ASCENT Project 80

Hydrogen and Power to Liquid (PtL) Concepts for SAF Production

Washington State University, Massachusetts Institute of Technology

PIs: (WSU) M. Garcia-Perez, M. Wolcott |
(MIT) S. Barrett

Co-PIs: (MIT) F. Allroggen | (WSU) S. Ha, X. Zhang

Collaborators: J. Male, K. Brandt

PMs: Nate Brown, Anna Oldani

Objective:

Evaluate the opportunities associated with novel approaches for integrating hydrogen production and Power-to-Liquid (PtL) concepts into SAF production systems, including specifically lifecycle GHG emissions benefits and cost impacts.

Project Benefits:

1. Analysis of current and future SAF and PtL pathways: pros & cons, co-location potential
2. Provide a harmonized model to compare GHGs and costs of novel & existing pathways while capturing uncertainty and variability
3. Derive recommendations for future SAF/PtL R&D: how to best combine C, H, and conversion tech for lowest cost and GHG emissions

Research Approach:

New & Existing SAF/PtL Pathways

Assess & identify pathways to: integrate H_2 prod., ($ reduction), new C, H sources with existing SAF facilities

Life-Cycle Analysis of GHG emissions (LCA)

Conduct **well/field-to-wake (WTW) LCA of GHG emissions** per unit fuel energy [gCO_2e/MJ]

Techno-economic Analysis (TEA)

Apply **discounted cash flow analysis** to compute the minimum selling price of the fuel.

Major Accomplishments (to date):

1. Defined electricity-based SAF pathways
2. Identified novel conversion pathways with renewable hydrogen use
3. Set up stochastic LCA and TEA framework for pathway analysis

Future Work / Schedule:

- Assessment of H_2 production, new C & energy sources with SAF
- LCA (gCO_2e/MJ) and TEA ($/L) model
- First-principles-based analyses of DAC

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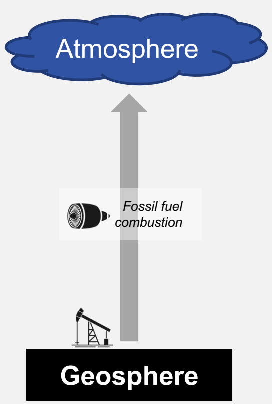
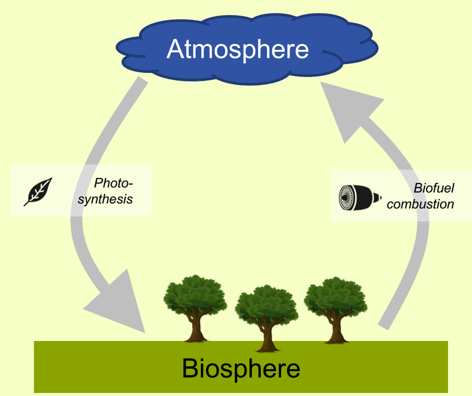
Energy carrier vectors for aviation – a typology

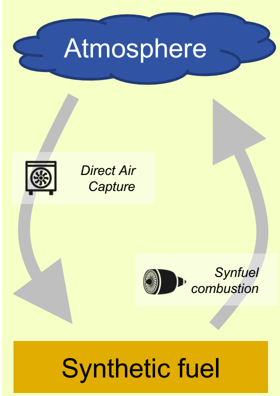
(Notional) change from current system

Drop-in or near-drop-in SAF | *Non-drop-in energy carriers*

	Fossil Jet-A	Waste- and biomass-based SAF	Power-and-biomass-to-Liquid (PBtL)	Power-to-Liquid	Hydrogen	Battery ?
H source	*Fossil H_2*	*Biomass and waste streams; currently supplemented by H_2 produced from SMR*	*Biomass and H_2 produced from renewable electricity*	*H_2 produced from low-carbon electricity*	*H_2 produced from low-carbon electricity or SMR with CCS*	
C source & C balance	*Fossil carbon*	*Biomass and waste streams**	*Biomass*	*Atmospheric CO_2 or waste CO_2 streams*	--	







* Using carbon from waste streams provides a carbon benefit if the carbon content of the waste stream would have been released to the atmosphere anyways.

Mapping electricity use in SAF production – a significant opportunity space.

PtL fuels are *a class of synthetic drop-in hydrocarbon fuels*, which use electricity as a major input "feedstock", especially for H_2 production, CO_2 extraction, and/or conversion into fuels.

BUT: ***A large range of pathway designs exists, including"hybrid" designs***

"Conventional" waste- and biomass-based SAF production

Electricity used as minor process input only

"Electricity-enhanced" waste- and biomass-based SAF production

"Conventional" SAF production processes with electricity as a significant input for feedstock production

Example:
HEFA using low-carbon hydrogen

"Electricity-optimized" SAF: Power-and-Biomass-to-Liquid

Biomass-based processes designed for electricity-based feedstocks

Example:
FT with recycling loop and H_2 from electrolysis

"Pure" PtL

Electricity as main input for feedstock production

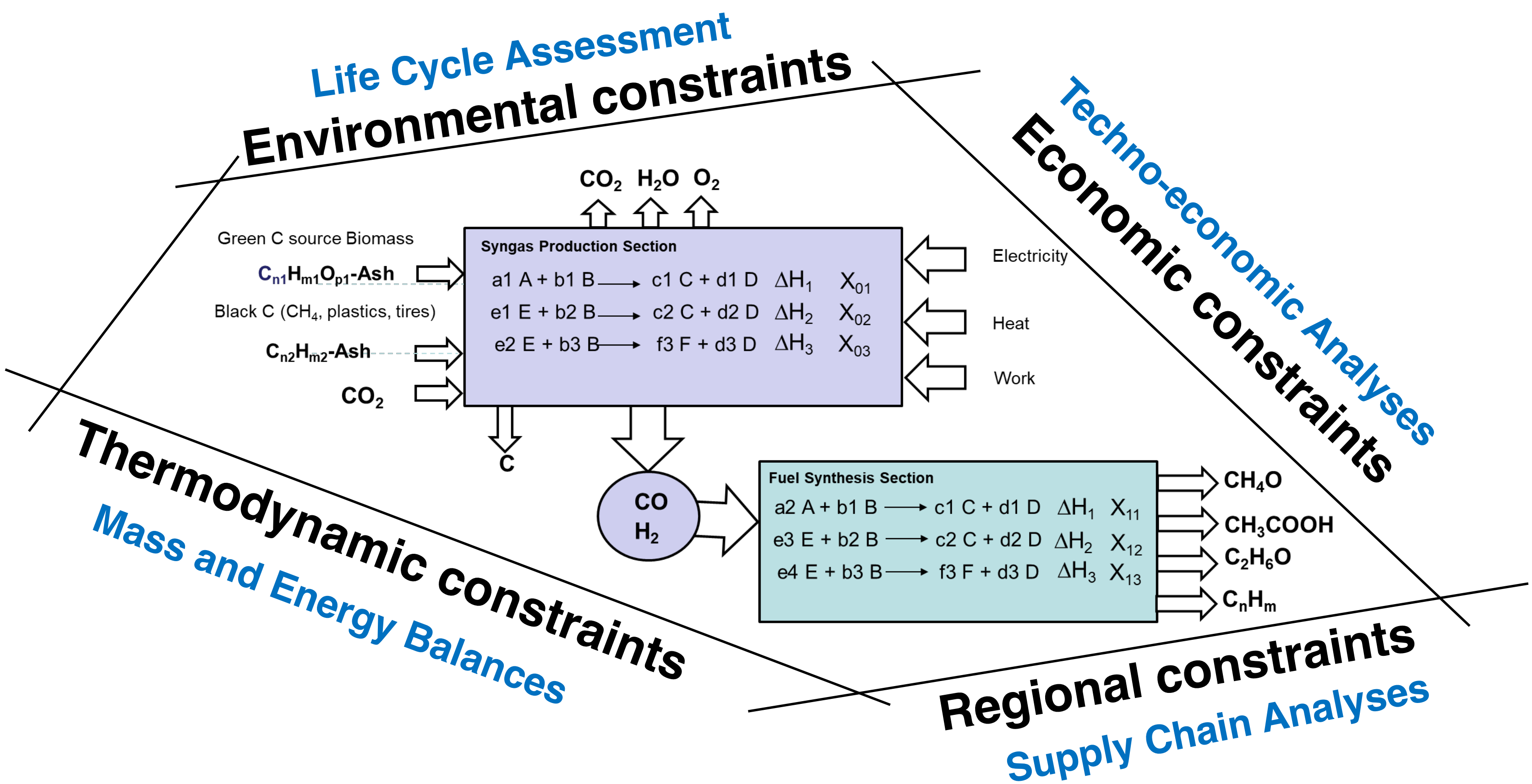
Example:
FT fed by H_2 from electrolysis and C from DAC

(Notional) electricity use

Novel conversion pathways with H_2

Objectives

Identify **Carbon, Hydrogen,** and **Energy sources (New Potential Feedstocks)** and **fuel conversion processes to enhance the economics and carbon intensity of the SAF.** Compare the **environmental footprint and economic sustainability indicators** of **the most promising approaches** with current SAF and conventional Power-to-Liquid pathways.

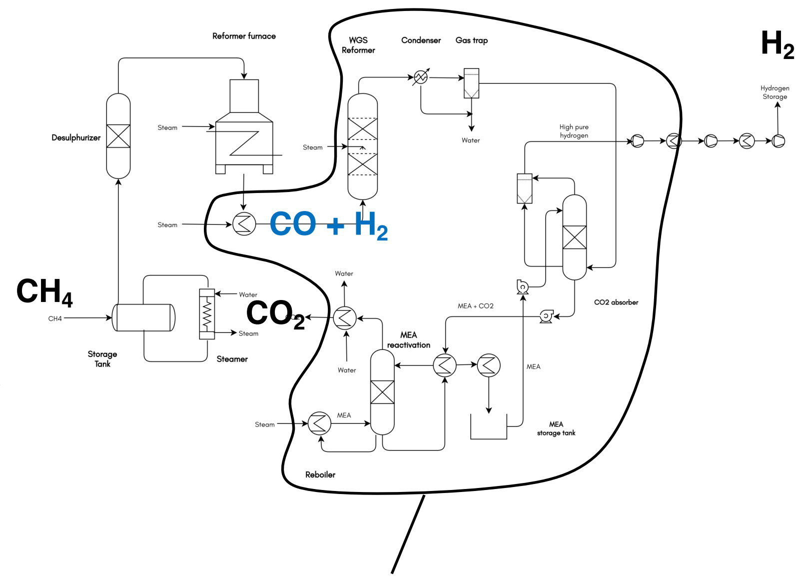


Novel conversion pathways with H_2

Review of new pathways to produce H_2

1. Steam Reforming (Low pressure, high pressure)
2. Dry Reforming
3. Auto-thermal Reforming
4. Methane Partial Oxidation
5. Thermal decomposition of hydrocarbons
6. Gasification of carbonaceous materials (biomass, coal, bitumen, MSW) with steam, CO_2 and O_2
7. Water Electrolysis (low and high temperature)
8. CO_2 Electrolysis

Steam Reforming



Section of an H_2 plant that may not be relevant when producing SAF

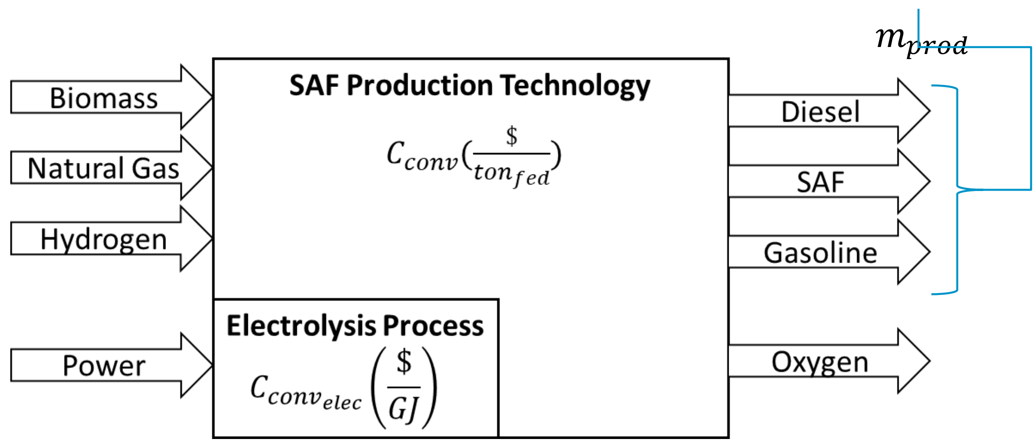
Goal: Write a Literature review on emerging and commercial hydrogen production technologies and techno-economic analysis of each of them.
The first draft is under review.

Technology-neutral framework

Lange has proposed simple models:

$$C_{prod}\ (\$/_{ton}) \approx \frac{C_{feed} + C_{conv}}{yield}$$

Resource Cost	Flowrate (tons)
C_b =70 $/ton	m_b
C_{NG} = 193 $/ton	m_{NG}
C_{H_2} = 4000 $/ton	m_{H_2}
C_{power} = 21.1 $/GJ	$W_{elec}/m_{prod}\ (\frac{GJ}{ton})$
C_{O_2} = 40 $/ton	m_{O_2prod}
C_{prod} ($/ton)	m_{prod}



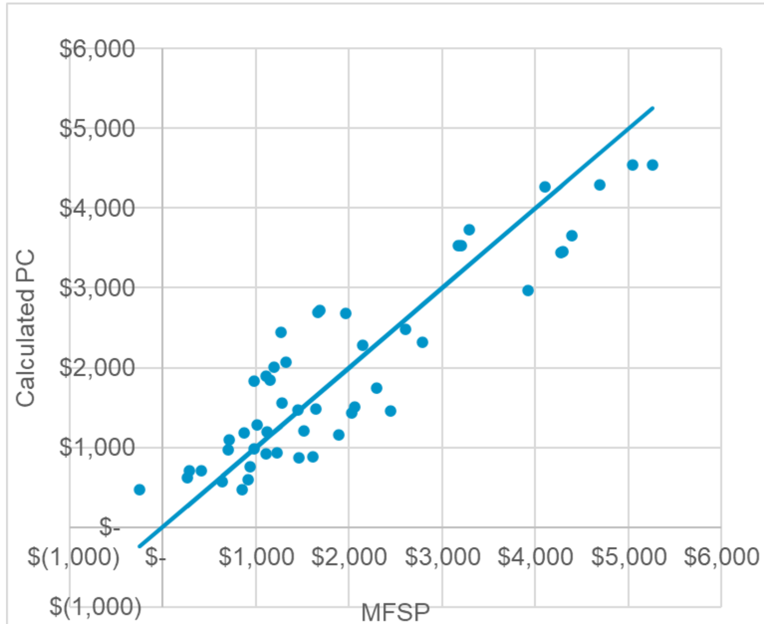
$$C_{prod} = \frac{(C_b + C_{conv}) \cdot m_b + C_{NG} \cdot m_{NG} + C_{H_2} \cdot m_{H_2} - C_{O_2} \cdot m_{O_2prod}}{m_{prod}} + (C_{power} + C_{conv_{elec}}) \cdot \frac{W_{elec}}{m_{prod}}$$

Lange, J.-P. Catalysis for biorefineries-performance criteria for industrial operation. *Catal. Sci. Technol.*, **2016**, *6*, 4759-4767.

Holistic analysis of sustainable fuel production

Data selection and correlation

- 50 Datapoints from 8 studies
  - 28 used to fit base PC calculation
- Uncertainty of \$615/ton
  - Reasonable for economic analysis – 30% error the norm



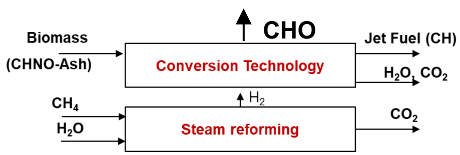
$$C_{prod} = \frac{(C_b + \$317) \cdot m_b + C_{NG} \cdot m_{NG} + C_{H_2} \cdot m_{H_2} - C_{O_2} \cdot m_{O_2 prod}}{m_{prod}} + (C_{power} + 39) \cdot \frac{W_{elec}}{m_{prod}}$$

- \$317/ton consistent with values in chemical industry (100-300 \$/ton) (Lange, 2019)
- \$39/GJ approximates the levelized cost of electrolysis
- All other variables obtained from cost data

The technology you use does not seem to be that important
What is vital, is the outcome of your technology

Stoichiometric models

Current Commercial Technologies



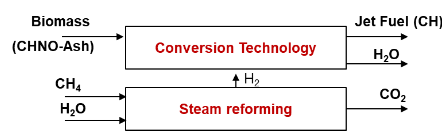
Yield = 0.09 – 0.23
MFSP = $2050-5190/ton

These very simple stoichiometric models consider that biomass O is removed preferentially from three molecules (CO_2, H_2O, and O_2). The C left is converted into a hydrocarbon

All O removed as CO_2

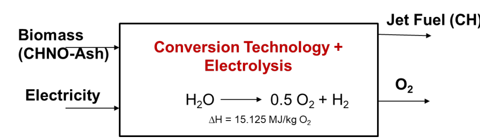
Yield = 0.34
PC = $1,195/ton
CI = 3.2 gCO2/MJ
RIN Effect = $605/ton
SPC = $590/ton

All O removed as H_2O with external H_2



Yield = 0.55
PC = $762/ton
CI = 25 gCO2/MJ
RIN Effect = $393/ton
SPC = $369/ton

All O removed as O_2 via electrolysis



Yield = 0.53
PC = $1,523/ton
CI = 11 gCO2/MJ
RIN Effect = $605/ton
SPC = $918/ton

[1]Yields Defined on biomass basis (tons distillate/tons biomass)
[2]CI calculated using WA average grid footprint (27 g/MJ)

PC: Production Cost
SPC: Subsidized production cost

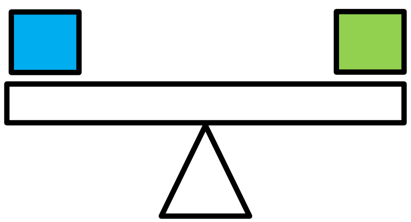
Holistic analysis of sustainable fuel production

Economic versus environmental trade-off

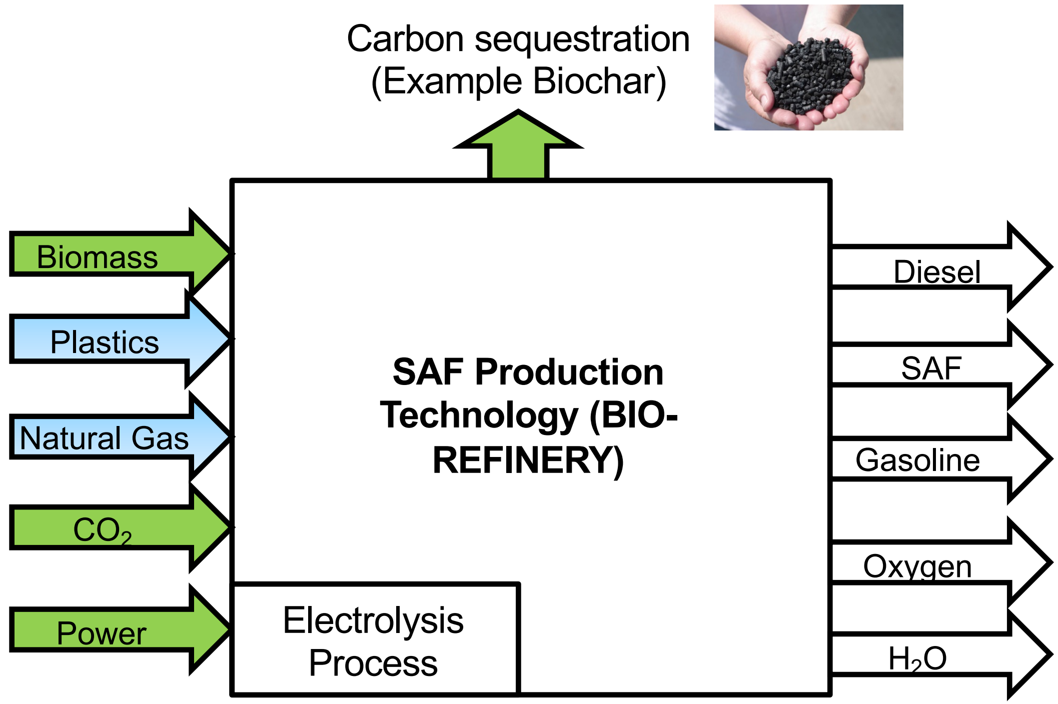
Economic advantages

Environmental advantages

Right Balance between Economic and Environmental competitive advantages?



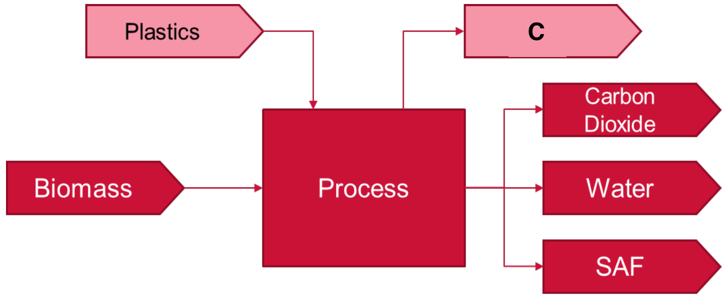
Balance will depend **on regulatory frame + incentive levels**



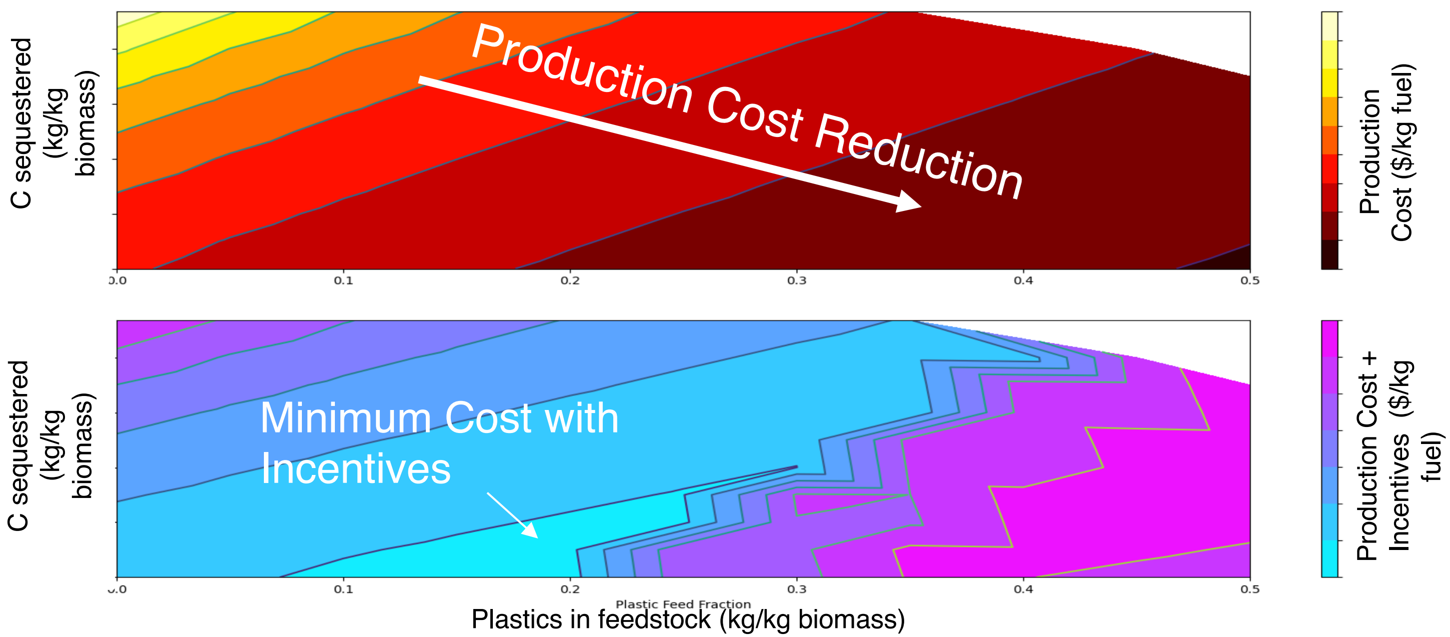
We will use the simplified models to study the trade-off between several technological alternatives

Holistic analysis of sustainable fuel production

Removal of O in the form of CO_2



Plastics addition versus carbon sequestration



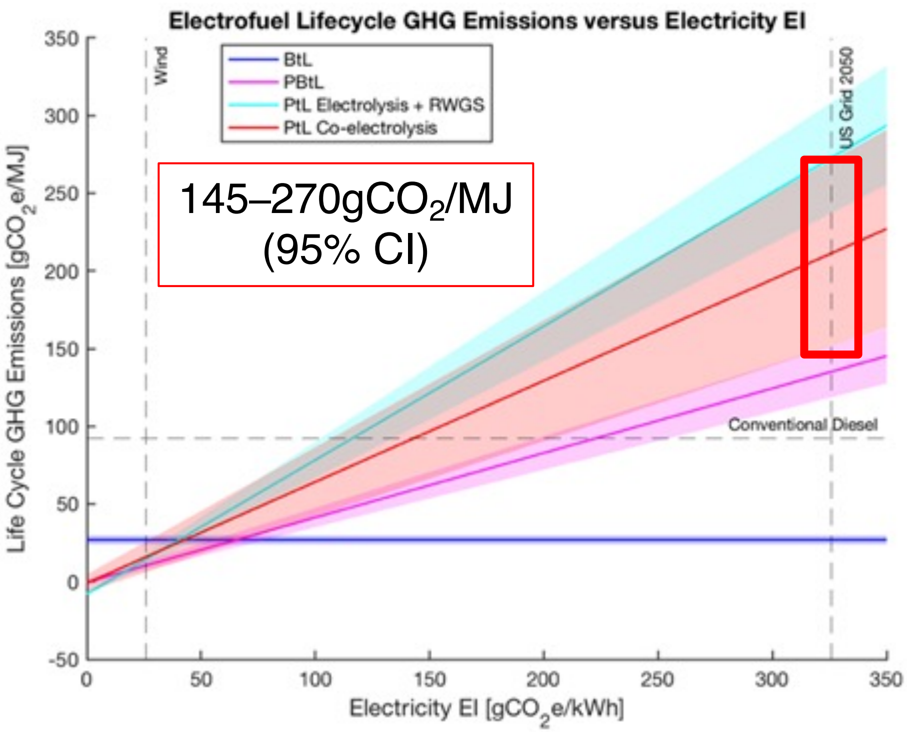
Carbon storage helps reduce the “carbon Intensity” of the fuel but reduces yield.

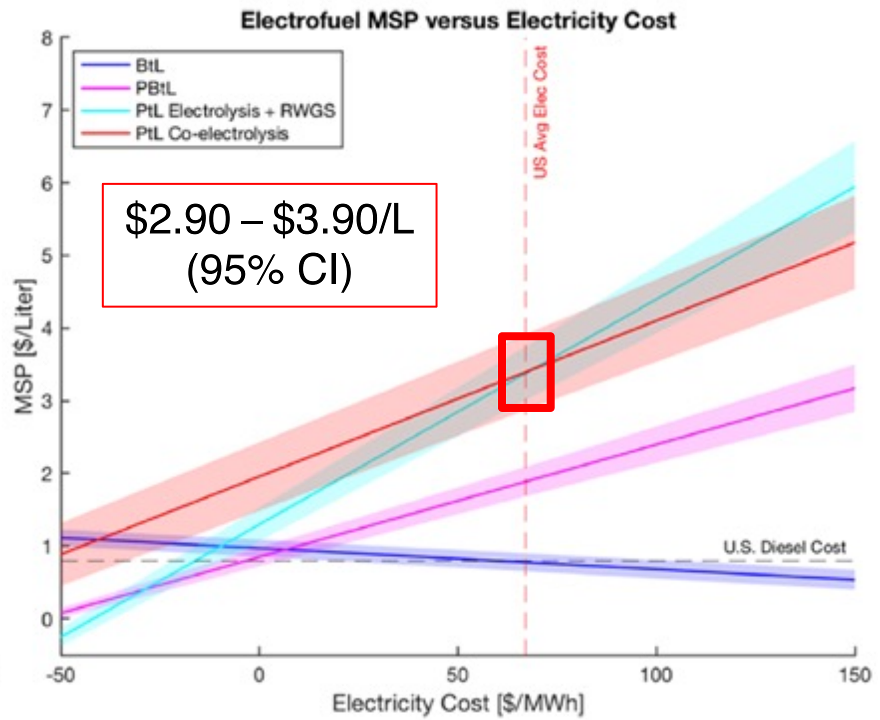
Plastics addition helps to increase yield but increases “carbon Intensity”

Under the incentives considered in our analysis (**RINs, LCFS**) the carbon sequestration benefits are insufficient to justify yield loss which directly impacts production cost. For the ideal model used there is run to add a very small quantity of plastics. This will increase the yield. Adding larger quantities will be penalized with the loss of incentives associated with environmental performance.

Need for stochastic LCA and TEA assessment for this project

- There may be uncertainties in lifecycle GHG emissions and minimum selling prices of jet fuel for existing, new, and combinations of SAF/PtL pathways, especially since they are not yet used at scale.
- Stochastic assessment will allow us to understand the range of possible GHG emissions and costs of novel pathways, given prevailing uncertainties, thereby helping to identify opportunities and risks as well as guiding further R&D for pathway characterization.





Isaacs et al. (2021), *Environmental Science & Technology.* Environmental and Economic Performance of Hybrid Power-to-Liquid and Biomass-to-Liquid Fuel Production in the United States

Uncertainty versus variability: a framework

Uncertainty

Refers to lack of data or an incomplete understanding of the factors that affect an outcome. <u>More/better data could reduce uncertainty.</u> (U.S. EPA, 2021). **Biofuel facility <u>cannot intentionally control</u> variable.**

Example
Feedstock transport mode share split (truck/rail/barge)

Primary focus in the context of analyzing novel unexplored technologies

Variability

Refers to inherent heterogeneity of diversity of data in an assessment. "A quantitative description of the range or spread of a set of values." <u>More/better data will not reduce variability</u> (U.S. EPA, 2021). **Variable can be intentionally controlled or differs regionally.**

Example
Jet volume fraction in product slate

To be captured as needed (e.g. for discussing different electricity inputs)

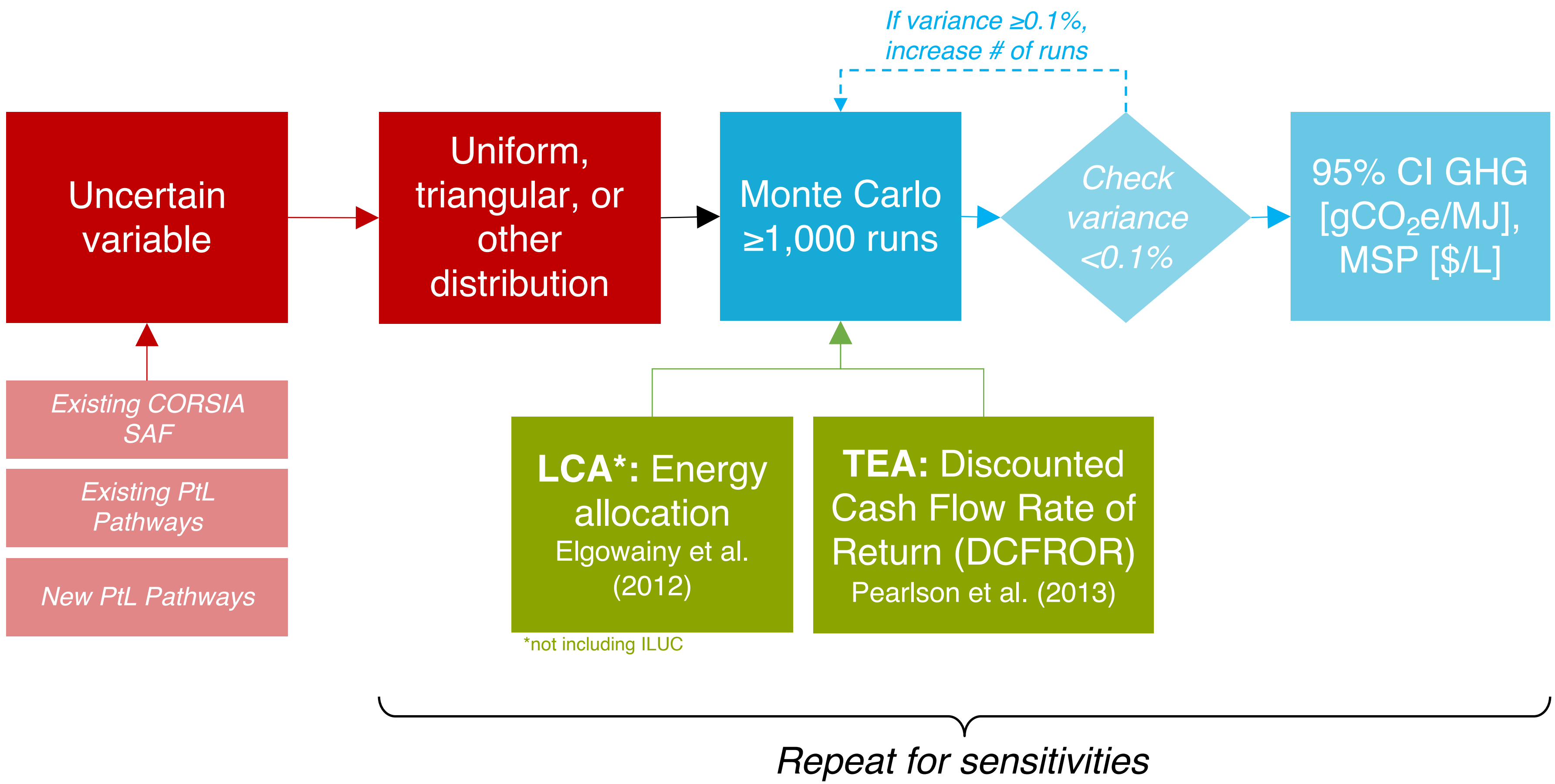
Sensitivity

Studying impact on dependent variable due to variability

Example
Impact on GHG emissions from differences in electricity carbon intensity

Environmental Protection Agency. (2021, December 13). *Uncertainty and Variability*. EPA. Retrieved March 9, 2022, from https://www.epa.gov/expobox/uncertainty-and-variability

LCA and TEA modeling approach



Elgowainy, A. et al. (2012) Life Cycle Analysis of Alternative Aviation Fuels in GREET. Argonne National Laboratory, Argonne, IL, USA.

Pearlson, M., Wollersheim, C., & Hileman, J. (2013). A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels, Bioproducts and Biorefining*, *7*(1), 89–96. https://doi.org/10.1002/bbb.1378

Example: HEFA UCO stochastic inputs

Raw Grease Collection ❯ UCO Rendering ❯ UCO Transport ❯ Fuel Production ❯ Jet Transport

Raw Grease Collection

Distance (km)
Mean: 155.8
σ: 36.7
Diesel truck (km/L)
Low: 2.09
Base: 2.47
High: 2.85

UCO Rendering

Natural Gas (MJ/kg UCO)
Low: 0.29
Base: 1.46
High: 2.24

Electricity (MJ/kg UCO)
Low: 0.063
Base: 0.15
High: 0.25

- Removing moisture from UCO
- dry vs. wet rendering
- Moisture content 28 ± 8.5% to 1.2 ± 0.8%

UCO Transport

Distance (km)
Low: 157.5
Base: 289
High: 420.5
Diesel truck (km/L)
Low: 2.13
Base: 2.3
High: 2.47

1st order assumption: distance to animal feed plant ~ refinery

Fuel Production

Product Slate % (Energy)
(Max Jet | Max Diesel)
Jet: 55.1 | 14.5
Diesel: 25.9 | 77
Naphtha: 7.9 | 2.1
Propane: 11.1 | 6.4

Natural Gas (MJ/kg Jet)
Low: 4.88
High: 6.83

Electricity (MJ/kg Jet)
0.22
0.31

Jet Transport

Distance to central tank (km):
Truck: 80 (63%)
Barge: 839 (8%)
Rail: 1287 (29%)

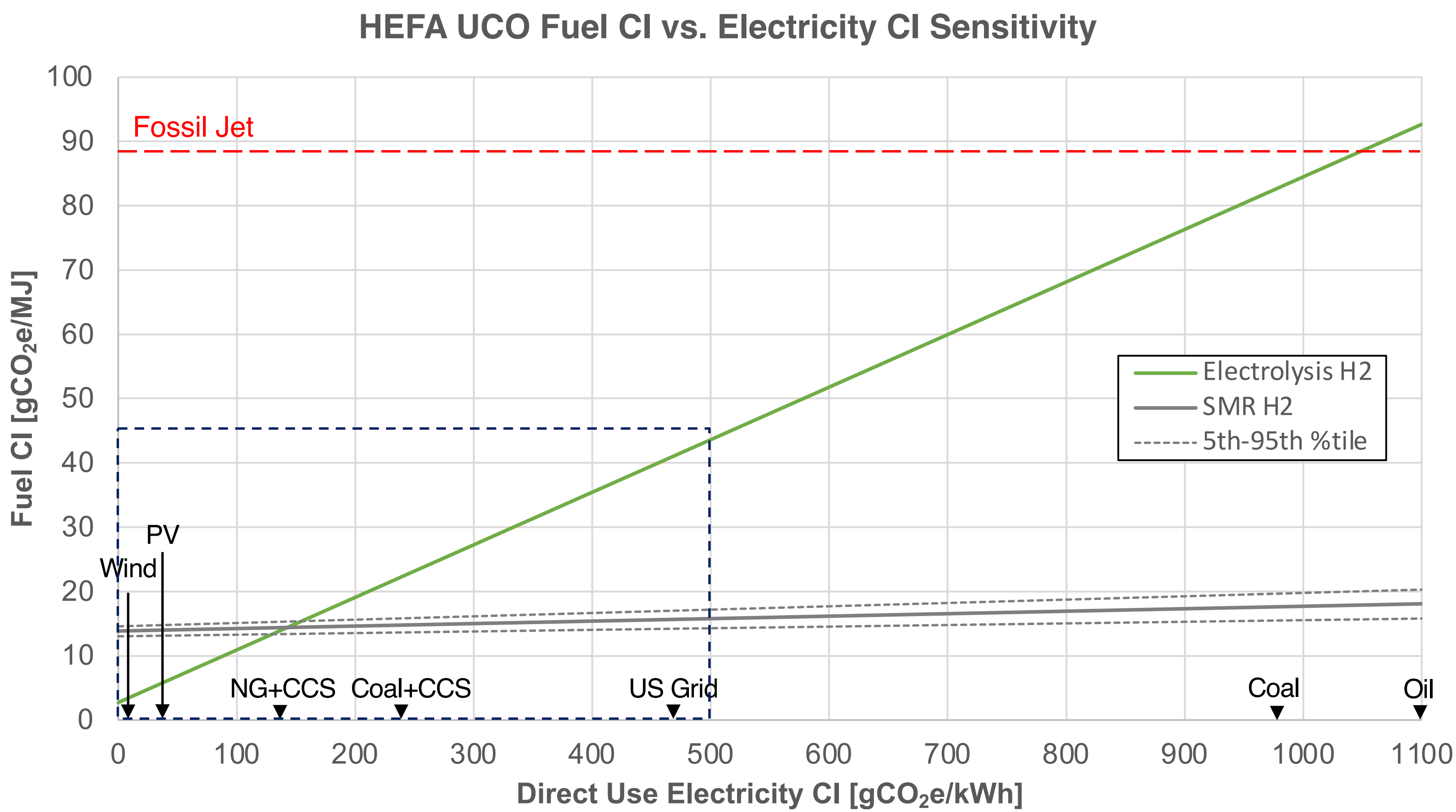
Distribution:
Truck: 48

Seber, G., Malina, R., Pearlson, M.N., Olcay, H., Hileman, J.I., Barrett, S.R.H., 2014. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. Biomass and Bioenergy 67, 108–118. doi:10.1016/j.biombioe.2014.04.024

Lopez, D., Mullins, J., & Bruce, D. (2010). Energy life cycle assessment for the production of biodiesel from rendered lipids in the US. *Ind Eng Chem Res*, *49*(2), 419-432.

Preliminary results.

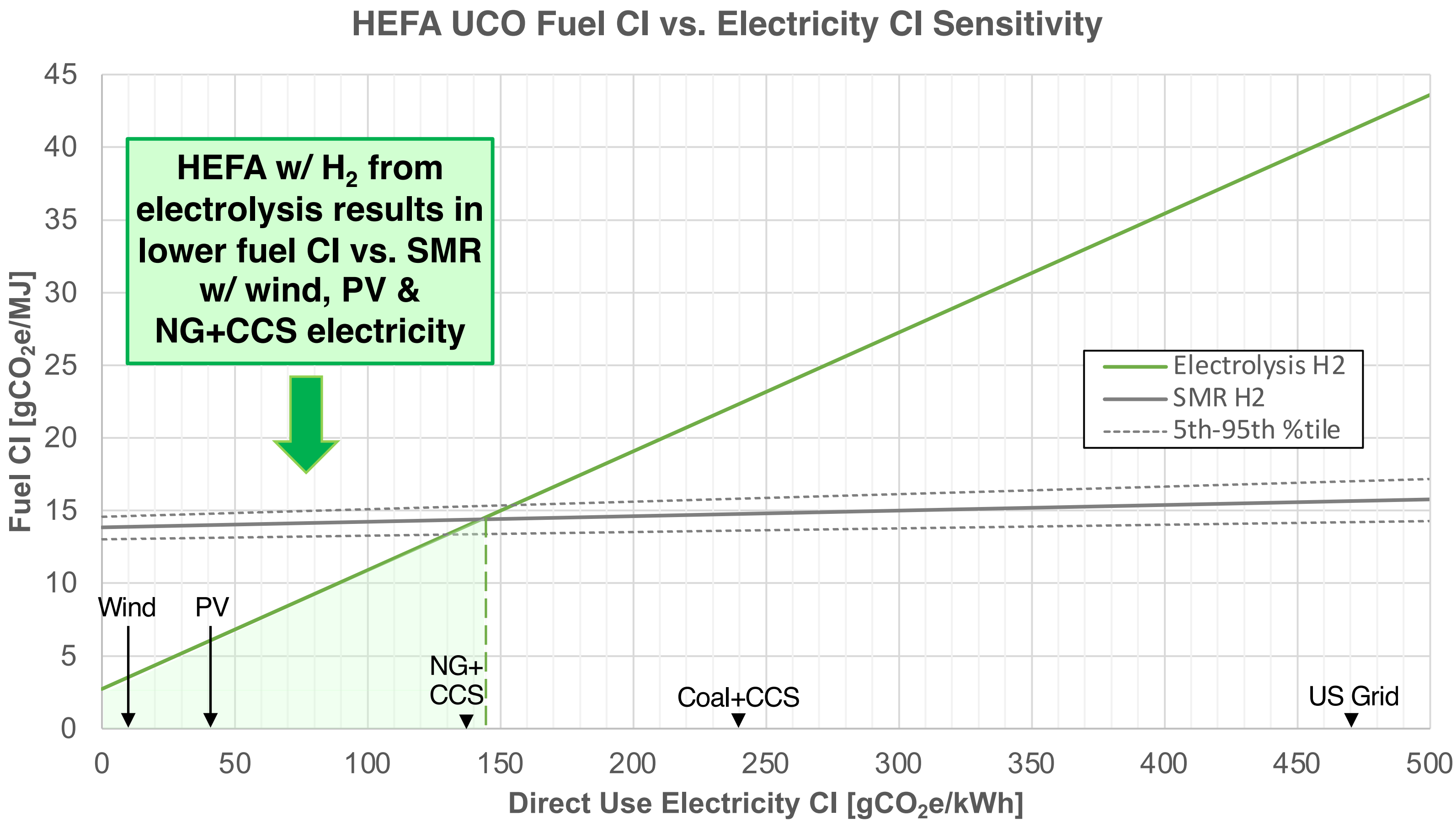
HEFA UCO stochastic LCA: H_2 source (SMR & Electrolysis) and sensitivity to electricity carbon intensity



- ~5% of direct process energy is electricity for HEFA UCO, thus sensitivity to electricity CI is low (*see grey SMR H_2 line*)
- When adding hydrogen from renewable electricity, the CI sensitivity increases significantly (*see green Electrolysis H_2 line*)

Preliminary results.

HEFA UCO stochastic LCA: H_2 source (SMR & Electrolysis) and sensitivity to electricity carbon intensity



- HEFA UCO w/ H_2 from electrolysis results in lower fuel CI vs. SMR w/ electricity <143gCO_2e/kWh
- Other possible sources: Hydro, Geothermal, Willow IGCC

Preliminary results.

Summary

Conclusions

- We have presented the SAF production problem to visualize the environmental, economic, and technical tradeoffs and to guide us in technology development
- In the case of syngas it imposes constraints into the design of systems that maximize carbon conversion efficiency
- Stochastic analysis for novel fuel pathways is important for fuel LCA/TEA to establish uncertainty
- Sensitivity studies, especially with electricity, will be useful for current and future PtL pathways to quantify the range of possible emissions reductions

Next Steps

- Develop a tool to estimate production costs and expected incentives if the yield of products and process inputs are known
- Propose new SAF production technologies integrated with different hydrogen production concepts
- Continue LCA/TEA model development and apply to more existing CORSIA-approved SAF pathways & feedstocks
- Adjust model for newly identified PtL pathways