

Opportunities and challenges for aviation e-fuels

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A multi-disciplinary research centre dedicated to advancing knowledge in Process Systems Engineering

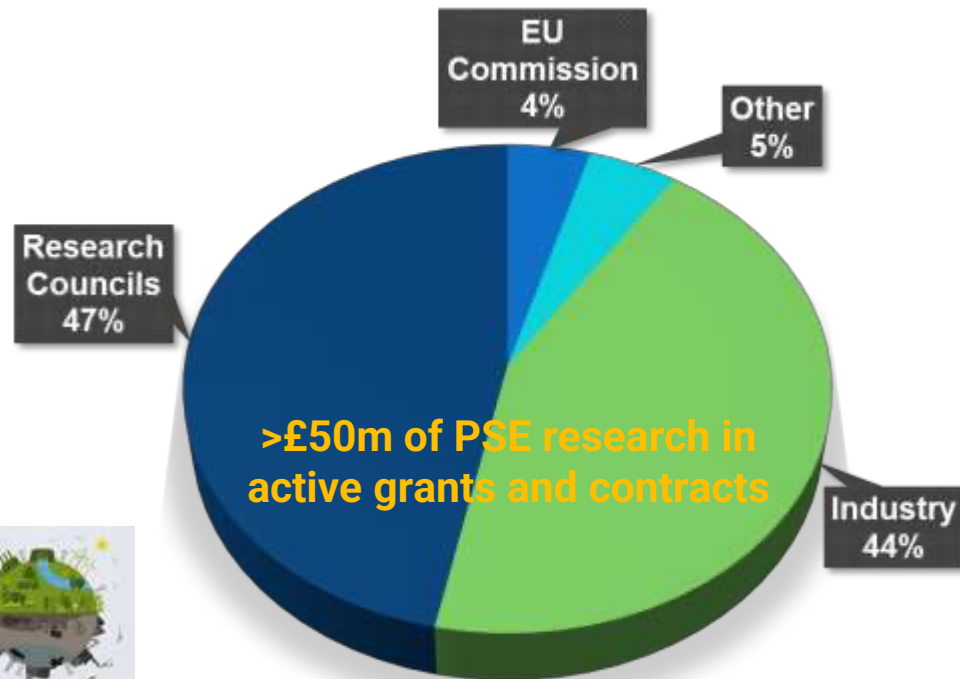
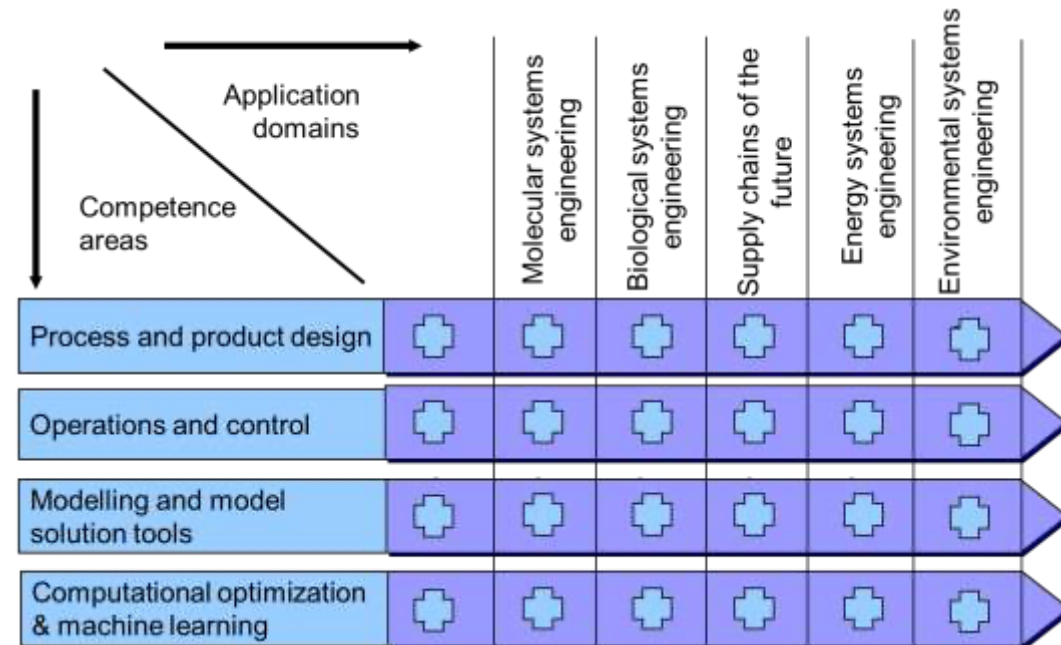
→ Manage and exploit complexity

→ Make an impact on industrial practice

Imperial College
London

UCL

10 departments 40 academics
>50 RAs >170 PhD students
>110 publications annually

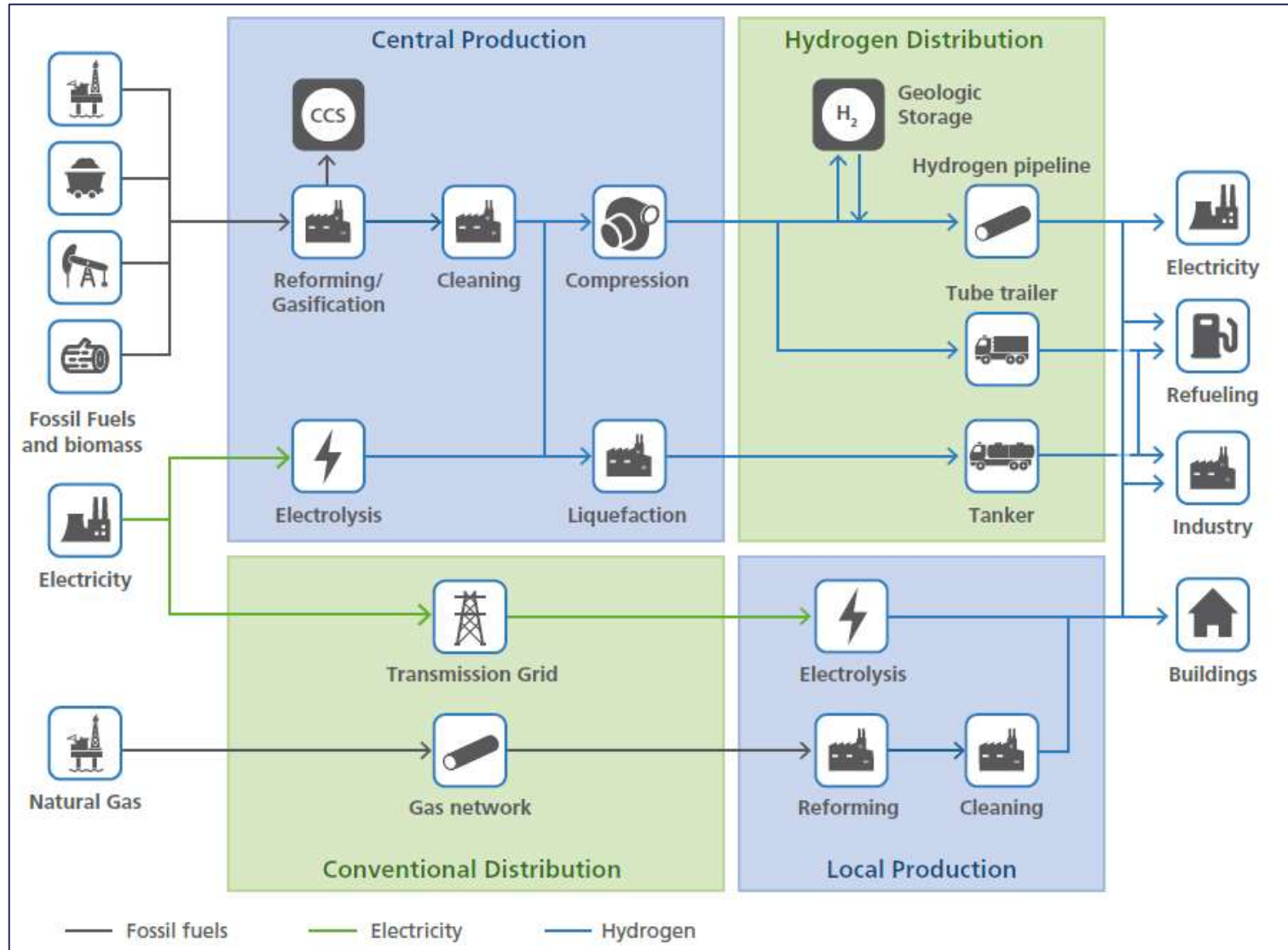


Check our latest activity report: [Link](#)

Hydrogen systems - context

- 3 “waves” of interest in hydrogen
- 1970s – oil shock
- 1990s – climate change, advances in electrochemical technology
- 2020s and beyond – low carbon systems thinking and net zero
 - Hydrogen is an effective point source solution for many problems
 - But not always the single best (e.g. heat pumps, battery vehicles, biofuels)
 - Better to think of it as “middleware”
 - Deployment needs a systems approach
 - Hydrogen benefits felt at scale
- Where do we go from here?
- My personal interests – energy systems engineering

Systems view



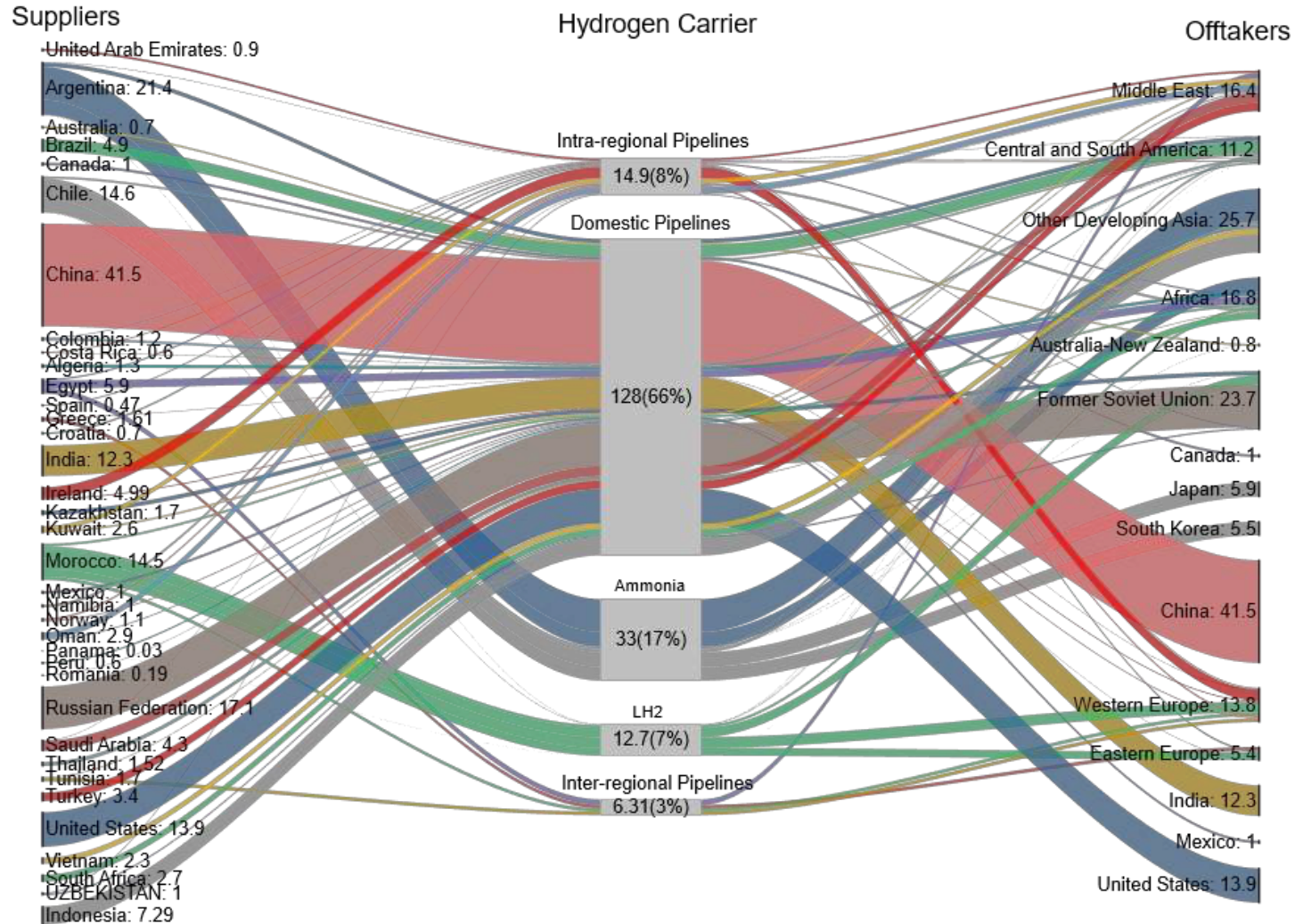
Future low carbon systems need **low carbon energy vectors**:

- Electricity
- Hydrogen
- Biofuels
- Synthetic fuels

Different regions will have different proportions...

New service: negative emissions

Systems modelling example: global hydrogen trade model

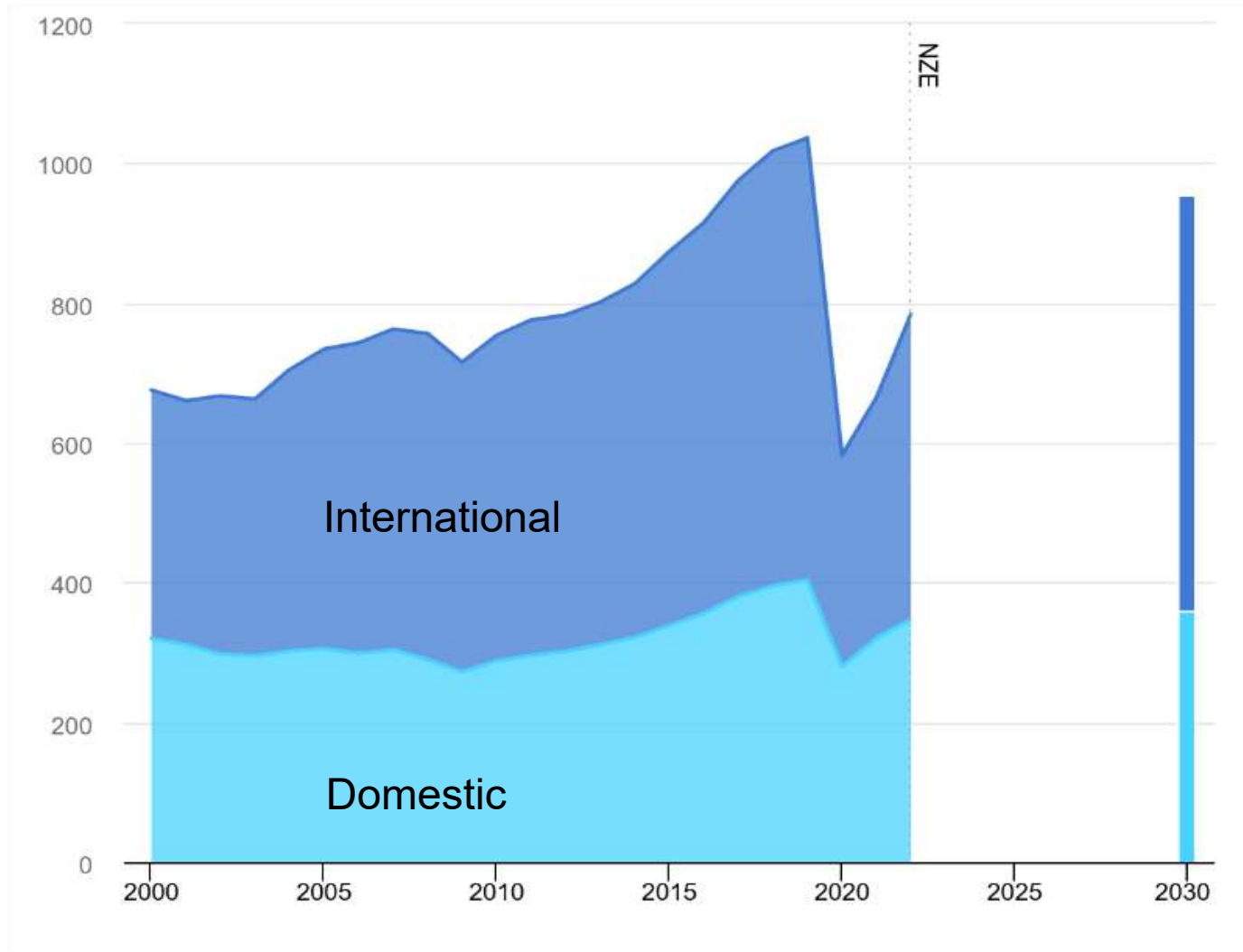


Hydrogen – potential roles in the future energy/industrial system

- Industrial feedstock and reductant
 - Existing and new processes (iron, synthetic fuels, ...)
- Industrial heating
- Low carbon power generation/CHP
- Transport
 - Heavier duty/longer range vehicles, trains, marine, aviation
- Energy storage and renewables integration/cost reduction
- Long distance low-carbon energy transport
- ...

Challenging environment for projects: offtake constrained?

The need for emissions reduction in aviation



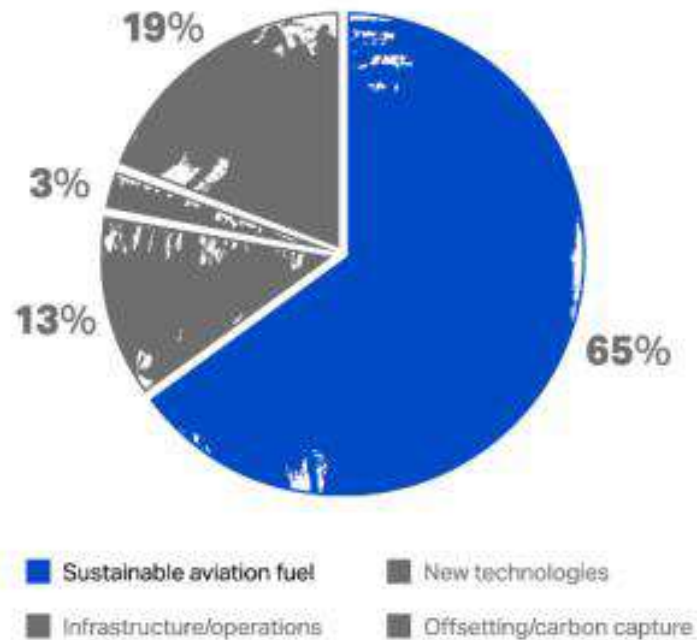
**CO2 emissions in aviation
in the Net Zero Scenario,
2000-2030, in million tons
per year**

Source: IEA (2023)

<https://www.iea.org/data-and-statistics/charts/co2-emissions-in-aviation-in-the-net-zero-scenario-2000-2030>

How to achieve net zero aviation

Contribution to achieving Net Zero Carbon in 2050



Expected SAF required for Net Zero 2050

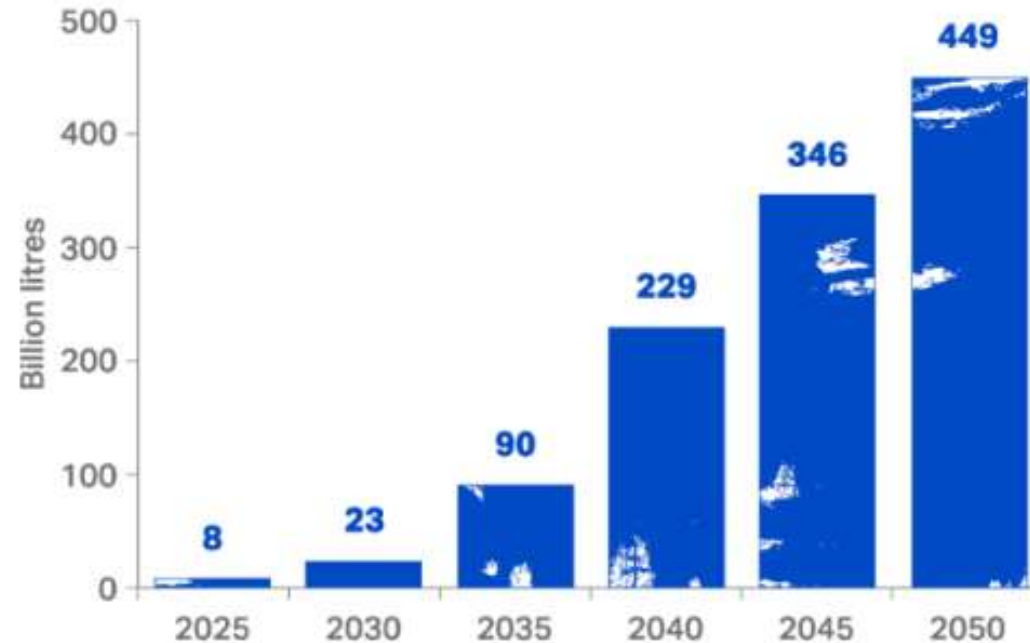
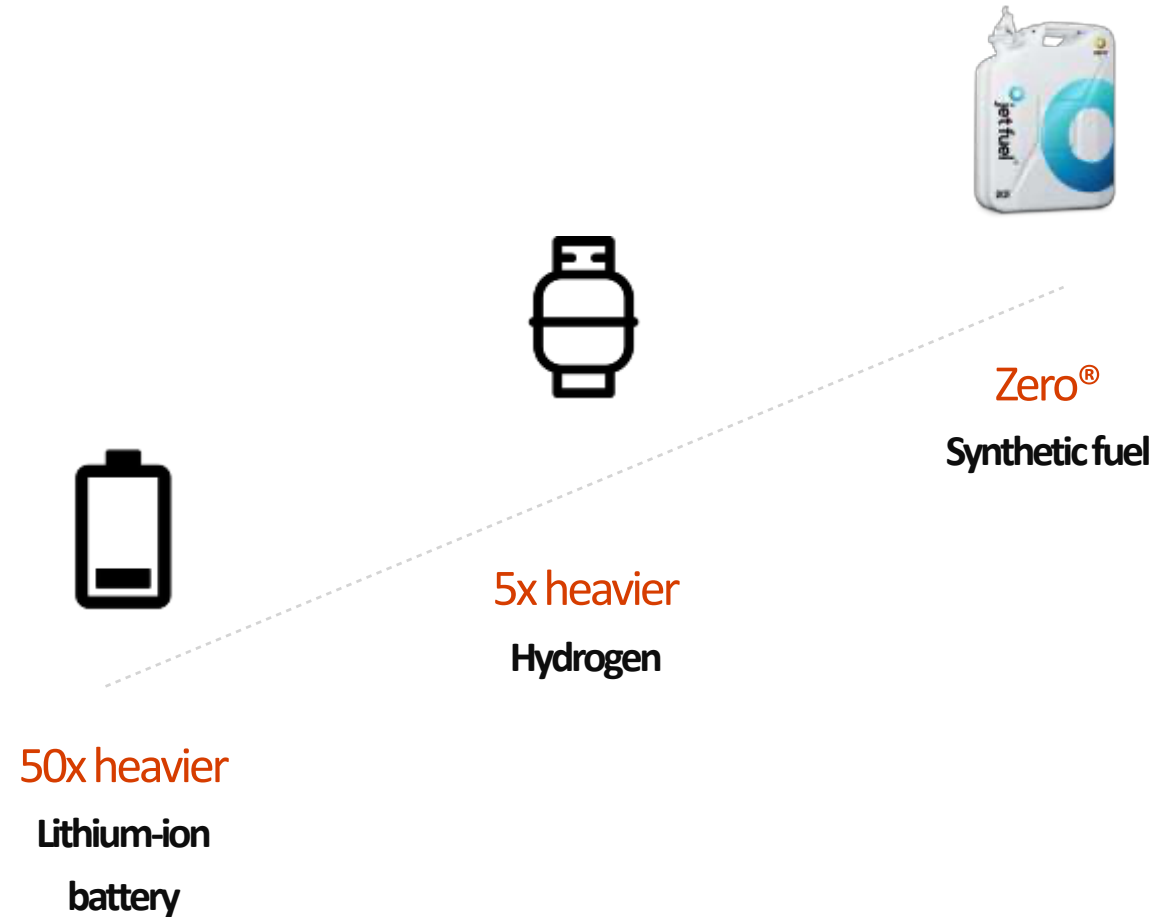


Figure 2 & 3: SAF contribution to achieving Net Zero Carbon in 2050

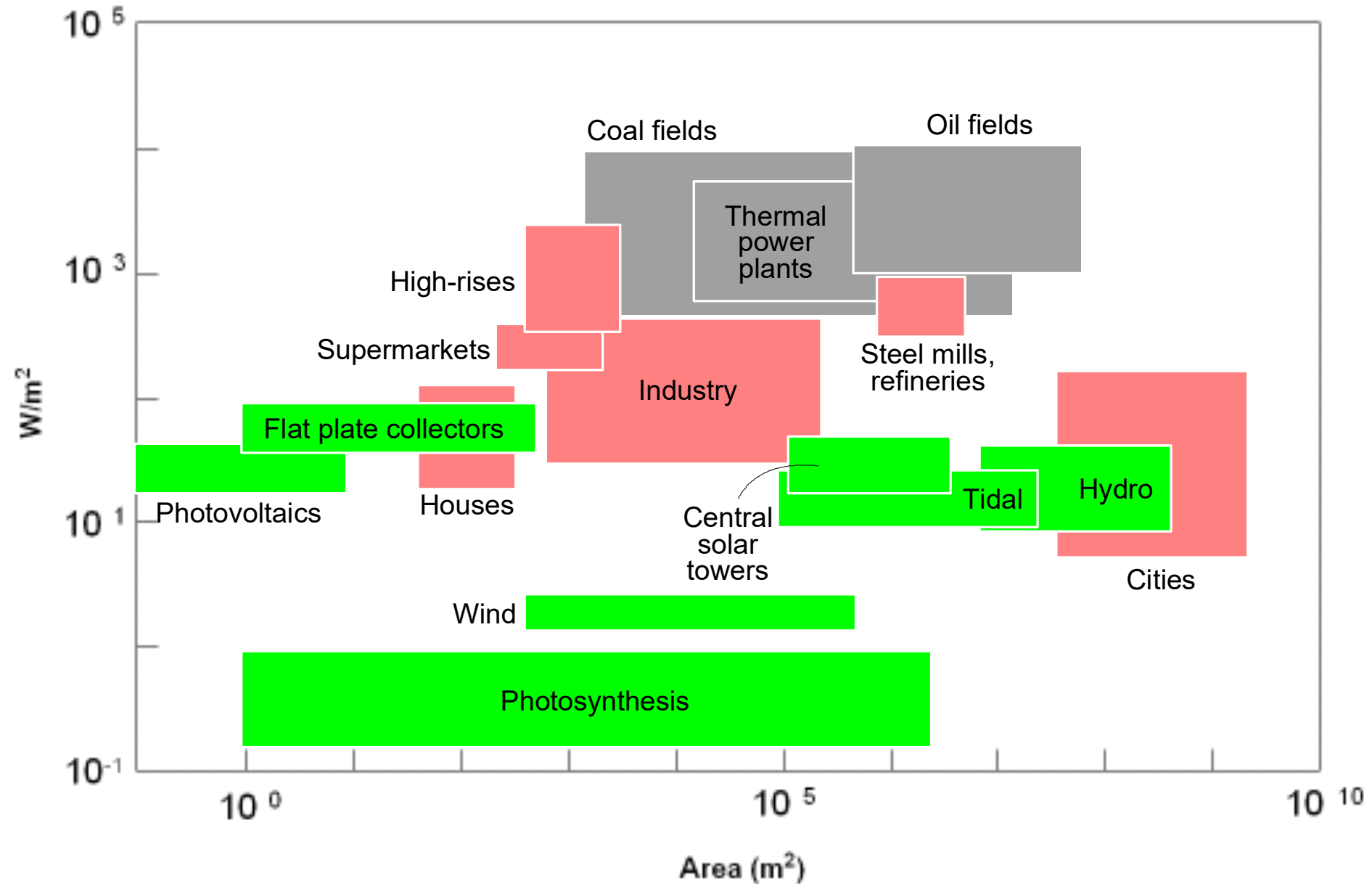
Source: IATA (2024) <https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---alternative-fuels>

Why hydrocarbon aviation fuels?

liquid fuel is lightweight
and requires less energy
to transport

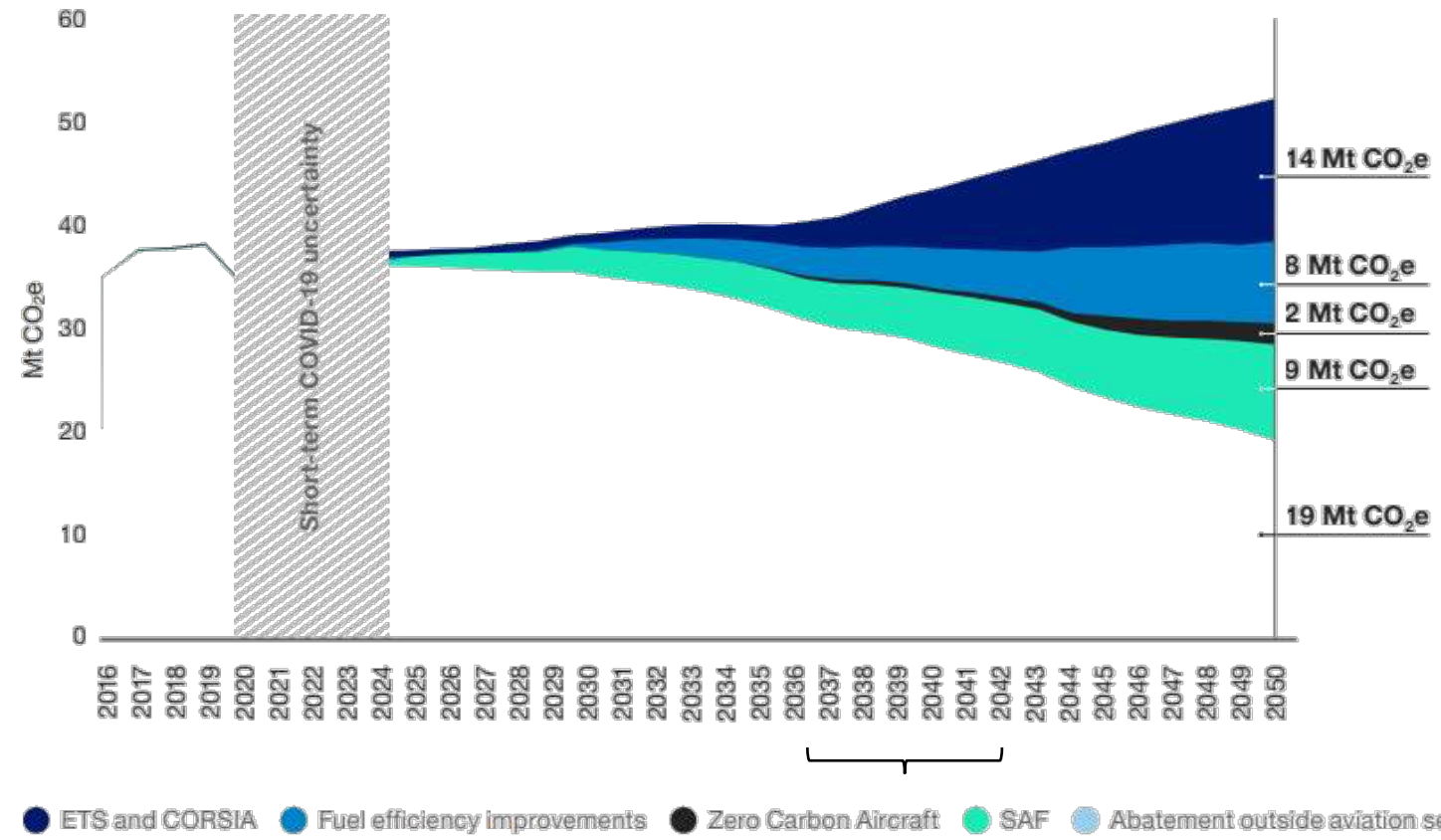


The energy density challenge

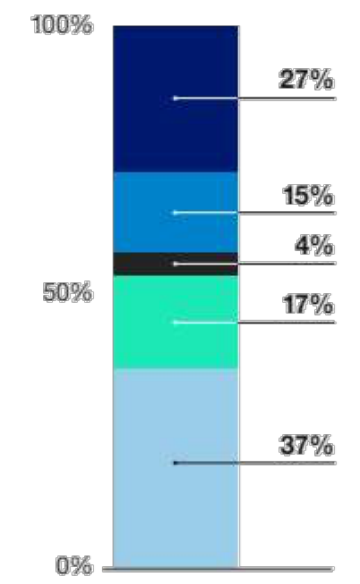


UK Jet Zero Strategy: Possible abatement measures

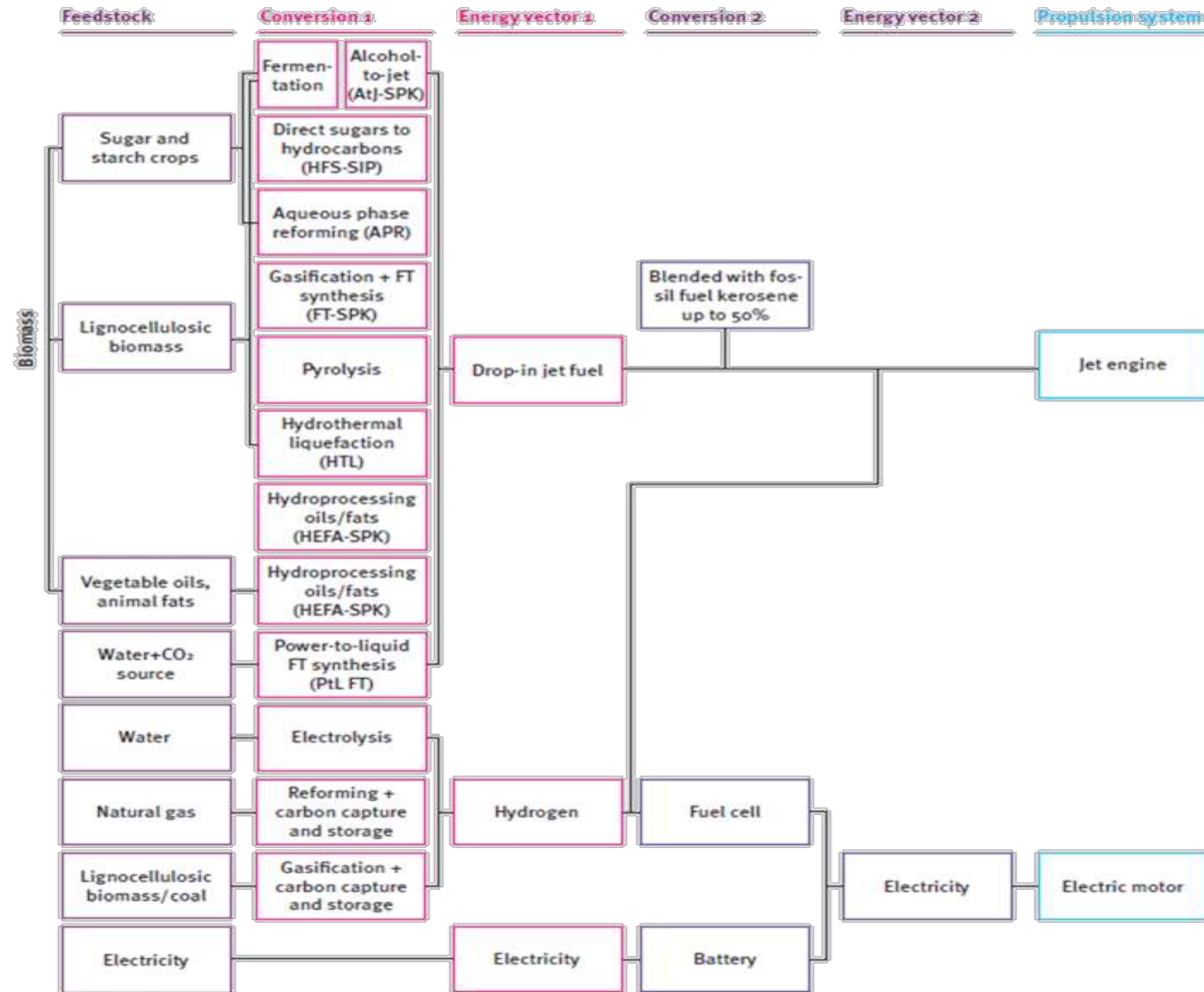
Our High Ambition Scenario



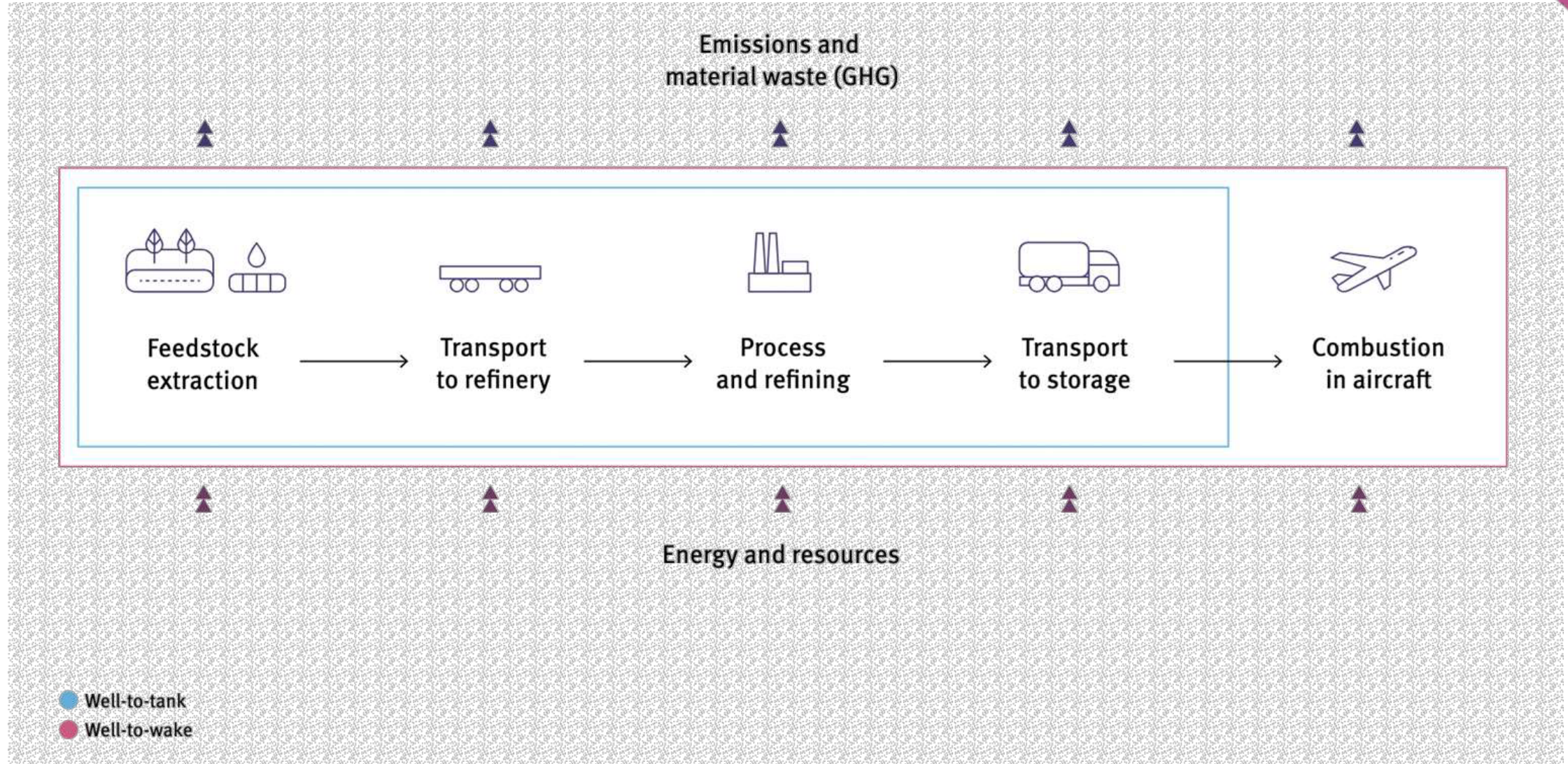
% abatement from each measure in 2050



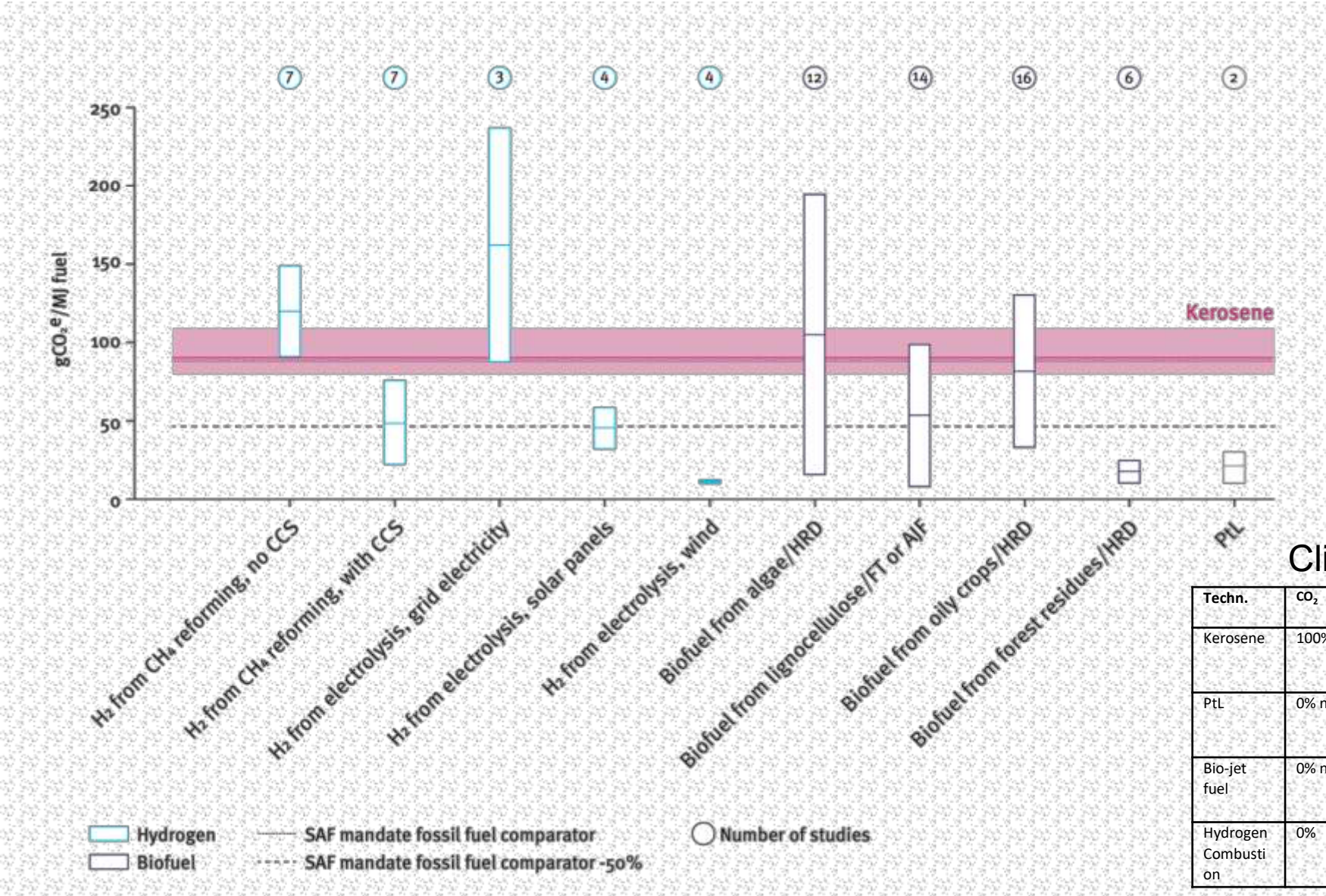
Low-carbon fuels and their production pathways:



Modelling # 1: Assessing the environmental impact



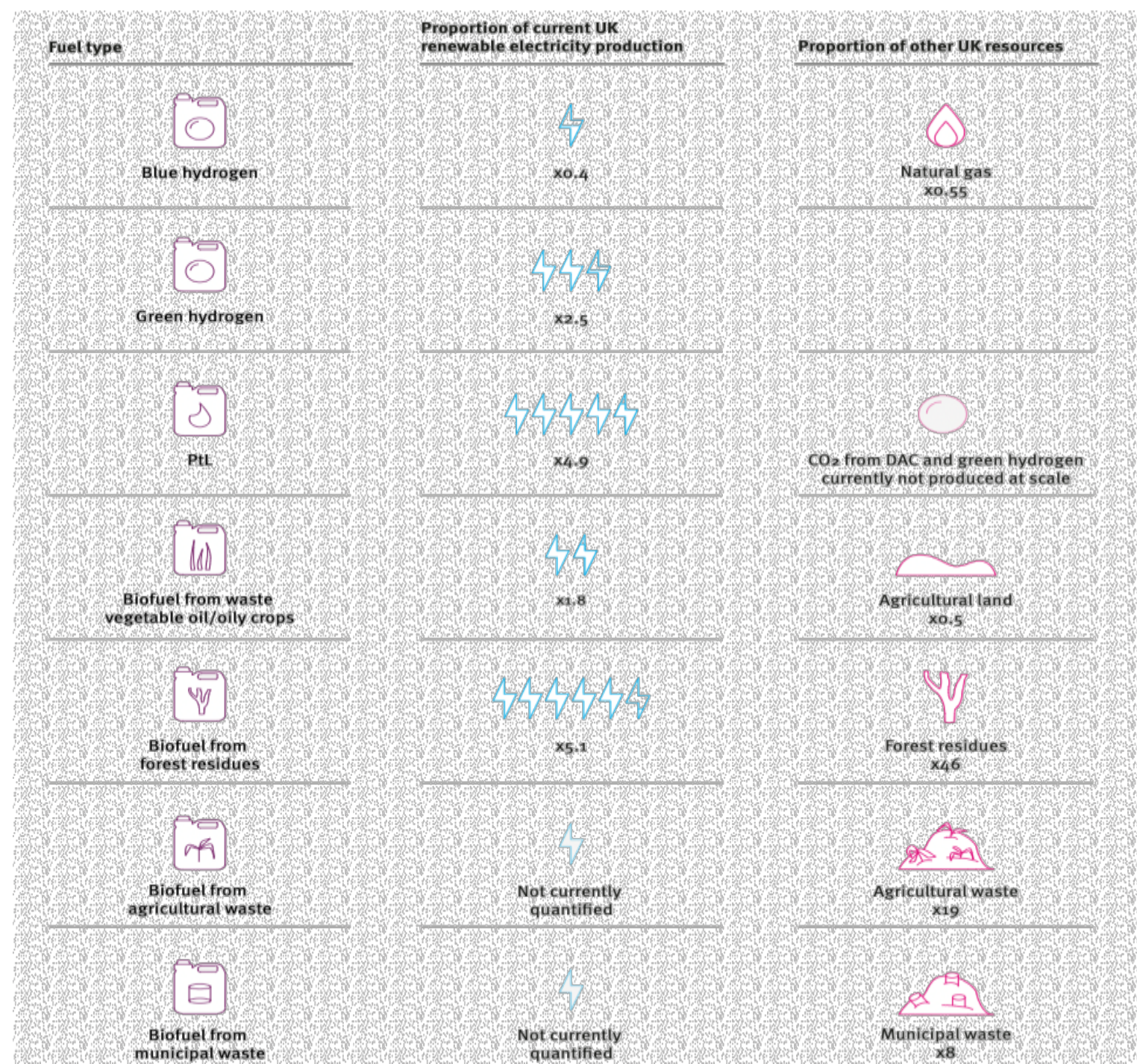
Assessing the environmental impact



Climate impacts breakdown

Techn.	CO ₂	NO _x	Water vapour	Contrails	Total
Kerosene	100%	100%	10%	100%	310% (range 205-415%) (ii)
PtL	0% net (iii)	100%	10%	75-100% (iv)	185-210%
Bio-jet fuel	0% net (v)	100%	10%	75-100%	185-210%
Hydrogen Combustion	0%	35%	25%	60%	120% (range 85-300%)

Resource demand and scale-up



Bio-based jet fuels

- IEA estimates 20% of demand by 2040 (currently ~0.01%) – seems optimistic
- Despite all the pathways, nearly all current fuel is hydroprocessed oil and fats (waste and virgin) and esters.
- Longer-term, we anticipate non oil-based pathways will dominate bio-based:
 - Gasification + FT (cf. several projects worldwide underway)
 - Alcohol to jet (building on 1G and 2G ethanol)
- Current bio-fuels do not fully conform to DEF STAN 91-091 due to e.g. lack of cycloalkanes and aromatics
- GHG emissions need to be tracked carefully
- New concept of “low-ILUC” crop rotations (e.g. production of Brassica as green cover rotation)

E-fuels - context

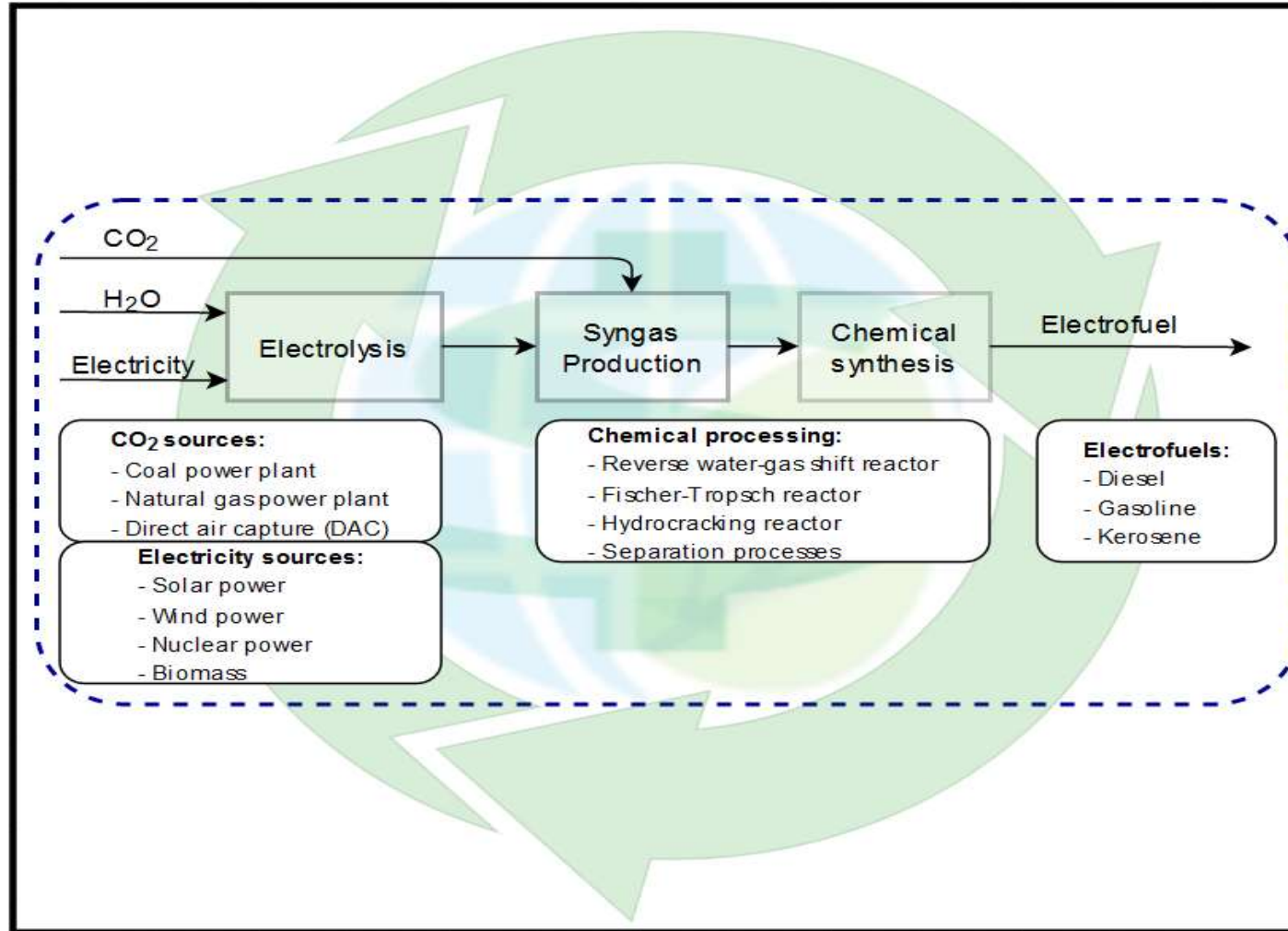
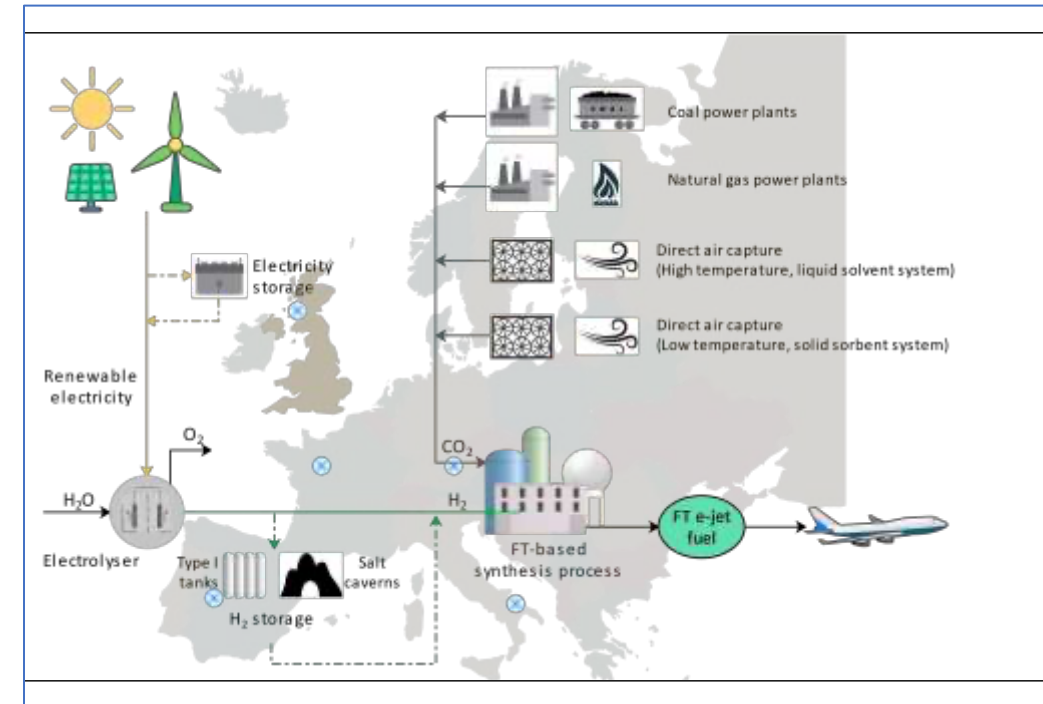
- In 2014:
 - Medium- and heavy-duty trucks with mean trip distances of >160 km:
 - Accounted for ~270 Mt CO₂ emissions ≈ 0.8% of global CO₂ emissions
 - Long trips in light-duty vehicles
 - accounted for an additional 40 Mt CO₂,
 - Aviation and other shipping modes (such as trains and ships)
 - emitted 830 and 1060 MtCO₂, respectively.
 - Altogether:
 - ~6% of global CO₂ emissions
- Aviation:
 - Difficult-to-decarbonize sector
 - Fuel energy density required
 - Refueling time

E-fuels categories

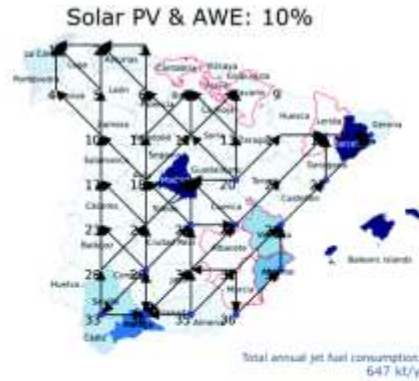
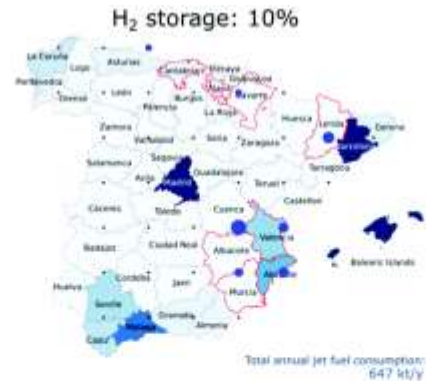
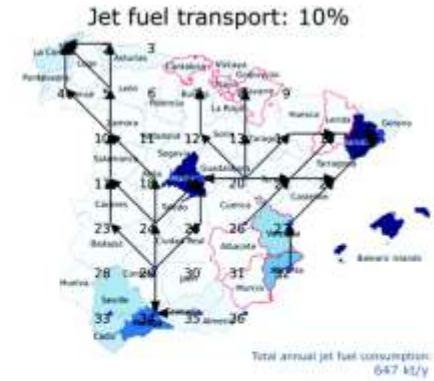
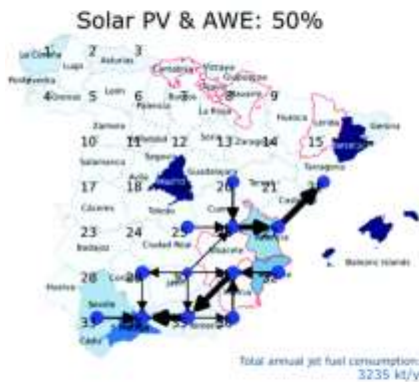
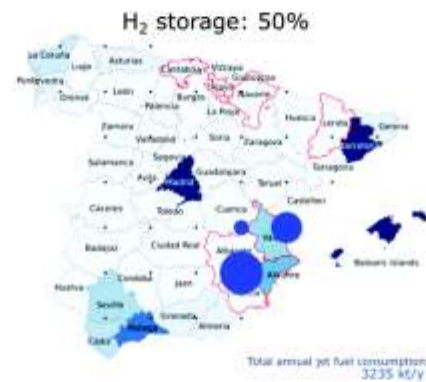
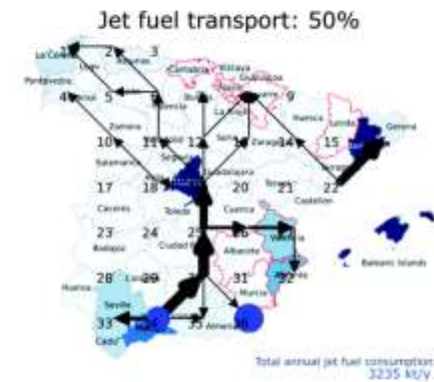
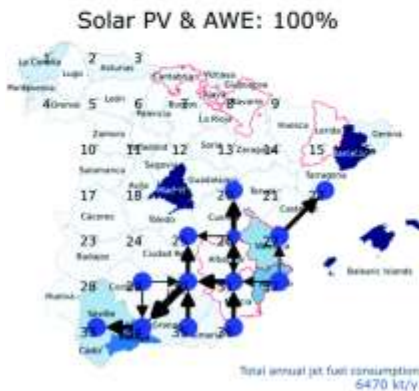
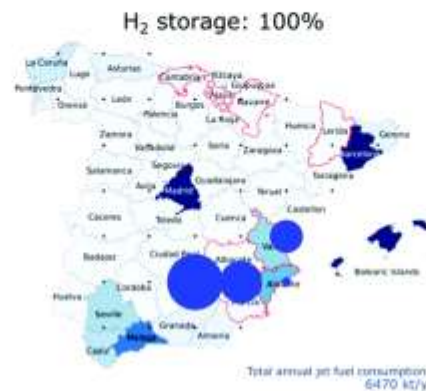
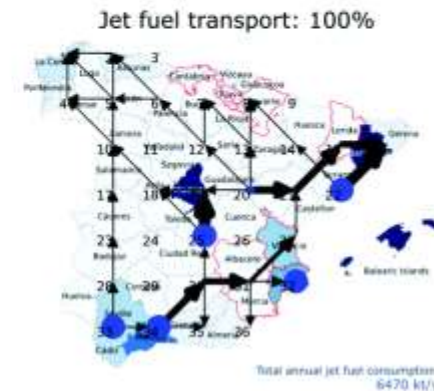
Feedstock	Syngas preparation	Syngas composition	1 st conversion step	Intermediate	2 nd conversion step (refining)	Product
CO ₂ + H ₂ O	Co-electrolysis	CO/H ₂	FT synthesis	Hydrocarbons	Hydrocracking	e-SAF
CO ₂ + H ₂	RWGS					
	Partial RWGS	CO/CO ₂ /H ₂	Fermentation	Ethanol	ETJ	
			Direct catalytic synthesis	Methanol	MTJ	

Source: *Source: ERM study for the New Energies Coalition (2023)*

Modelling #2: Techno-economic assessment



Modelling #4: Supply chain optimisation



Putting it all together: Levelised costs

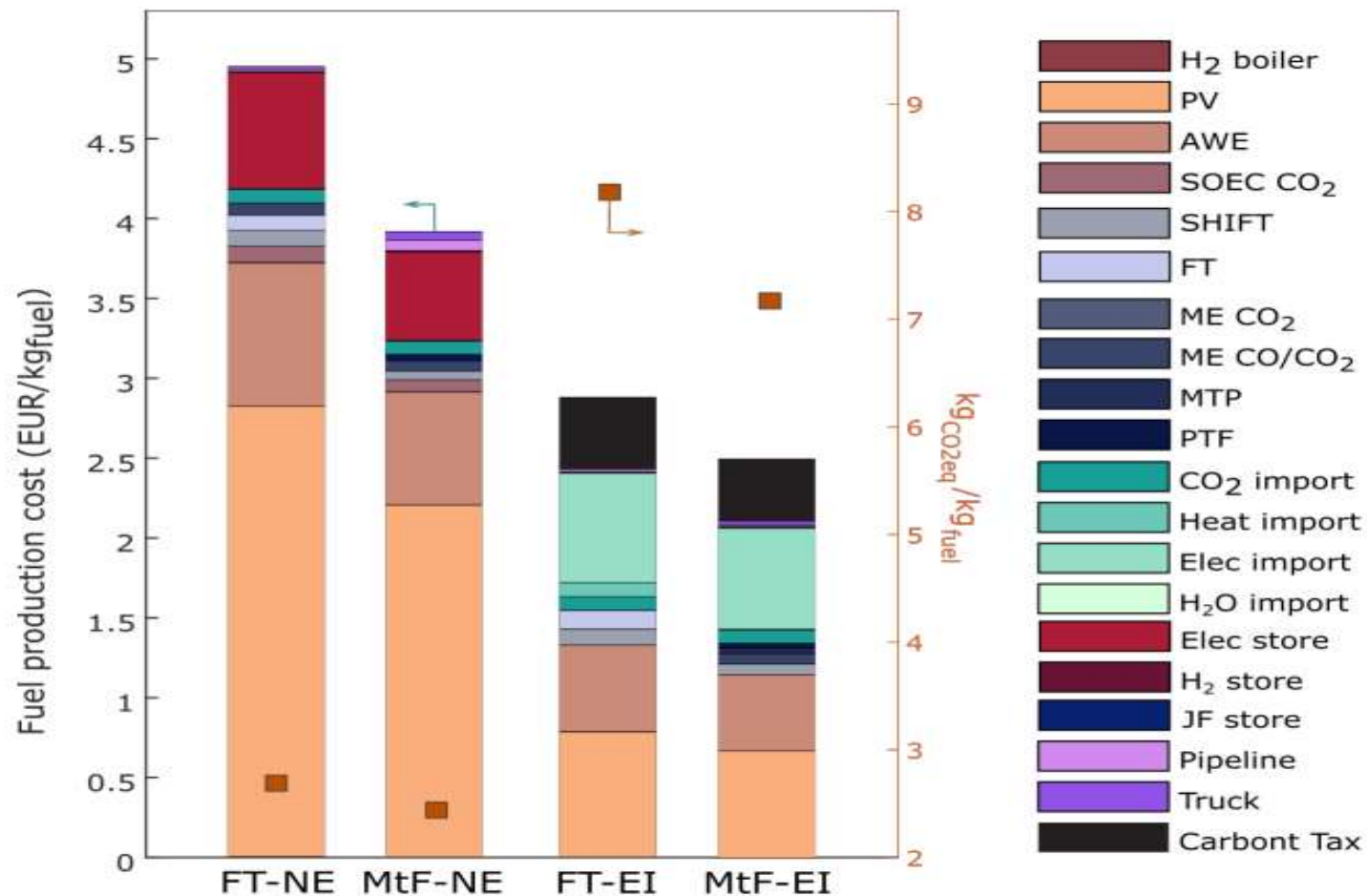
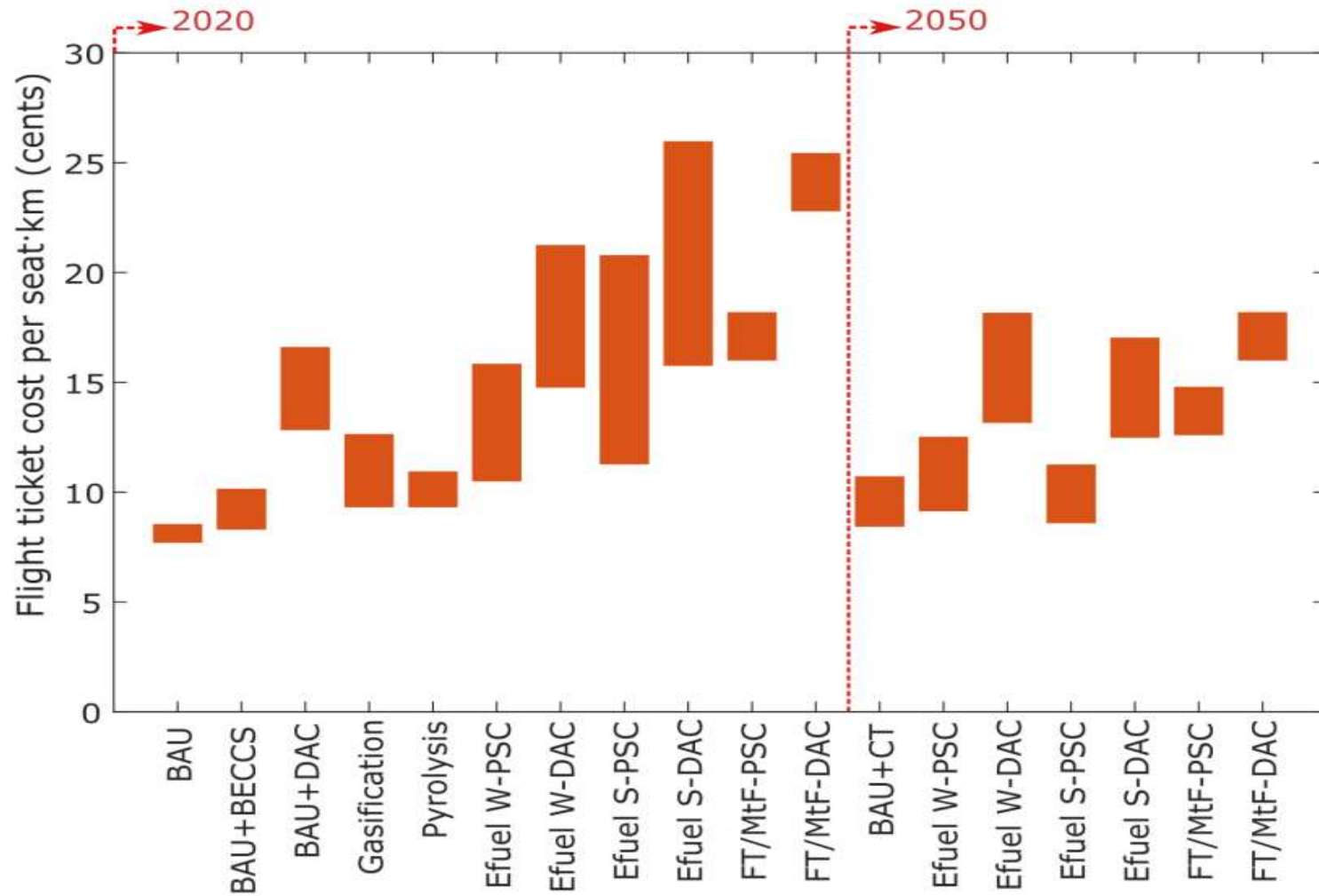


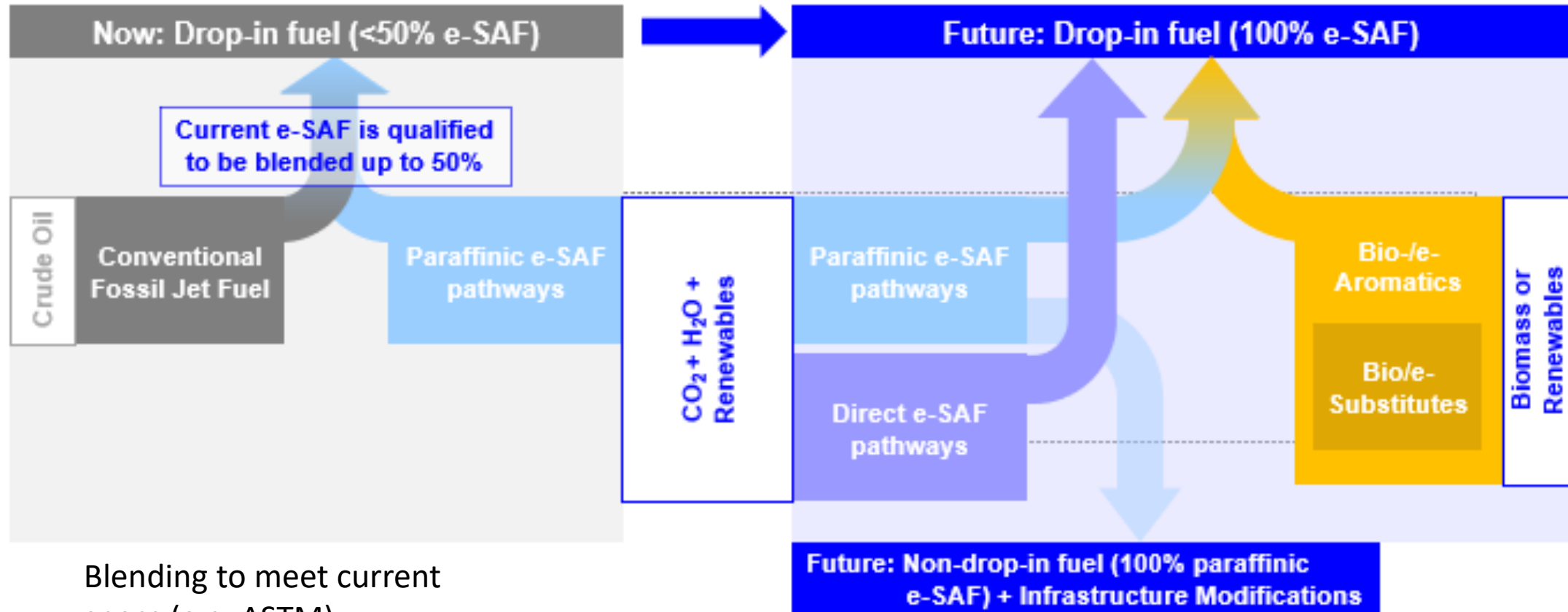
Fig. 7 Production costs and lifecycle CO₂ emissions for the production of jet fuel from solar energy. FT: Fischer-Tropsch; MtF: Methanol to fuels; NE: No import of energy to the network; EI: Energy import allowed (natural gas and electricity from the grid)

Effect on flight ticket cost



13 Total cost of flight ticket per available seat km.

E-fuels – near term and long-term



Blending to meet current specs (e.g. ASTM)

Pathways to meet specifications without fossil jet

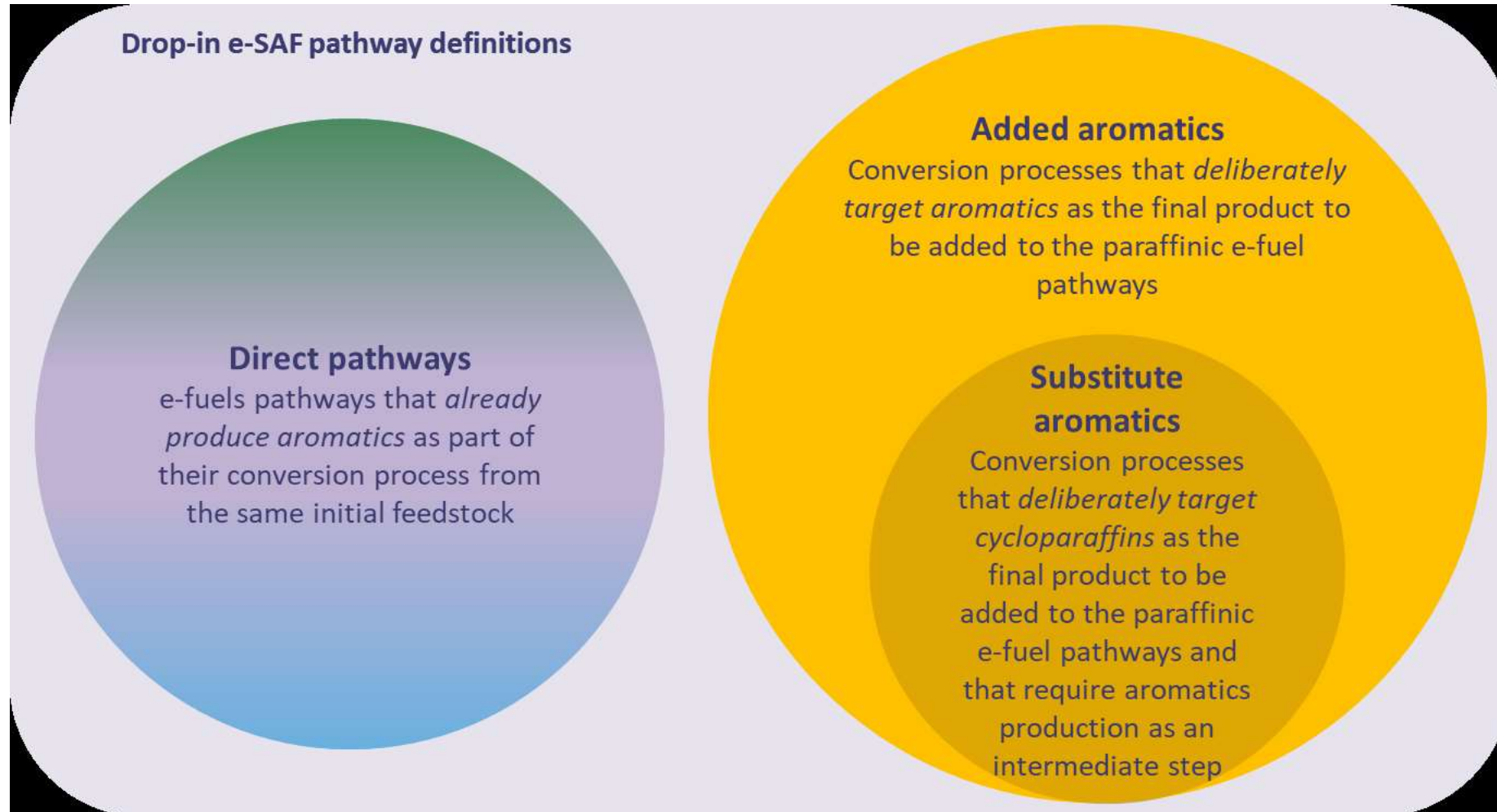
Properties and certification

- Jet A fuel must reach ASTM specification D1655
- Jet A-1 fuel must meet:
 - DEF STAN 91-91 (Jet A-1),
 - ASTM specification D1655 (Jet A-1), and
 - IATA Guidance Material (Kerosene Type), NATO Code F-35.

Typical physical properties for Jet A / Jet A-1^[11]

	Jet A-1	Jet A
Flash point	38 °C (100 °F)	
Autoignition temperature	210 °C (410 °F) ^[9]	
Freezing point	-47 °C (-53 °F)	-40 °C (-40 °F)
Max adiabatic burn temperature	2,230 °C (4,050 °F) open air burn temperature: 1,030 °C (1,890 °F) ^{[12][13][14]}	
Density at 15 °C (59 °F)	0.804 kg/L (6.71 lb/US gal)	0.820 kg/L (6.84 lb/US gal)
Specific energy	43.15 MJ/kg (11.99 kWh/kg)	43.02 MJ/kg (11.95 kWh/kg)
Energy density	34.7 MJ/L (9.6 kWh/L) ^[15]	35.3 MJ/L (9.8 kWh/L)

Two routes to 100% drop in



Routes to 100% drop-in: status

e-fuel category		TRL / Level of activity	Feedstock constraints	ASTM Qualification status
		<ul style="list-style-type: none"> ○ TRL 8-9 and high activity ○ TRL 5-7 and mid activity ○ TRL 1-4 and low activity 	<ul style="list-style-type: none"> ○ Low constraints ○ Medium constraints ○ High constraints 	<ul style="list-style-type: none"> ○ Many qualified ○ Few qualified/ in progress ○ None qualified
Drop-in	Direct pathways	TRL5-6: still at a relatively early stage, with some developers pursuing this space. Projected rate of supply ramp up is expected to be slower.	Do not rely on external feedstocks to obtain aromatic content. Depend on CO ₂ and renewable electricity availability.	One ASTM qualified pathway (ATJ-SKA) but limited to <50% blend, others in the process of obtaining qualification
	Paraffinic pathways + Added aromatics (A) or substitutes (S)	<p>(A) Could utilize technologies present in existing refineries (e.g. CNRs) with feedstock from mature (e.g. HEFA) or maturing (Gasification + FT) routes</p> <p>(S) Currently, all pilot/demo stage routes to cycloparaffins have aromatic intermediate products, whilst routes without prior aromatic hydrotreatment are at R&D/lab scale. There still remains significant uncertainty over level of cycloparaffins needed to replace aromatics for seal swelling as well.</p>	<p>Aromatics & Substitutes</p> <p>Rely on obtaining feedstocks (e.g. bio or e-naphtha, 2G bioethanol) from other low carbon fuel pathways, which might imply competition for feedstock (and bio-SAF pathways may also need aromatics)</p>	<p>Aromatics & Substitutes</p> <p>One 50% ASTM qualified pathway (CHJ), several others in the process of certification</p> <p>Paraffinic components</p> <p>Multiple ASTM qualified pathways (max 50%)</p>
Non drop-in	Paraffinic (SPK) fuels	<p>Paraffinic components</p> <p>Similar TRL to Direct pathways (5-6), but higher level of developer activity</p>	<p>Paraffinic components</p> <p>Same as for Direct pathways</p>	100% paraffinic fuels: (due to non drop in nature)

Figure 14: Overview of e-fuels categories: Technology readiness, Feedstock constraints and ASTM Qualifications status.

Source: ERM study for the New Energies Coalition (2023)

100% drop-in – costs/GHG/...

All e-SAF are expected to have similar costs and GHG reduction potential, but the direct pathways will have an advantage in terms of ease of fuel transportation and handling.

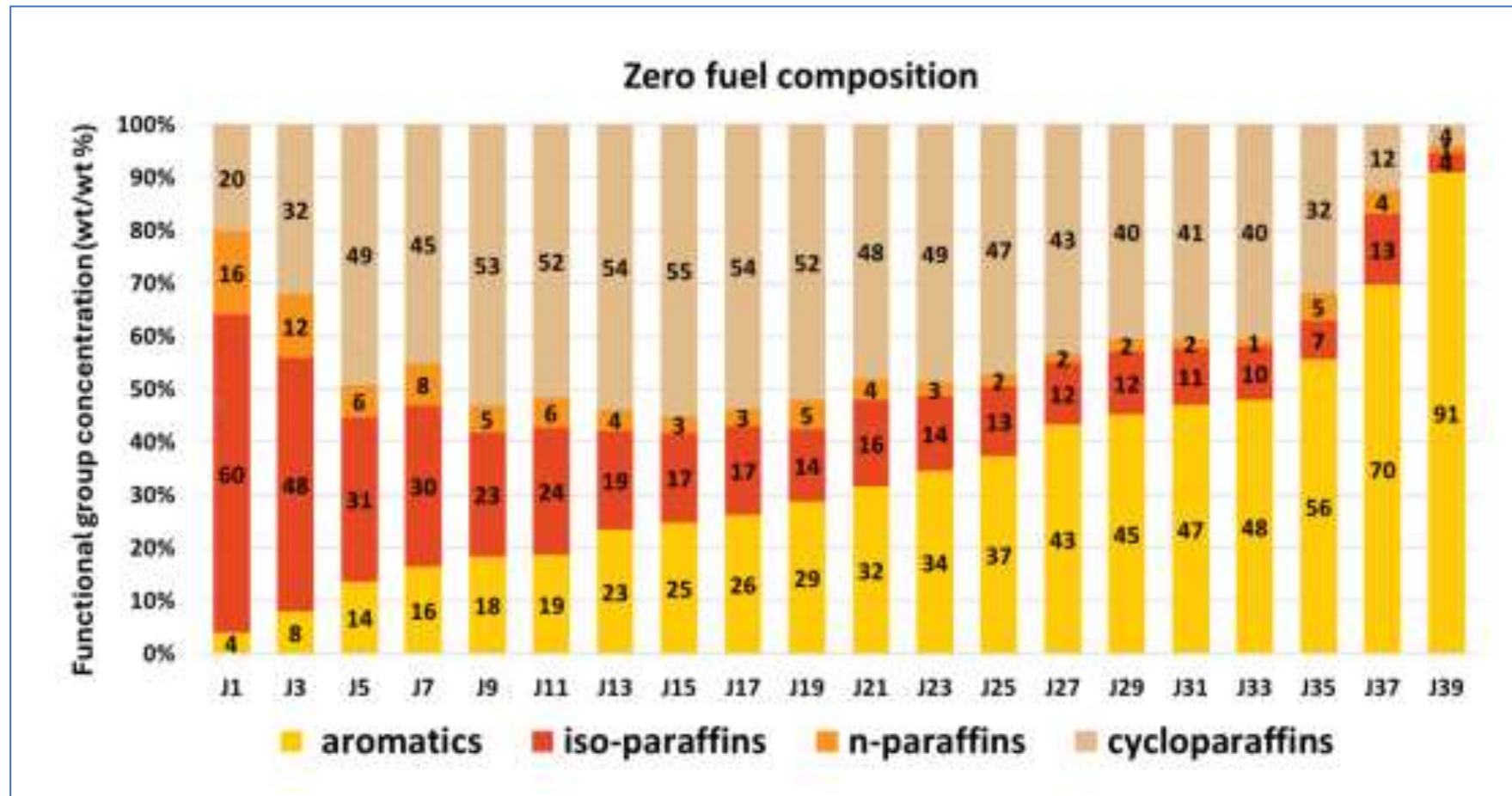
e-fuel category		Fuel production costs	Infrastructure costs	GHG emissions reduction potential	Wider sustainability considerations
		<ul style="list-style-type: none"> Medium production costs High production costs Higher production costs 	<ul style="list-style-type: none"> Lower infrastructure costs Medium infrastructure costs Higher infrastructure costs 	<ul style="list-style-type: none"> High reduction potential Medium reduction potential Low reduction potential 	<ul style="list-style-type: none"> Low risks Medium risks High risks
Drop-in	Direct pathways	Potentially slightly higher than blending, but within uncertainty margin	Lowest as fewest changes expected to infrastructure	As per paraffinic component below. May have slight benefit in terms of transportation GHGs as only one 'set' of molecules needs to be transported	No high risks identified for any pathways – but there are some considerations related to water and land needs, and usage of mined resources
	Paraffinic pathways + Added aromatics (A) or substitutes (S)	Expected to be slightly lower than other two categories as can benefit from use of cheaper bio-based feedstock (but note future competition for bio-based feedstock from bio-SAF and chemicals)	Highest as essentially two 'sets' of molecules need to be transported and stored then blended	Aromatics & Substitutes Very good if waste-based biomass used, and renewable hydrogen used for upgrading	For bio-aromatics, impact on water and land usage is highly dependent on feedstock (crop-based vs. waste-based)
Non drop-in	Paraffinic (SPK) fuels	Expected to be similar to Direct Pathways	Higher than Direct but lower than blending	Paraffinic components Can be very good if renewable heat used for processing and renewable electricity is used to produce hydrogen and capture CO ₂	0 aromatic content potentially beneficial regarding non-CO ₂ effects and local air quality

Figure 15: Assessment of e-fuel categories: Production costs, Infrastructure requirements, Emissions reduction potential and Sustainability considerations.

Source: ERM study for the New Energies Coalition (2023)

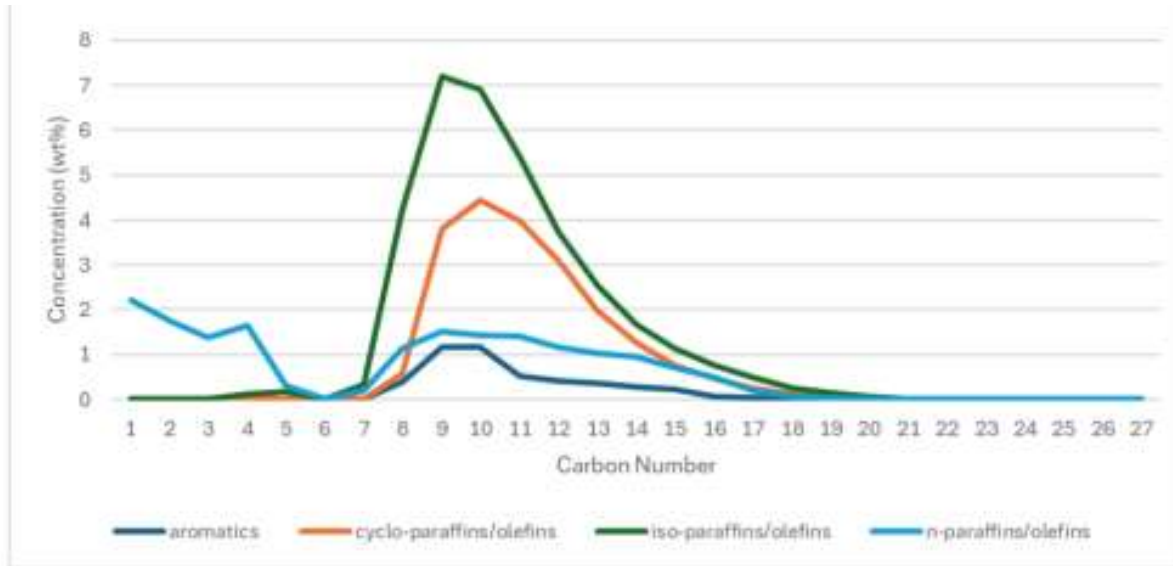
Modelling #6: (PI) Machine learning and chemistry optimisation

- Machine learning # 1: how process conditions (catalyst, H:C ratio, residence time, T, P, ...) influence product composition



Modelling 6: (PI) Machine learning and chemistry optimisation

- Machine learning # 2: how product composition affects properties: integration of thermodynamics and ML:



Property	Test Unit	Guarantee	Limit	Test Method	
				ASTM	IP
Appearance	Clear, bright and visually free from solid matter and			visual	
Colour		Report		D 156 or D 8045	
Particulate Contamination	mg/l	1.0	Max	D 5452	423
Particulate, at point of manufacture, cumulative channel particle counts		Channel Counts			564 or 565 or 577
24µm(c)		Report	Report		
26µm(c)		Report	Report		
≥14µm(c)		Report	Report		
≥22µm(c)		Report	Report		
≥25µm(c)		Report	Report		
≥30µm(c)		Report	Report		
Total Acidity	mg KOH/g	0.025	Max	D 3242	354
Aromatics	% vol	25	Max	D 1319	156
Or Total Aromatics	% vol	26.5	Max	D 6379	436
Sulphur, Total	% mass	0.30	Max	D 1286 or D 2622 or D 4294 or D 5453	336
Sulphur, Mercaptan or Doctor Test	% mass	0.0030	Max	D 3227	342
Non Hydroprocessed components	% vol.	Negative		D 4952	30
Mildly Hydroprocessed components	% vol.	Report			
Severely hydroprocessed Components	% vol.	Report			
Synthetic Components	% vol.	Report			
Fatty Acid Methyl Ester	Mg/kg	50	Max	D 7797	585,583 590,599
Distillation	°C			D 86 or 7345	123
Initial Boiling Point	°C	Report			
Fuel Recovered	°C				
10 % vol	°C	205	Max		
50 % vol	°C	Report			
90 % vol	°C	Report			
End Point	°C	300	Max		
Residue	% vol	1.5	Max		
Loss	% vol	1.5	Max		
Flash Point	°C	58 [40] (1)	Min	D 3828 or D 56	170 or 523
Density at 15 °C	kg/m³	775.0-840.0		D 1298 or D 4052	160 or 365
Freezing Point	°C	-47	Max	D 2386 or D 5972 or D 7153 D 7154	16 or 435 or 528 or 529
Viscosity at -20 °C	cs (mm²/s)	8.000	Max	D 445 or D 7042	71
Specific Energy, net	MJ/kg	42.80	Min	D 3338 or D 4809	12 or 355
Smoke Point	Mm	25	Min	D 1312	598
or Smoke Point	Mm	18	Min	D 1322	598

100% drop-in PtL – it is possible!



100% drop-in PtL – it is possible!



E-SAF – current challenges

- Availability of green hydrogen
 - Other unmet demand for renewable or nuclear electricity
 - Electrolyser supply chain
 - Policy uncertainty
- Availability of biogenic or atmospheric CO₂
 - Geolocalisation of biogenic CO₂
 - Immaturity of direct air capture supply chain
- Cost reduction from learning by doing
 - Chicken and egg problem
- Blending mandates for E-SAF (e.g. EU and UK) will help overcome

E-SAF – opportunities

- Ability to monetise stranded renewable electricity resources
 - Hydropower far from demand centres (e.g. Canada, Ethiopia, ...)
 - Solar (e.g. Australia)
 - Wind (e.g. Scotland)
- Ability to monetise green H2 and provide offtake to delayed projects
- Both supported by ease of transport of liquid fuels vs electrons or H2
- Target price insensitive markets
 - Defence markets which need sovereign supply
 - Can be SMR nuclear-driven
 - Corporate aviation with steep scope 3 GHG emissions reduction targets

Further opportunities for synthetic fuels

- E-fuels and gasification based, starting from basic building blocks
- Optimise the chemistry for performance:
 - Energy density
 - Freeze point
 - Lubricity
 - Heat transfer
- Optimise the chemistry for emissions:
 - Explore seal-swelling chemistry (e.g. switch aromatics to cycloalkanes)
 - Minimise formation of contrail nucleation sites
- Collaborate with OEMs and regulators
- Need for integration – interconnectedness of modelling and high sensitivity of e.g. cost to e.g. selectivity and conversion

Summary

- A range of SAFs are available
- Some, e.g. HEFA are mature but will be limited by supply
- Others, e.g. e-fuels are potentially unlimited but require significant capital investment and are currently relatively costly
- Lifecycle analysis and process optimisation are important in ensuring low overall climate impacts
- Policy support is emerging but still somewhat fragmented
 - It should also be creative and outcome-oriented rather than prescriptive
 - Balance between industrial strategy (e.g. domestic production) versus best cost and environmental impact (e.g. book and claim)
- Need to provide support across the value chain (production, storage, transport and end-use) as it is only as strong as its weakest link