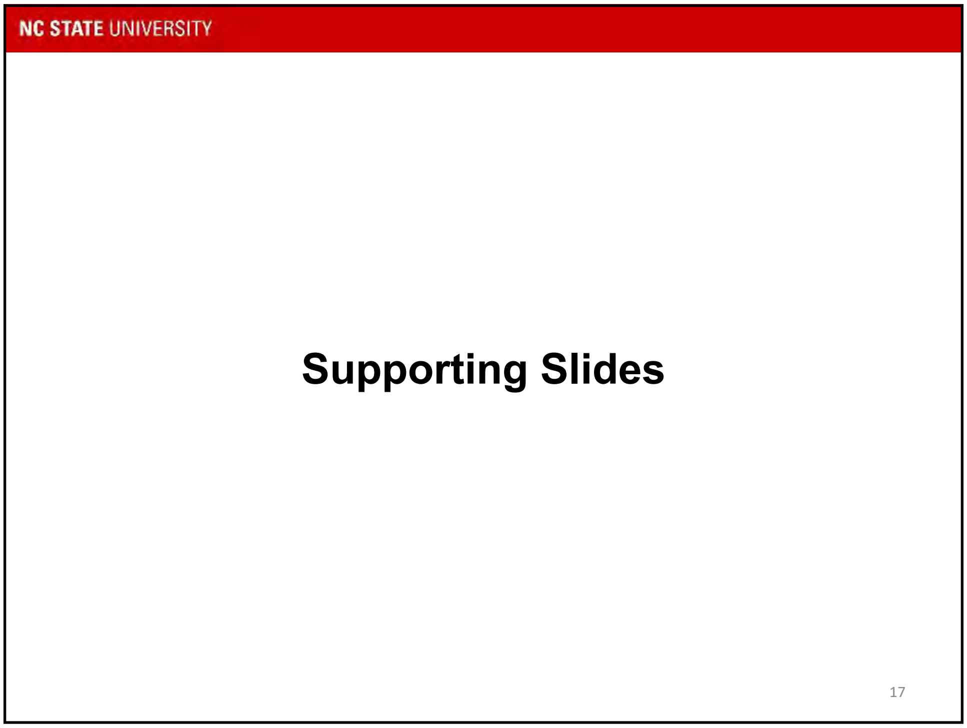
Joint-Faculty Appointment
Idaho National Laboratory

www.drdanijones.com

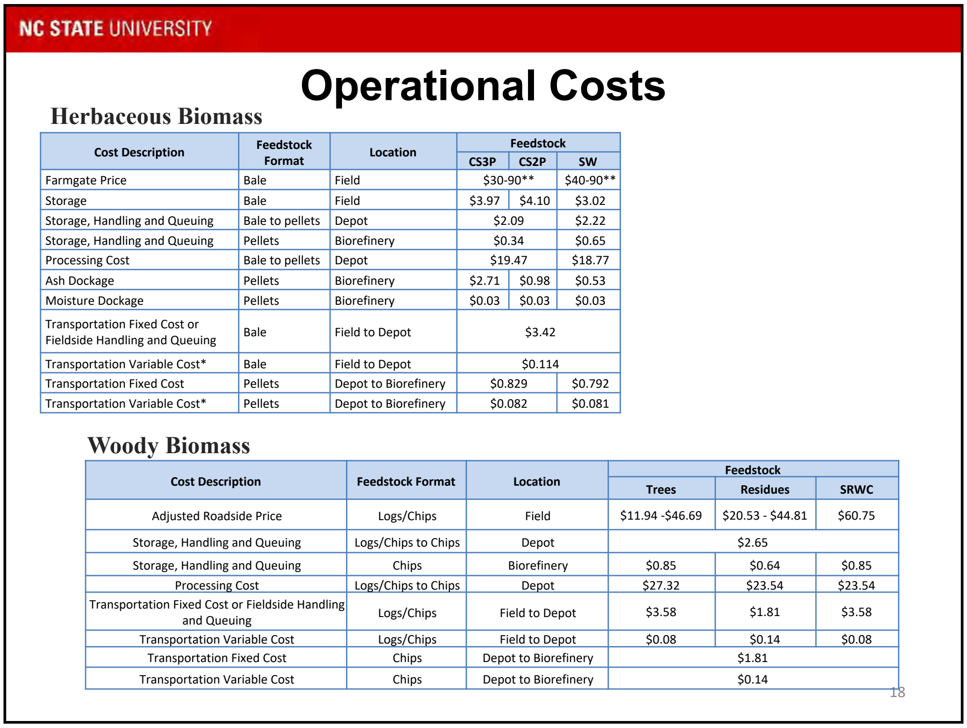
dsjones5@ncsu.edu

DrDaniJones

Linkedin



Supporting Slides



Operational Costs

Herbaceous Biomass

Cost Description	Feedstock Format	Location	Feedstock		
			CS3P	CS2P	SW
Farmgate Price	Bale	Field	$30-90**		$40-90**
Storage	Bale	Field	$3.97	$4.10	$3.02
Storage, Handling and Queuing	Bale to pellets	Depot	$2.09		$2.22
Storage, Handling and Queuing	Pellets	Biorefinery	$0.34		$0.65
Processing Cost	Bale to pellets	Depot	$19.47		$18.77
Ash Dockage	Pellets	Biorefinery	$2.71	$0.98	$0.53
Moisture Dockage	Pellets	Biorefinery	$0.03	$0.03	$0.03
Transportation Fixed Cost or Fieldside Handling and Queuing	Bale	Field to Depot	$3.42		
Transportation Variable Cost*	Bale	Field to Depot	$0.114		
Transportation Fixed Cost	Pellets	Depot to Biorefinery	$0.829		$0.792
Transportation Variable Cost*	Pellets	Depot to Biorefinery	$0.082		$0.081

Woody Biomass

Cost Description	Feedstock Format	Location	Feedstock		
			Trees	Residues	SRWC
Adjusted Roadside Price	Logs/Chips	Field	$11.94 -$46.69	$20.53 - $44.81	$60.75
Storage, Handling and Queuing	Logs/Chips to Chips	Depot	$2.65		
Storage, Handling and Queuing	Chips	Biorefinery	$0.85	$0.64	$0.85
Processing Cost	Logs/Chips to Chips	Depot	$27.32	$23.54	$23.54
Transportation Fixed Cost or Fieldside Handling and Queuing	Logs/Chips	Field to Depot	$3.58	$1.81	$3.58
Transportation Variable Cost	Logs/Chips	Field to Depot	$0.08	$0.14	$0.08
Transportation Fixed Cost	Chips	Depot to Biorefinery	$1.81		
Transportation Variable Cost	Chips	Depot to Biorefinery	$0.14		

Feedstock Characteristics

Herbaceous Biomass Blended Feedstock Targets

Carbohydrates content ≥ 59%
Ash content ≤5%
Moisture content ≥ 20%

Herbaceous Biomass Feedstock Characteristics

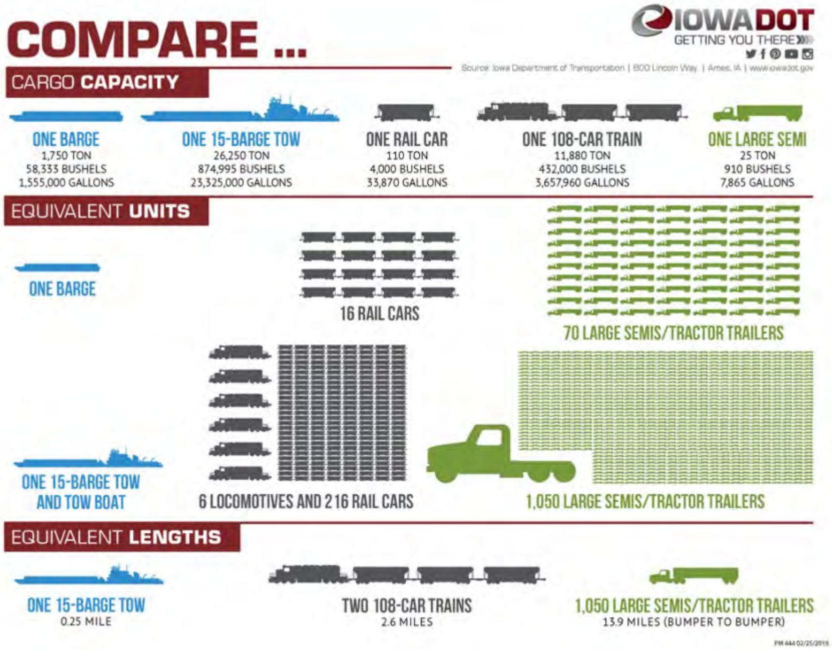
Feedstock	Carbohydrates	Ash	Moisture
Switchgrass	66.4%	6.3%	9.9%
Corn stover (2P)	59.6%	7.2%	10.6%
Corn stover (3P)	56.9%	11.6%	10.6%

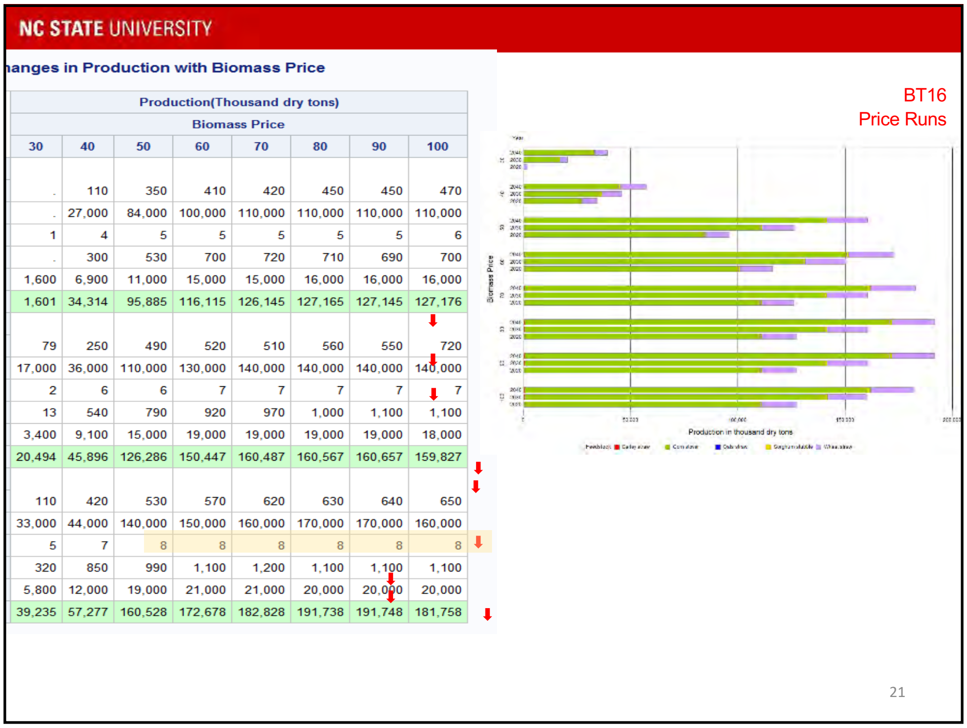
Woody Biomass Blended Feedstock Targets

Moisture	Carbon	Ash		
		CFP Design Case	CFP 2020 SOT	IDL Design Case
≤ 10%	≥ 50.51%	≤ 1%	≤ 1.75%	≤ 3%

Woody Biomass Feedstock Characteristics

Resource Type	Feedstock Type	Ash Content (%)
Forest land resources (FLR)	Trees	0.8
	Forest residues	1.5
Short rotation woody crops (SRWC)	Pine	0.8
	Poplar	1.87
	Willow	1.997
	Eucalyptus	1.5



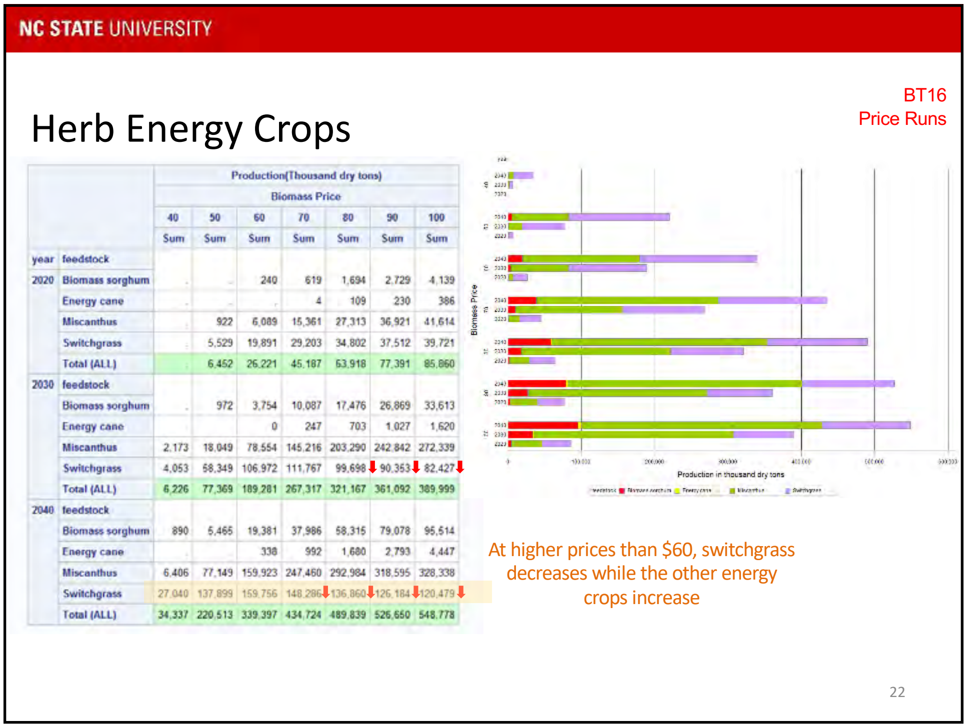


NC STATE UNIVERSITY

anges in Production with Biomass Price

BT16
Price Runs

Production(Thousand dry tons)							
Biomass Price							
30	40	50	60	70	80	90	100
.	110	350	410	420	450	450	470
.	27,000	84,000	100,000	110,000	110,000	110,000	110,000
1	4	5	5	5	5	5	6
.	300	530	700	720	710	690	700
1,600	6,900	11,000	15,000	15,000	16,000	16,000	16,000
1,601	34,314	95,885	116,115	126,145	127,165	127,145	127,176
							⬇
79	250	490	520	510	560	550	720
17,000	36,000	110,000	130,000	140,000	140,000	140,000	⬇ 140,000
2	6	6	7	7	7	7	⬇ 7
13	540	790	920	970	1,000	1,100	1,100
3,400	9,100	15,000	19,000	19,000	19,000	19,000	18,000
20,494	45,896	126,286	150,447	160,487	160,567	160,657	159,827 ⬇ ⬇
110	420	530	570	620	630	640	650
33,000	44,000	140,000	150,000	160,000	170,000	170,000	160,000
5	7	8	8	8	8	8	8 ⬇
320	850	990	1,100	1,200	1,100	1,100 ⬇	1,100
5,800	12,000	19,000	21,000	21,000	20,000	20,000 ⬇	20,000
39,235	57,277	160,528	172,678	182,828	191,738	191,748	181,758 ⬇



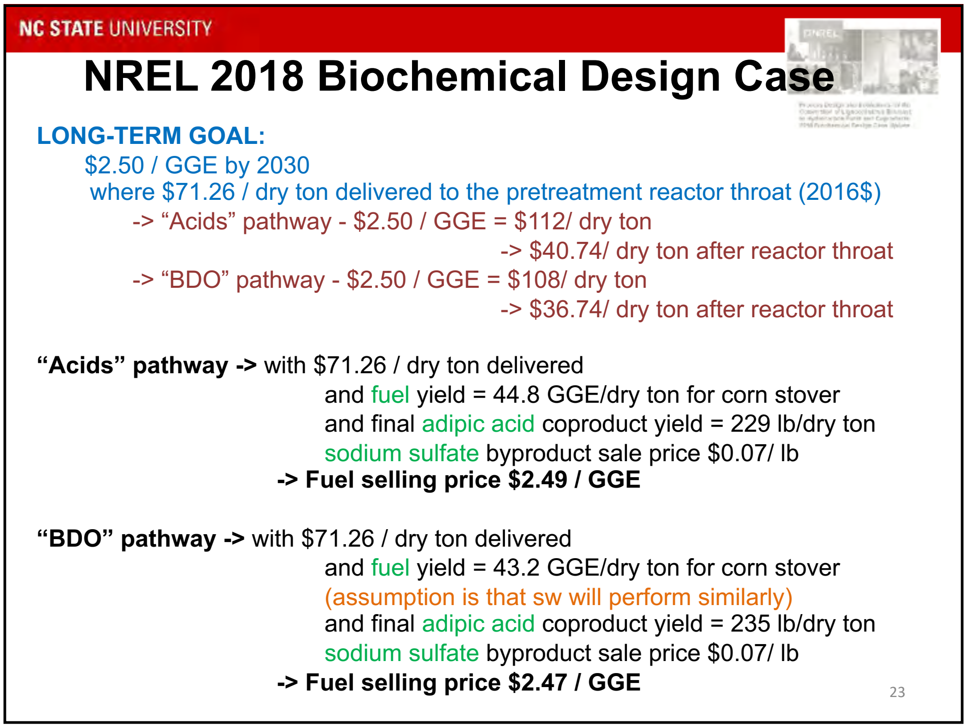
NC STATE UNIVERSITY

Herb Energy Crops

BT16
Price Runs

		Production(Thousand dry tons)						
		Biomass Price						
		40	50	60	70	80	90	100
		Sum	Sum	Sum	Sum	Sum	Sum	Sum
year	feedstock							
2020	Biomass sorghum	.	.	240	619	1,694	2,729	4,139
	Energy cane	.	.	.	4	109	230	386
	Miscanthus	.	922	6,089	15,361	27,313	36,921	41,614
	Switchgrass	.	5,529	19,891	29,203	34,802	37,512	39,721
	Total (ALL)	.	6,452	26,221	45,187	63,918	77,391	85,860
2030	feedstock							
	Biomass sorghum	.	972	3,754	10,087	17,476	26,869	33,613
	Energy cane	.		0	247	703	1,027	1,620
	Miscanthus	2,173	18,049	78,554	145,216	203,290	242,842	272,339
	Switchgrass	4,053	58,349	106,972	111,767	99,698 ⬇	90,353 ⬇	82,427 ⬇
	Total (ALL)	6,226	77,369	189,281	267,317	321,167	361,092	389,999
2040	feedstock							
	Biomass sorghum	890	5,465	19,381	37,986	58,315	79,078	95,514
	Energy cane	.		338	992	1,680	2,793	4,447
	Miscanthus	6,406	77,149	159,923	247,460	292,984	318,595	328,338
	Switchgrass	27,040	137,899	159,756	148,286 ⬇	136,860 ⬇	126,184 ⬇	120,479 ⬇
	Total (ALL)	34,337	220,513	339,397	434,724	489,839	526,650	548,778

At higher prices than $60, switchgrass decreases while the other energy crops increase



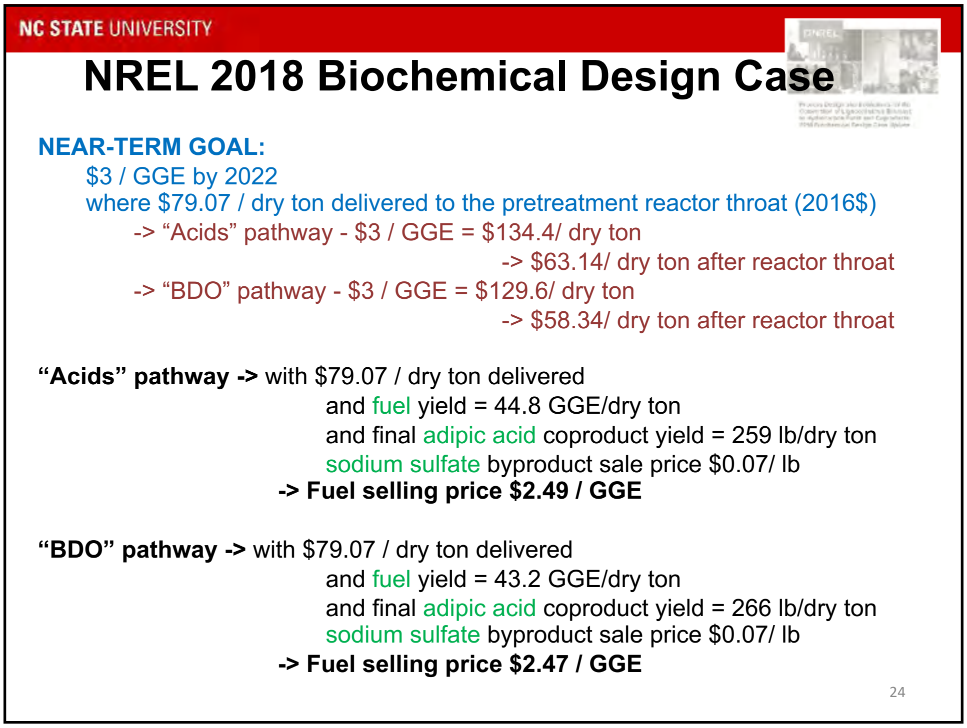
NREL 2018 Biochemical Design Case

LONG-TERM GOAL:

$2.50 / GGE by 2030
where $71.26 / dry ton delivered to the pretreatment reactor throat (2016$)
-> "Acids" pathway - $2.50 / GGE = $112/ dry ton
-> $40.74/ dry ton after reactor throat
-> "BDO" pathway - $2.50 / GGE = $108/ dry ton
-> $36.74/ dry ton after reactor throat

"Acids" pathway -> with $71.26 / dry ton delivered
and fuel yield = 44.8 GGE/dry ton for corn stover
and final adipic acid coproduct yield = 229 lb/dry ton
sodium sulfate byproduct sale price $0.07/ lb
-> Fuel selling price $2.49 / GGE

"BDO" pathway -> with $71.26 / dry ton delivered
and fuel yield = 43.2 GGE/dry ton for corn stover
(assumption is that sw will perform similarly)
and final adipic acid coproduct yield = 235 lb/dry ton
sodium sulfate byproduct sale price $0.07/ lb
-> Fuel selling price $2.47 / GGE



NREL 2018 Biochemical Design Case

NEAR-TERM GOAL:

$3 / GGE by 2022
where $79.07 / dry ton delivered to the pretreatment reactor throat (2016$)
-> "Acids" pathway - $3 / GGE = $134.4/ dry ton
-> $63.14/ dry ton after reactor throat
-> "BDO" pathway - $3 / GGE = $129.6/ dry ton
-> $58.34/ dry ton after reactor throat

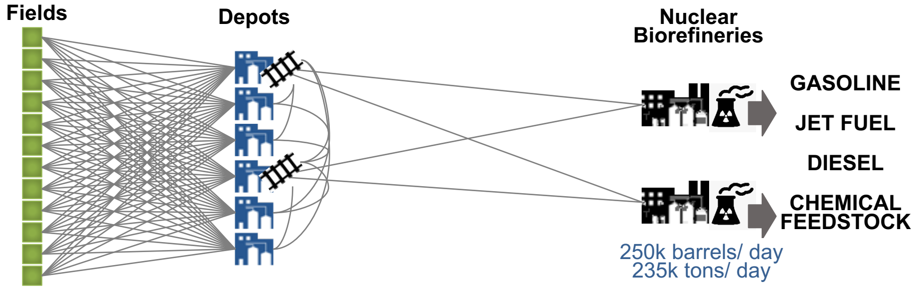
"Acids" pathway -> with $79.07 / dry ton delivered
and fuel yield = 44.8 GGE/dry ton
and final adipic acid coproduct yield = 259 lb/dry ton
sodium sulfate byproduct sale price $0.07/ lb
-> Fuel selling price $2.49 / GGE

"BDO" pathway -> with $79.07 / dry ton delivered
and fuel yield = 43.2 GGE/dry ton
and final adipic acid coproduct yield = 266 lb/dry ton
sodium sulfate byproduct sale price $0.07/ lb
-> Fuel selling price $2.47 / GGE

DEPOT CONFIGURATIONS DRIVEN BY FEEDSTOCK QUALITY

- Moisture
  - ≤ 30% (dry) → Ash
    - ≤ 10% → Lignin
      - ≤ 15% Pellet Depot or Anaerobic Digestion Depot
      - >15% Pellet Depot or Pyrolysis Depot
    - >10% → Lignin
      - ≤ 15% Pellet Depot Anaerobic Digestion Depot
      - >15% Pellet Depot
  - >30% (wet) → Ash
    - ≤ 10% → Lignin
      - ≤ 15% Anaerobic Digestion Depot
      - >15% Hydrothermal Liquefaction
    - >10% → Lignin
      - ≤ 15% Anaerobic Digestion Depot
      - >15% Hydrothermal Liquefaction

Carbon Mobilization



Fields

Depots

Nuclear Biorefineries

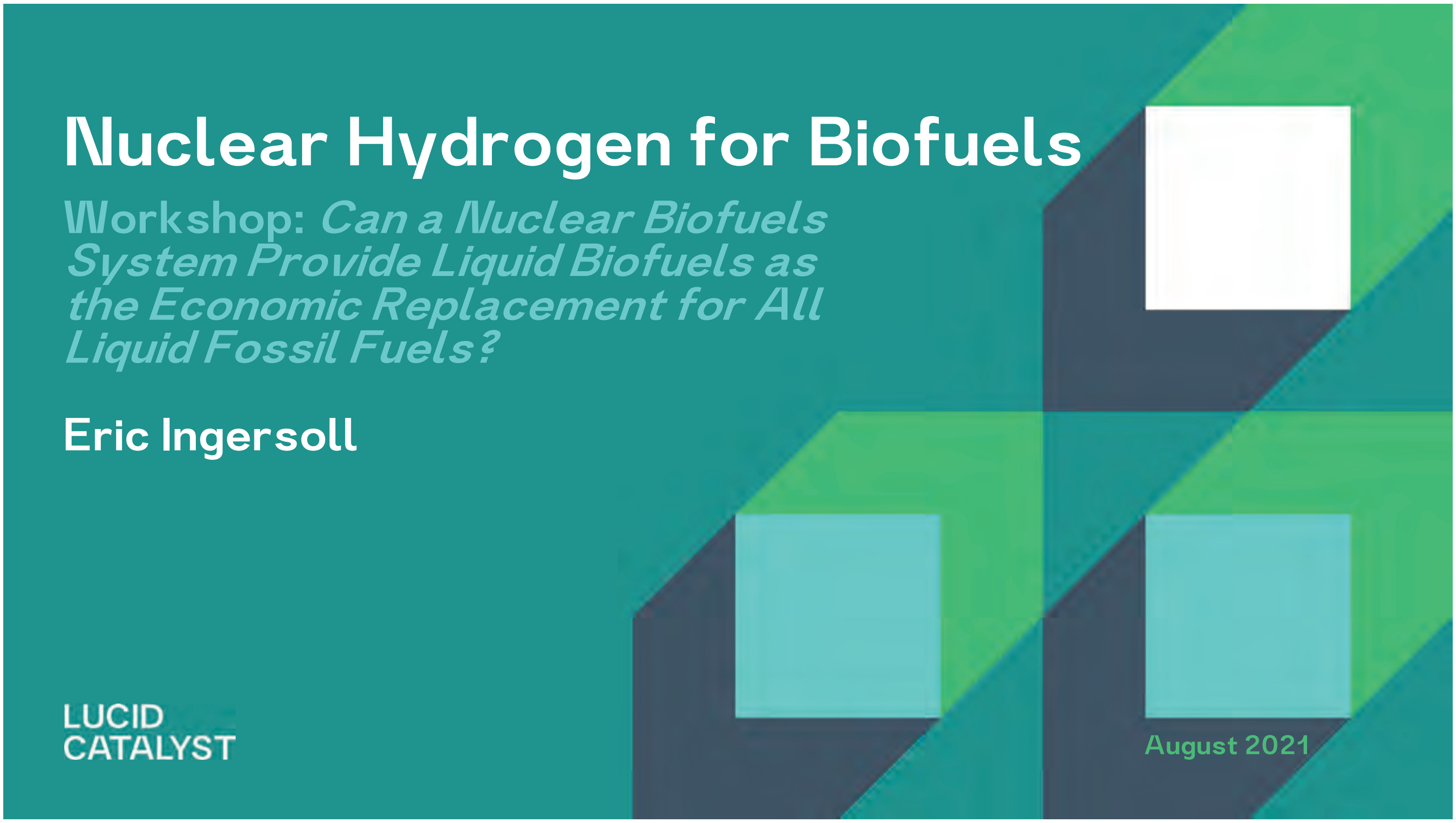
GASOLINE

JET FUEL

DIESEL

CHEMICAL FEEDSTOCK

250k barrels/ day
235k tons/ day



Nuclear Hydrogen for Biofuels

Workshop: *Can a Nuclear Biofuels System Provide Liquid Biofuels as the Economic Replacement for All Liquid Fossil Fuels?*

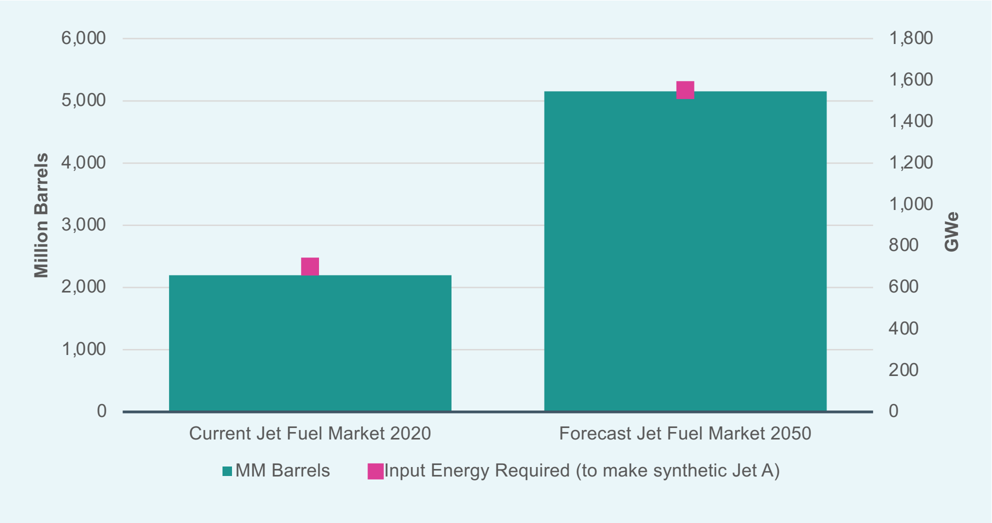
Eric Ingersoll

LUCID
CATALYST

August 2021

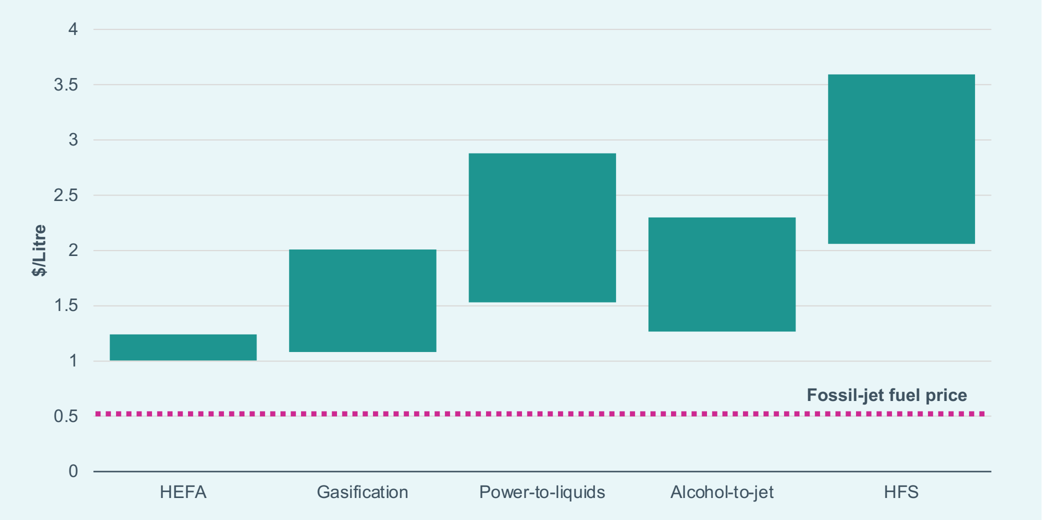
Growth in demand for Jet Fuel

Current and forecast market for Jet Fuel



Sustainable Aviation Fuels

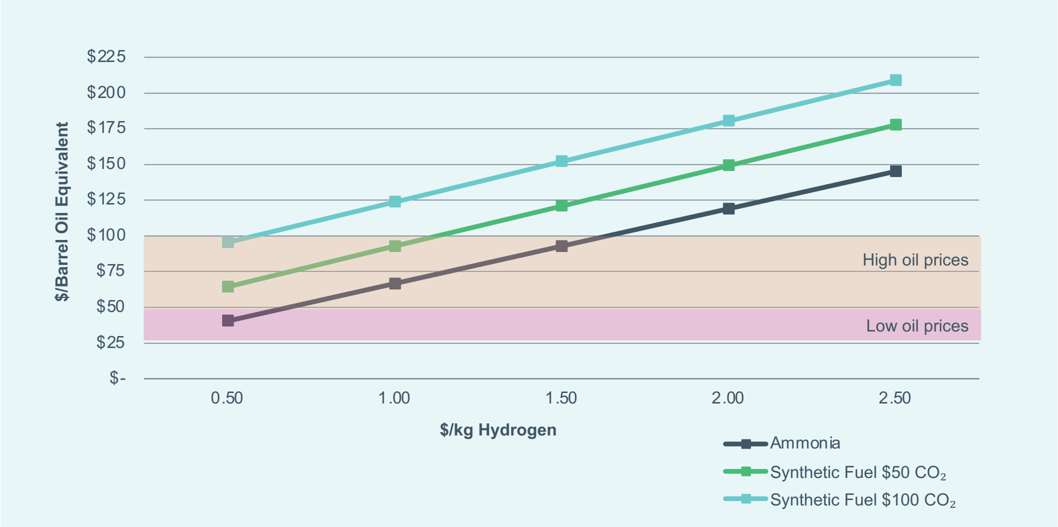
Sustainable aviation fuels production cost comparison



LucidCataly: Nuclear Hydrogen for Biofuels

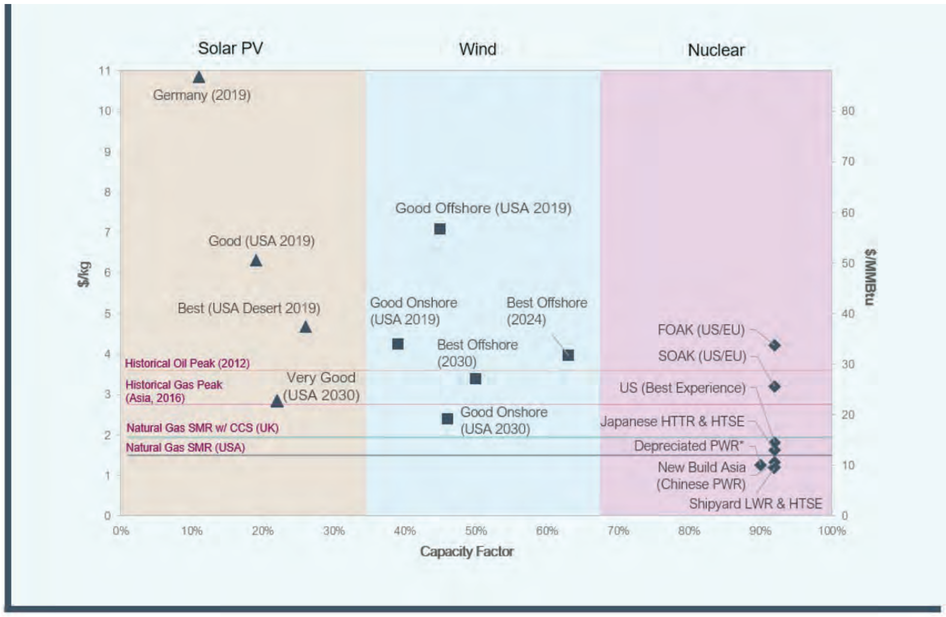
Oil Prices and the Hydrogen Economy

Oil price ‘guardrails’ of the hydrogen economy



LucidCataly: Nuclear Hydrogen for Biofuels

Hydrogen production costs

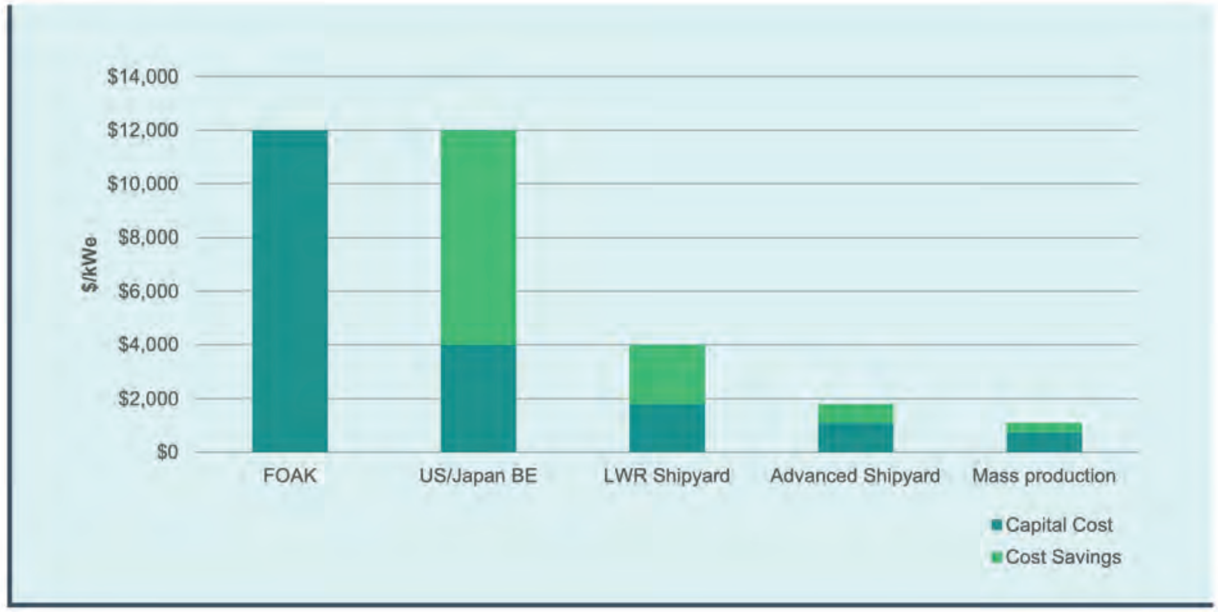


LucidCataly: Nuclear Hydrogen for Biofuels

Hydrogen/Synfuels Gigafactory

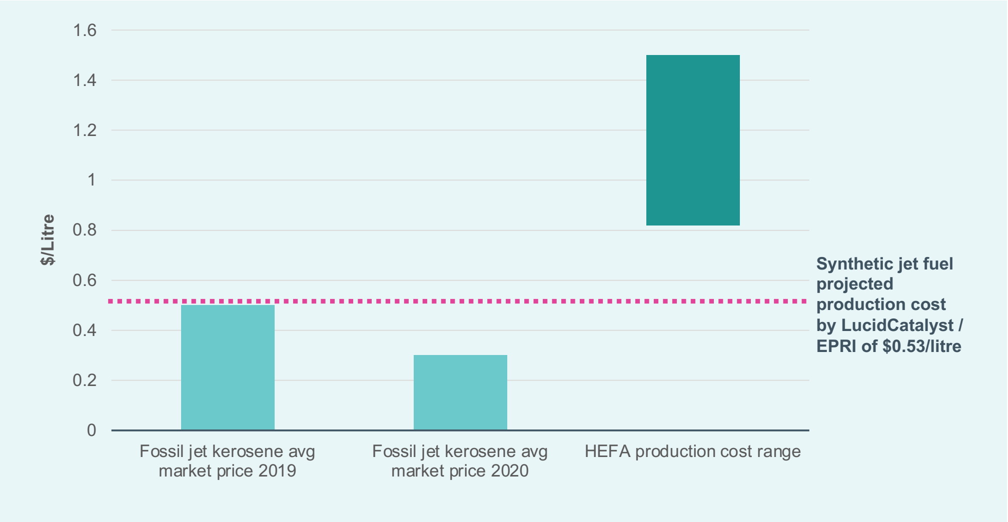
LucidCataly: Nuclear Hydrogen for Biofuels

Evolution of cost reduction from first-of-a-kind construction projects to mass manufactured products



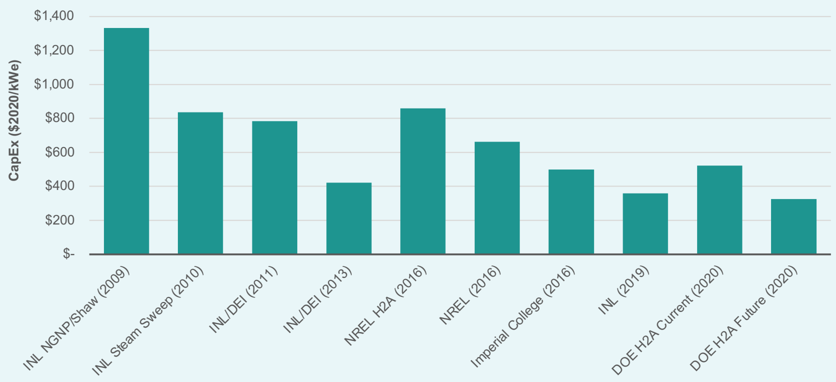
Costs of jet fuel

Current and forecast costs for Jet Fuel



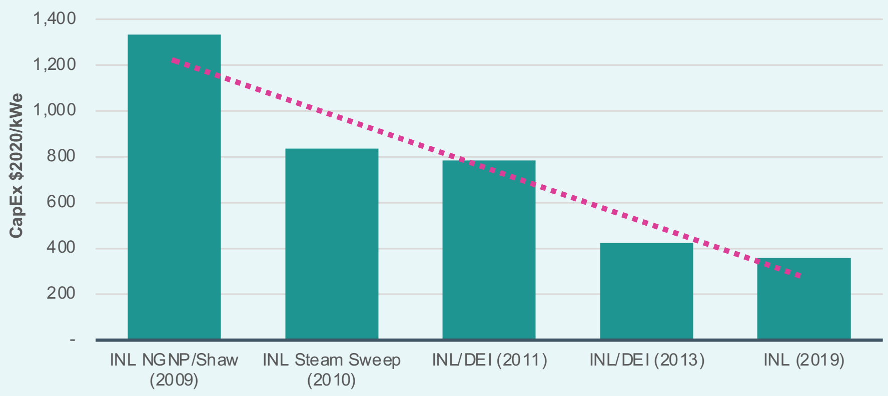
Recent review of HTSE cost studies

Projected capital cost of HTSE coupled to high temperature heat



Capital cost of 250MW class HTSE coupled to nuclear plant

Clear downward trend in projected costs as the refinement of the designs improves



Further integration opportunities

- Generate steam for electrolyzer (increase electrical output ~4%)
- Co-electrolysis of CO2 and H2O (with process CO2)
- Tighter thermal integration in biomass processing
- Dual use of cooling towers for ACR (with co-production of hydrogen)
    - ~300,000 tonnes CO2/GWt through the cooling tower
- Backup power supply to grid in periods of very low RE output

---

Conclusions

- Recent studies indicate Nuclear + CO2 to fuels can get into the range of today’s fossil fuel liquids
- Radically improved deployment model required to achieve cost targets
    - These are demonstrated based on best practices in other industries
- Use of these systems with low-cost biofuel inputs will further lower product costs
- Reducing required land footprint will be critical
- Nuclear enhances the scalability of the approach

References

LucidCatalyst & EPRI (Forthcoming).

Bloomberg NEF, Sustainable Aviation Fuels: The Outlook," p. 6, June 17, 2021.

LucidCatalyst (2020); Dominion Engineering. “HTSE Plant Cost Model for the INL HTSE Optimization Study. R6928-00-01, Revision 1,” 2013; and Idaho National Laboratories (2010), “Nuclear-Integrated Ammonia Production Analysis. Technical Evaluation Study. Project No. 23843. Document ID: TEV-666. Revision 2,” 2010.

LucidCatalyst (2020), “Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals,” September 2020.

INL/Shaw (2007), “Next Generation Nuclear Plant: Pre- Conceptual Design Report”; INL (2009), “High-Temperature Electrolysis for Large-Scale Hydrogen and Syngas Production from Nuclear Energy-System Simulation and Economics International Conference on Hydrogen Production”; INL (2010). “Hydrogen Production via HTSE, Sensitivity to HTGR Reactor Outlet Temperature, Economic Analysis”; Dominion Engineering (2013). “HTSE Plant Cost Model for the INL HTSE Optimization Study”; INL (2019), “Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest”; NREL/DOE (2016), “Hydrogen Production Cost from Solid Oxide Electrolysis”;

NREL (2017), “The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen”; Imperial College (2017), “Future cost and performance of water electrolysis: An expert elicitation study”; NREL (2019), “Emerging manufacturing technologies for fuel cells and electrolyzers”; DOE (2020), “H2A: Hydrogen Analysis Production Models”.

LucidCatalyst delivers strategic thought leadership to enable rapid decarbonization and prosperity for all.

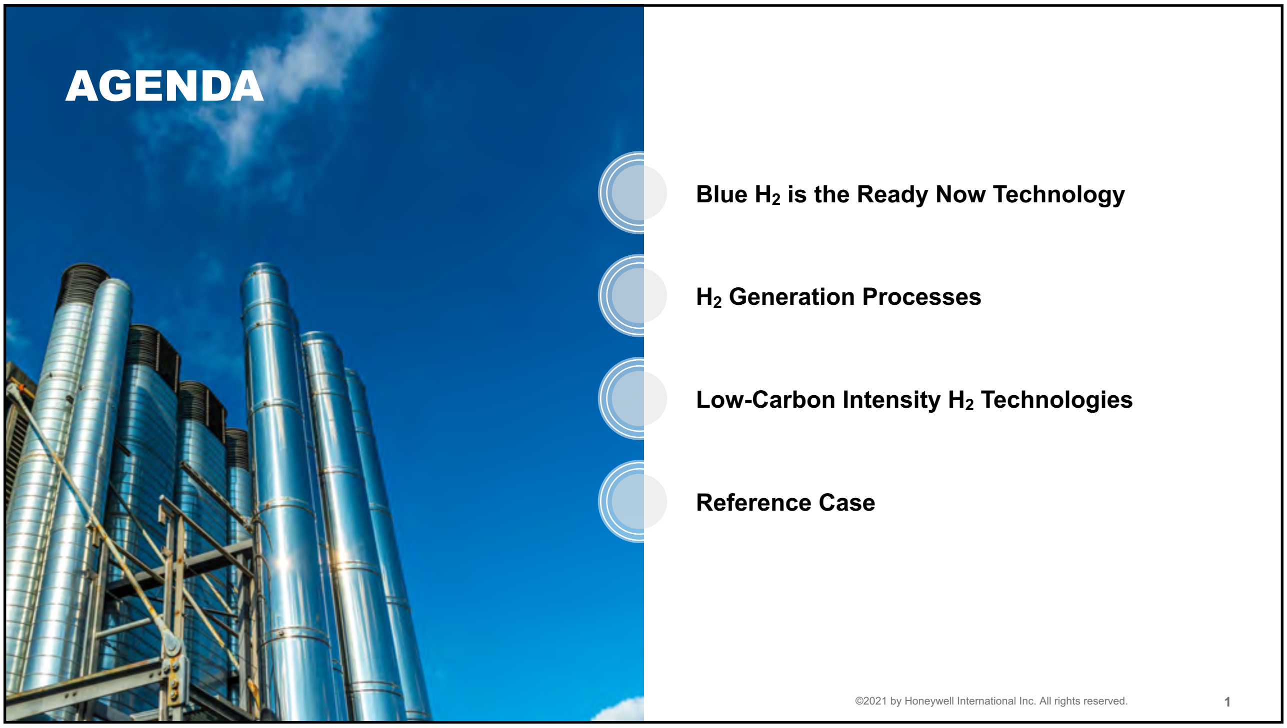
LUCID
CATALYST

lucidcatalyst.com

LOW-CARBON INTENSITY H_2 PRODUCTION

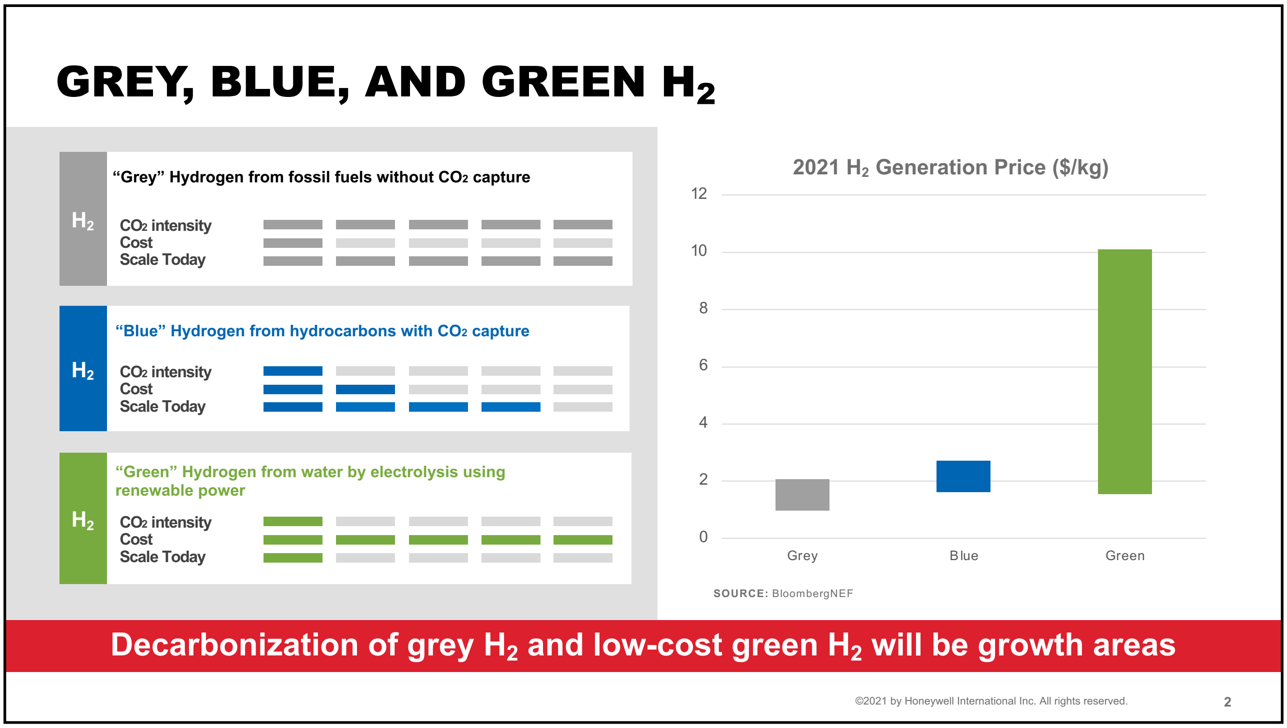
Powering the CO_2 Countdown

ADDISON CRUZ
ADVANCED R&D ENGINEER, BLUE H2 DEVELOPMENT, HONEYWELL UOP



AGENDA

- Blue H_2 is the Ready Now Technology
- H_2 Generation Processes
- Low-Carbon Intensity H_2 Technologies
- Reference Case



GREY, BLUE, AND GREEN H_2

H_2 **"Grey" Hydrogen from fossil fuels without CO_2 capture**

CO_2 intensity	■	■	■	■	■
Cost	■	□	□	□	□
Scale Today	■	■	■	■	■

H_2 **"Blue" Hydrogen from hydrocarbons with CO_2 capture**

CO_2 intensity	■	□	□	□	□
Cost	■	■	□	□	□
Scale Today	■	■	■	■	□

H_2 **"Green" Hydrogen from water by electrolysis using renewable power**

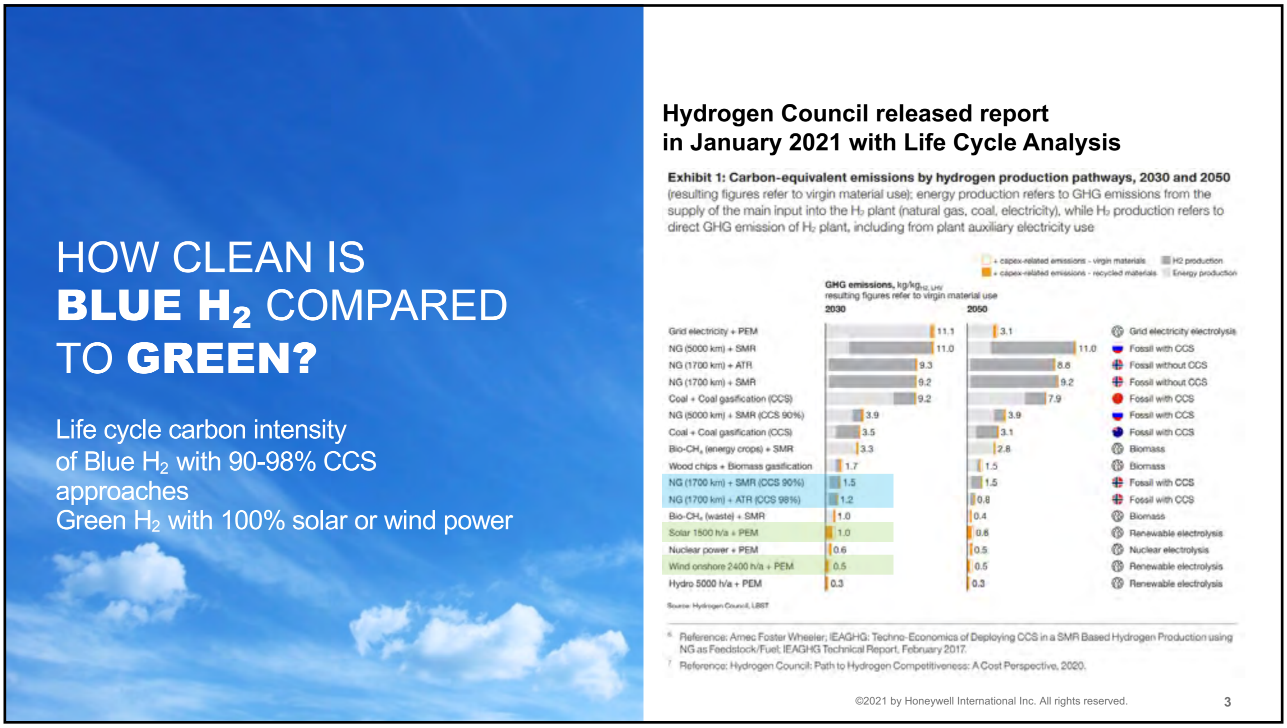
CO_2 intensity	■	□	□	□	□
Cost	■	■	■	■	■
Scale Today	■	□	□	□	□

2021 H_2 Generation Price ($/kg)

SOURCE: BloombergNEF

Decarbonization of grey H_2 and low-cost green H_2 will be growth areas

---



HOW CLEAN IS **BLUE H_2** COMPARED TO **GREEN?**

Life cycle carbon intensity of Blue H_2 with 90-98% CCS approaches Green H_2 with 100% solar or wind power

Hydrogen Council released report in January 2021 with Life Cycle Analysis

Exhibit 1: Carbon-equivalent emissions by hydrogen production pathways, 2030 and 2050 (resulting figures refer to virgin material use); energy production refers to GHG emissions from the supply of the main input into the H_2 plant (natural gas, coal, electricity), while H_2 production refers to direct GHG emission of H_2 plant, including from plant auxiliary electricity use

GHG emissions, $kg/kg_{H2, LHV}$ resulting figures refer to virgin material use

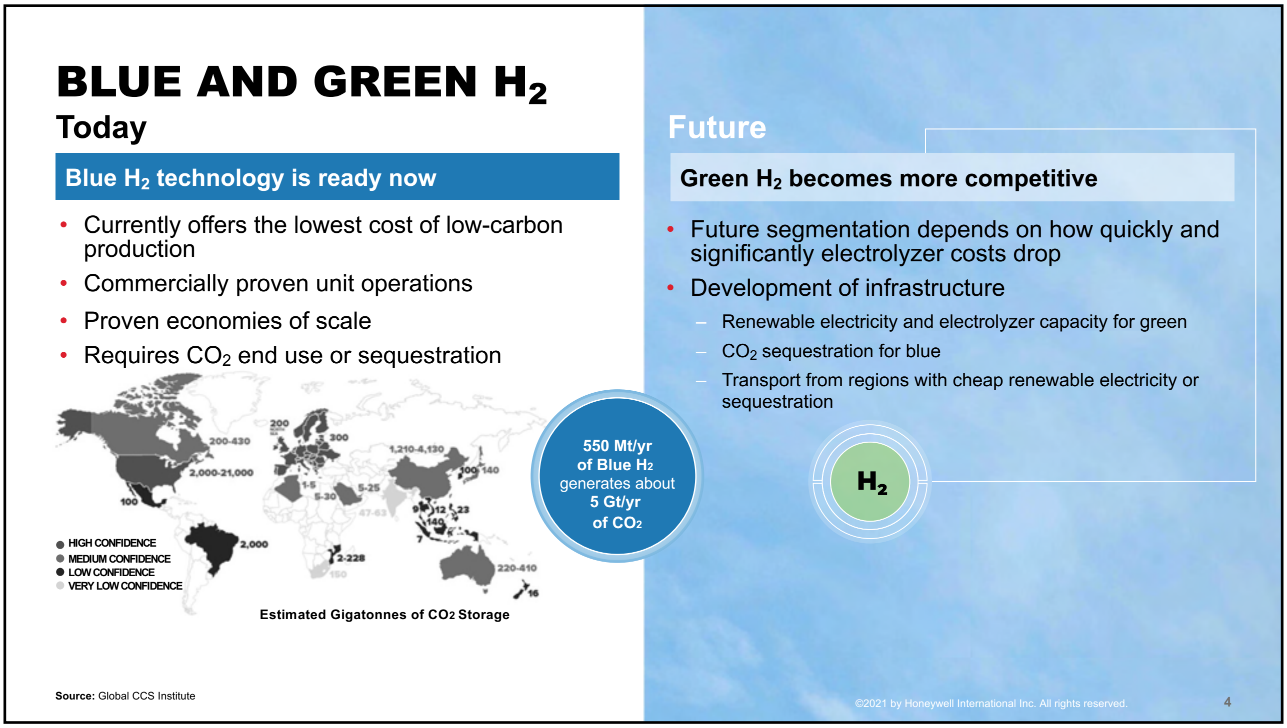
	2030	2050	
Grid electricity + PEM	11.1	3.1	Grid electricity electrolysis
NG (5000 km) + SMR	11.0	11.0	Fossil with CCS
NG (1700 km) + ATR	9.3	8.8	Fossil without CCS
NG (1700 km) + SMR	9.2	9.2	Fossil without CCS
Coal + Coal gasification (CCS)	9.2	7.9	Fossil with CCS
NG (5000 km) + SMR (CCS 90%)	3.9	3.9	Fossil with CCS
Coal + Coal gasification (CCS)	3.5	3.1	Fossil with CCS
Bio-CH_4 (energy crops) + SMR	3.3	2.8	Biomass
Wood chips + Biomass gasification	1.7	1.5	Biomass
NG (1700 km) + SMR (CCS 90%)	1.5	1.5	Fossil with CCS
NG (1700 km) + ATR (CCS 98%)	1.2	0.8	Fossil with CCS
Bio-CH_4 (waste) + SMR	1.0	0.4	Biomass
Solar 1500 h/a + PEM	1.0	0.8	Renewable electrolysis
Nuclear power + PEM	0.6	0.5	Nuclear electrolysis
Wind onshore 2400 h/a + PEM	0.5	0.5	Renewable electrolysis
Hydro 5000 h/a + PEM	0.3	0.3	Renewable electrolysis

Source: Hydrogen Council, LBST

---

[6] Reference: Amec Foster Wheeler; IEAGHG: Techno-Economics of Deploying CCS in a SMR Based Hydrogen Production using NG as Feedstock/Fuel; IEAGHG Technical Report, February 2017.

[7] Reference: Hydrogen Council: Path to Hydrogen Competitiveness: A Cost Perspective, 2020.



BLUE AND GREEN H_2

Today

Blue H_2 technology is ready now

- Currently offers the lowest cost of low-carbon production
- Commercially proven unit operations
- Proven economies of scale
- Requires CO_2 end use or sequestration

Estimated Gigatonnes of CO_2 Storage

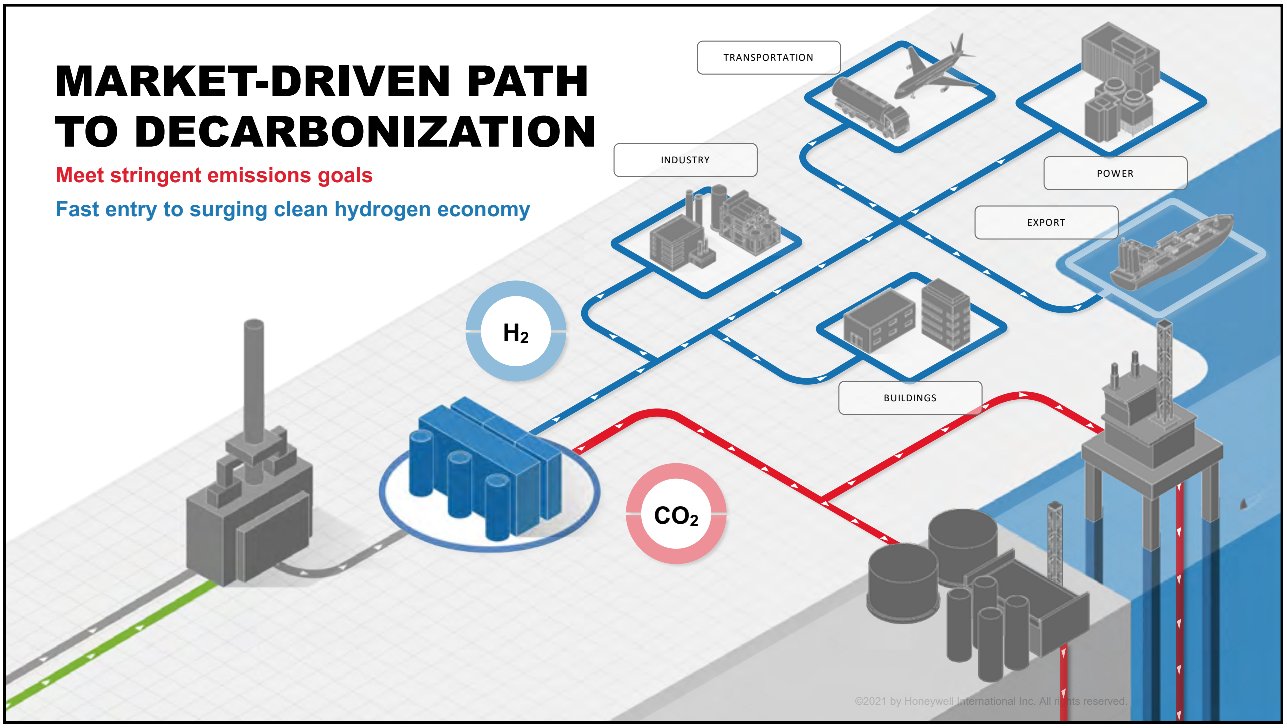
Source: Global CCS Institute

550 Mt/yr
of Blue H_2
generates about
5 Gt/yr
of CO_2

Future

Green H_2 becomes more competitive

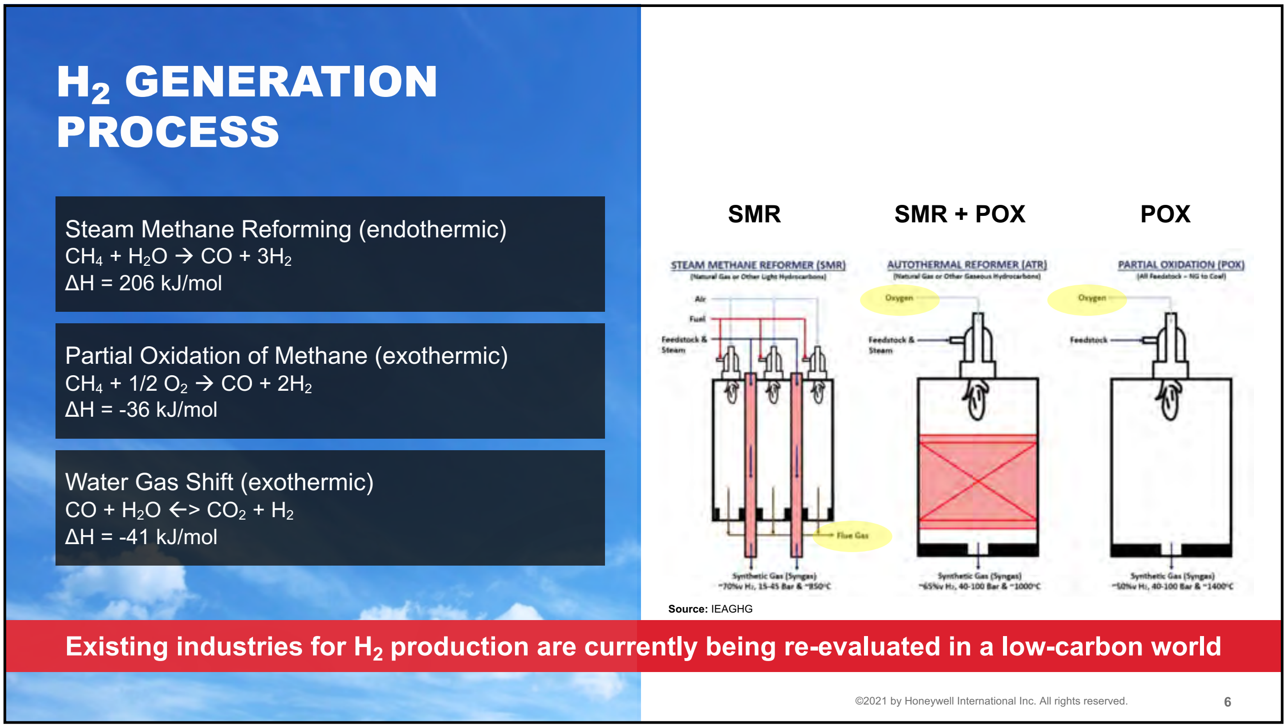
- Future segmentation depends on how quickly and significantly electrolyzer costs drop
- Development of infrastructure
  - Renewable electricity and electrolyzer capacity for green
  - CO_2 sequestration for blue
  - Transport from regions with cheap renewable electricity or sequestration



MARKET-DRIVEN PATH TO DECARBONIZATION

Meet stringent emissions goals

Fast entry to surging clean hydrogen economy



H$_2$ GENERATION PROCESS

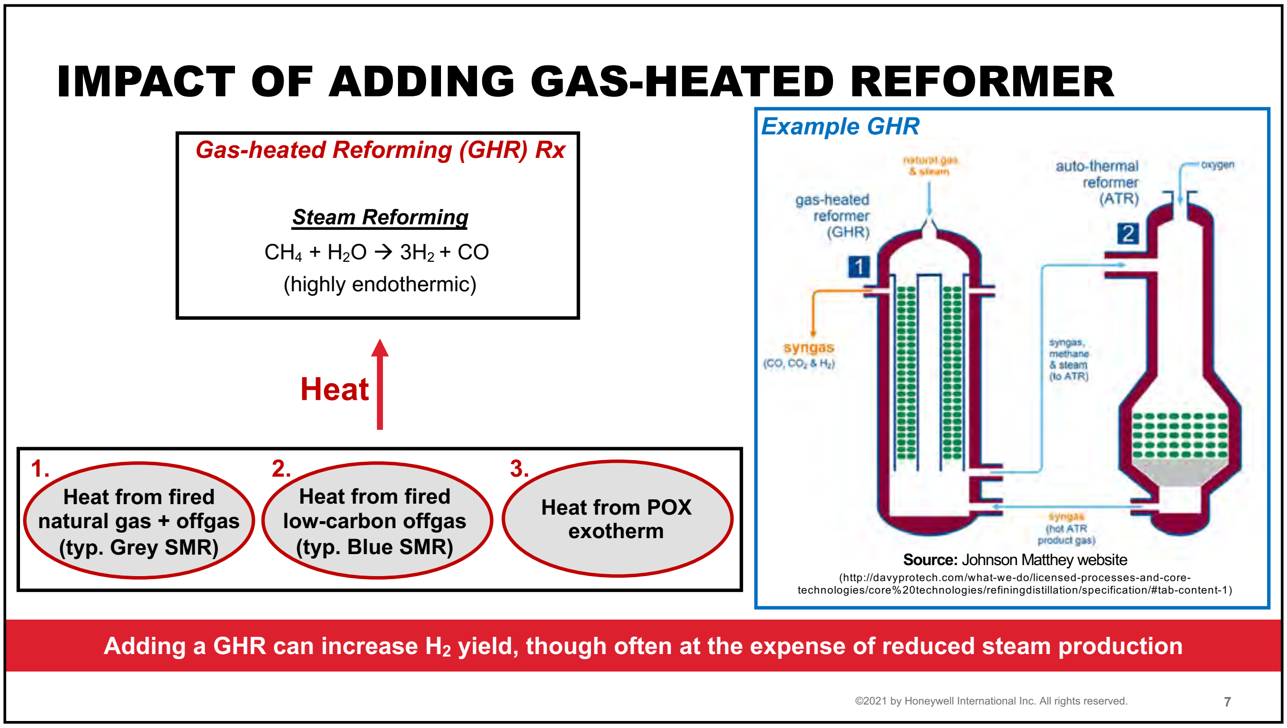
Steam Methane Reforming (endothermic)
$CH_4 + H_2O \rightarrow CO + 3H_2$
$\Delta H = 206$ kJ/mol

Partial Oxidation of Methane (exothermic)
$CH_4 + 1/2\ O_2 \rightarrow CO + 2H_2$
$\Delta H = -36$ kJ/mol

Water Gas Shift (exothermic)
$CO + H_2O \leftrightarrow CO_2 + H_2$
$\Delta H = -41$ kJ/mol

Source: IEAGHG

Existing industries for H$_2$ production are currently being re-evaluated in a low-carbon world



IMPACT OF ADDING GAS-HEATED REFORMER

Gas-heated Reforming (GHR) Rx

Steam Reforming

$CH_4 + H_2O \rightarrow 3H_2 + CO$
(highly endothermic)

Heat

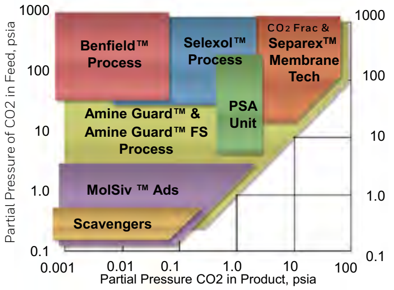
1. Heat from fired natural gas + offgas (typ. Grey SMR)
2. Heat from fired low-carbon offgas (typ. Blue SMR)
3. Heat from POX exotherm

Example GHR

Source: Johnson Matthey website
(http://davyprotech.com/what-we-do/licensed-processes-and-core-technologies/core%20technologies/refiningdistillation/specification/#tab-content-1)

Adding a GHR can increase H$_2$ yield, though often at the expense of reduced steam production

COMMERCIALIZED UOP CO_2 SEPARATIONS TECHNOLOGIES



Chemical Solvents

- **Amine Guard™ & Amine Guard FS Process**
  UOP is largest licensor of high concentration MEA-based systems; formulated solvents have lower Opex vs. MEA (> 600 units)
- **Benfield™**
  Totally inorganic solvent for pressurized flue gas & industrial processes (> 650 units)
- **Advanced Solvent for Carbon Capture**
  Direct CO_2 capture from flue gas for refining, power, steel, cement, and natural gas industries (seeking first commercial application)

Physical Solvents

- **SeparALL™ Process**
  H_2S/CO_2 selectivity using Selexol solvent for sources containing sulfur or in oxidative conditions (>50 units)

Note: Solvent processes can be used in hybrid cycles with other technologies like PSA, membranes, and cryogenics to optimize CO_2 capture

Adsorbents

- **Polybed™ Pressure Swing Adsorption (PSA) System**
  Optimized adsorbents and cycles for CO_2 rejection (>1000 units, 3 operating in CO_2 application)

Cryogenics & Membranes

For capture of CO_2 at higher partial pressure

- **Separex™ Membrane Systems**
  Significant experience in Petrobras Presalt capturing & sequestering CO_2 (>300 units)
- **Ortloff CO_2 Fractionation**
  Not only captures but also provides CO_2 as a high purity liquid product (2 operating units)

UOP is leveraging existing technologies and expertise to deliver differentiation in this new Blue H_2 market

Existing, Proven Commercialized Technologies can be utilized for CO_2 Capture @ Blue H_2 Plants

---

REFERENCE – CARBON CAPTURE AND SEQUESTRATION

Project Overview

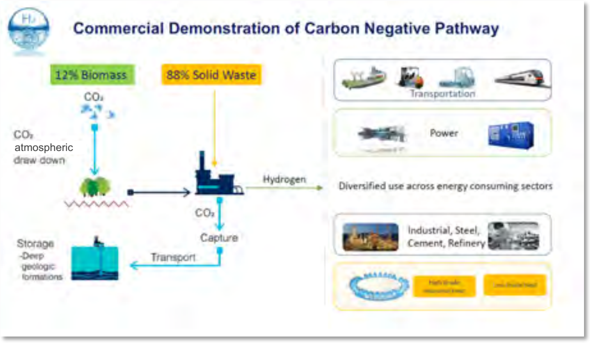
UOP selected as technology provider for carbon capture and H_2 purification for clean H_2 production from gasifier at Wabash Valley Resources in West Terra Haute, Indiana

Why it Matters

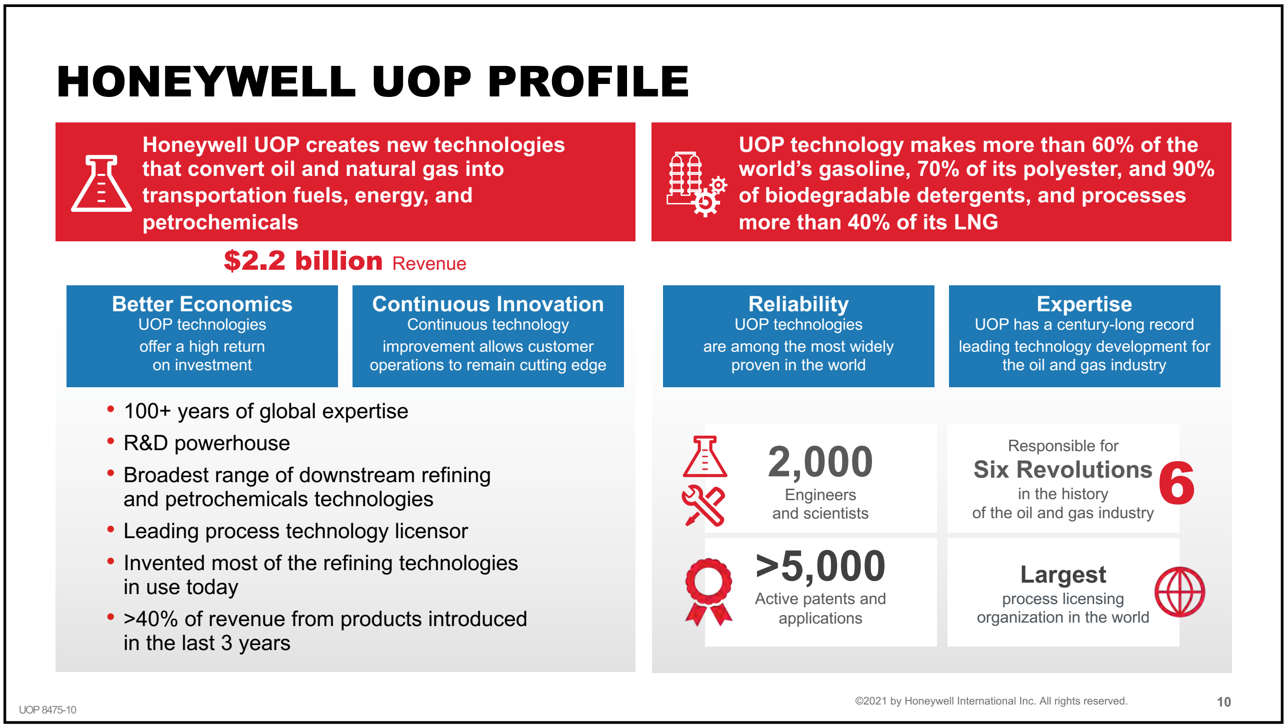
- One of the largest CCS projects (1.65 Mt/yr CO_2)
- Second US project to sequester CO_2 in permanent geologic storage (not EOR)
- Demonstrates large-scale, commercially viable CCS project under current regulatory and policy framework

Technology

Integration of Modular Molsiv, Modular Ortloff CO_2 Fractionation System, Modular PSA



UOP announced as CCS technology provider for large project in early April



HONEYWELL UOP PROFILE

Honeywell UOP creates new technologies that convert oil and natural gas into transportation fuels, energy, and petrochemicals

UOP technology makes more than 60% of the world's gasoline, 70% of its polyester, and 90% of biodegradable detergents, and processes more than 40% of its LNG

$2.2 billion Revenue

Better Economics
UOP technologies offer a high return on investment

Continuous Innovation
Continuous technology improvement allows customer operations to remain cutting edge

Reliability
UOP technologies are among the most widely proven in the world

Expertise
UOP has a century-long record leading technology development for the oil and gas industry

- 100+ years of global expertise
- R&D powerhouse
- Broadest range of downstream refining and petrochemicals technologies
- Leading process technology licensor
- Invented most of the refining technologies in use today
- >40% of revenue from products introduced in the last 3 years

2,000
Engineers and scientists

Responsible for
Six Revolutions **6**
in the history of the oil and gas industry

>5,000
Active patents and applications

Largest
process licensing organization in the world

UOP 8475-10

FOLLOW US

https://www.uop.com/

https://twitter.com/HoneywellUOP

https://www.youtube.com/user/Honeywell

https://www.linkedin.com/company/uop

https://www.accessuop.com/

UOP 8455-11

Vertimass

Transformative fungible biofuels.

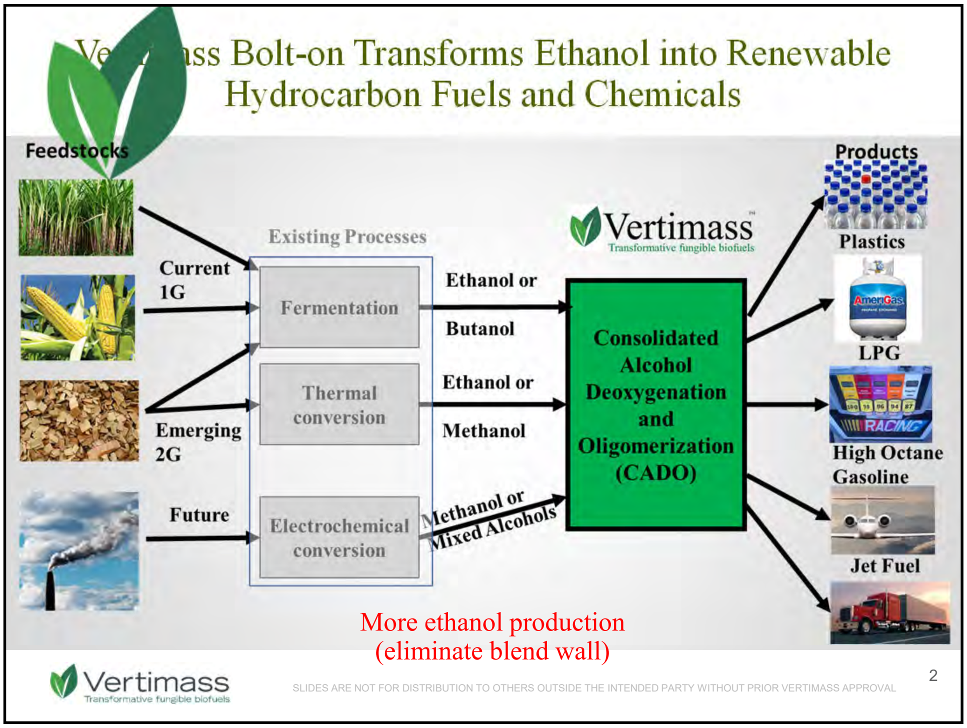
Low-cost, low-carbon, sustainable fuels now

Conversion of Biomass to Hydrocarbon Fuels and Chemicals

Nuclear Biofuels Webinar

John Hannon, PhD, Chief Operating Officer

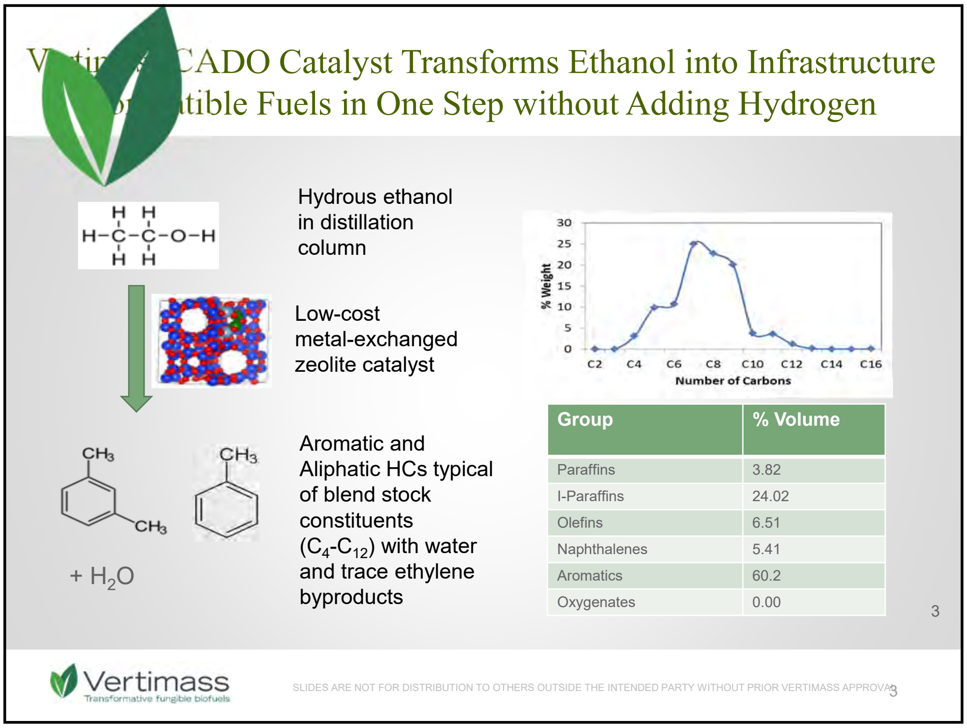
August 18, 2021



Ve ass Bolt-on Transforms Ethanol into Renewable Hydrocarbon Fuels and Chemicals

More ethanol production
(eliminate blend wall)

V tim CADO Catalyst Transforms Ethanol into Infrastructure Co atible Fuels in One Step without Adding Hydrogen



Hydrous ethanol in distillation column

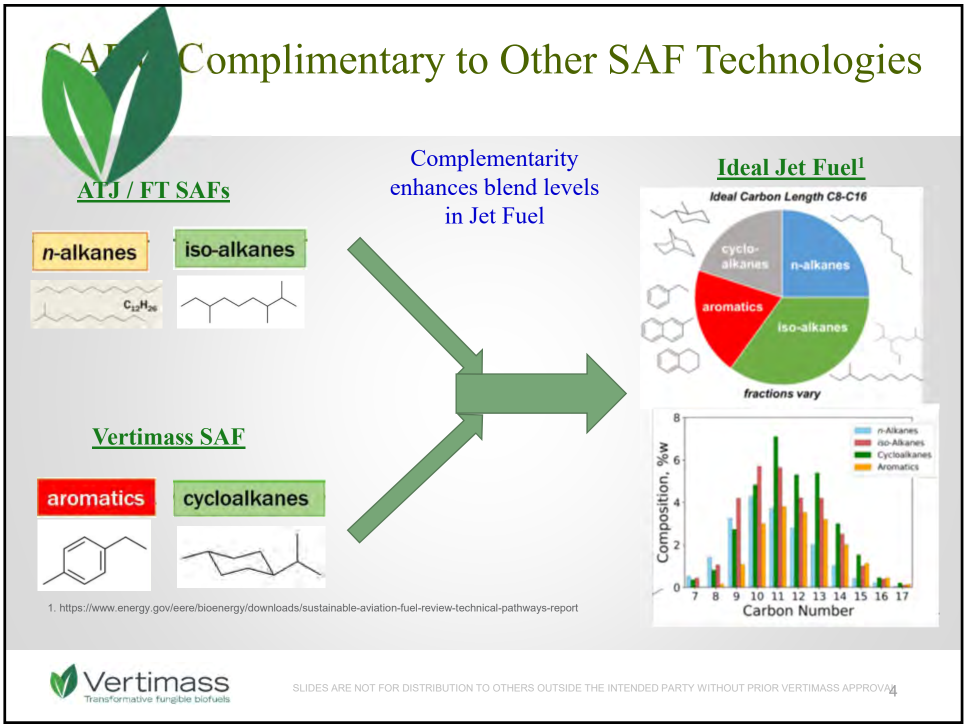
Low-cost metal-exchanged zeolite catalyst

Aromatic and Aliphatic HCs typical of blend stock constituents (C_4-C_{12}) with water and trace ethylene byproducts

Group	% Volume
Paraffins	3.82
I-Paraffins	24.02
Olefins	6.51
Naphthalenes	5.41
Aromatics	60.2
Oxygenates	0.00

Vertimass
Transformative fungible biofuels

CA Complimentary to Other SAF Technologies



ATJ / FT SAFs

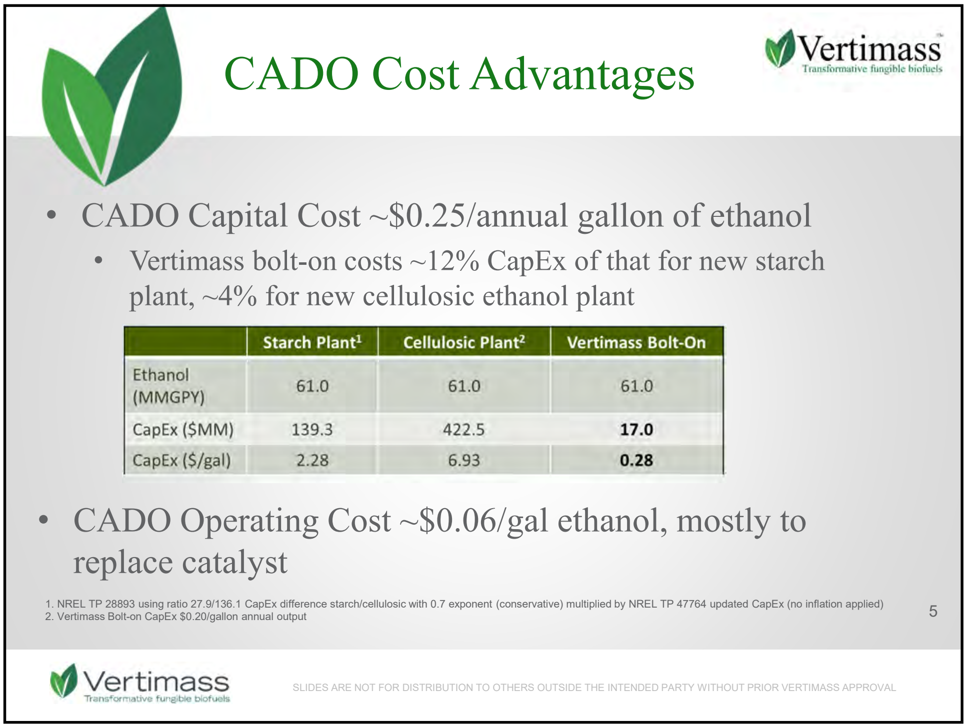
Complementarity enhances blend levels in Jet Fuel

Ideal Jet Fuel[1]

Vertimass SAF

1. https://www.energy.gov/eere/bioenergy/downloads/sustainable-aviation-fuel-review-technical-pathways-report

Vertimass
Transformative fungible biofuels



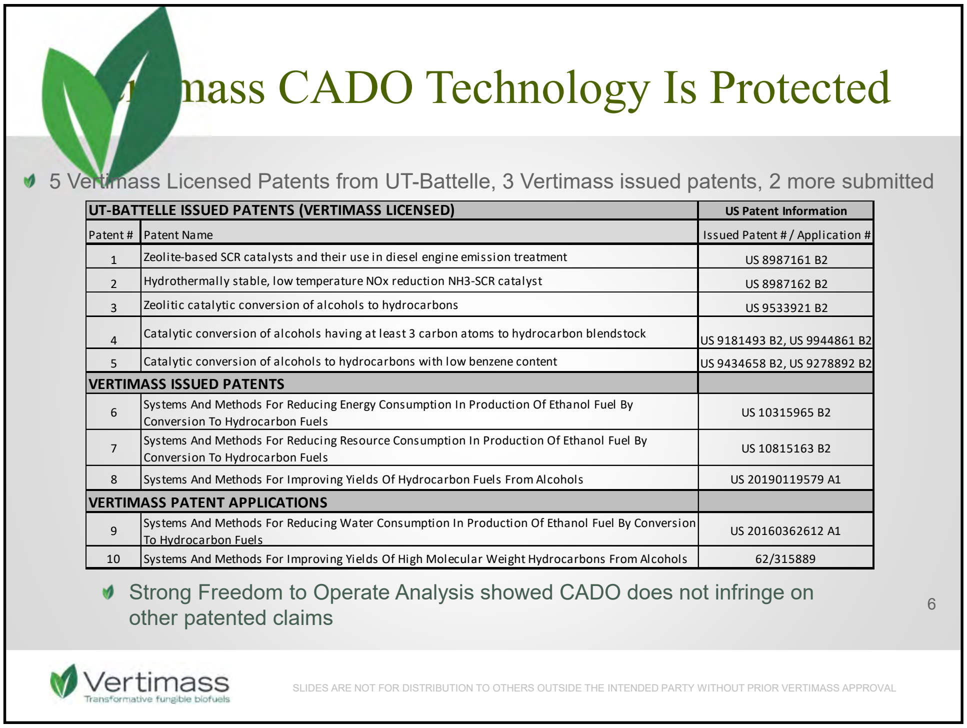
CADO Cost Advantages

- CADO Capital Cost ~$0.25/annual gallon of ethanol
  - Vertimass bolt-on costs ~12% CapEx of that for new starch plant, ~4% for new cellulosic ethanol plant

	Starch Plant[1]	Cellulosic Plant[2]	Vertimass Bolt-On
Ethanol (MMGPY)	61.0	61.0	61.0
CapEx ($MM)	139.3	422.5	**17.0**
CapEx ($/gal)	2.28	6.93	**0.28**

- CADO Operating Cost ~$0.06/gal ethanol, mostly to replace catalyst

1. NREL TP 28893 using ratio 27.9/136.1 CapEx difference starch/cellulosic with 0.7 exponent (conservative) multiplied by NREL TP 47764 updated CapEx (no inflation applied)
2. Vertimass Bolt-on CapEx $0.20/gallon annual output



mass CADO Technology Is Protected

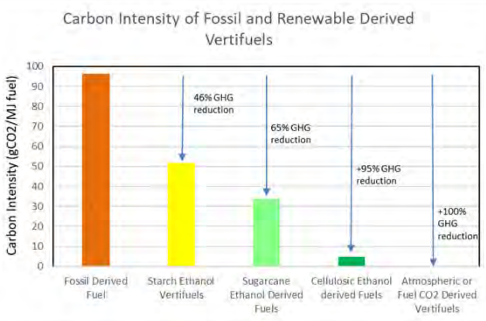
- 5 Vertimass Licensed Patents from UT-Battelle, 3 Vertimass issued patents, 2 more submitted

UT-BATTELLE ISSUED PATENTS (VERTIMASS LICENSED)		**US Patent Information**
Patent #	Patent Name	Issued Patent # / Application #
1	Zeolite-based SCR catalysts and their use in diesel engine emission treatment	US 8987161 B2
2	Hydrothermally stable, low temperature NOx reduction NH3-SCR catalyst	US 8987162 B2
3	Zeolitic catalytic conversion of alcohols to hydrocarbons	US 9533921 B2
4	Catalytic conversion of alcohols having at least 3 carbon atoms to hydrocarbon blendstock	US 9181493 B2, US 9944861 B2
5	Catalytic conversion of alcohols to hydrocarbons with low benzene content	US 9434658 B2, US 9278892 B2
VERTIMASS ISSUED PATENTS		
6	Systems And Methods For Reducing Energy Consumption In Production Of Ethanol Fuel By Conversion To Hydrocarbon Fuels	US 10315965 B2
7	Systems And Methods For Reducing Resource Consumption In Production Of Ethanol Fuel By Conversion To Hydrocarbon Fuels	US 10815163 B2
8	Systems And Methods For Improving Yields Of Hydrocarbon Fuels From Alcohols	US 20190119579 A1
VERTIMASS PATENT APPLICATIONS		
9	Systems And Methods For Reducing Water Consumption In Production Of Ethanol Fuel By Conversion To Hydrocarbon Fuels	US 20160362612 A1
10	Systems And Methods For Improving Yields Of High Molecular Weight Hydrocarbons From Alcohols	62/315889

- Strong Freedom to Operate Analysis showed CADO does not infringe on other patented claims

Ve ass CADO Passes on Ethanol Greenhouse Gas (GHG) Emission Reductions

Greenhouse Gas Reductions[1,2]	
Alcohol Feedstock	% GHG reductions
Starch	46%*
Sugarcane	65%
Cellulosic	>95%
Atmospheric & Flue Gas CO_2	100% ++

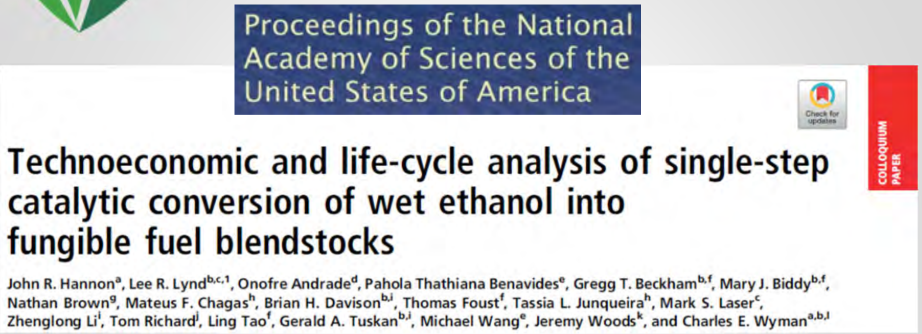

Carbon Intensity of Fossil and Renewable Derived Vertifuels

* Recent work with Life Cycle Associates shows ability to increase GHG emissions >50% for even corn ethanol with Vertimass technology **(BTEX coproduction)**

1. Renewable Fuels Association (RFA) http://ethanolrfa.org
2. Scully et al, 2021, https://iopscience.iop.org/article/10.1088/1748-9326/abde08

---

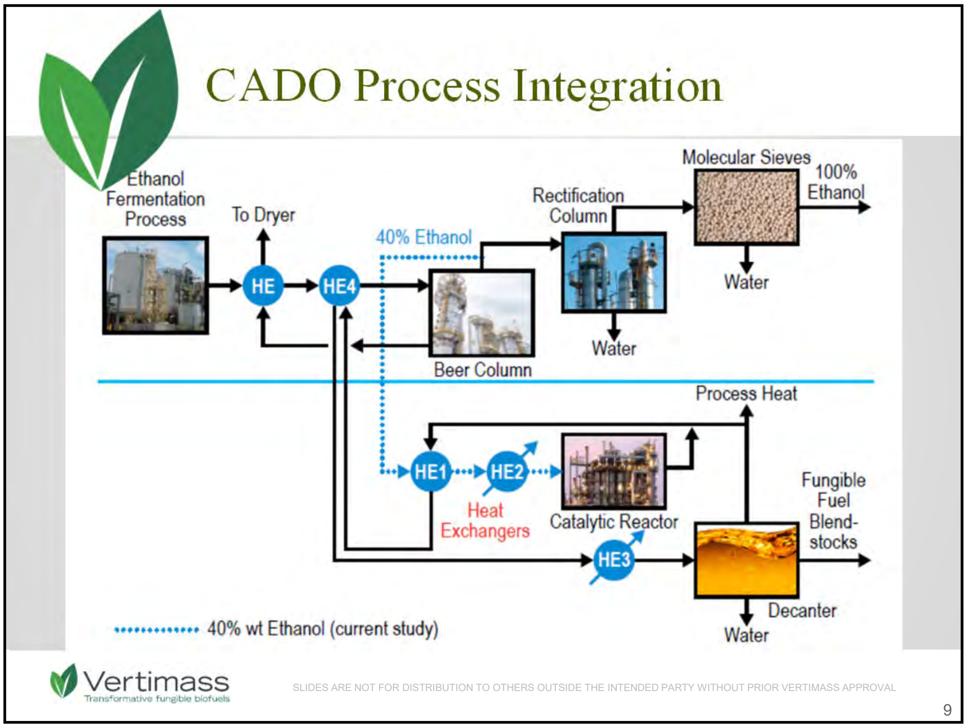
estigious PNAS Publication Validated CADO Technology Attributes


Proceedings of the National Academy of Sciences of the United States of America

Technoeconomic and life-cycle analysis of single-step catalytic conversion of wet ethanol into fungible fuel blendstocks

John R. Hannon[a], Lee R. Lynd[b,c,1], Onofre Andrade[d], Pahola Thathiana Benavides[e], Gregg T. Beckham[b,f], Mary J. Biddy[b,f], Nathan Brown[g], Mateus F. Chagas[h], Brian H. Davison[b,i], Thomas Foust[f], Tassia L. Junqueira[h], Mark S. Laser[c], Zhenglong Li[i], Tom Richard[j], Ling Tao[f], Gerald A. Tuskan[b,i], Michael Wang[e], Jeremy Woods[k], and Charles E. Wyman[a,b,l]

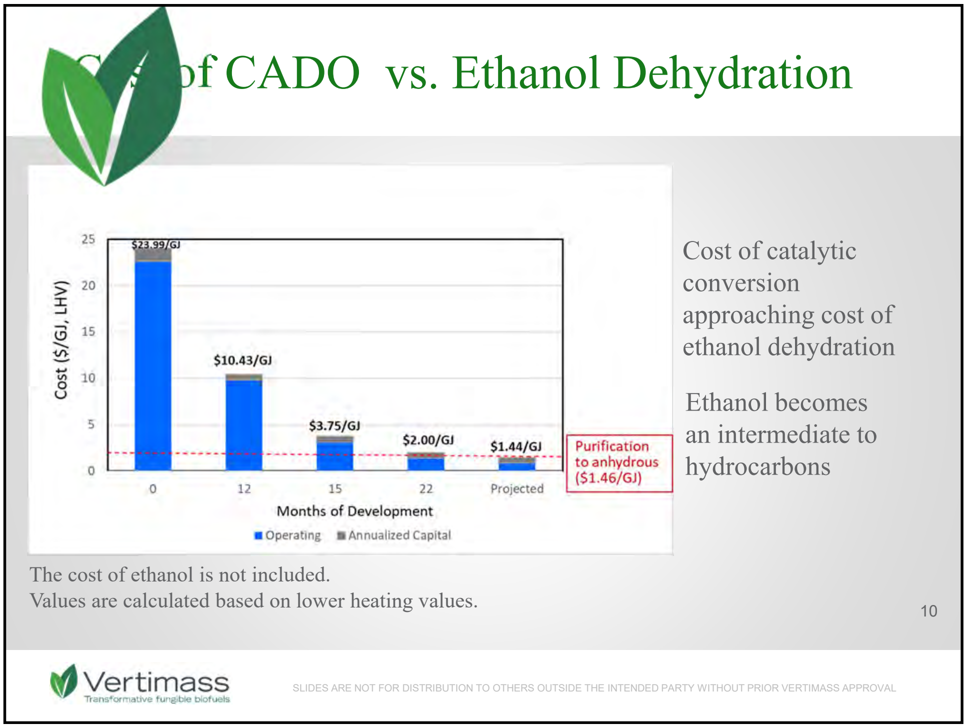
19 coauthors from 12 industrial, academic, and government institutions



CADO Process Integration

•••••••••••• 40% wt Ethanol (current study)

Vertimass
Transformative fungible biofuels



C s of CADO vs. Ethanol Dehydration

Cost of catalytic conversion approaching cost of ethanol dehydration

Ethanol becomes an intermediate to hydrocarbons

The cost of ethanol is not included.
Values are calculated based on lower heating values.

Vertimass
Transformative fungible biofuels

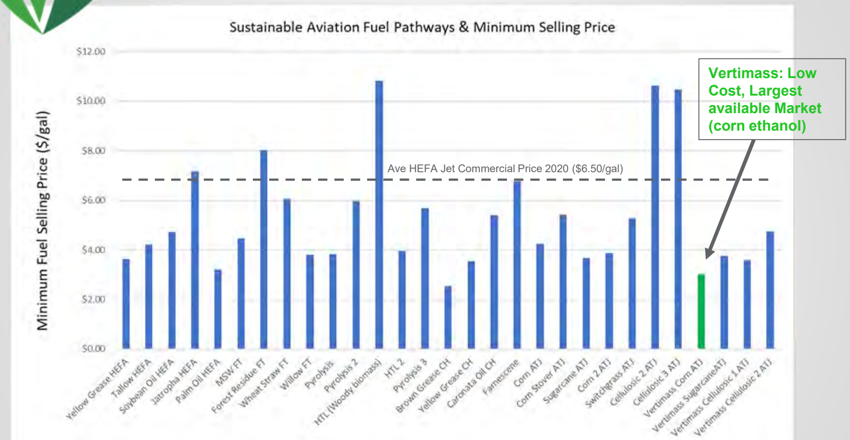
vious Awards and Validation

- First DOE Award ($2.0 mil) to produce green gasoline and BTEX from ethanol (including 3rd party technology investigations on technology)
- First winners of the National Corn Growers Association (Consider Corn Challenge)
- Second DOE Award ($1.4 mil) to accelerate commercialization – started this last month to focus on ethanol to jet fuel
- ChemCatBio Award to investigate catalyst with national laboratories
- Biofuels Digest ranked Vertimass number 18 of Top 40 Emerging Companies in Advanced BioEconomy (October 2017)

Vertimass
Transformative fungible biofuels

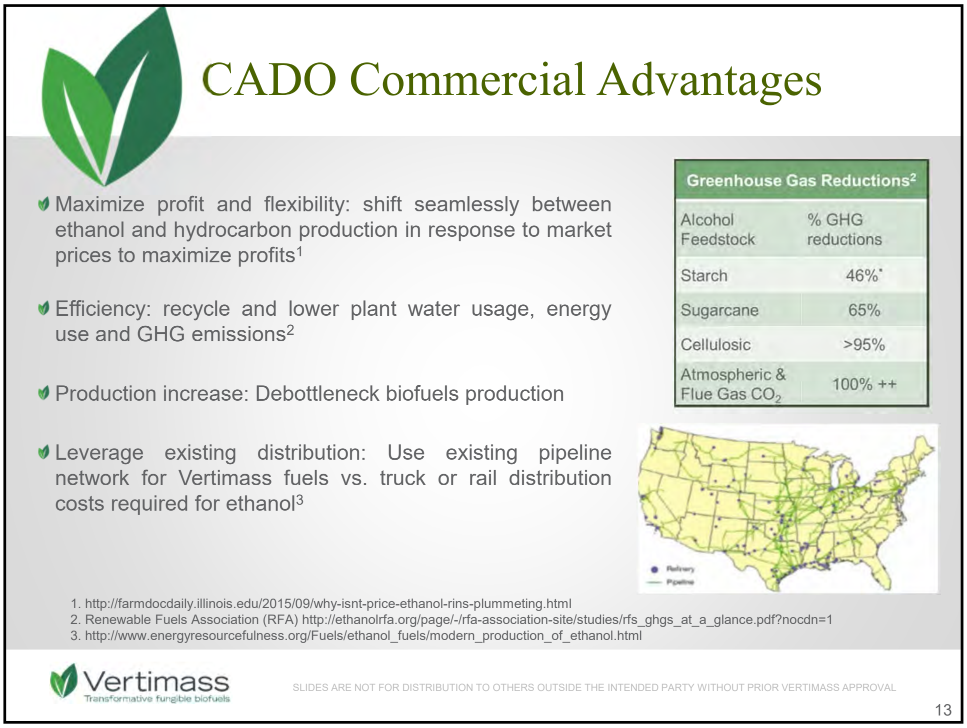
---

avorable CADO Cost for SAF [1,2]



1: IEA Report 2021, 2: Hannon et al PNAS 2019

Vertimass
Transformative fungible biofuels



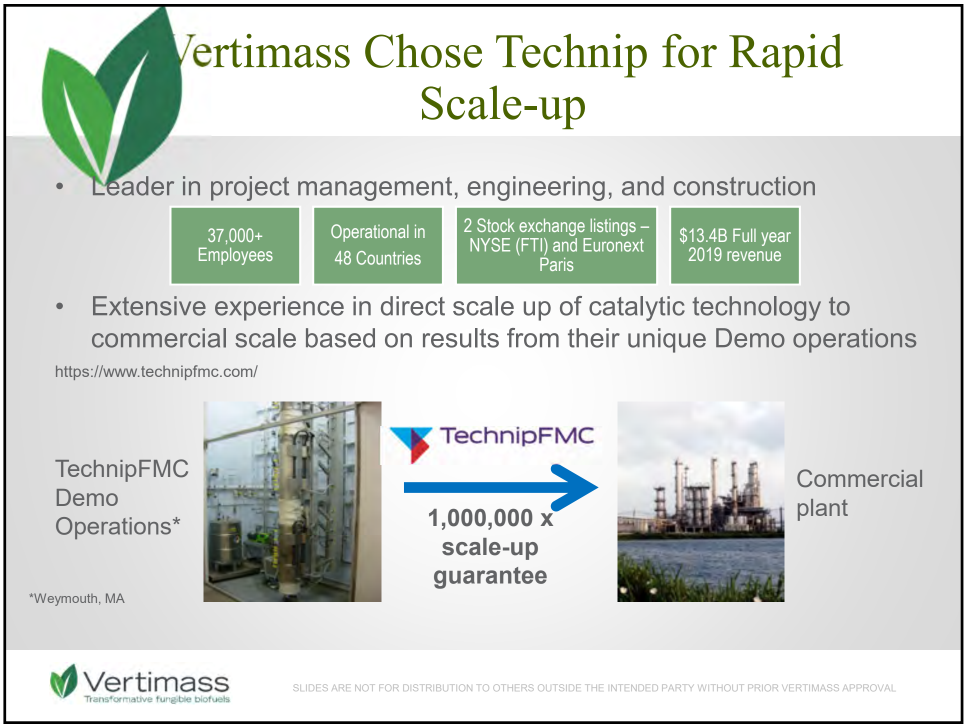
CADO Commercial Advantages

- Maximize profit and flexibility: shift seamlessly between ethanol and hydrocarbon production in response to market prices to maximize profits[1]
- Efficiency: recycle and lower plant water usage, energy use and GHG emissions[2]
- Production increase: Debottleneck biofuels production
- Leverage existing distribution: Use existing pipeline network for Vertimass fuels vs. truck or rail distribution costs required for ethanol[3]

Greenhouse Gas Reductions[2]

Alcohol Feedstock	% GHG reductions
Starch	46%*
Sugarcane	65%
Cellulosic	>95%
Atmospheric & Flue Gas CO_2	100% ++

1. http://farmdocdaily.illinois.edu/2015/09/why-isnt-price-ethanol-rins-plummeting.html
2. Renewable Fuels Association (RFA) http://ethanolrfa.org/page/-/rfa-association-site/studies/rfs_ghgs_at_a_glance.pdf?nocdn=1
3. http://www.energyresourcefulness.org/Fuels/ethanol_fuels/modern_production_of_ethanol.html



Vertimass Chose Technip for Rapid Scale-up

- Leader in project management, engineering, and construction

37,000+ Employees	Operational in 48 Countries	2 Stock exchange listings – NYSE (FTI) and Euronext Paris	$13.4B Full year 2019 revenue

- Extensive experience in direct scale up of catalytic technology to commercial scale based on results from their unique Demo operations

https://www.technipfmc.com/

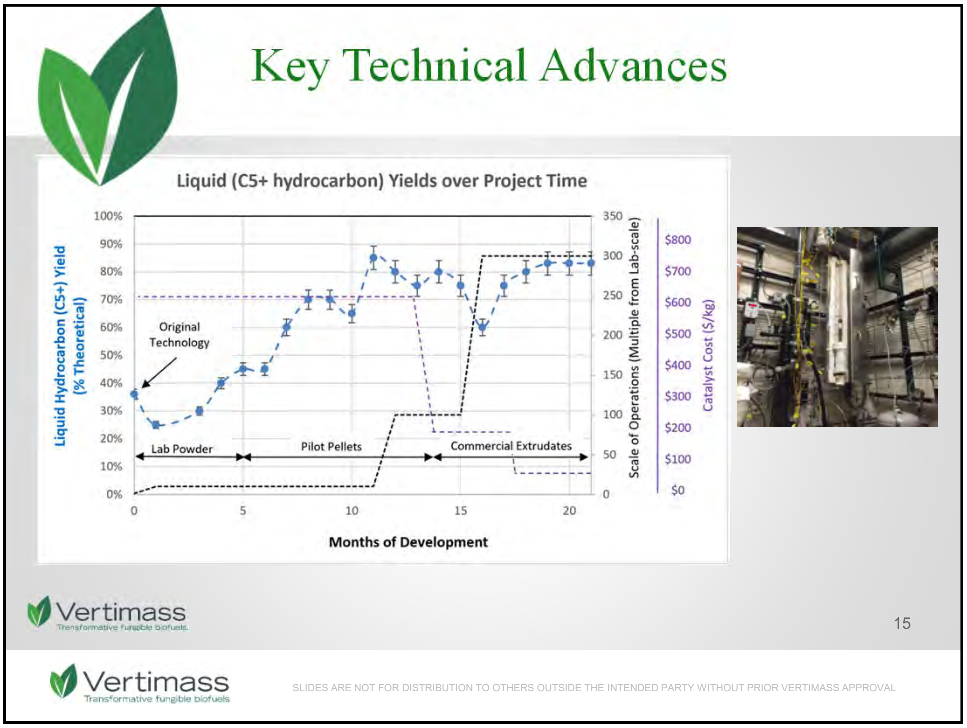
TechnipFMC Demo Operations*

TechnipFMC

1,000,000 x scale-up guarantee

Commercial plant

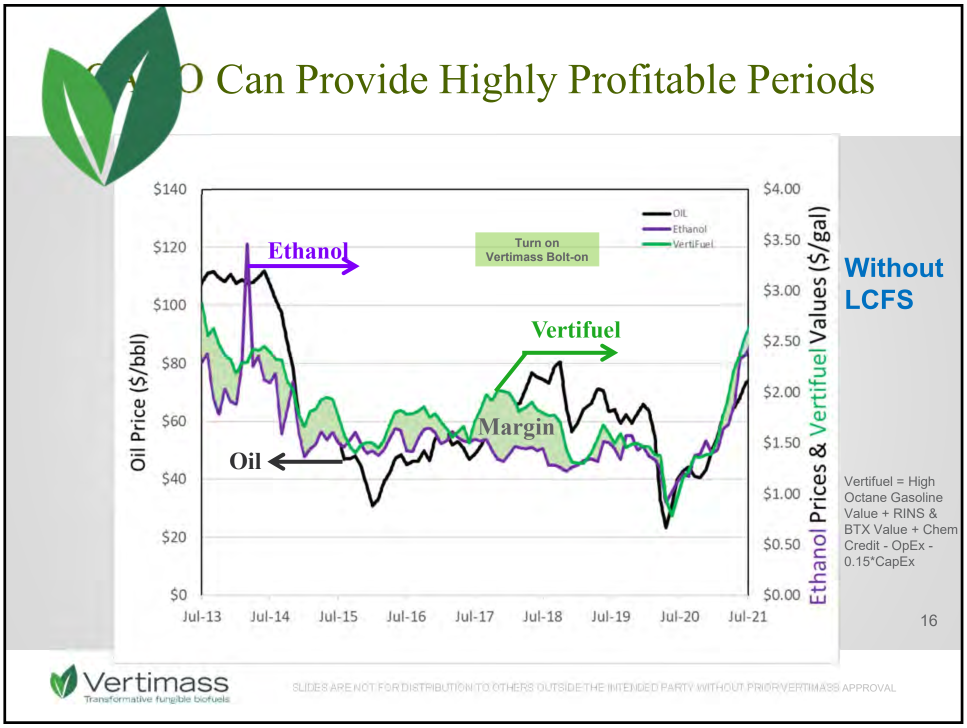
*Weymouth, MA



Key Technical Advances

Vertimass
Transformative fungible biofuels

Vertimass
Transformative fungible biofuels

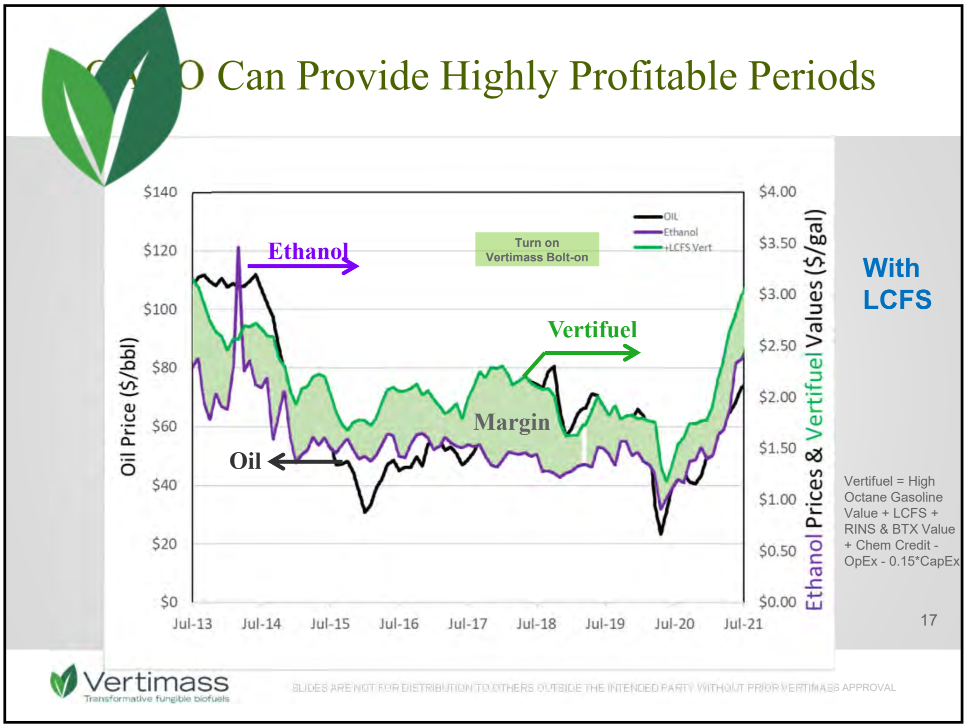


CA O Can Provide Highly Profitable Periods

Without LCFS

Vertifuel = High Octane Gasoline Value + RINS & BTX Value + Chem Credit - OpEx - 0.15*CapEx

Vertimass
Transformative fungible biofuels

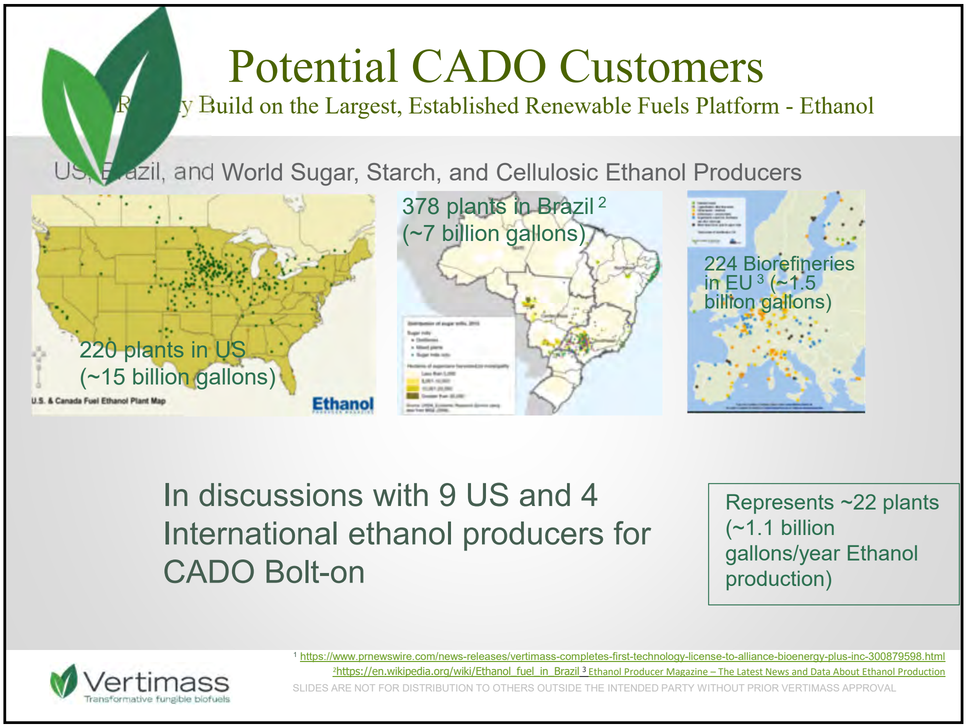


C O Can Provide Highly Profitable Periods

With LCFS

Vertifuel = High Octane Gasoline Value + LCFS + RINS & BTX Value + Chem Credit - OpEx - 0.15*CapEx

Vertimass
Transformative fungible biofuels



Potential CADO Customers

R y Build on the Largest, Established Renewable Fuels Platform - Ethanol

US, Brazil, and World Sugar, Starch, and Cellulosic Ethanol Producers

220 plants in US (~15 billion gallons)

378 plants in Brazil[2] (~7 billion gallons)

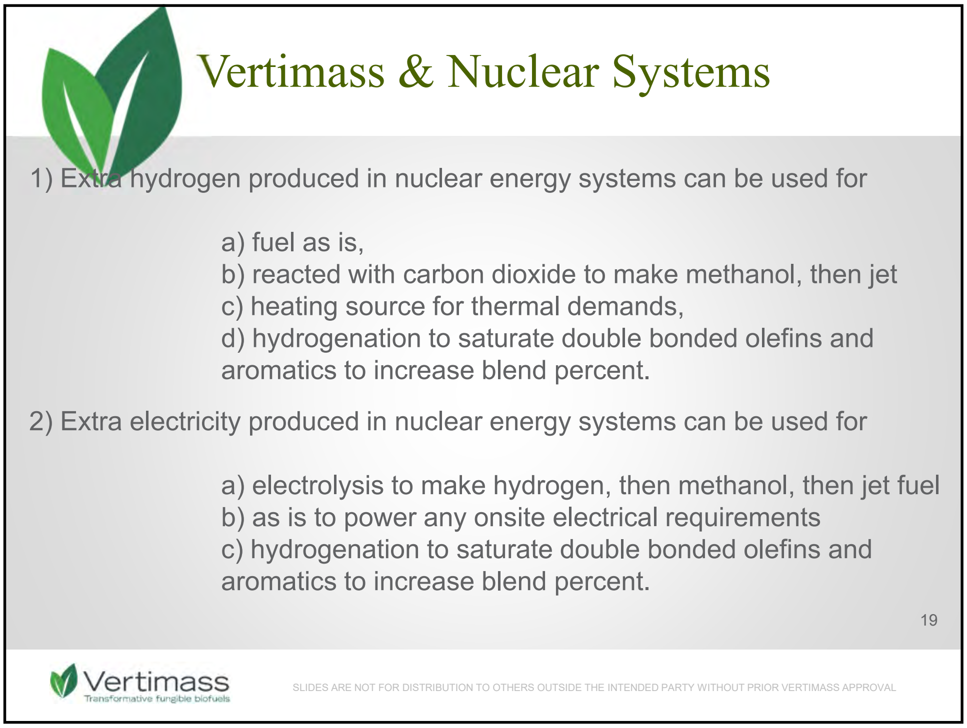
224 Biorefineries in EU[3] (~1.5 billion gallons)

In discussions with 9 US and 4 International ethanol producers for CADO Bolt-on

Represents ~22 plants (~1.1 billion gallons/year Ethanol production)

[1] https://www.prnewswire.com/news-releases/vertimass-completes-first-technology-license-to-alliance-bioenergy-plus-inc-300879598.html
[2] https://en.wikipedia.org/wiki/Ethanol_fuel_in_Brazil [3] Ethanol Producer Magazine – The Latest News and Data About Ethanol Production

Vertimass
Transformative fungible biofuels



Vertimass & Nuclear Systems

1) Extra hydrogen produced in nuclear energy systems can be used for

   a) fuel as is,
   b) reacted with carbon dioxide to make methanol, then jet
   c) heating source for thermal demands,
   d) hydrogenation to saturate double bonded olefins and aromatics to increase blend percent.

2) Extra electricity produced in nuclear energy systems can be used for

   a) electrolysis to make hydrogen, then methanol, then jet fuel
   b) as is to power any onsite electrical requirements
   c) hydrogenation to saturate double bonded olefins and aromatics to increase blend percent.

The Vertimass Team – Synergistic Expertise

Day to Day Management

Senior Advisor

Charles Wyman, PhD, President and CEO
- 10 yr. exp. operating engineering, and startup companies
- 17 yr. leadership at National Renewable Energy Lab
- 18 yr. professor at Uni New Hampshire, Dartmouth, UCR
- Founder, SAB Chair Mascoma Corporation
- Extensive experience with process development

John Hannon, PhD, COO
- Consultant/due diligence start-up & investment technoeconomic evaluations
- Led technoeconomics for start up Mascoma Corporation
- 5 yr. oil and gas engineer Schlumberger

Tom Mullen, Executive Vice President
- 2-term Riverside County Board of Supervisors, (annual budget of $2B)
- Founder, President & CEO, Viresco Energy
- Awarded UCR Anderson School of Management, Leader of the Year & National American Planning Association's Distinguished Leadership Award

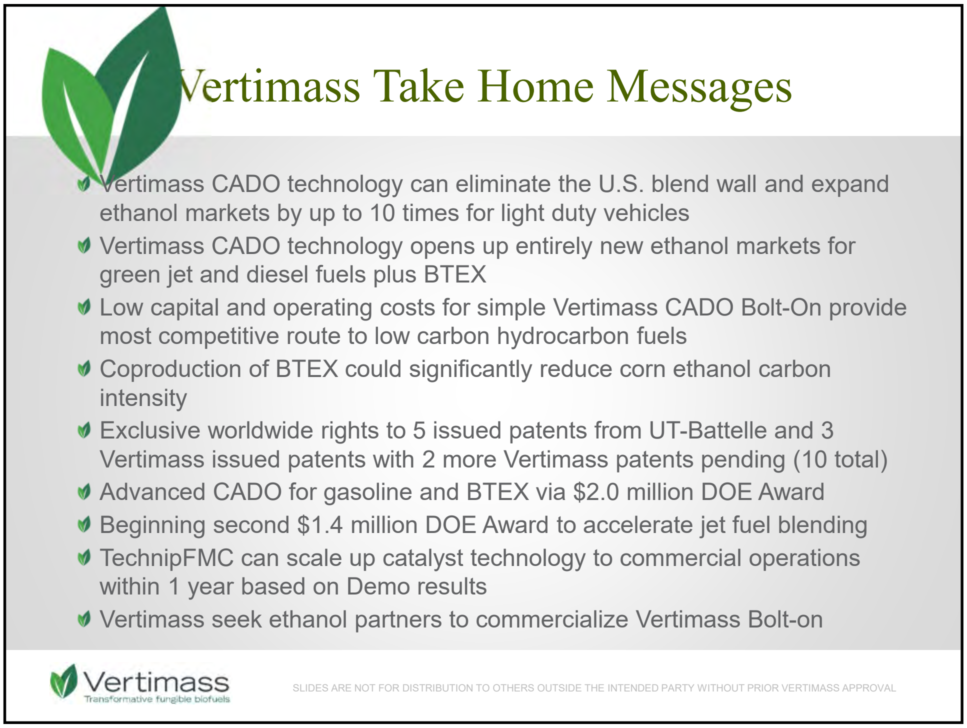
William Shopoff, Chairman
- President and Chief Executive Officer of Shopoff Realty Investments, L.P.
- More than 40 years of real estate and investment experience
- Expertise in partnership structure, debt placement, venture capital and investment underwriting

Vertimass Team – Inventor Partners

Martin Keller, PhD, Board Member
- Director of National Renewable Energy Laboratory
- President of the Alliance for Sustainable Energy
- Over 15 years experience in startup biotechnology company
- Founding Director for DOE funded BioEnergy Research Center

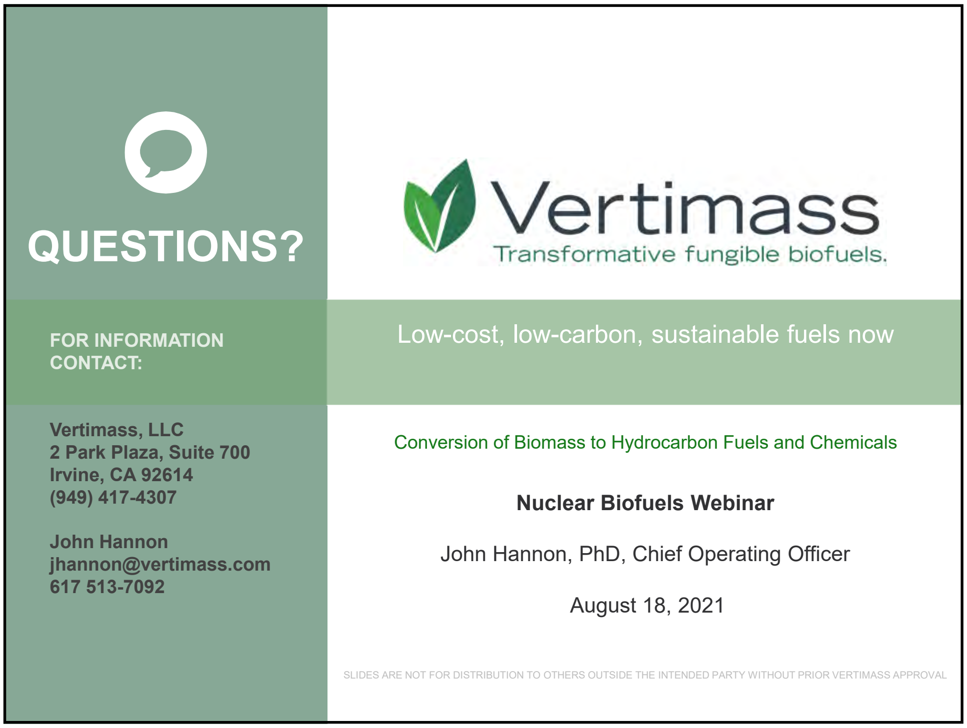
Brian Davison, PhD, Technology Development Engineer
- Chief Scientist for ORNL Biotechnology
- 3 decades in bioenergy R&D reactor design, separations, modeling, and molecular biology
- R&D100 award for succinic acid bioproduction

Chaitanya Narula, PhD, Catalyst Development Scientist
- Recently retired Distinguished R&D scientist at ORNL
- 3 decades in automotive materials chemistry, catalysis, thin films, and ceramic precursor technologies
- Former Staff Technical Specialist and Group Leader, Ford Research Laboratory



Vertimass Take Home Messages

- Vertimass CADO technology can eliminate the U.S. blend wall and expand ethanol markets by up to 10 times for light duty vehicles
- Vertimass CADO technology opens up entirely new ethanol markets for green jet and diesel fuels plus BTEX
- Low capital and operating costs for simple Vertimass CADO Bolt-On provide most competitive route to low carbon hydrocarbon fuels
- Coproduction of BTEX could significantly reduce corn ethanol carbon intensity
- Exclusive worldwide rights to 5 issued patents from UT-Battelle and 3 Vertimass issued patents with 2 more Vertimass patents pending (10 total)
- Advanced CADO for gasoline and BTEX via $2.0 million DOE Award
- Beginning second $1.4 million DOE Award to accelerate jet fuel blending
- TechnipFMC can scale up catalyst technology to commercial operations within 1 year based on Demo results
- Vertimass seek ethanol partners to commercialize Vertimass Bolt-on



QUESTIONS?

FOR INFORMATION CONTACT:

Vertimass, LLC
2 Park Plaza, Suite 700
Irvine, CA 92614
(949) 417-4307

John Hannon
jhannon@vertimass.com
617 513-7092

Vertimass
Transformative fungible biofuels.

Low-cost, low-carbon, sustainable fuels now

Conversion of Biomass to Hydrocarbon Fuels and Chemicals

Nuclear Biofuels Webinar

John Hannon, PhD, Chief Operating Officer

August 18, 2021

SLIDES ARE NOT FOR DISTRIBUTION TO OTHERS OUTSIDE THE INTENDED PARTY WITHOUT PRIOR VERTIMASS APPROVAL

Nuclear Biorefinery Options

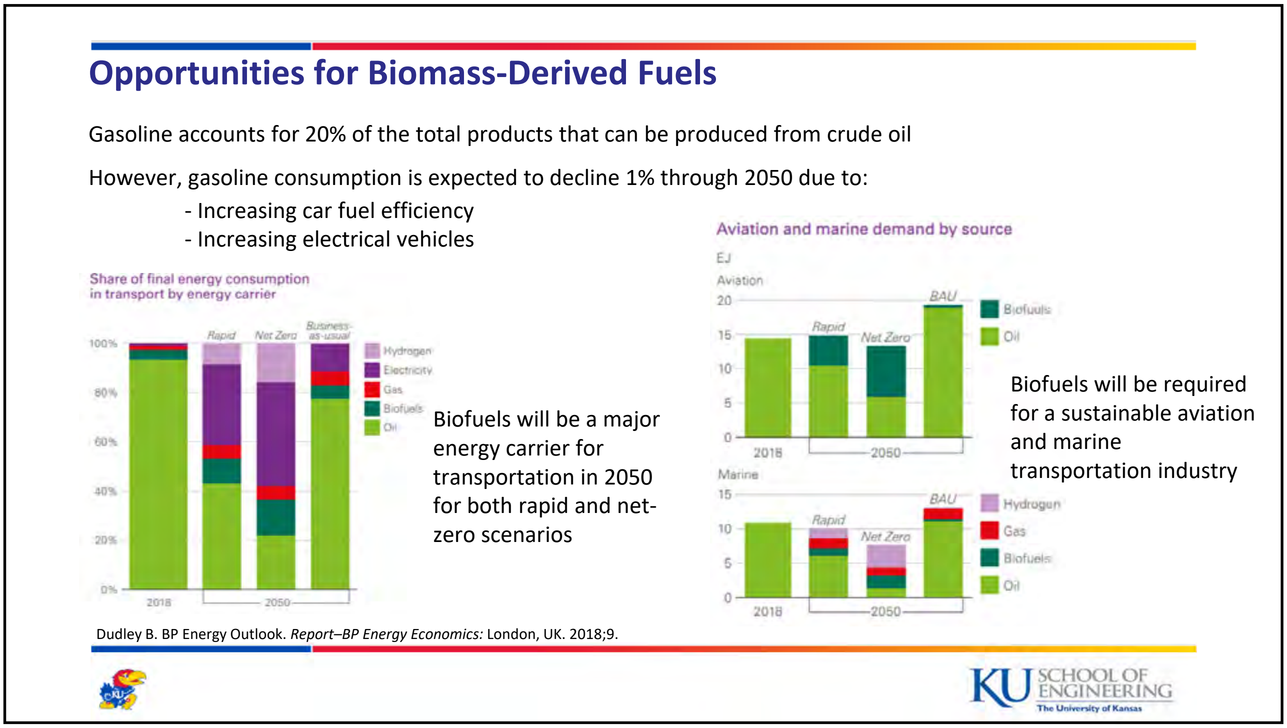
Direct Hydrodeoxygenation of Lignocellulosic Biomass into Liquid Hydrocarbon Fuels

Ana Rita C. Morais, Ph.D.
Assistant Professor
Chemical & Petroleum Engineering Department
University of Kansas

ana.morais@ku.edu

Outlook

- Background on:
  - Opportunities for biomass-derived fuels
  - Current production of liquid fuels – Advantages and Limitations
  - Production of liquid fuels – integration with petrochemical industry
- Proposed Concept
  - Direct Catalytic Conversion of Biomass using conventional catalysis
  - Main results
  - Conclusions



Opportunities for Biomass-Derived Fuels

Gasoline accounts for 20% of the total products that can be produced from crude oil

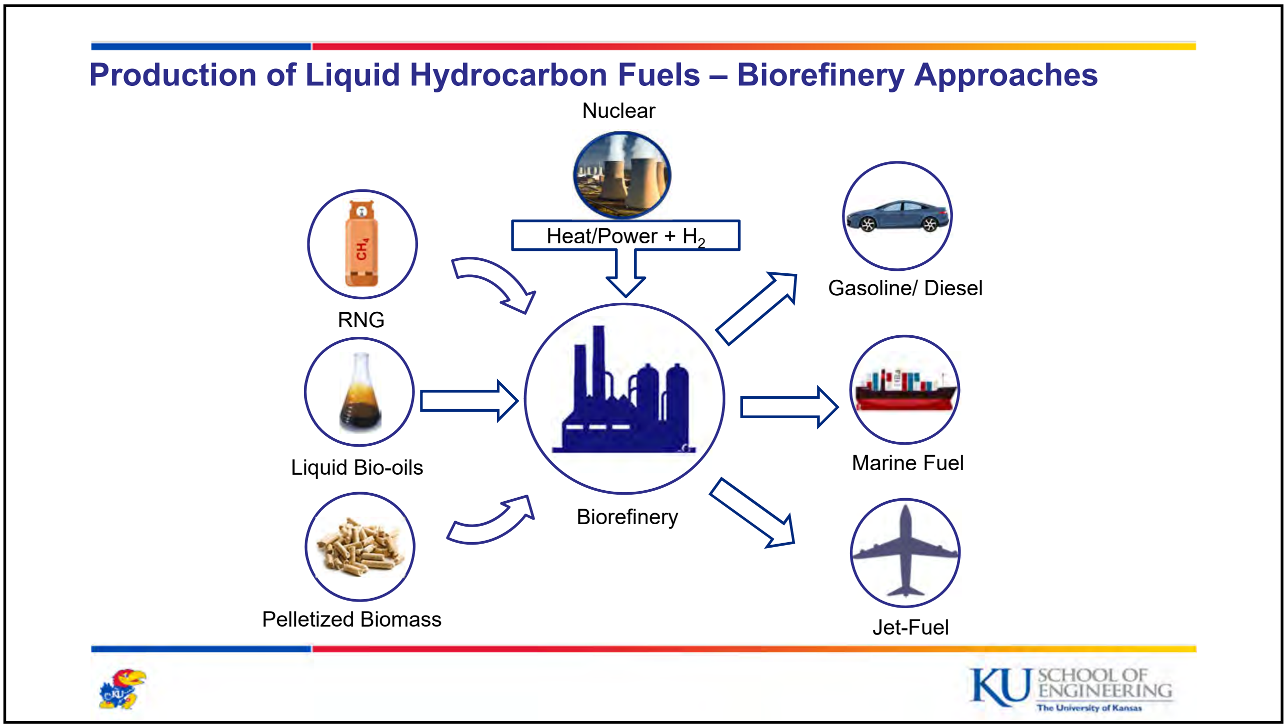
However, gasoline consumption is expected to decline 1% through 2050 due to:

- Increasing car fuel efficiency
- Increasing electrical vehicles

Biofuels will be a major energy carrier for transportation in 2050 for both rapid and net-zero scenarios

Biofuels will be required for a sustainable aviation and marine transportation industry

Dudley B. BP Energy Outlook. *Report–BP Energy Economics:* London, UK. 2018;9.



Production of Liquid Hydrocarbon Fuels – Biorefinery Approaches

Nuclear

Heat/Power + H_2

RNG

Liquid Bio-oils

Pelletized Biomass

Biorefinery

Gasoline/ Diesel

Marine Fuel

Jet-Fuel

Research Statement

Rationale

- Catalytic conversion of (whole) biomass to liquid paraffins and aromatics

Challenges

- Directly convert biomass into liquid paraffins and aromatics with high carbon yields
- Use of relative mild operating conditions
- Develop a robust technology able to process all types of biomasses

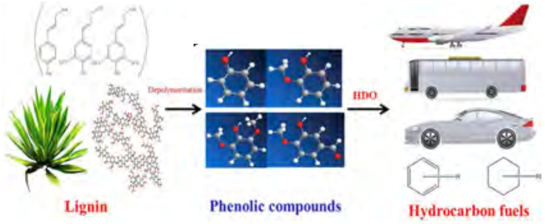
Goal

- Develop an one-step hydrodeoxygenation technology using conventional catalysts
- Use milder operating conditions relative to those published in the literature
- Obtain > 90% carbon yield
- Produce gasoline-like alkanes that can be subject to oligomerization reaction to produce marine and jet-type fuel

KU SCHOOL OF ENGINEERING
The University of Kansas

Catalytic Conversion of Biomass into Liquid Hydrocarbons – What has been done so far?

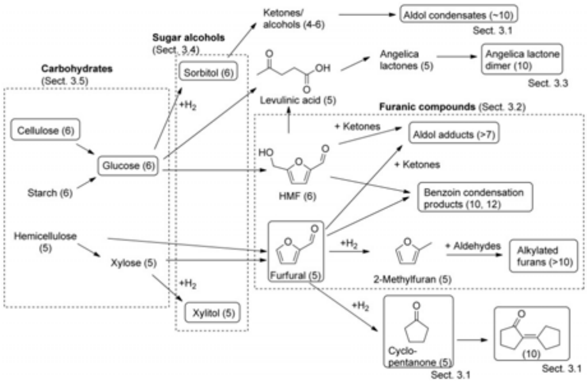
Shu et al. Biomass and Bioenergy, 2020



Depolymerization of lignin followed by hydrodeoxygenation into hydrocarbon fuels

(16.2%–62.8% yields)

Nakagawa et al. ChemSusChem, 2015

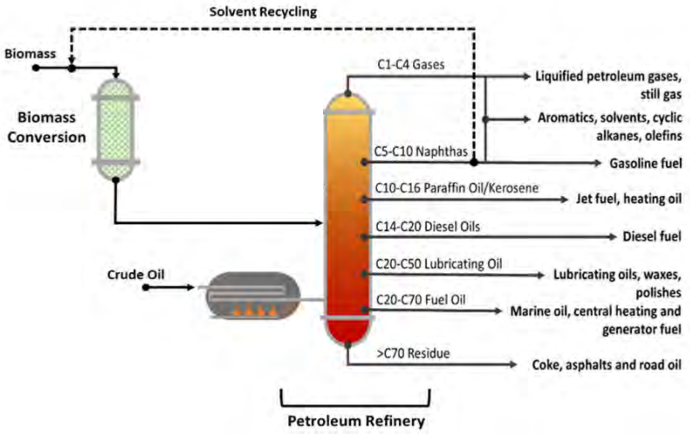


Either approach requires (at least) a two-step process

Depolymerization of biomass carbohydrates followed by conversion of carbohydrate precursors into hydrocarbon fuels

KU SCHOOL OF ENGINEERING
The University of Kansas

Production of Liquid Hydrocarbon Fuels – Proposed Approach



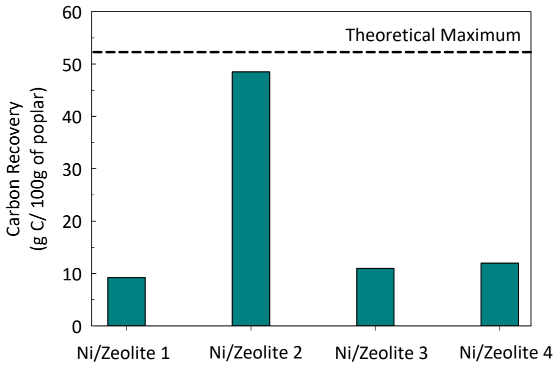
Simplified schematic of biomass platform integrated with the existing petroleum refinery to produce recycled- and 'bio-petrochemicals'

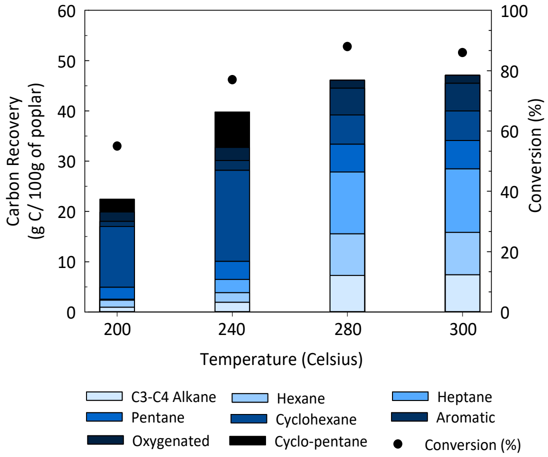
Opportunities:

- Use of available refinery assets

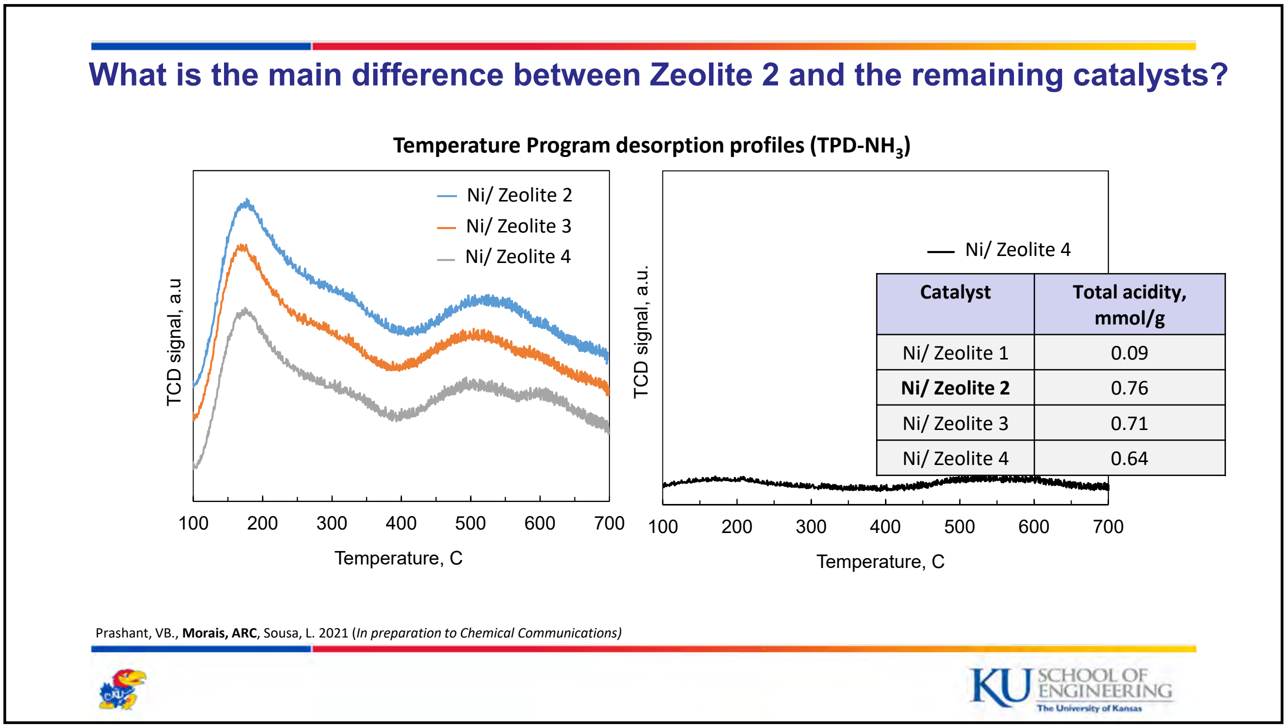
Direct Hydrodeoxygenation of Whole Biomass into Liquid Hydrocarbons

Rationale: Develop a feedstock agnostic technology for direct catalytic conversion of biomass into liquid hydrocarbons - H_2 & hydrocarbon solvent at relatively low temperatures (< 300 °C)





Prashant, VB., **Morais, ARC**, Sousa, L. 2021 (*In preparation to Chemical Communications*)
Forsberg, CW., Dale, BE., Jones, DS., Hossain, T., **Morais, ARC**., Wendt LM. 2021. Applied Energy. *2021, 298, 117225*

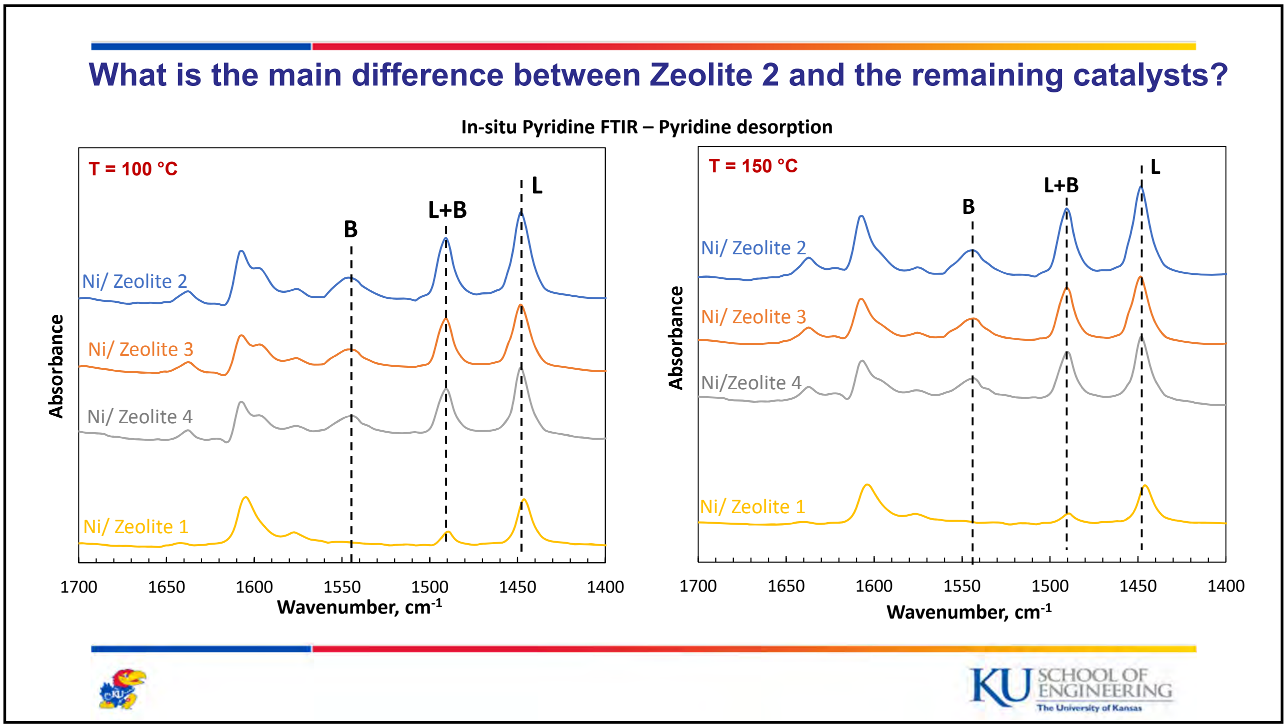


What is the main difference between Zeolite 2 and the remaining catalysts?

Temperature Program desorption profiles (TPD-NH_3)

Catalyst	Total acidity, mmol/g
Ni/ Zeolite 1	0.09
Ni/ Zeolite 2	0.76
Ni/ Zeolite 3	0.71
Ni/ Zeolite 4	0.64

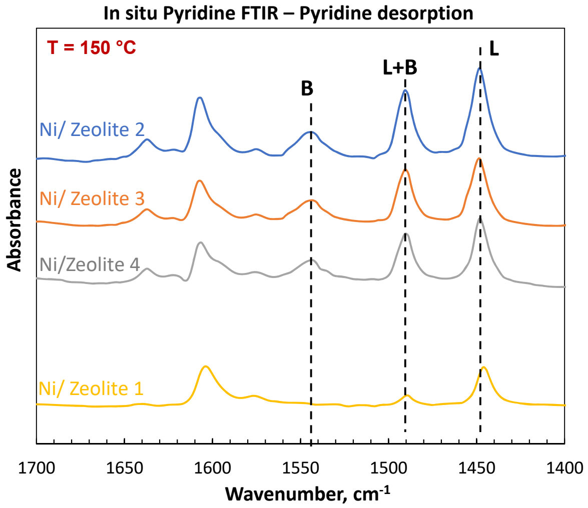
Prashant, VB., **Morais, ARC**, Sousa, L. 2021 (*In preparation to Chemical Communications*)



What is the main difference between Zeolite 2 and the remaining catalysts?

In-situ Pyridine FTIR – Pyridine desorption

What is the main difference between Zeolite 2 and the remaining catalysts?



Catalyst	L/B ratio
Ni/ Zeolite 1	-
Ni/ Zeolite 2	**1.85**
Ni/ Zeolite 3	1.77
Ni/ Zeolite 4	1.78

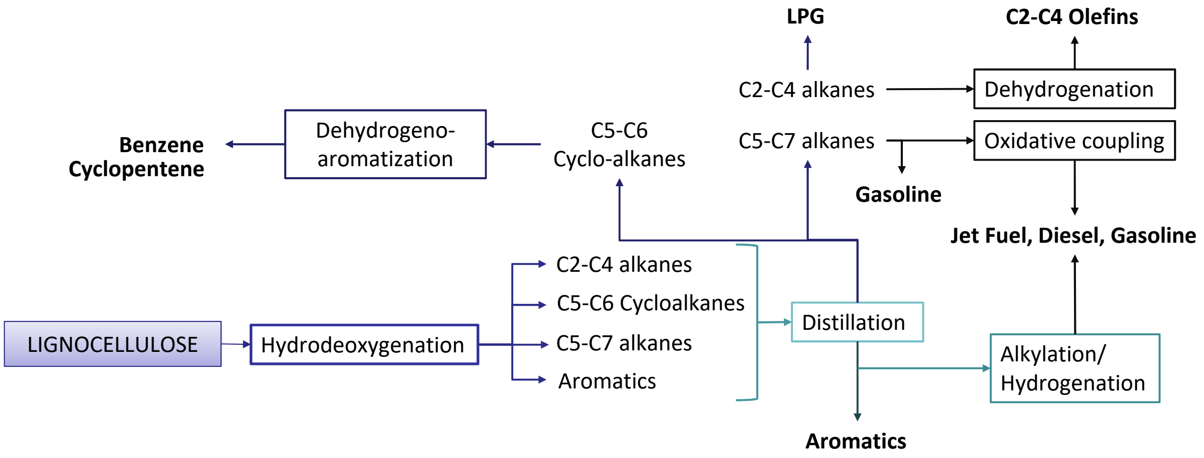
What is the main difference between Zeolite 2 and the remaining catalysts?

Sample	Si/Al (Molar Ratio)	Surface Area S_{BET} (m^2/g)	External Surface Area (m^2/g)	Total pore Volume (cc/g)
Ni/ zeolite 1	18	333	88	0.2
Ni/ zeolite 2	14	480	162	0.389
Ni/ zeolite 3	14	432	178.2	0.282
Ni/ zeolite 4	14	354	149	0.195

Ni/Zeolite 2 has very specific properties, such as surface area, total pore volume acidity, etc., that is crucial for the conversion of biomass into paraffins and aromatics at high carbon yields

- **Extensive experimental and modeling studies are needed to understand the effect of catalyst's properties on the performance of the HDO reaction**

Conversion Approaches for C6 and C7 Alkanes



LPG

C2-C4 Olefins

C2-C4 alkanes

Dehydrogenation

Benzene
Cyclopentene

Dehydrogeno-aromatization

C5-C6
Cyclo-alkanes

C5-C7 alkanes

Oxidative coupling

Gasoline

Jet Fuel, Diesel, Gasoline

C2-C4 alkanes

C5-C6 Cycloalkanes

C5-C7 alkanes

Aromatics

LIGNOCELLULOSE

Hydrodeoxygenation

Distillation

Alkylation/
Hydrogenation

Aromatics

Conclusions

- This work suggests the possibility of integrating lignocellulosic biomass conversion in petrochemical refineries to produce a range of alkanes and aromatic products.

- Nearly 90% conversion of lignocellulosic biomass into alkanes of variable order and aromatic compounds was achieved.

- Larger pore volumes and high surface area, combined with the proper catalyst acidity, are key factors driving the depolymerization and hydrodeoxygenation of lignocellulose.

- The intermediate products of depolymerization and hydrodeoxygenation of biomass can be further processed to products of higher market demand. For example:

  - The lower order alkanes derived from biomass can be further converted to alkanes of higher order via oxidative coupling reactions.

  - The lower order alkanes can be also converted to light olefins via dehydrogenation reactions.

Acknowledges

National Chemical Laboratory

Dr. Prashant Niphadkar
Dr. Vijay Bokade

Michigan State University
Founded 1855

Dr. Bruce E. Dale
Dr. Leonardo Sousa

CEBC
CENTER FOR ENVIRONMENTALLY BENEFICIAL CATALYSIS
The University of Kansas

Dr. Bala Subramaniam
Anoop Uchagawkar

FCT

KU SCHOOL OF ENGINEERING
The University of Kansas

Shell's Gas-to-Liquids (Fischer-Tropsch) Technology and Opportunities in the Energy Transition

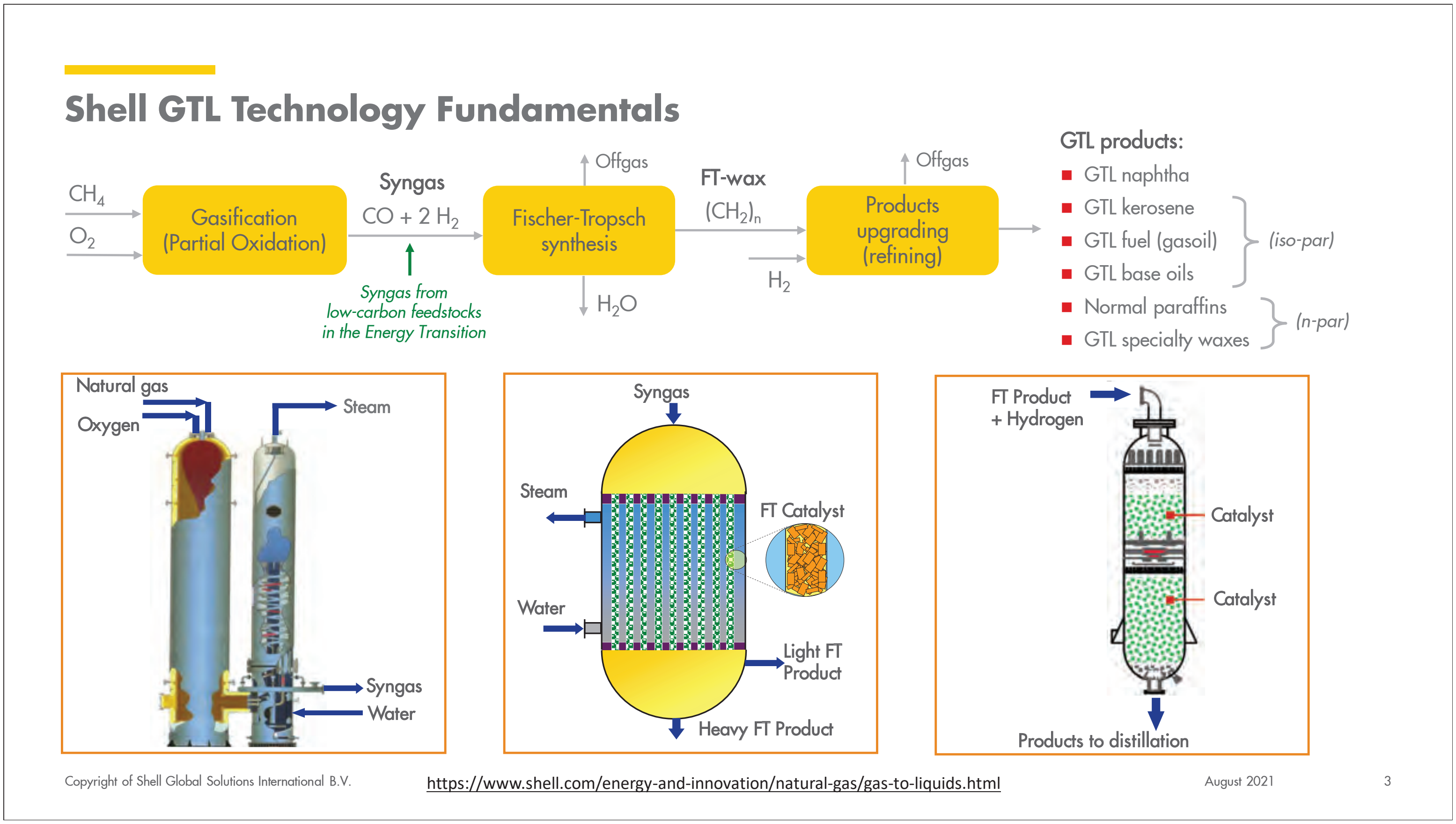
Nuclear Biofuels webinar
18 August 2021

Svetlana van Bavel
Shell Global Solutions International B.V.
Senior Process Engineer Gas-to-Liquids

Definitions & cautionary note

The companies in which Royal Dutch Shell plc directly and indirectly owns investments are separate legal entities. In this presentation "Shell", "Shell Group" and "Group" are sometimes used for convenience where references are made to Royal Dutch Shell plc and its subsidiaries in general. Likewise, the words "we", "us" and "our" are also used to refer to Royal Dutch Shell plc and its subsidiaries in general or to those who work for them. These terms are also used where no useful purpose is served by identifying the particular entity or entities. ''Subsidiaries'', "Shell subsidiaries" and "Shell companies" as used in this presentation refer to entities over which Royal Dutch Shell plc either directly or indirectly has control. Entities and unincorporated arrangements over which Shell has joint control are generally referred to as "joint ventures" and "joint operations", respectively. Entities over which Shell has significant influence but neither control nor joint control are referred to as "associates". The term "Shell interest" is used for convenience to indicate the direct and/or indirect ownership interest held by Shell in an entity or unincorporated joint arrangement, after exclusion of all third-party interest.

This presentation contains forward-looking statements (within the meaning of the U.S. Private Securities Litigation Reform Act of 1995) concerning the financial condition, results of operations and businesses of Royal Dutch Shell. All statements other than statements of historical fact are, or may be deemed to be, forward-looking statements. Forward-looking statements are statements of future expectations that are based on management's current expectations and assumptions and involve known and unknown risks and uncertainties that could cause actual results, performance or events to differ materially from those expressed or implied in these statements. Forward-looking statements include, among other things, statements concerning the potential exposure of Royal Dutch Shell to market risks and statements expressing management's expectations, beliefs, estimates, forecasts, projections and assumptions. These forward-looking statements are identified by their use of terms and phrases such as "aim", "ambition", ''anticipate'', ''believe'', ''could'', ''estimate'', ''expect'', ''goals'', ''intend'', ''may'', ''objectives'', ''outlook'', ''plan'', ''probably'', ''project'', ''risks'', "schedule", ''seek'', ''should'', ''target'', ''will'' and similar terms and phrases. There are a number of factors that could affect the future operations of Royal Dutch Shell and could cause those results to differ materially from those expressed in the forward-looking statements included in this presentation, including (without limitation): (a) price fluctuations in crude oil and natural gas; (b) changes in demand for Shell's products; (c) currency fluctuations; (d) drilling and production results; (e) reserves estimates; (f) loss of market share and industry competition; (g) environmental and physical risks; (h) risks associated with the identification of suitable potential acquisition properties and targets, and successful negotiation and completion of such transactions; (i) the risk of doing business in developing countries and countries subject to international sanctions; (j) legislative, fiscal and regulatory developments including regulatory measures addressing climate change; (k) economic and financial market conditions in various countries and regions; (l) political risks, including the risks of expropriation and renegotiation of the terms of contracts with governmental entities, delays or advancements in the approval of projects and delays in the reimbursement for shared costs; (m) risks associated with the impact of pandemics, such as the COVID-19 (coronavirus) outbreak; and (n) changes in trading conditions. No assurance is provided that future dividend payments will match or exceed previous dividend payments. All forward-looking statements contained in this presentation are expressly qualified in their entirety by the cautionary statements contained or referred to in this section. Readers should not place undue reliance on forward-looking statements. Additional risk factors that may affect future results are contained in Royal Dutch Shell's Form 20-F for the year ended December 31, 2020 (available at www.shell.com/investor and www.sec.gov). These risk factors also expressly qualify all forward-looking statements contained in this presentation and should be considered by the reader. Each forward-looking statement speaks only as of the date of this presentation, 18 August 2021. Neither Royal Dutch Shell plc nor any of its subsidiaries undertake any obligation to publicly update or revise any forward-looking statement as a result of new information, future events or other information. In light of these risks, results could differ materially from those stated, implied or inferred from the forward-looking statements contained in this presentation.
We may have used certain terms, such as resources, in this presentation that the United States Securities and Exchange Commission (SEC) strictly prohibits us from including in our filings with the SEC. Investors are urged to consider closely the disclosure in our Form 20-F, File No 1-32575, available on the SEC website www.sec.gov.



Shell GTL Technology Fundamentals

GTL products:

- GTL naphtha
- GTL kerosene
- GTL fuel (gasoil)
- GTL base oils
- Normal paraffins
- GTL specialty waxes

https://www.shell.com/energy-and-innovation/natural-gas/gas-to-liquids.html

August 2021

Shell GTL Products have premium quality and are used in a wide range of applications that are robust in Energy Transition

* Energy Transition: "The world will be deeply electrified, but molecules remain important"

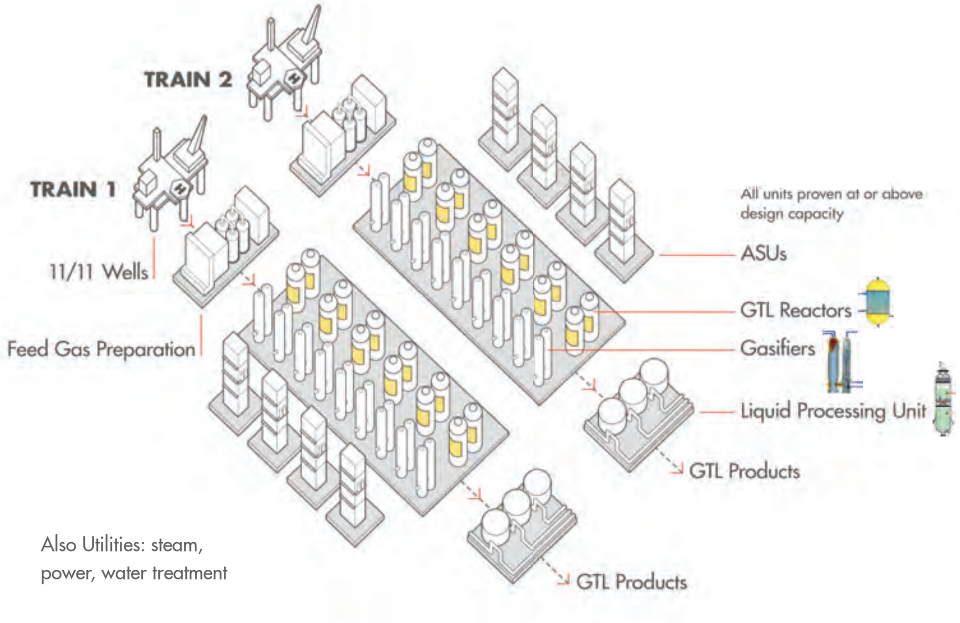
** Using low-carbon feedstocks (bio/waste/power/CO_2) instead of natural gas results in the same type of molecules as GTL products (only with very low CI)

August 2021

Pearl GTL

Integrated Gas-to-Liquids facility

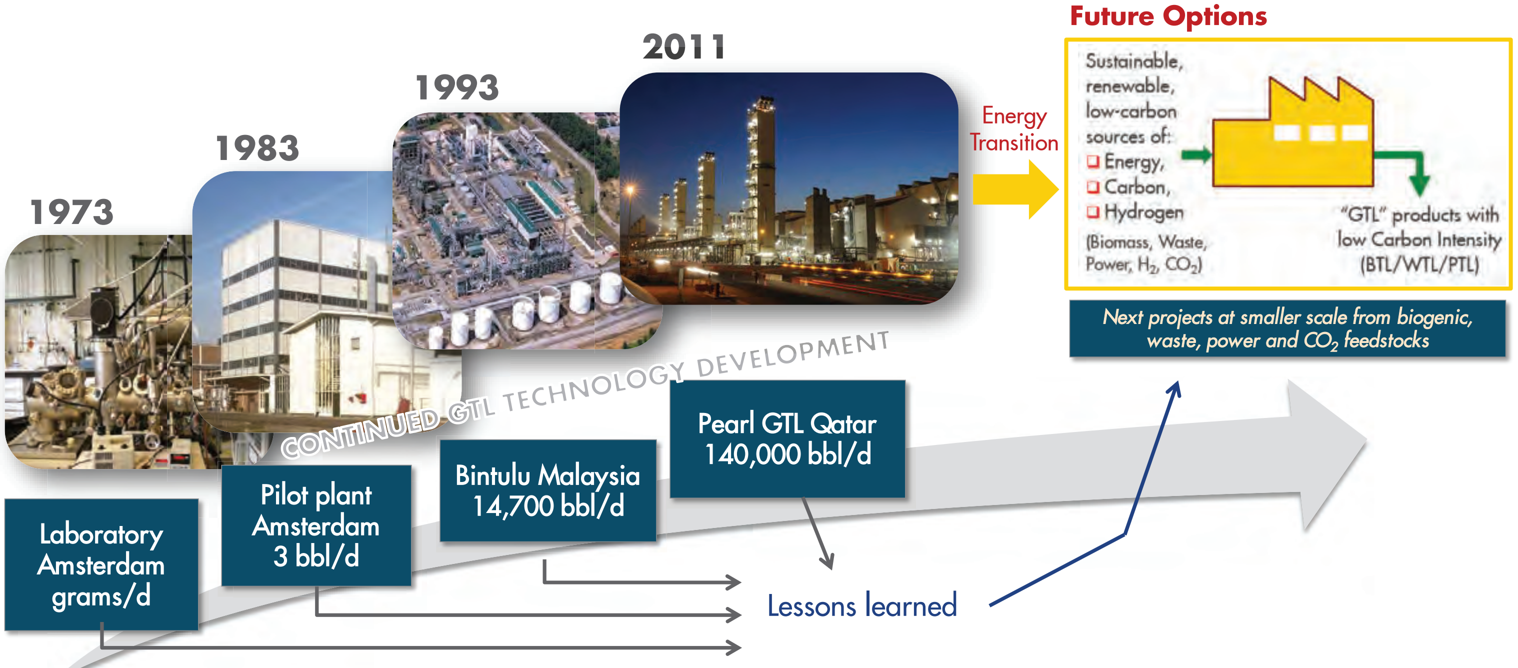
- 1.6 Bcf/d of Wet Gas
- **140 kbbl/d GTL products**
- 120 kbbl/d NGLs/Ethane
- Full integration from offshore to refined products
- **In production since 2011**



Also Utilities: steam, power, water treatment

https://www.shell.com/about-us/major-projects/pearl-gtl.html

A 40+ Year Journey of Technology and Product Innovation



Laboratory Amsterdam grams/d

Pilot plant Amsterdam 3 bbl/d

Bintulu Malaysia 14,700 bbl/d

Pearl GTL Qatar 140,000 bbl/d

Lessons learned

Energy Transition

Future Options

Sustainable, renewable, low-carbon sources of:

- ☐ Energy,
- ☐ Carbon,
- ☐ Hydrogen

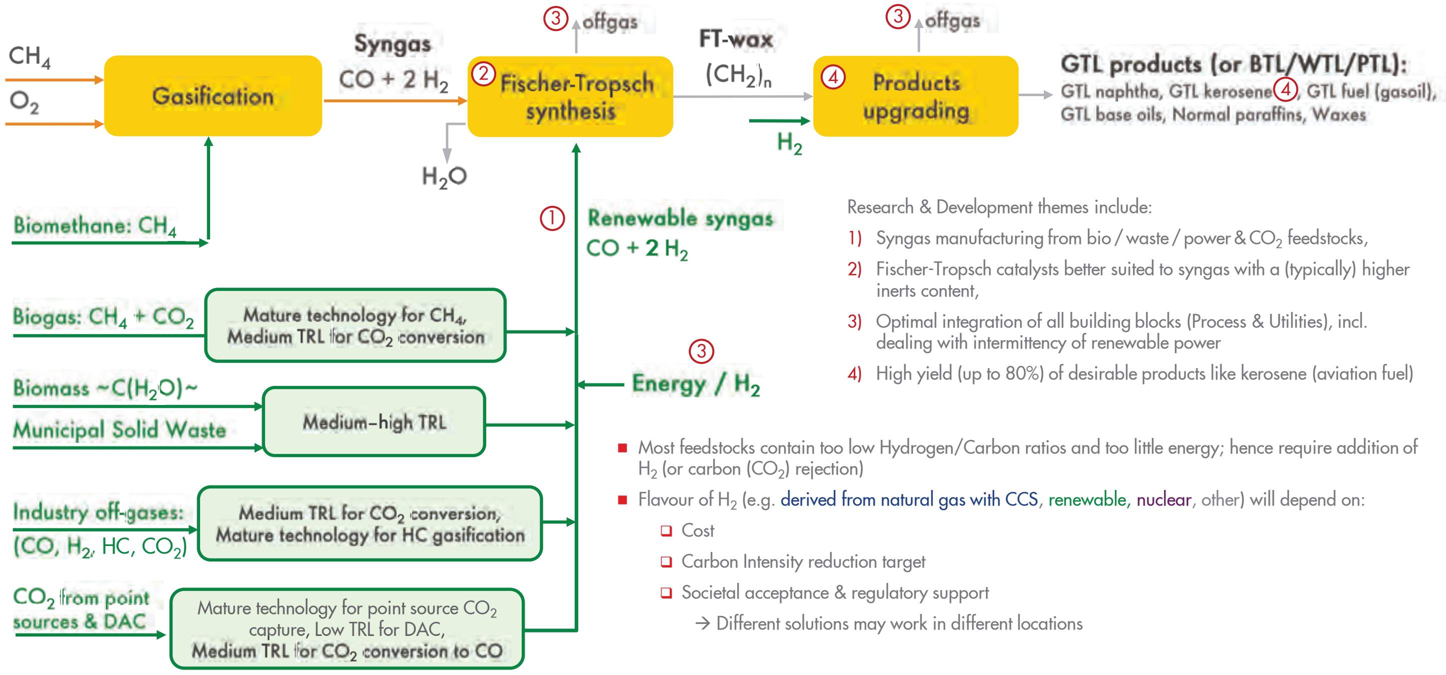
(Biomass, Waste, Power, H_2, CO_2)

"GTL" products with low Carbon Intensity (BTL/WTL/PTL)

Next projects at smaller scale from biogenic, waste, power and CO_2 feedstocks

(Note: Historic timeline was not schedule driven)

Shell GTL (Fischer-Tropsch) Technology as an enabler in the Energy Transition



CH_4

O_2

Gasification

Syngas

$CO + 2\ H_2$

② **Fischer-Tropsch synthesis**

③ offgas

H_2O

FT-wax

$(CH_2)_n$

H_2

④ **Products upgrading**

③ offgas

GTL products (or BTL/WTL/PTL):
GTL naphtha, GTL kerosene ④, GTL fuel (gasoil), GTL base oils, Normal paraffins, Waxes

Biomethane: CH_4

① **Renewable syngas**
$CO + 2\ H_2$

Biogas: $CH_4 + CO_2$ — Mature technology for CH_4, Medium TRL for CO_2 conversion

Biomass ~$C(H_2O)$~
Municipal Solid Waste — Medium–high TRL

③ **Energy / H_2**

Industry off-gases:
(CO, H_2, HC, CO_2) — Medium TRL for CO_2 conversion, Mature technology for HC gasification

CO_2 from point sources & DAC — Mature technology for point source CO_2 capture, Low TRL for DAC, Medium TRL for CO_2 conversion to CO

Research & Development themes include:

1) Syngas manufacturing from bio / waste / power & CO_2 feedstocks,
2) Fischer-Tropsch catalysts better suited to syngas with a (typically) higher inerts content,
3) Optimal integration of all building blocks (Process & Utilities), incl. dealing with intermittency of renewable power
4) High yield (up to 80%) of desirable products like kerosene (aviation fuel)

- Most feedstocks contain too low Hydrogen/Carbon ratios and too little energy; hence require addition of H_2 (or carbon (CO_2) rejection)
- Flavour of H_2 (e.g. derived from natural gas with CCS, renewable, nuclear, other) will depend on:
  - ☐ Cost
  - ☐ Carbon Intensity reduction target
  - ☐ Societal acceptance & regulatory support
    - → Different solutions may work in different locations

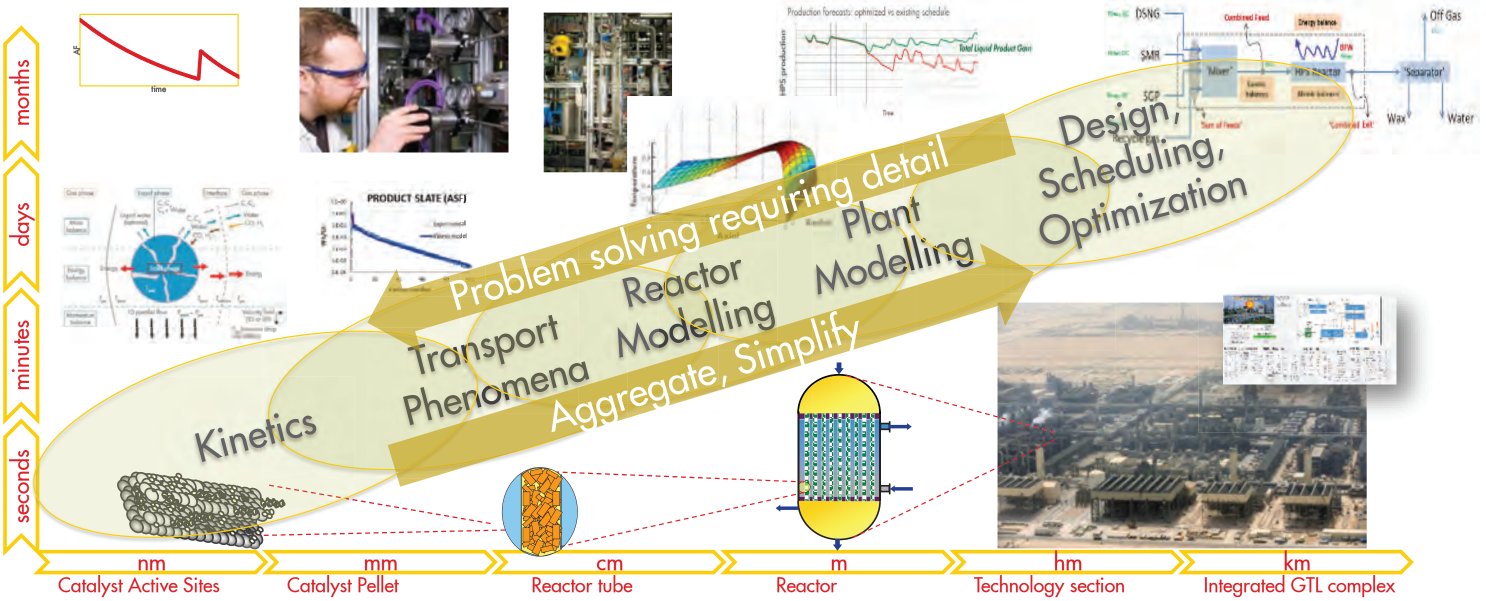
Multi-scale Modelling & Digitalization for GTL Technology

Catalyst improvement
effective opportunity selection

µflow & Pilot Plant R&D steer
acceleration of technology deployment

Technology support
optimal operation, reactor design

Scheduling, business planning
Project development, Catalyst renew strategy



nm — Catalyst Active Sites

mm — Catalyst Pellet

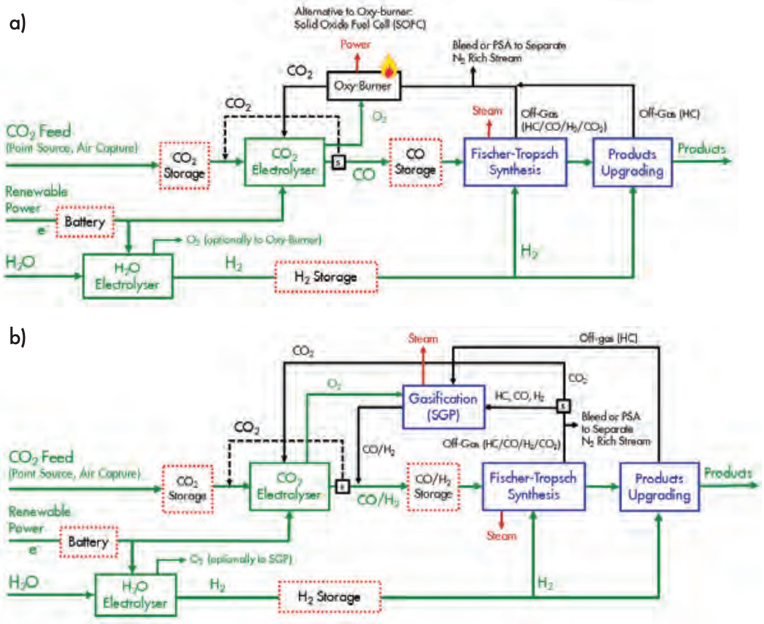
cm — Reactor tube

m — Reactor

hm — Technology section

km — Integrated GTL complex

Exploring Optimal Process & Utilities Integration in PTL concepts



S. van Bavel, S. Verma, E. Negro, M. Bracht, Integrating CO_2 Electrolysis into the Gas-to-Liquids–Power-to-Liquids Process, *ACS Energy Lett*. **2020**, 5, 2597–2601, https://pubs.acs.org/doi/full/10.1021/acsenergylett.0c01418

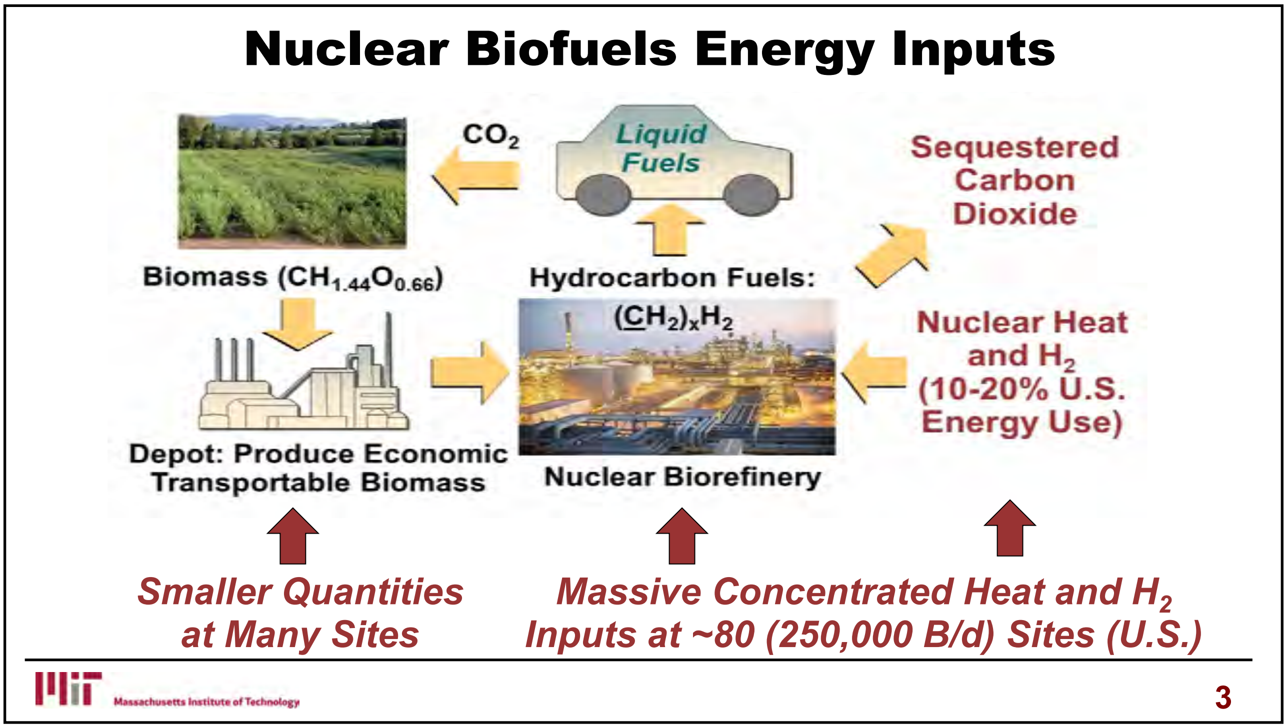
Matching Nuclear Reactors to Nuclear Biomass Systems

Charles Forsberg (*cforsber@mit.edu*)
Massachusetts Institute of Technology
Cambridge, MA

Workshop: Can a Nuclear Biofuels System Enable Liquid Biofuels as the
Economic Low-carbon Replacement for All Liquid Fossil Fuels and
Hydrocarbon Feedstocks with Negative Carbon Emissions
August 18, 2021: 10:00-1:30 Eastern
Webinar Series: 10:00-1:30 Eastern; August 4, 11 and 18

Presentation Outline

- Nuclear Biofuels Energy Inputs
- Nuclear Hydrogen Production
- Nuclear Heat Production
- Depot Energy Options



Nuclear Biofuels Energy Inputs

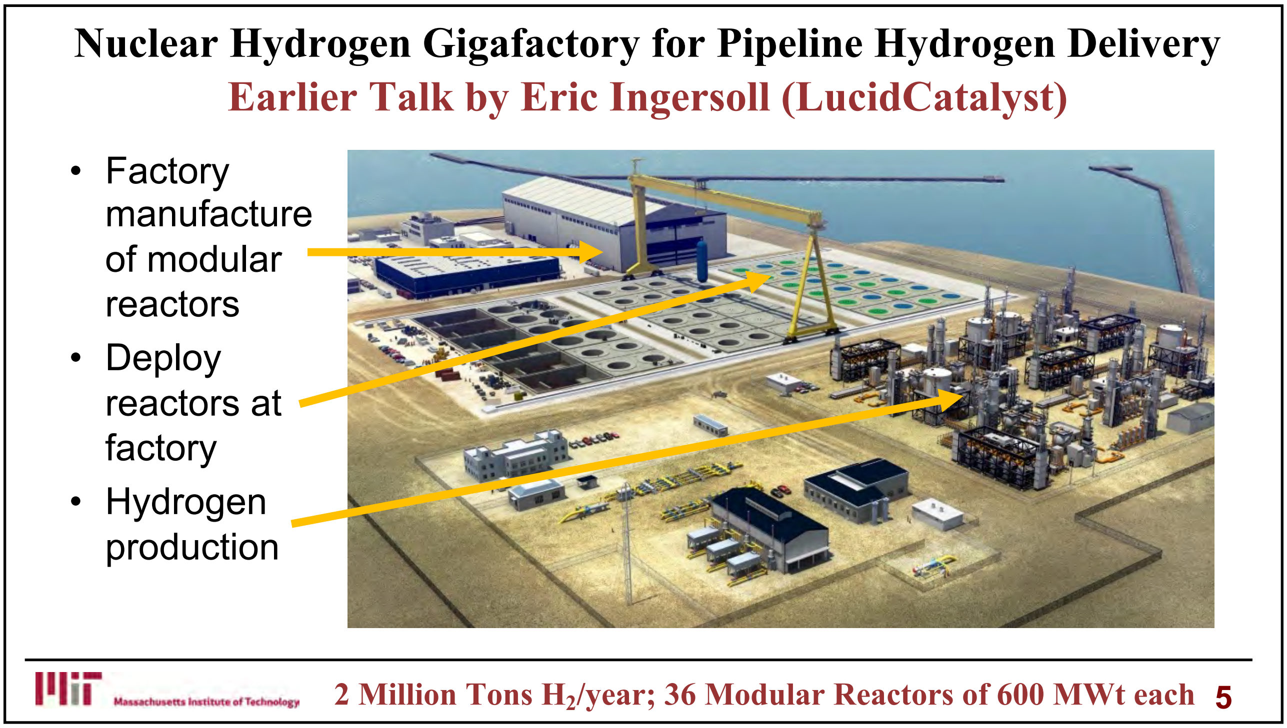
Smaller Quantities at Many Sites

Massive Concentrated Heat and H_2 Inputs at ~80 (250,000 B/d) Sites (U.S.)

Nuclear Hydrogen Production Options

Stand Alone Production

Integrated with Electricity Production

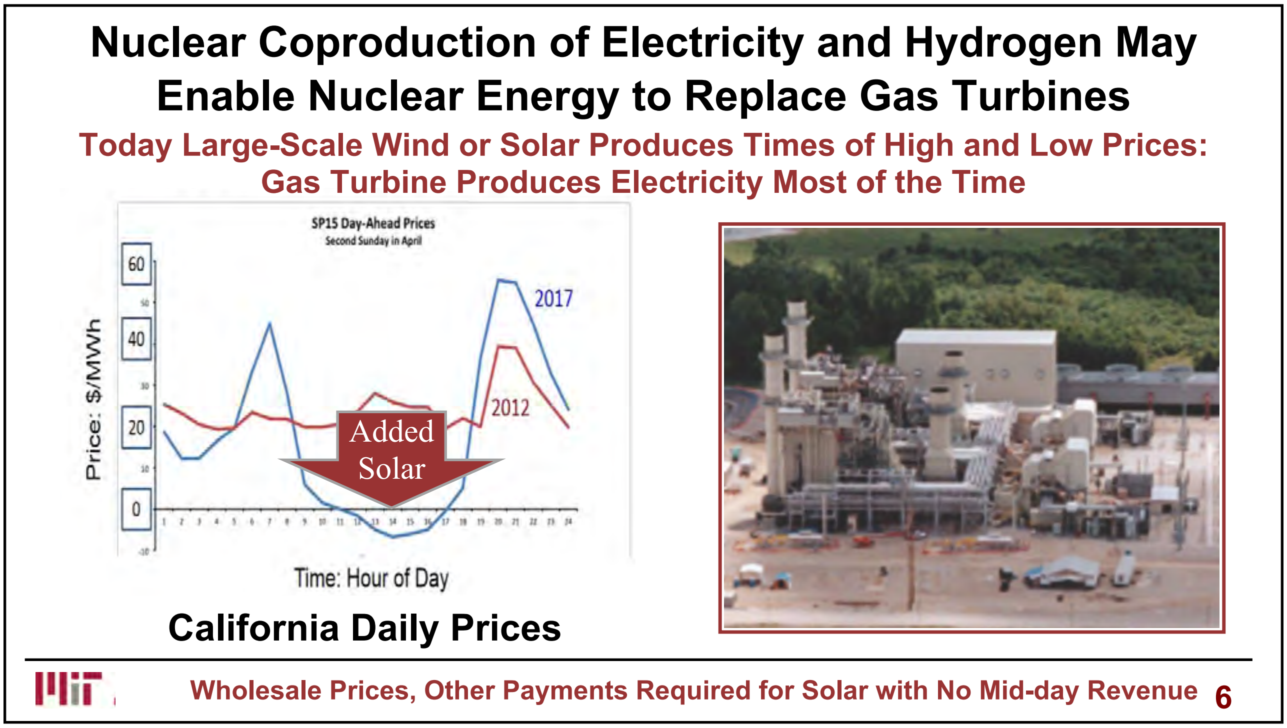


Nuclear Hydrogen Gigafactory for Pipeline Hydrogen Delivery

Earlier Talk by Eric Ingersoll (LucidCatalyst)

- Factory manufacture of modular reactors
- Deploy reactors at factory
- Hydrogen production

2 Million Tons H_2/year; 36 Modular Reactors of 600 MWt each



Nuclear Coproduction of Electricity and Hydrogen May Enable Nuclear Energy to Replace Gas Turbines

Today Large-Scale Wind or Solar Produces Times of High and Low Prices: Gas Turbine Produces Electricity Most of the Time

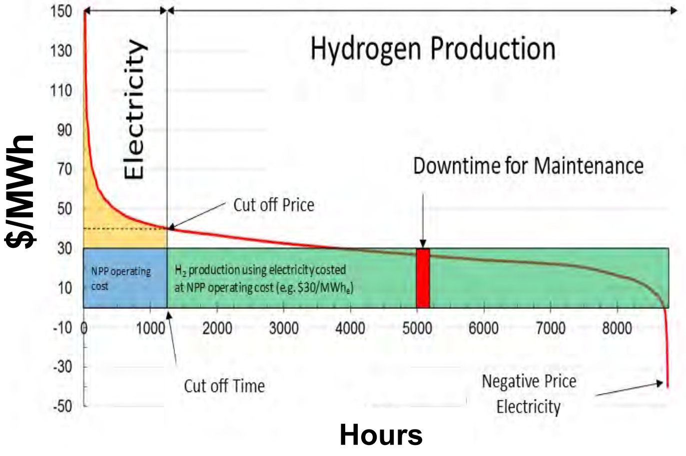
California Daily Prices

Wholesale Prices, Other Payments Required for Solar with No Mid-day Revenue

Base-load Nuclear Reactors May Economically Replace Gas Turbines Producing Electricity and Hydrogen

- Electrolysis plants are very capital intensive
- Must run plants at high capacity factors for cheap hydrogen
- Integrate with nuclear plants to produce peak electricity and hydrogen

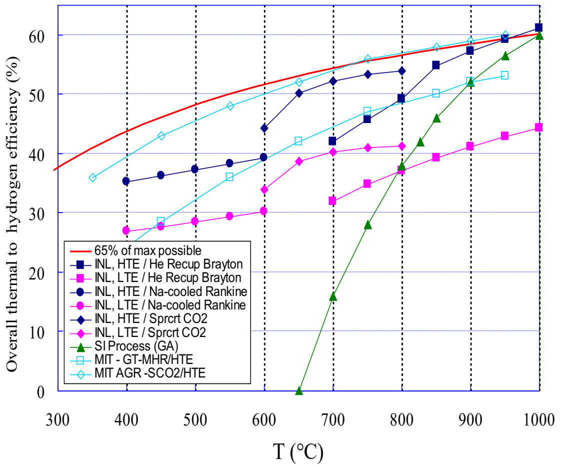
Electricity Price Curve over One Year



Strategy to Maximize Revenue That Reduces Hydrogen Costs

There Are Two Major Nuclear Hydrogen Production Options: Water Electrolysis and Steam Electrolysis (Demo Stage)

- High Temperature Electrolysis (HTE) needs steam and electricity inputs
- HTE couples to nuclear plants that produce heat and electricity
- HTE Advantages
  - Lower capital costs
  - HTE (blue) is 20 to 30% more efficient than water electrolysis (pink)



Efficiency is Hydrogen Heat / Thermal Energy Input

DOE/Utility Nuclear Hydrogen Demonstration Projects

Three demonstration projects for hydrogen production at existing nuclear power plants

- Base-load nuclear plant operation
- Variable electricity to the grid

Schedule:

- Exelon: Nine-Mile Point NPP; LTE/PEM. H_2 production beginning ~Jan. 2022
- Energy Harbor; LTE/PEM; Contract start anticipate by Oct. 2022
- Xcel Energy: HTE/SOEC; tie into plant thermal line engineering has been completed; Official project start anticipated by Jan. 2022.

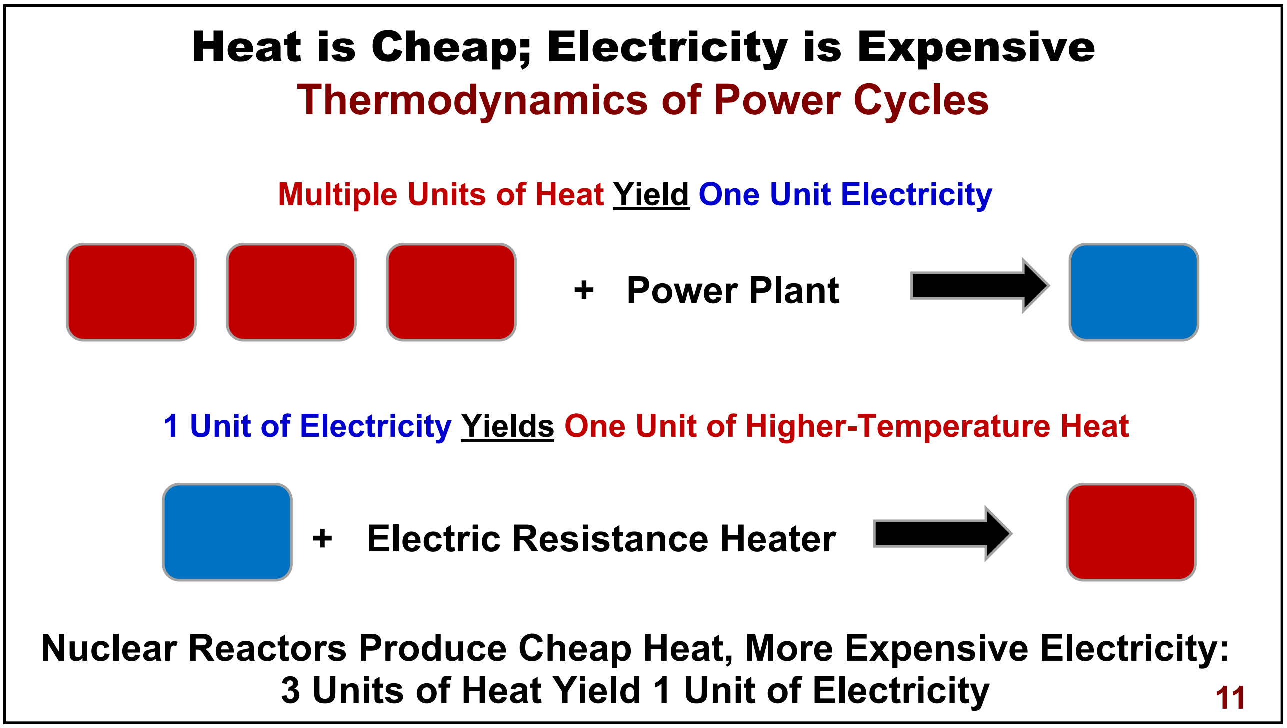
Davis-Besse Nuclear Power Plant LTE-PEM

Nine Mile Point Nuclear Power Plant LTE/PEM

Thermal & Electrical Integration at Xcel Energy Nuclear Plant HTE/Vendor 1

HTE/ SOEC efficiency is 20-30% higher than LTE/PEM

Nuclear Heat Production Options



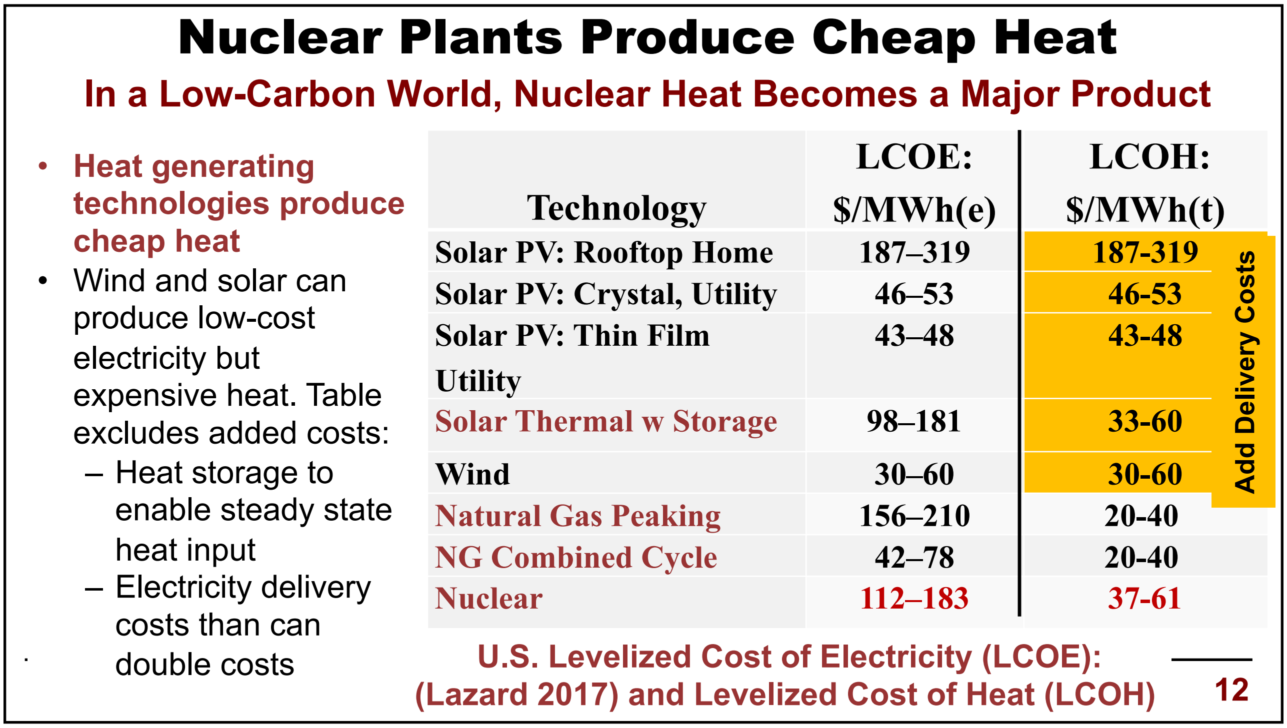
Heat is Cheap; Electricity is Expensive

Thermodynamics of Power Cycles

Multiple Units of Heat Yield One Unit Electricity

1 Unit of Electricity Yields One Unit of Higher-Temperature Heat

Nuclear Reactors Produce Cheap Heat, More Expensive Electricity:
3 Units of Heat Yield 1 Unit of Electricity



Nuclear Plants Produce Cheap Heat

In a Low-Carbon World, Nuclear Heat Becomes a Major Product

- **Heat generating technologies produce cheap heat**
- Wind and solar can produce low-cost electricity but expensive heat. Table excludes added costs:
  - Heat storage to enable steady state heat input
  - Electricity delivery costs than can double costs

Technology	LCOE: $/MWh(e)	LCOH: $/MWh(t)
Solar PV: Rooftop Home	187–319	187-319
Solar PV: Crystal, Utility	46–53	46-53
Solar PV: Thin Film Utility	43–48	43-48
Solar Thermal w Storage	98–181	33-60
Wind	30–60	30-60
Natural Gas Peaking	156–210	20-40
NG Combined Cycle	42–78	20-40
Nuclear	112–183	37-61

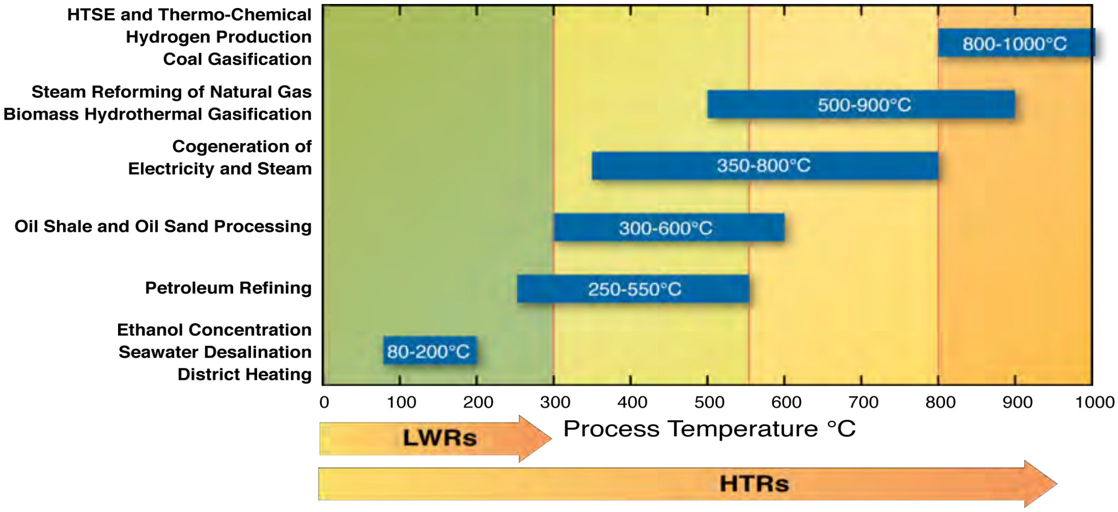
Add Delivery Costs

U.S. Levelized Cost of Electricity (LCOE): (Lazard 2017) and Levelized Cost of Heat (LCOH)

Different Biofuel Chemical Processes Require Different Peak Temperatures

Process	Temperatures (°C)
Biomass Drying	80 to 200
Torrification	250
Fast Pyrolysis	500
Refining (Distillation)	250 to 550
Cracking	700

Different Reactors Required For Different Applications

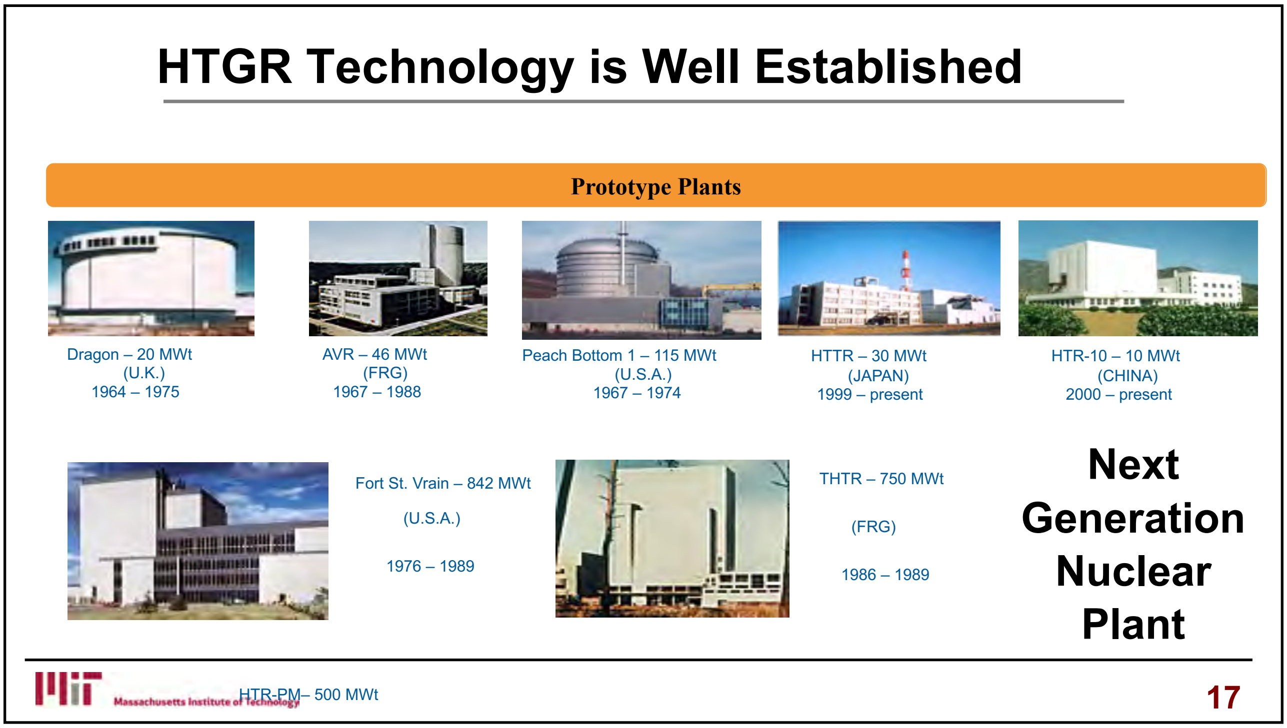


Required Temperatures Determines Reactor Type

Coolant	Inlet Temp. (°C)	Exit Temp. (°C)	Ave. Temp. (°C)	Status
Water	270	290	280	Commercial
Sodium	450	550	500	2020s
Helium	350	750	550	2020s: Designed for Industrial Heat
Salt	600	700	650	2030s

High-Temperature Gas-Cooled Reactors

Developed for Electricity and High-Temperature Industrial Heat



HTGR Technology is Well Established

Prototype Plants

Dragon – 20 MWt
(U.K.)
1964 – 1975

AVR – 46 MWt
(FRG)
1967 – 1988

Peach Bottom 1 – 115 MWt
(U.S.A.)
1967 – 1974

HTTR – 30 MWt
(JAPAN)
1999 – present

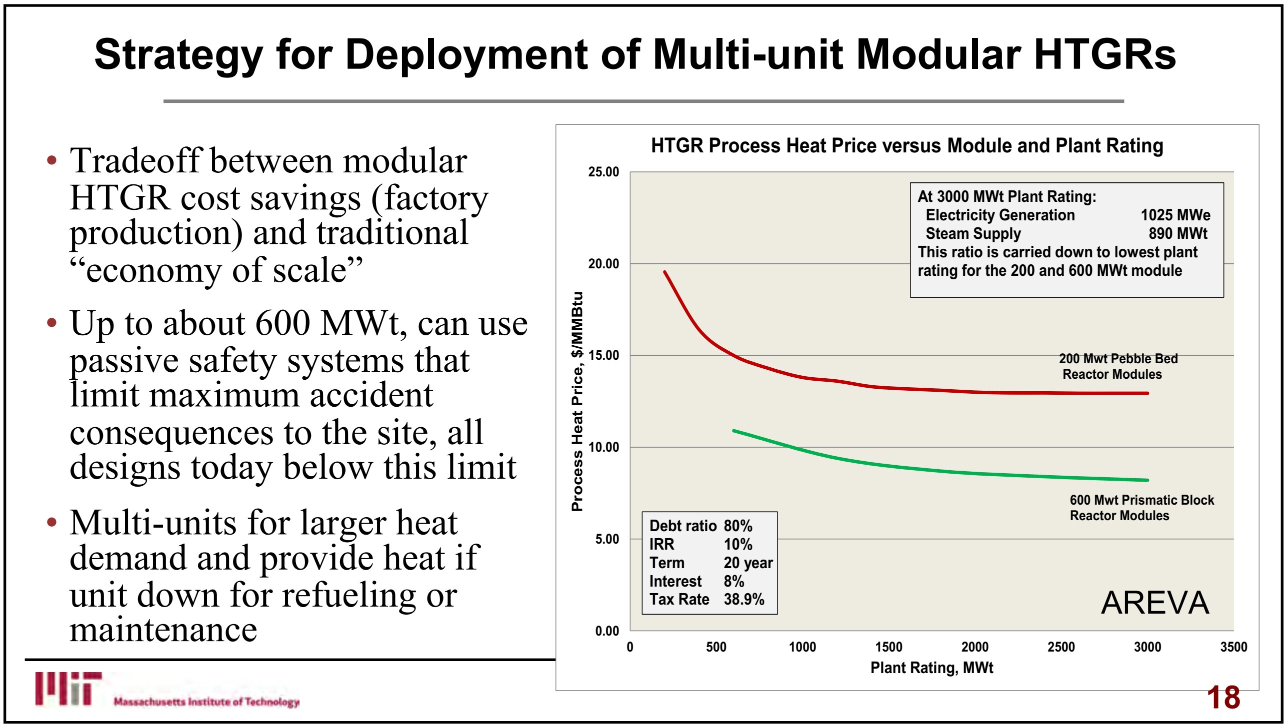
HTR-10 – 10 MWt
(CHINA)
2000 – present

Fort St. Vrain – 842 MWt
(U.S.A.)
1976 – 1989

THTR – 750 MWt
(FRG)
1986 – 1989

Next Generation Nuclear Plant

HTR-PM– 500 MWt



Strategy for Deployment of Multi-unit Modular HTGRs

- Tradeoff between modular HTGR cost savings (factory production) and traditional “economy of scale”
- Up to about 600 MWt, can use passive safety systems that limit maximum accident consequences to the site, all designs today below this limit
- Multi-units for larger heat demand and provide heat if unit down for refueling or maintenance

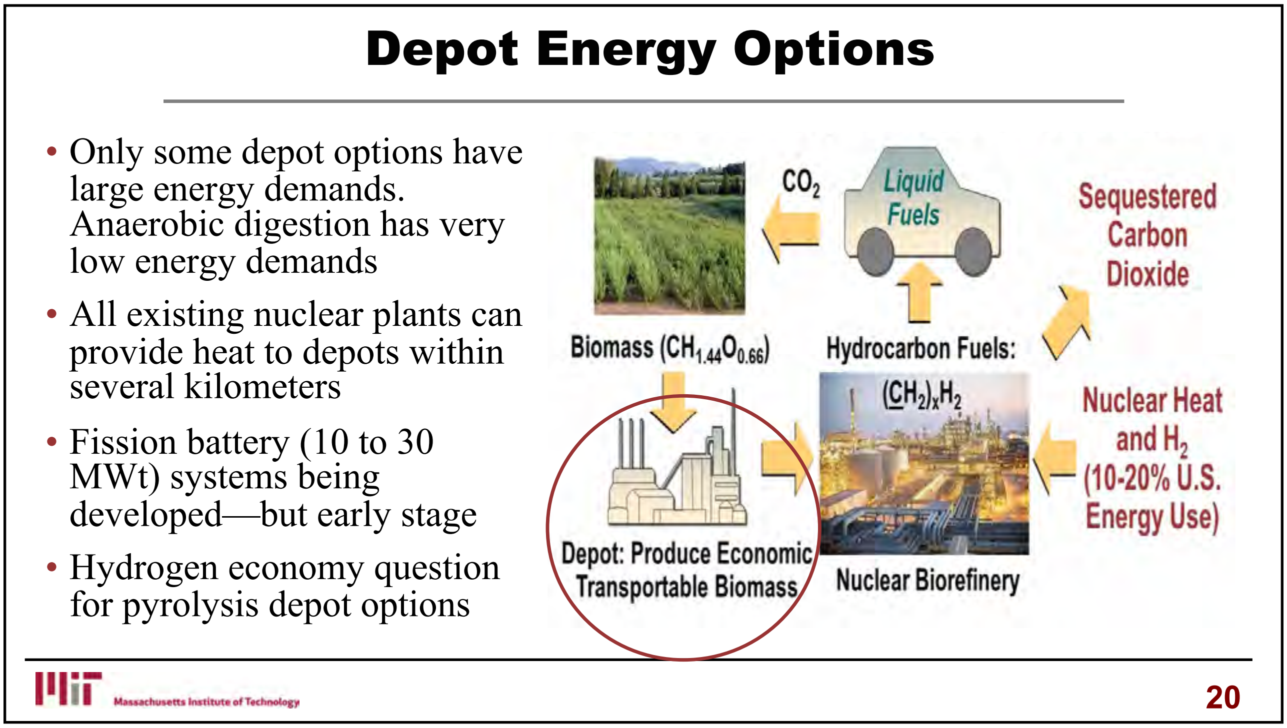
HTGR Process Heat Price versus Module and Plant Rating

At 3000 MWt Plant Rating:
Electricity Generation 1025 MWe
Steam Supply 890 MWt
This ratio is carried down to lowest plant rating for the 200 and 600 MWt module

Debt ratio	80%
IRR	10%
Term	20 year
Interest	8%
Tax Rate	38.9%

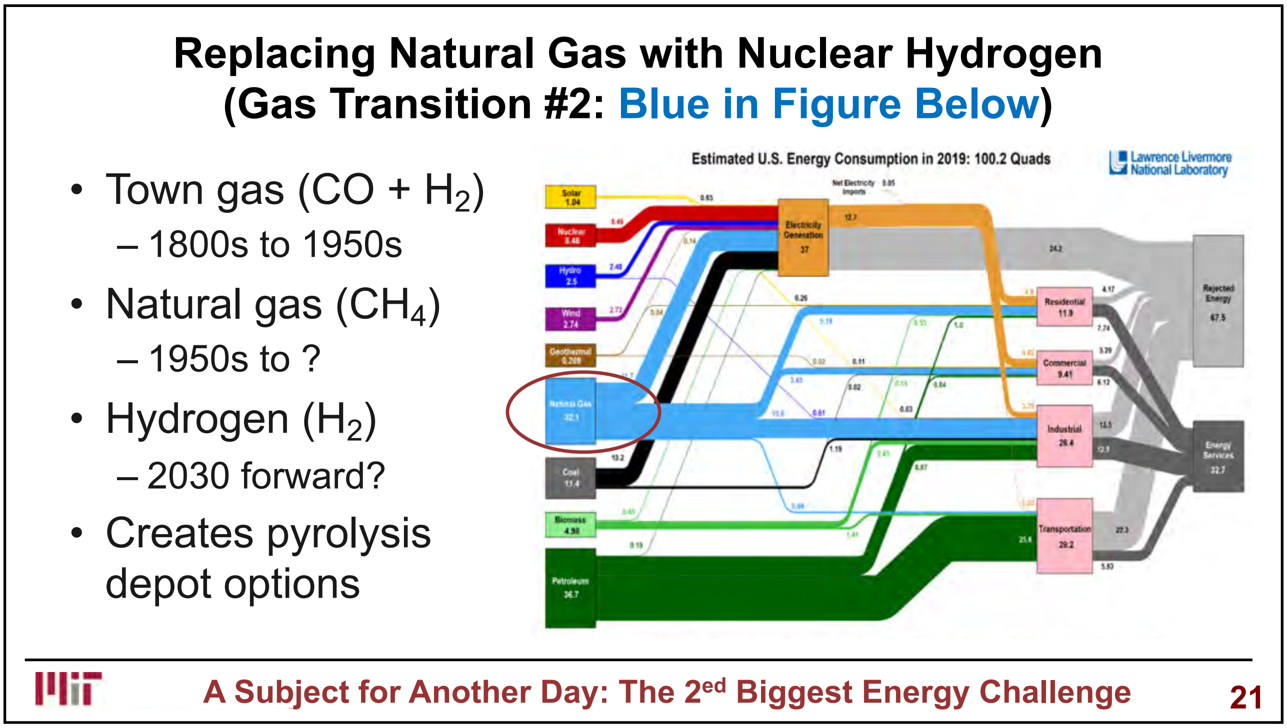
Current Status of High-Temperature Gas-Cooled Reactors

- Major DOE/Industrial program to commercialize HTGRs
  - Next Generation Nuclear Plant
  - DOW Chemical lead the industrial partnership
  - Fuel fuel testing and detailed designs
- Cheap natural gas put the program on hold except fuel qualification (long-lead time item)
- Effort is being reassembled, some of what is public and much of which is private
- Chinese first full-scale pebble-bed HTGR coming on line 2021



Depot Energy Options

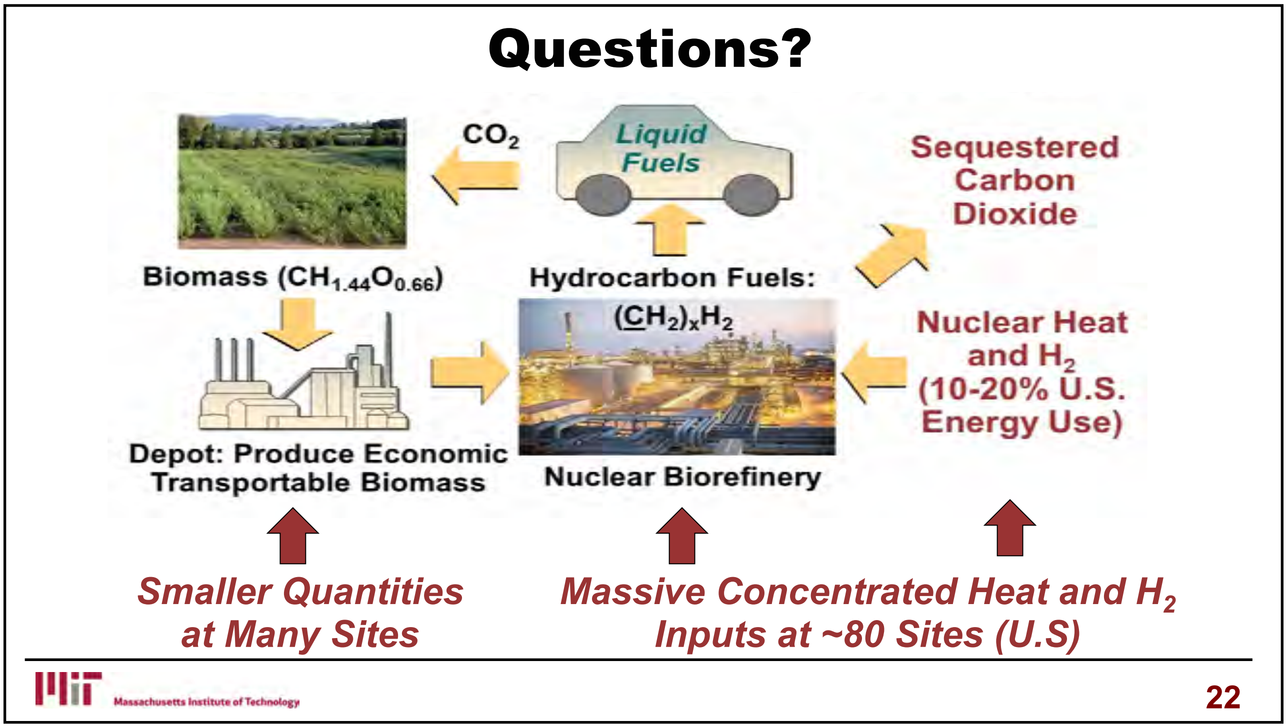
- Only some depot options have large energy demands. Anaerobic digestion has very low energy demands
- All existing nuclear plants can provide heat to depots within several kilometers
- Fission battery (10 to 30 MWt) systems being developed—but early stage
- Hydrogen economy question for pyrolysis depot options



Replacing Natural Gas with Nuclear Hydrogen (Gas Transition #2: Blue in Figure Below)

- Town gas (CO + H_2)
  - 1800s to 1950s
- Natural gas (CH_4)
  - 1950s to ?
- Hydrogen (H_2)
  - 2030 forward?
- Creates pyrolysis depot options

A Subject for Another Day: The 2ed Biggest Energy Challenge

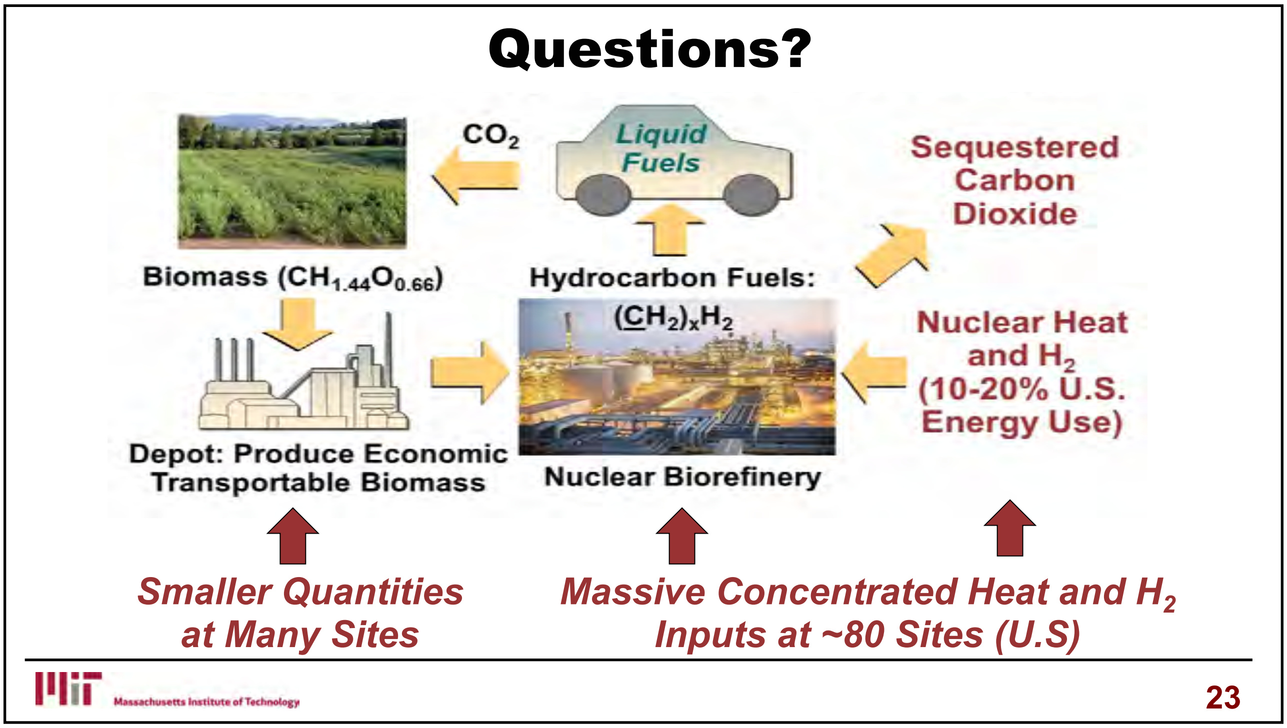


Questions?

Smaller Quantities at Many Sites

Massive Concentrated Heat and H_2 Inputs at ~80 Sites (U.S)

Massachusetts Institute of Technology



Questions?

CO_2

Liquid Fuels

Sequestered Carbon Dioxide

Biomass ($CH_{1.44}O_{0.66}$)

Hydrocarbon Fuels: $(CH_2)_xH_2$

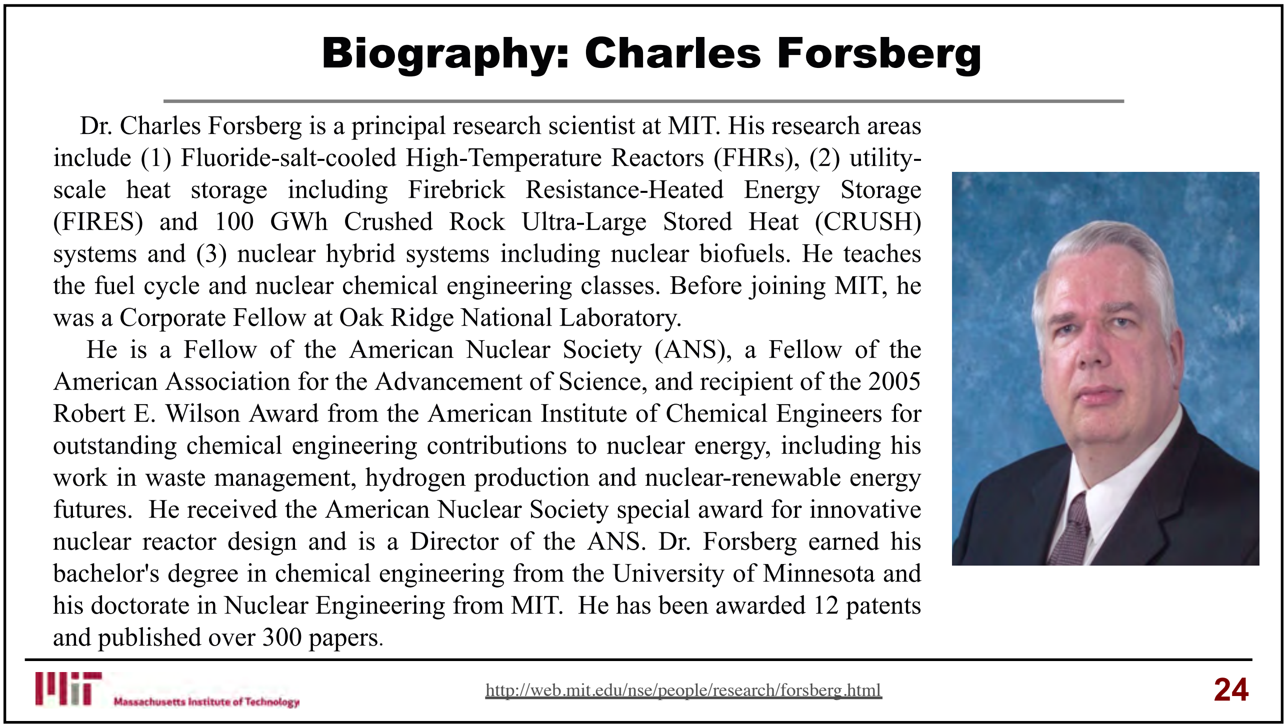
Nuclear Heat and H_2 (10-20% U.S. Energy Use)

Depot: Produce Economic Transportable Biomass

Nuclear Biorefinery

Smaller Quantities at Many Sites

Massive Concentrated Heat and H_2 Inputs at ~80 Sites (U.S)

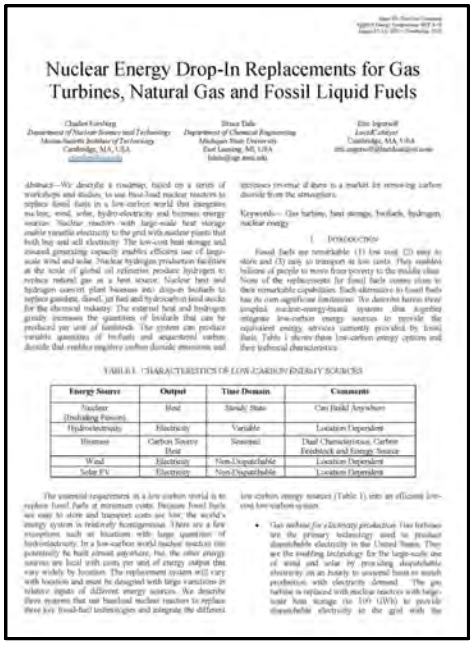


Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include (1) Fluoride-salt-cooled High-Temperature Reactors (FHRs), (2) utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh Crushed Rock Ultra-Large Stored Heat (CRUSH) systems and (3) nuclear hybrid systems including nuclear biofuels. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.

http://web.mit.edu/nse/people/research/forsberg.html



Nuclear Energy Drop-In Replacements for Gas Turbines, Natural Gas and Fossil Liquid Fuels

Applied Energy

ELSEVIER

Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries

C.W. Forsberg, B.E. Dale, D.S. Jones, T. Hossain, A.R.C. Morais, L.M. Wendt

https://doi.org/10.1016/j.apenergy.2021.117225

Nuclear path to H_2 Earthshot Target: $1/kg-$H_2$ within a decade