ASCENT Project 80

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

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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:

- Critical assessment of H_2 production, new C & energy sources with SAF
- LCA and TEA model development & adjustment
- gCO_2e/MJ, $/L of current/future SAF/PtL

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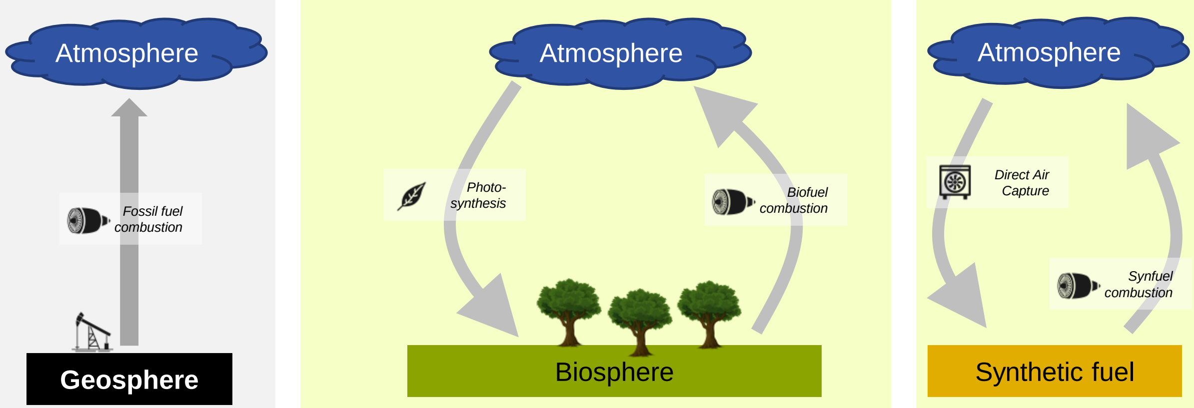
Energy carrier vectors for aviation – a typology

(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*	--	

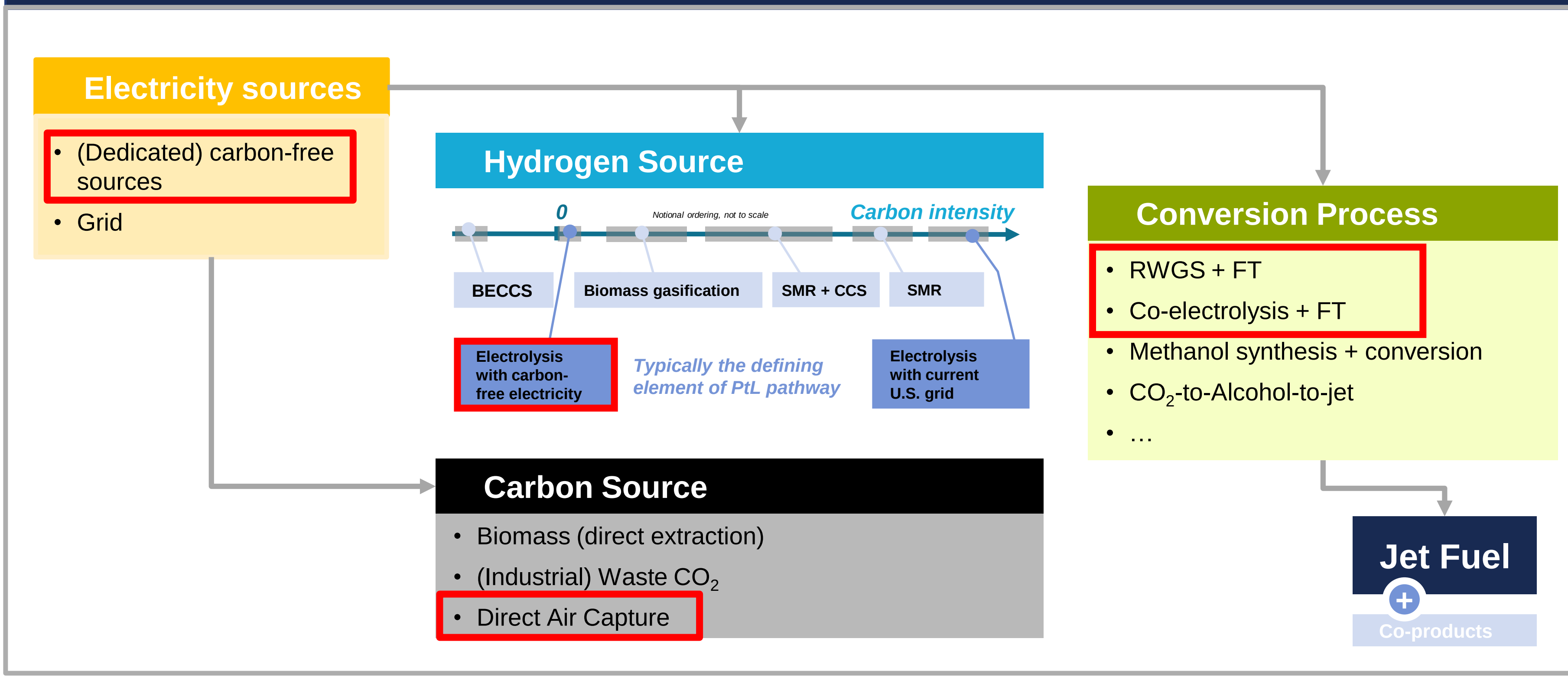


* Using carbon from waste streams provides a carbon benefit if the carbon content of the waste stream would have been released to the atmosphere anyways.

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.

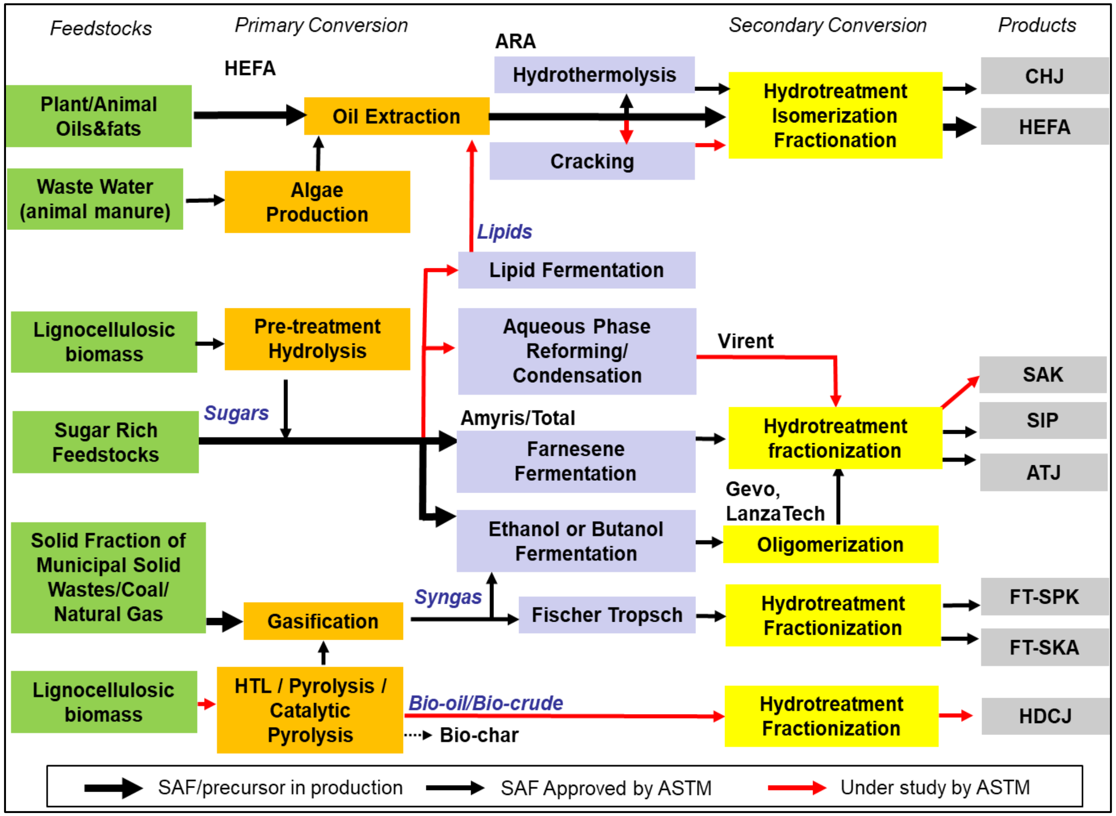
<u>BUT:</u> A large number of pathway designs exists and a large number of potential “hybrid” designs

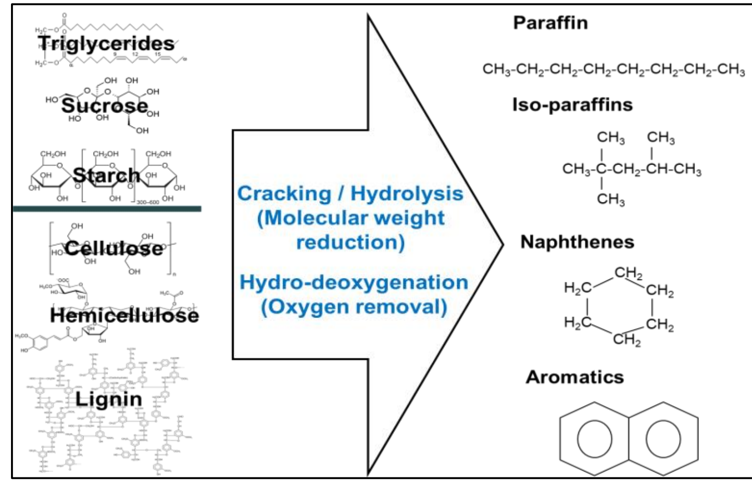


“Common” PtL pathway

Motivation

Results from ASCENT 1





Conducted TEA for six SAF production Technologies: (1) Fischer-Tropsch, (2) Fast pyrolysis (3) Alcohol-to-Jet, (4) Aqueous phase reforming, (5) Direct Sugar to hydrocarbons (DSHC), (6) Hydro-processed Esters and Fatty Acids (HEFA).

MFSP

HEFA: 1150 - 1430 $/MT

Others: 2050-5190 $/MT

$$MFSP = \frac{Feedstock\ Price\ + Conversion\ Cost}{Product\ Yield}$$

Yield

HEFA: 0.86 - 0.91

Others: 0.09-0.23

Conversion Cost ($ / ton feedstock)

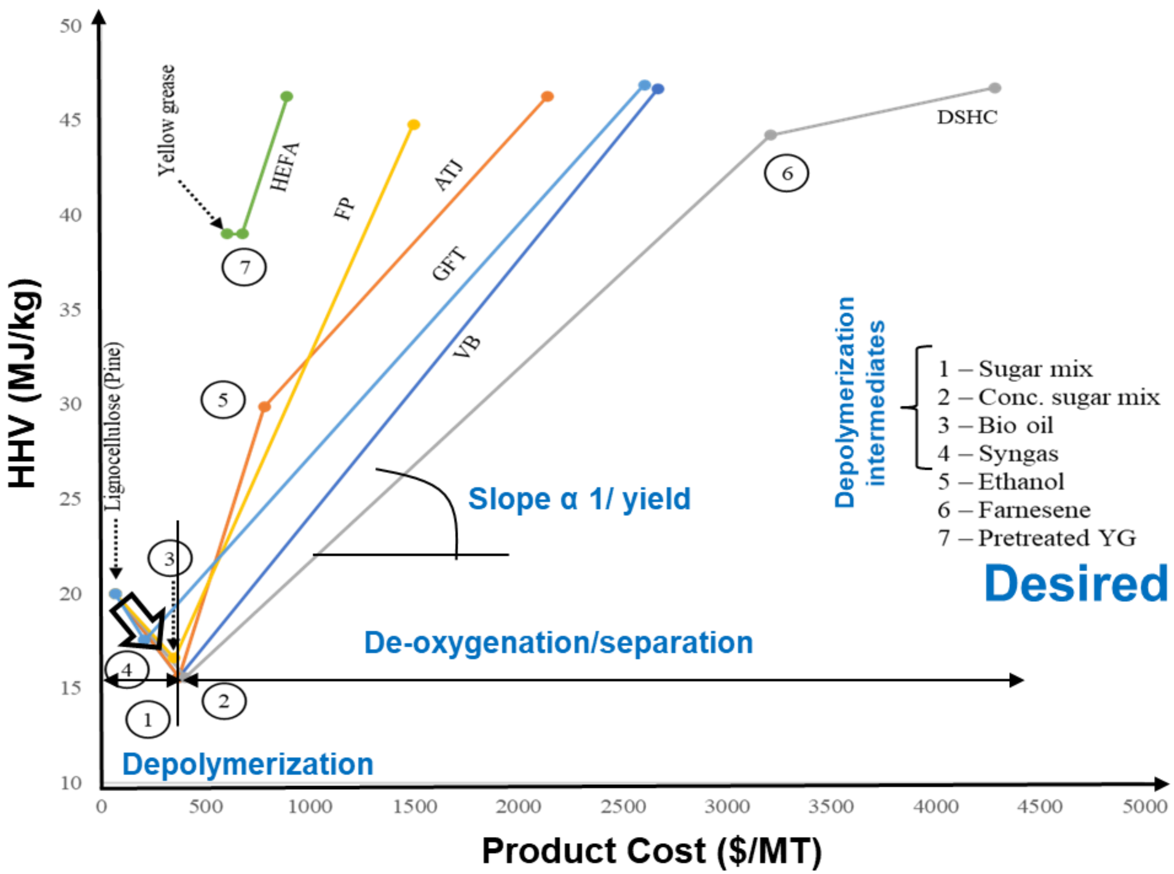
HEFA: 208-210

Others: 164-406

Maximizing C conversion Efficiency is critical to produce cheap SAF.

Motivation

O removal mechanism is also critical for SAFs production



Uncertainties of these estimations +/- 30 % or higher

The main cost differences observed are in the **deoxygenation step**

$$2O + C \rightarrow CO_2$$

42 g **15.7 g**

$$O + 2H \rightarrow H_2O$$

42 g **5.2 g**

To increase product yield, **O must be removed as H_2O, we must avoid CO_2 formation.**

To become economically viable **($600/MT fuel)** at a biomass cost of **$65/MT**, jet fuel yield from a lignocellulosic material must be close to **61 wt. %**

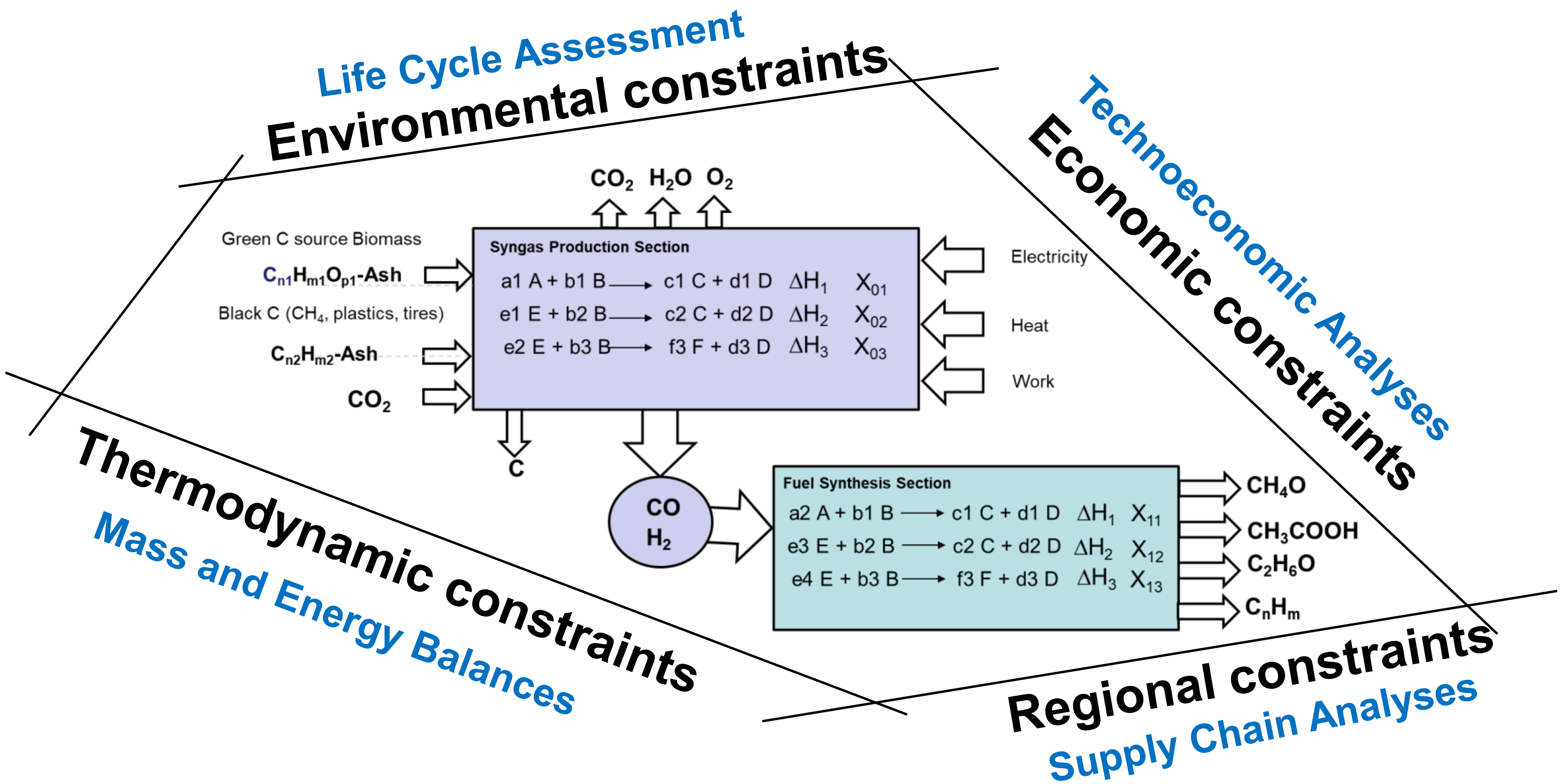
$$Yield = \frac{Feedstock\ Price + Conversion\ Cost}{Jet\ Fuel\ Market\ price} = \frac{65\left(\frac{\$}{MT}\right) + 300\left(\frac{\$}{MT}\right)}{600\left(\frac{\$}{MT}\right)} = \mathbf{0.61}$$

Novel conversion pathways with H_2

Objectives

Identify **Carbon, Hydrogen** and **Energy sources (New Potential Feedstocks)** as well **as fuel conversion processes to enhance economics and carbon intensity of the SAF.**

Compare the **environmental footprint and economic sustainability indicators** of **the most promising approaches** with current SAF as well as conventional Power-to-Liquid pathways.

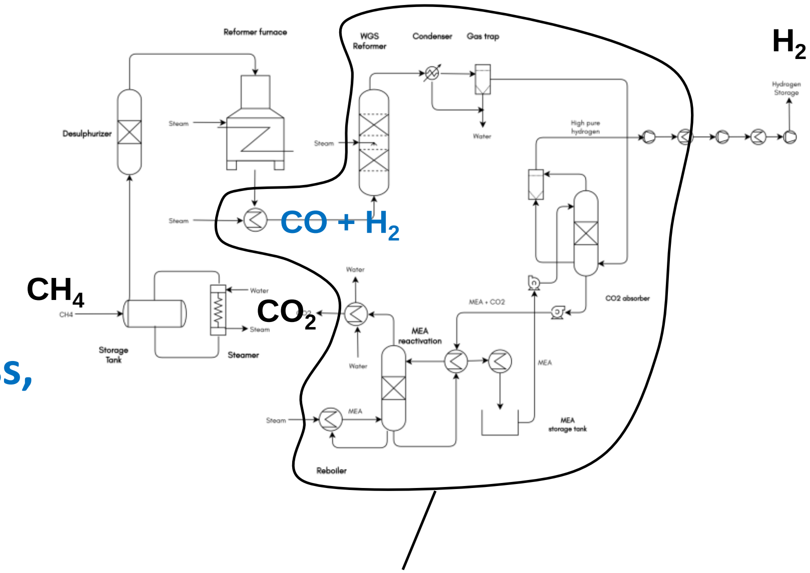


Novel conversion pathways with H_2

Review of new Pathways to Produce Hydrogen

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

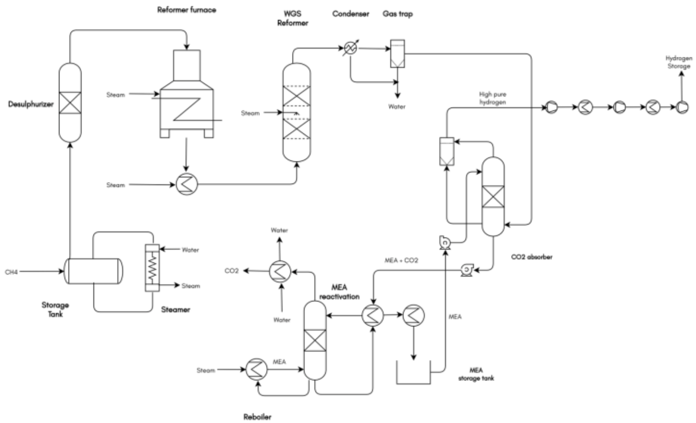


Section of a H_2 plant that may not be relevant when producing SAF

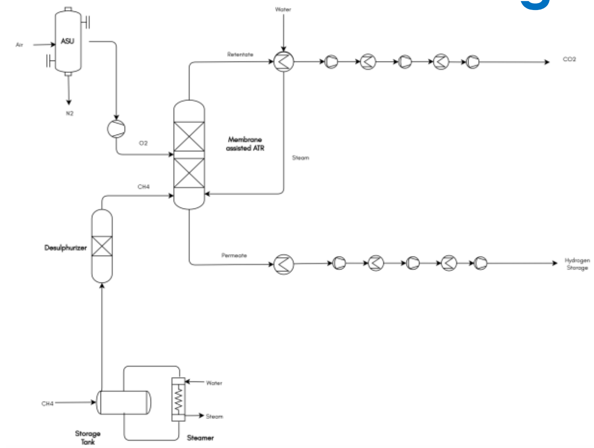
Goal: Write a Literature review on emerging hydrogen production technologies and technoeconomic analysis of each of them.

Review of new Pathways to Produce Hydrogen

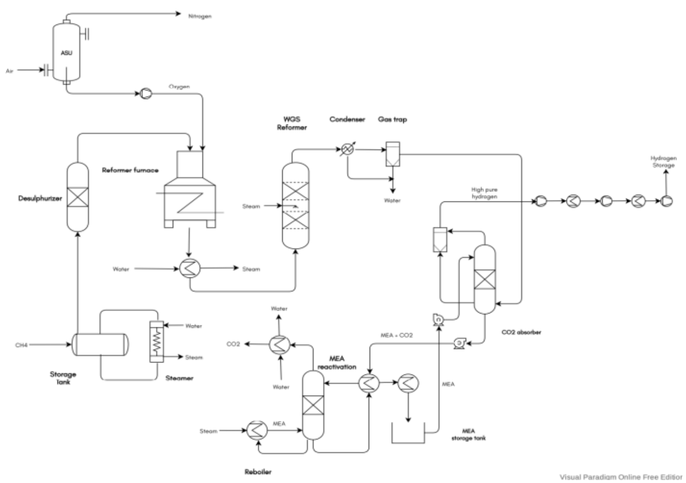
Steam Reforming



Auto-thermal Reforming

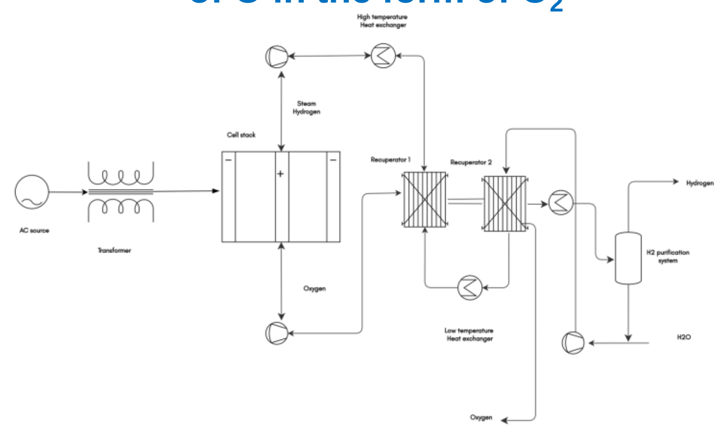


Methane Partial Oxidation



High temperature Electrolysis

Very high energy efficiency and allows removal of O in the form of O_2



Great Opportunities for technology integration. Bi-weekly meeting with panel of experts from PNNL and WSU to identify potential Synergisms.

Conceptual Evolution of SAF Production Technologies

Current Technologies

Yield = 0.09 – 0.23

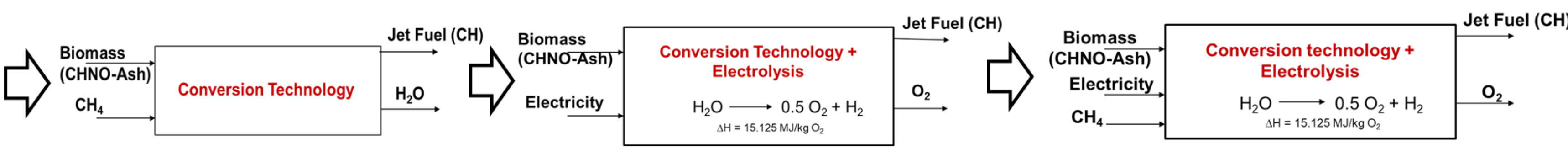
MFSP = $ 2050-5190 /ton

Yield = 0.34

MFSP = $ 794/ton

Yield = 0.55

MFSP = $ 550/ton



Yield = 1.22

MFSP = $ 339/ton

Yield = 0.53

MFSP = $ 650/ton

Yield = 0.71

MFSP = $ 531/ton

SAF production technologies that use all the C contained in the biomass, that remove O in the form of O_2 via electrolysis and that take advantage of the low price of CH_4 as much as possible are likely to be the most successful SAFs production technologies.

Conceptual Evolution of SAF Production Technologies

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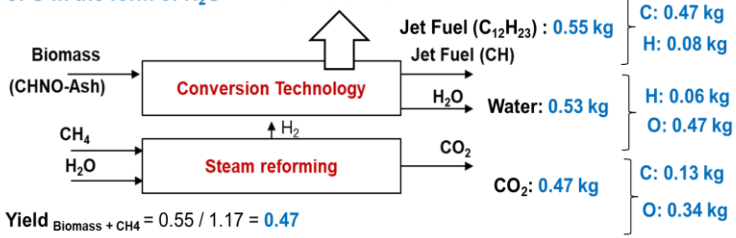
Removal of O in the form of H_2O

Heat: - 0.93 MJ

Biomass: 1 kg
- C: 0.47 kg
- H: 0.06 kg
- O: 0.47 kg

Methane: 0.17 kg
- C: 0.13 kg (21 %)
- H: 0.04 kg

Water: 0.38 kg
- H: 0.04 kg
- O: 0.34 kg



$\text{Yield}_{\text{Biomass + CH4}} = 0.55 / 1.17 = 0.47$

$\text{Yield}_{\text{Biomass}} = 0.55 / 1 = 0.55$

C Efficiency = 0.47 / 0.60 = 0.78

CH_4 **Cost:** $ 192/ ton

$Q = H_{fuel} - H_{CH4} - H_{biomass} = 26.1 - 27.1 = -0.93$ MJ

Energy Efficiency = 26.1/27.1 * 100= 96.6

MFSP = [(Feedstock price) ($/ton of feedstock) + conversion cost ($/ton feedstock)] / yield (t fuel/ton feedstock)

MSFP = (70 + (0.17* 192) + 200) / 0.55 = 550 $/ton

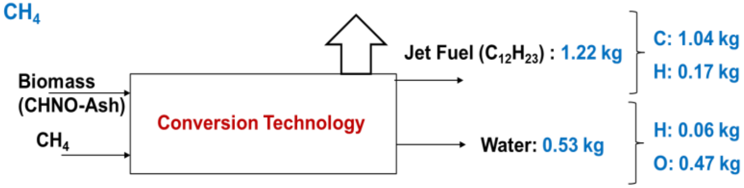
Removal of O in the form of H_2O with co-processing with CH_4

Heat: - 1.33 MJ

Biomass: 1 kg
- C: 0.47 kg
- H: 0.06 kg
- O: 0.47 kg

Methane: 0.75 kg
- C: 0.56 kg (54 %)
- H: 0.19 kg

Very high level of non-renewable C



$\text{Yield}_{\text{Biomass + CH4}} = 1.22 / 1.75 = 0.70$

$\text{Yield}_{\text{Biomass}} = 1.22 / 1 = 1.22$

C Efficiency = 1.04/1.04 = 1

CH_4 **Cost:** $ 192/ ton

$Q = H_{fuel} - H_{CH4} - H_{biomass} = 58.1 - 59.4 = -1.33$ MJ

Energy Efficiency = 58.1/59.4 * 100= 97.8

MFSP = [(Feedstock price) ($/ton of feedstock) + conversion cost ($/ton feedstock)] / yield (t fuel/ton feedstock)

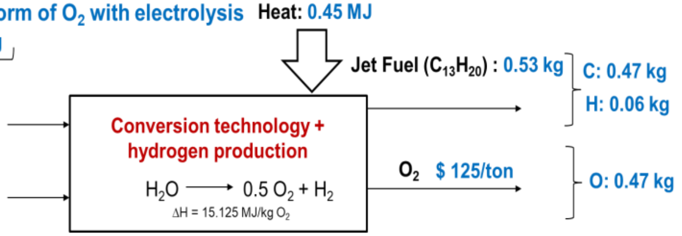
MSFP = (70 + (192*0.75) +200) / 1.22 = $ 339.3 / ton ← Lowest cost

Removal of O in the form of O_2 with electrolysis

Heat: 0.45 MJ

Biomass: 1 kg
- C: 0.47 kg
- H: 0.06 kg
- O: 0.47 kg

Electricity



Cleanest fuel but more expensive. MFSP could be reduced with lower electricity costs

$\text{Yield}_{\text{Biomass}} = 0.53 / 1 = 0.53$

$C_{\text{Efficiency}} = 0.47 / 0.47 = 1$

$W_{\text{Electricity}} = 15.125 * 0.047 = 7.11$ MJ

Biomass = $ 4.19 /GJ ($70/dry ton)
Methane = $ 3.47 /GJ ($192/dry ton)
Electricity = $ 18.9 /GJ ($ 0.067/kWh)

$Q = H_{fuel} - H_{CH4} - H_{biomass} - W_{electricity} = 25.2 - 17.6 - 7.1 = 0.45$ MJ

Energy Efficiency = 25.2/(26.7+ 0.45) = 1

MFSP = [70 + 7.11 * 18.9 + 200 – 125*0.47)] / 0.53 = [70 + 134 + 200 - 59] / 0.53 = $ 650/ton

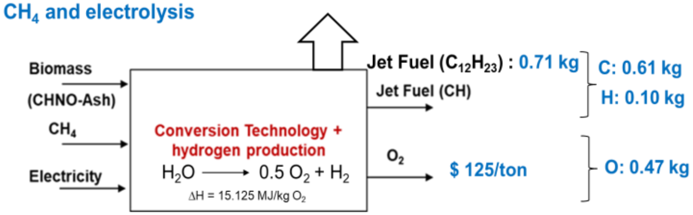
Removal of O in the form of O_2 with co-processing with CH_4 and electrolysis

Heat: - 1.31 MJ

Biomass: 1 kg
- C: 0.47 kg
- H: 0.06 kg
- O: 0.47 kg

CH4: 0.188 kg
- C: 0.141 kg (23 %)
- H: 0.047 kg

It may be acceptable to use some natural gas together with electricity if we are able to comply with the Clean Fuel Standards.



$\text{Yield}_{\text{Biomass + CH4}} = 0.718 / 1.188 = 0.60$

$\text{Yield}_{\text{Biomass}} = 0.718 / 1 = 0.72$

$C_{\text{Efficiency}} = 0.61 / 0.61 = 1$

$W_{\text{Electricity}} = 15.125 * 0.047 = 7.1$ MJ

Methane = $ 3.47 /GJ ($192/dry ton)
Biomass = $ 4.19 /GJ ($70/dry ton)
Electricity = $ 18.9 /GJ ($ 0.067/kWh)

$Q = H_{fuel} - H_{CH4} - H_{biomass} - W_{electricity} = 33.7 - 10.34 - 17.6 - 7.1 = -1.31$ MJ

Energy Efficiency = 33.7/35.0 * 100= 0.96

MFSP = [70 + 192* 0.188 + 7.11 * 18.9 + 200 – 125* 0.47)] / 0.718 = [70 + 36 + 134 + 200 - 59] / 0.718 = 531 $/ton

This project will guide optimization of SAF production through providing quantitative data to support informed decision-making on the choice of SAF production pathways

Synthesis of New SAF Concepts

Rules of Thumb for SAF Process Synthesis (Developed with the help of a Panel of Experts)

Maximize C Conversion efficiencies (Use all the C contained in Cellulose, Hemicellulose and Lignin)

Develop Co-products from C rich streams

Choose a technology that allows to control the fraction of C going to jet fuel

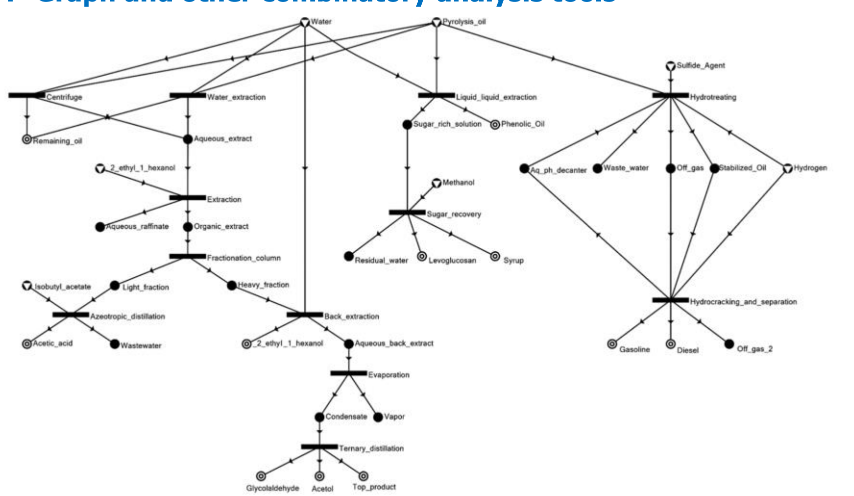
Use auto-thermal adiabatic processes whenever possible.

Heat integration is critical to ensure economic viability.

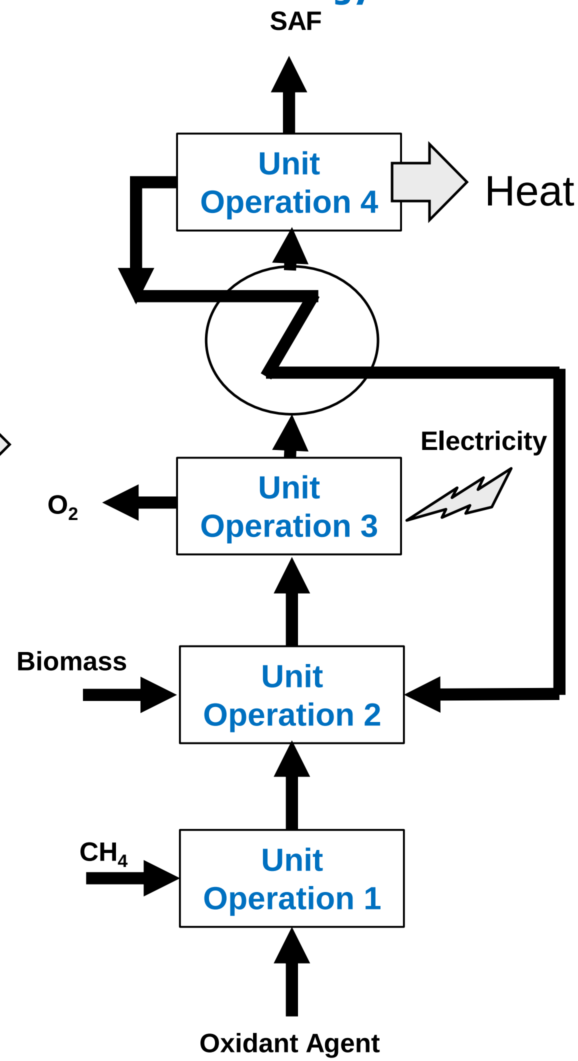
Consider high pressure processing only if downstream synthesis requires it.

Under most circumstances it is cheaper to heat with natural gas than with electricity. This rule should be revisited as more cheap renewable electricity There are some cases in which electricity may be very cheap.

P-Graph and other combinatory analysis tools



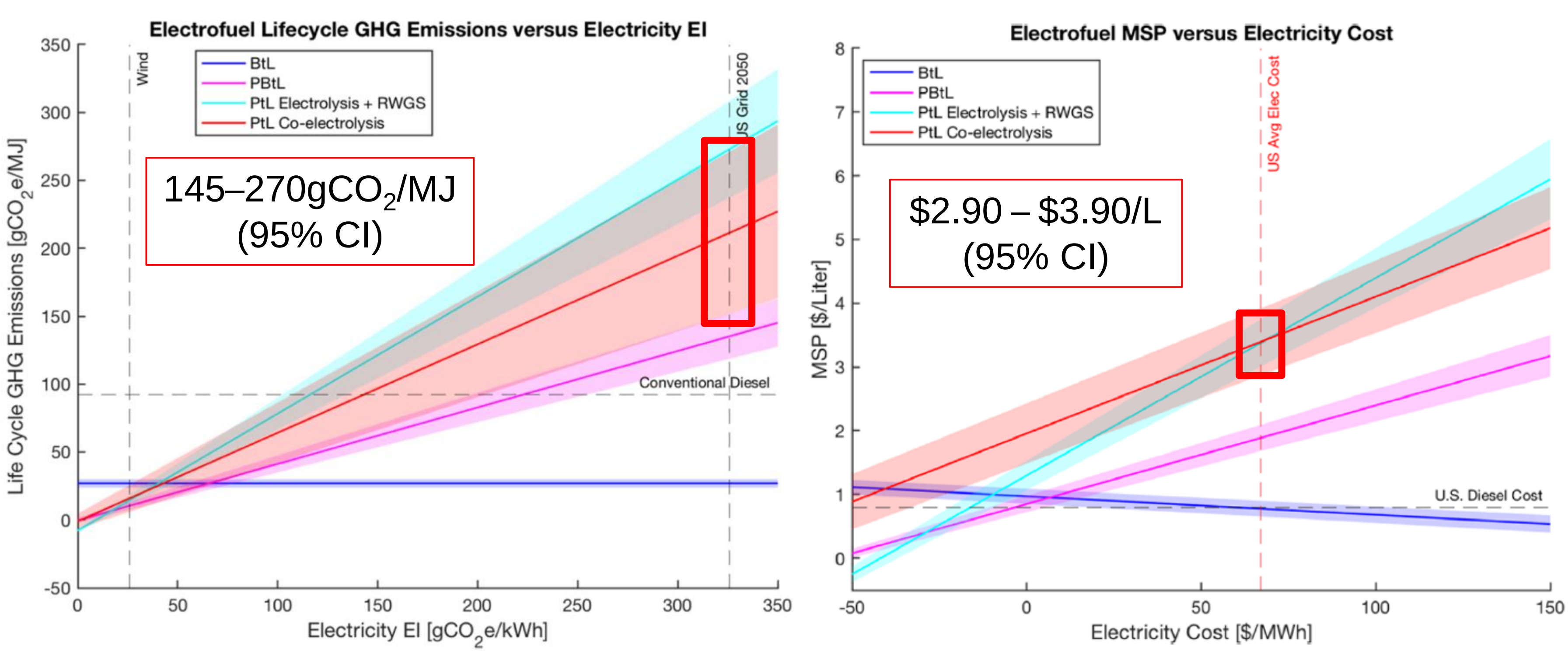
Generic Scheme of SAF production Technology



Expected benefits: This project will outline new pathways for SAF production.

Need for stochastic LCA and TEA assessment for this project

- There may be <u>uncertainties</u> 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 vs. 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)

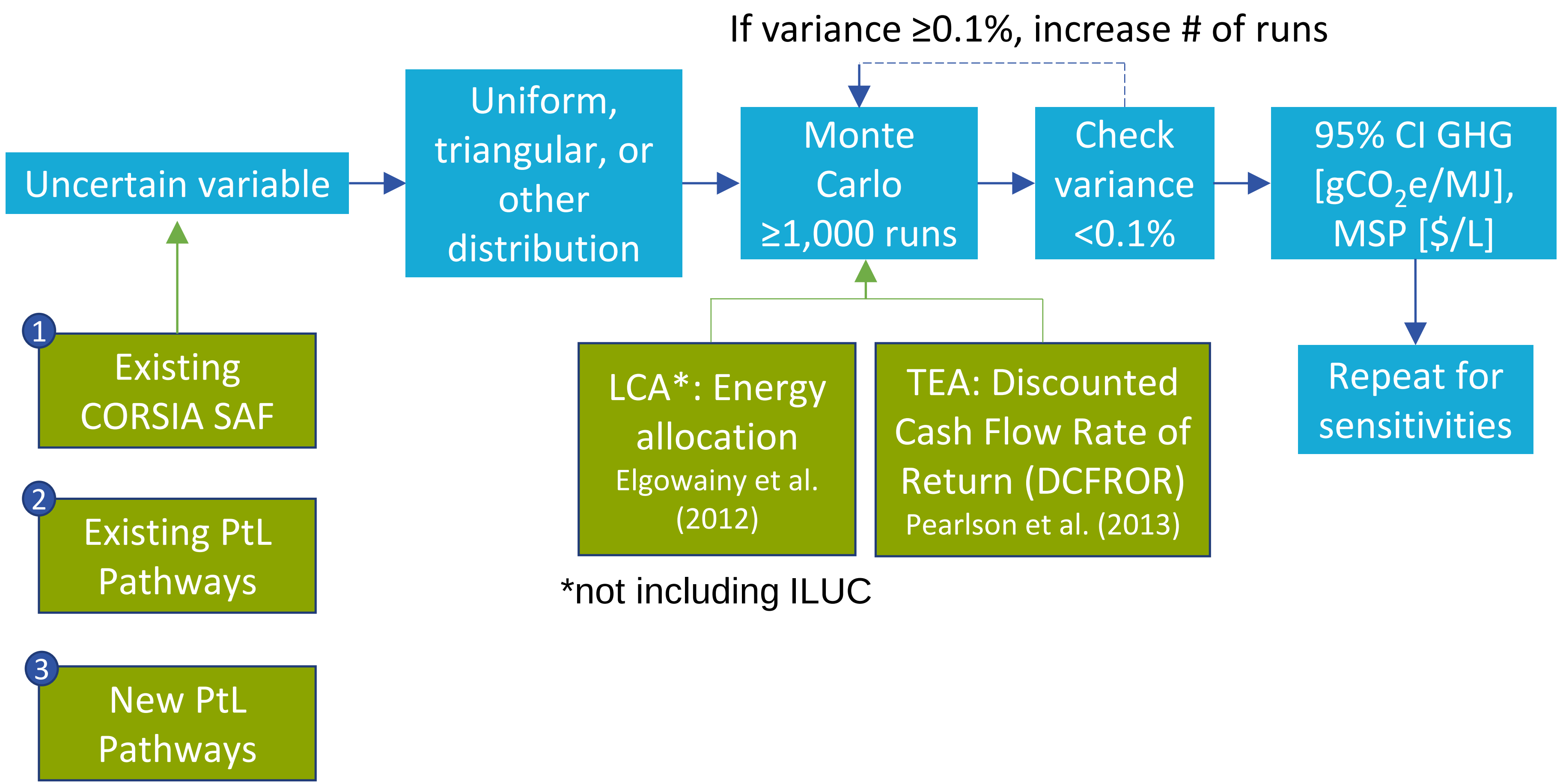
Sensitivity

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