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solutions that transform

Low Carbon Fuels, Feedstocks & Energy Sources Panel

Potential Contributions of Advanced Manufacturing toward Industrial Decarbonization

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3 August 2023

We develop, scale and deploy solutions in the transition to low-carbon, low-cost energy systems

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SOURCE → MAKE → MOVE → STORE → USE

500 Enterprise Employees

TOP WORK PLACES 2019 Chicago Tribune

TOP WORK PLACES 2020 Chicago Tribune

TOP WORK PLACES 2021 Chicago Tribune

TOP WORK PLACES 2022 Chicago Tribune

We work collaboratively to address critical energy challenges impacting gases, liquids, efficiency and infrastructure

OTD Operations Technology Development	UTD Utilization Technology Development	ETP Emerging Technology Program	LCRI LOW-CARBON RESOURCES INITIATIVE

GTI Energy Technical Expertise

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Expanding supplies of affordable and clean energy

- Hydrogen production
- Unconventional natural gas and oil production
- Geologic modeling and reservoir characterization
- Hydraulic fracturing diagnostics, optimization, and reservoir flow modelling
- Enhanced recovery
- Liquefied natural gas (LNG)
- Enhanced geothermal systems

Transforming energy into clean fuels, power, and chemicals

- Integrated biofuels technology
- Gasification
- Syngas processing
- CO_2 capture and utilization
- Carbon management
- Chemical research and process development
- Renewable natural gas and gas quality
- Hydrogen technologies
- Advanced power cycle development
- Waste heat utilization

Ensuring safe, efficient, resilient, and reliable infrastructure

- Methane emissions, monitoring, mitigation, and reduction
- Data integrity and risk management
- Smart utility information technology tools
- CO_2, H_2, and natural gas underground storage
- Infrastructure rehabilitation and improvements
- Materials and analytical testing

Delivering efficient and sustainable end use solutions

- Residential/commercial appliances, equipment, and building systems
- Industrial process heat and steam
- Power generation and combined heat and power
- Alternative transportation fuels
- Natural gas-solar thermal hybrid equipment
- CO_2 capture and utilization

U.S. Final Energy Product Mix

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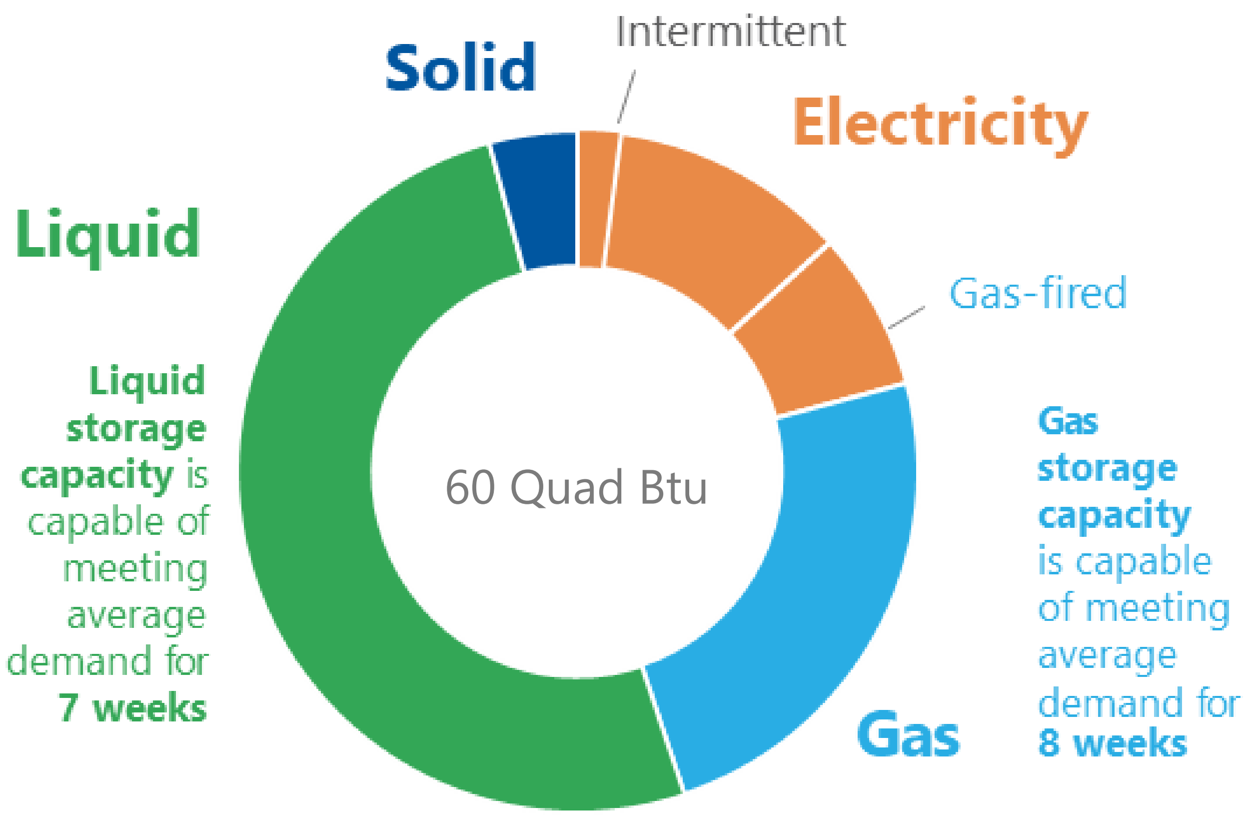
- Most energy products supplied to end use customers today are in the form of a fuel, remainder as electricity

  ~50% liquid, 25% gas
- Approximately 95% of all final energy products used today are underpinned by fuels (partially to balance renewable intermittency)
- Fuels provide stable, long-term storage of energy
- Today's gas storage capable of meeting U.S. demand for ~2 months



(2020, Quad Btu, excluding non-energy use of fuels)

Source: U.S. Energy Information Administration

Reaching Net-Zero in 2050

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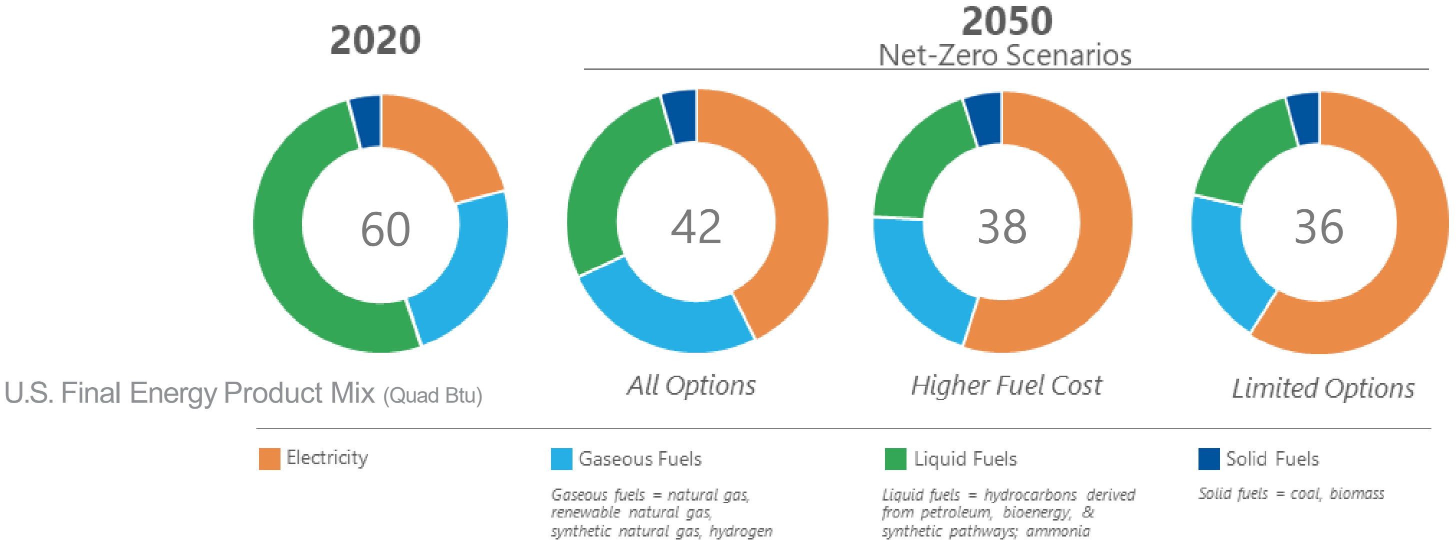
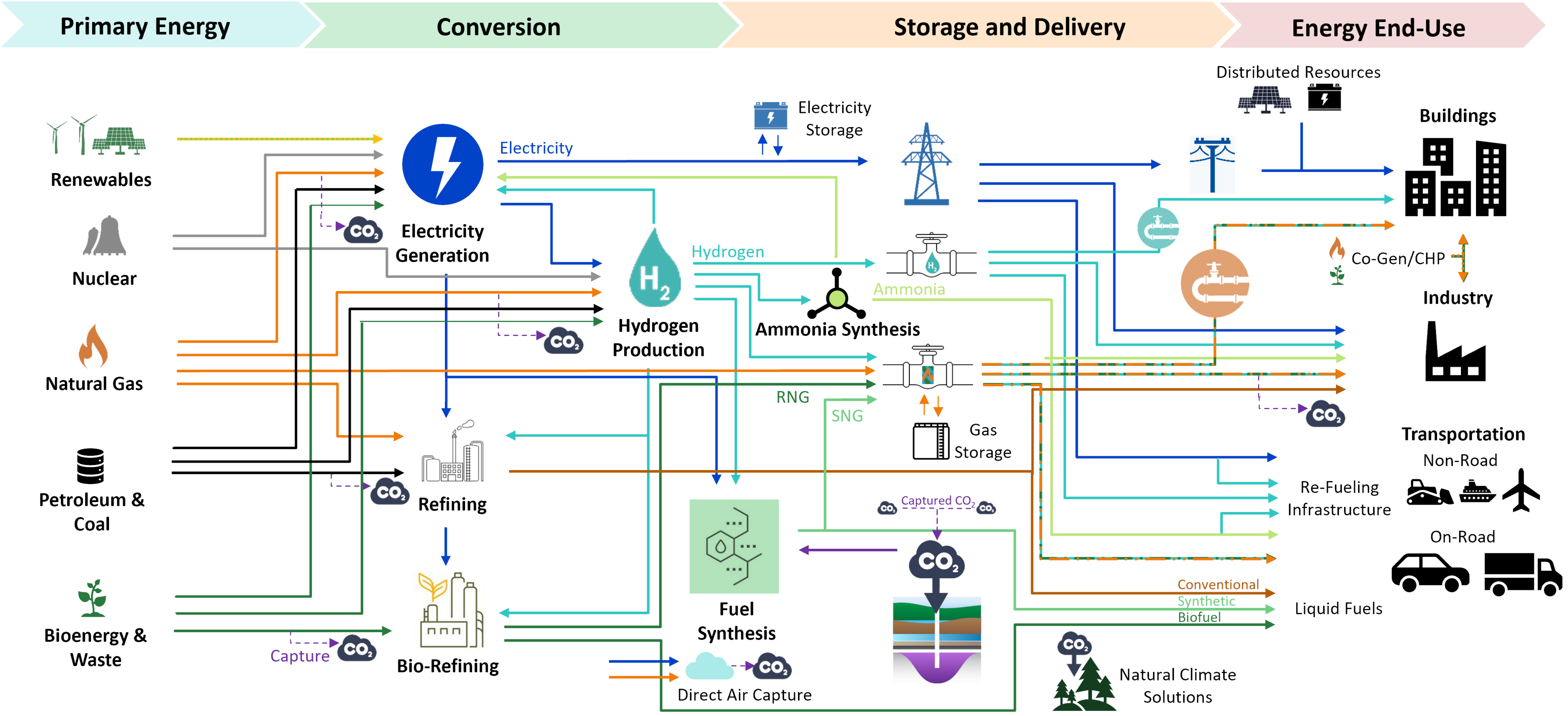
- In collaboration with EPRI, a comprehensive U.S. Energy system modeling effort was conducted to evaluate least-cost pathways to achieve net-zero carbon emissions across the entire U.S. economy by 2050



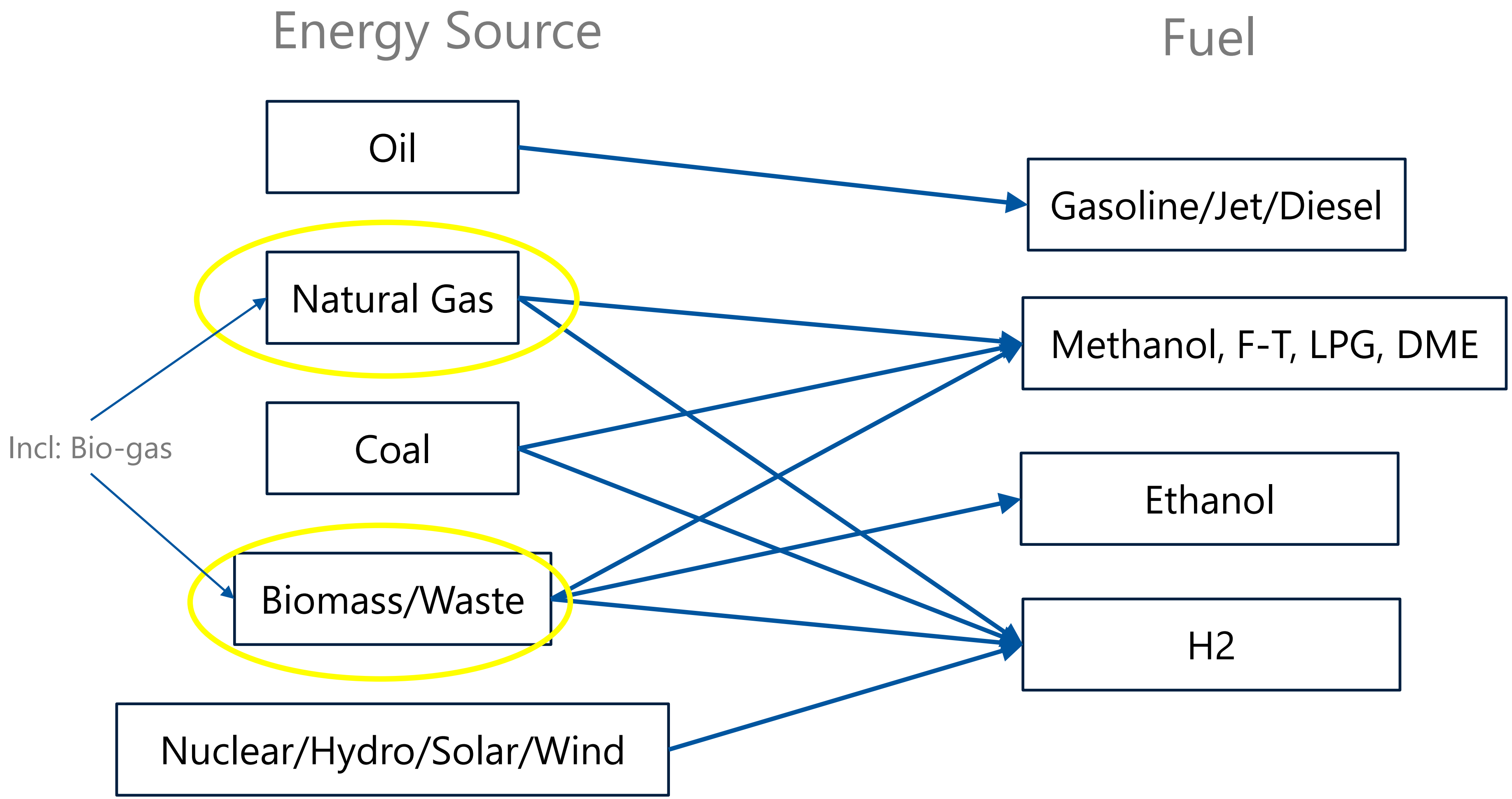
Source: LCRI Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis

- Improved energy efficiency, electrification, and less energy-intensive activities combine to reduce final energy 25% to 38%, even with 80% GDP growth
- By 2050, the share of electricity grows considerably under every scenario and ~50% of all energy is supplied to end-use markets as a fuel (est. market of ~1B Metric Tons by 2050)

Scope of LCRI U.S. Energy System Model



Fuel Sources



Gas (natural gas, biogas, synthetic gas) Pathways

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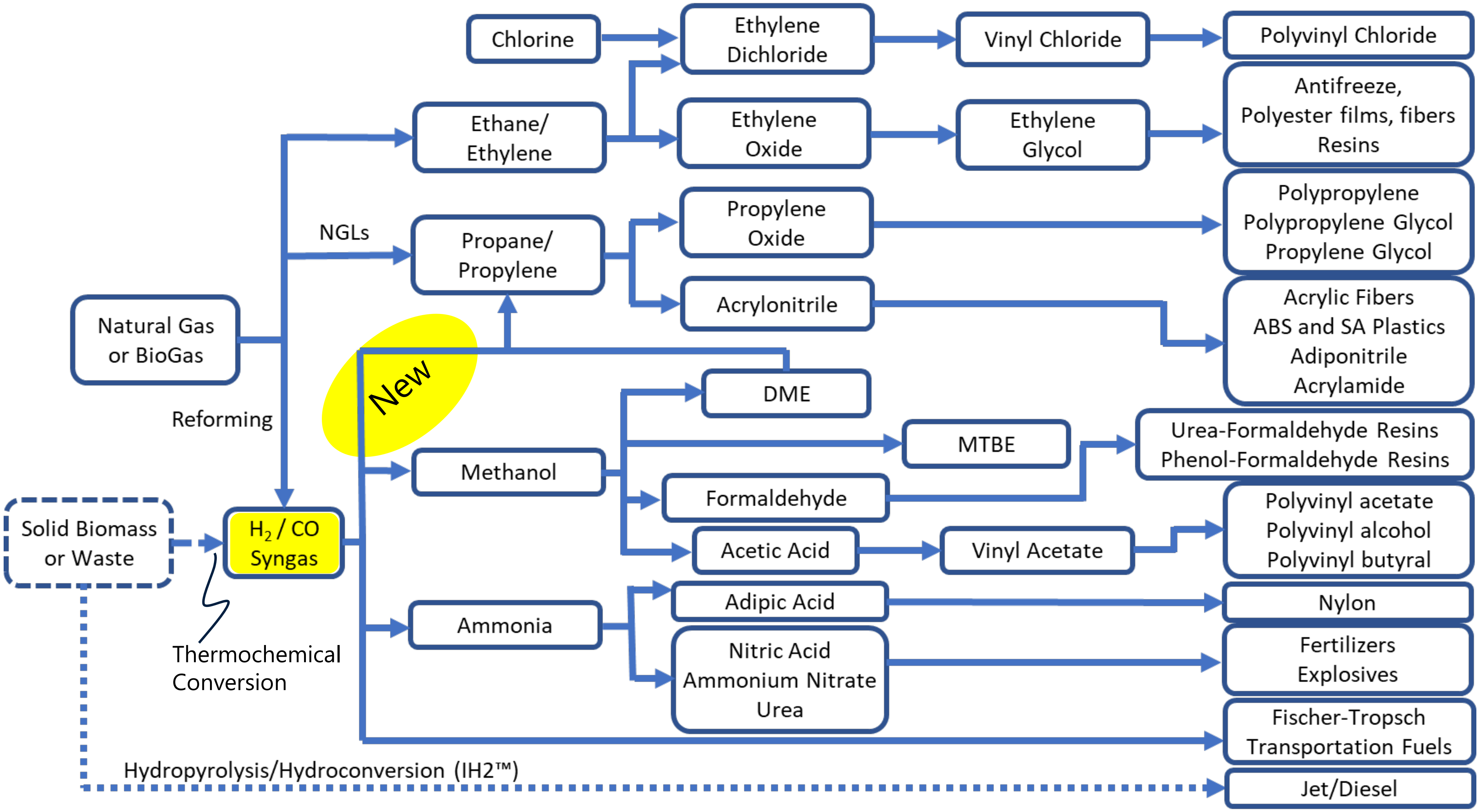

All products accessible from sustainable feedstocks

The Need for Renewable Propane

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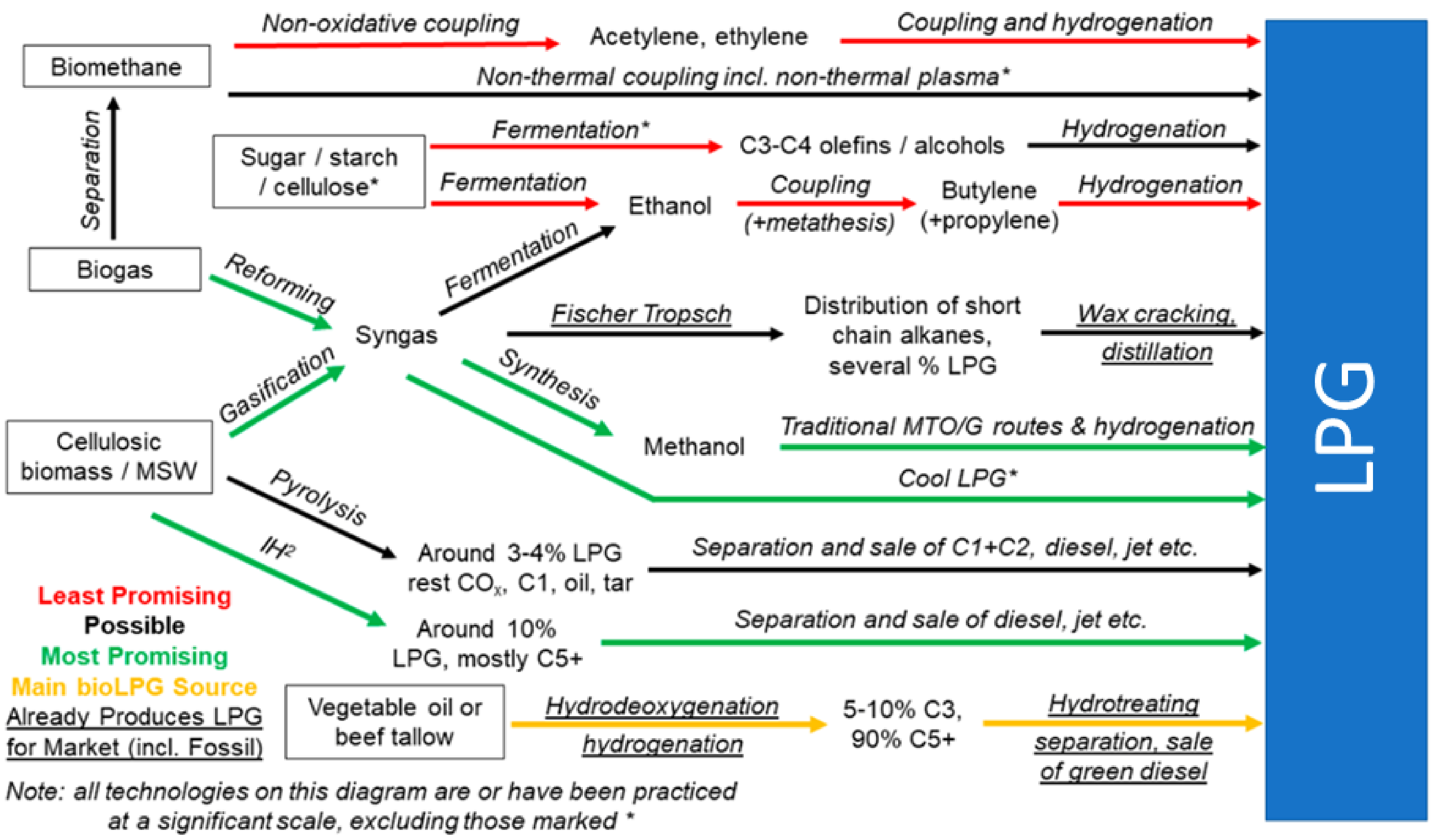
- LPG is versatile, with a variety of uses in industry, in agriculture, in homes, for transportation fuel, and for recreational purposes
- U.S. demand > 20M MT/yr (>10B gallons/yr) and >330M MT/yr worldwide[1]
- Most of U.S. rural population does not have access to natural gas pipelines and rely on LPG for space heating, water heating, and clothes drying
  - 7 million U.S. households rely on LPG for space heat
- However, LPG is a fossil fuel byproduct and availability will decline as those markets shrink
  - Many users have no viable substitute for home heating and cooking, including Indian reservations and the rural poor
  - Globally, 4B people lack modern energy cooking services and nearly 1B people in Sub-Saharan Africa cook with traditional solid fuels (resulting in est ~0.5M deaths/yr)
- Providing affordable, bio-derived propane in the U.S. will have direct, measurable, environmental justice impact

[1]2021 Propane Education & Research Council, Frost & Sullivan and World LPG Association

Pathways to Renewable Propane

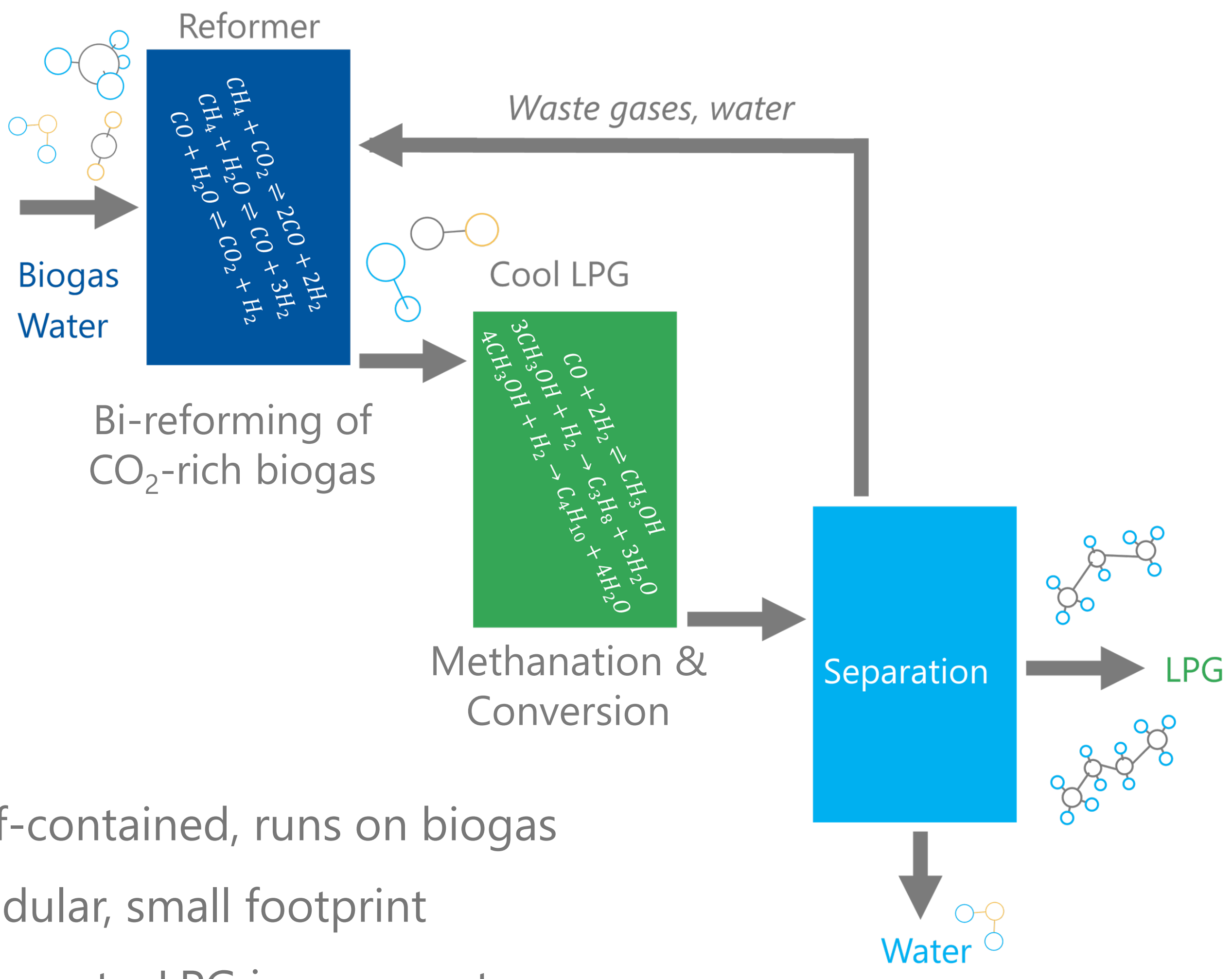
Common issues:

- Feedstock availability limitations
- Low selectivity
- Low-value byproducts
- High process cost
- Low flexibility to market forces



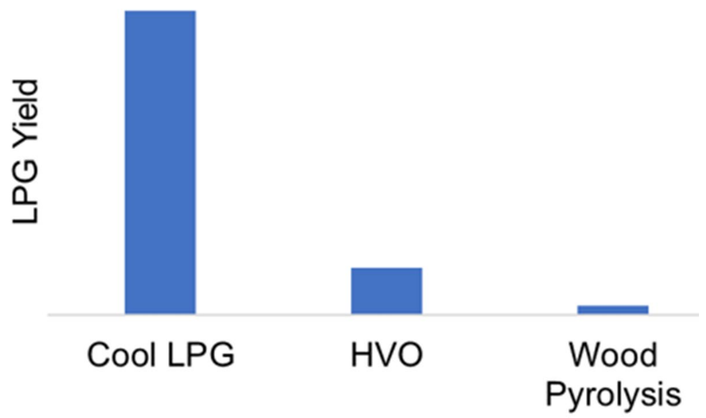
Chen, K. C. *et al. Energies* **2021**, 14, 3916. https://doi.org/10.3390/en14133916

GTI's "Cool LPG" Process

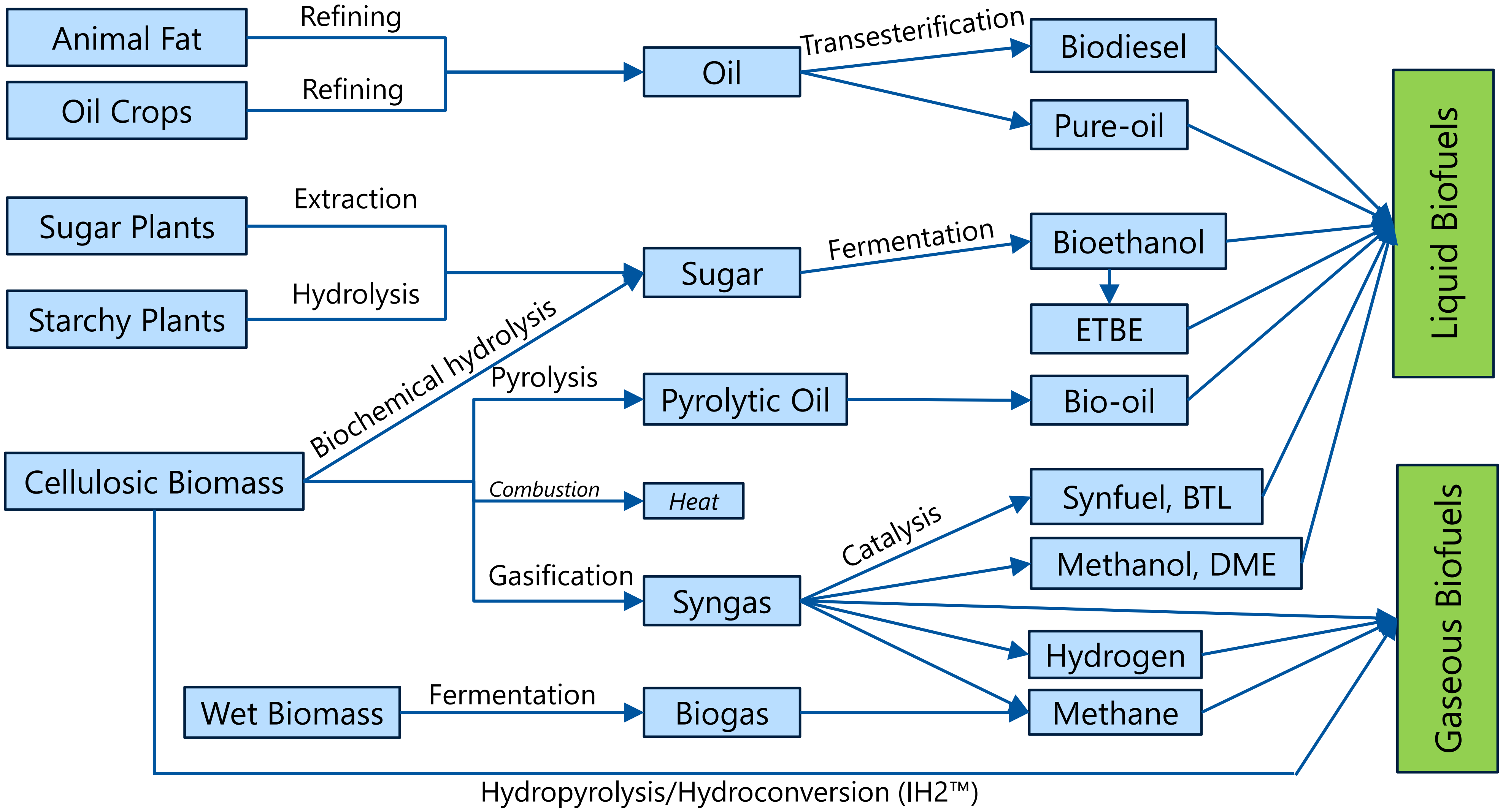


- ✓ Self-contained, runs on biogas
- ✓ Modular, small footprint
- ✓ Syngas-to-LPG in one reactor

- ✓ Takes advantage of GTI Energy's Cool Reformer to convert CO_2 to LPG
- ✓ Utilizes proprietary catalysts in both stages – but can run on alternative syngas feeds
- ✓ Waste gas can be recycled or used as fuel



Biomass/Waste Pathways



Scaling Fuel Production with Feedstock

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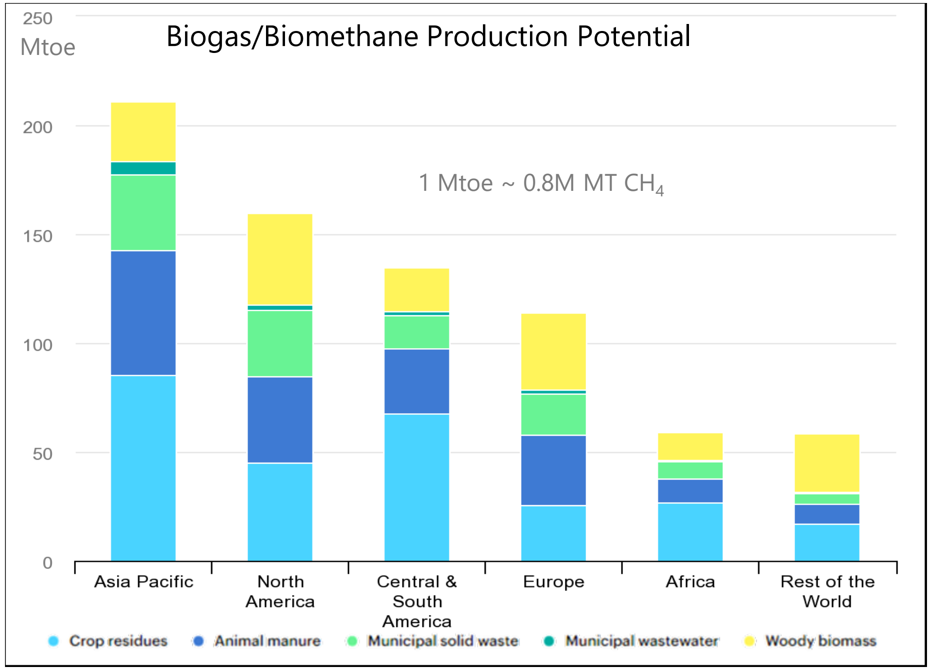
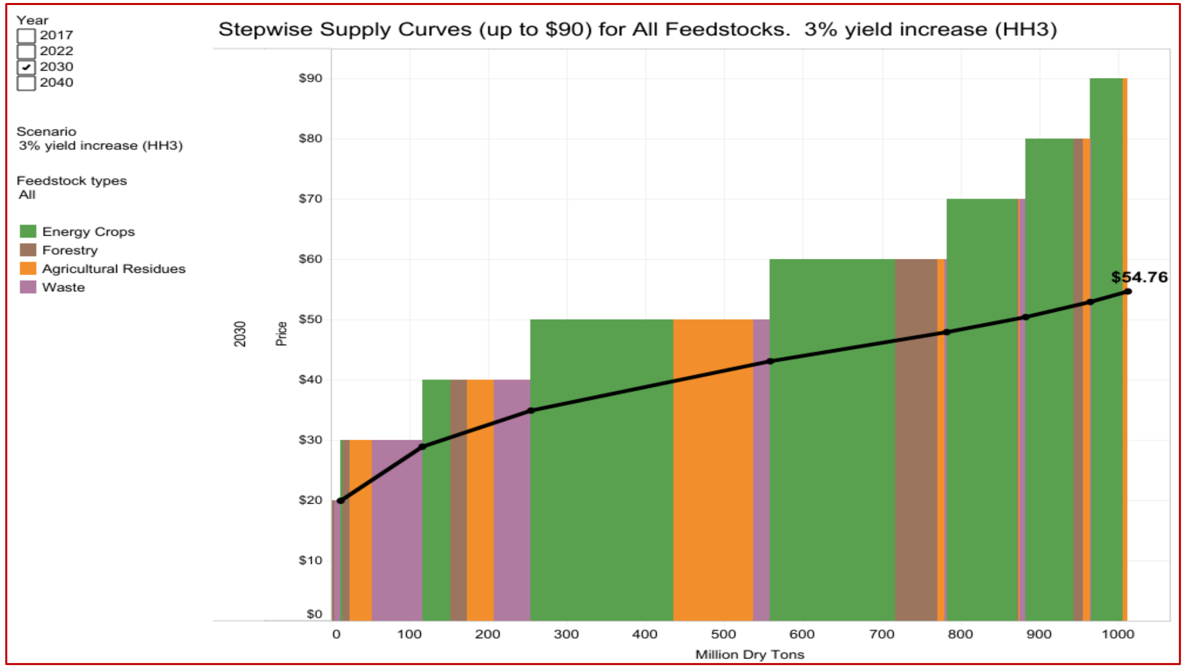
- Biogas a smaller fraction of available biomass/waste feedstock (<125MT)
- Landfill and AD biogas expected to primarily be directed to pipeline RNG and onsite power

- DOE "Billion Ton 2016" report identifies potential for >700MT cellulosic feedstocks available by 2030
- Suggests technologies for conversion of cellulosic feedstocks more impactful



Source: IEA Production potential for biogas or biomethane by feedstock source, 2018



Please cite as: 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.

Products from Biomass & Waste Gasification through Syngas

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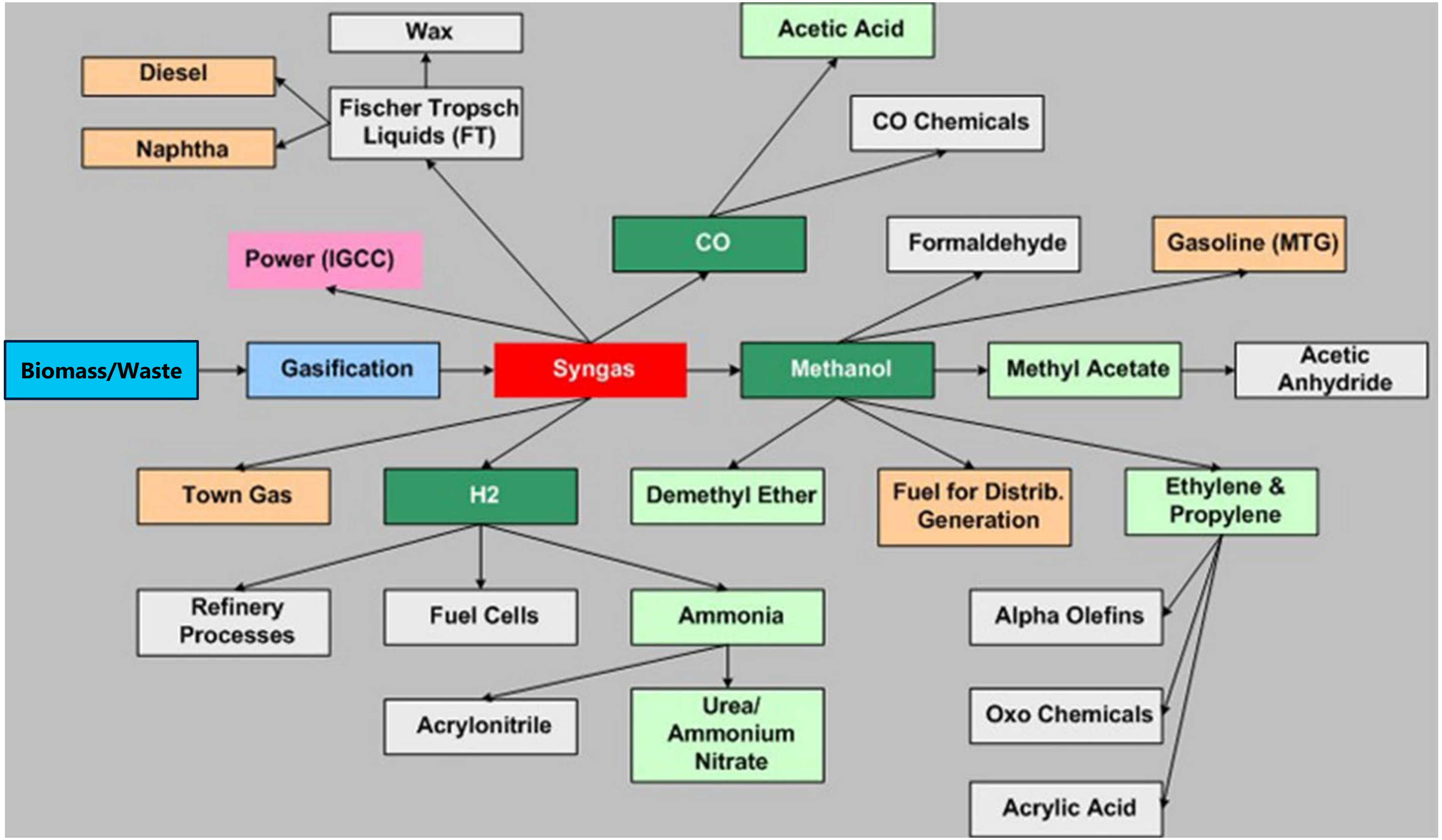

Advanced Syngas Manufacturing Possibilities

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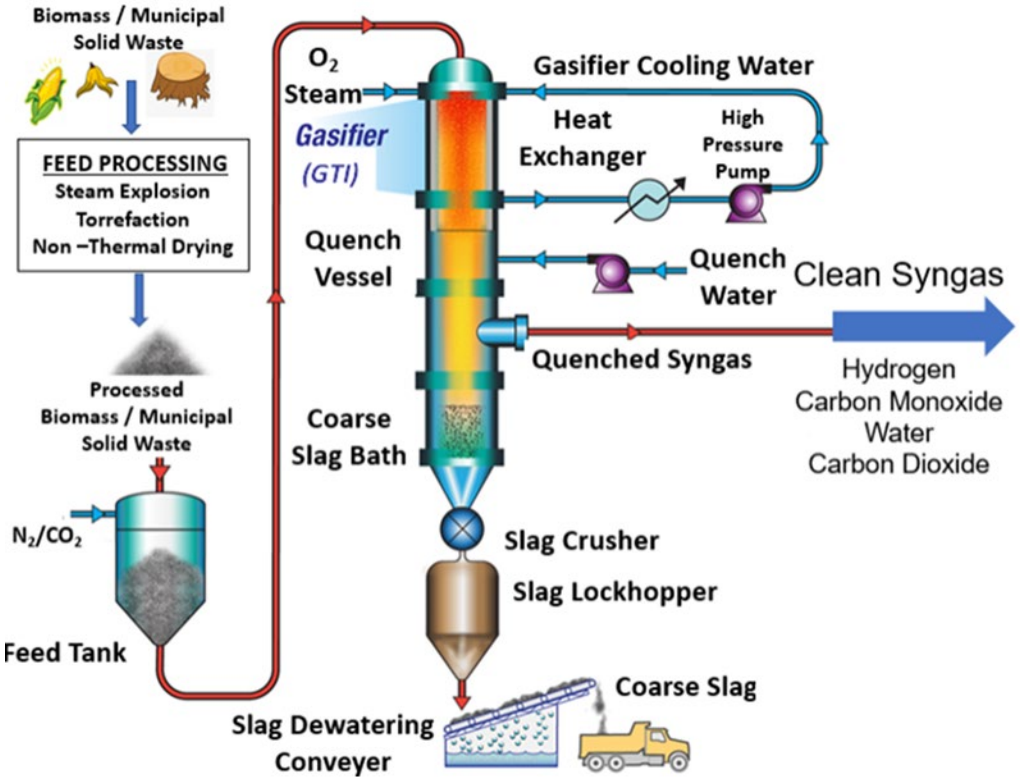
- Biomass gasification proven and commercialized (fixed and fluidized bed)
  – Remains relatively expensive and dependent on incentives (LCFS, RFS)
- Potentially lower-cost advanced gasification routes to sustainable products:
  1. Entrained flow biomass/waste gasification through torrefaction
  2. "Bio-eFuel" gasification route utilizing electrolysis for oxygen and hydrogen enrichment
  3. Blended POX/Biomass for near-term, net-negative, low-cost hydrogen production

GTI's BioR-GAS Gasification Process

- Developing capability for biomass conversion via advanced entrained flow gasification
- High-temperature gasification eliminates need for subsequent tar reformer or hot oxygen burner
- Focus is on efficient and effective pre-processing of feedstock to ensure suitability for pressurized feed to gasification reactor
- Biomass (corn stover) pilot testing under DOE-sponsored project highly successful – also investigating additional feedstocks including MSW



In-situ Reverse Water Gas Shift Enhanced Gasification to Produce "Bio-eFuels"

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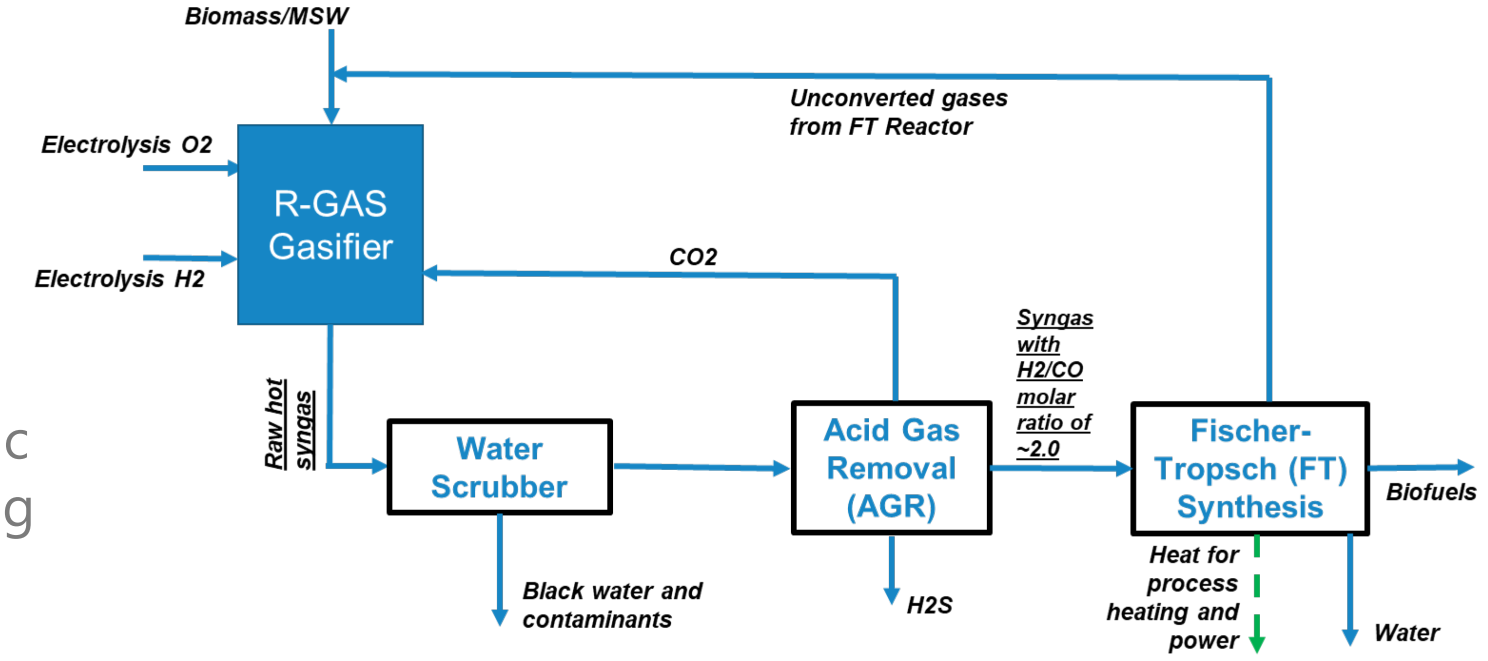
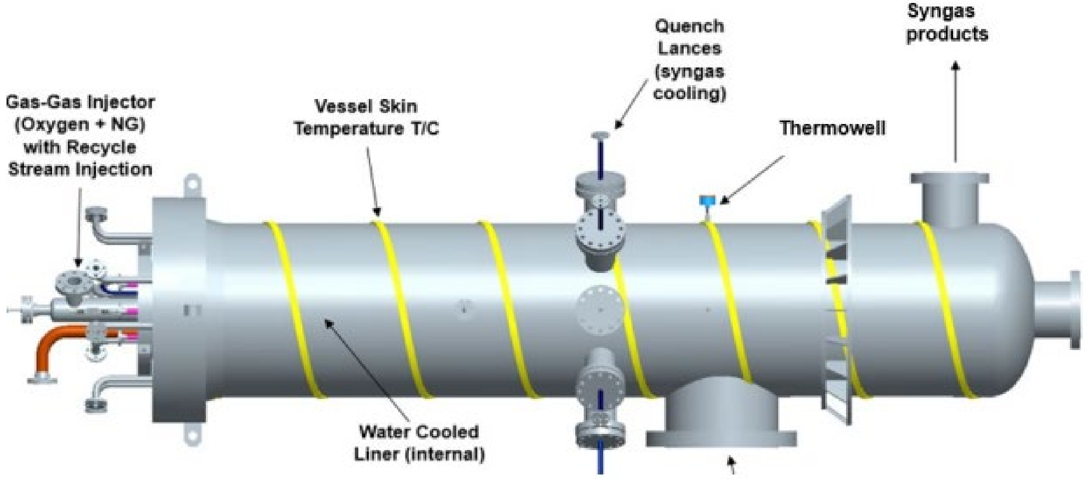
- Hydrogen injected at entrained-flow gasification zone exit to react with CO_2 gasification products and CO_2 recycled from AGR
- Leverages high heat content in syngas to drive fast endothermic reactions, significantly accelerating reduction of CO_2 by H_2 via RWGS reactions
  - Renewable H_2 provided via electrolysis



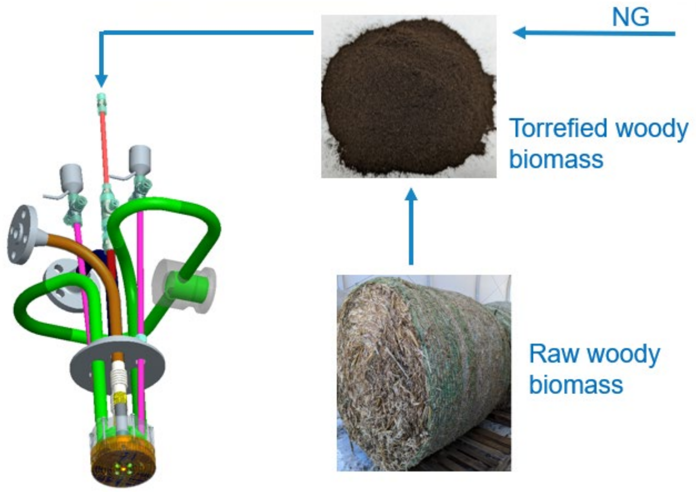
- Biofuel yield increased by **~2.75X** compared to traditional gasification-FT pathway
  - ~189 gal/dry ton biomass vs ~69 gal/dry ton biomass
  - **>25% improvement** in levelized cost of biofuel

Advanced POX for NG and Biomass Blends

- Co-injection of Natural Gas and biomass in partial oxidation (POX) reactor to achieve net-negative H_2 production
  - **SMR/ATR alternatives cannot provide net-negative emissions**
- Application of rocket-engine-inspired feed injectors for POX reactor for both solid and gaseous feedstocks



	ATR w/CCS	R-GAS POX (100% NG) w/CCS	R-GAS POX (60% NG/40% biomass) w/CCS
Total Emissions (kg CO2e/kg H2)	3.35	3.50	-0.43
LCOH ($/kg)	1.59	1.49	1.84



TEA/LCA figures are based on the NETL-2022/3241 report released by the U.S. Department of Energy in April 2022.

Summary

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- U.S. energy system modeling shows net-zero future will be heavily reliant on gaseous and liquid fuels, which will largely be produced from biogenic feedstocks
- There are many pathways to sustainable products and biofuels, but most scalable route is from cellulosic feedstocks to syngas through processes such as pyrolysis and gasification
  - Sustainable aviation, marine and LPG fuels present most urgent need since these industries are otherwise difficult to decarbonize
- Ample advanced manufacturing opportunities to reduce cost of biogas and syngas conversion to liquid and gaseous fuels

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Questions?

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