# Can We Replace All Crude Oil Using a Cellulosic Liquid Biofuels System with Nuclear-Assisted Massive Heat and Hydrogen Inputs?

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*October 14, 2022*
*Oak Ridge National Laboratory*

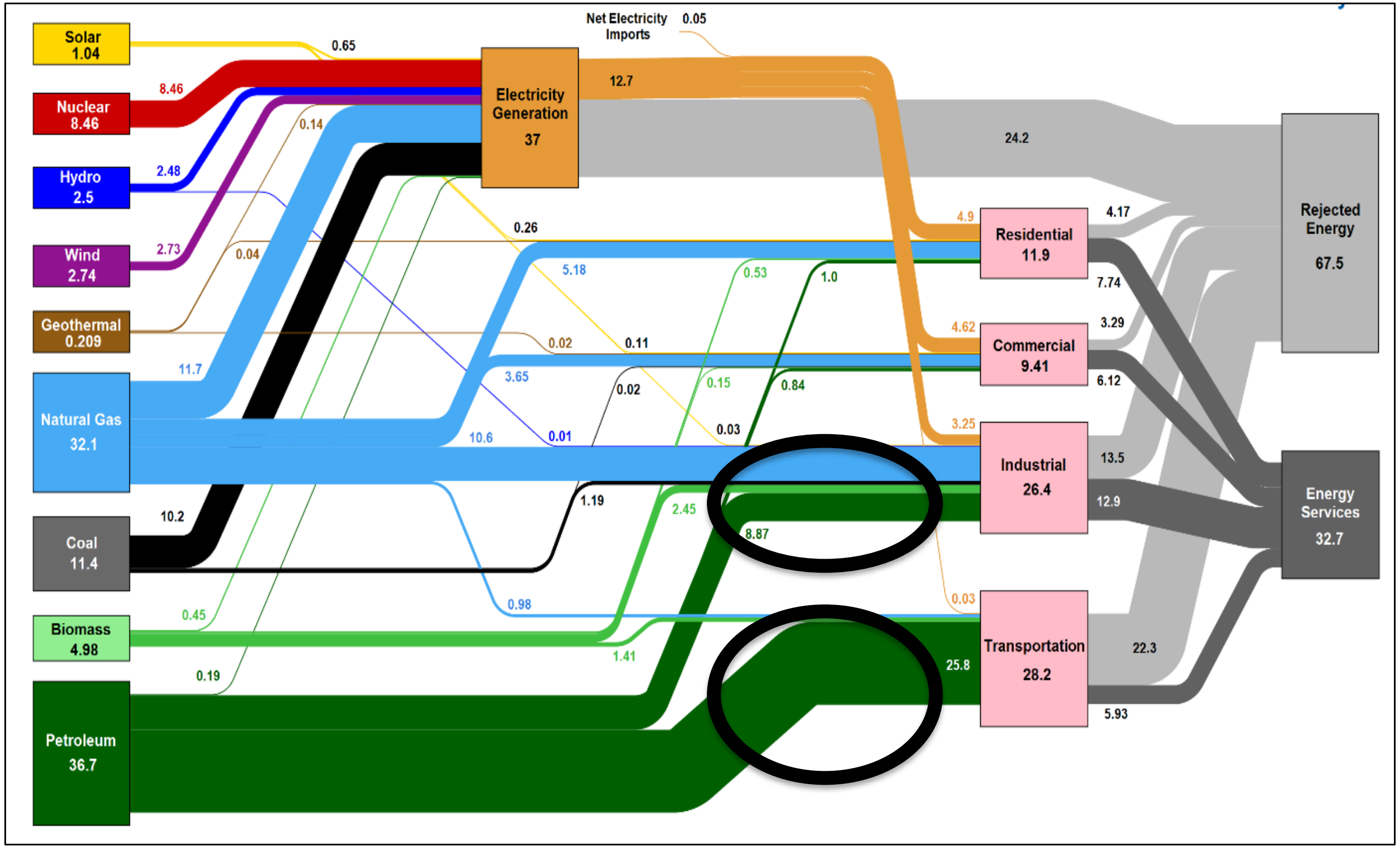
# Goals

- Replace all crude oil (domestic and international) with economic drop-in liquid hydrocarbon fuels with no major impacts on food and fiber prices
- Enable economic large-scale negative carbon emissions
- Minimize changes to enable fast low-carbon transition—faster scale up of hydrocarbon alternatives
- Enable greater rural prosperity / economic opportunities

**Goals / Conclusions from Several Studies and Three Workshops**

# Liquid Hydrocarbons Are Central To The U.S. Economy

- Crude oil provides 48% of U.S. energy and feed stocks to the final customer
- Drop-in hydrocarbon replacement for crude oil will decarbonize half the U.S. economy
- Option to partly replace natural gas




**Globally Oil Provides One-Third Energy Demand**

# The World Will Not Stop Using Liquid Hydrocarbons

- Embedded by 150 years of technology development and infrastructure investments
- Multiple uses—not just energy!
  - Dense transportable energy source
  - Energy storage
  - Chemical feedstock
  - Chemical reducing agent
  - Enable high-temperature radiative heat transfer in industry

| Product | U.S.: Millions of barrels per day |
|---|---|
| Finished motor gasoline | 8.034 |
| Distillate fuel oil (diesel fuel and heating oil) | 3.776 |
| Hydrocarbon gas liquids (HGLs) | 3.197 |
| Kerosene-type jet fuel | 1.078 |
| Still gas | 0.611 |
| Asphalt and road oil | 0.342 |
| Petrochemical feedstocks | 0.286 |
| Petroleum coke | 0.260 |
| Residual fuel oil | 0.217 |
| Miscellaneous products and other liquids | 0.152 |
| Lubricants | 0.100 |
| Special napthas | 0.045 |
| Aviation gasoline | 0.011 |
| Kerosene | 0.008 |
| Waxes | 0.004 |
| Total petroleum products | 18.120 |

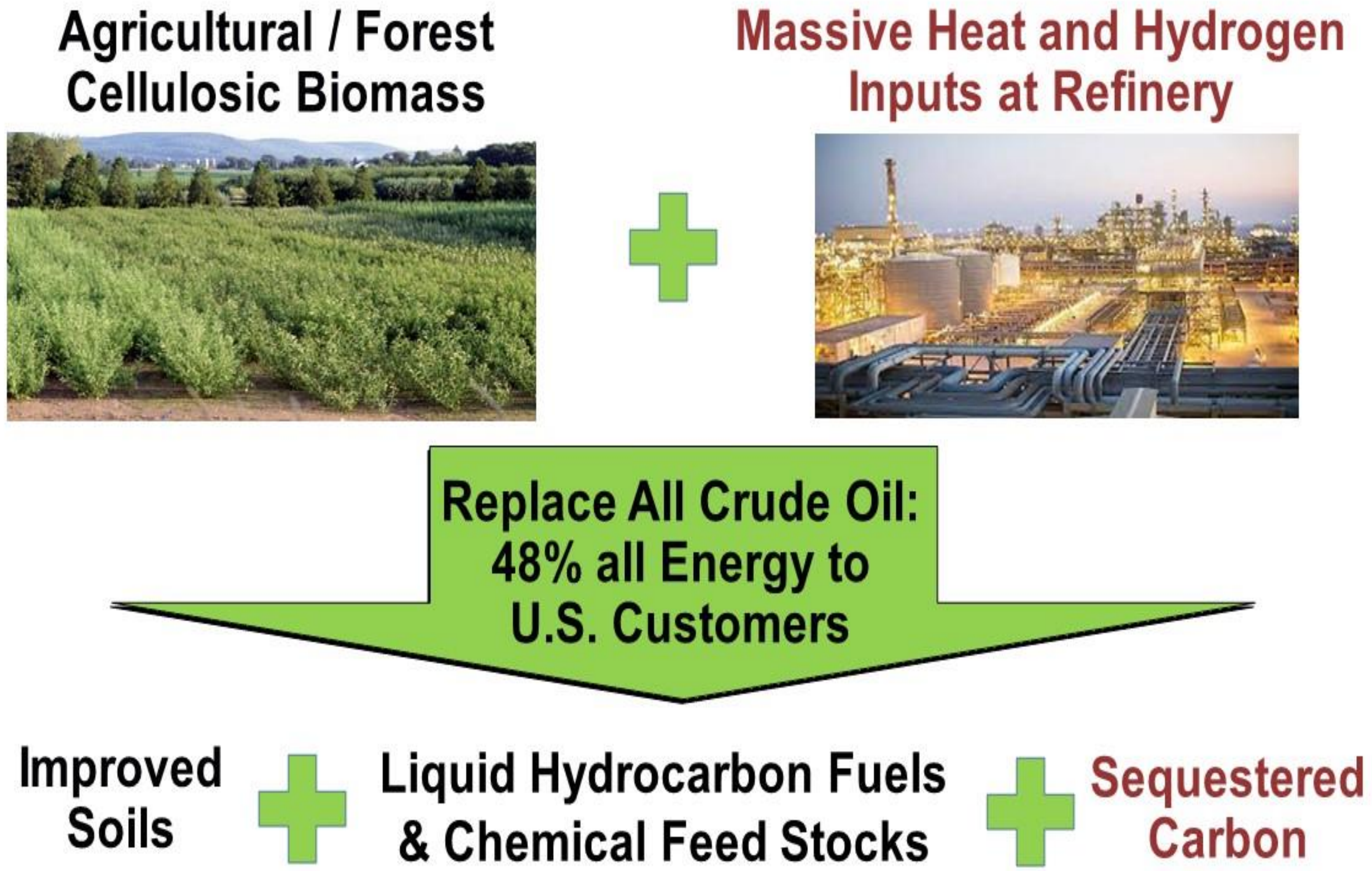
C. Forsberg, "What is the Demand for Low-Carbon Liquid Hydrocarbon Fuels and Feedstocks?" *Applied Energy Symposium: MIT* A+B, Cambridge, MA, APEN-MIT-2022_6226. July 5-8, 2022. https://www.energy-proceedings.org/category/mitab2022/

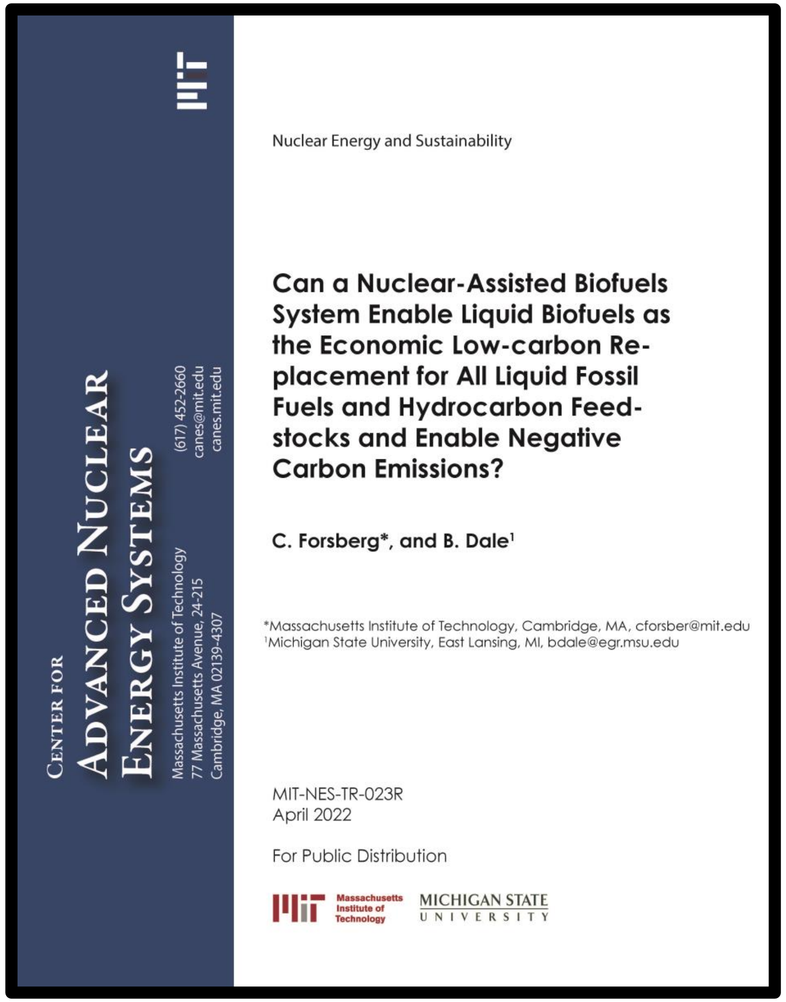
# Liquid Hydrocarbons Can be Made From Many Feed Stocks

- Fossil fuels: oil (primary source), coal and natural gas
- Carbon dioxide from air or water with addition of massive quantities of hydrogen (Electric fuels). Very expensive
- Biomass

**Hydrocarbons from Biomass and Carbon Dioxide Can be Made with No Increase in Atmospheric Carbon Dioxide Levels**

# The Big Picture: Replacing All Crude Oil



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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?**

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C. W. Forsberg and C., B. Dale, *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?*, Massachusetts Institute of Technology, MIT-NES-TR-023R. April 2022, https://canes.mit.edu/download-a-report

# Is There Enough Biomass in the U.S. and Globally to Replace All Crude Oil without Major Impacts on Food and Fiber Prices?

# We Can Replace All Crude Oil, But

- Can't be based on starches (corn), sugars (sugar cane) or oils (soybean, other) because of limited resource base
  - These feed stocks viable only for niche (small) markets
  - Current basis for biofuels
- Sufficient cellulosic feed stock (corn stover, forest debris, energy crops, etc.) if done right
  - Cellulose is the most abundant form of biomass on earth
  - Not a human food

# External Heat and Hydrogen During Processing Reduces Biomass Feedstock Required Per Unit of Product

| Function | Traditional Biofuels | External Heat + Hydrogen Biofuels |
|---|---|---|
| **1. Source of carbon for fuel or chemical feedstock** | **Biomass Carbon** Oxygenated or hydrocarbon | **Biomass Carbon** Hydrocarbons maximize energy per carbon |
| **2. Method for oxygen removal (40% of Biomass)** | **Biomass carbon** to remove oxygen as $CO_2$ | External **Hydrogen** to remove oxygen as water |
| **3. Energy source for biorefinery** | **Biomass carbon** to carbon dioxide | External nuclear **Heat** and hydrogen |
| **4. Limits to biofuels production** | **Biomass carbon** limited supply | **150% U.S. demand without impacting food / fiber prices** |

# Chemistry Basis: Heat and Hydrogen Inputs to Convert all Bio-Carbon into Liquid Fuels and Reduce Biomass Inputs

## Conventional Biofuels (Large Biomass Feedstock Requirements)

| Biomass | + | Oxygen | → | Hydrocarbons | + | Carbon Dioxide |
|---|---|---|---|---|---|---|
| $CH_{1.44}O_{0.66}$ | | $O_2$ | | $(CH_2)_xH_2$ | | $CO_2$ |

Carbon used to make hydrocarbon fuels (gasoline, diesel and jet fuel), remove oxygen and provide energy for the process

## Nuclear-Assisted (Reduced Biomass Feedstock Requirements)

| Biomass | + | Hydrogen | + | Nuclear | → | Hydrocarbons | + | Water |
|---|---|---|---|---|---|---|---|---|
| $CH_{1.44}O_{0.66}$ | | $H_2$ | | Heat | | $(CH_2)_xH_2$ | | $H_2O$ |

**Carbon only in hydrocarbon product, sufficient cellulosic biomass**

# Sufficient U.S. Cellulosic Feedstock for 25 Million Barrels per Day Hydrocarbons Without Large Impact on Food and Fiber Prices

## We Estimate 2050 Demand 10 to 20 Million Barrels/Day

- External heat and hydrogen doubles hydrocarbon fuel production per ton of biomass feed stock
- Can use feed stocks that are good carbon sources (wet biomass including kelp) but poor energy sources
- Can pay more for biomass because hydrogen (not biomass) is the largest cost component in product (discussed later)

# U.S. Cellulosic Biomass Feedstock Supply

- Most abundant type of biomass
- Minimize impact on food and fiber prices
- U.S. ~3,000 million tons/yr (at least)
- Equivalent 25+ million barrels/day crude oil
- U.S. consumes 18 million barrels/ day of crude oil

- 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
- Double cropping: +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

**In Addition, Marine Sources Such as Kelp**

# What Is the System Design?

# Economics Have Driven Oil Refineries to Large Sizes (Typical Refinery 250,000 Barrels per Day)

- Economics of Scale
- Ability to change product slate over the year that maximizes revenue (gasoline versus home heating oil, etc.)
- Ability to blend low-grade (low-cost) crude oils with other crude oils to enable using lower-cost feed stocks

# Same Economics Drives to Large Bio-refineries

## Modified Oil Refinery with Front-End Bio-Crude Production

**250,000 Barrel/day**

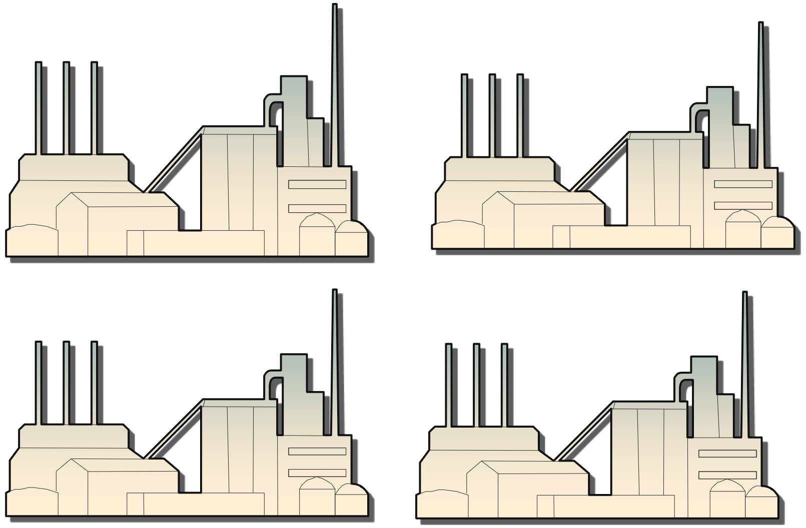
**Option for Crude-Oil Refinery with Front-End Changes**

- Nuclear reactors provide **gigawatts of heat** input; not “burn” biomass to operate refinery
- **Pipeline Hydrogen** from natural gas with CCS and nuclear steam electrolysis removes oxygen from biomass that is 40% oxygen by weight
- **External heat and $H_2$**
  - **More than doubles hydrocarbon fuels per ton of biomass reducing land demand by more than two**
  - **Enables use of lower-grade biomass feed stocks**

# Economic Shipping Distance for Raw Biomass is 30 to 50 Miles

## Need Depots to Convert Raw Biomass Into Shippable form to Refinery:

Cellulosic Biomass Shipped Short Distances to Depots



Depots Convert Local Low-Density Biomass into Economically Shippable Commodity

250,000 b/d Integrated Bio-refinery for Liquid Hydrocarbons

# Depot System Design

Create Economic Shippable Commodity to Refinery

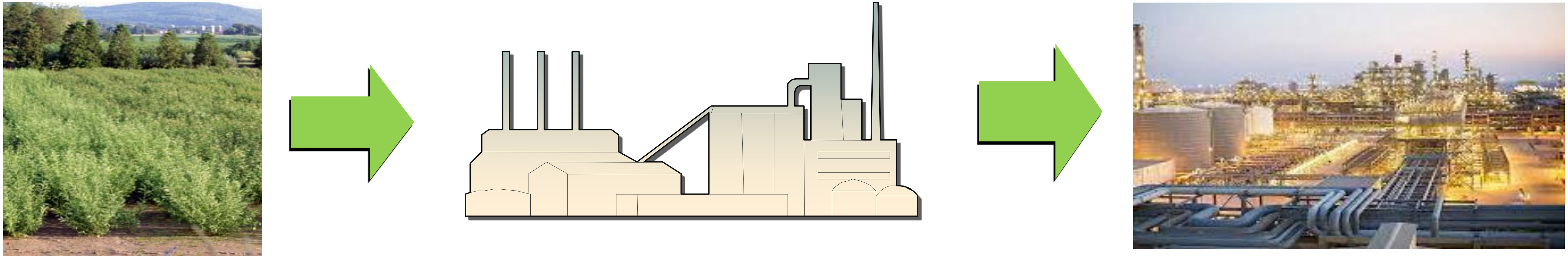
Produce Other Products

Recycle Nutrients to Soils

Enable Local & Farm Economic Opportunities

# The Local Depot Is The Enabling Technology

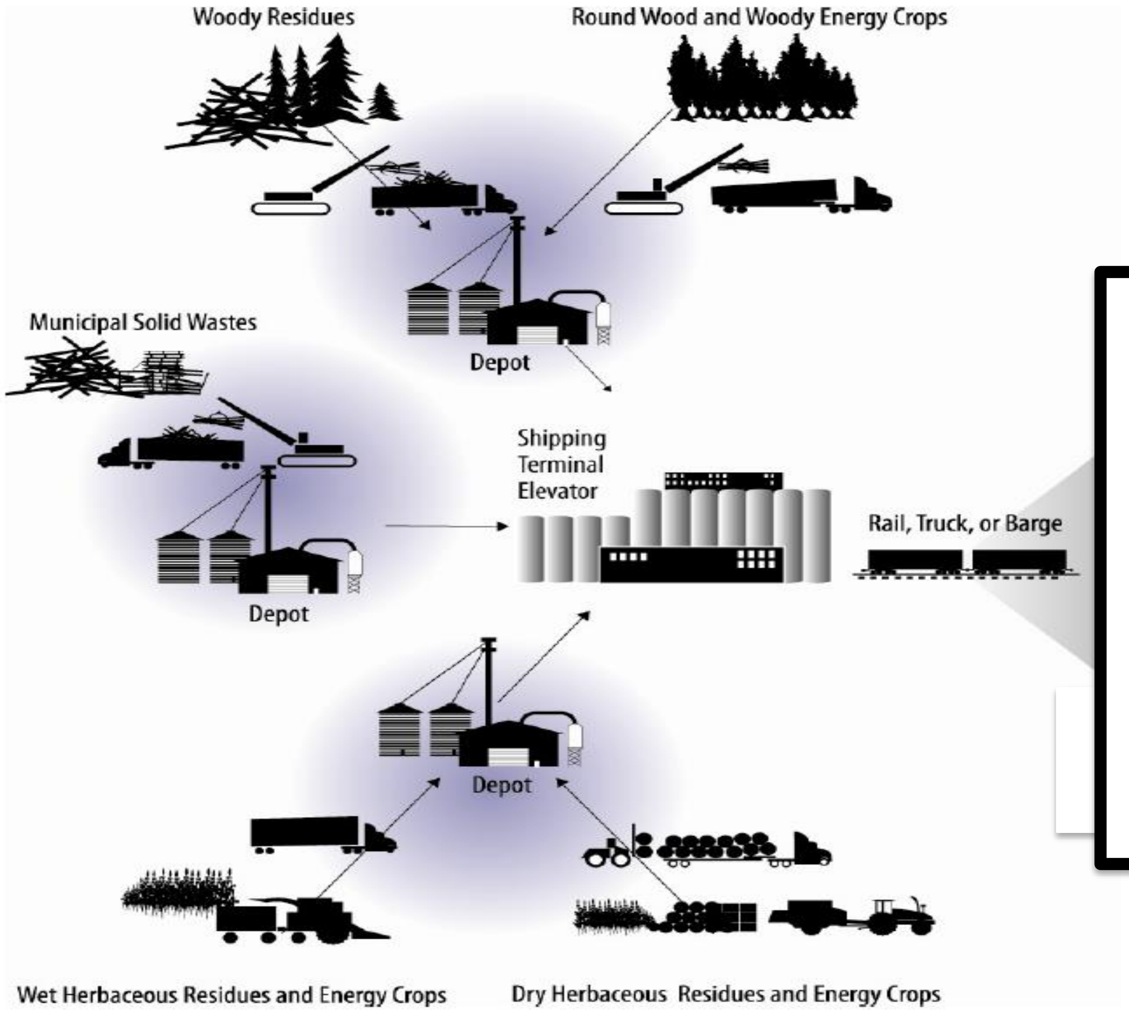
## Not Economic to Ship Low-Density Biomass Long Distances



- Local depots convert local raw biomass into storable, economic shippable (unit train and pipeline) commodities to large biorefineries
- Depots have multiple other functions
  - Recycle nutrients and some carbon back to the soil
  - Produce secondary products to increase farm revenue (Example: alfalfa leaves for animal food, stems for liquid hydrocarbon production)

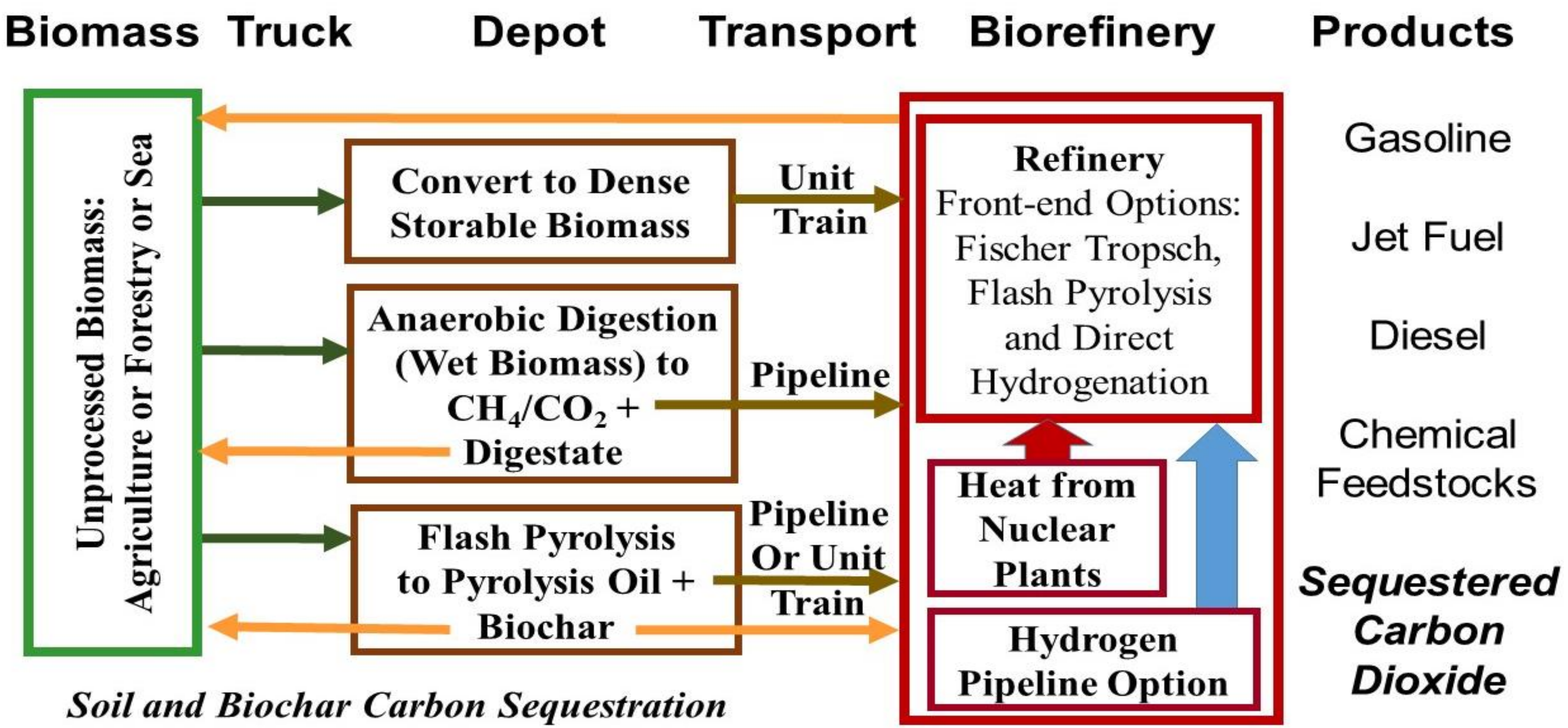
# Depots Convert Diverse Biomass Into a Few Commodity Feedstocks for the Refinery

- Forests
  - Forest wastes
  - Paper and pulp plant wastes
- Municipal wastes
- Agriculture
  - Corn stover
  - Wheat straw
  - Double crops
  - Energy crops
- Maritime (Kelp, etc.)




Large Bio-refineries with Massive Heat and Hydrogen Inputs

# We Have Three Major Depot Options




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

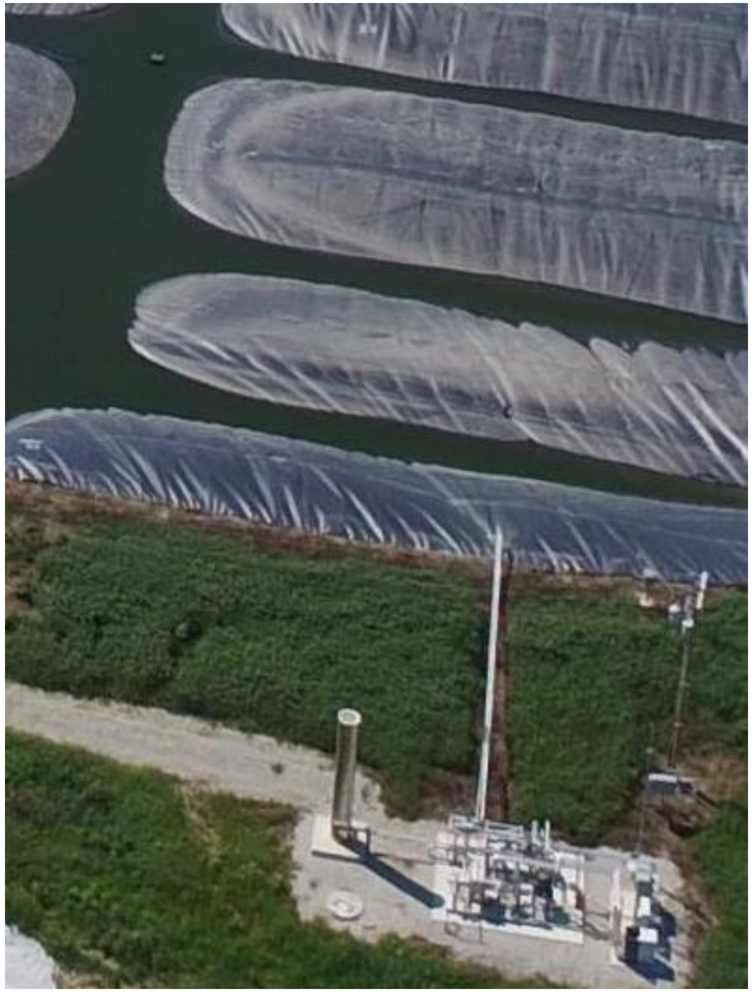
# Pelletization Creates Dense, Stable, Shippable Product

- Increase bulk density from $< 60$ kg/m$^3$ to $> 600$ kg/m$^3$
- Variants of process used to ship animal feeds and biomass for combustion


**DRAX Power Station (UK) Burns 7 Million Tons Pellets per Year**

# Anaerobic Digestion Produces Methane ($CH_4$), Carbon Dioxide ($CO_2$) and Digestate

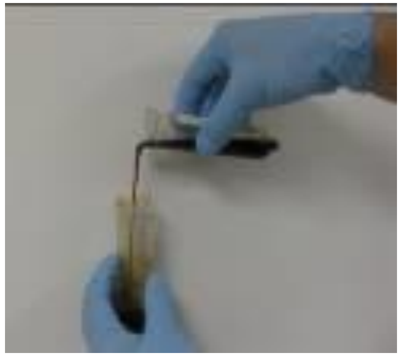
- Ship anaerobic $CO_2$/$CH_4$ and/or purified $CH_4$ by pipeline, store like natural gas
- Process is commercial for some feedstocks in some countries
- Digestate contains almost all the nutrients for recycle to soil and demonstrated at scale to improve long-term soil productivity with soil carbon sequestration



# Biofuels Fast Pyrolysis Depot Option

## Commercial on a Small Scale

| | | | | | | |
|---|---|---|---|---|---|---|
| **Biomass** | → | **Bio-oil** | **+** | **Char** | **+** | **Gases** |
| **(100%)** | **=** | **(up to 70%)** | **+** | **(~15%)** | **+** | **(~15%)** |

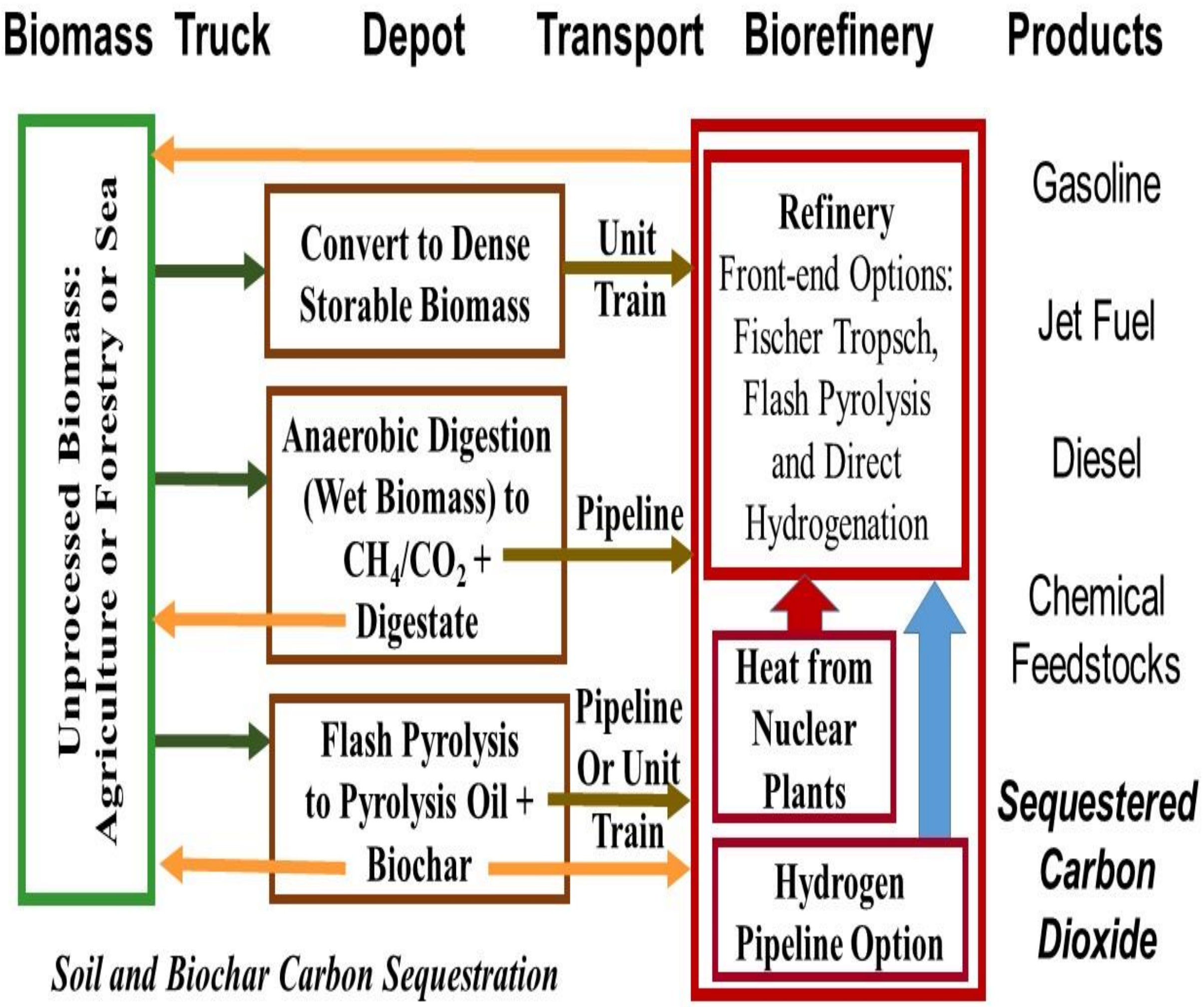
- Pyrolysis is thermal composition without oxygen (~500ºC)
- If external energy inputs (Fission Batteries), more product produced
- **Char with nutrients recycled to soil (Carbon sequestration)**

C. H. Lam et. al, "Towards Sustainable Hydrocarbon Fuels with Biomass Fast Pyrolysis Oil and Electrocatalytic Upgrading", *Sustainable Energy and Fuels*, 1 (2) April 2017

G. L. Hawkes, S. Bragg-Sitton and H. Hu, "Nuclear-Assisted Carbon-Negative Biomass to Liquid Fuel Process Integration with High Temperature Steam Electrolysis" *ICAPP 21*, October 2021

# Can Recycle Nutrients, Sequester Carbon in Soil and Improve Long-Term Soil Productivity

- Food, paper and timber remove soil nutrients with no built-in recycle loop
- **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 and improve soil properties



# Refinery Design

**Front-end Processes Create a Bio-Crude**

**Refinery Converts Bio-Crude to Refined Products**

# Modify Existing Refineries for Depot Feeds

**250,000 Barrel/day**

**Option for Crude-Oil Refinery with Front-End Changes**

- Front-end processes create bio-crude
  - Fischer Tropsch (Anaerobic digestion and pelletized biomass feedstock)
  - Direct hydrogenation (pelletized biomass and pyrolysis oil feedstock)
  - Flash Pyrolysis (pelletized biomass feedstock)
- Require conventional refinery for conversion into final gasoline, diesel, jet fuel and chemical feedstock products
- Crude oil refinery incrementally converts from 100% crude oil to 100% biomass feed stocks
  - Blend feed stocks to match refinery capabilities

# Refineries Require Massive Heat Inputs

- Existing refineries burn the equivalent of 10% of the crude oil to operate (~5% U.S. energy consumption)
- Heat demand in gigawatts
- Bio-refinery feedstock will drag in large quantities of water, Larger heat demand
- Nuclear energy can provide steady-state low-carbon heat

Dow and X-Energy agreement for nuclear reactors to provide process heat at a Dow Texas plant site

# Bio-Refineries Require Massive Hydrogen Inputs

- Today: Steam methane reforming of natural gas with sequestration of carbon dioxide with multiple process options
  - Lowest cost option if low-cost gas and sequestration sites
  - Some systems can sequester 97% carbon dioxide
- Nuclear with high-temperature (steam) electrolysis
  - High efficiency relative to alternatives
  - Early pre-commercial deployment
- Electrolysis with wind and solar: Too early for evaluation
  - Uneconomic today because of high capital cost of electrolyzers
  - Very expensive hydrogen if operate electrolyzer at low part load
  - Low capacity factor with solar (25%)


- American Petroleum Institute, (October 12, 2022) The Potential Role of Blue Hydrogen in Low-Carbon Energy Markets in the U.S. https://www.api.org/~/media/Files/News/2022/10/12/API-ICF-Hydrogen-Report

# Cost Structure of New Biofuels System

**Cellulosic Biomass ($CH_{1.44}O_{0.66}$) Carbon Feedstock**

- Partly replacing biomass feedstocks with nuclear heat and external $H_2$
- Liquid fuels provide half the energy to final customer
- **U.S. feedstock for 25+ million barrels of oil per day; Use 18 million barrels/day and decreasing**

| Biofuel Cost Category | Cost Oil Equivalent ($/Barrel) |
|---|---|
| Hydrogen ($2/kg) | 38 |
| Biomass at refinery gate | 23 |
| Add capital to refinery | 7 |
| Total | 68 |

# The Cost Structure Can Dramatically Increase Available Cellulosic Biomass

- With traditional biofuels, the biomass is the primary cost
- With new strategy, biomass is does not drive biofuels prices.
- Can pay a more for biomass
  - For 90 years the challenge of American agriculture has been excess production
  - Corn yields from 20 to 180 bushels per acre—and rising
  - Single crop rather than double crop land because no market
  - What if somebody decided to pay farmers a little more for biomass?
  - If history is a guide, massive increases in cellulosic biomass likely
  - Similar options with forests and other sources of cellulosic biomass

# Other Considerations

# Cellulosic Biofuels with External Heat and $H_2$ Minimize Impacts on Food and Fiber Prices

- Feedstock is cellulosic biomass, not a major food source
- Integrated systems can boost food and fiber production
  - Depots separate valuable components (proteins, carbohydrates, etc.) from cellulosic materials. Many of these are animal foods
  - Depots recycle of carbon and nutrients to improve long-term soil productivity (vs food mining nutrients)
- U.S. agriculture not fully utilizing resources (example: little double cropping that also reduces soil erosion)

# System Enables Large Negative Carbon Emissions

- Depots recycle carbon to soil (digestate and biochar) that improves soil productivity while sequestering carbon
- Refinery can vary carbon dioxide sequestration based on <u>relative prices of feedstock, sequestered carbon dioxide and biofuels</u>
  - Second class of products from biorefinery
  - Adjust fuel/sequestered carbon dioxide production based on prices of biomass, biofuels and hydrogen
  - **Stabilize price of liquid hydrocarbons (fuels)**

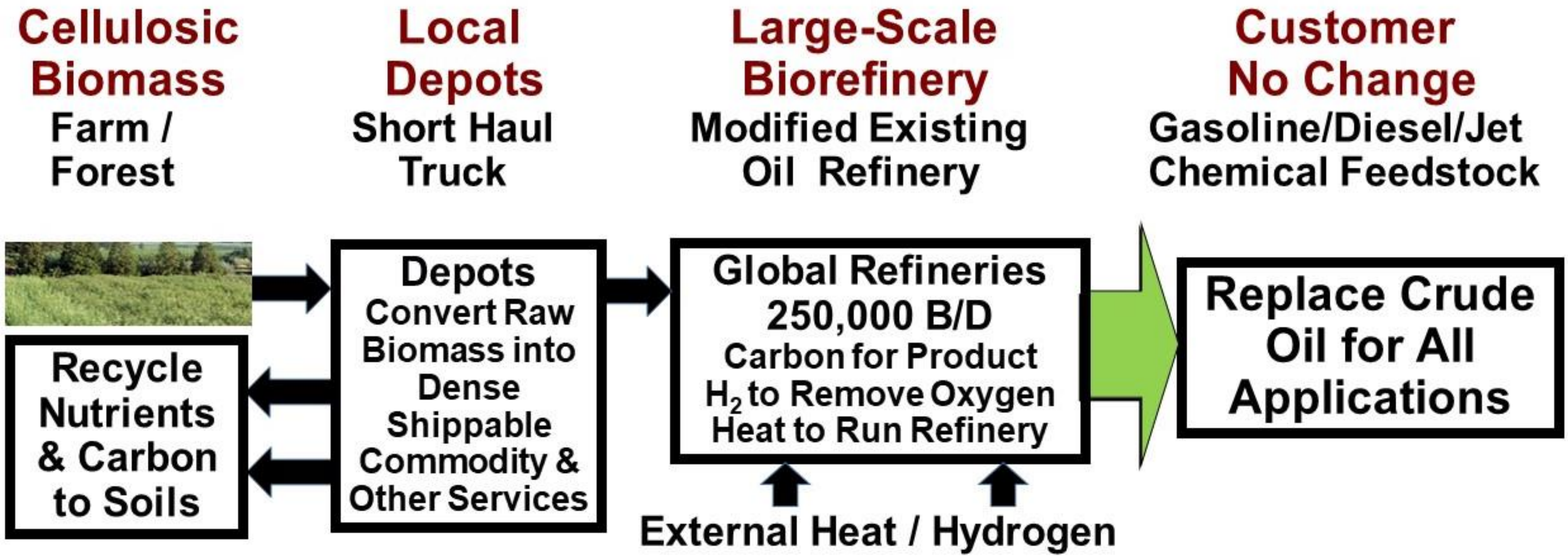
# Potentially Massive Positive Impacts on Rural America, American Soils and American Forests

- Recycle of carbon recycles nutrients and improvise long-term soil productivity—not mining soils like food production
- Creates a market for forest wastes—incentive to recycle these wastes with reduced potential for forest fires
- Large increases in rural incomes

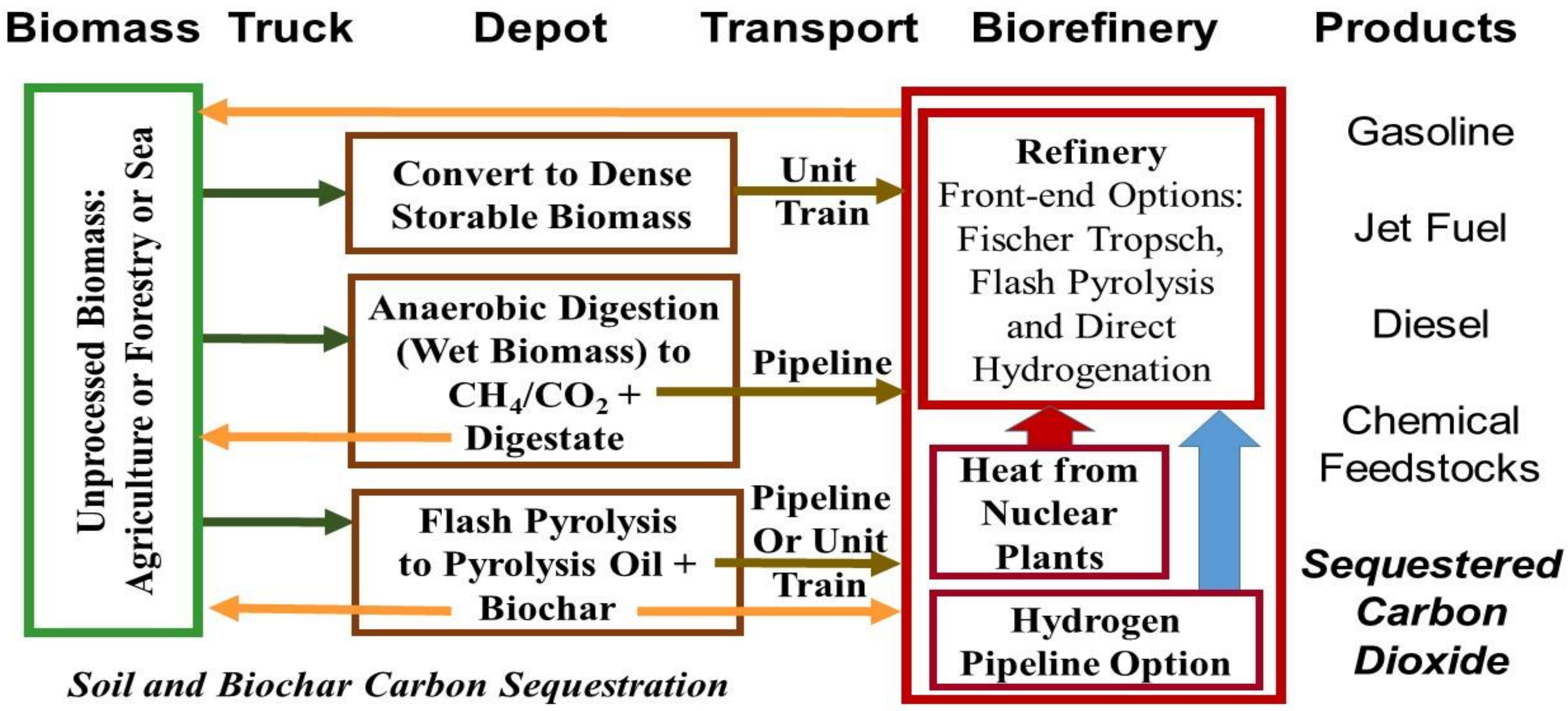
# Uncertainties Are Significant

- U.S. hydrocarbon demand 2050
  - 10 million barrels/day with highly successful electricity and hydrogen substitution into multiple liquid hydrocarbon markets
  - 20 million barrels/day if fail to solve energy storage challenges and need liquid hydrocarbons to fix storage challenge
- Cellulosic inventories
  - No detailed assessment if the goal is carbon to produce fuel versus burning biomass as energy source (traditional accounting, campfire model)
  - Wildcards: Marine sources (Kelp, etc.) not accounted for; Capability of American agriculture over time to boost production if price incentives
  - Competing carbon demand for renewable natural gas
- Processing: Efficient direct hydrogenation of cellulosic biomass

# Conclusion: Cellulosic Hydrocarbon Biofuels Can Replace Crude Oil, Decarbonize a Third of the Global Economy & Sequester Carbon with Massive External Heat / $H_2$ Inputs



# Questions



Biomass
Truck
Depot
Transport
Biorefinery
Products
Unprocessed Biomass: Agriculture or Forestry or Sea
Convert to Dense Storable Biomass
Unit Train
Anaerobic Digestion (Wet Biomass) to $CH_4/CO_2$ + Digestate
Pipeline
Flash Pyrolysis to Pyrolysis Oil + Biochar
Pipeline Or Unit Train
Refinery
Front-end Options: Fischer Tropsch, Flash Pyrolysis and Direct Hydrogenation
Heat from Nuclear Plants
Hydrogen Pipeline Option
Gasoline
Jet Fuel
Diesel
Chemical Feedstocks
*Sequestered Carbon Dioxide*
*Soil and Biochar Carbon Sequestration*

# 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-assisted cellulosic 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.

# Nuclear-Assisted Biofuels Is Not New

NUCLEAR ENERGY FOR A LOW–CARBON-DIOXIDE–EMISSION TRANSPORTATION SYSTEM WITH LIQUID FUELS

FUEL CYCLE AND MANAGEMENT

KEYWORDS: *liquid fuels, shale oil, biofuels, oil refining*

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*The two major energy challenges for the United States are to replace crude oil in our transportation system and reduce greenhouse gas emissions. A multilayer strategy to replace oil using nuclear energy and various carbon sources (fossil fuels, biomass, or air) is described that (a) allows the continued use of liquid fuels (ethanol, gasoline, diesel, and jet fuel) in the transport sector, (b) does not require major changes in lifestyle by the consumer, and (c) ultimately eliminates carbon dioxide emissions from the transport sector. Nuclear energy is used to provide electricity, heat, and ultimately hydrogen, with the hydrogen produced by either electrolysis or more advanced thermochemical production methods.*

*In the near term, nuclear energy can provide low-temperature heat (steam) for ethanol production and electricity for transportation. Midterm options include low-temperature heat and limited quantities of hydrogen for processing cellulosic biomass into liquid fuels (ethanol and lignin-derived hydrocarbons) and providing high-temperature heat for (a) traditional refining and (b) underground oil production and refining. In the longer term, biomass becomes the feedstock for liquid-fuels production, with nuclear energy providing heat and large quantities of hydrogen for complete biomass conversion to hydrocarbon fuels. Nuclear energy could be used to provide over half the total energy required by the transportation system, and the use of oil in the transport sector could potentially be eliminated within several decades.*

I. INTRODUCTION

The two major energy challenges for the United States are to replace crude oil in our transportation system and eliminate greenhouse gas emissions. A series of studies have been conducted on methods to use nuclear energy to replace some or all of the crude oil and ultimately eliminate carbon dioxide emissions from the transportation system. These options are described and quantified. Together the options provide a transition strategy to eliminate oil for the transportation sector. The starting point for such an analysis is an understanding of the existing and future demand for liquid fuels.

I.A. Choice of Transport Fuel

The dominance of liquid hydrocarbon fuels for transportation is based on several factors: (a) they can be easily made from crude oil, and (b) they have major advantages in terms of high energy density, ease of refueling, and safety. Energy density strongly impacts engine choices, vehicle weight, fuel economy, and the distance between refuelings. Table I shows the properties of various possible future transport fuels[1] with different types of engines. These data show significant advantages in safety and vehicle range by using liquid fuels such as diesel versus less conventional fuels.

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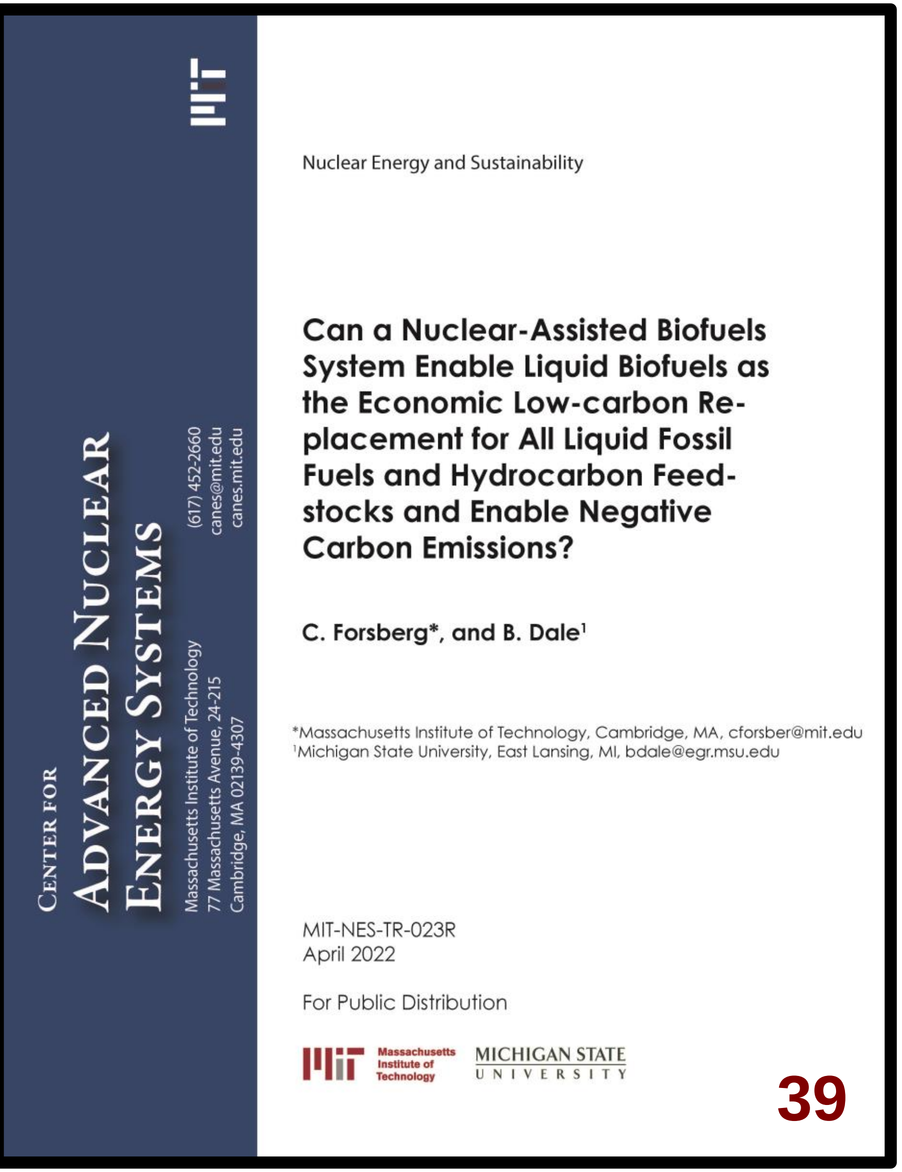
C. W. Forsberg, "Nuclear Energy for a Low-Carbon-Dioxide-Emission Transportation System with Liquid Fuels," *Nuclear Technology*, **164**, 348-367, December 2008. https://doi.org/10.13182/NT164-348

C. W. Forsberg and C., B. Dale, *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?*, Massachusetts Institute of Technology, MIT-NES-TR-023R. April 2022**,** https://canes.mit.edu/download-a-report



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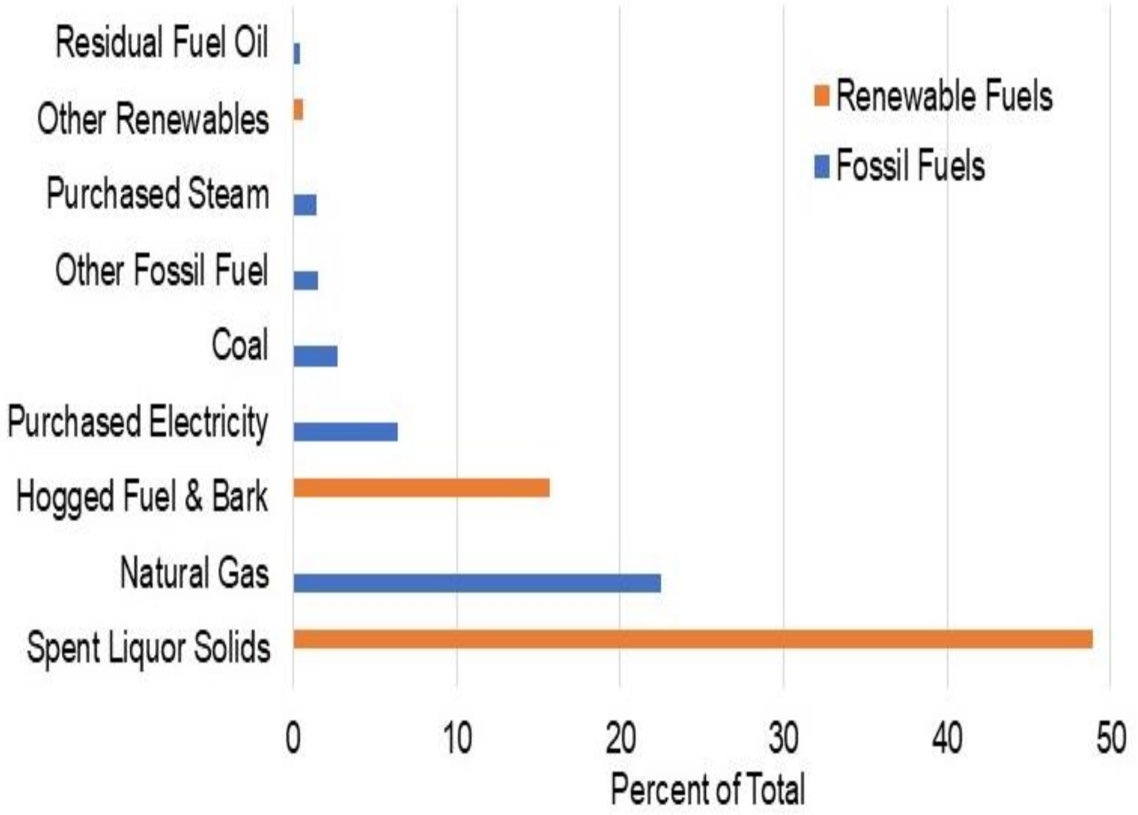
# Nuclear Energy for Conversion of Pulp and Paper Plants into Pulp, Paper and Liquid Hydrocarbon Biofuels Plants



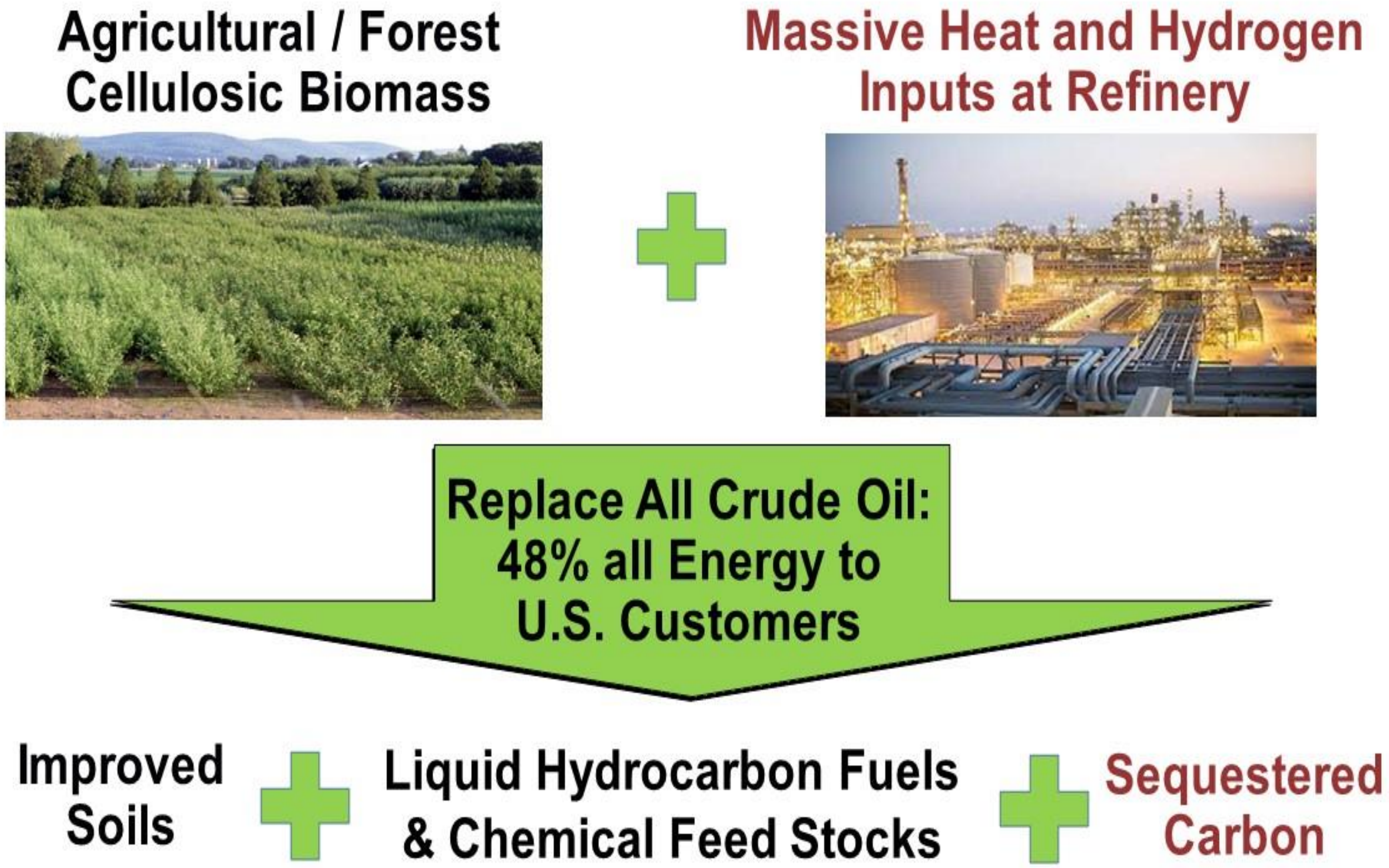

Energy Consumption of Pulp and Paper Plant

- Paper and pulp mills have massive energy consumption
- Most energy input from burning biomass wastes from the paper making process (Left: orange lines)
- If external heat and hydrogen replaces burning biomass, waste biomass can be converted into hydrocarbon liquids
- Large increase in plant revenues and production of low-carbon biofuels
- Unique nuclear energy market

C. W. Forsberg and C., B. Dale, *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?*, Massachusetts Institute of Technology, MIT-NES-TR-023. April 2022. https://canes.mit.edu/download-a-report

Charles Forsberg (cforsber@mit.edu)

# Replacing All Crude Oil with Cellulosic Feed Stocks to Produce Drop-In Hydrocarbon Fuels (Gasoline, Diesel, Jet Fuel, Chemical Feed-stocks)




- Reduce atmospheric carbon dioxide content
- Fast transition to low-carbon future with drop-in gasoline, diesel and jet fuel
- No major impacts on food and fiber prices
- Minimize cellulosic feed stock requirements with external heat + hydrogen for biomass conversion to hydrocarbons (remove O, add H, process heat)


C. W. Forsberg and C., B. Dale, *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?*, Massachusetts Institute of Technology, MIT-NES-TR-023. April 2022. https://canes.mit.edu/download-a-report



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# Abstract: 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?

This report integrates the results of a series of studies and three virtual workshops held in August 2021 to address the question: *Can a nuclear-assisted biofuels system enable liquid biofuels as the economic low-carbon replacement for all liquid fossil fuels and hydrocarbon feedstocks and simultaneously enable negative carbon emissions?* "Economic" is defined as economically competitive relative to other low-carbon replacement options for crude oil. "All" refers to the capability to replace the 18 million barrels of oil per day used by the United States. "Nuclear-assisted" refers to the provision of massive quantities of low-carbon heat and hydrogen at the refinery to fully utilize the carbon content of the cellulosic biomass feedstocks for liquid hydrocarbon production.

A system is proposed that decarbonizes about half of the U.S. economy while improving long-term soil productivity and sequestering carbon from the atmosphere. In the U.S. almost half the energy consumed by the final customer is in the form of liquid hydrocarbons. The feedstock used to produce these liquid hydrocarbons is primarily crude oil—but a small fraction of liquid hydrocarbons are produced from coal, natural gas and biomass. Liquid hydrocarbons are used as (1) an energy source, (2) a method for daily-to-seasonal energy storage, (3) a chemical feedstock, (4) a chemical reducing agent, (5) a method to enhance high-temperature heat transfer in many furnaces and industrial processes and (6) other purposes. As a consequence, the U.S. consumes ~18 million barrels of crude oil per day to produce liquid hydrocarbons. While there are substitutes for liquid hydrocarbons for some applications, our assessment is that the costs and difficulty will dramatically increase if liquid hydrocarbon use goes much below the equivalent of 10 million barrels per day of crude oil. New uses of liquid hydrocarbons to partly replace coal and natural gas could increase demand to the equivalent of 20 million barrels per day of oil.

One can produce and burn liquid hydrocarbons from biomass without any net addition of carbon dioxide to the atmosphere. Plants grow by removing carbon dioxide from the atmosphere; thus, burning biomass does not result in any net addition of carbon dioxide to the atmosphere. Biomass is typically 40% oxygen. To remove this oxygen to create hydrocarbon liquids, there are two options.  The first option is to use biomass as (1) a feedstock, (2) an energy source to operate the process and (3) a supply of carbon to remove the biomass oxygen as carbon dioxide. The second option is to use external heat and hydrogen to remove the oxygen as water and produce liquid hydrocarbons. The use of massive quantities of external heat and hydrogen for hydrocarbon liquid fuels production reduces the biomass feedstock per unit of liquid hydrocarbon product by more than a factor of two reducing land use by more than a factor of two. Many cellulosic feedstocks unsuitable for liquid hydrocarbon production are viable feedstocks with external heat and hydrogen inputs. As a result, there is sufficient cellulosic feedstocks to meet U.S. and global liquid fuels hydrocarbon demand without significant impacts on food and fiber prices.

The heat and hydrogen (heat plus electricity) are produced using base-load nuclear power plants—the most economic form of nuclear energy. If low-price natural gas, there is also the option of producing hydrogen from natural gas with sequestration of the carbon dioxide. The biomass is locally processed in depots to produce commodity feedstocks that can be shipped long distances to large biorefineries (250,000 barrels per day, oil equivalent) similar to existing refineries except modifications of front-end processes. The depot system enables local recycle of nutrients back to the soil. The biorefinery can produce variable quantities of liquid hydrocarbon fuels and carbon dioxide for sequestration enabling removal of carbon dioxide from the atmosphere. Preliminary estimates are that the liquid hydrocarbon costs are equivalent to crude oil at between $60 and $70 per barrel. The largest cost is for hydrogen with biomass feedstocks and refinery costs a smaller fraction of the total cost.