Cellulosic Hydrocarbon Liquids with Massive External Heat and Hydrogen Inputs to Replace All Crude Oil, Enable Negative Carbon Emissions and Support Sustainable Agriculture and Forestry

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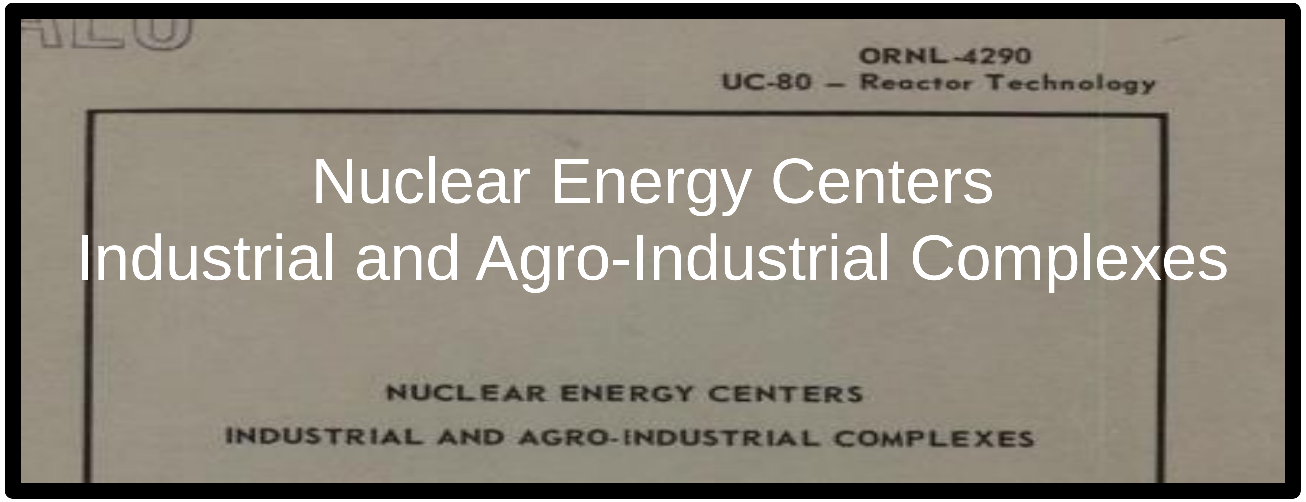
Must Consider Global Agro-Industrial-Energy Systems:

Alvin Weinberg Strategy (1960s-1970s): First Director of ORNL

What is required for a world of 10 billion people with a middle-class standard of living?

Global Agro Industrial Energy Systems



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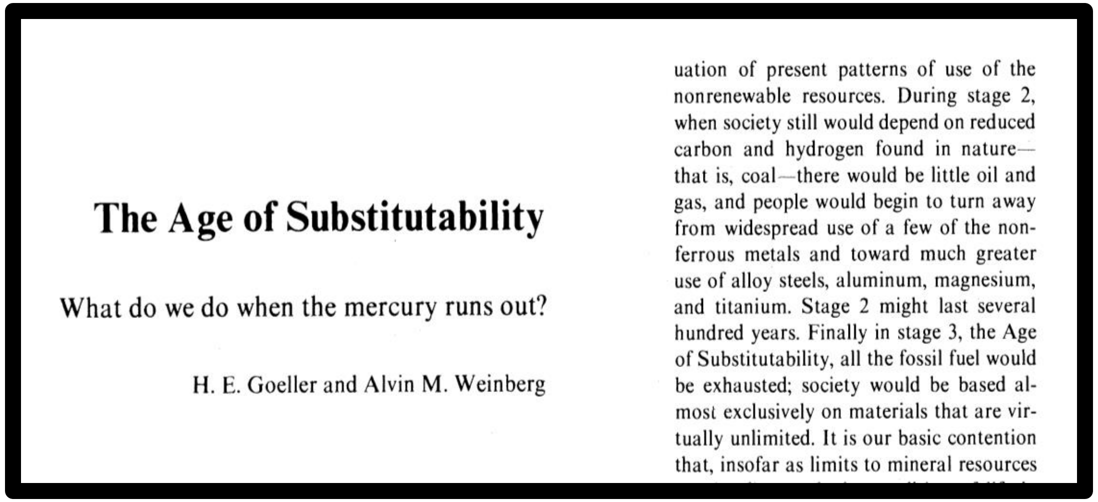
Global Availability of Materials



The Age of Substitutability

What do we do when the mercury runs out?

H. E. Goeller and Alvin M. Weinberg

uation of present patterns of use of the nonrenewable resources. During stage 2, when society still would depend on reduced carbon and hydrogen found in nature—that is, coal—there would be little oil and gas, and people would begin to turn away from widespread use of a few of the nonferrous metals and toward much greater use of alloy steels, aluminum, magnesium, and titanium. Stage 2 might last several hundred years. Finally in stage 3, the Age of Substitutability, all the fossil fuel would be exhausted; society would be based almost exclusively on materials that are virtually unlimited. It is our basic contention that, insofar as limits to mineral resources

https://www.science.org/doi/10.1126/science.191.4228.683

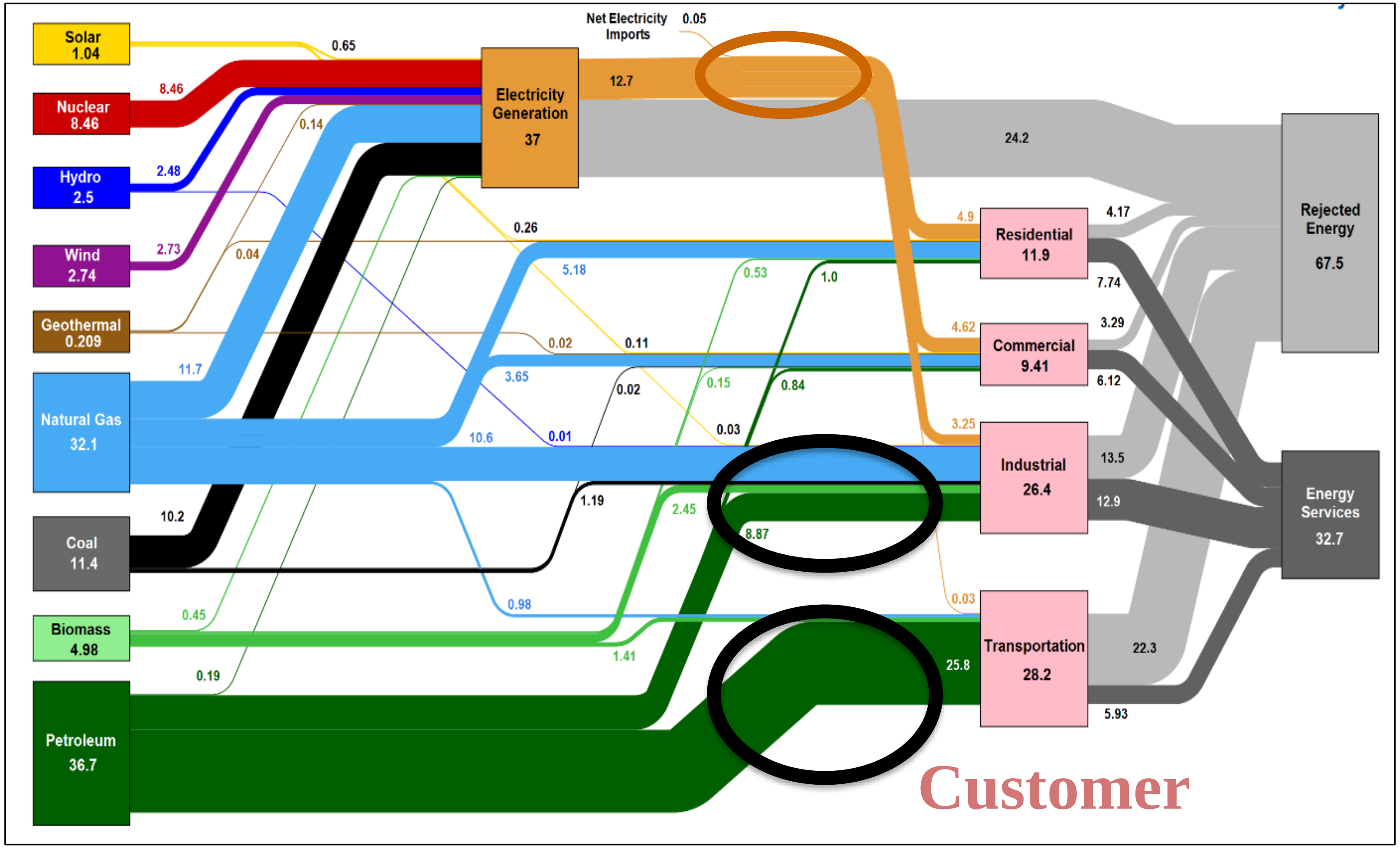
C. W. Forsberg and A. M. Weinberg, "Advanced Reactors, Passive Safety, and the Acceptance of Nuclear Energy", *Annual Reviews of Energy*, **15**: 133-152 (1990). https://www.annualreviews.org/doi/pdf/10.1146/annurev.eg.15.110190.001025

Goals

- Replace all crude oil with economic drop-in liquid hydrocarbon fuels and chemical feedstocks with no major impacts on food and fiber prices
- Enable economic large-scale negative carbon emissions
- Support long-term sustainable agriculture and forestry
- Minimize industrial changes to enable fast low-carbon transition—faster scale up of hydrocarbon alternatives
- Enable greater rural prosperity / economic opportunities

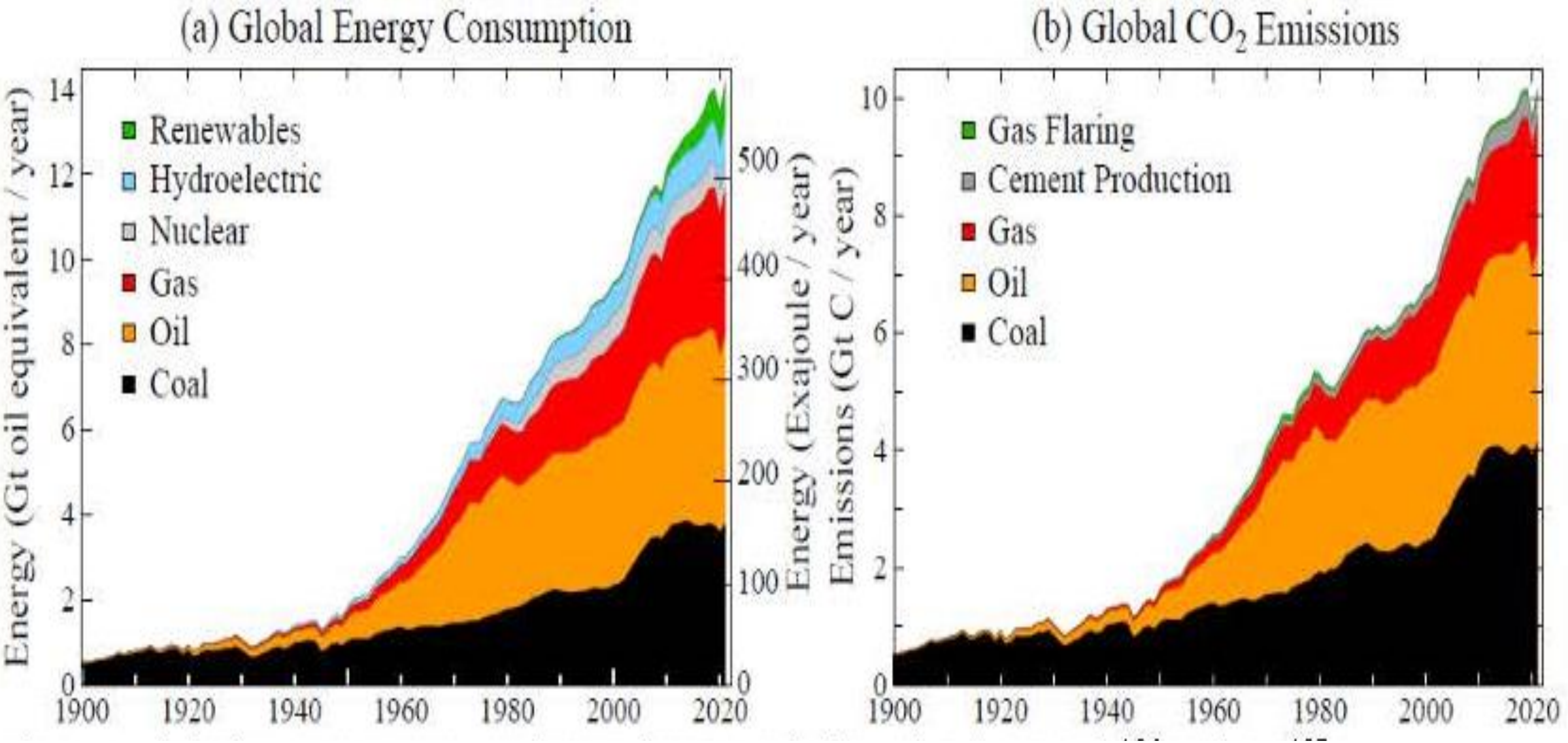
Liquid Hydrocarbons Are Central To The U.S. Economy

- **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
- Electricity 18% total energy to customer



Globally Oil Provides One-Third Energy Demand

Global Breakdown of Energy Sources and CO_2 Releases



Hefner et al (a) and BP (b)

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. W. Forsberg, "What is the Long-Term Demand for Liquid Hydrocarbon Fuels and Feedstocks?" *Applied Energy*, 341, 121104 (1 July 2023). https://doi.org/10.1016/j.apenergy.2023.121104

We Estimate Future Use at 10 to 16 Million Barrels / Day

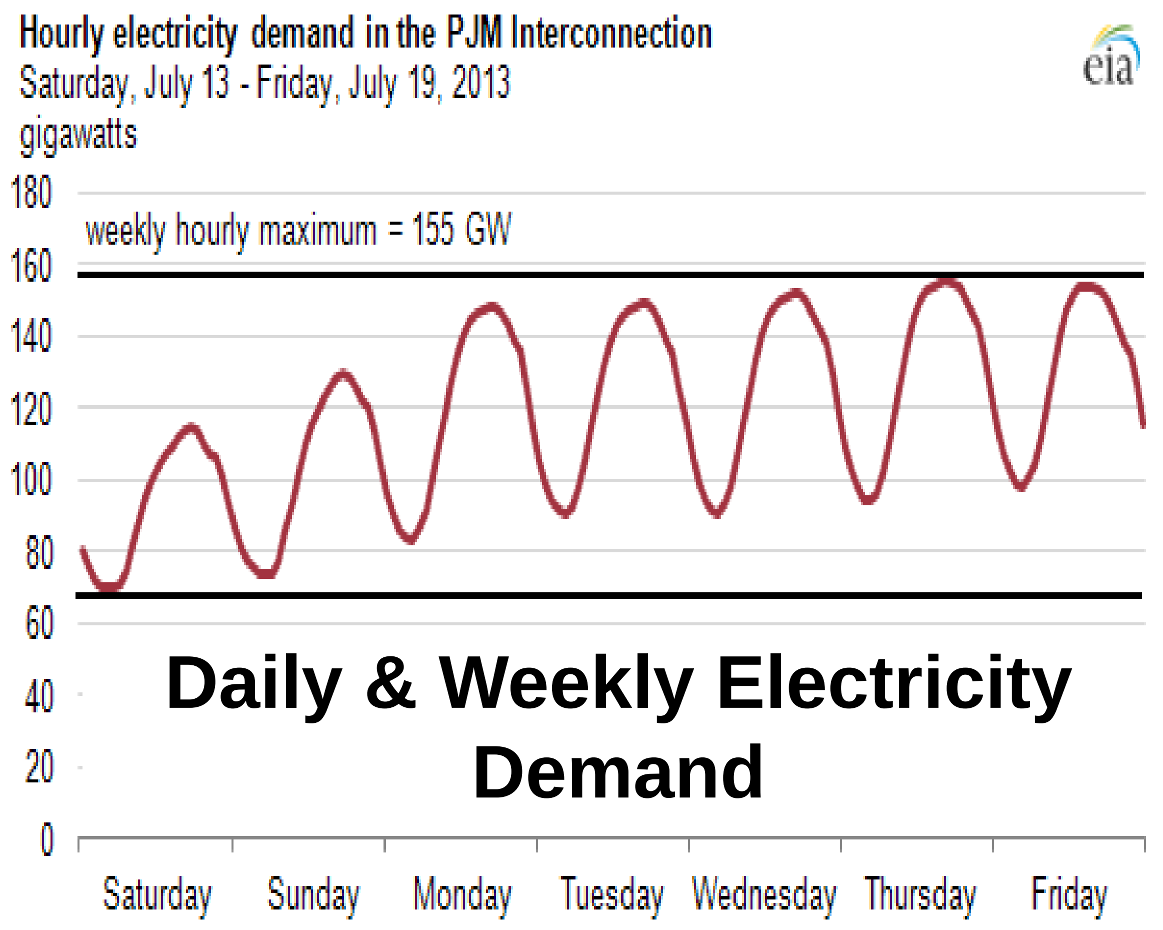
Existing U.S. Crude Oil Use: 18 Million Barrels per Day

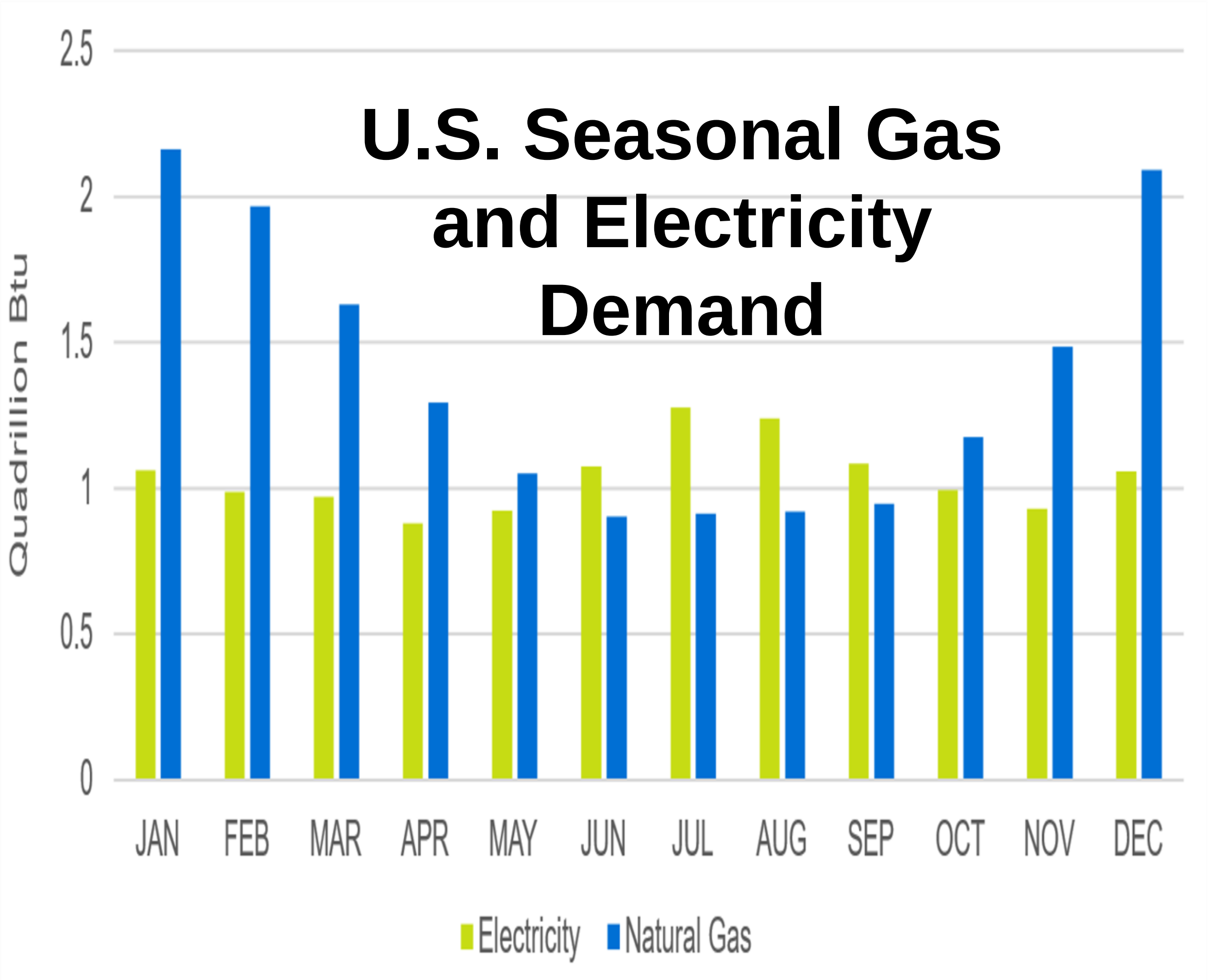
- Large-scale use of hybrid and plug-in hybrid light vehicles
- Limited use of all-electric vehicles because of high battery costs
- **Largest uncertainty ($6.1 \cdot 10^6$/day)—liquid hydrocarbons replace hourly to seasonal energy storage functions of coal and natural gas**

Hydrocarbon Liquid Use	10^6 Barrels/day
Chemical Applications	2.4
Trucks/Aircraft	4.0
Light Vehicles	2 to 3
New Uses/Other	1.0
Energy Storage	6.1

- C. W. Forsberg, "What is the Long-Term Demand for Liquid Hydrocarbon Fuels and Feedstocks?" *Applied Energy*, 341, 121104 (1 July 2023). https://doi.org/10.1016/j.apenergy.2023.121104

Biggest Hydrocarbon Fuel Demand Uncertainty:
What Replaces Natural Gas and Coal Role as Stored Energy?





American Gas Association, 2021. Net Zero Emissions Opportunities for Gas Utilities.
https://www.aga.org/globalassets/research--insights/reports/aga-net-zero-emissions-opportunities-for-gas-utilities.pdf

Very Large Scale Use of All-Electric Vehicles Not Viable

Solution for the Global Wealthy 10%, Not Society-Wide Solution

- Internal combustion engine vehicles are low cost because made of earth-abundant materials: iron, aluminum, sand and plastic
- All-electric vehicles are expensive because large-use of non-earth-abundant materials (Right: Table)
- Using non-earth-abundant materials not viable if the goal is moving 10 billion people into the middle class

https://www.science.org/doi/10.1126/science.191.4228.683

Element	Kg/Vehicle
Copper	53.2
Lithium	8.9
Nickel	39.9
Manganese	24.5
Cobalt	13.3
Graphite	66.3
Zinc	0.1
Rare Earths	0.5

J. Winters, By the Numbers: Electric Vehicles Require Imported Numbers, Mechanical Engineering (March 2023)
Infographic: Electric Vehicles Need Imported Minerals - ASME

Technology Can Not Address High Cost of Less-Abundant Elements and Long Lead Times for New Mines

- Recovering less abundant elements expensive because of low ore concentrations
- Nickel alone requires mining more ore than for all the iron and steel in a gasoline-fueled car
- Lead time for a typical mine is 16; multi-decade time frame for expansion of all-electric vehicle production assuming cost is not consideration
- Need new battery chemistry: lithium & cobalt are a very small part of the challenge

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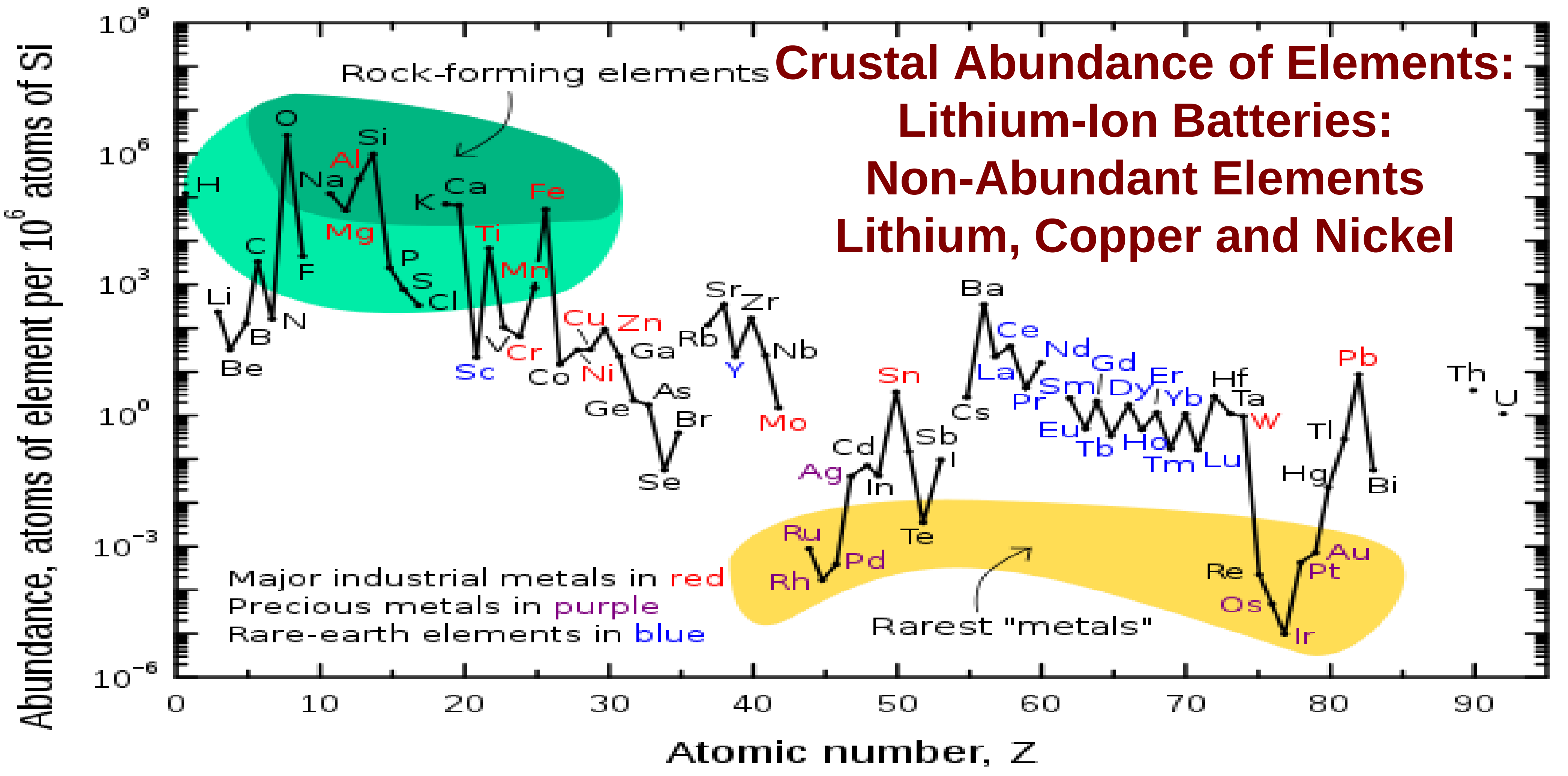
J. Winters, “By the Numbers: Electric Vehicles Require Imported Numbers”, *Mechanical Engineering* (March 2023)
Infographic: Electric Vehicles Need Imported Minerals - ASME
International Energy Agency, *The Role of Critical Materials in Clean Energy Transitions*, March 2022

Global Systems Must Be Built with Abundant Materials



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

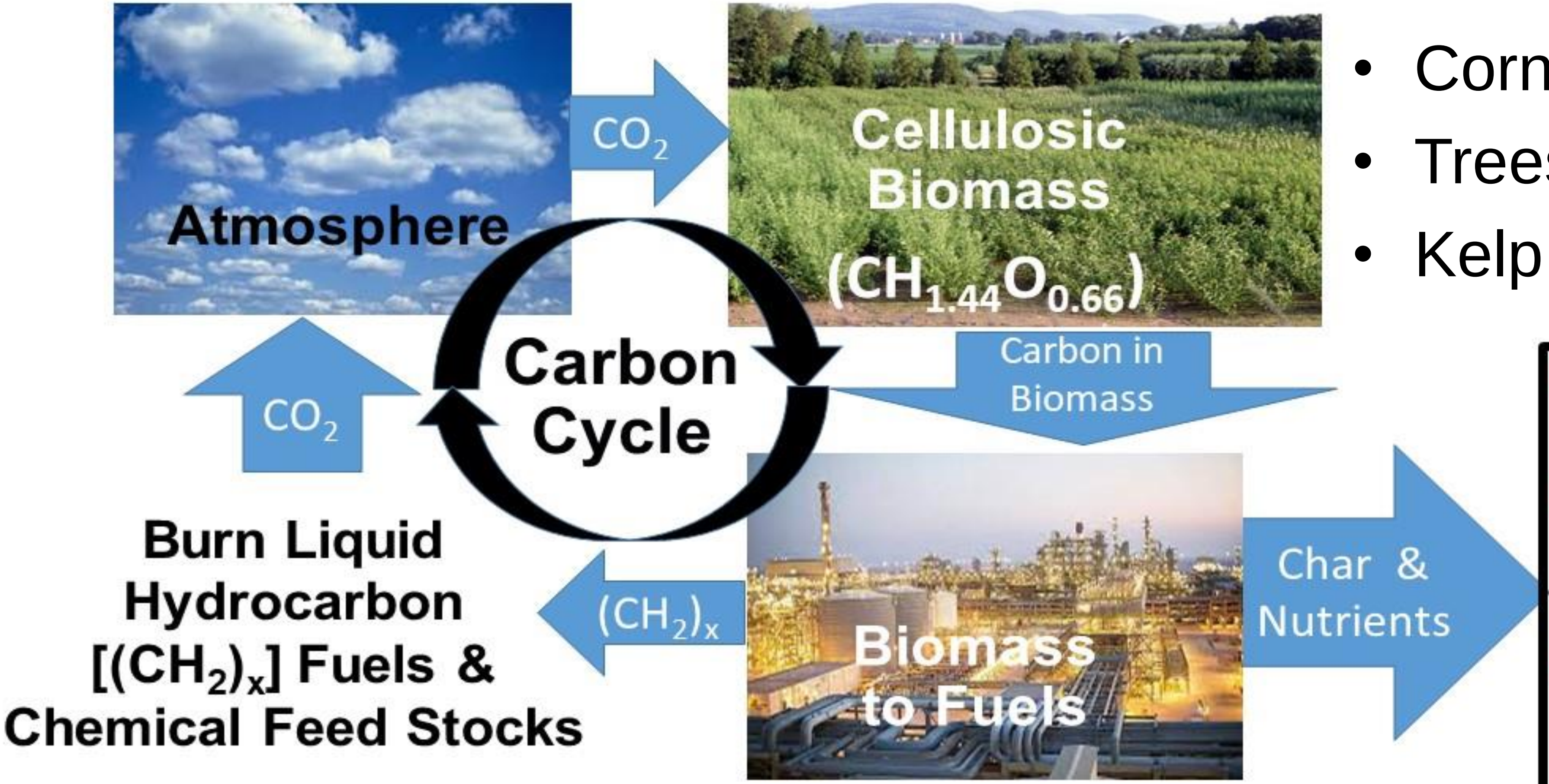
Hydrocarbons made from Biomass and Carbon Dioxide Can be Made with No Increase in Atmospheric Carbon Dioxide Levels

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

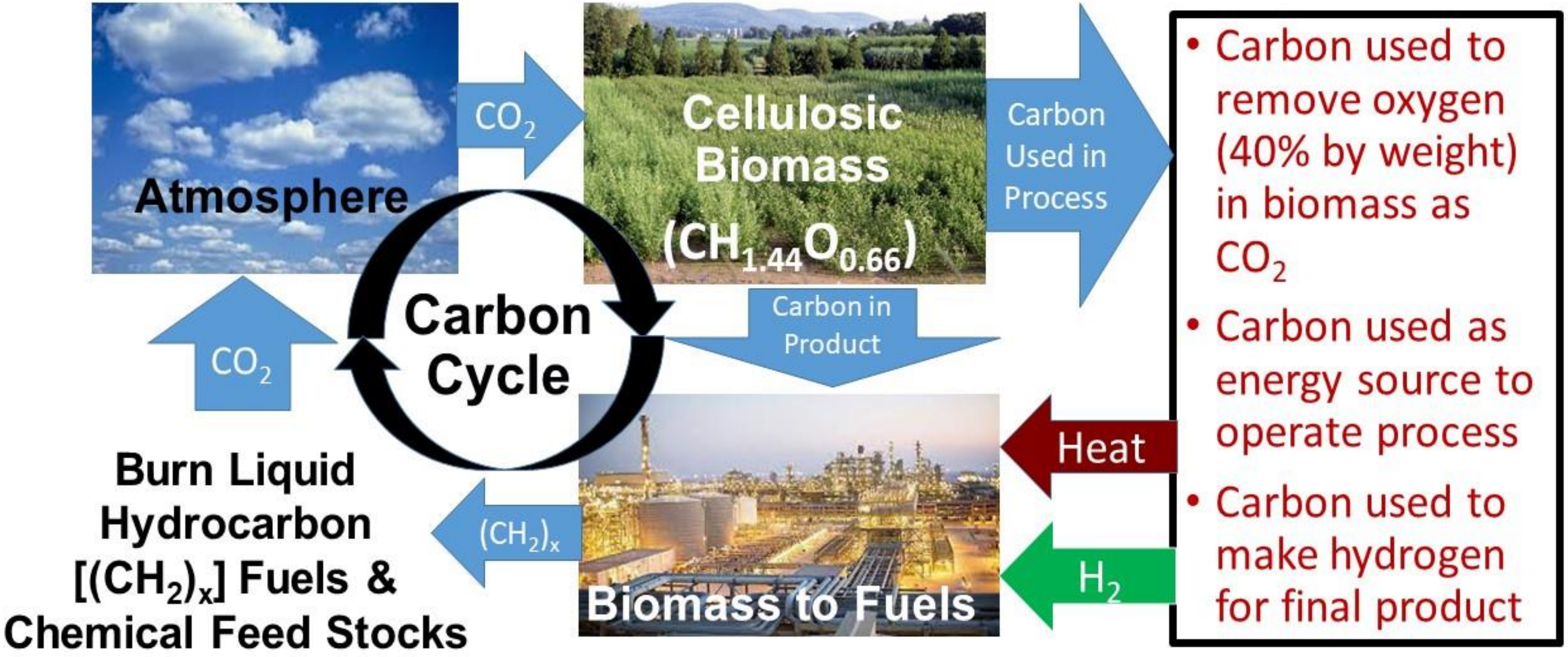
Biofuels Production Can Produce Hydrocarbon Fuels (Gasoline, Diesel, Jet Fuel), Sequestered Carbon and Recycle Nutrients



- Corn stover (Agriculture)
- Trees (Forest)
- Kelp (Sea)

- Sustainable Agriculture
- Sequester carbon in soil as char
- Recycle nutrients to soil

Conventional Cellulosic Liquid Hydrocarbon Biofuels Production Limited by Available Biomass for Conversion Process



Conversion Process

Large Fraction of Bio-Carbon to Carbon Dioxide in Processing

Need to Eliminate Campfire Model of Biofuels Production

Use External Heat and Hydrogen for Conversion Process

Biomass Energy Sources
for Conversion Process

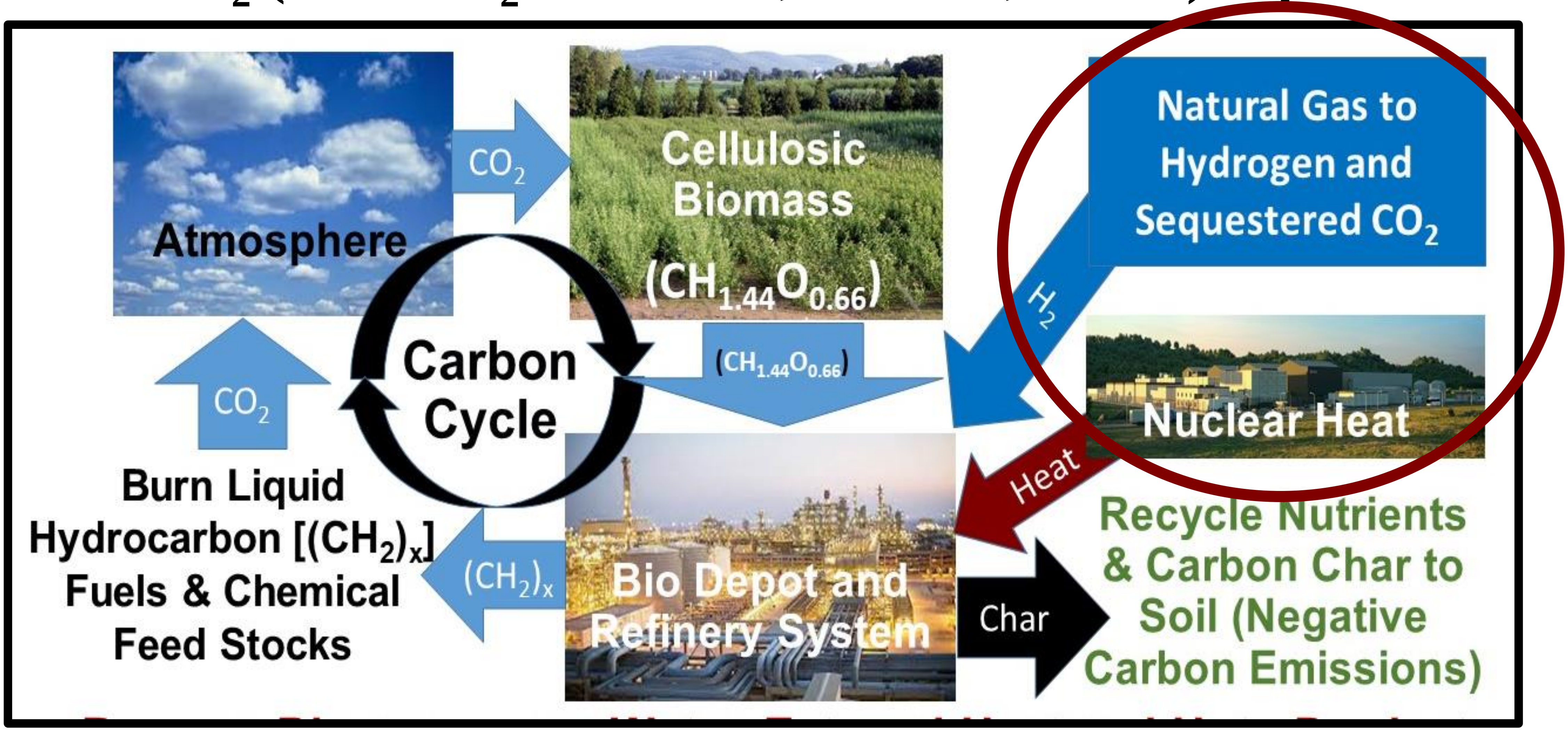
Or

Reserve Biomass Carbon
for Final Products

Increases U.S. Biofuels Potential from 6 to 25 Million Barrels per Day

U.S. Demand Today: 18 $\times 10^6$ B/D, Future Estimates: 10 to 20 $\times 10^6$ B/D

Minimize Feedstock Limits with Massive External Heat and H_2 (NG to H_2 with CCS, Nuclear, Other) Inputs



U.S.: ~25 Million Barrels / Day

Bio-Oxygen Removed As Water, H_2 to Product, Process Heat

What Is the System Design?

C. W. Forsberg, “What is the Long-Term Demand for Liquid Hydrocarbon Fuels and Feedstocks?” *Applied Energy*, 341, 121104 (1 July 2023). https://doi.org/10.1016/j.apenergy.2023.121104
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
C. W. Forsberg, C. W, B. E. Dale, D. S. Jones, T. Hossain, A.R.C. Morais and L. M. Wendt, “Replacing Liquid Fossil Fuels and Hydrocarbon Chemical Feedstocks with Liquid Biofuels from Large-Scale Nuclear Biorefineries”, *Applied Energy,* 298, 117525, 15 September 2021. Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries - ScienceDirect

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**
  - **Enables use of lower-grade biomass feed stocks**

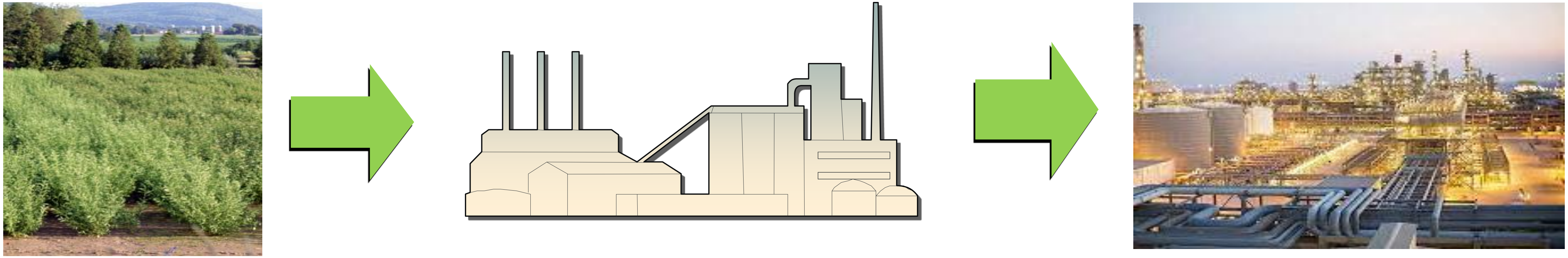
C. W. Forsberg and B. Dale, “Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels?”, *Hydrocarbon Processing*, January 2023. Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels? (hydrocarbonprocessing.com)

Depot System Design

Enable Shipping of Local Biomass to Central Bio-Refinery

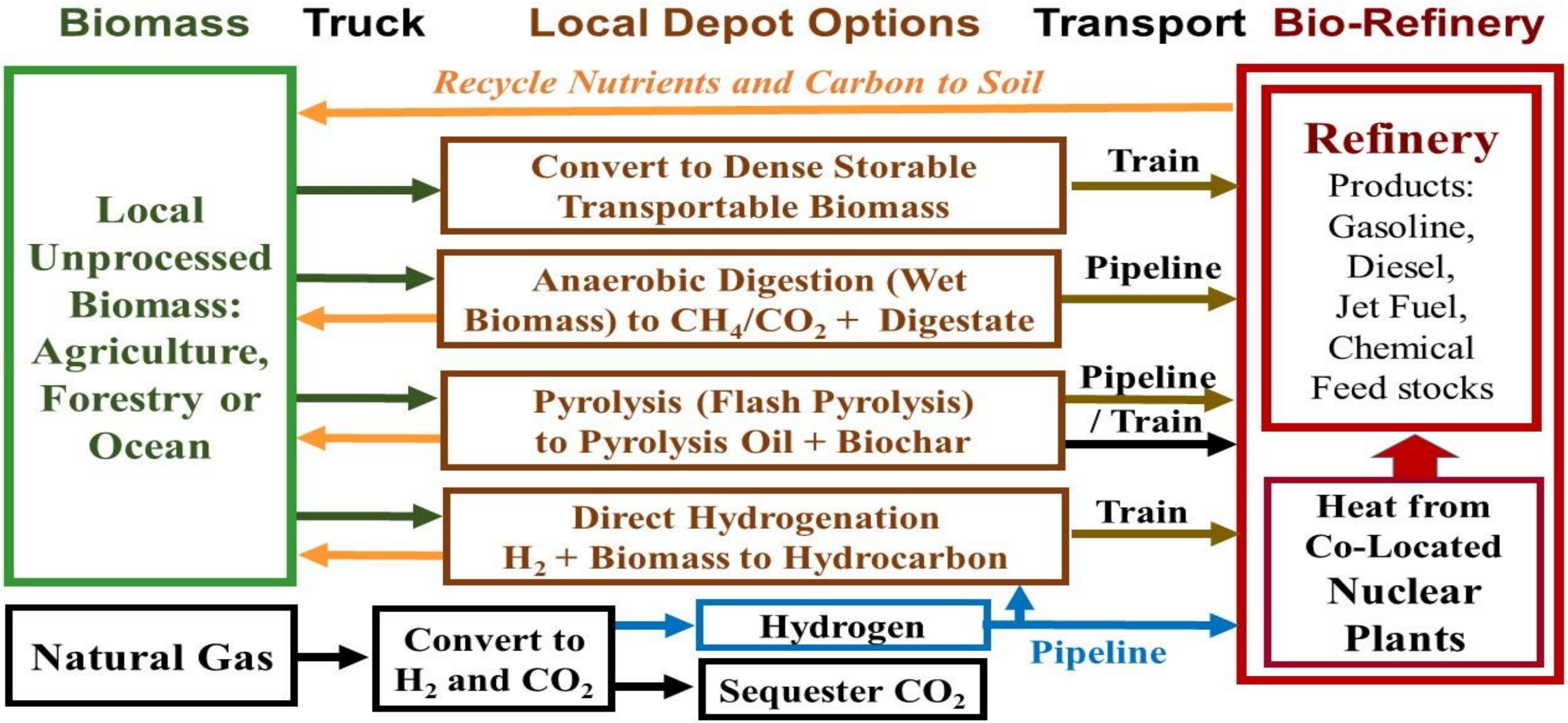
Not Economic to Ship Low-Density Biomass Long Distances

Local Depots to Provide Economically Shippable Biomass Commodities



- 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)

We Have Four 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

AFEX-treated, loose | AFEX-treated, pellets

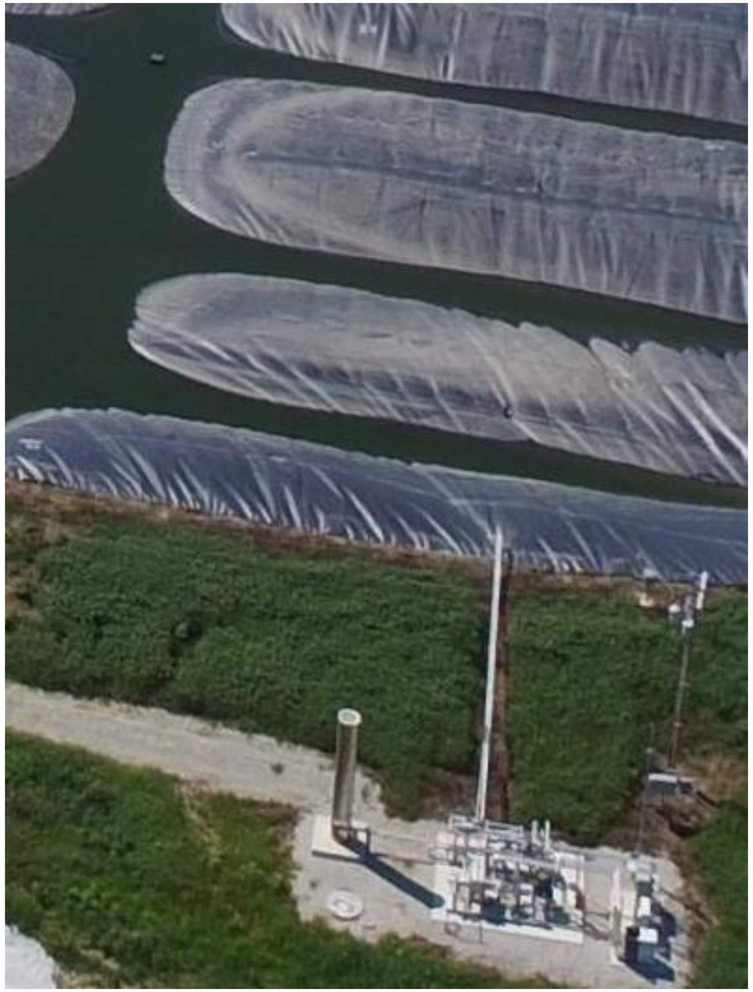
Corn stover

Wheat straw

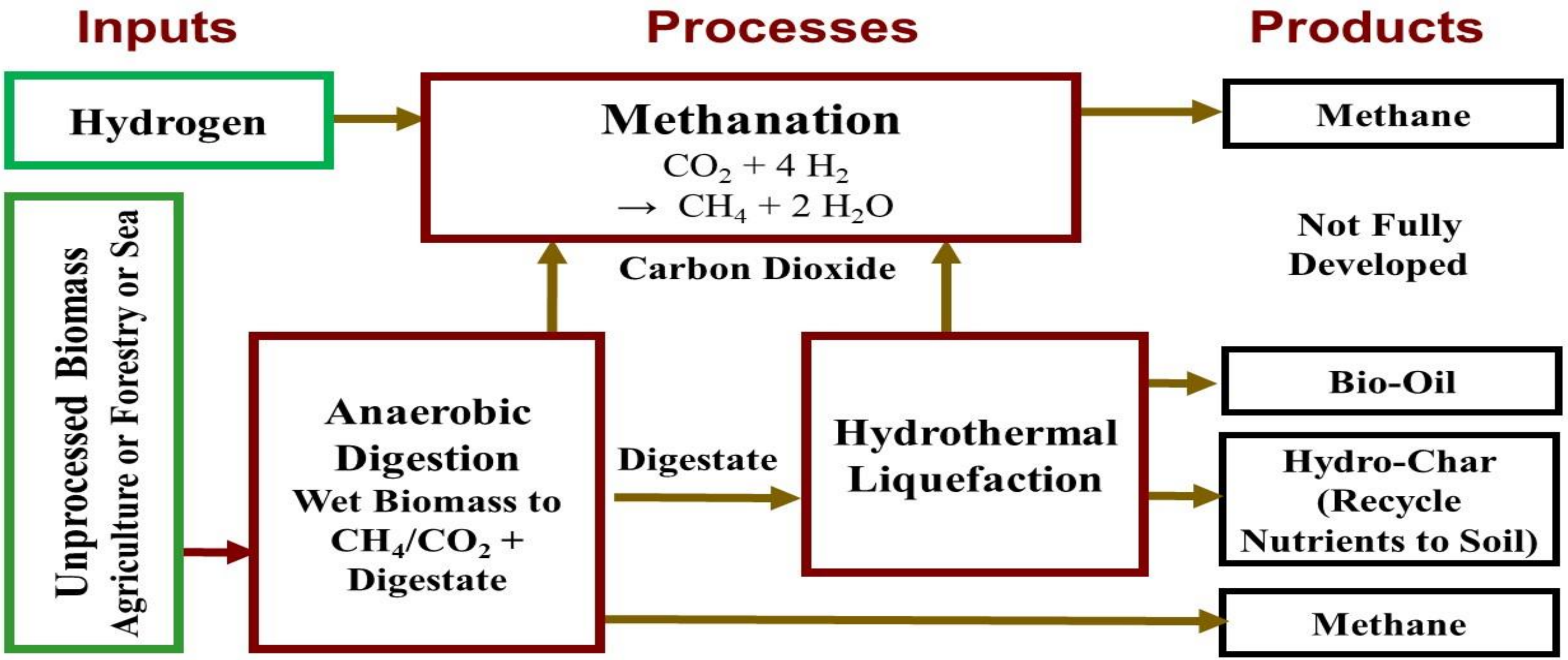
DRAX Power Station (UK) Burns 7 Million Tons Pellets per Year

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



Advanced Anaerobic Digestion Options Can Produce Methane (CH_4), Bio-Oils and Char for Soil Nutrient Recycle

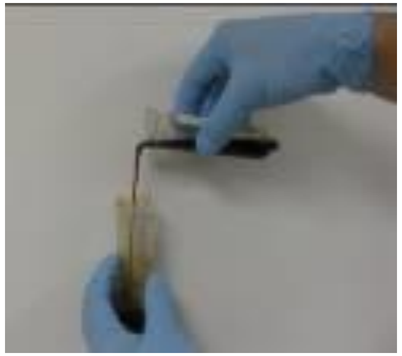


- N. Kassem et al., Integrating Anaerobic Digestion, Hydrothermal Liquefaction, and biomethanation within a Power-to-Gas Framework for Dairy Waste Management and Grid Decarbonization: a Techno-Economic Assessment", *Sustainable Energy and Fuels*, DOI: d0se00608d. July 2020

Biofuels Fast Pyrolysis Depot Option

Commercial on a Small Scale: Ship Bio-oil to Refinery

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

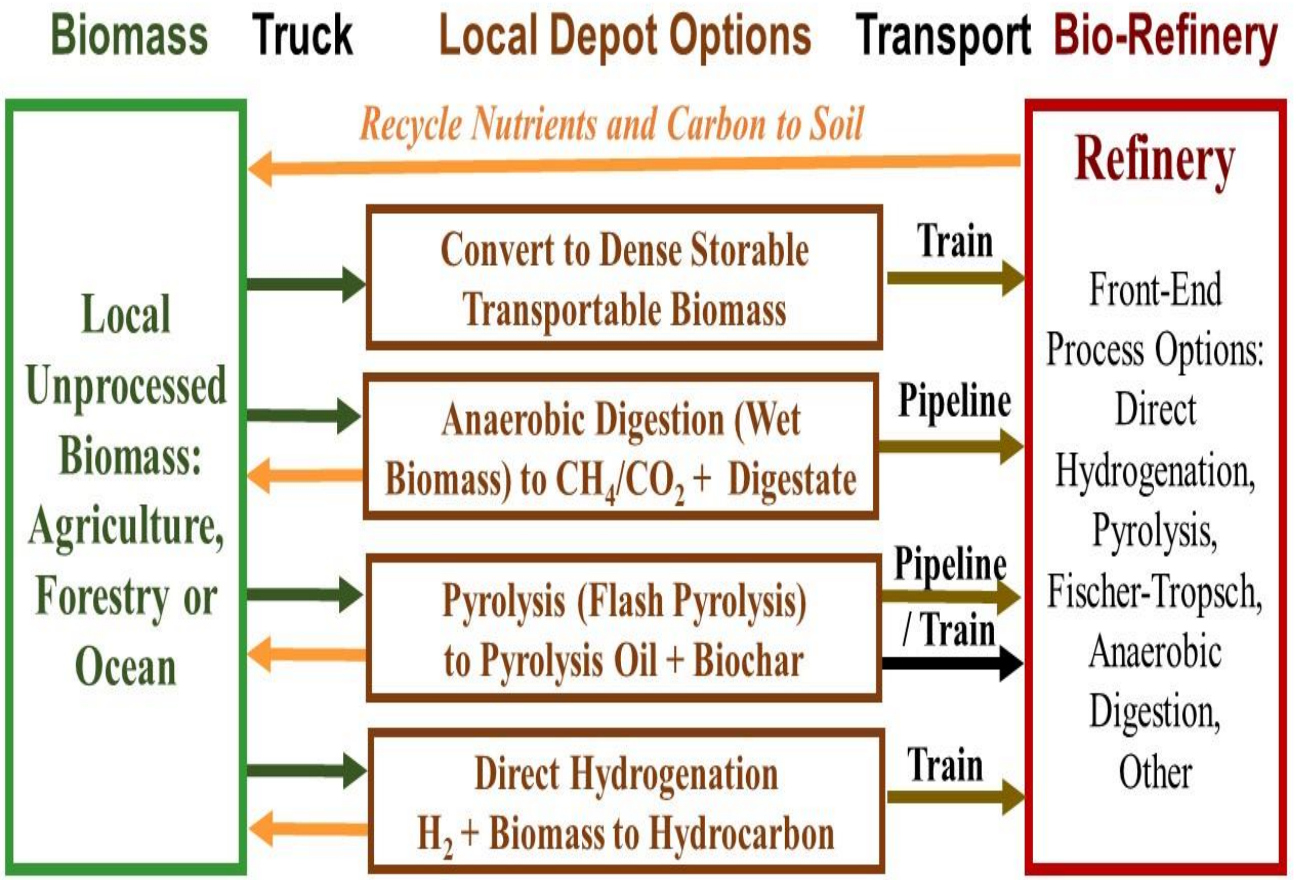
G. L. Hawkes, S. Bragg-Sitton and H. Hu, "Nuclear-Assisted Carbon-Negative Biomass to Liquid Fuel Process Integration with High Temperature Steam Electrolysis" *ICAPP 21*, October 2021

Can Convert Biomass Directly into Hydrocarbons with Direct Hydrogenation

- Large-scale refinery process to convert heavy oils into gasoline, diesel and jet fuel
- Used to desulfurize oils (sulfur and oxygen have similar chemistries)
- Requires massive quantities of hydrogen
- Earlier work including large-scale pre-commercial plants to convert coal to liquid fuels
- Work on biomass feedstocks is at an earlier stage of development

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)**
  - Recycle nutrients back to agriculture and forests
  - Recycle carbon char or digestate to sequester carbon and improve soil properties



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

Refinery Design

Front-end Processes Create a Bio-Crude

Refinery Converts Bio-Crude to Refined Products

C. W. Forsberg and B. Dale, “Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels?”, *Hydrocarbon Processing*, January 2023. Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels? (hydrocarbonprocessing.com)

Modify Existing Refineries for Depot Feeds

250,000 Barrel/day

Modify 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 upgrade/ conversion into final gasoline, diesel, jet fuel and chemical feedstock products
- Existing refineries incrementally convert from 100% crude oil to 100% biomass feed stocks

Multiple Options to Process Bio-Crude Oil to Meet Refinery Requirements

- Two requirements to convert bio-crude oil into a feedstock that matches refinery requirements.
  - Remove oxygen
  - Crack into smaller molecules
- Main line options for upgrade: hydrogenation and Fluid Catalytic Cracking (FCC)
- Large hydrogen inputs maximize conversion of biofuel carbon into drop-in fuels versus some of that carbon leaving refinery as carbon dioxide

250,000 Barrel/day

Option for Crude-Oil Refinery with Front-End Changes

S. Van Dyk et al, 'Drop-In' Biofuels: the Key Role that Co-Processing will Play in its Production' International Energy Agency Biofuels. 2019

Bio-Refinery Has Massive Steady-State Heat Demand to be Provided by Nuclear Energy

- 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 Seadrift Texas site

Elgowainy, A, et. al, "Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries," *Environmental Science and Technology*, 48, 7612-7624, 2014. https://doi.org/10.1021/es5010347

Bio-Refineries Require Massive Hydrogen Inputs

- Today: Natural gas to hydrogen with sequestration of CO_2
  - Lowest cost option if low-cost gas and sequestration sites
  - Some systems can sequester 98+% carbon dioxide, match green hydrogen
- Nuclear with high-temperature (steam) electrolysis
  - High efficiency relative to alternatives
  - Demonstration at Prairie Island Nuclear Power Plant
- Electrolysis with wind and solar: Too early for evaluation
  - Uneconomic today because of high capital cost of electrolyzers
  - Very expensive H_2 if operate electrolyzer at low part load
  - Low capacity factor with solar (25%)

National Energy Technology Laboratory, Comparison of Commercial, State-of-the-Art Fossil-Based Hydrogen Production Technologies, DOE/NETL-2022/3241 (April 12, 2022)

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

C. Bauer et. al., (2022) On the Climate Impacts of Blue Hydrogen Production, *Sustainable Energy & Fuels*, 9, 66-75. 10.1039/d1se01508g

Hydrogen Drives 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
- DOE program to drive H_2 prices to $1/kg
- **Lower cost hydrogen reduces cost of liquid hydrocarbon biofuels**
- **If DOE H_2 cost goal achieved, massive benefit to biofuels**

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 Dramatically Increases Cellulosic Hydrocarbon Liquid Production Potential

- With traditional biofuels, the biomass is the primary cost
- With new strategy, biomass is does not drive liquid biofuels costs—hydrogen primary cost.
  - External heat and hydrogen doubles liquid fuels production per ton of biomass
  - Can pay a more for biomass without large increases in final liquid hydrocarbon production costs
    - Massive increases in biomass production if pay more
    - Alternative feed stocks become economic (kelp, other)

Cost Structure Makes Cellulosic Hydrocarbons the Low-Cost Low-Carbon Option at Scale

Cellulosic Hydrocarbon Biofuels

- Cellulosic is the most common form of biomass: corn stover, trees, kelp, etc.
- Replace all crude oil with external heat and hydrogen inputs (Minimize feedstock)
- Need two hydrogen atoms per carbon atom to liquid fuels

Traditional Biofuels from vegetable oil, fats, sugars and carbohydrates

- Compete with food; insufficient to replace all crude oil
- Insufficient feedstock

Electric Fuels made from Carbon Dioxide

- Require 6 hydrogen per carbon
- Expensive hydrogen

U.S. History On Biomass Production

- For 90 years, the problem has been excess agricultural production
- Corn yields from 20 to 180 bushels per acre with parallel increase in corn stover—and rising
- **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

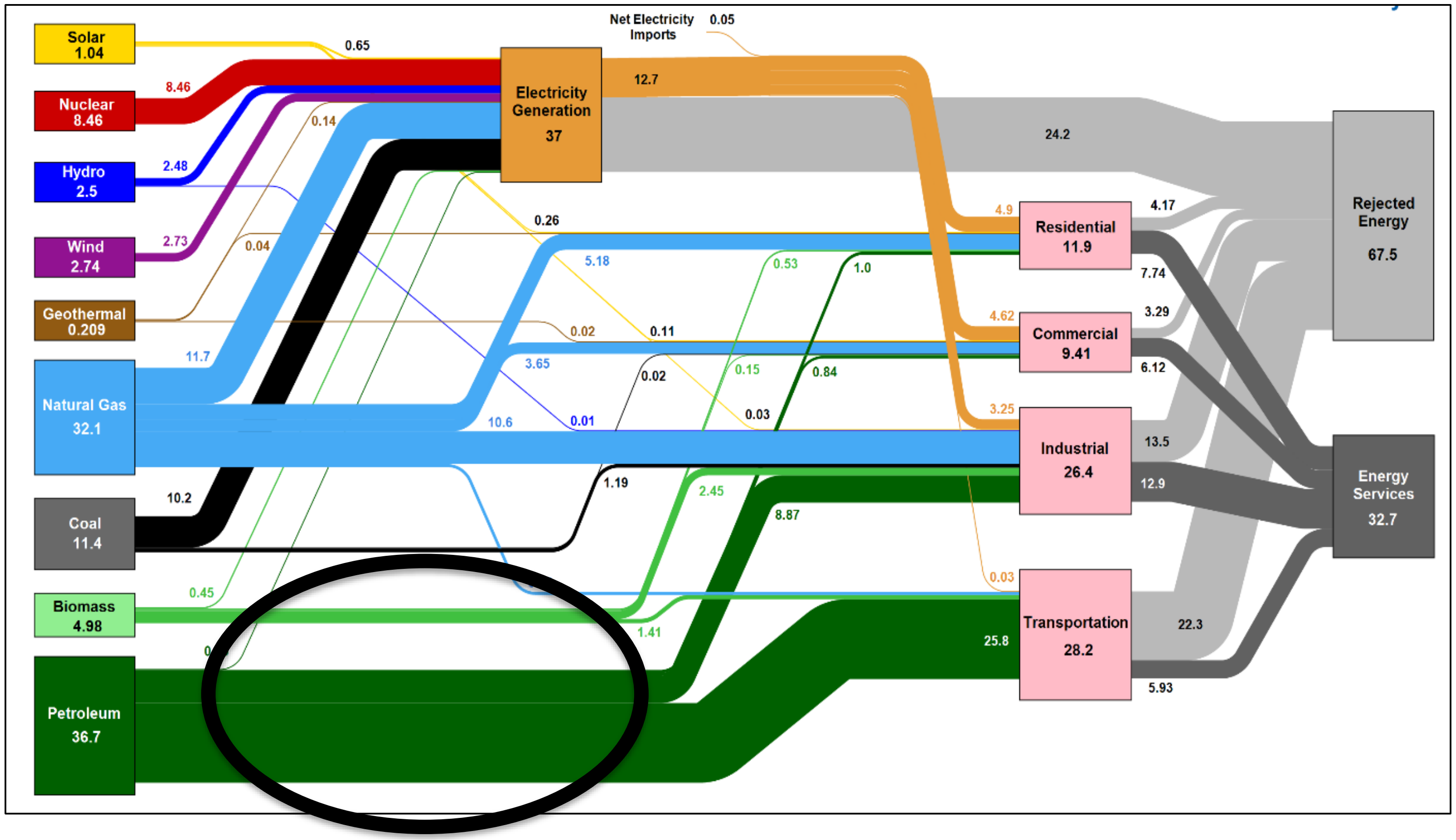
- Feedstock is cellulosic biomass, not a major food source
- Integrated systems can boost food and fiber production
  - Depots separate valuable components (proteins, carbohydrates, etc.) from cellulosic materials. Many of these are animal foods
  - Depots recycle of carbon and nutrients to improve long-term 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 (U.S.: $85/ton)
  - Adjust fuel/sequestered carbon dioxide production based on prices of biomass, biofuels and hydrogen
  - **Stabilize price of liquid hydrocarbons (fuels)**

Largest Nuclear Energy Market (>Half Energy in Oil Sector)

- High Temperature Reactors (possibly SFRs) at refineries
- Hydrogen production (any reactor type)
- Fission batteries at depots (By far, the largest fission battery market)

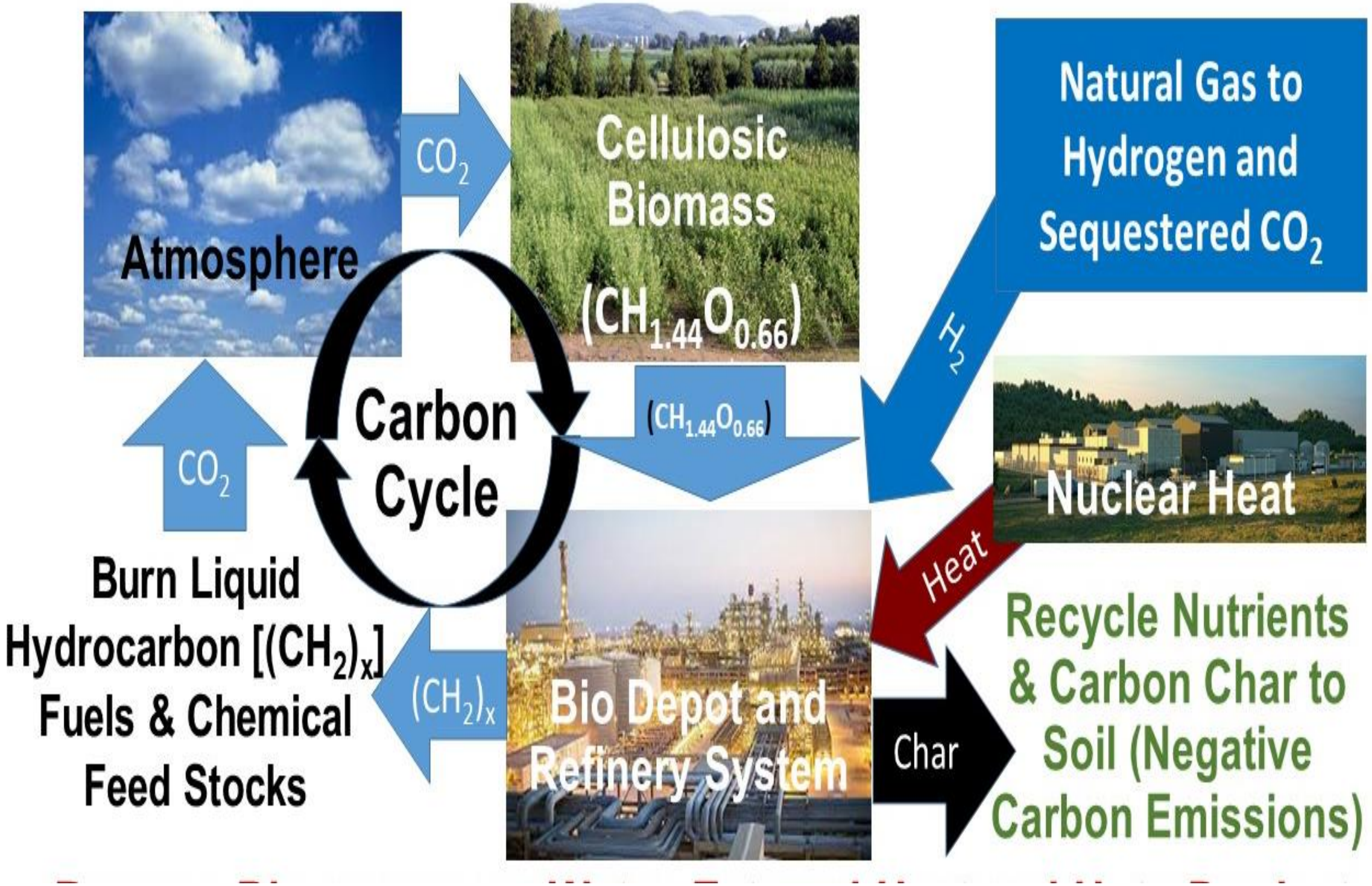


Globally Oil Provides One Third of Total Energy Demand

· C. W. Forsberg and B. Dale, “Nuclear Energy: Enabling Production of Food, Fiber, Hydrocarbon Biofuels, and Negative Carbon Emissions,” *Nuclear News*, January 2023.

Fast Track to Decarbonize Half U.S. Economy

- Not replace most of the world's infrastructure
- Use mostly existing energy system
- Built upon American strengths
  - Agriculture
  - Oil and Gas Industry (Keep gas, refineries & products)

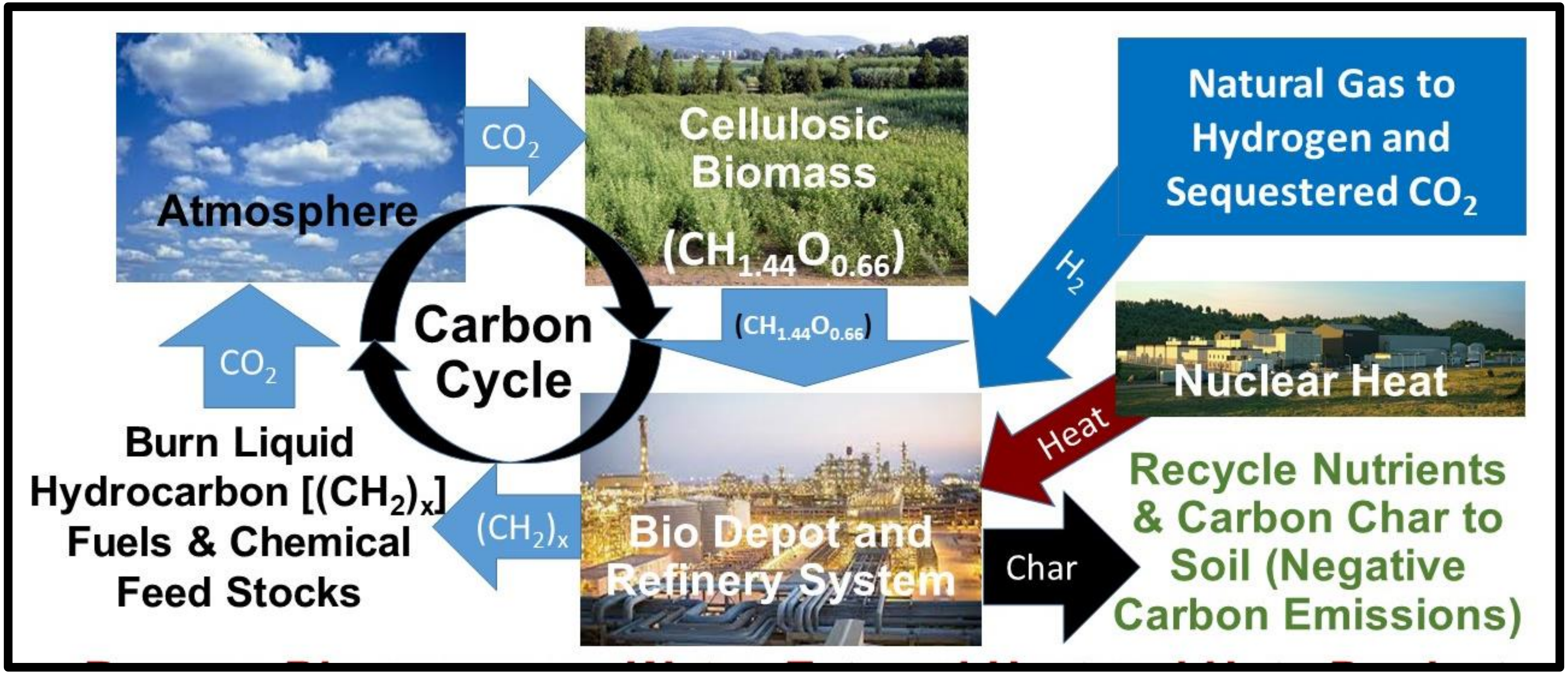


U.S. Potential to Replace Most Crude Oil in 20 Years

- Historical implementation of fracking (gas industry) and ethanol (agriculture) was less than 20 years
- Implementation policy: The U.S. should guarantee for X years a minimum price for liquid cellulosic hydrocarbons per barrel to reduce investment risk
  - Oil prices in last 50 years have varied from $20 to 180 per barrel on inflation adjusted basis
  - Risk of oil price collapse is the primary risk (barrier) for large-scale investment in large-scale hydrocarbon biofuels

Conclusions: We Can Replace All Crude Oil

Fastest Strategy to Decarbonize the Economy



Built on American Strengths: Agriculture, Oil/Gas & Nuclear

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 former 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.

Abstract: Can We Replace All Crude Oil Using a Cellulosic Liquid Biofuels System with Massive Heat and Hydrogen Inputs?

Based on a results of a series of studies and three virtual workshops held in August 2021, we address the question of whether we can domestically and globally replace all crude oil with hydrocarbon cellulosic (corn stover, forest debris, kelp, etc.) biofuels using massive heat and hydrogen inputs at the refinery. This is without major impacts on food and fiber prices, improving long-term soil productivity and negative carbon emissions. Plants remove carbon dioxide from the air. If they are converted into biofuels and burnt with release of carbon dioxide to the air, there is no net change in atmospheric carbon dioxide levels. 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. The U.S. consumes ~18 million barrels of crude oil per day to produce liquid hydrocarbons. If replace crude oil with low-carbon biofuels, decarbonize about half the U.S. economy.

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 carbon feedstock, (2) an energy source to operate the process including production of hydrogen 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 feed stocks unsuitable for liquid hydrocarbon production are viable feed stocks with external heat and hydrogen inputs. As a result, there is sufficient cellulosic feed stocks to meet U.S. and global liquid fuels hydrocarbon demand without significant impacts on food and fiber prices. It also changes the economics. The largest cost of the final liquid hydrocarbon is hydrogen (oxygen removal from biomass and hydrogenation), not biomass. One can pay more for cellulosic biomass.

The heat and hydrogen (heat plus electricity) can be produced using base-load nuclear power plants—the most economic form of nuclear energy. If low-price natural gas, there is the option of producing hydrogen from natural gas with sequestration of the carbon dioxide. Recent studies indicate that such blue hydrogen can have greenhouse impacts similar to green (wind and solar) hydrogen.

The biomass is locally processed in depots to produce commodity feed stocks that can be economically shipped long distances to large bio refineries (250,000 barrels per day, oil equivalent)—mostly existing refineries with modifications of front-end processes. The depot system serves two functions. First, it converts low-density biomass into higher density intermediate commodities that can be economically shipped long distances. Second, it enables local recycle of nutrients back to the soil. Unlike production of food and fiber, we do not want trace nutrients in our fuel and thus design the system to recycle these nutrients (K, P, etc.) back to the soil. The bio refinery 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 $70 per barrel assuming hydrogen at $2/kg. Large integrated refineries are used for three reasons. First, there is economics of scale. Second, large oil refineries blend different crude oils to produce a feedstock they can process. This reduces the cost of the feedstock. It also enables existing refineries to incrementally convert from crude oil feed stocks to biomass feed stocks. Last, the large refineries can produce variable quantities of liquid fuels depending upon the relative demand as a function of time.

References

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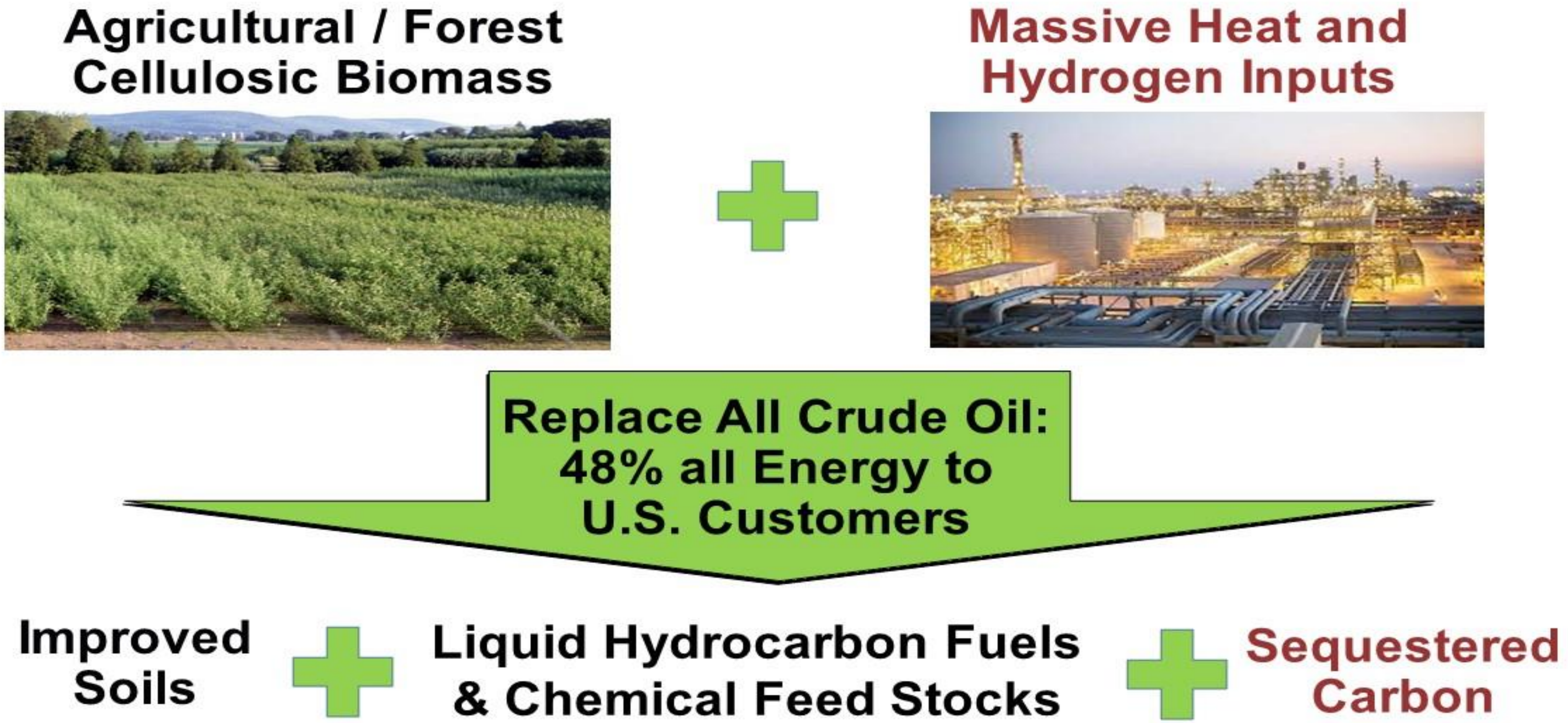
Questions



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