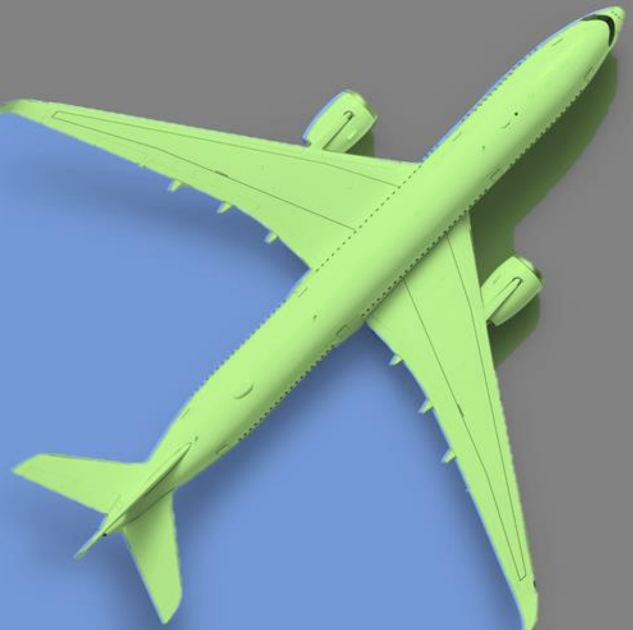
SAF: Soaring over The Blend Wall

A Strategic and Technoeconomic Special Report



NexantECA

December 2023

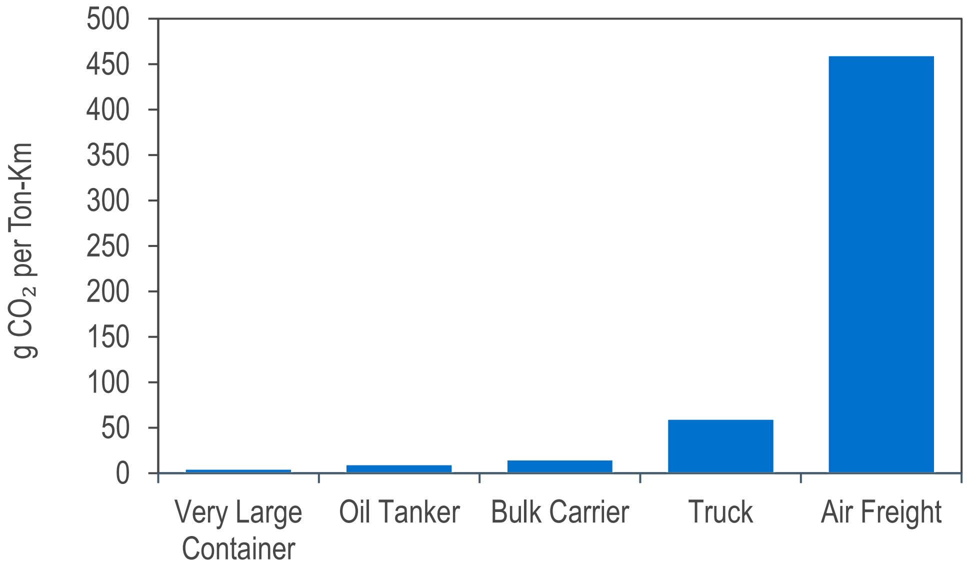
The transition towards climate neutrality and circular economy will have a profound impact on existing assets and radically change the economic drivers for the selection of new technologies

- The world is facing unprecedented challenges. The market landscape is evolving with a heightened emphasis on opportunities offered as well as the risks presented by climate change and the need to meet the increased commitments to achieving **net-zero emissions**.
- The large-scale and complex nature of climate change makes it uniquely challenging, especially in the context of **economic decision making**. The implications of climate change that need to be considered are today as well as long term.
- With climate risk affecting asset valuations, the capital market appetite shifted towards investments with **good ESG performance and competitive financial returns**.

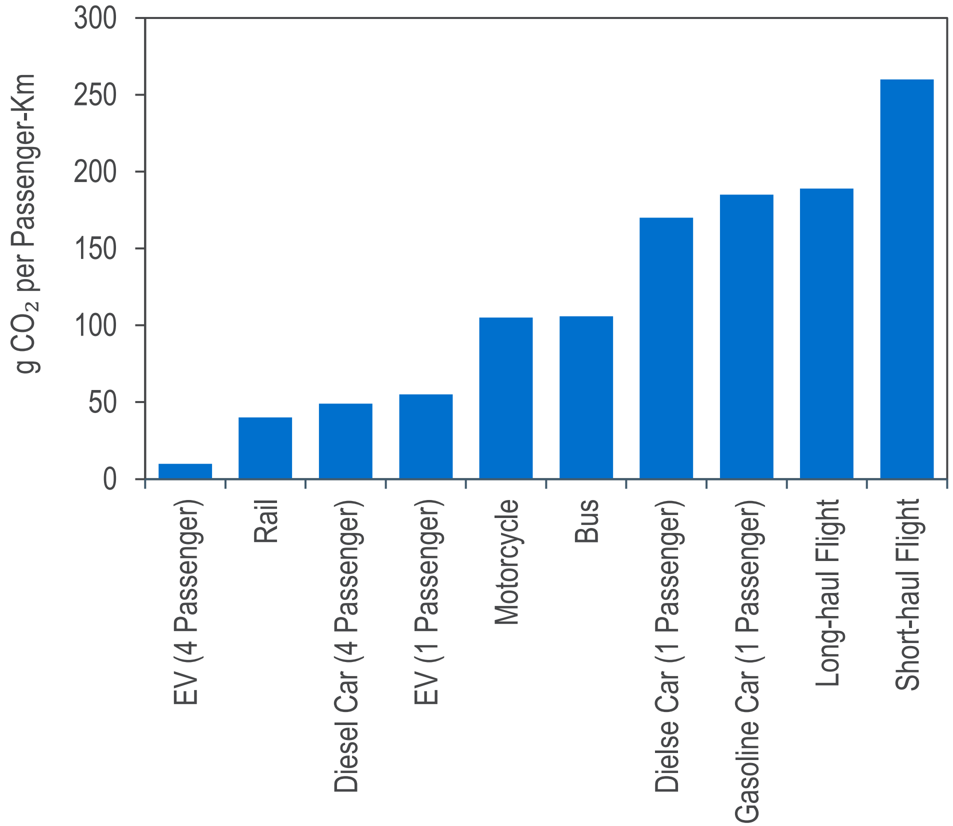
Air travel decarbonization is a VERY high priority

Jet has the highest carbon footprint per Ton/Km when compared to other modes of freight transport

Carbon Intensity of Freight



Carbon Intensity of Transport



Air travel has few options for decarbonization

Other options beyond SAF are scarce

- Non-SAF options are being pursued but have technical or other fatal flaws that limit their ability to contribute emissions cuts on the necessary scale. These include:
  - **Alternative propulsion**: New ways of powering aircraft beyond the current jet engine using liquid kerosene fuel model, most notably focusing on hydrogen and/or battery electric aircraft. Hydrogen or electrically powered aviation has practical applications, especially for shorter "commuter" flights. However, **longer flights and freight aviation will likely continue to require combustible liquid aviation fuel**. Even if alternatives engine types can power larger aircraft for longer distances, aircraft are highly expensive and long-lived than road vehicles, reducing the speed at which fleets can turn over, while safety concerns around emerging alternatives are, per individual vehicle, orders of magnitude greater than for, say, passenger cars.
  - **Offsets/carbon credits:** Offsets or carbon credits are a way to get to NET zero; while they do not eliminate emissions, an equal amount of carbon must be stored elsewhere, and companies may offset their emissions with credit for sequestration. While offsets have been pivotal to some companies' plans, the validity of many credit schemes and their ability to drive actual emissions reductions has been increasingly called into question, with regulatory authorities likely to continue to push for direct emissions reduction as their preferred option. **This makes offsets a riskier play, as uncertainty around not only consumer but regulatory acceptance is high.**

Overview of current Low CI SAF Technologies

Most Commercial

Technology	Process Description	Key Feedstocks	Key Players
Hydrotreated Vegetable Oil (HVO)	Feedstock is converted using H_2 to remove O_2 and produce hydrocarbon fuel components	Vegetable oils UCO Tallow	Neste Eni TotalEnergies
Alcohol-to-Jet (ATJ)	Fermentation of lignocellulosic, sugar or starch feedstocks into alcohols, which is further processed into SAF	Ethanol Isobutanol	Gevo LanzaJet
Gasification and FischerTrospch (G-FT)	Converts carbon-containing material to synthesis gas and subsequently FT products including SAF	Crop waste Forest residue MSW	Fulcrum Velocys
Power-to-Liquid (PTL) / eFuels	Similar to FT process, but using green H_2 and captured CO_2 for synthesis gas generation	Green H_2 Captured CO_2	Arcadia eFuels Nordic Electrofuels

Least commercial

UCO: Used cooking oil; MSW: Municipal solid waste

Though possible for 'short haul flights' also called 'commuter flights', short trips of a few hundred miles (e.g., NY to DC) are doable with hydrogen and electric power—for longer haul flights (e.g., NY to London) or cargo flights, sustainable aviation fuel will be required to decarbonize air transportation

Current approved SAF blendstocks are limited to 50 percent maximum—meaning they require fossil fuels to be blended with

SAF Approval Status under ASTM D7566

Status	Class	Process	Feedstock	Max Blend (% v/v)
Annex A1 (2009)	FT-SPK	Fischer-Tropsch (FT) hydroprocessed SPK	Syngas	50
Annex A2 (2011)	HEFA-SPK	SPK from hydroprocessed esters and fatty acids	Fatty acids and fatty acid esters	50
Annex A3 (2014)	HFS-SIP	Synthesized Iso-Paraffin	Sugar	10
Annex A4 (2015)	FT-SPK/A	FT-SPK plus alkylation of light aromatics	Syngas	50
Annex A5 (2016)	ATJ-SPK	Dehydration of isobutanol or ethanol	Ethanol and isobutanol	50
Annex A6 (2020)	CHJ	Hydrothermal conversion of fatty acid esters and free fatty acids	Fatty acids and fatty acid esters	50
Annex A7 (2020)	HC-HEFA-SPK	Hydroprocessed esters and fatty acids	Fatty acids and fatty acid esters, Algae	10

Functional properties further these limitations (such as viscosity) leading to a functional blend limit closer to 30 percent

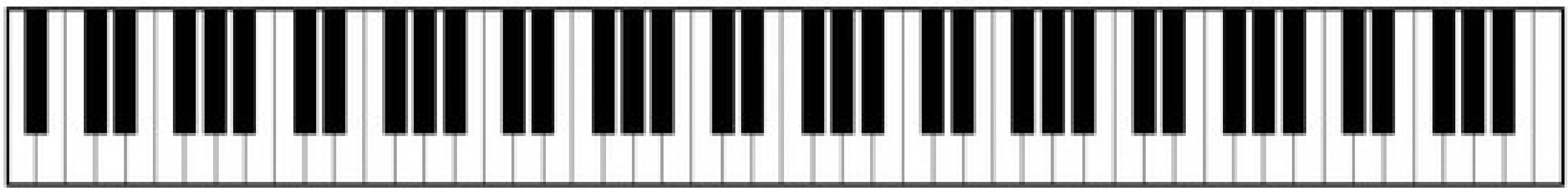
The blend wall problem creates net zero problems

- In order to reach net zero emissions by 2050, one of two approaches must be taken:
  - **Highly Negative Emission Product:** Since it is blended at only 30-50 percent, a highly carbon negative feedstock must be used. These would likely be at a VERY high cost. **This is unlikely to be cost effective.**
  - **Produce a Finished SAF that does not require blending**: This requires new and additional blendstocks to be used in conjunction with existing SAF approaches. **This is likely to be at a higher cost than existing SAF approaches but will allow net zero aspirations to be reached.**

Aviation fuel is made of a complex mixture of molecules—in careful proportions to get the desired properties

Jet Fuel Components - PIANO

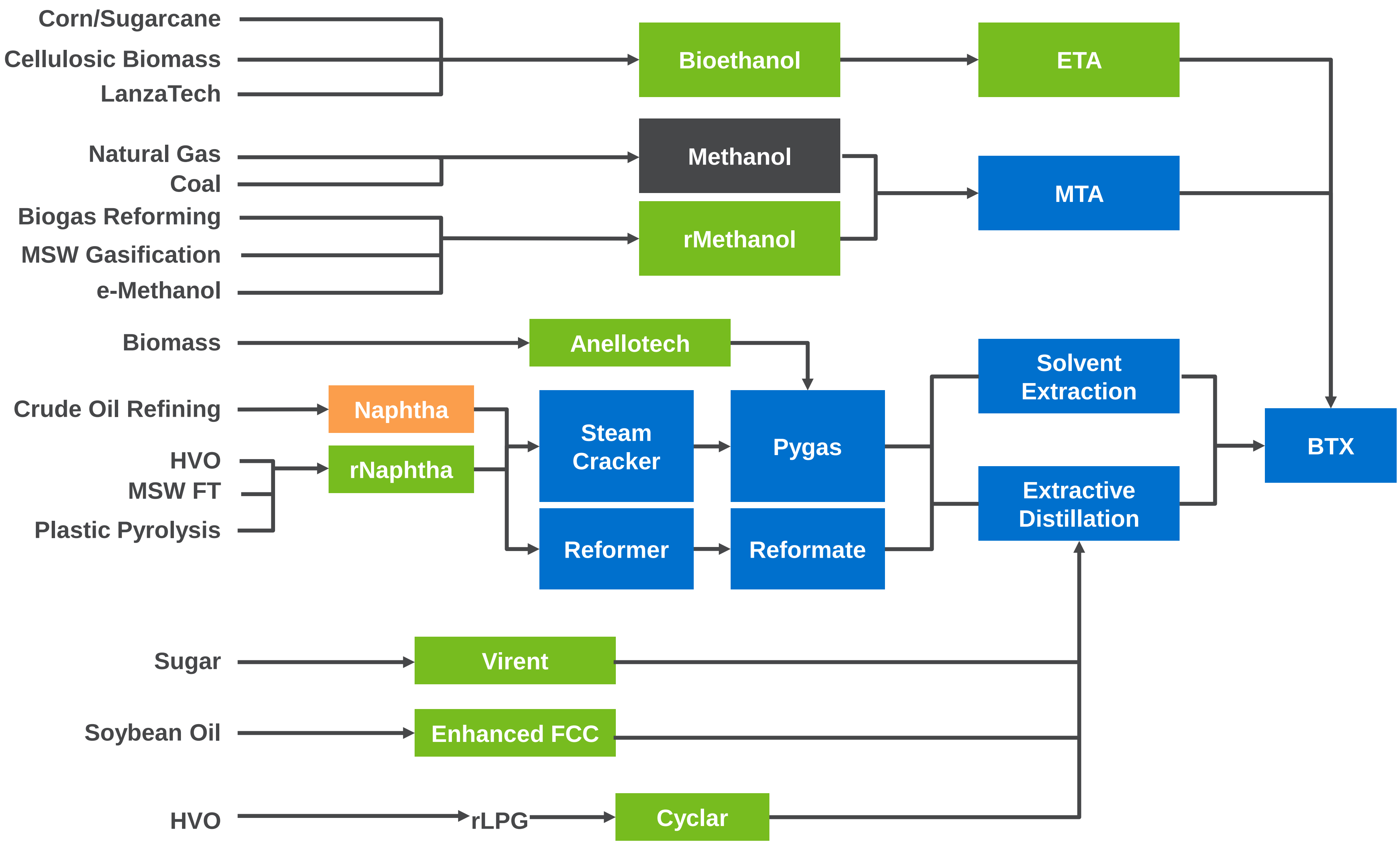
Component	Composition, (%)	Impact on Fuel Property
Paraffin	10	High gravimetric energy content, low volumetric energy content, high combustion quality, poor low temperature fluidity
Iso-Paraffin	40	Increased branching improves cetane value, high gravimetric energy content, low volumetric energy content, high combustion quality,
Aromatics	20	Smoke point, blending properties, low gravimetric energy content, high volumetric energy content, low combustion quality
Naphthenes	30	Low gravimetric energy content, high volumetric energy content, high combustion quality
Olefins	<1	Poor thermal oxidation stability, high deposit formation



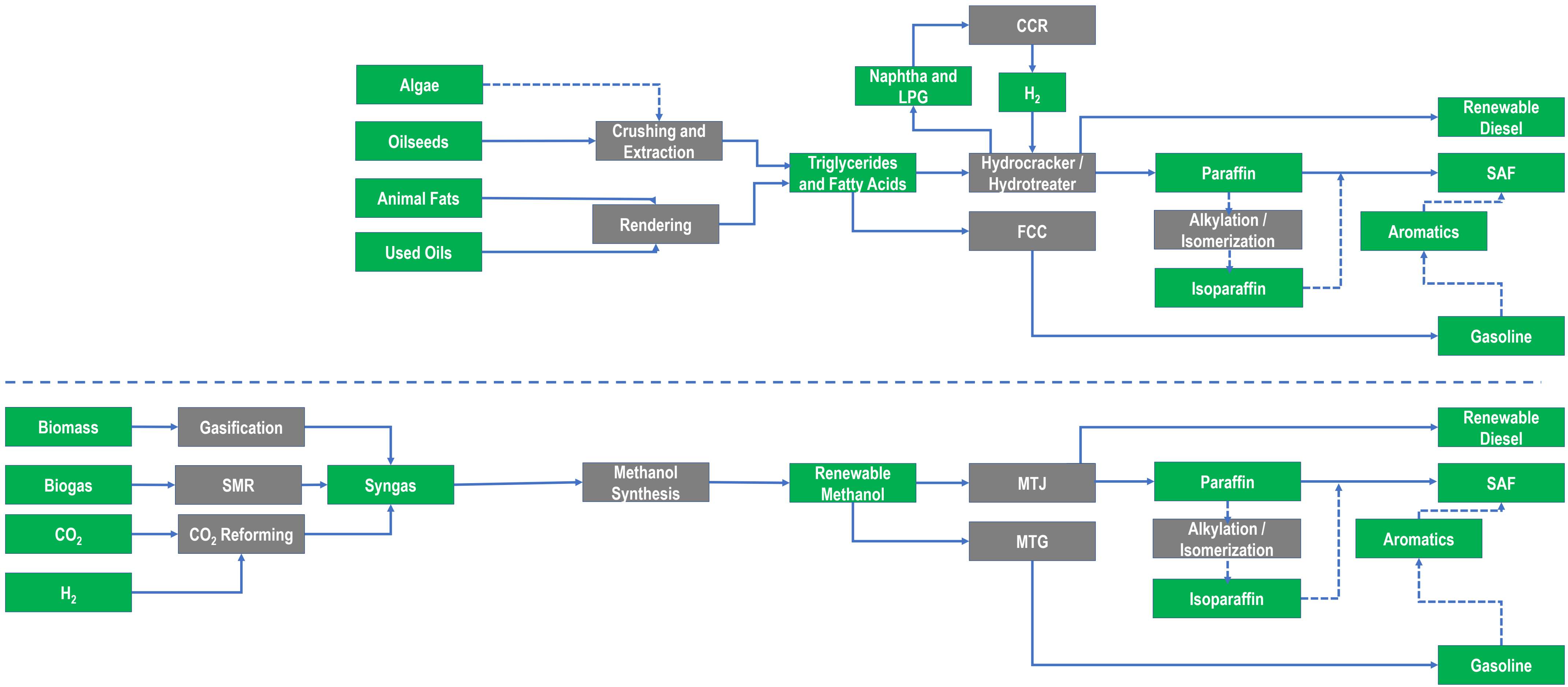
NexantECA is modelling existing technologies to modify the SAF to meet fuel specifications

- The following units, common to many refineries, can have applications in producing fuel components and intermediates for use beyond HVO/HEFA applications:
  - **Alkylation Unit:** Isoparaffins
  - **Isomerization Unit:** Isoparaffins
  - **FCC:** Aromatics and Olefins
  - **CCR:** Hydrogen for other Units
  - **Delayed Coker:** Biomass to Crude
- By integrating such units together, it is possible to produce an SAF that CAN be used unblended with refinery jet fuel. Several examples follow:
  - **HVO integration:** Includes FCC, CCR, and Isomerization/Alkylation
  - **Ethanol to Jet Integration:** Includes ETG and Isomerization/Alkylation
  - **Methanol to Jet Integration:** Includes MTG and Isomerization/Alkylation
  - **FT and e-fuels Integration:** FCC, and Isomerization/Alkylation

Several Bioaromatics technologies are under development as well that could help to produce a 100% low CI SAF



Several Potential Routes can be integrated to produce finished SAF that can meet ASTM D-1566 and will not be restricted by blending rates



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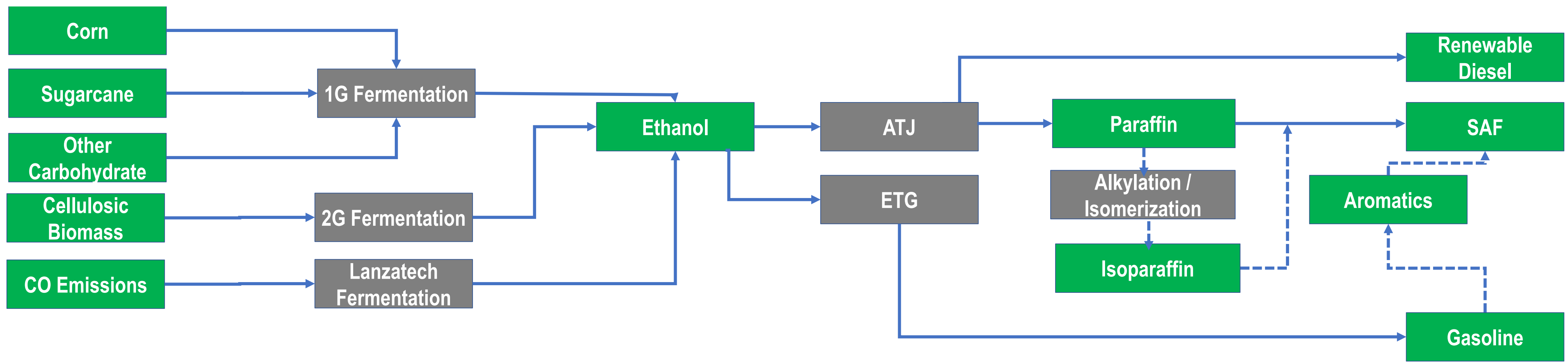

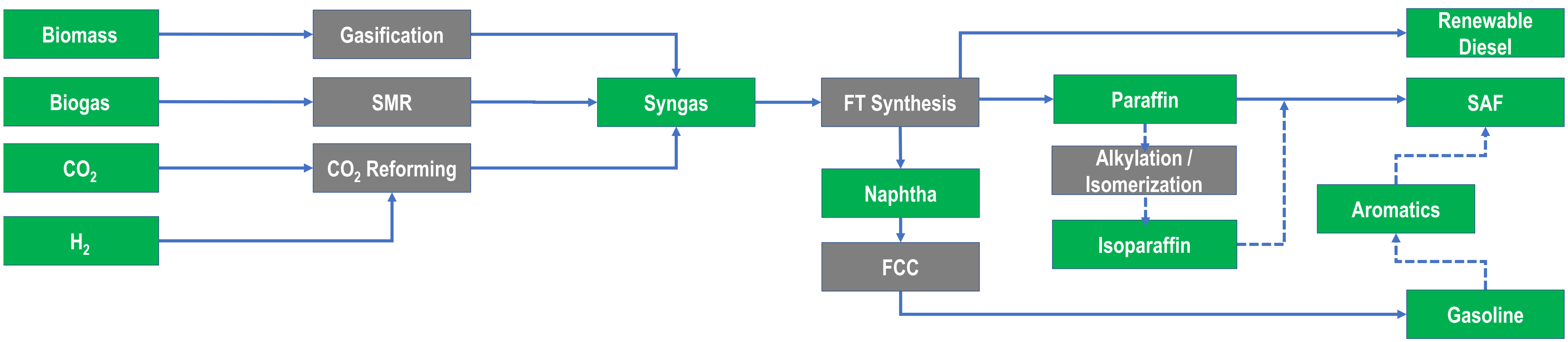

NexantECA is publishing a technoeconomic and strategic study

- **NexantECA has investigated from a technoeconomic and carbon intensity perspective:**
  - Fully Blended 100% SAF, suitable for use without blending with fossil fuels:
  - UCO Triglyceride HVO / CCR / ISOM / Triglyceride FCC
  - FT / ISOM / FCC from Biomass Gasification-Based syngas
  - eFT / ISOM / FCC from PTL-Based syngas
  - MTJ / ISOM / MTA from Biomass Gasification-Based methanol
  - eMTJ / ISOM / eMTA from PTL-Based methanol
  - ETJ / ISOM / ETA from Both First and Next Generation ethanol
- **NexantECA has considered the following questions:**
  - What is the lowest cost route to a 100% blended SAF that doesn't require blending with fossil fuel?
  - How low can carbon intensity go while still being blended with fossil fuels?
  - What is the most cost effective at reducing carbon intensity?

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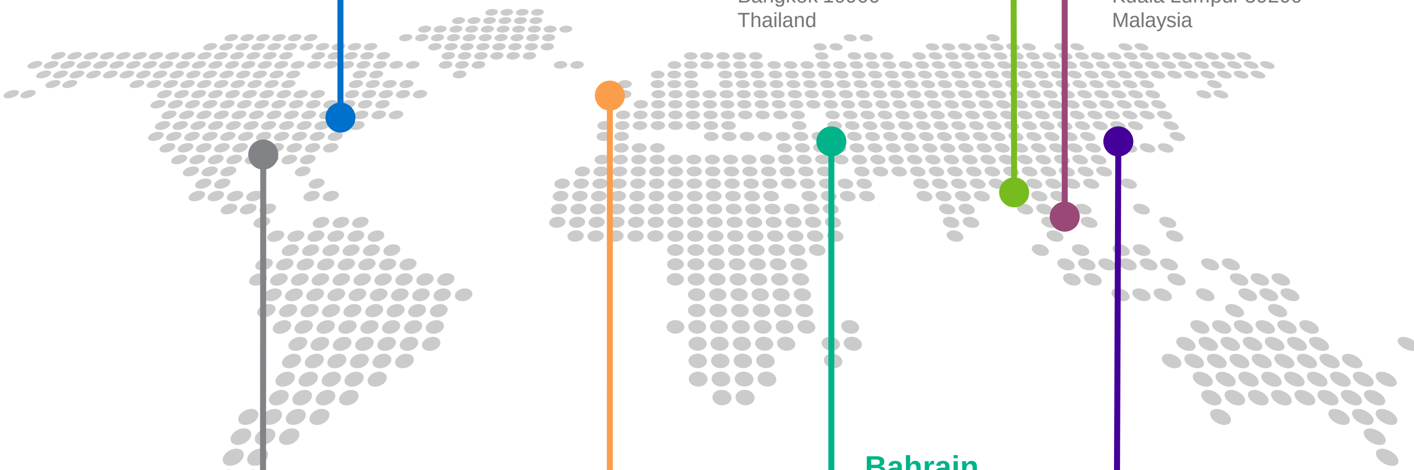

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