Hydrogen- and Bio-based Solutions for What?

Roberto Schaeffer

Eduardo Muller-Casseres

Marianne Zotin

14 October 2021

Webinar IASS/CBAE/COPPE

Hydrogen-based and Bio-based Pathways to Climate Neutrality in Brazil and Europe

Healthy Competition or Contradictory Developments?

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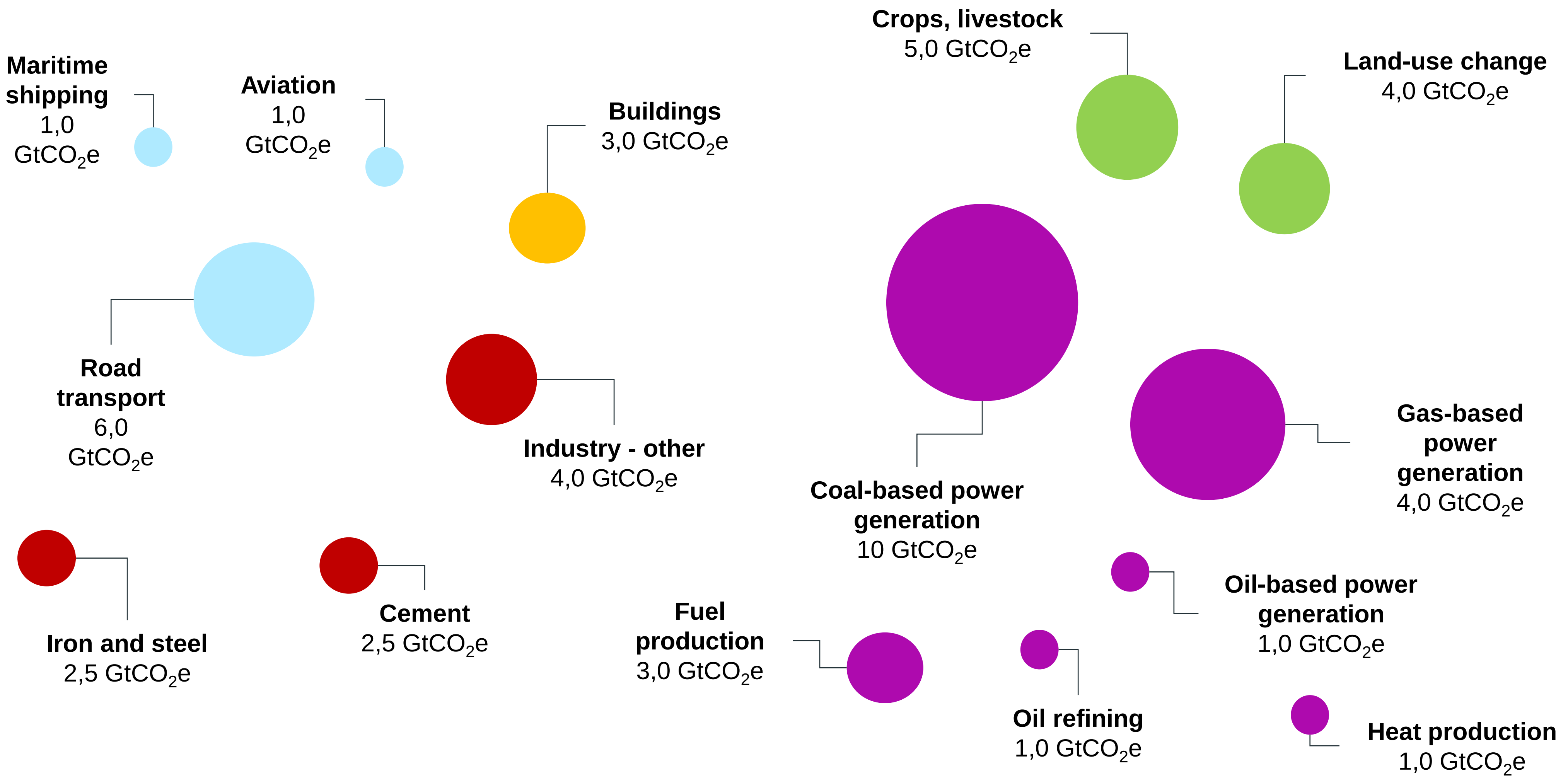
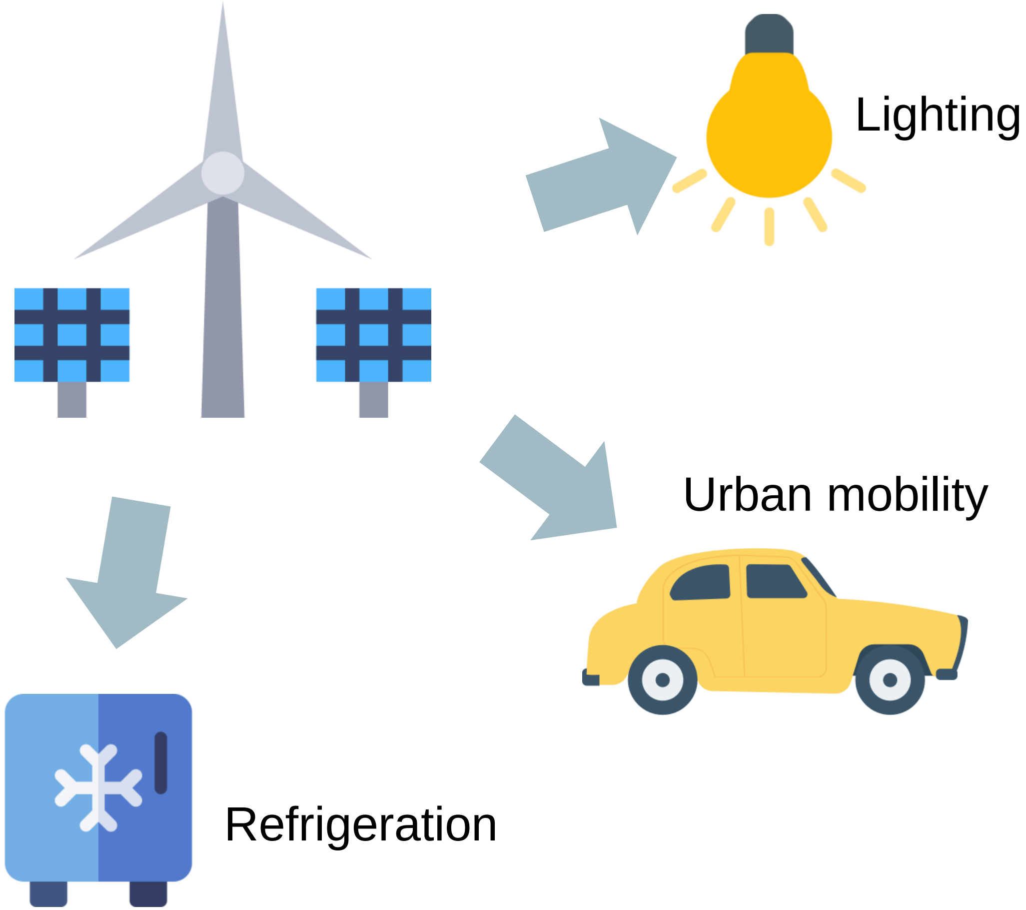
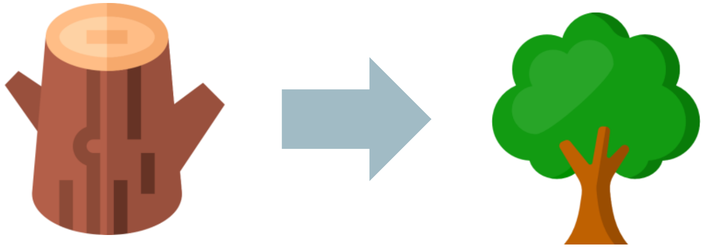
Yearly GHG emissions - World



Approximate values. Years used as reference: 2017/2018/2019

Low-hanging fruits!



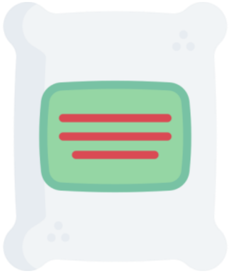


Avoid deforestation

Crédito das figuras: flaticon/Freepik, flaticon/DinosoftLabs

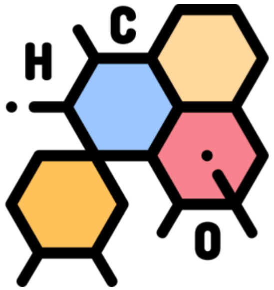
On the other hand, Hard-to-Abate

Iron and steel industry



Cement industry

Aluminum industry

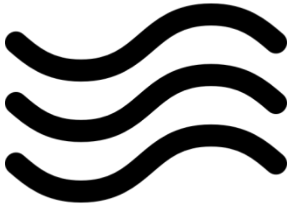


Chemical industry

Long-distance road transport

Air transport

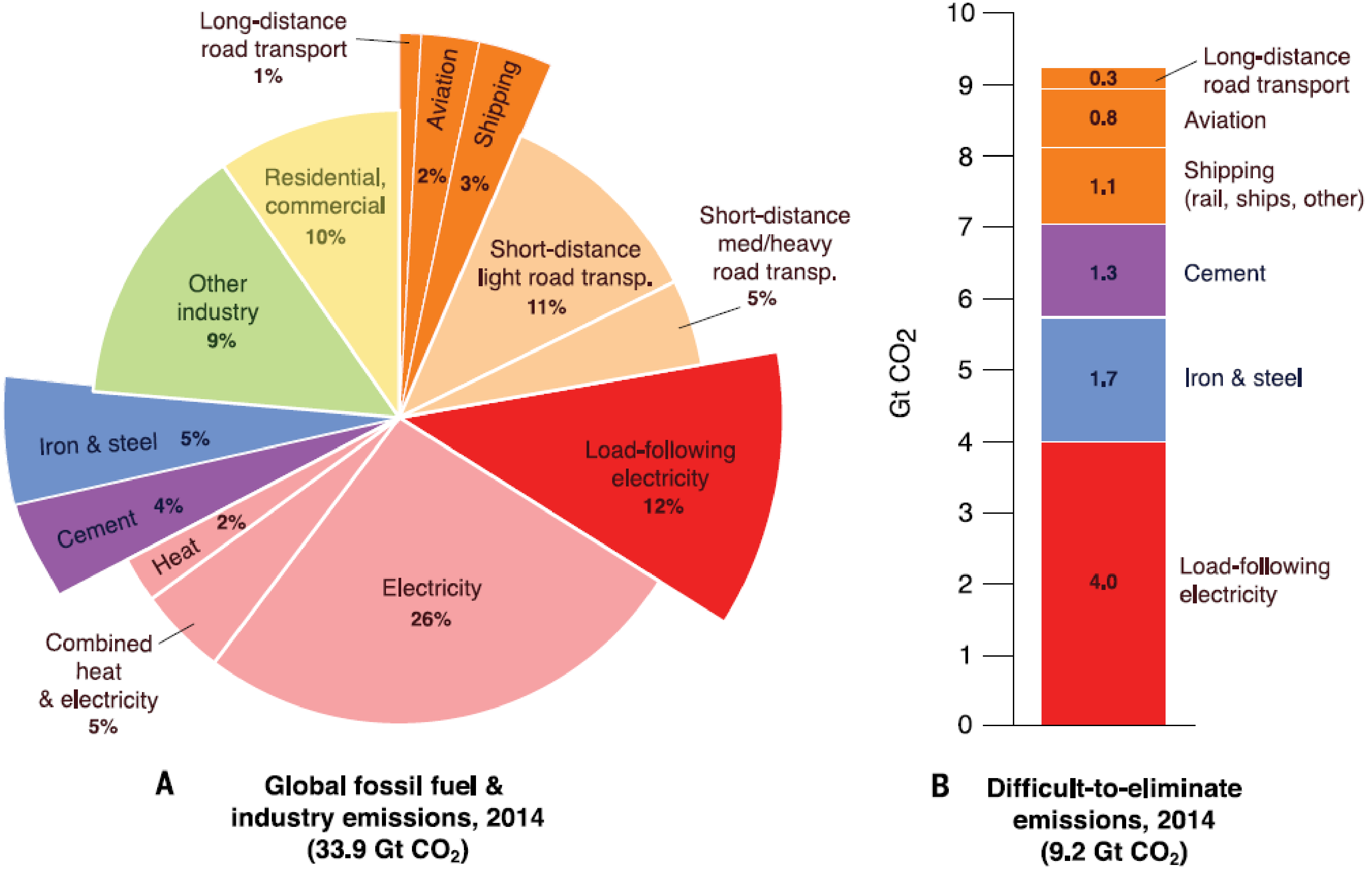
Maritime shipping



Load-following electricity

Icons: flaticon/Freepik, flaticon/DinosoftLabs, flaticon/Smashicons

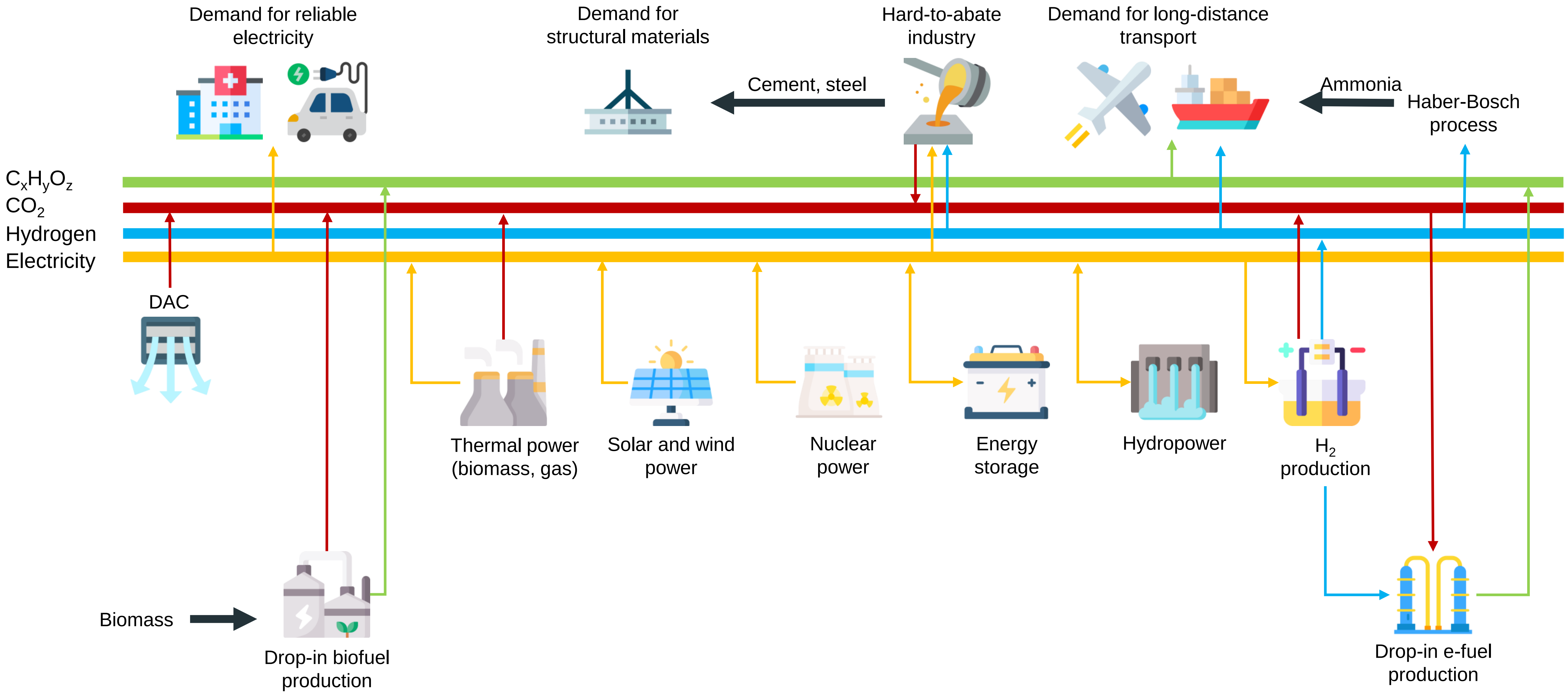
Hard-to-Abate CO_2



Bioenergy & hydrogen

Source: Davis et al. (2018) – Net-zero emissions energy systems

Hard-to-Abate and carbon neutrality



Source: own elaboration based on Davis et al. (2018). Icons: flaticon/Freepik, flaticon/DinosoftLabs, flaticon/Good Ware

But when we talk about H2 there are fifty shades of grey here …

- **Black if made with coal**
- **Grey if made with natural gas (more than 70% of all H2 produced today)**
- **Blue with added CCS**
- **Pink if made from nuclear energy**
- **Turquoise if made from natural gas from pyrolysis heating until H2 departs leaving solid C behind**
- **Green from electrolysis (less than 2% today comes from electrolysis) with renewables (ideally with solid-oxide electrolysers or proton-exchange membranes (PEMS)**

- **At present grey H2 costs about USD$1-1.5/kg**
- **Add colour and you add a premium**
- **No one yet is making blue H2 at scale, but cost will probably double (USD$2-3/kg)**
- **Green H2 costs USD$ 3-10/kg**
- Today we only have 3 GW of electrolyser capacity
- We may need more than 100 GW by 2030 (or in less than 10 years)

1. Industry

Hydrogen- and bio-based solutions for the industry sector

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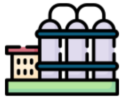
Main challenges for decarbonizing heavy industry

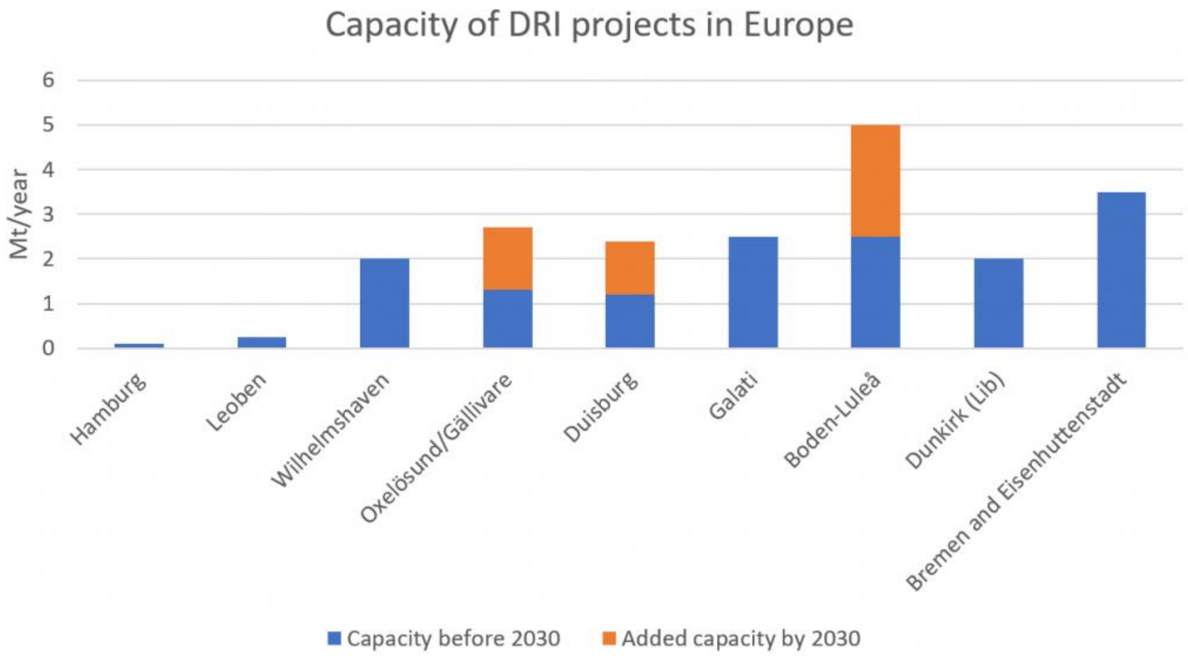
	HIGH-TEMPERATURE HEAT	NON-ENERGY USE	PROCESS EMISSIONS
 **IRON AND STEEL** 6% of global direct GHG emissions 7% of final energy consumption	Iron ore melting: ~1700°C (blast furnace) and ~1000°C (direct reduction)	Use of reducing agents and a carbon source to meet steel properties (~1%)	In case of carbon-based reductants (~75% of CO_2 emissions)
 **CEMENT** 7% of global direct GHG emissions 7% of final energy consumption	Limestone calcination: ~900°C		Decomposition of limestone, releasing - 0.5 tCO_2/t clinker
 **CHEMICALS** 6.5% of global direct and indirect GHG emissions 12% of final energy consumption	E.g., steam cracker: ~900°C	Oil and gas are used as both energy and feedstock	Relevant for ammonia and metanol production
	Not easily electrified!	A carbon-based feedstock is needed!	Renewable energy use is not enough!

Icons: flaticon/Freepik, flaticon/DinosoftLabs, flaticon/Smashicons

Addressing high-temperature heat provision and reducing agents in the steel sector

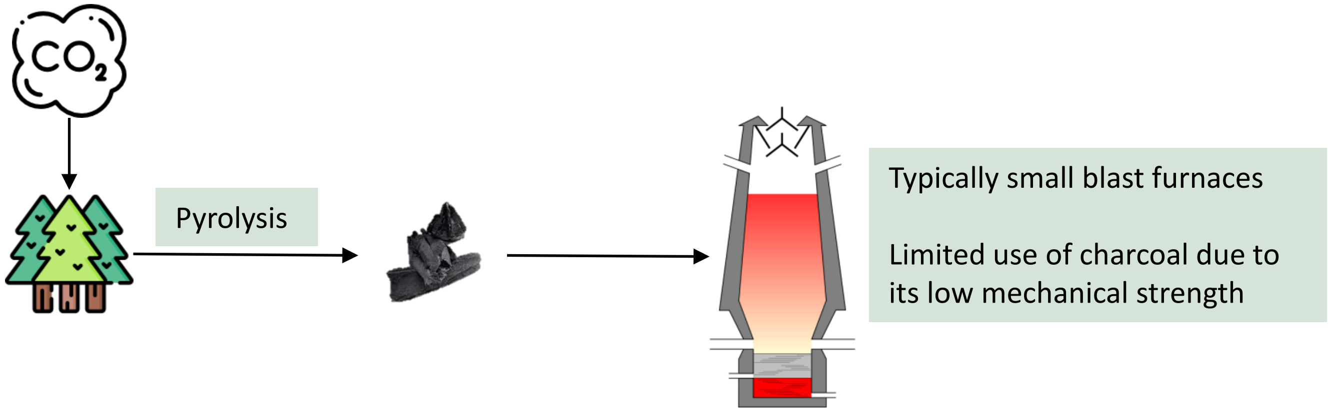
1. Green hydrogen to produce high-temperature heat and to reduce iron ore

~97% CO_2 emissions reduction relative to BF-BOF



2. Use of biomass (charcoal) as reducing agent in blast furnaces

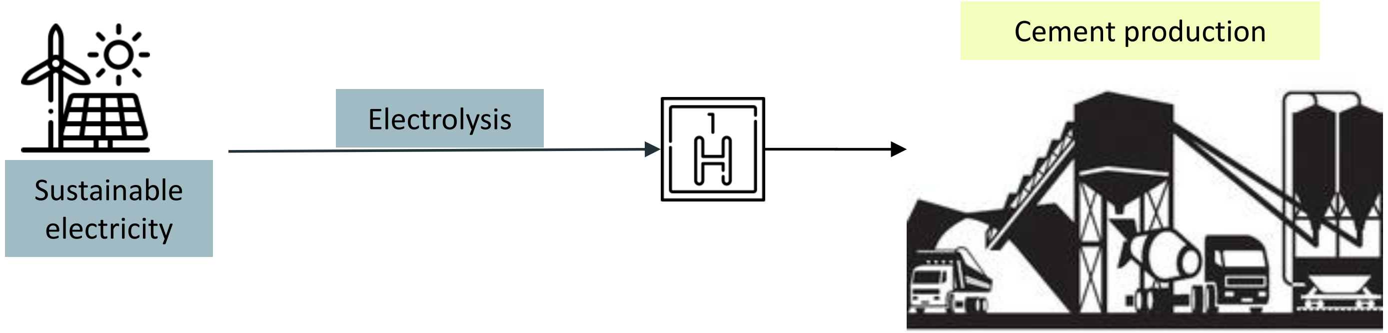
More than 50% of steel production in Brazil is based on charcoal; however, d-LUC and i-LUC should be addressed



Addressing high-temperature heat provision in the cement sector

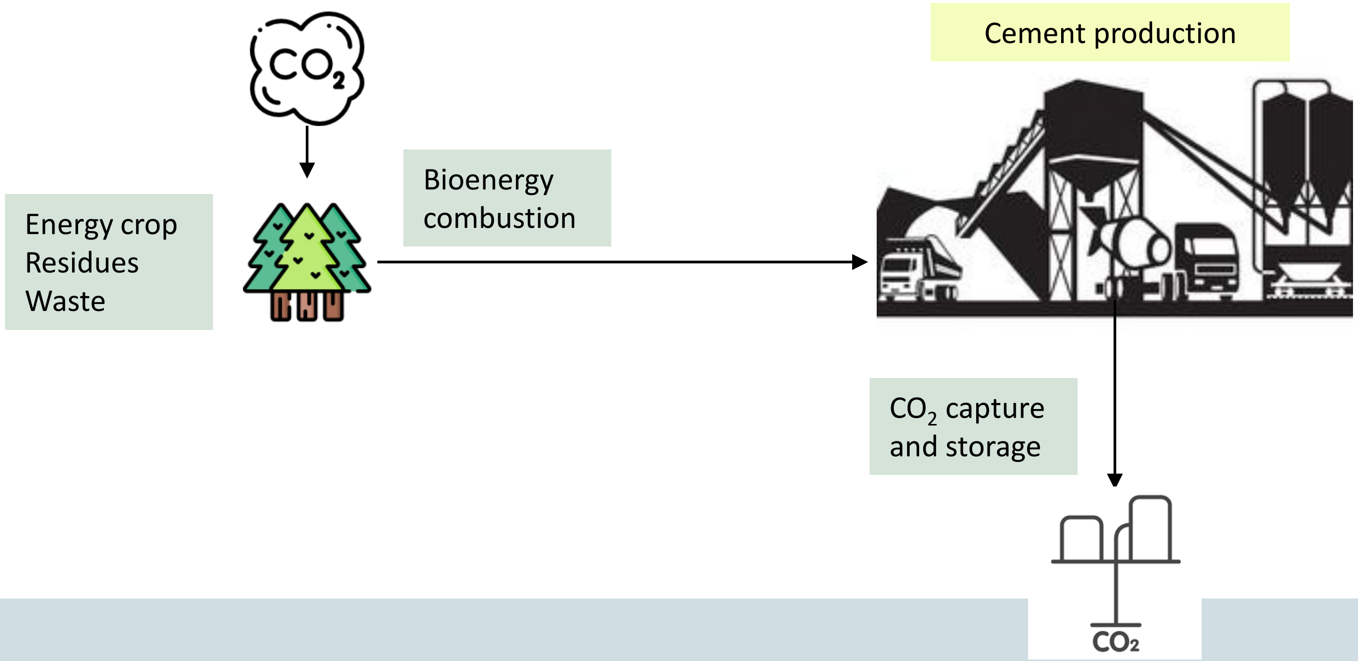
1. Use of green hydrogen in cement kilns

Enables the reduction of CO_2 emissions from combustion



2. Use of sustainable biomass with CCS in cement kilns to achieve negative emissions (BECCS)

Most climate change scenarios indicate the need of CDR to achieve stringent climate goals



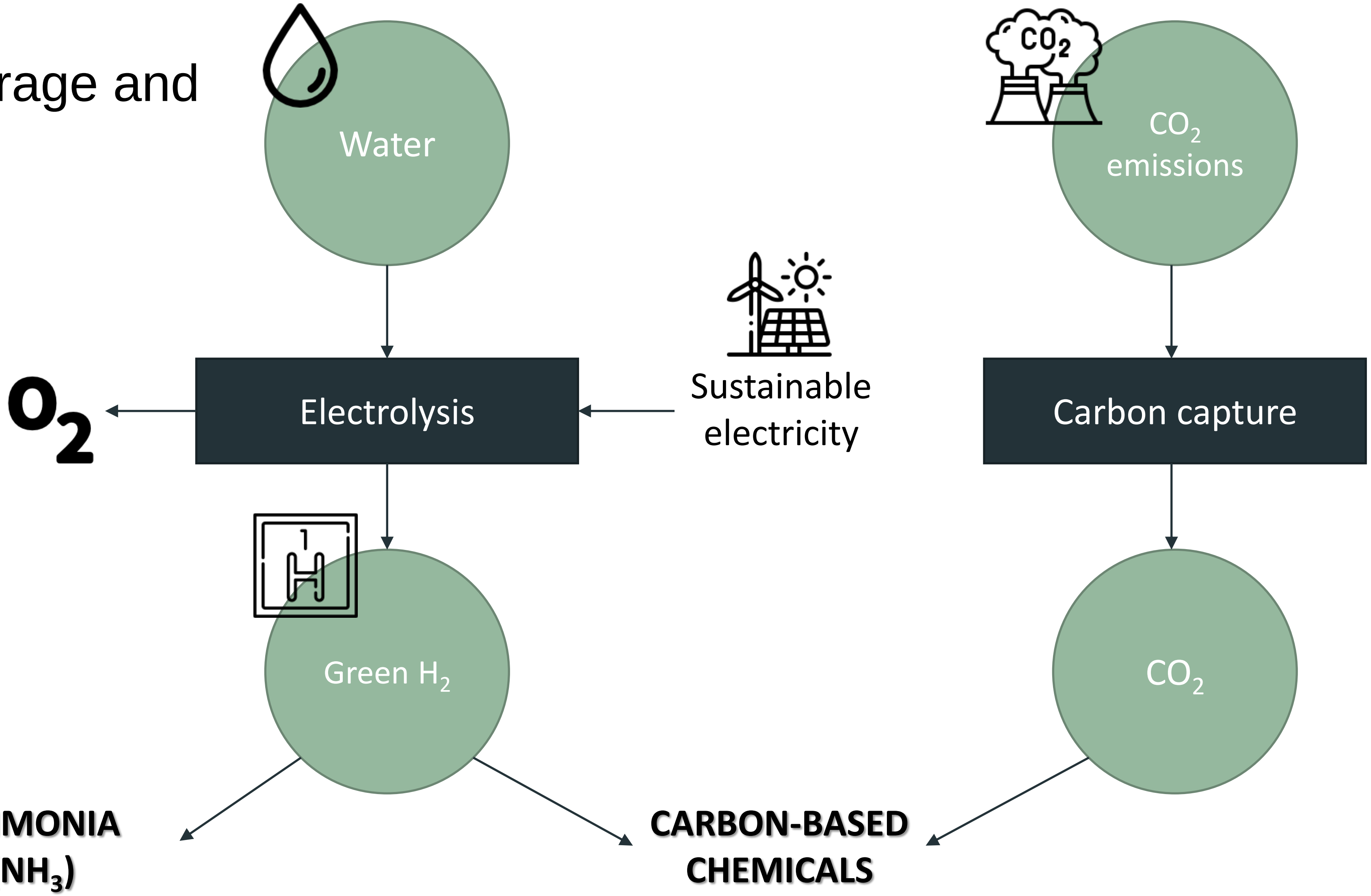
Icons: flaticon/Freepik, flaticon/DinosoftLabs, flaticon/Smashicons

Addressing the feedstock transition in the chemical sector

1. Carbon capture, storage and utilization (CCUS) + Hydrogen

Sustainable (and stable) electricity promoting highly non-spontaneous reactions

Scale of O_2 co-production



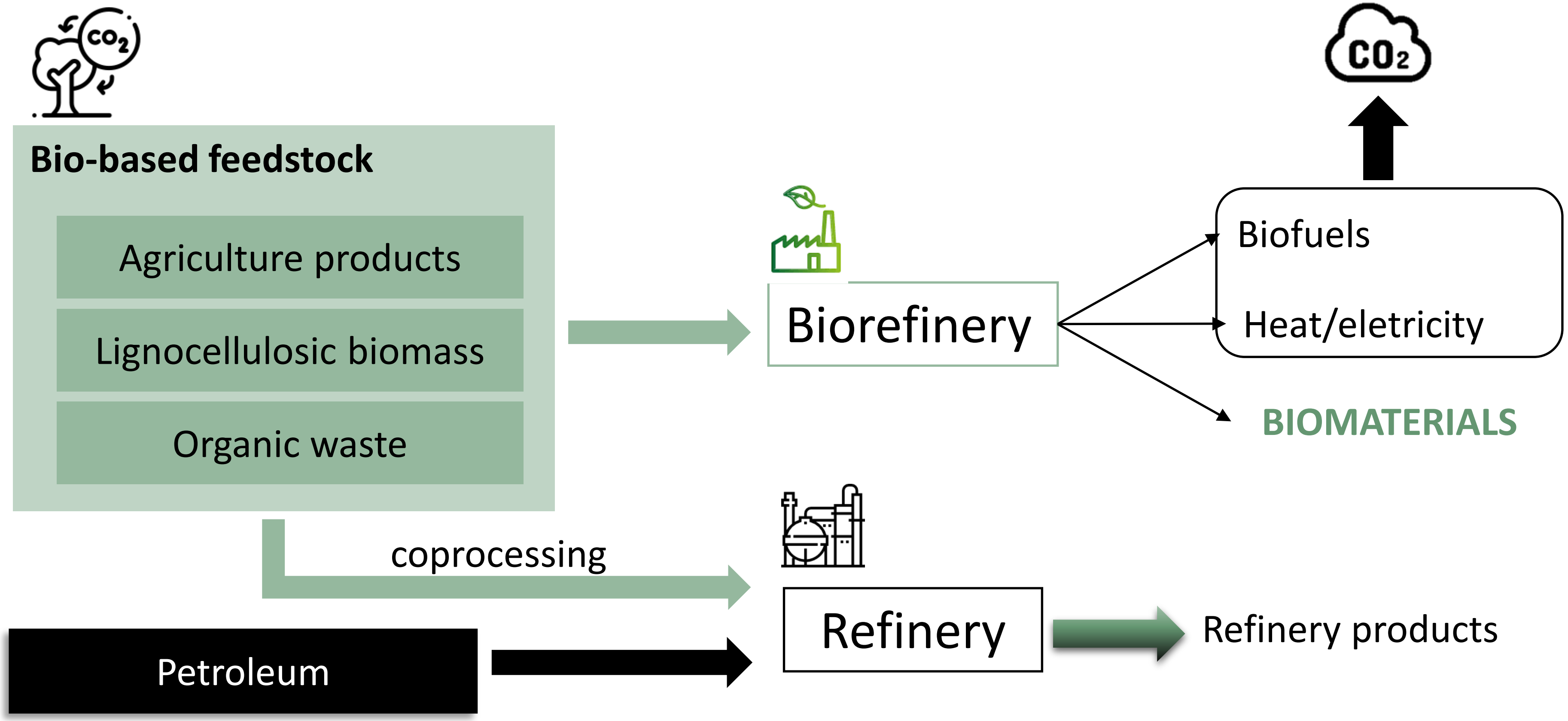
Icons: flaticon/Freepik, flaticon/DinosoftLabs, flaticon/Smashicons

Addressing the feedstock transition in the chemical sector

2. **Bio-based feedstock**

Synergies with bio-based strategies in other sectors

Carbon storage in long lifetime biomaterials



Icons: flaticon/Freepik, flaticon/DinosoftLabs, flaticon/Smashicons

2. Aviation and shipping

Hydrogen- and bio-based solutions for the international transport sector

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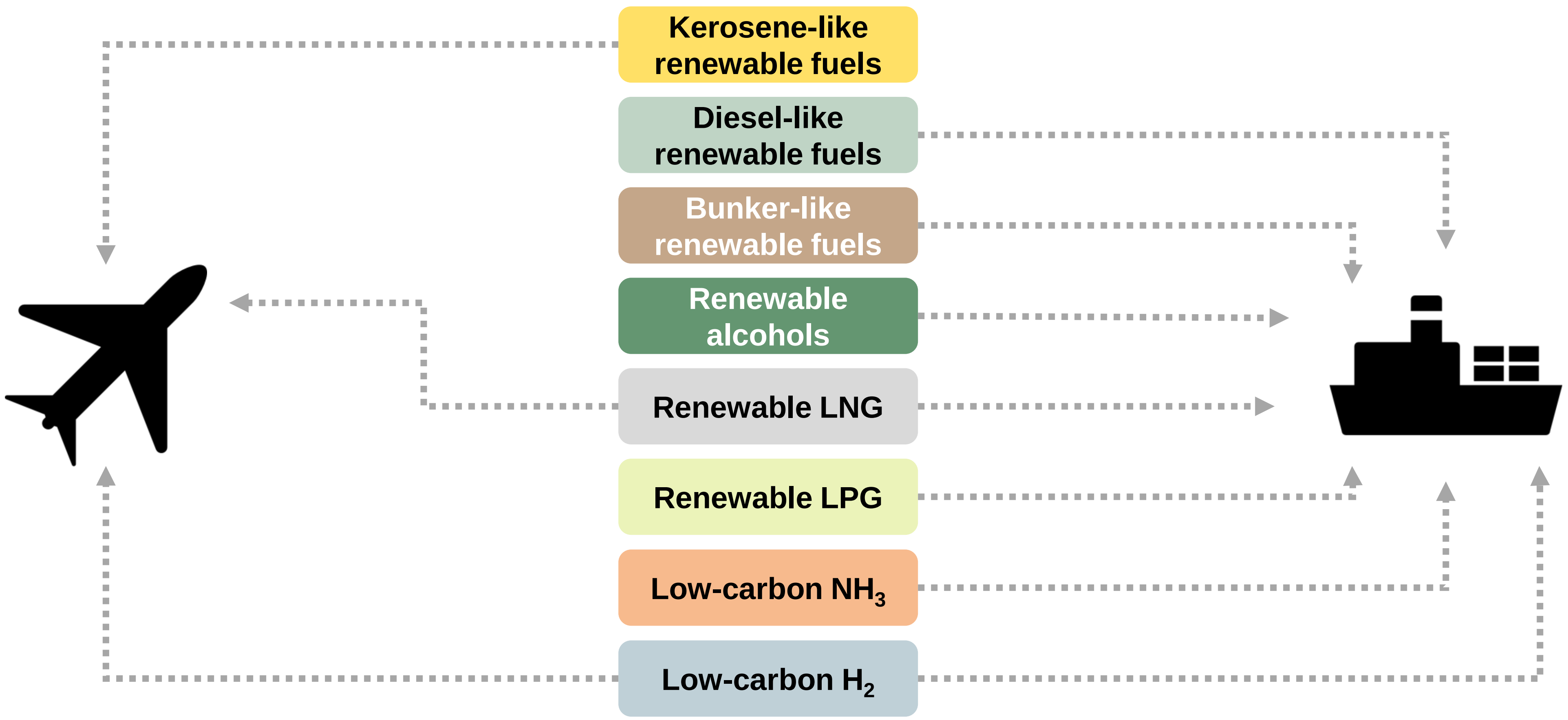
In principle main fuel options do exist …



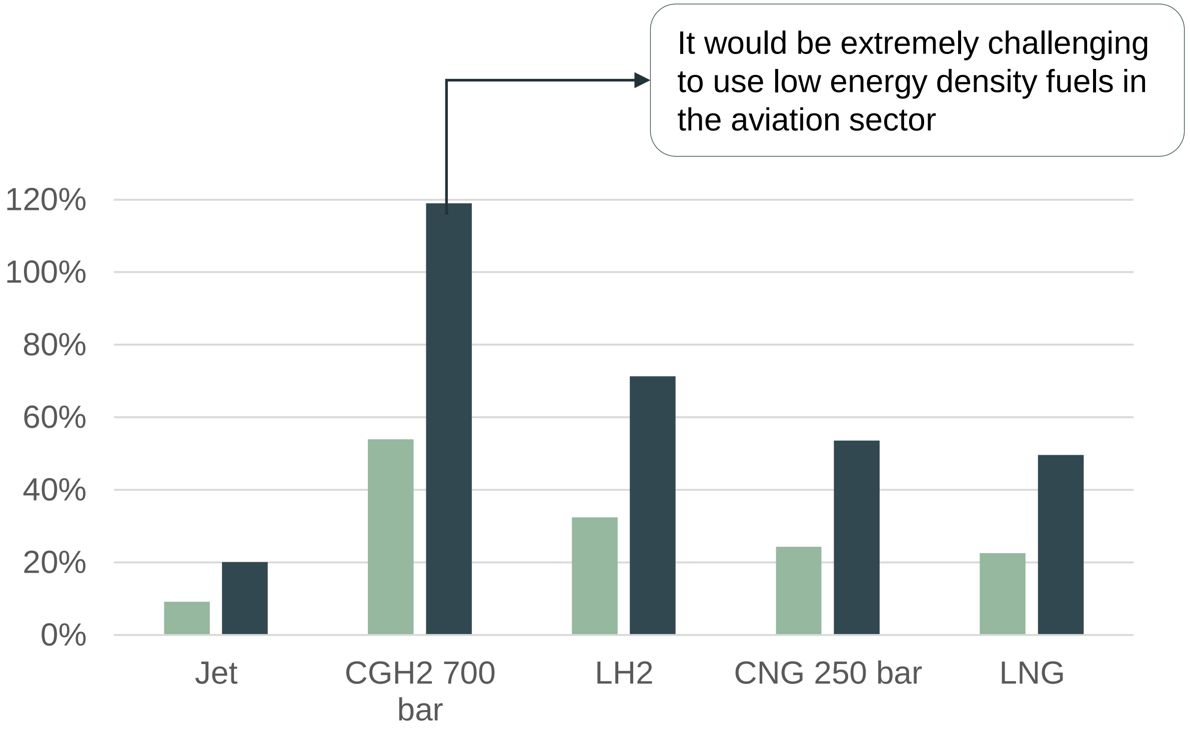
Is it possible to use H_2 in airplanes?

Short-haul

Dublin-Frankfurt (1,000 km)
Boeing 737-800
Total Fuel: 7,200 kg (jet fuel)
Max Take-Off Weight: 79,000 kg

Long-haul

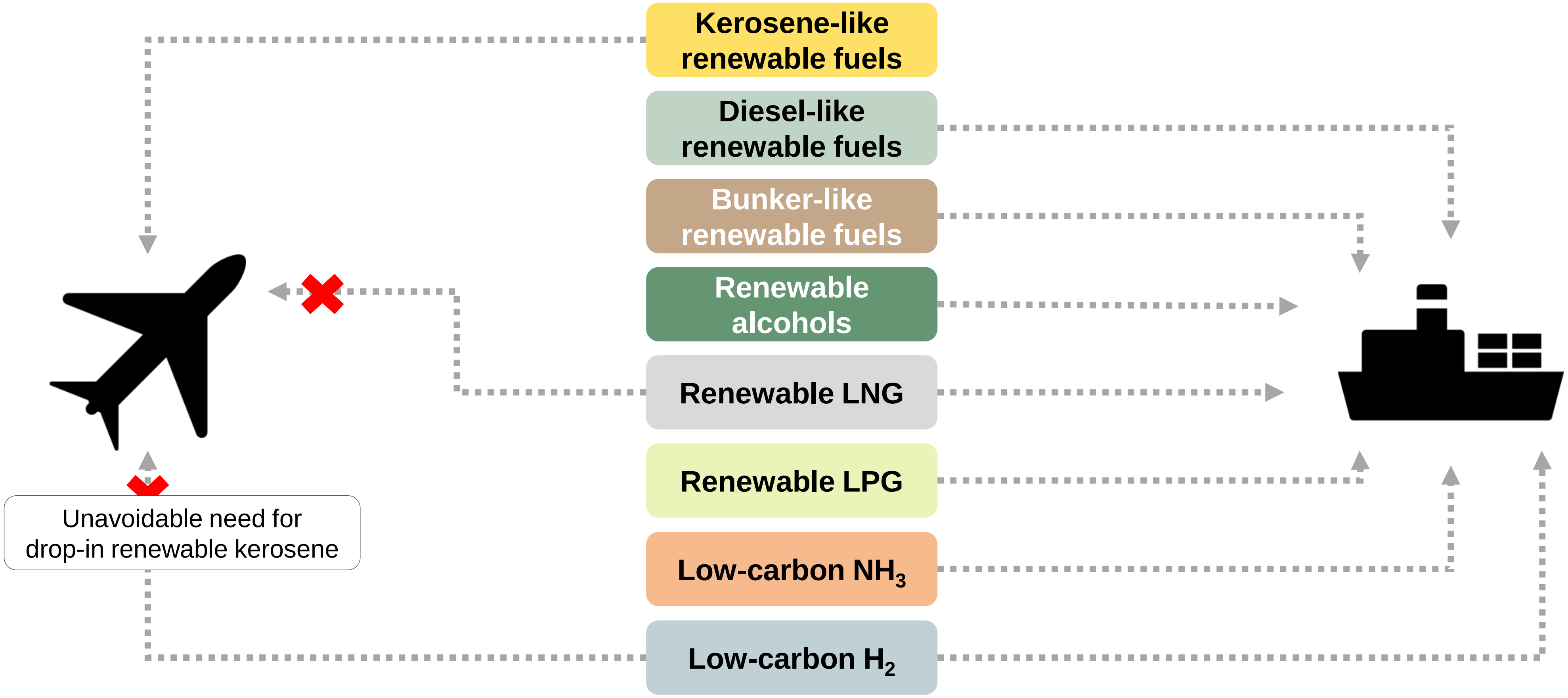
London-Buenos Aires (11,000 km)
Airbus A380
Total Fuel: 112,500 kg (jet fuel)
Max Take-Off Weight: 560,000 kg



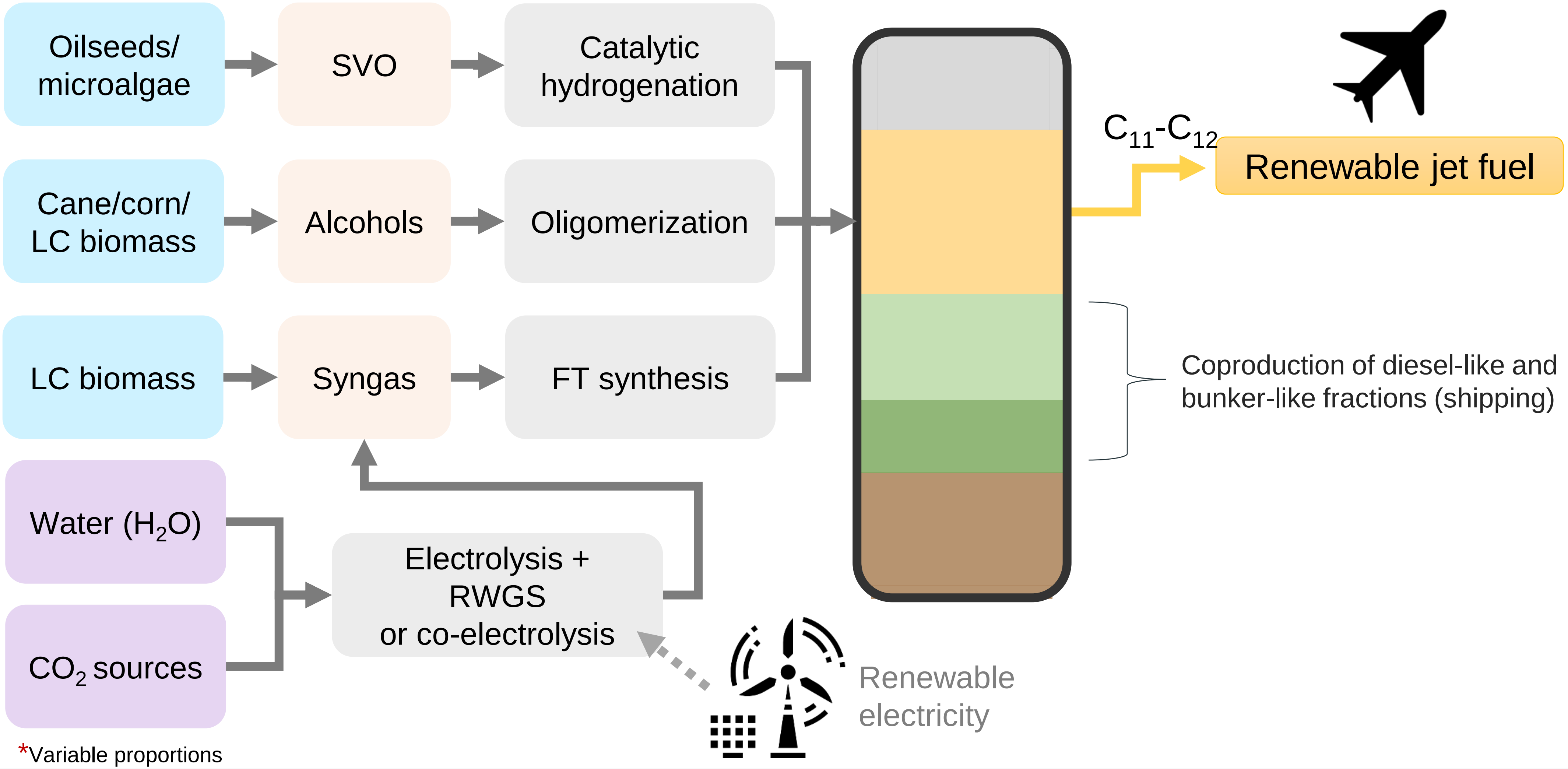
$$\frac{\text{Fuel Mass + Fuel Storage System Mass}}{\text{Maximum Take-Off Weight}}$$

Source: Grey et al. 2021. Icons: freepik/flaticon

As such, less options…



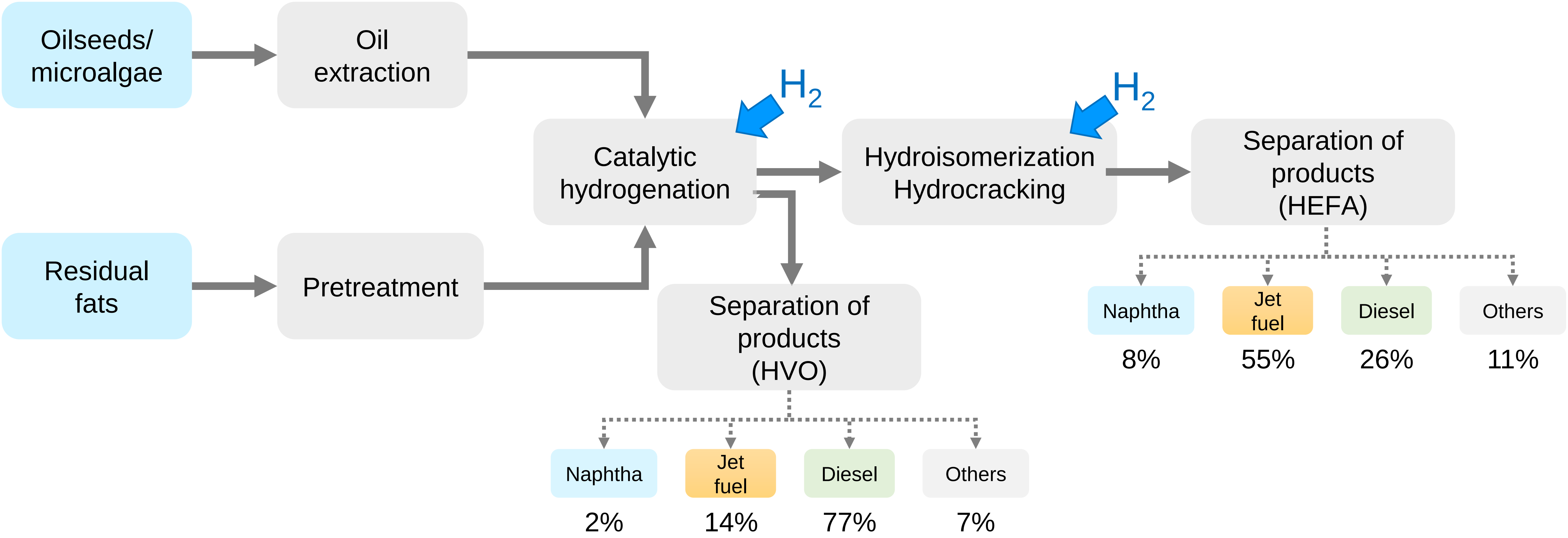
Renewable jet fuel: how?



*Variable proportions

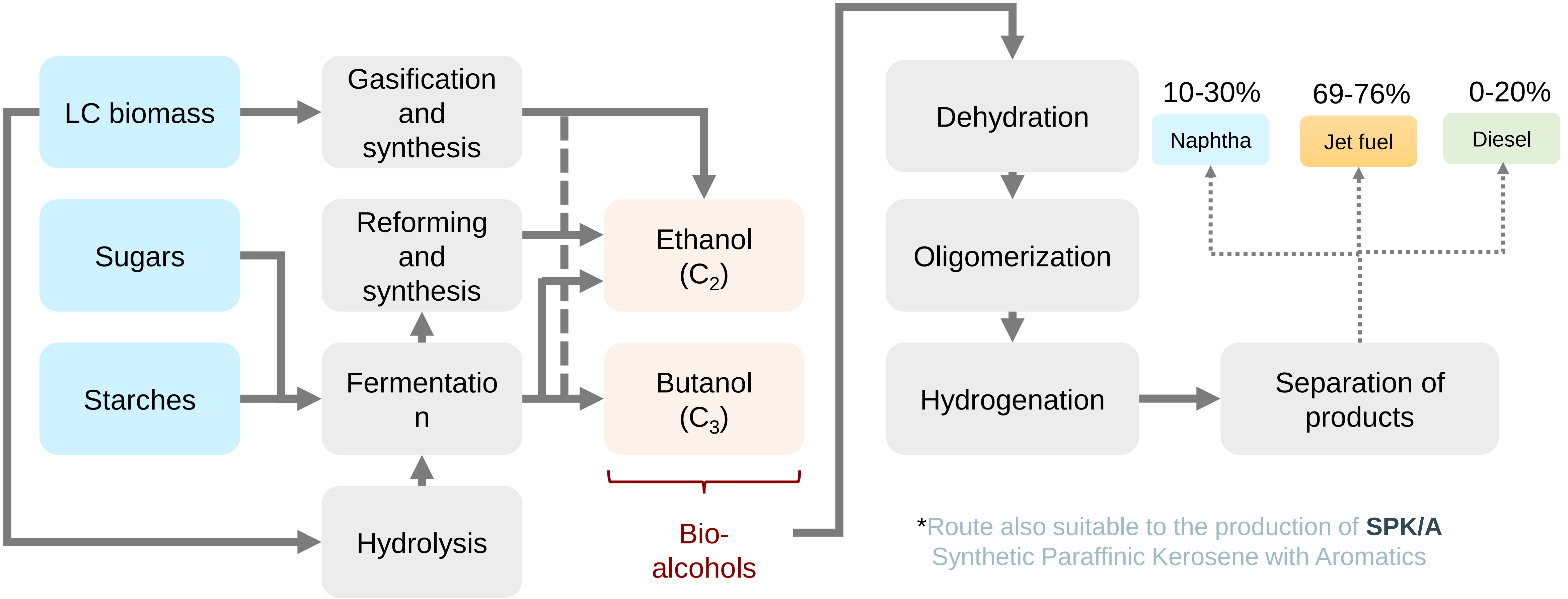
HEFA-SPK

Synthetic paraffinic kerosene from hydroprocessed fatty acids and esters



AtJ-SPK

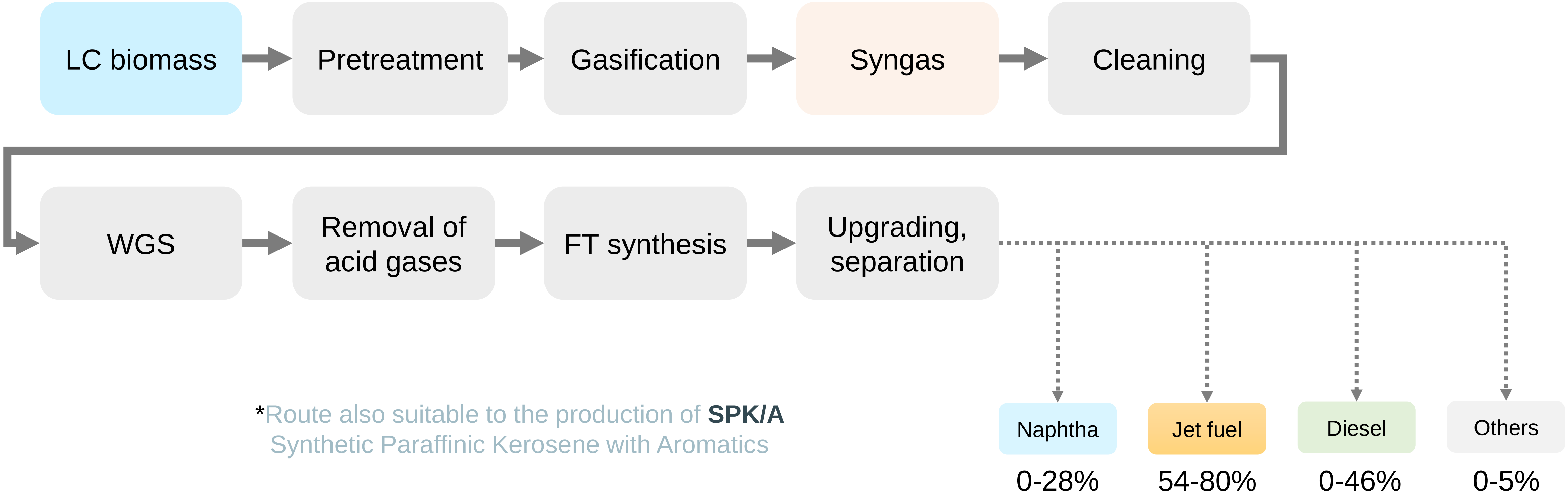
Synthetic paraffinic kerosene* from oligomerized alcohols



*Route also suitable to the production of **SPK/A**
Synthetic Paraffinic Kerosene with Aromatics

FT-SPK (BtL)

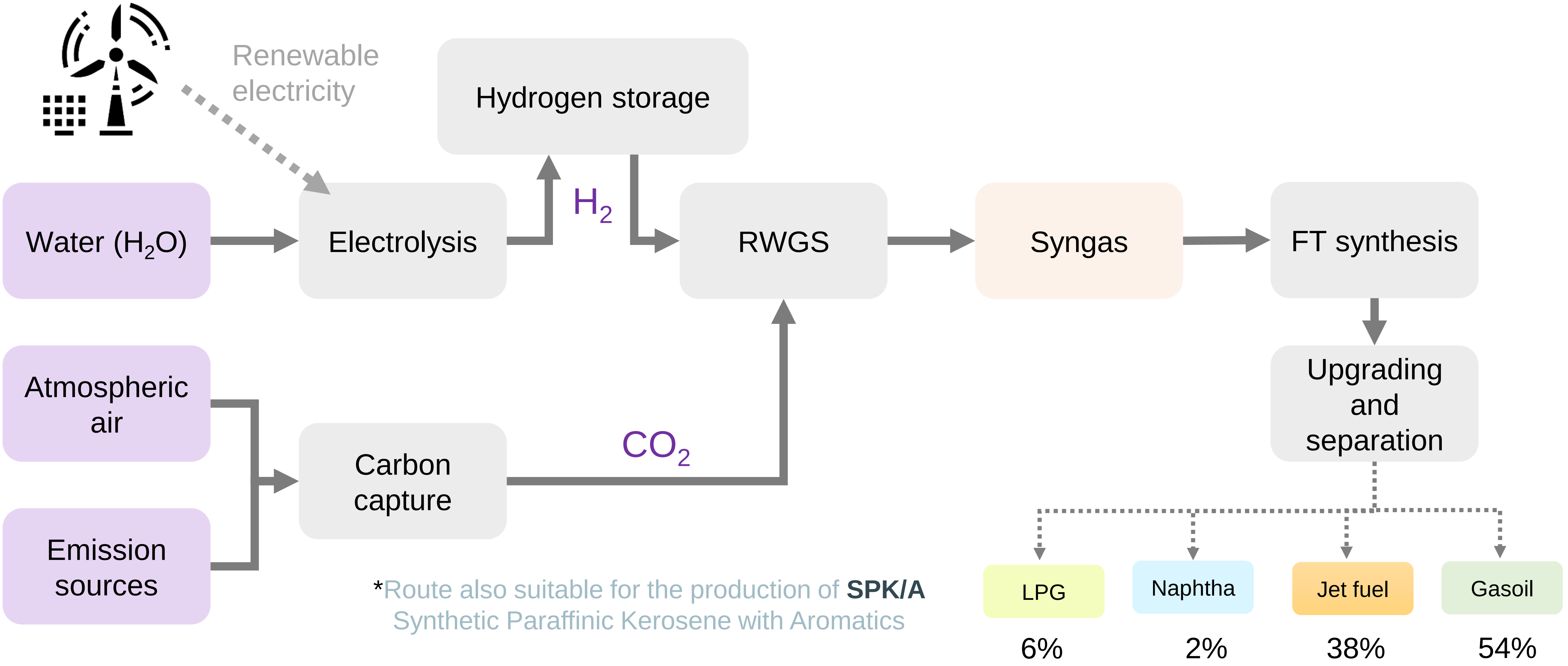
Synthetic paraffinic kerosene* from Fischer-Tropsch synthesis



*Route also suitable to the production of **SPK/A**
Synthetic Paraffinic Kerosene with Aromatics

e-SPK

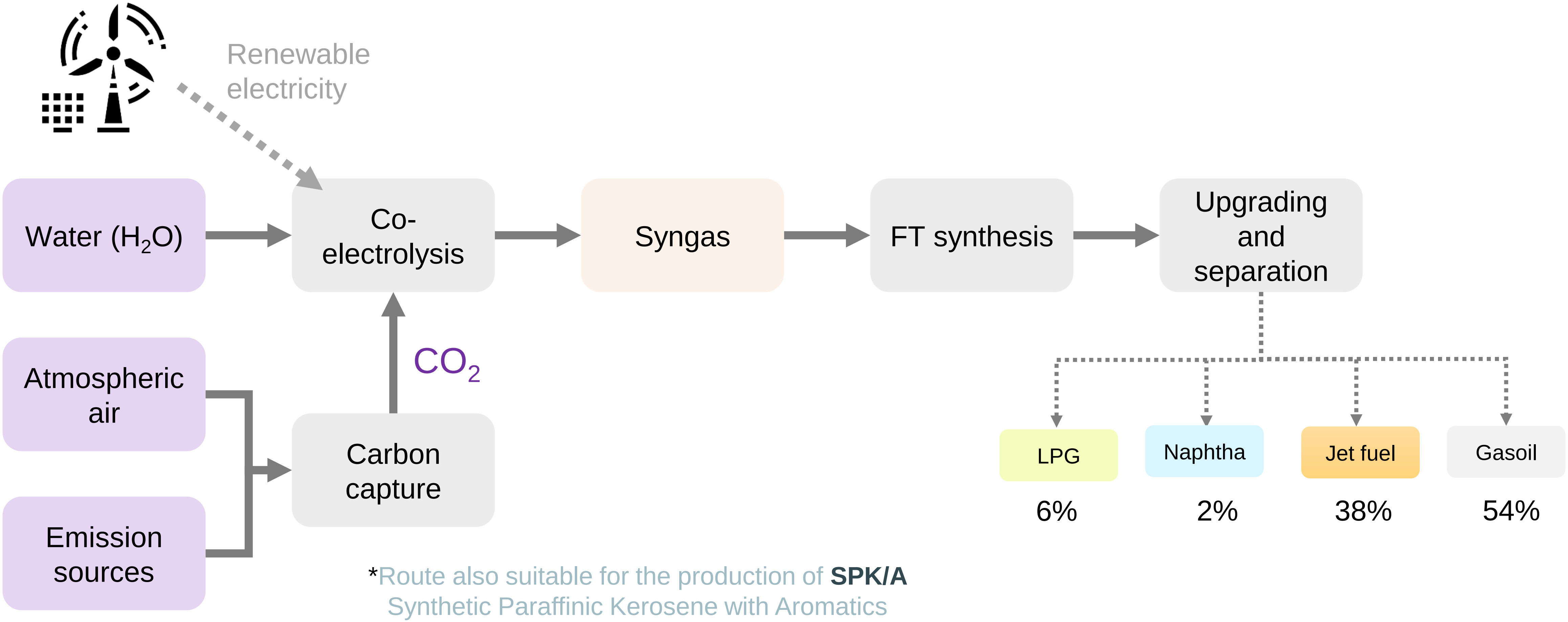
Synthetic paraffinic kerosene* from renewable hydrogen – route 1



*Route also suitable for the production of **SPK/A** Synthetic Paraffinic Kerosene with Aromatics

e-SPK

Synthetic paraffinic kerosene* from renewable hydrogen – route 2



*Route also suitable for the production of **SPK/A**
Synthetic Paraffinic Kerosene with Aromatics

Renewable fuels for shipping

Group 1:
Distilled biofuels

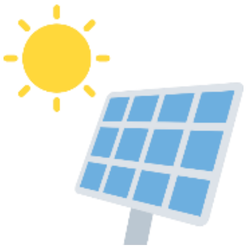
- SVO
- Biodiesel
- HVO
- HDPO
- FT-diesel

Group 2: Alcohols and liquefied gases

- Bio-LNG
- Biomethanol
- Bioethanol

Group 3:
Hydrogen-based fuels

- Green H_2
- Green NH_3
- e-diesel
- e-LNG
- e-methanol



Icons: freepik/flaticon

Criteria for Comparative Analysis

AVAILABILITY

Feedstock and production infrastructure

APPLICABILITY

Existing fleet and bunkering infrastructure

TECHNOLOGICAL MATURITY

Readiness level (production and use)

ENERGY DENSITY

Requirement of space for fuel storage

ECONOMIC

LCOE - fuel, bunkering and ship modifications

SAFETY

Safety in operation and toxicity

STANDARDS

Existence of standards and certifications

LOCAL SUSTAINABILITY

Air pollutant emissions, impacts on water

GLOBAL SUSTAINABILITY

Direct and indirect GHG emissions

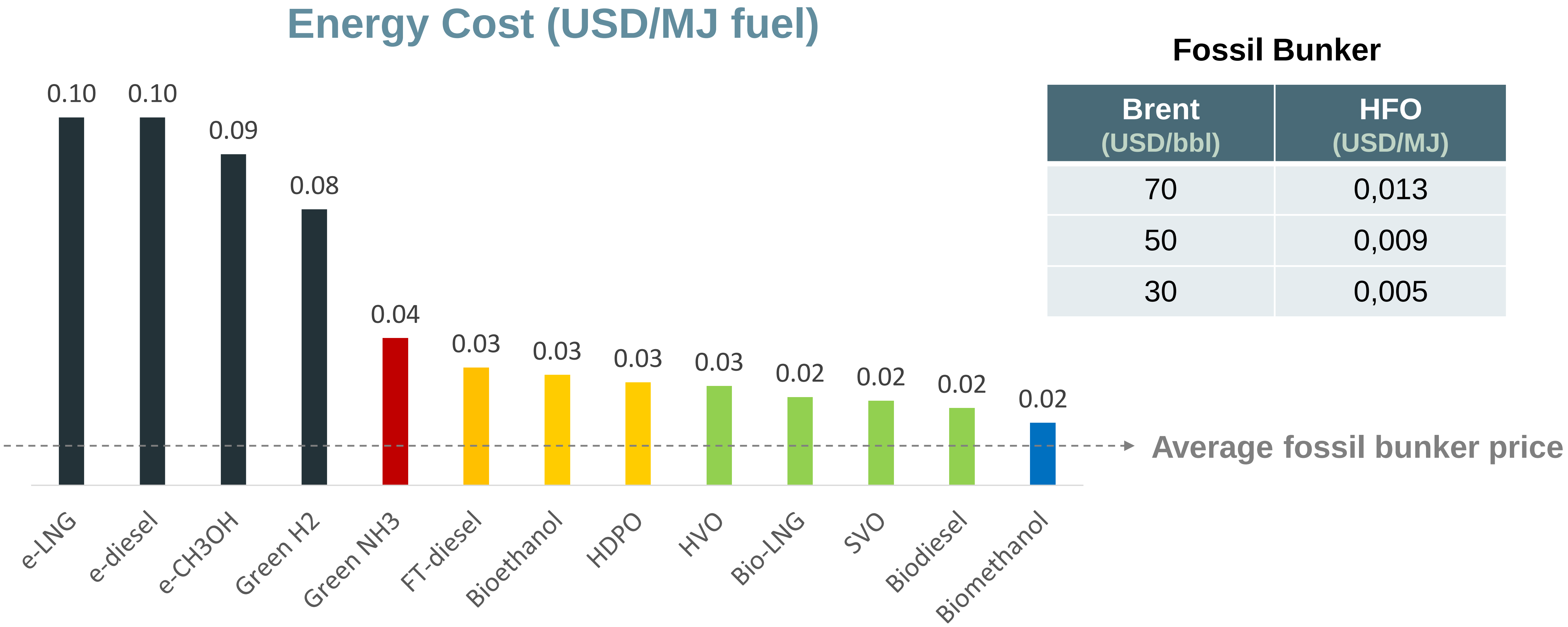
Technical

Economic

Environmental

Icons: freepik/flaticon

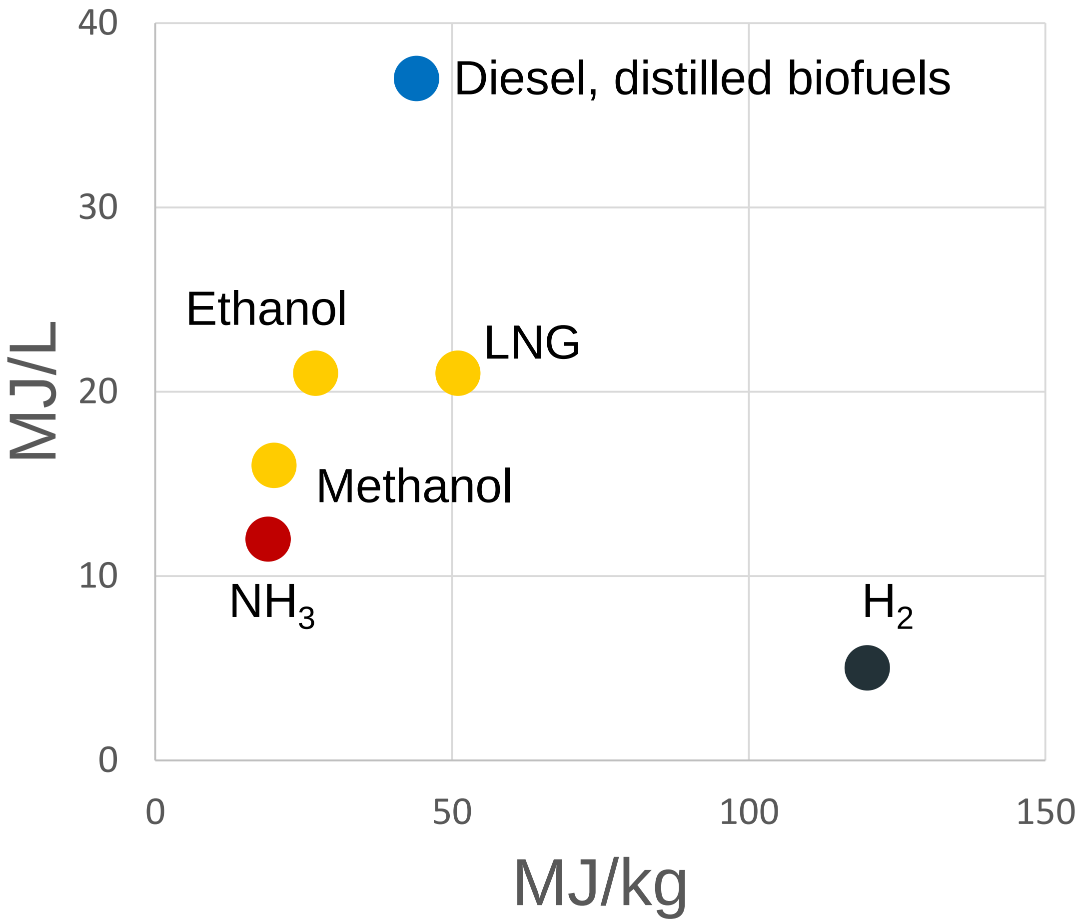
Economic Criterion



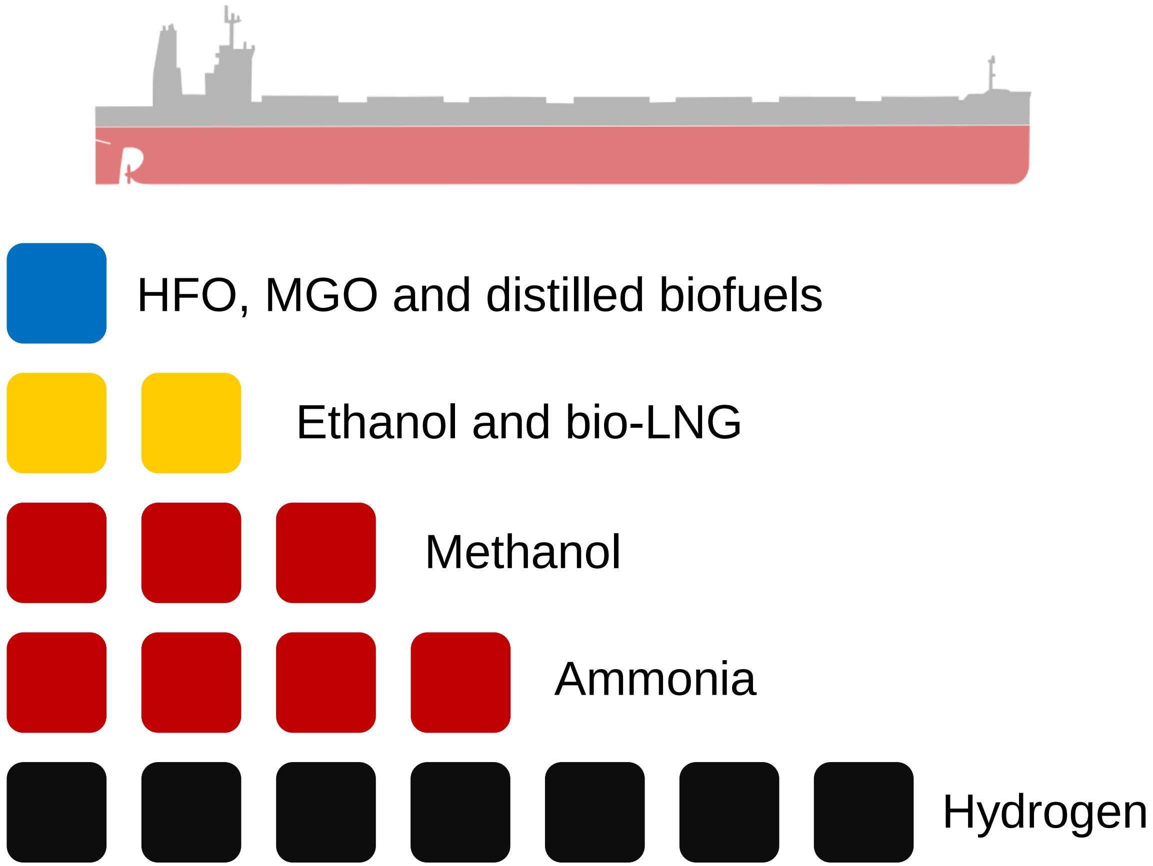
Fossil Bunker

Brent (USD/bbl)	HFO (USD/MJ)
70	0,013
50	0,009
30	0,005

Energy Density Criterion



Space required for fuel storage



Operational Safety

MGO

- Flammable liquid and vapour
- Toxic to aquatic life
- Aspiration hazards

LNG

- Highly flammable gas
- Cryogenic gas risks

Hydrogen

- Highly flammable gas
- Cryogenic gas risks

Biomethanol

- Highly flammable liquid and vapour
- Toxic if swallowed or in contact with skin

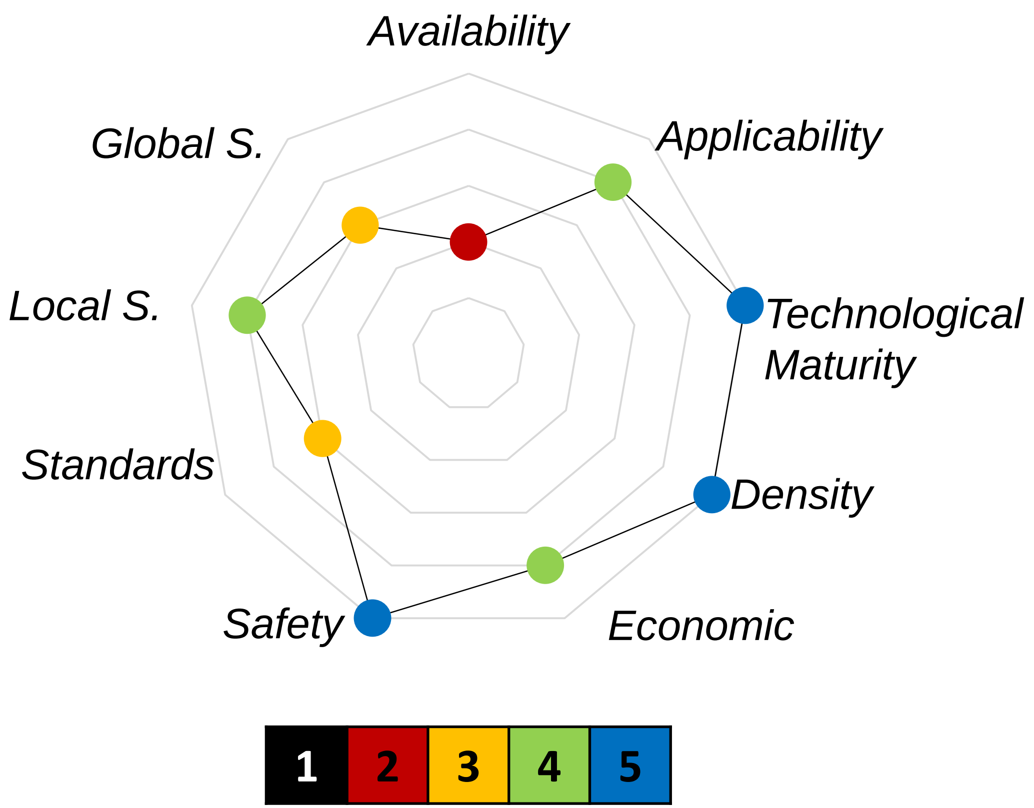
Ammonia

- Flammable gas
- Gas under pressure
- Toxic, skin burns
- Toxic to aquatic life

SVO (Straight Vegetable Oil)

STRENGHTS

- Drop-in biofuel
- Mature production technology
- Good energy density



WEAKNESSES

- Competition with other uses
- Land use change threats

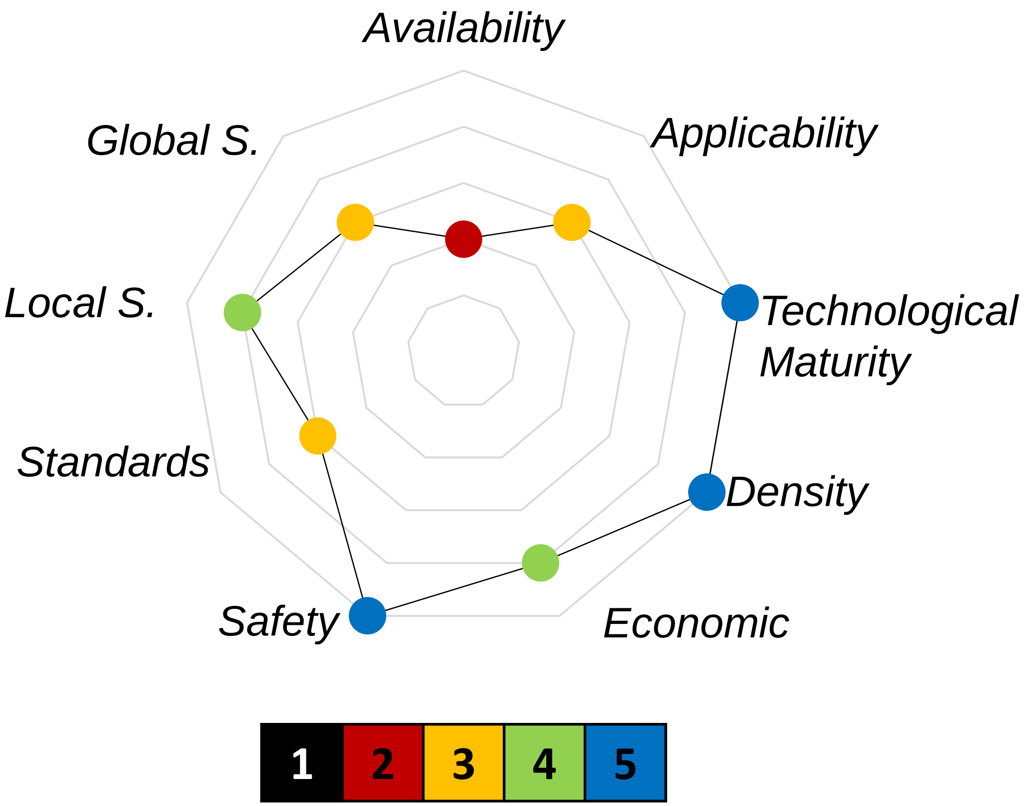
Biodiesel (FAME/FAEE)

STRENGHTS

Drop-in biofuel

Mature production technology

Good energy density



WEAKNESSES

Competition with other uses

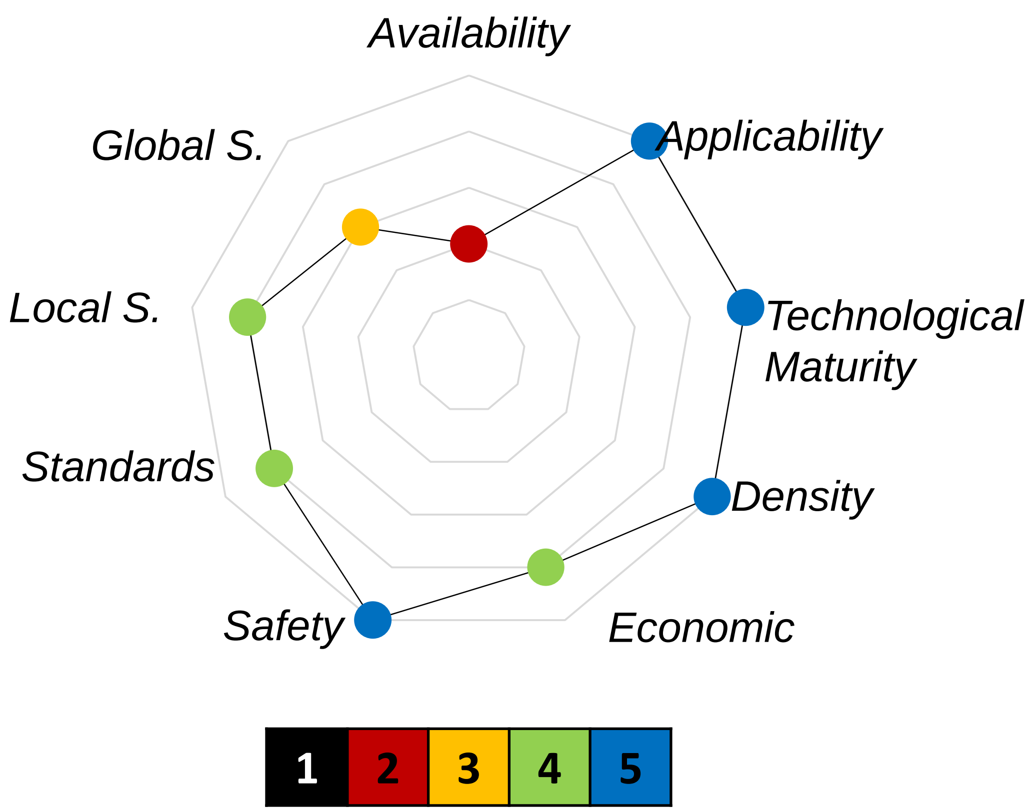
Land use change threats

Low quality compared to HVO

HVO (Hydrotreated Vegetable Oil)

STRENGHTS

- Drop-in biofuel
- Mature production technology
- Good energy density
- High quality



WEAKNESSES

- Competition with other uses
- Land use change threats

HDPO (Hydrotreated Pyrolysis Oil)

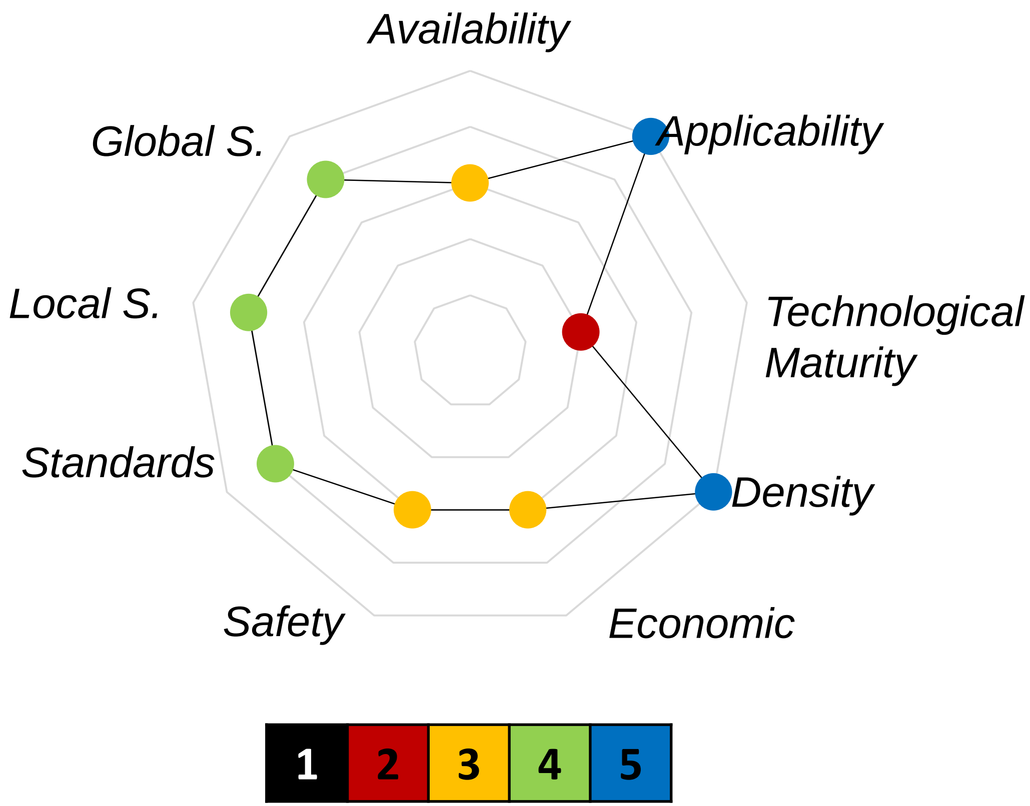
STRENGHTS

Drop-in biofuel

Better feedstock availability

Good energy density

High quality



WEAKNESSES

Technology not well developed yet

Higher cost

FT-diesel (Biomass-derived Diesel)

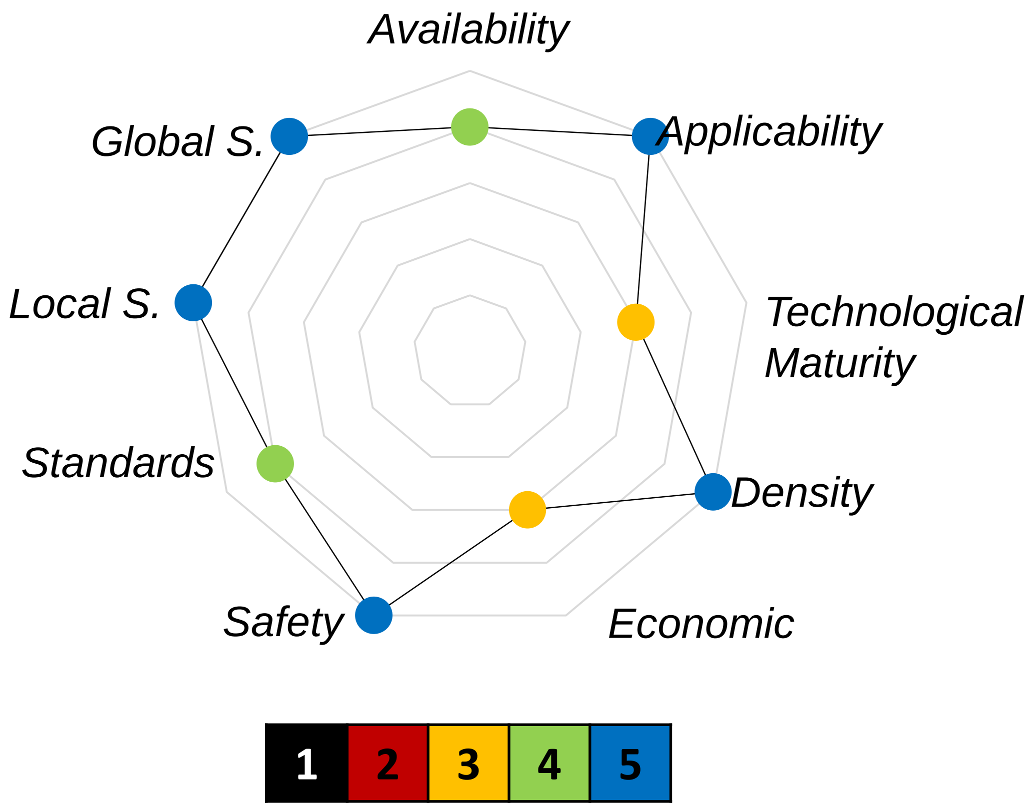
STRENGHTS

Drop-in and high quality

Fischer-Tropsch coproducts

Very high global sustainability

Feedstock availability



WEAKNESSES

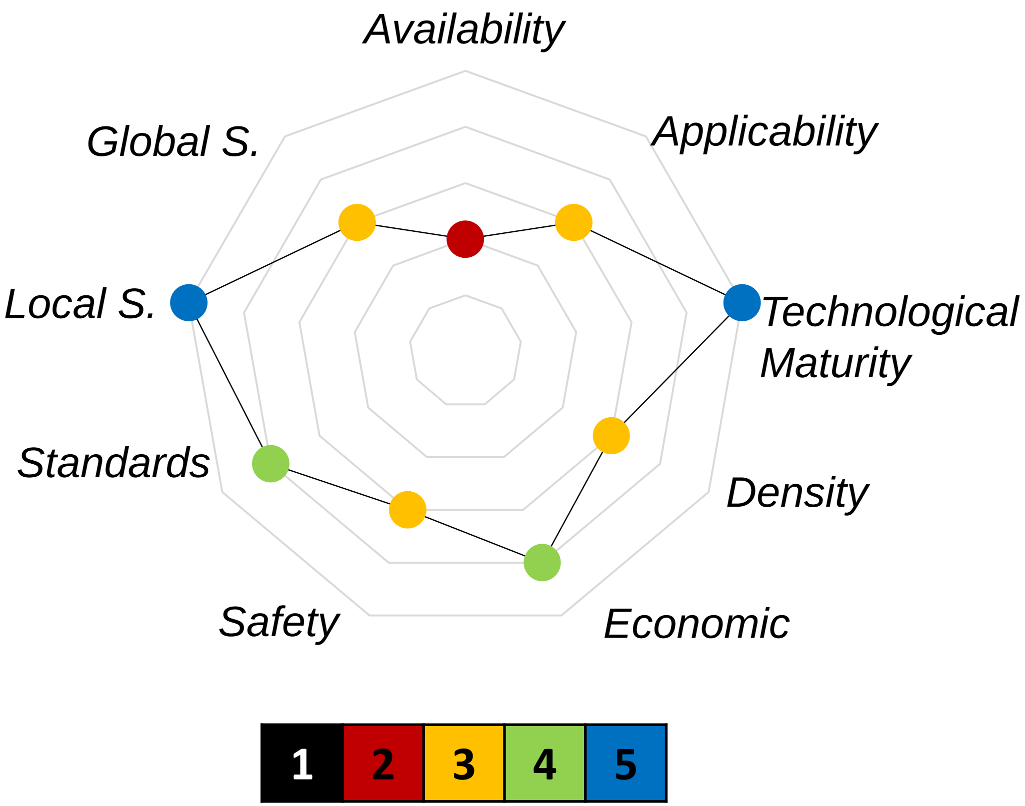
Not yet in commercial stage

Costs higher than SVO/HVO

Bio-LNG (Liquefied Biomethane)

STRENGHTS

- Mature production and liquefaction
- Interesting cost
- Very low air pollutant emissions



WEAKNESSES

- Geographically dispersed resources
- Heterogeneous feedstock
- Requires dual-fuel engine
- Methane slip

Bio-CH_3OH (Biomethanol)

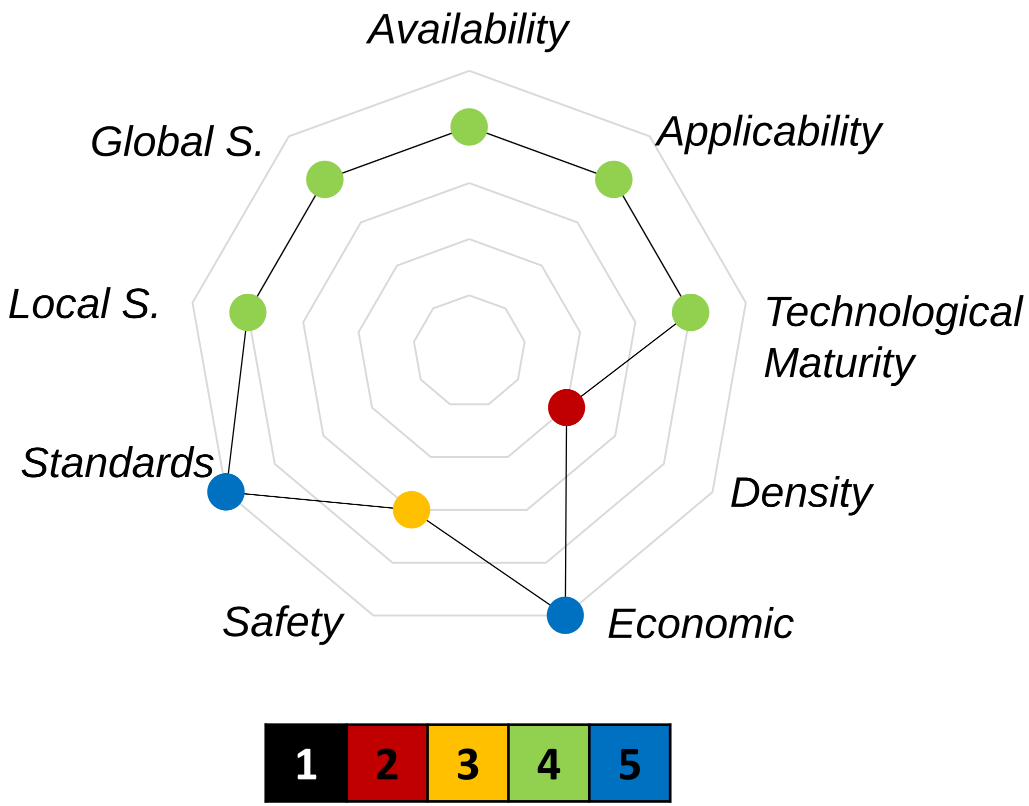
STRENGHTS

Good feedstock availability

Existing infrastructure

Competitive costs

Easier to storage than LNG



WEAKNESSES

Requires dual-fuel engine

Intermediate energy density

Flammability

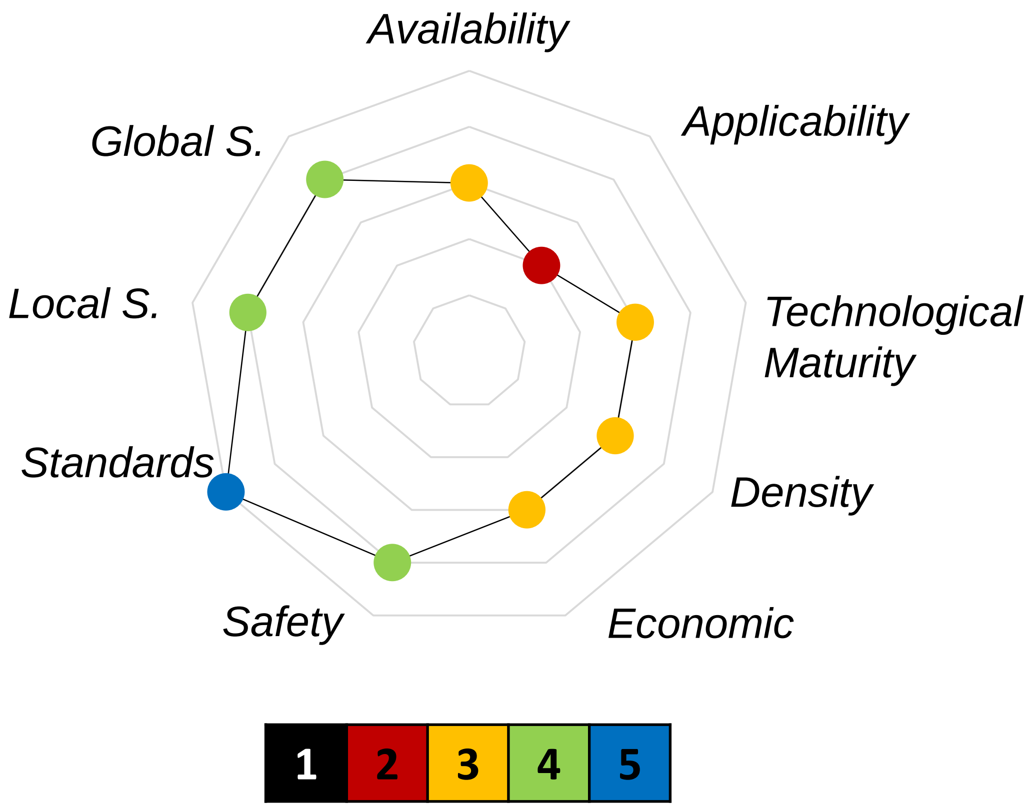
Bio-C_2H_5OH (Bioethanol)

STRENGHTS

Mature production process

Safe biofuel

Standards available



WEAKNESSES

Use in diesel engine requires booster

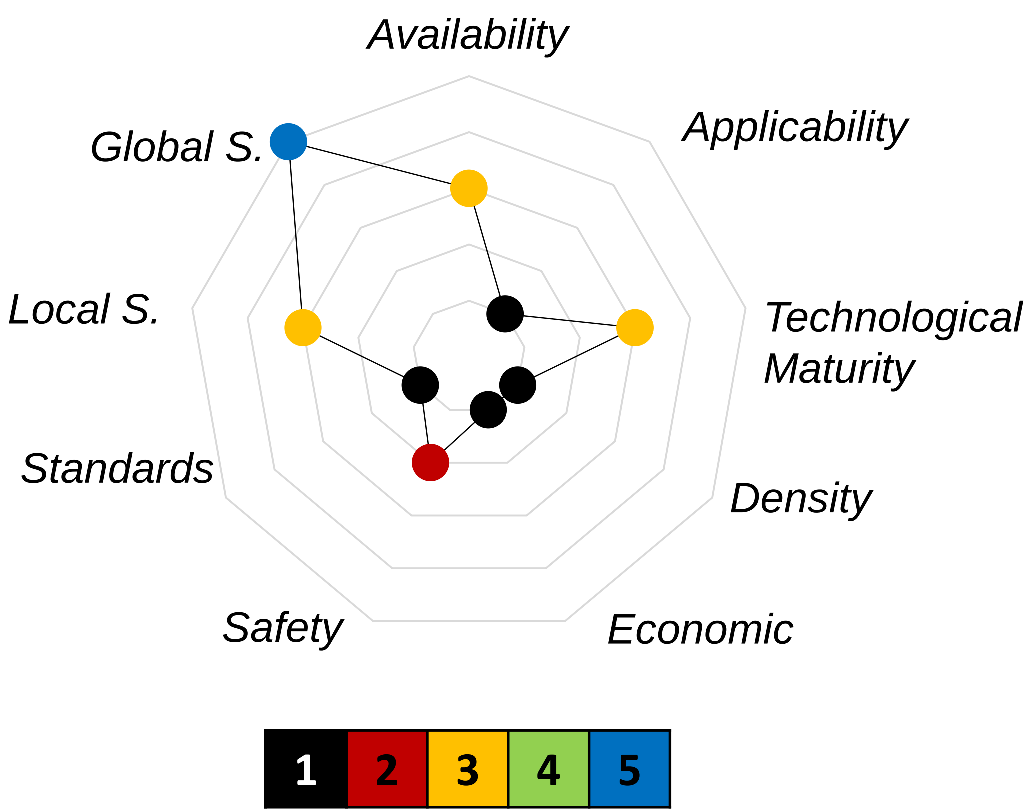
Intermediate energy density

Green H_2 (Renewable-based Hydrogen)

STRENGHTS

Very high global sustainability

No air pollutant emissions



WEAKNESSES

Low TRL and applicability

Safety concerns

Cost of electrolysis

Poor energy density

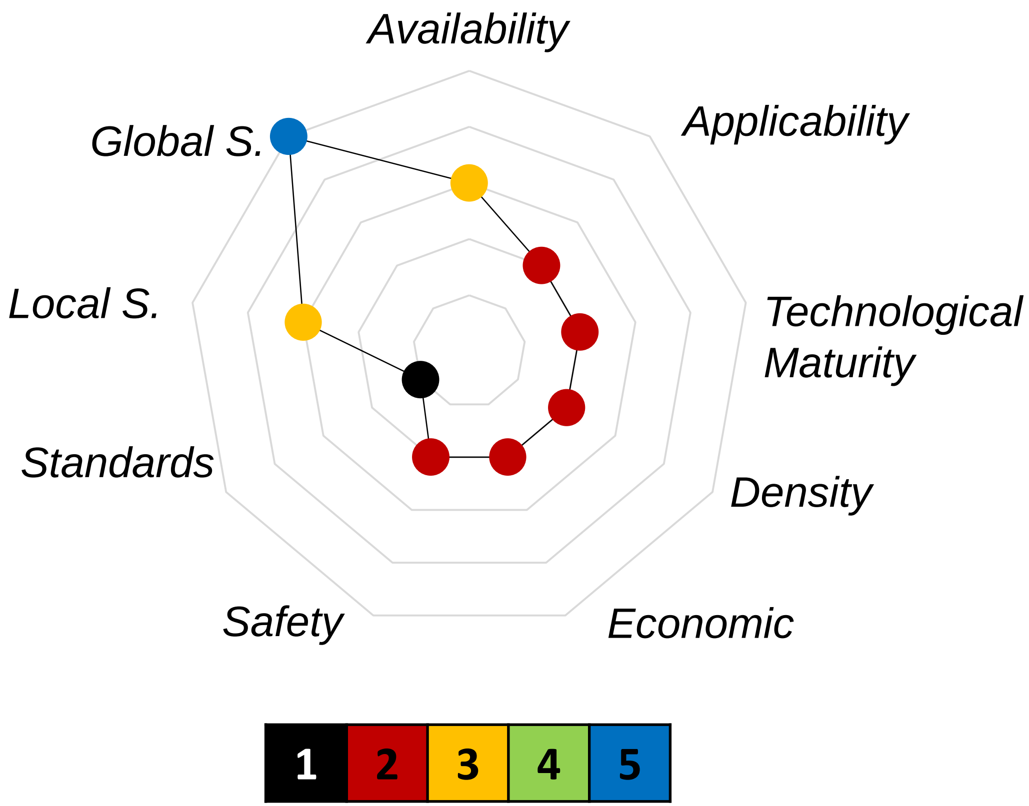
Green NH_3 (Renewable-based Ammonia)

STRENGHTS

Very high global sustainability

No air pollutant emissions

Haber-Bosch, mature process



WEAKNESSES

Low TRL and applicability

Safety concerns

Cost of electrolysis

Poor energy density (but > H_2)

e-diesel (Green H_2-based Diesel)

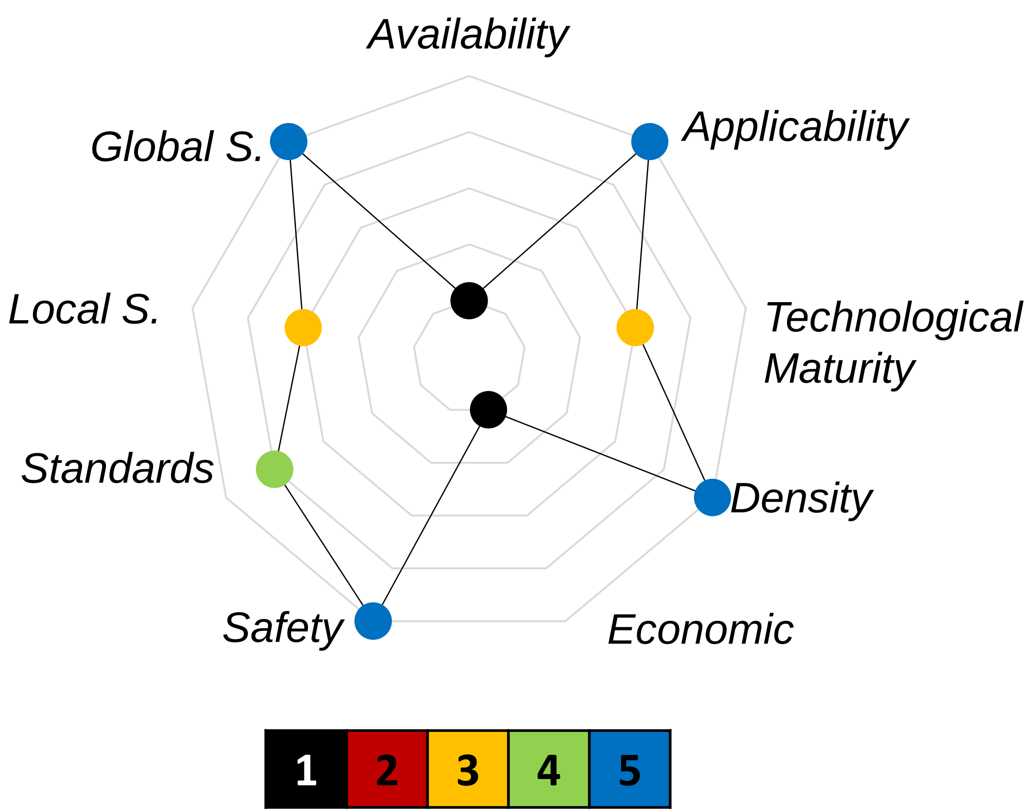
STRENGHTS

Drop-in and high quality

Fischer-Tropsch coproducts

Very high global sustainability

Good energy density



WEAKNESSES

Not available in the near-term

High costs

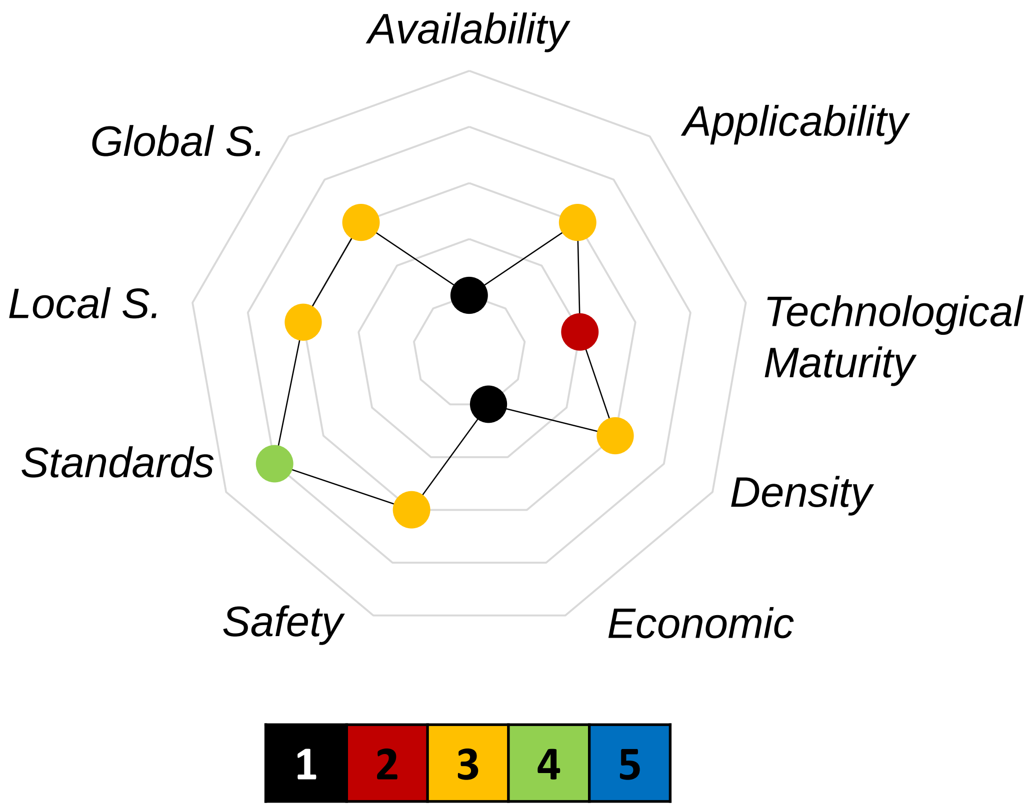
Water consumption

e-LNG (Green H_2-based LNG)

STRENGHTS

Mature CH_4 production and liquefaction

CO2 recycling



WEAKNESSES

High costs

CO_2 unavailable (DAC/CCS)

Only dual-fuel engines

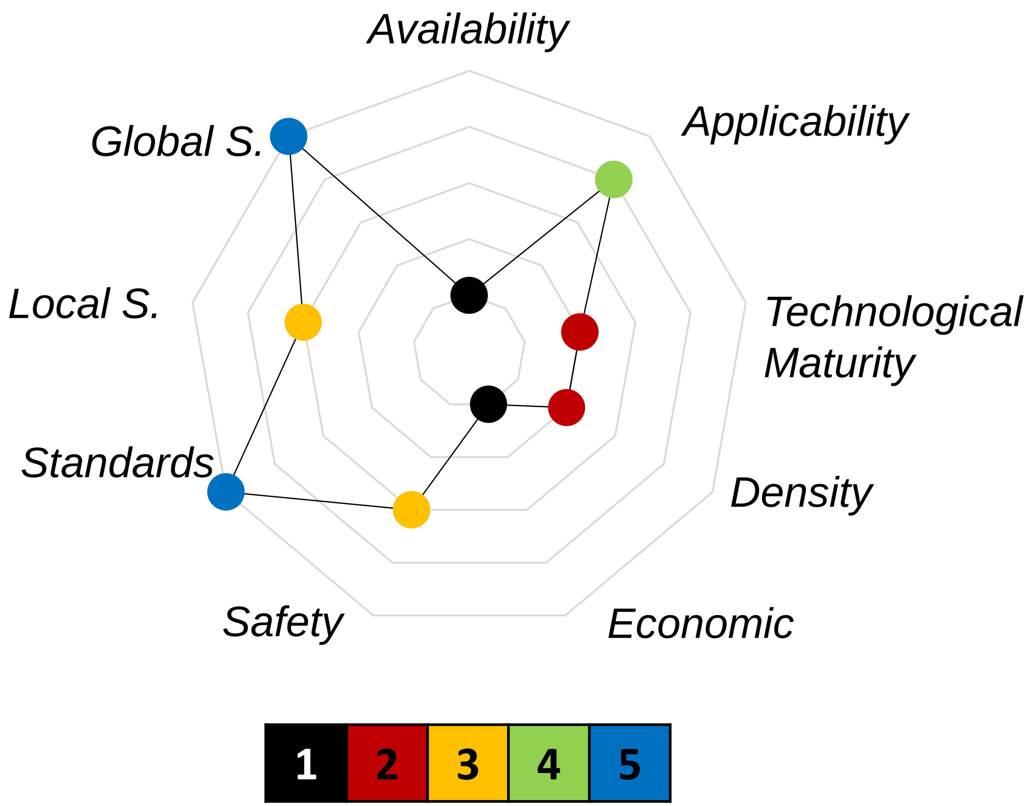
Methane slip

e-CH_3OH (Green H_2-based Methanol)

STRENGHTS

Storage advantages (bio-LNG or e-LNG)

CO2 recycling



WEAKNESSES

High costs

CO_2 unavailable

H_2O consumption

MJ/L ≈ bunker ÷ 2,5

Criteria Weights

AVAILABILITY

APPLICABILITY

TECHNOLOGICAL MATURITY

ENERGY DENSITY

ECONOMIC

SAFETY

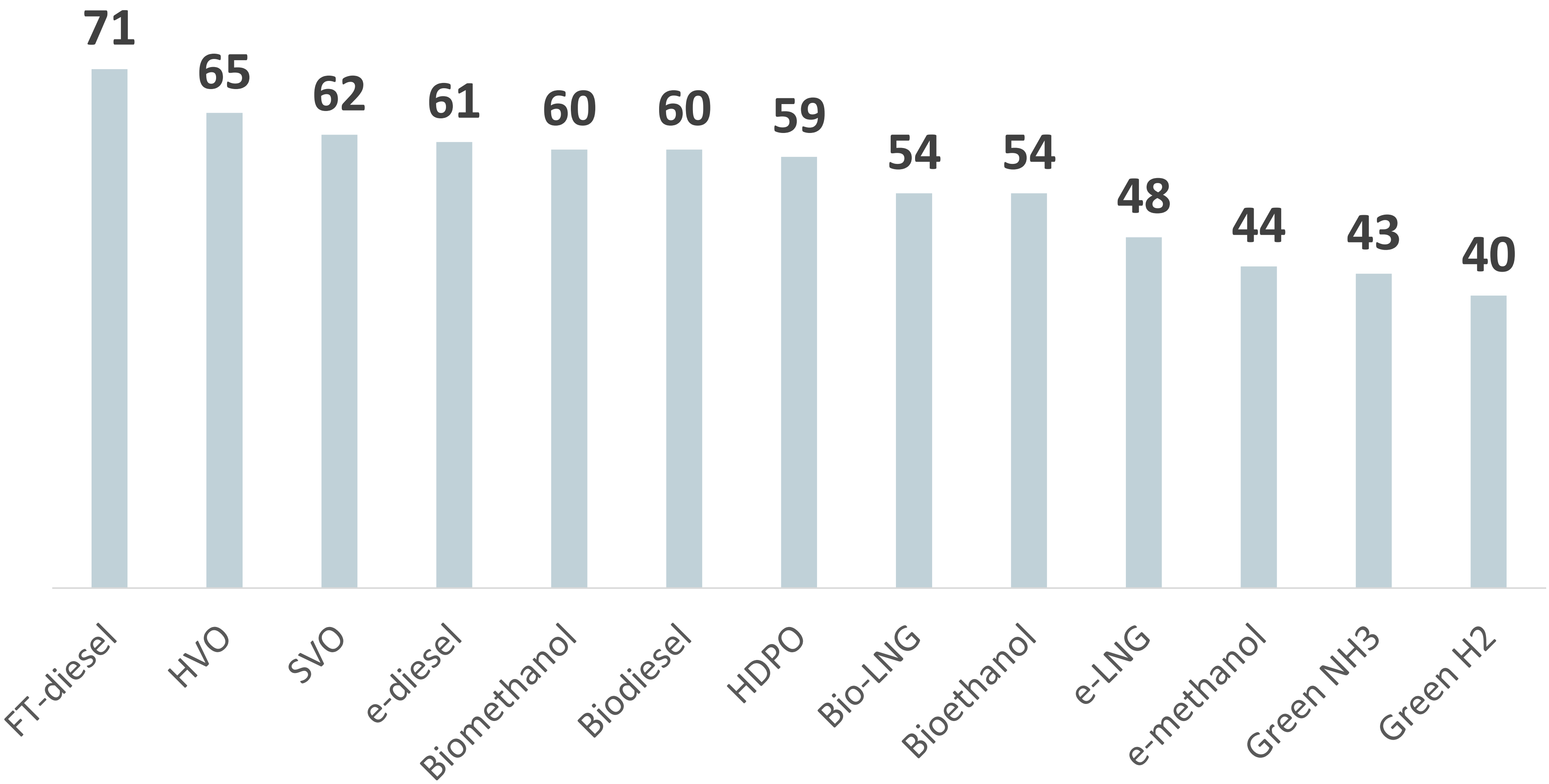
STANDARDS

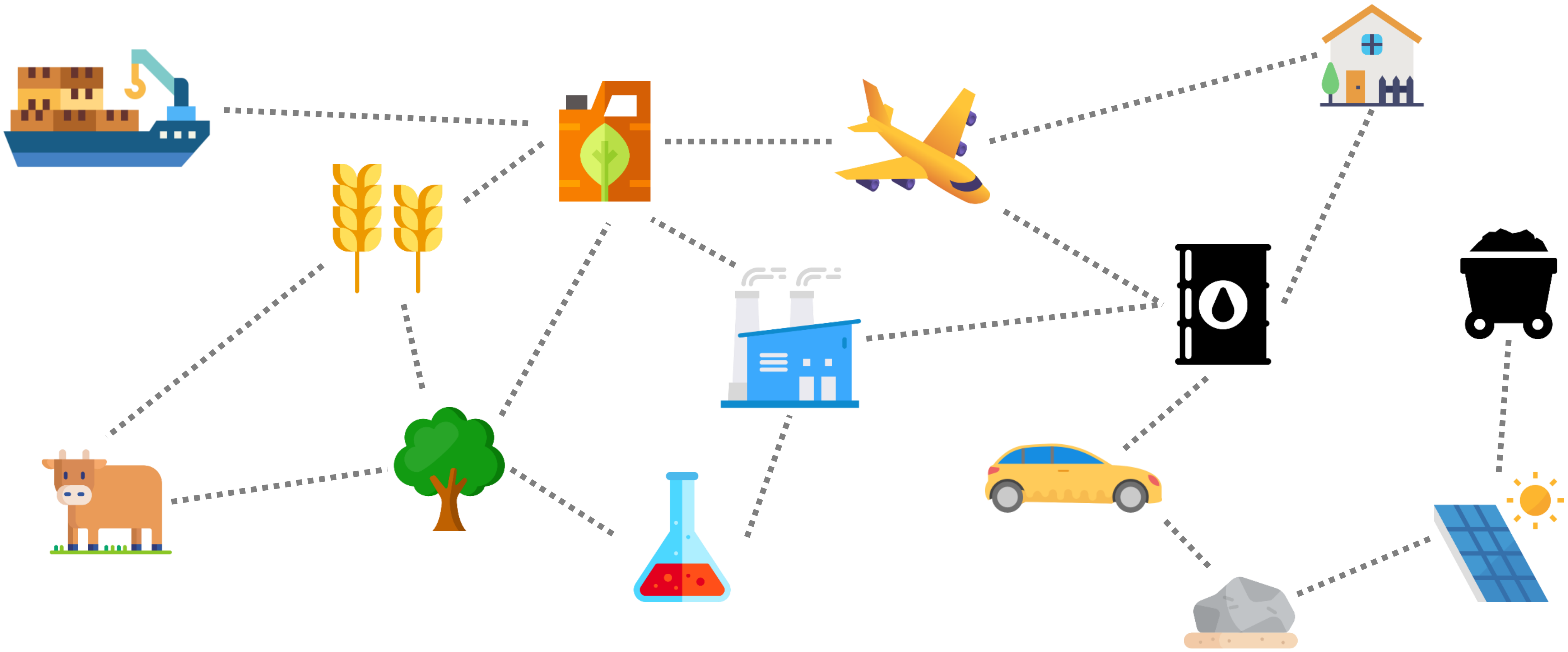
LOCAL SUSTAINABILITY

GLOBAL SUSTAINABILITY

Icons: freepik/flaticon

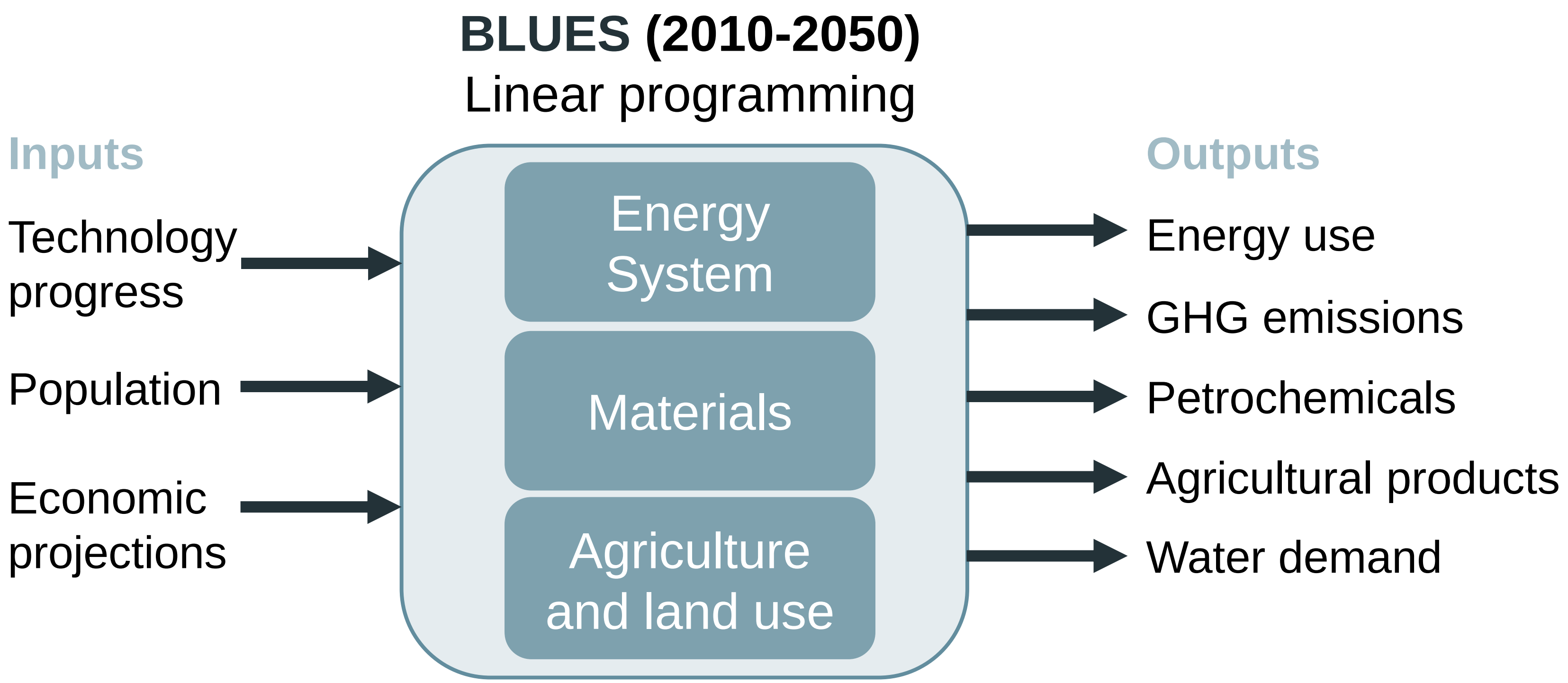
Score and Ranking





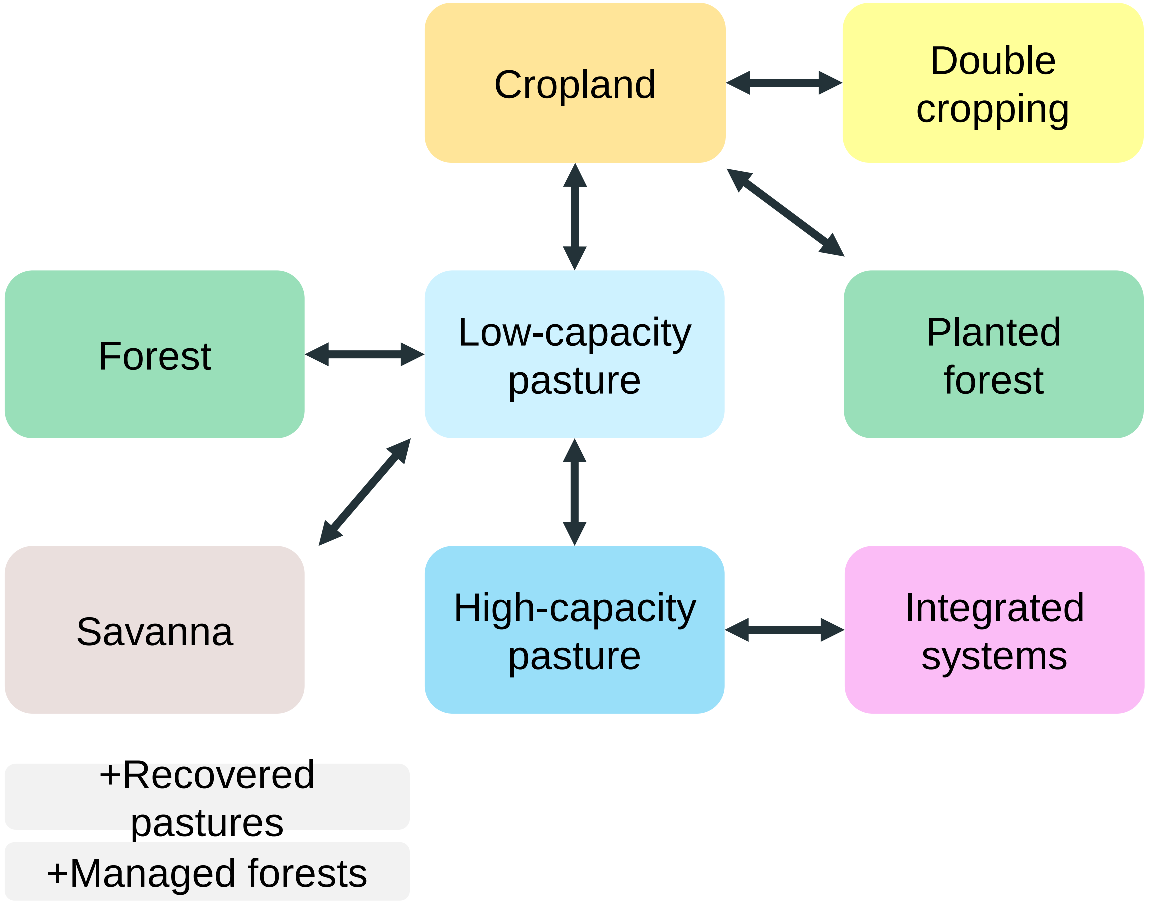
What is an integrated assessment perspective on these matters with a special focus on aviation and shipping?

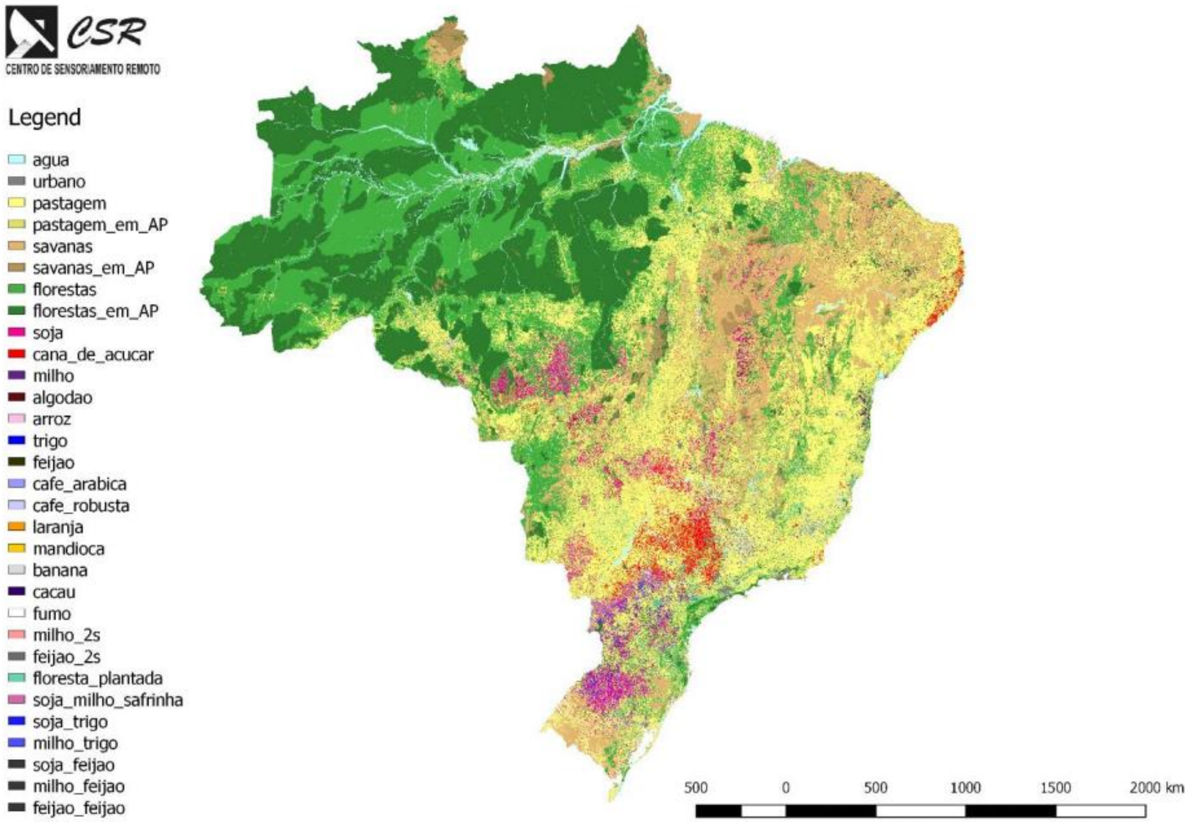
The BLUES model



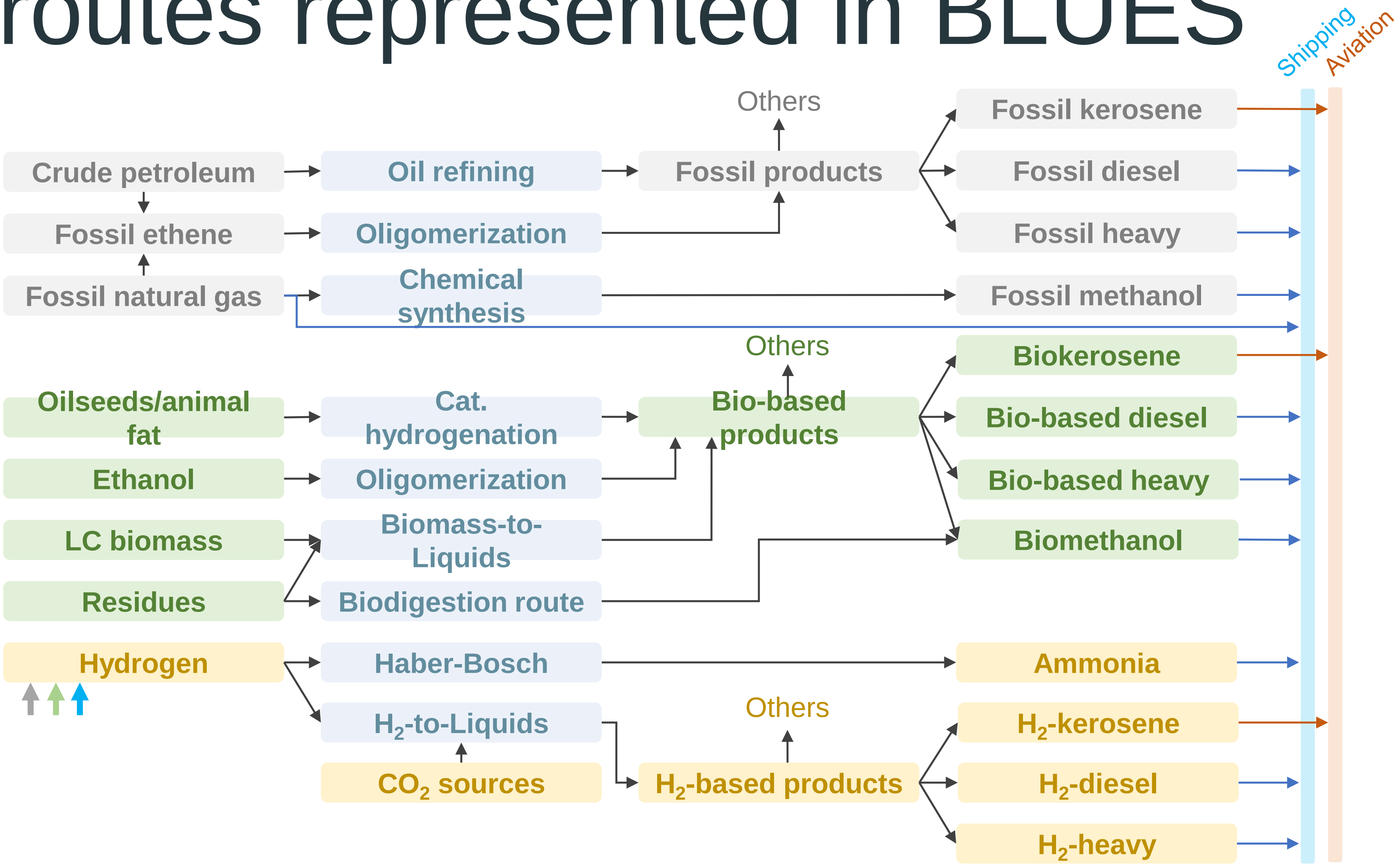
5 regions

Land-use change in the BLUES model

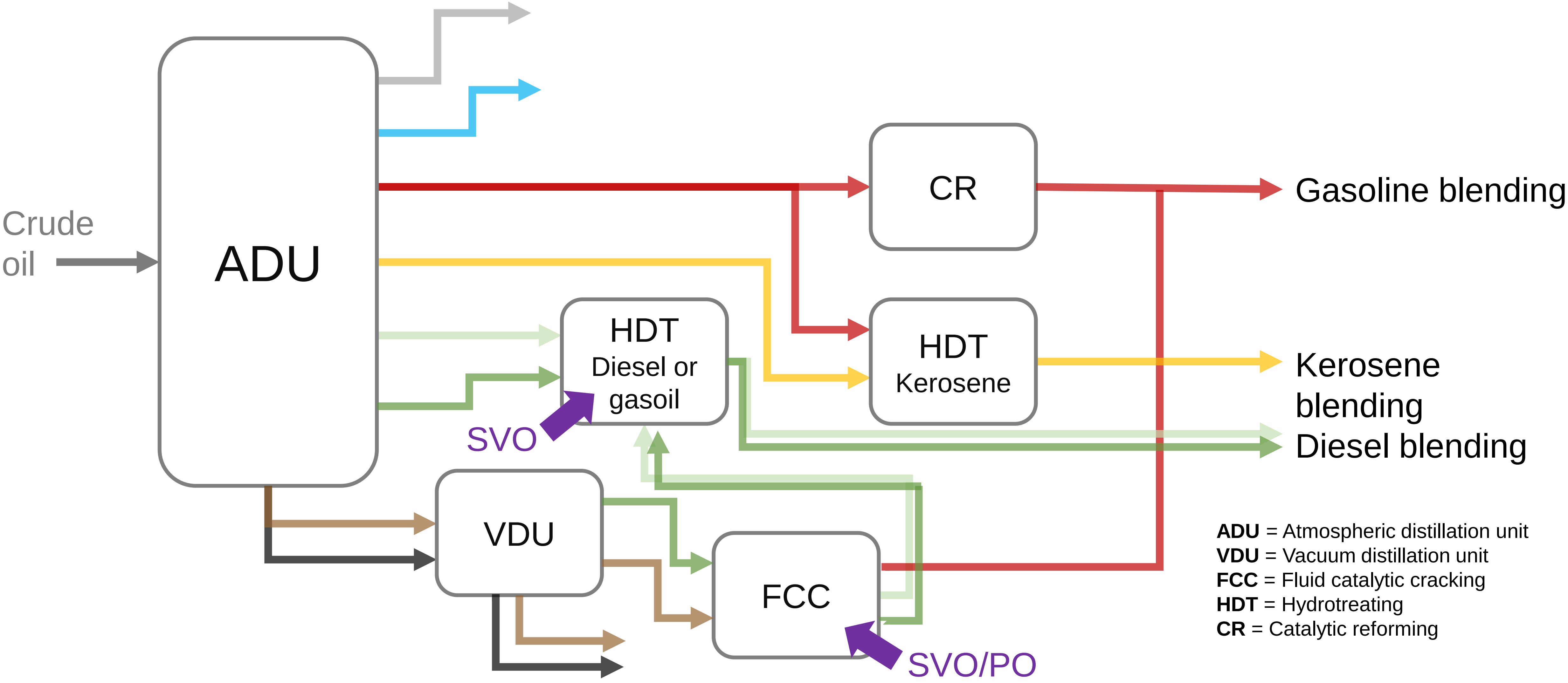




Fuel routes represented in BLUES



Additionally, coprocessing…



ADU = Atmospheric distillation unit
VDU = Vacuum distillation unit
FCC = Fluid catalytic cracking
HDT = Hydrotreating
CR = Catalytic reforming

Design of scenarios: our choice

Originally, four scenarios:

Carbon budget:
Global IAM, Brazil as a region in a World below 2ºC

IATA

Current policy view
IATA2050 as a restriction

IMO

Current policy view
IMO2050 as a restriction

IATA IMO

Combination of the first two scenarios

B2C

Climate policy scenario:
Brazil **well-below 2ºC**

In a second moment, sensitivity analyses:

For simplicity, IATA/ICAO scenarios are referred to as IATA

IATA IMO (KeroExp)

IATA_IMO with Brazil becoming a major aviation biofuel exporter

IATA IMO (Sml BtL)

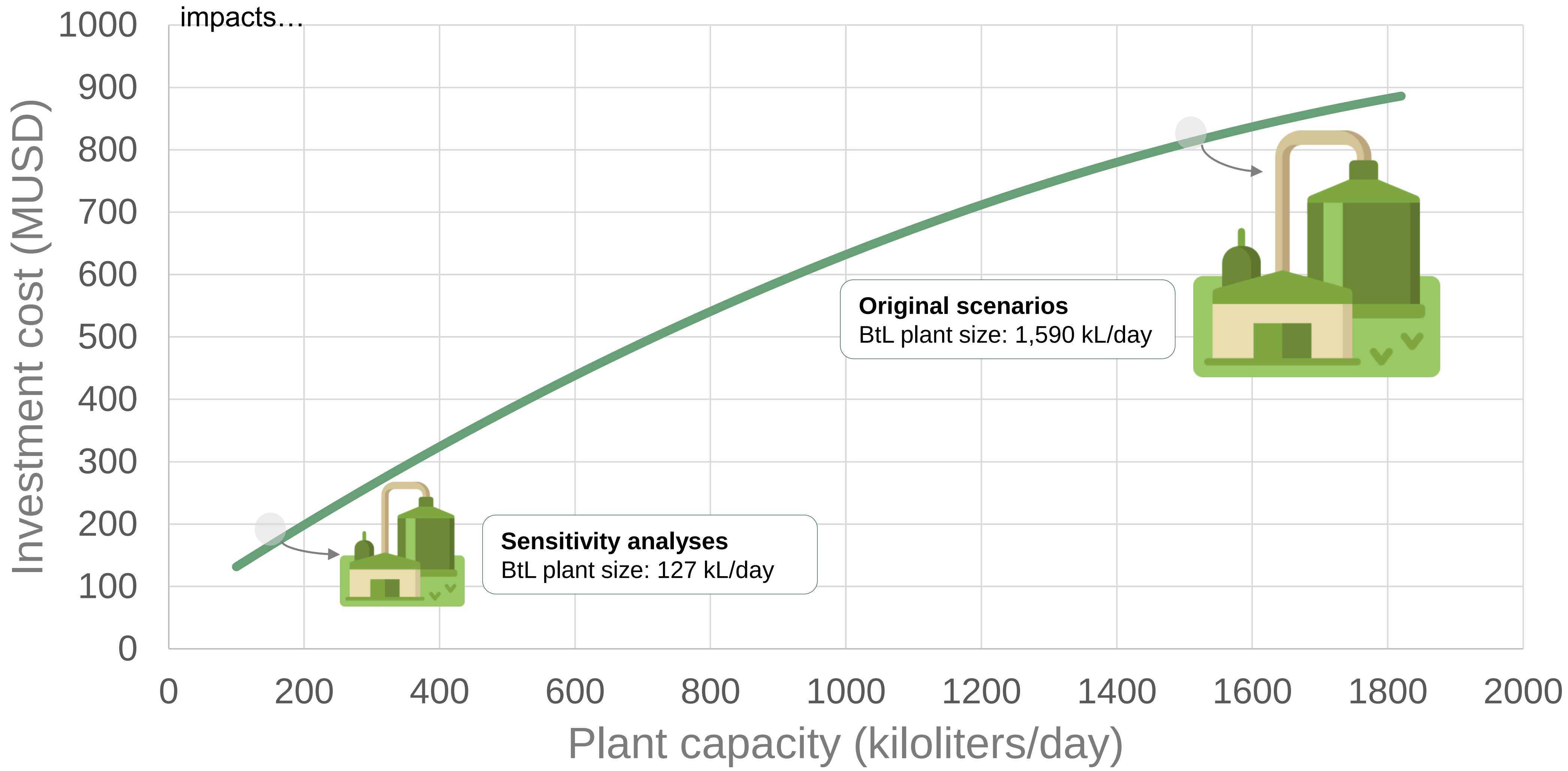
IATA_IMO considering smaller BtL plants

B2C (Sml BtL)

B2C considering smaller BtL plants

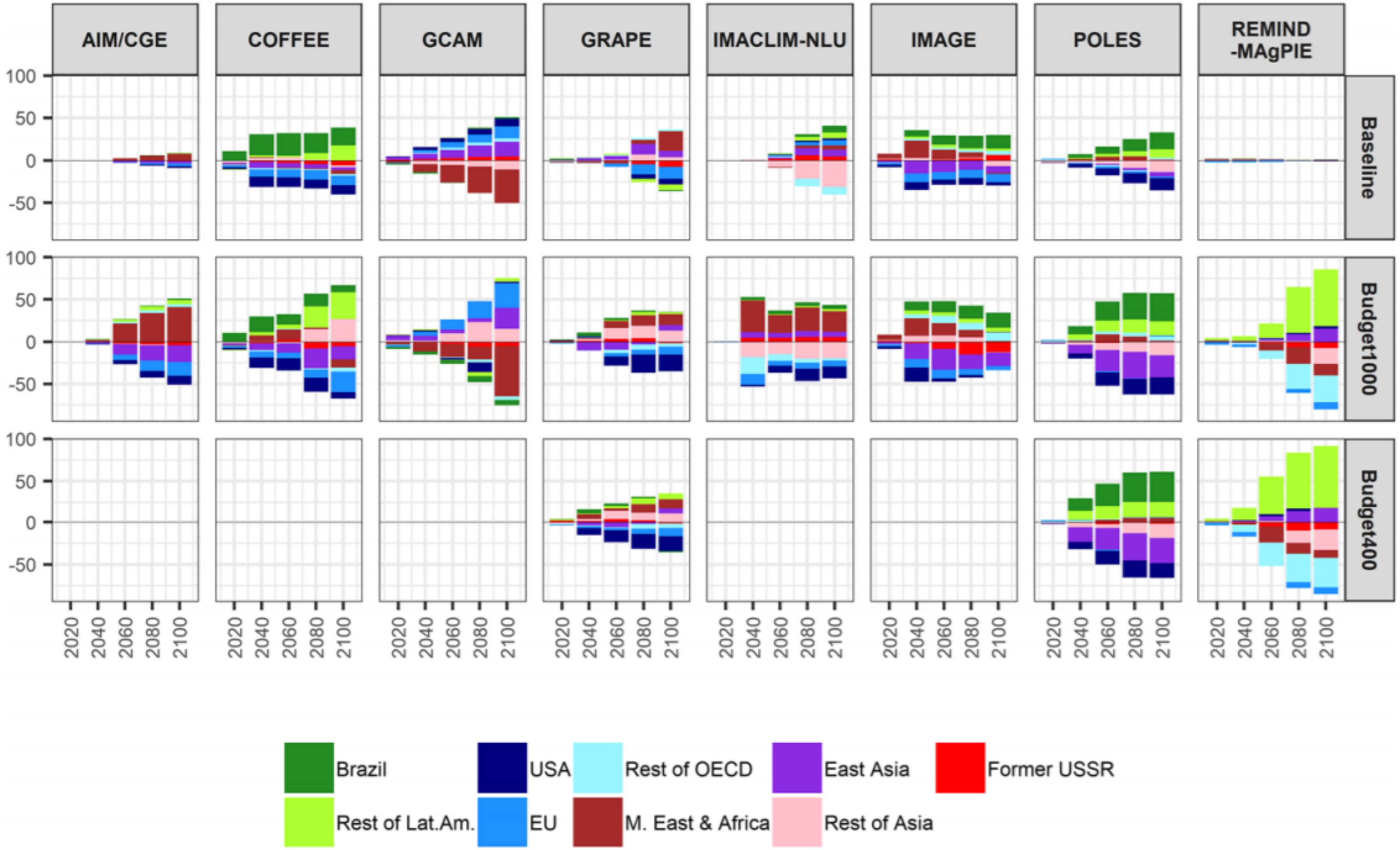
A comment on Biomass-to-Liquids…

Small variations in the cost parameters of **BtL** may have significant impacts…



A comment on the KeroExp scenario…

Net trade of bioenergy (primary EJ)



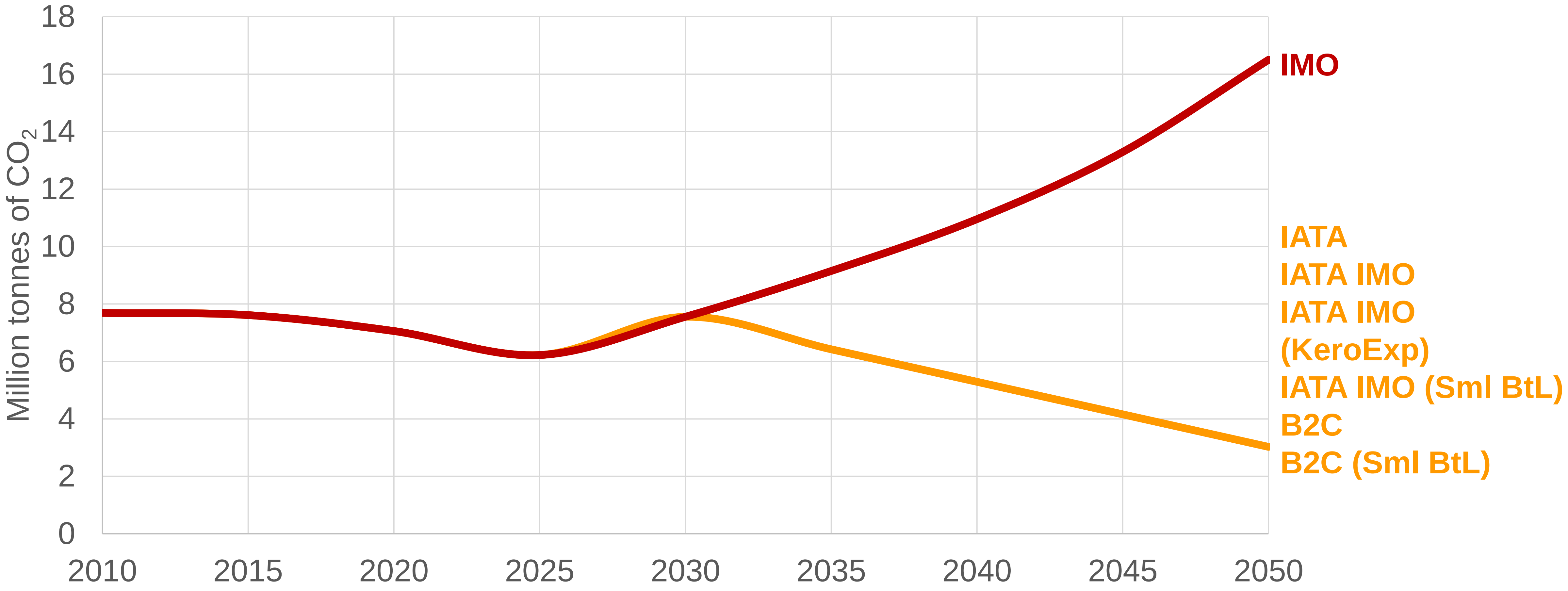
Several global IAM scenarios see Brazil as a major bioenergy exporter from 2030 onwards

In this context, biokerosene may be an important export product

IATA IMO (KeroExp) scenario
(Two times the original kerosene demand)

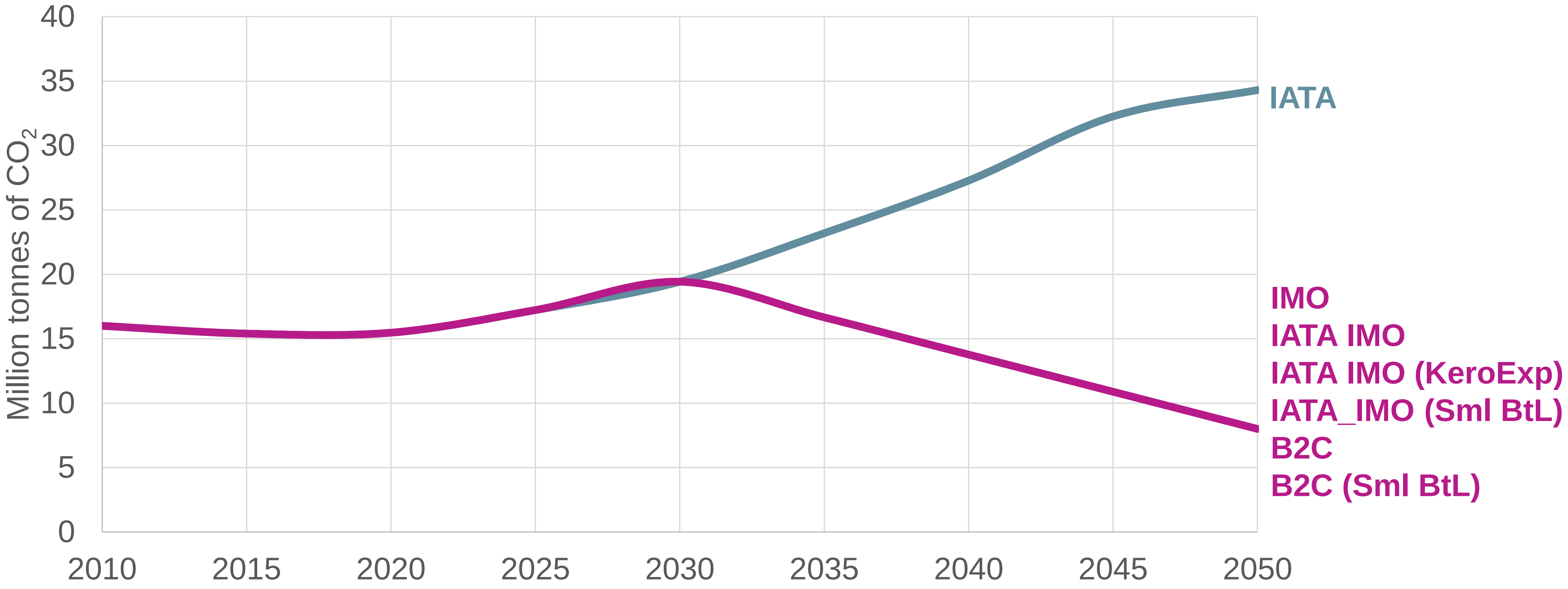
Source: Daioglou et al. (2020)

International aviation CO_2 emissions*



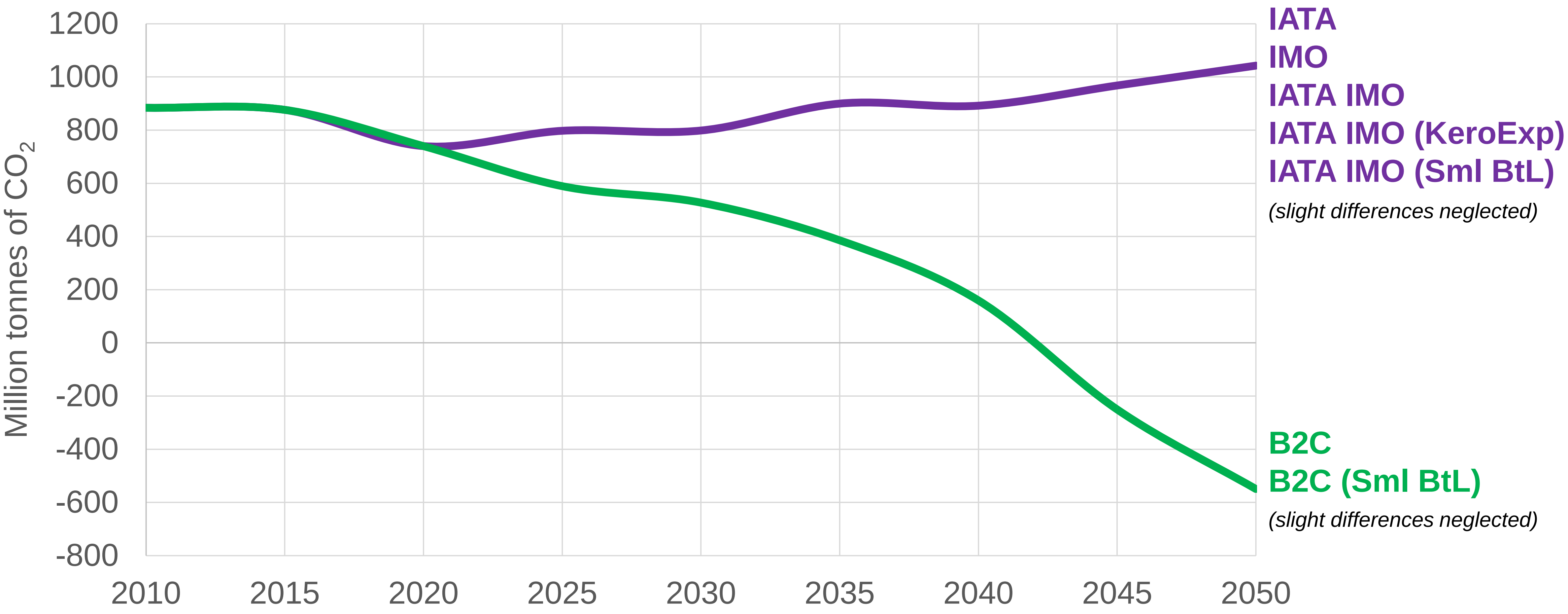
* International emissions associated with the Brazilian fuel supply (not total international aviation emissions)

International shipping CO_2 emissions*



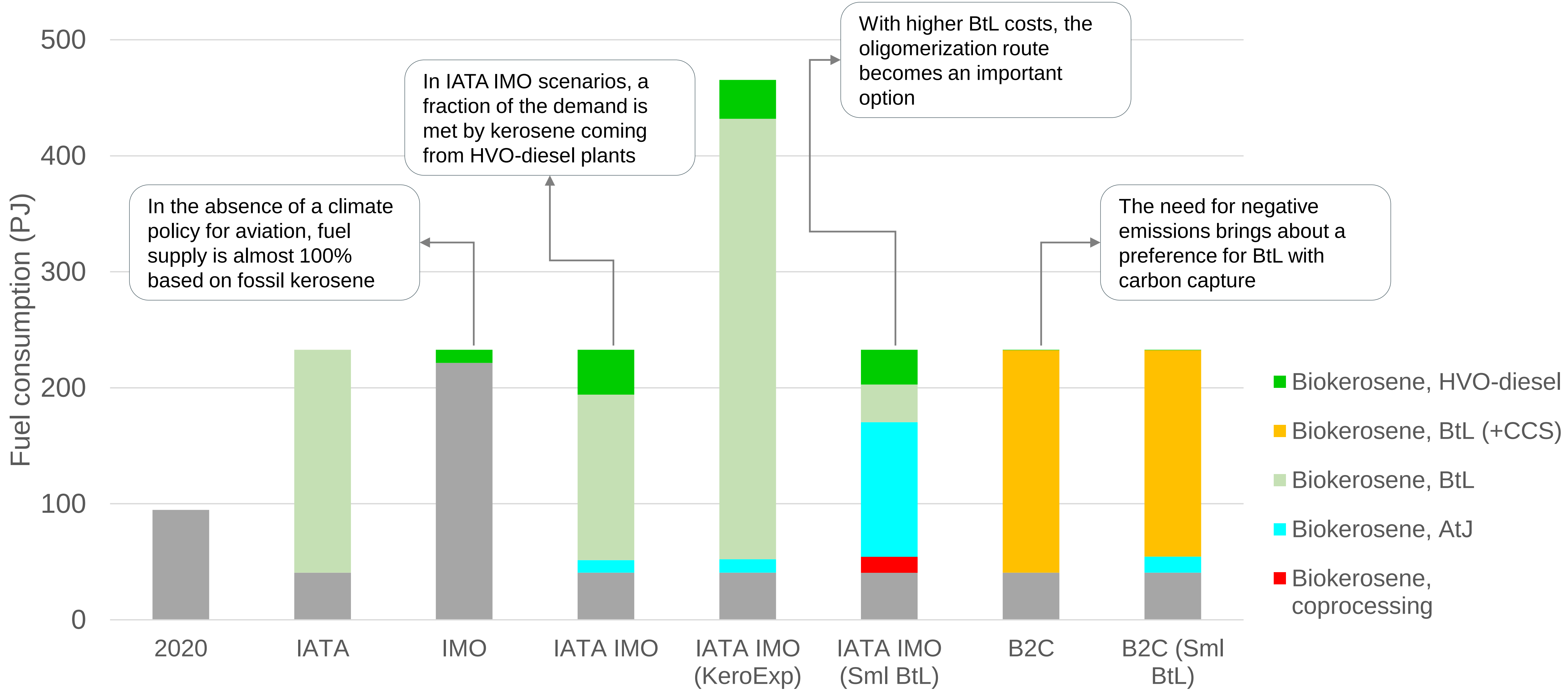
* International emissions associated with the Brazilian fuel supply (not total international shipping emissions)

Brazilian CO_2 emissions*

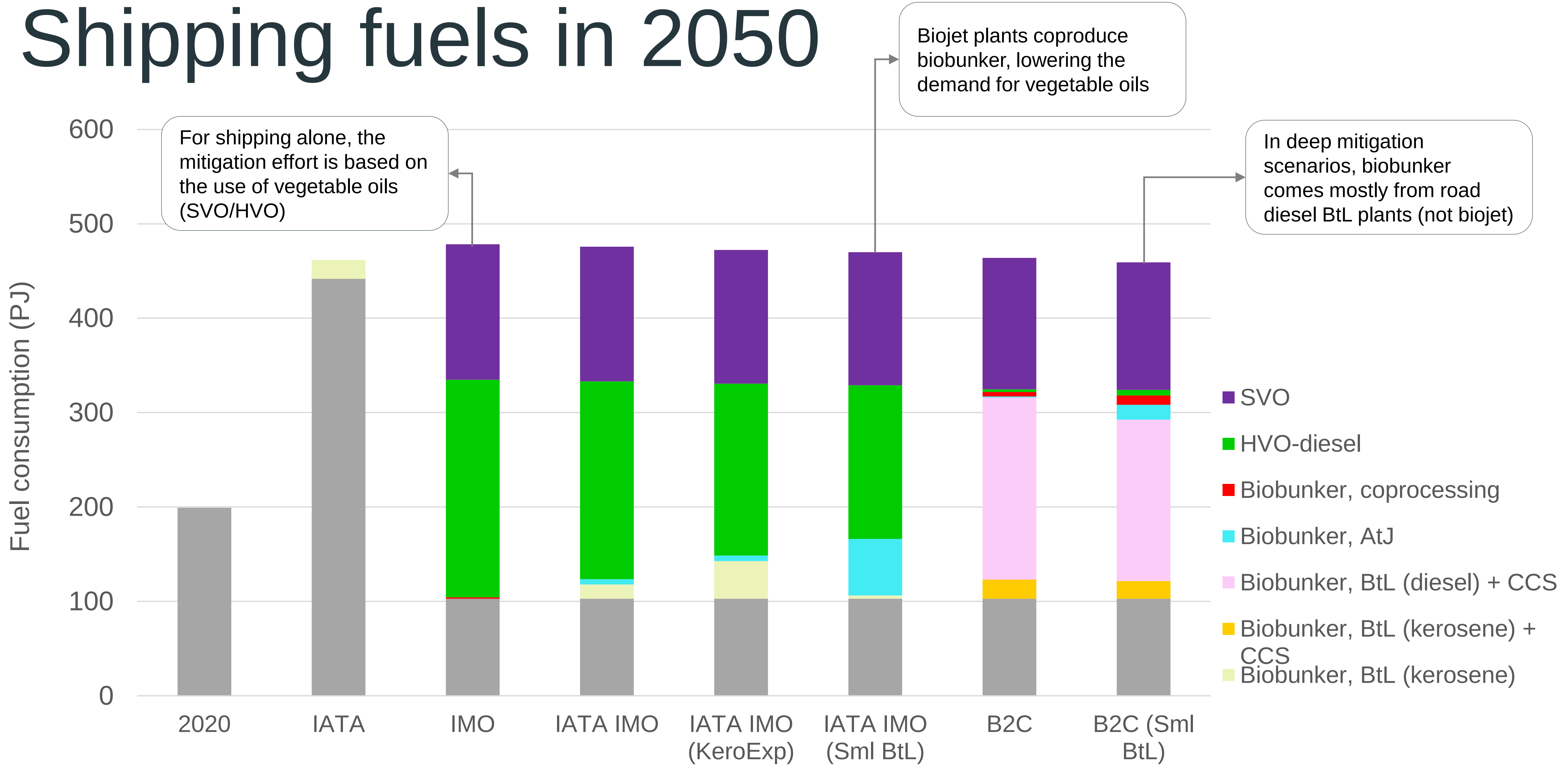


* Does not include the emissions shown in the two previous graphs (which are international)

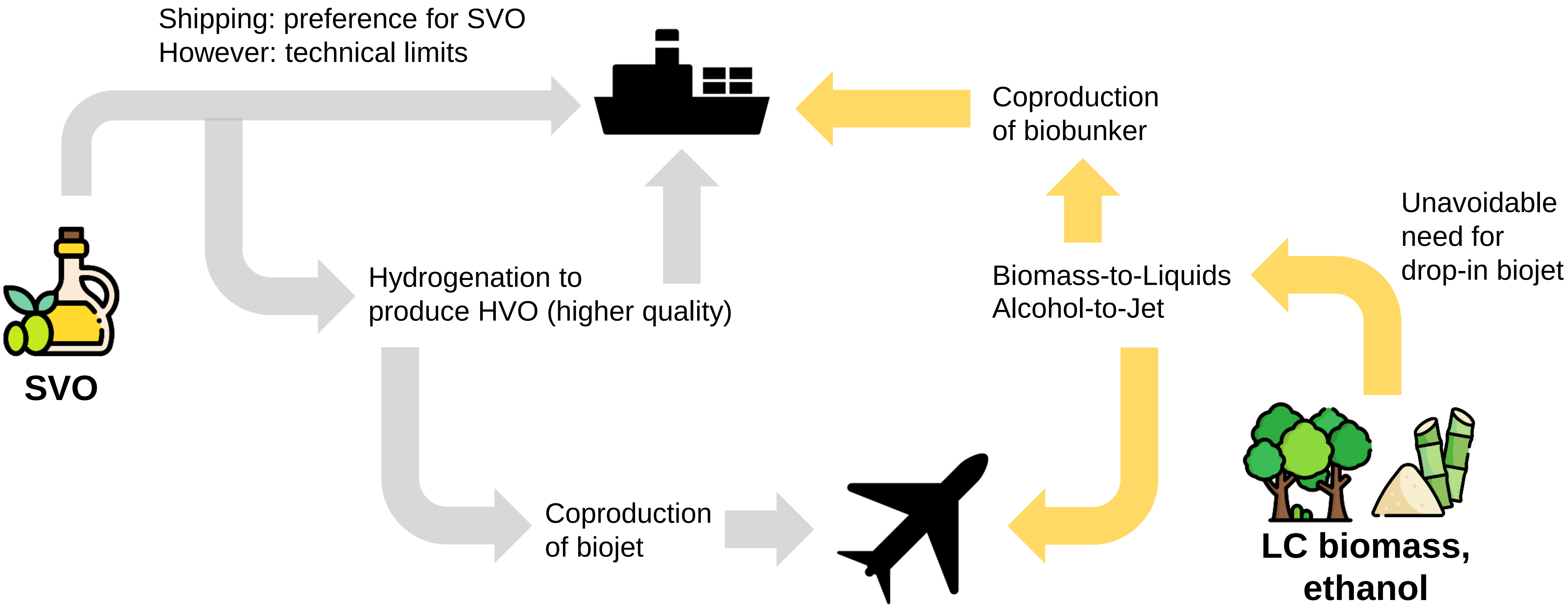
Aviation fuels in 2050



Shipping fuels in 2050



Is there a synergy between sectors?



However, the difference in the size of the two sectors does not allow a full-scale synergy → B2C scenarios: shipping fuels mostly associated with road diesel plants

Icons: Freepik/flaticon

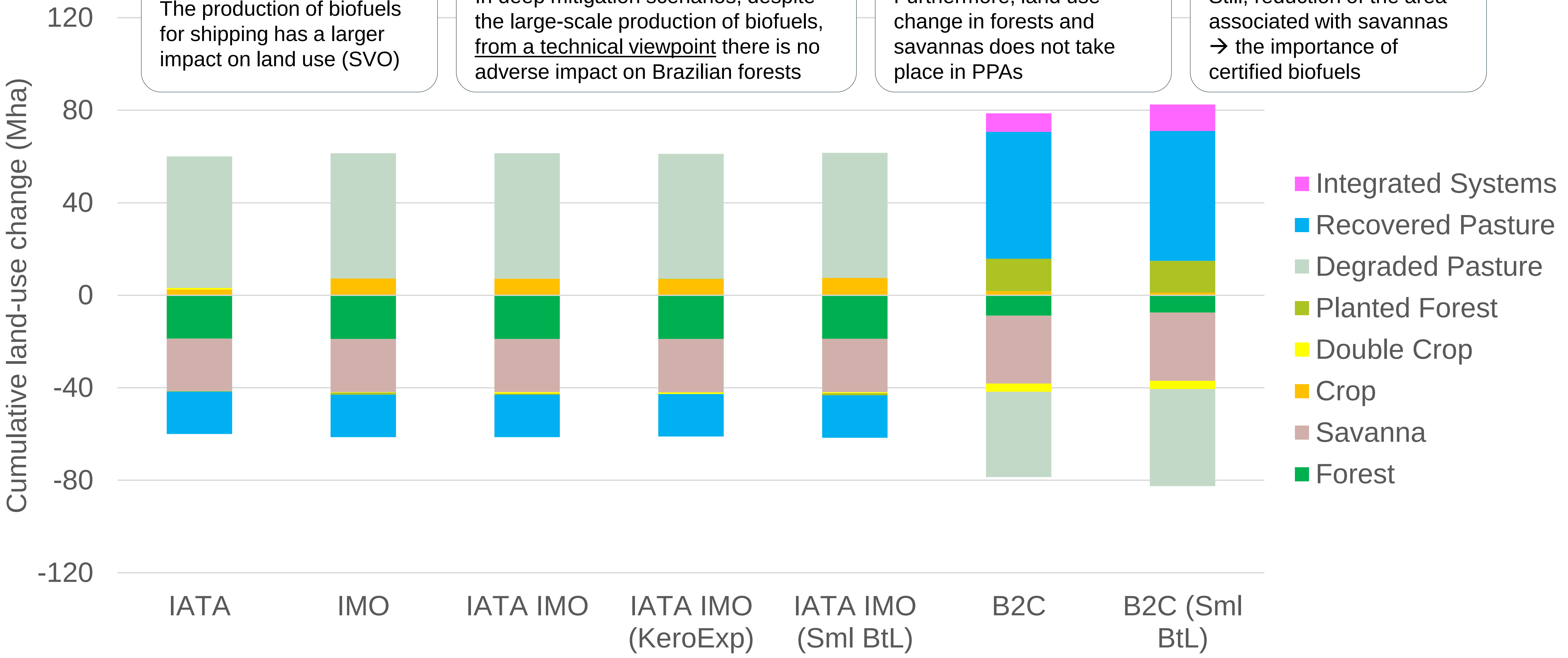
Changes in land use dynamics

The production of biofuels for shipping has a larger impact on land use (SVO)

In deep mitigation scenarios, despite the large-scale production of biofuels, from a technical viewpoint there is no adverse impact on Brazilian forests

Furthermore, land use change in forests and savannas does not take place in PPAs

Still, reduction of the area associated with savannas → the importance of certified biofuels



Concluding remarks (1/2)

- **Fuel switch** is key to mitigate GHG emissions in industry, aviation and shipping sectors
- In the case of **industry H2 is probably the way to go,** but it is not the only option
- From an IAM perspective, **drop-in biofuels** are the most promising alternatives for both aviation an shipping
- Brazil: shipping >> aviation (in 2020: 200 PJ versus 100 PJ)
- As such a **synergy** between these two sectors is **somehow limited**
- This synergy would probably be greater **if the opposite were true** (premium fuel demand >> residual fuel demand)
- Still a **certain degree of synergy** can be observed

Concluding remarks (2/2)

- **BtL** and **AtJ** kerosene plants produce significant amounts of bunker fuels
- Interestingly, **HVO-diesel** plants built to fuel the marine sector coproduce kerosene
- National climate policy → need for **negative emissions**
- Therefore, large amounts of **BECCS** – biojet plants, but especially **biobased road diesel** plants
- In these scenarios, biobunker stands out as a **major byproduct**
- The BtL sensitivity analysis is particularly important: the **uncertainties** associated with the **gasification + Fischer-Tropsch route** can give room to other production routes (e.g., AtJ)
- In sum, **there is no silver bullet for HtA sectors** in the short to medium term though
- **Different** niche markets do exist for different geographies, sectors and realities

Thanks

Roberto Schaeffer, Eduardo Müller-Casseres and Marianne Zotin

roberto@ppe.ufrj.br

cenergia