From Refinery to Aircraft

Navigating the Complex Journey of Sustainable Aviation Fuel in the EU

Elisabeth Woeldgen, University of Hasselt, Belgium

Stargate

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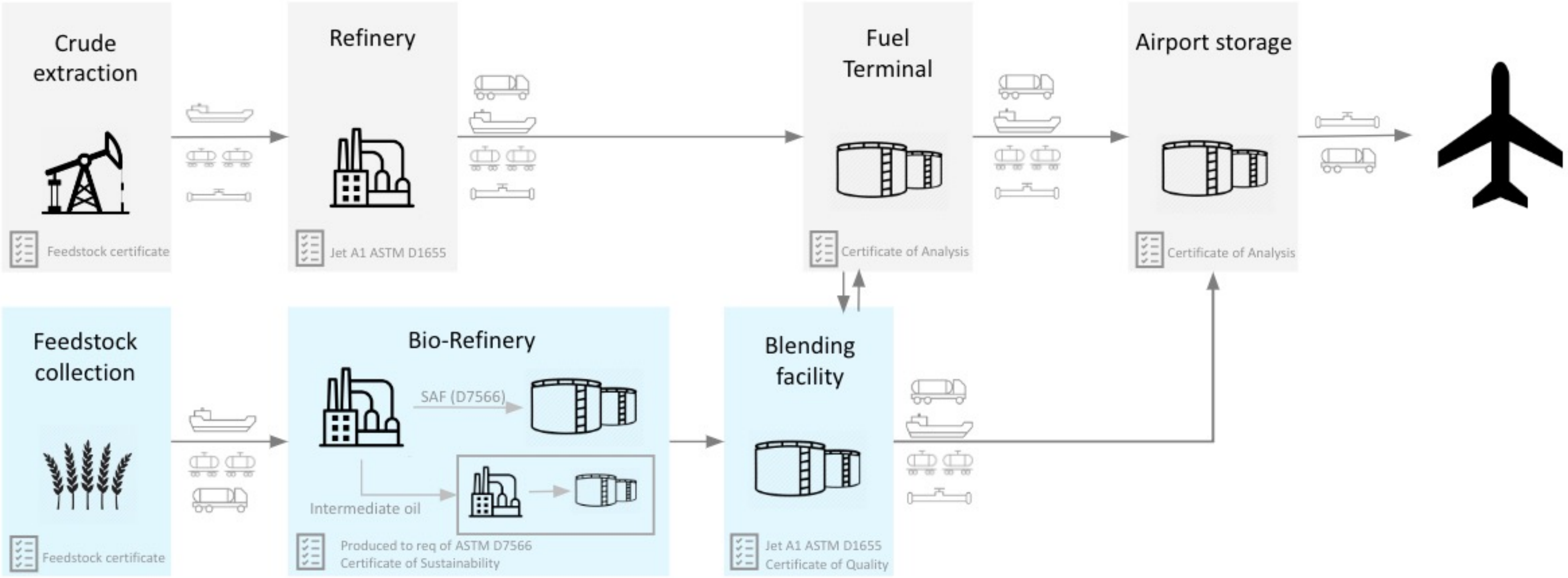
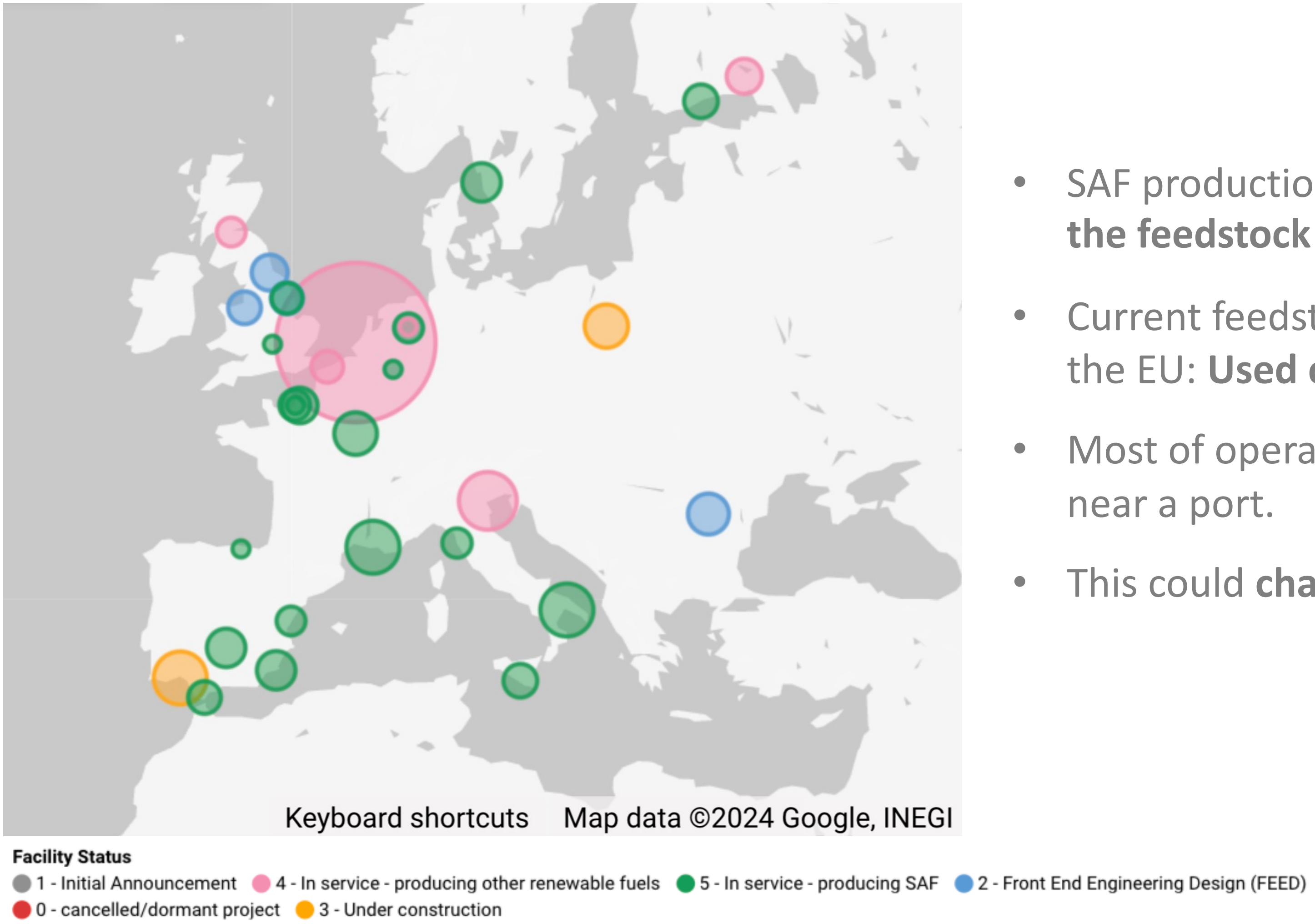
Aviation Fuel Supply Chain



SBC Production



ICAO tracker of SAF facilities, 2024

- SAF production facilities locations depend mostly on **where the feedstock is coming from**, and how it is supplied.
- Current feedstock most widely used for SAF production in the EU: **Used cooking oil** (UCO).
- Most of operational SAF production facilities are located near a port.
- This could **change** as we ramp up SAF production.

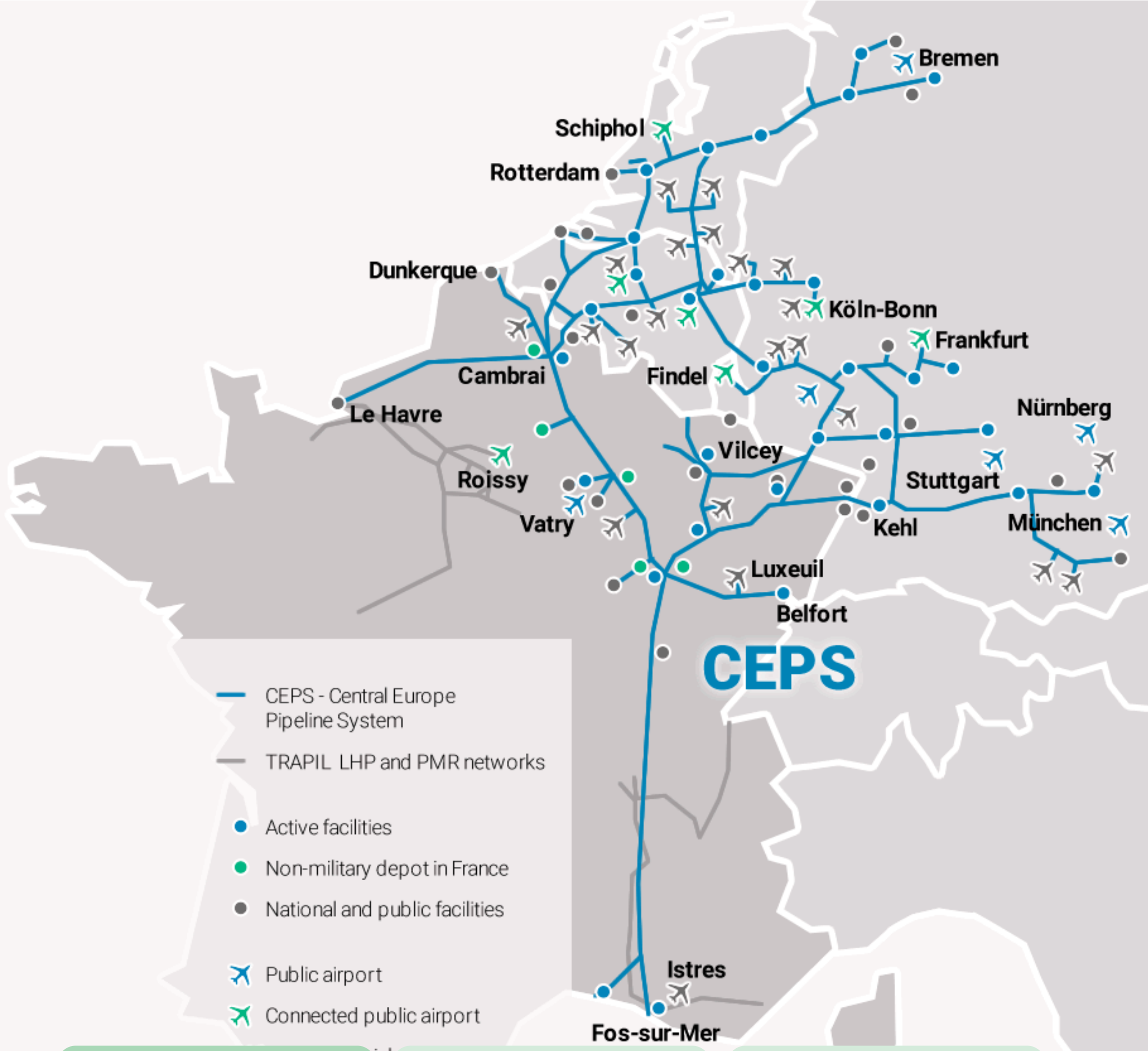
Supply Chain | Blending | Opportunity

Intermediate Storage Facilities

- **Strategic location**, typically located near ports or industrial areas (cheap land)
- **Connectivity**: Access to pipeline, railway, waterway, and road tankers
- Large **storage capacity** for different fuels (crude oil, biofuels, refined petroleum products, chemical and feedstocks, LNG, LPG)
- **Fuel handling expertise** and facilities (e.g. additives)
- **Fuel lab** on site or partnership with another lab
- Provides storage buffer
- **Blending** facilities

From Fuel Terminals to Airports

Fuel transportation



- Pipeline, rail, waterway (barge), road tanker
- Depends on the **geography**, **infrastructure**, **contractual partnerships**, and **fuel demand**

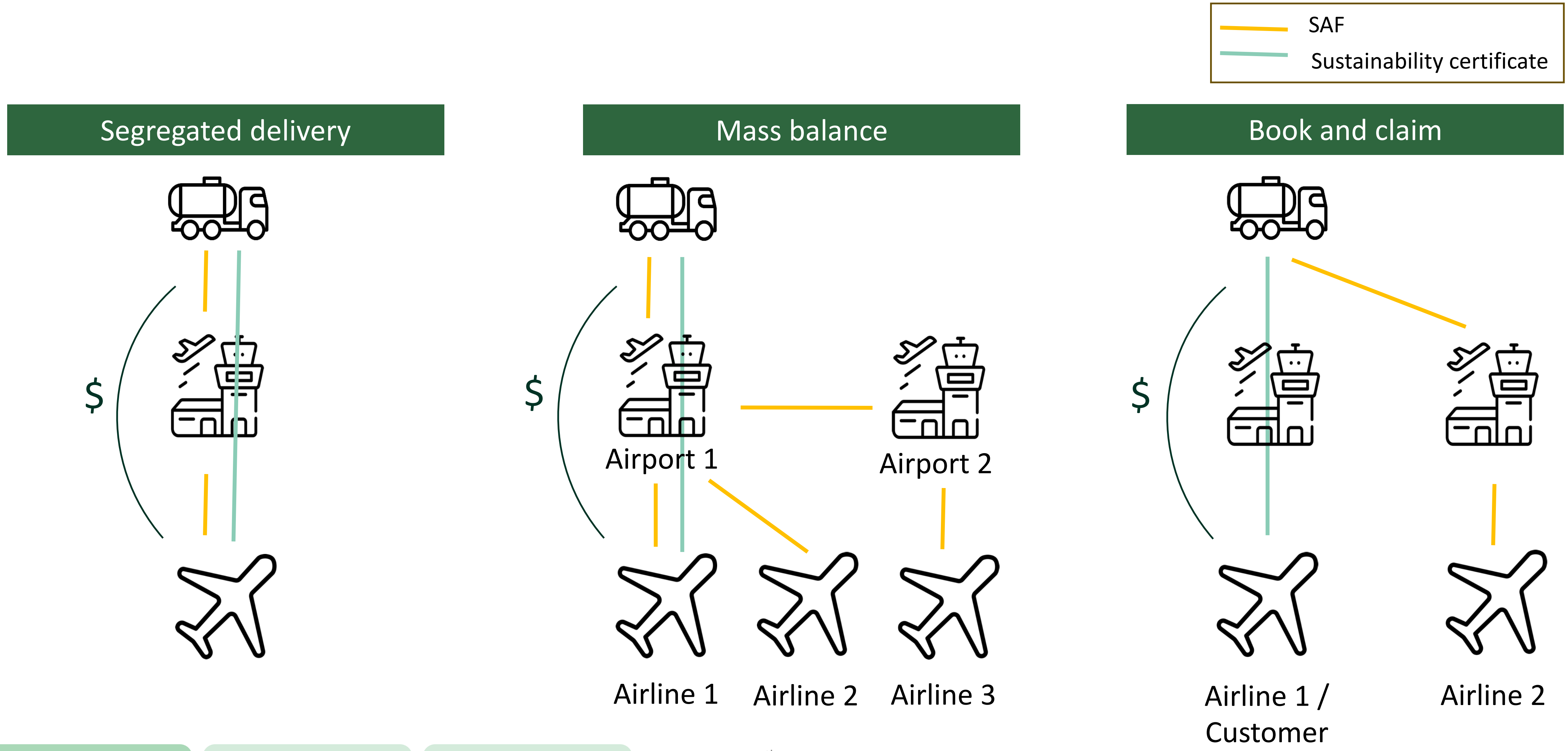
Brussels Airport

- Central European Pipeline System (CEPS)
- Fuel injected at a terminal (e.g. Rotterdam) and directly available at BAC

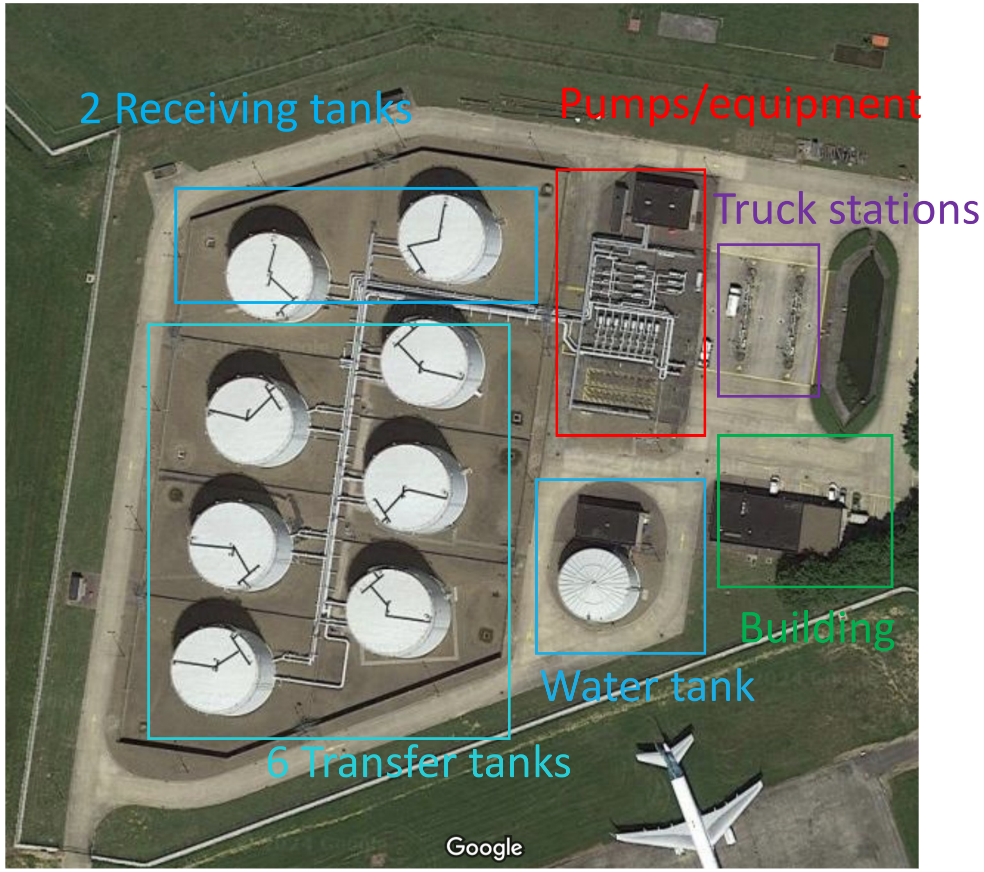
Lisbon Airport (own estimation)

- Primarily supplied by trucks
- ≈66,667 truckloads annually, or 183 daily

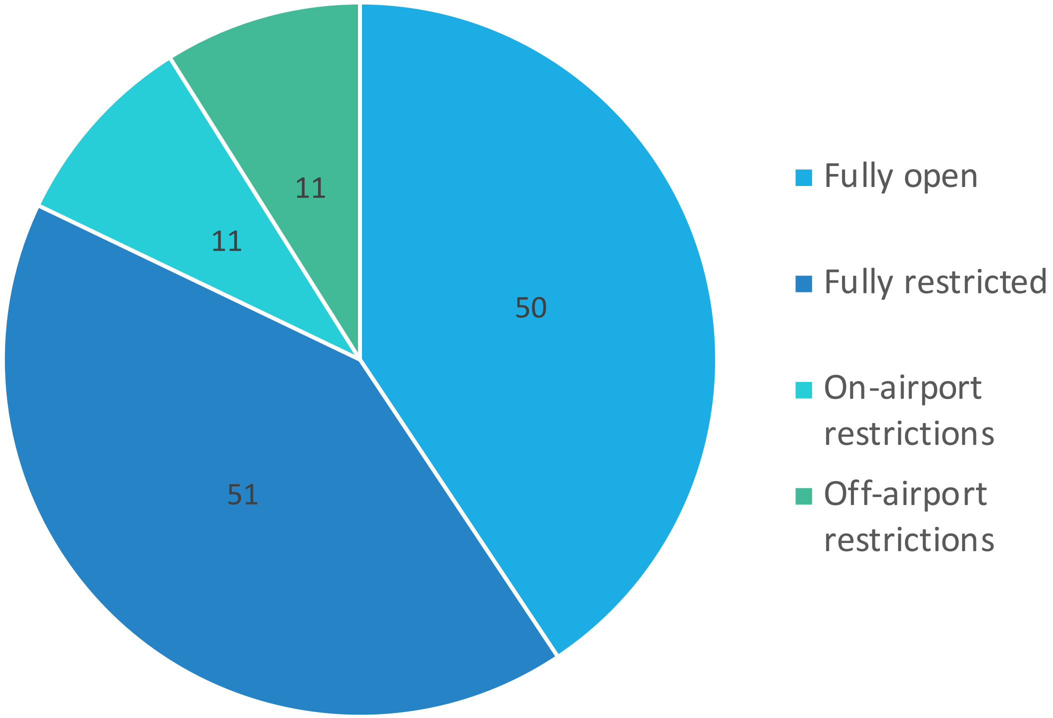
SAF Sustainability Certificates



Airport Fuel Storage



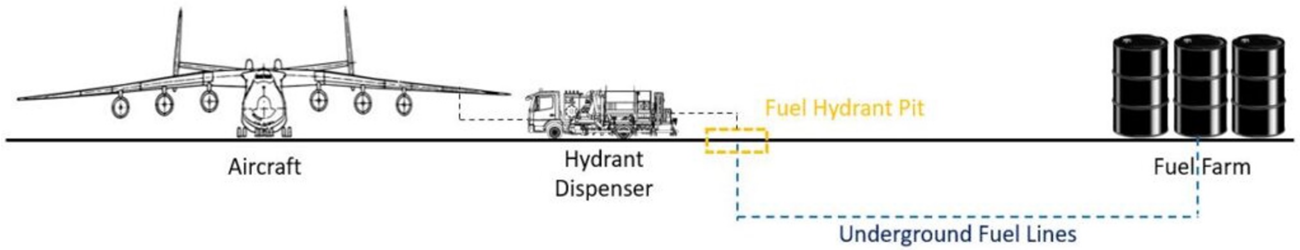
Overall distribution of type of access to fuel infrastructure*



*across a sample of 123 airports
IATA, 2024

Supply Chain | Blending | Opportunity

Fuel Distribution System

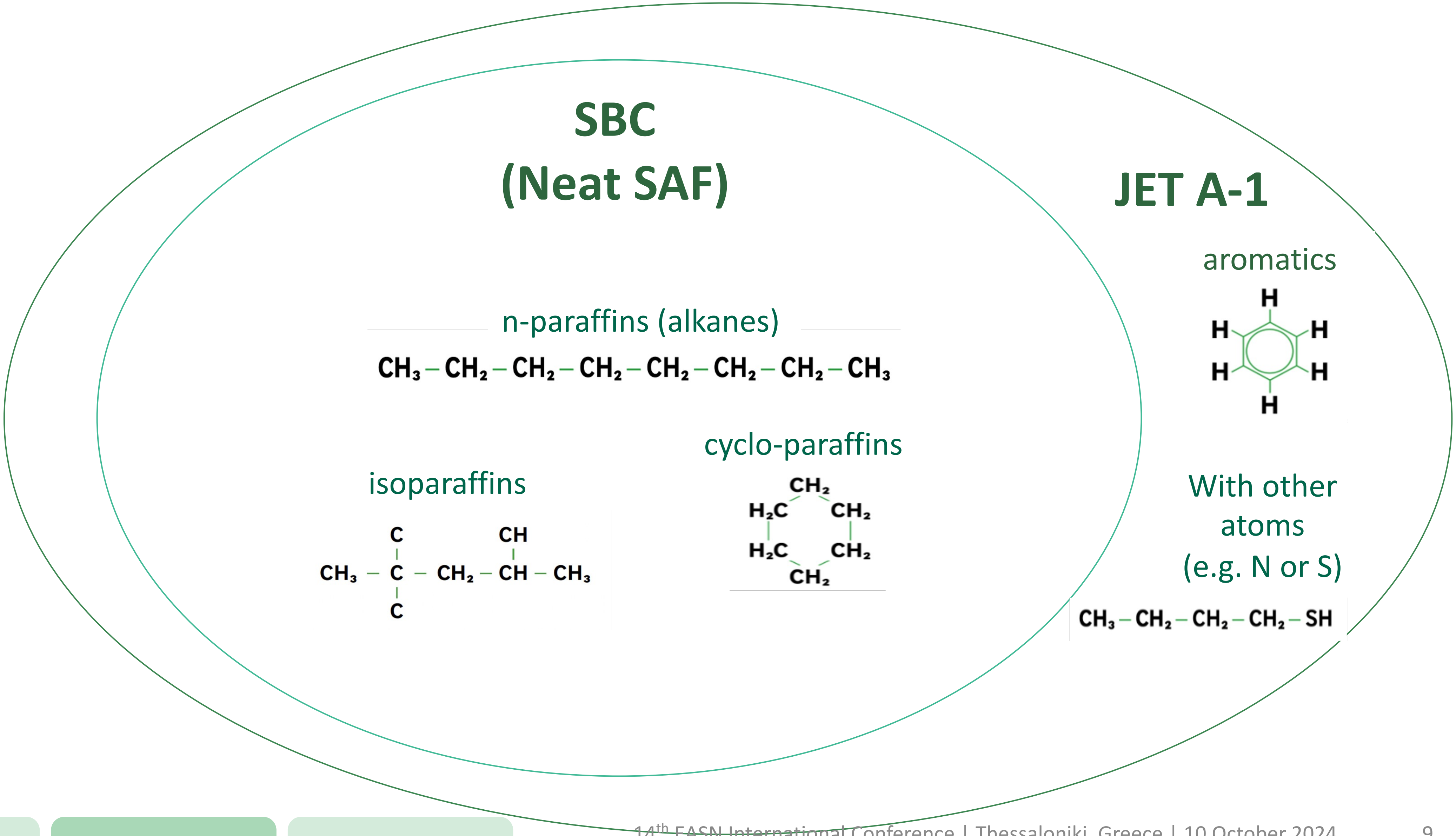


Refueling truck

truck

Supply Chain
Blending
Opportunity

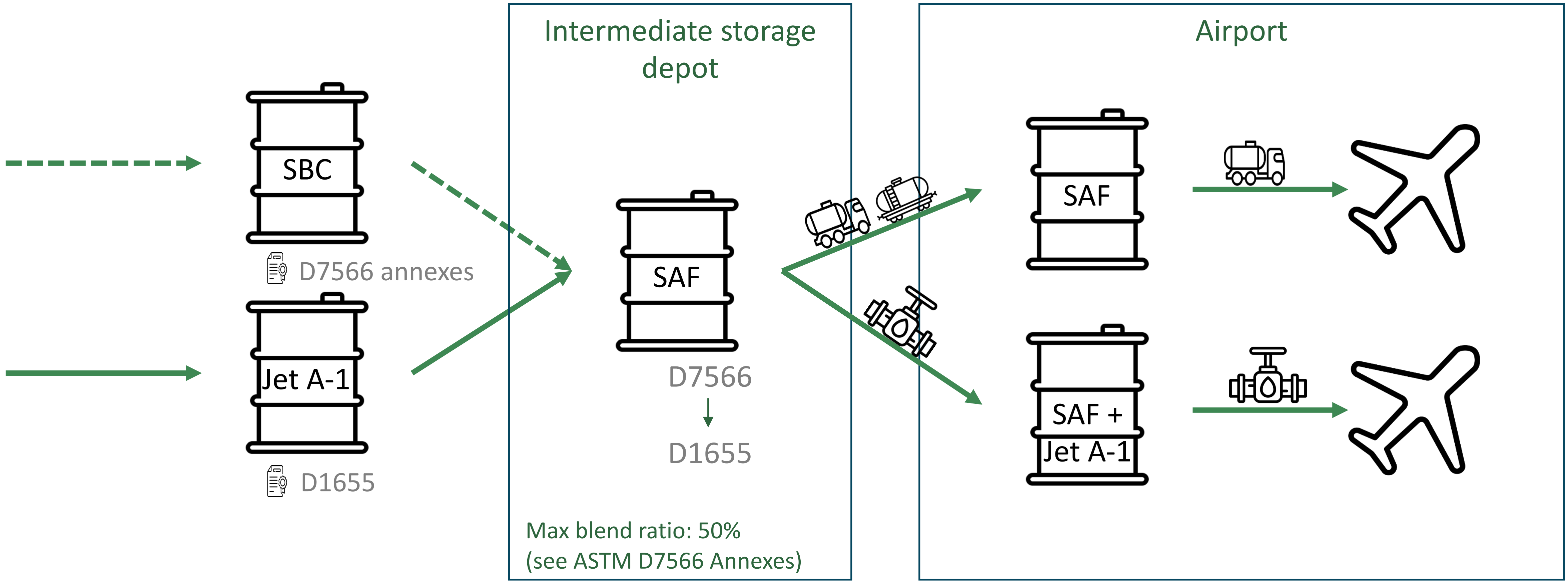
Blending



SBC
(Neat SAF)
JET A-1
n-paraffins (alkanes)
$CH_3-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_3$
isoparaffins
cyclo-paraffins
aromatics
With other atoms (e.g. N or S)
$CH_3-CH_2-CH_2-CH_2-SH$

Blending

Certification & Transportation



Blending

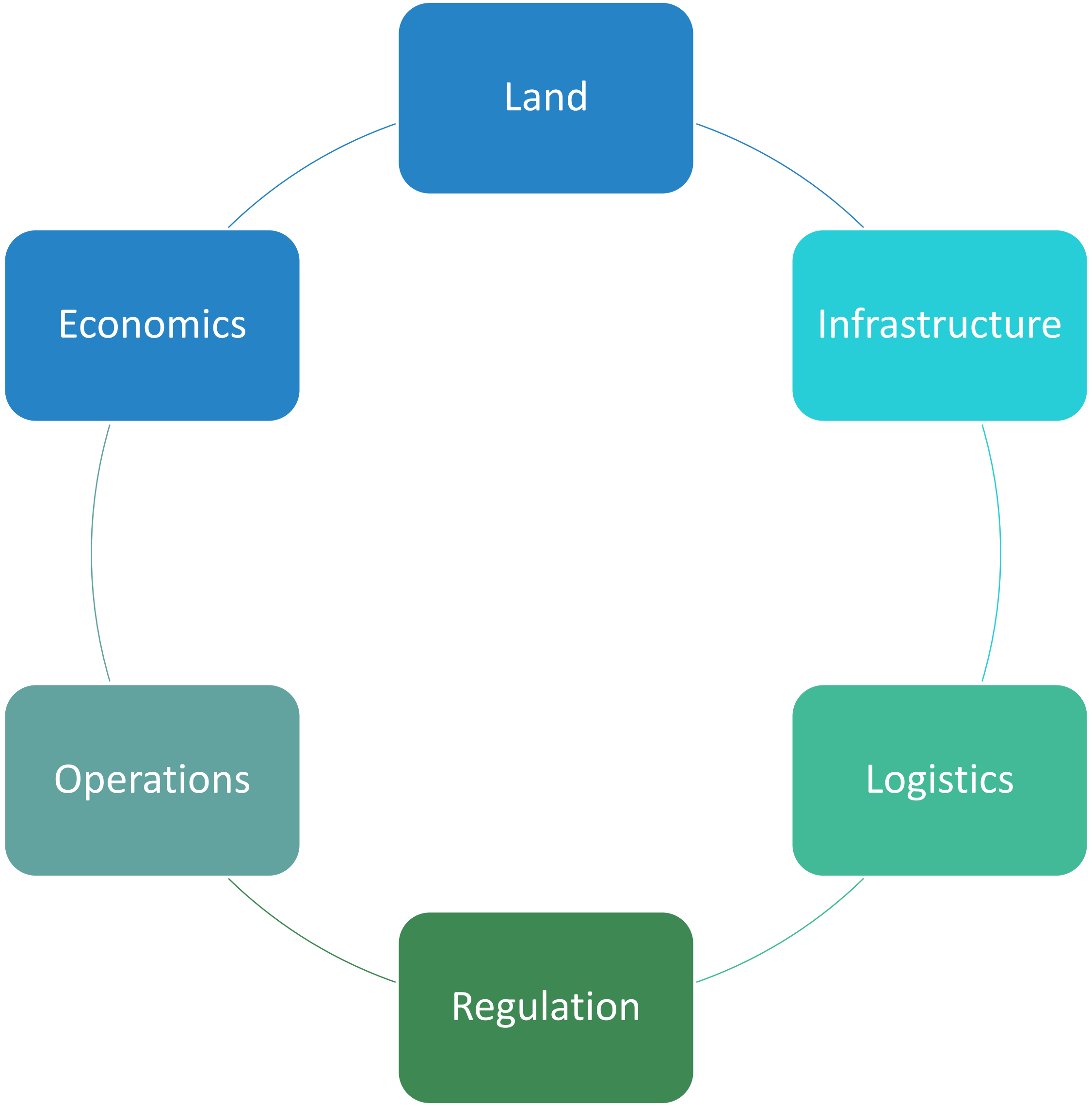
Types of blending processes*

- **Sequential blending**
  - Introducing the denser component before the lighter one into the tank.
  - Additional equipment (e.g. tank side entry mixers or recirculation systems) required to meet the homogeneity requirements.
- **Inline blending**
  - Introduced the two components together in a separate tank with adequate mixing energy.
  - Preferred option.

* Pouring the two fuels together in a tank is not acceptable as layers would form in the tank, with the higher density (CJF) on the bottom of the tank, and the lower density (SBC) on top.

Blending

Locations



SAF Distribution Strategies Opportunity

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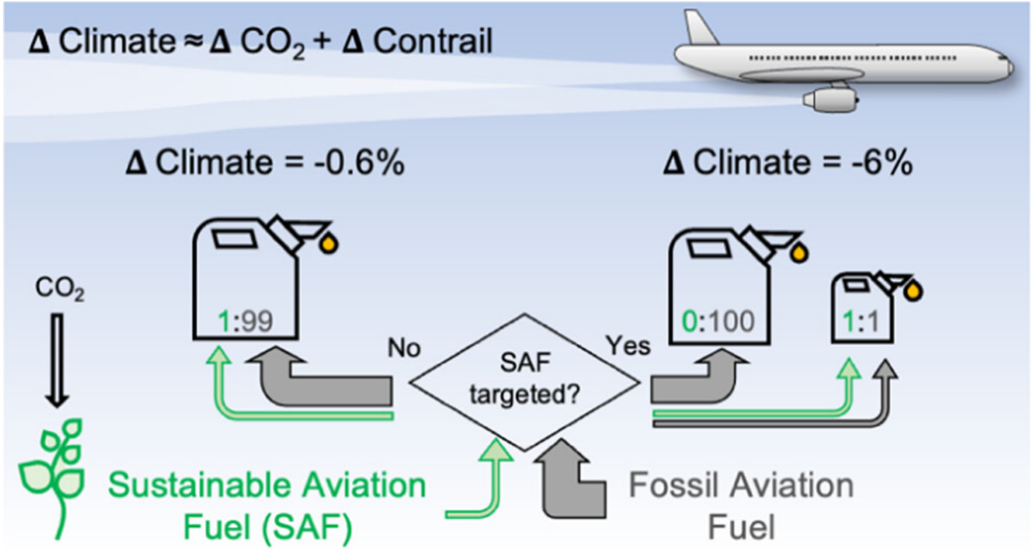

Reductions in EF_{total} from the SAF allocation by $\Delta EF_{contrail}$ with a **50%** $\boldsymbol{p_{blend}}$ (−6.5 to −6.2%) is approximately **9 to 15 times larger** than the baseline scenario with uniform distribution (−0.8 to −0.4%)*.

(Teoh et al., 2022)

Motivation

1. Teoh et al. studied the **theoretical best case** climate benefit of **allocating SAF** on specific flights.
   - ➪ Large potential benefits
   - ➪ Complex supply chain
2. **ReFuelEU** mandate: SAF uniformly distributed across all airports following a transition period.
3. Project **Stargate** offered valuable insights and expertise on SAF.

→ Collaboration between Roger Teoh, Marc Stettler, Robert Malina and Elisabeth Woeldgen

Objectives

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What are **feasible** SAF **distribution strategies** to enhance climate benefits of ReFuelEU and UK SAF mandates?

What are feasible distribution strategies?

What are the associated **climate benefits**?

What are the additional **supply chain** costs?

Which of the distribution scenarios has the best benefit-to-cost **ratio**?

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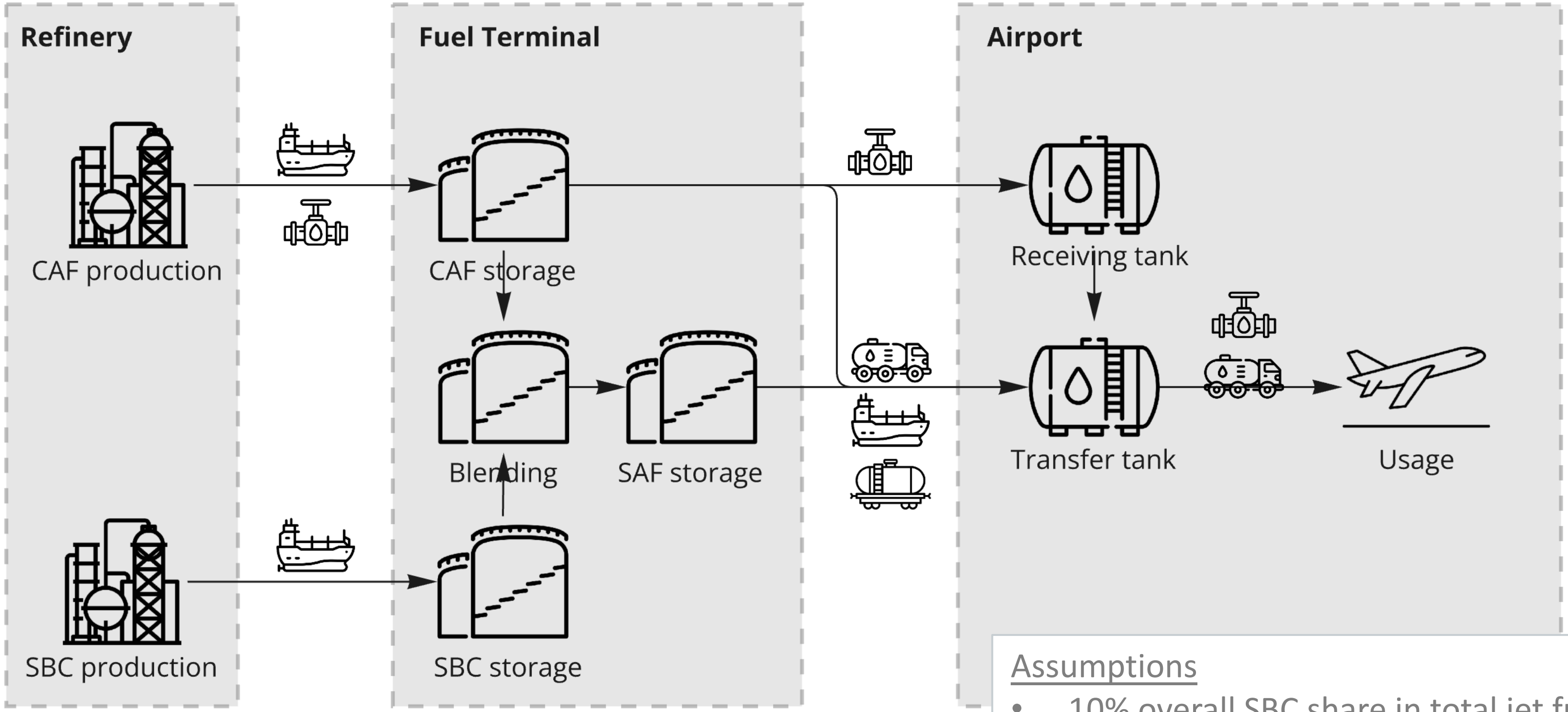
Supply Chain | Blending | Opportunity

Deployment Strategies – Baseline

Baseline



Assumptions
- 10% overall SBC share in total jet fuel consumption.
- 30% blend ratio.
- Year-long operations for SBC production and blending.

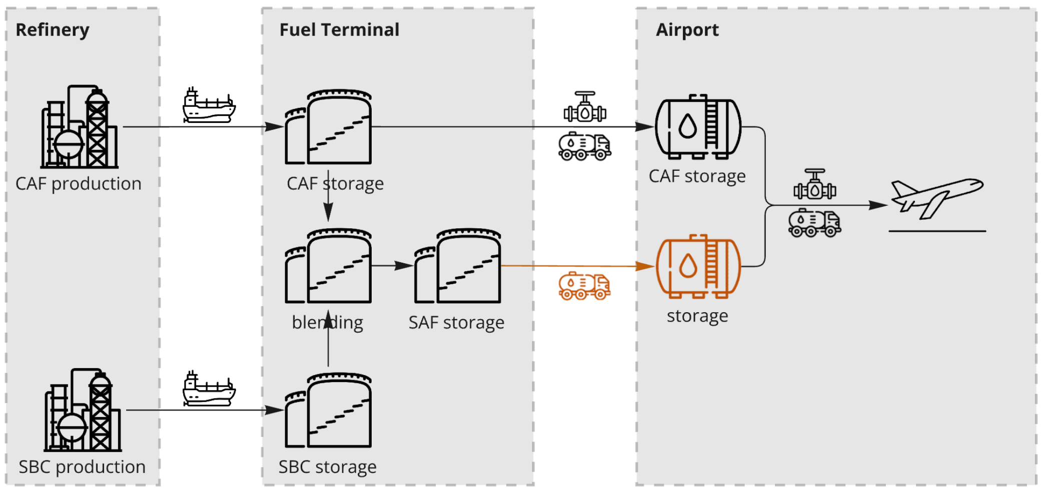
Supply Chain | Blending | Opportunity

Deployment Strategies – Diurnal

Assumptions – Diurnal

- A fixed mass of SAF supply is supplied to airports every day by road tanker.
- SAF is stored in separate (additional) tanks at the airport.
- SAF is transferred to A/C the same way as with conventional aviation fuel (CAF).
- Targeted distribution: all flights departing from 16:00 local time will be provided with SAF at a 30% blend ratio until the supply runs out (total SBC volumes amount to 10% of total jet fuel supply).

Diurnal Supply SAF to A/C between 1600 – 0300 UTC.



Deployment Strategies – Diurnal & CF

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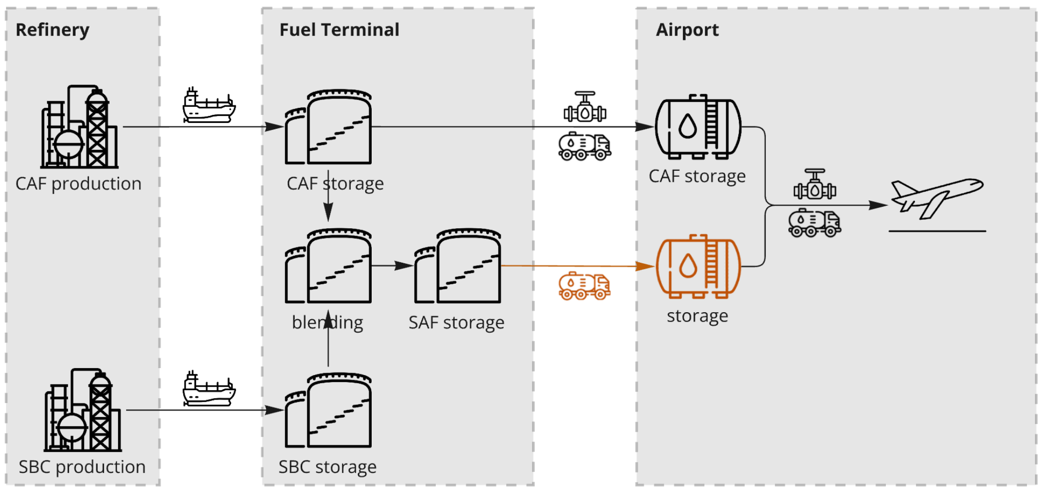
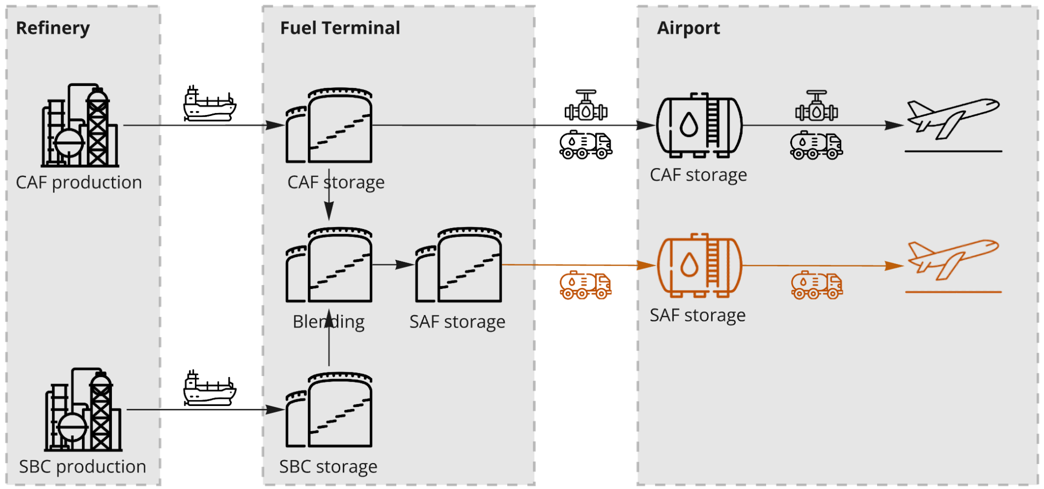
Assumptions – Diurnal and contrail forecasting

- A fixed mass of SAF supply is supplied to airports every day by road tanker.
- SAF is stored in separate (additional) tanks at the airport.
- SAF is transferred to specific A/C only by refueler tank (no hydrant system).
- Targeted distribution: all flights departing from 16:00 local time will be provided with SAF at a 30% blend ratio until the supply runs out (total SBC volumes amount to 10% of total jet fuel supply) .

Diurnal Supply SAF to fights departing 1600 – 0300 UTC.



Diurnal and contrail forecasting Supply SAF to fights departing 1600 – 0300 UTC and forecasted to form at least 250 km of persistent contrails

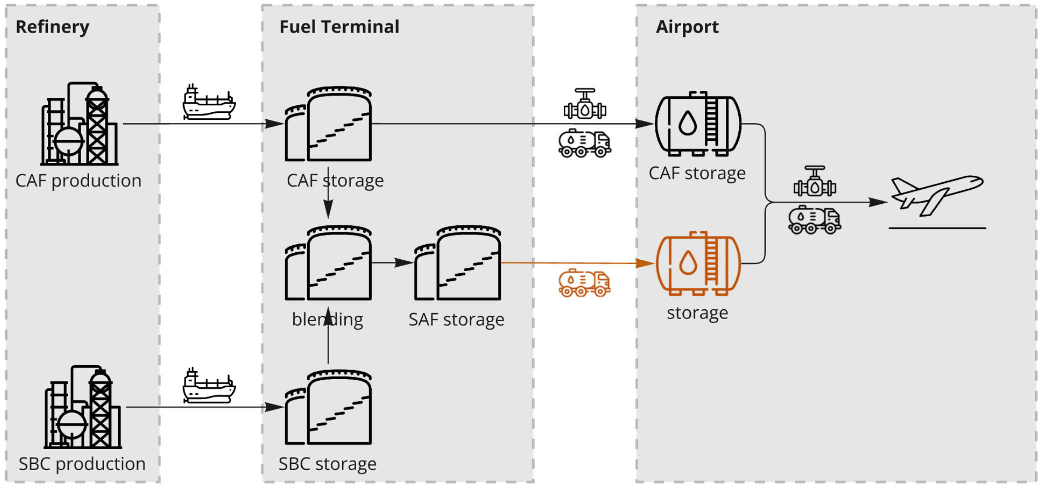


Deployment Strategies – Seasonal

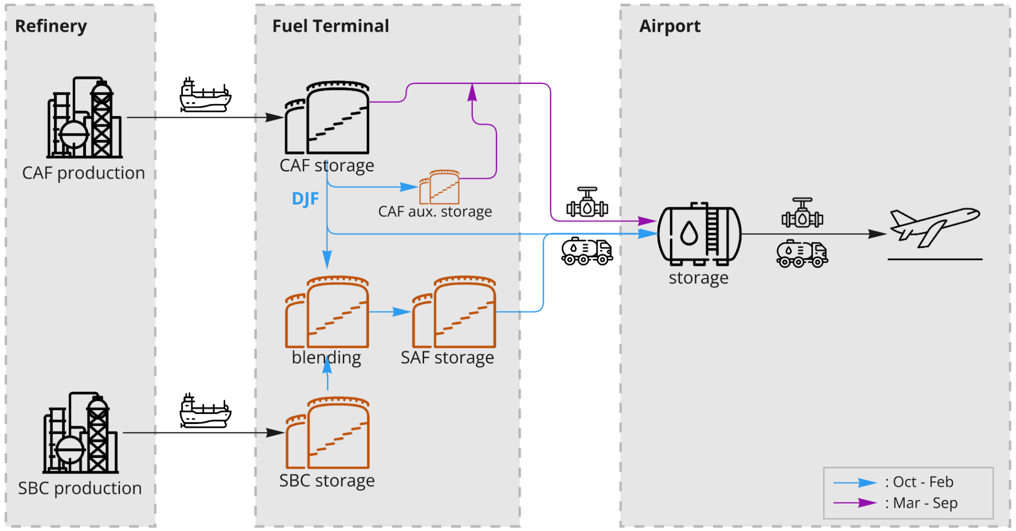
Assumptions – Seasonal

- SAF is only used from October to February.
- SBC is produced all year-long and stored at a fuel terminal.
- When SAF is used, more CAF is stored at the terminal.
- SAF is transported to airports, stored at airports and refueled on A/C the same way as CAF.
- SAF blended at 30% and targeted to flights during the winter (October – February) until supply runs out.

Diurnal Supply SAF to fights departing 1600 – 0300 UTC.



Seasonal Supply SAF to airports from October to February.



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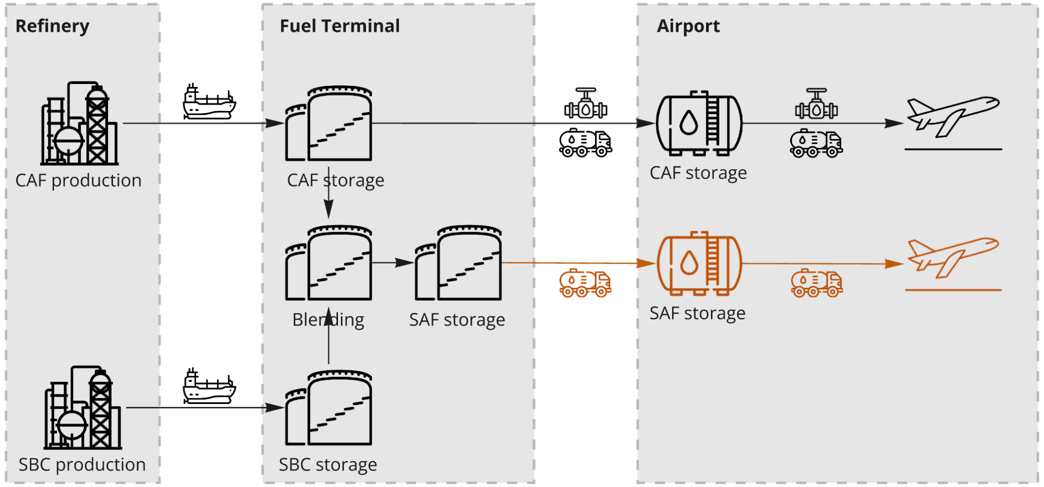

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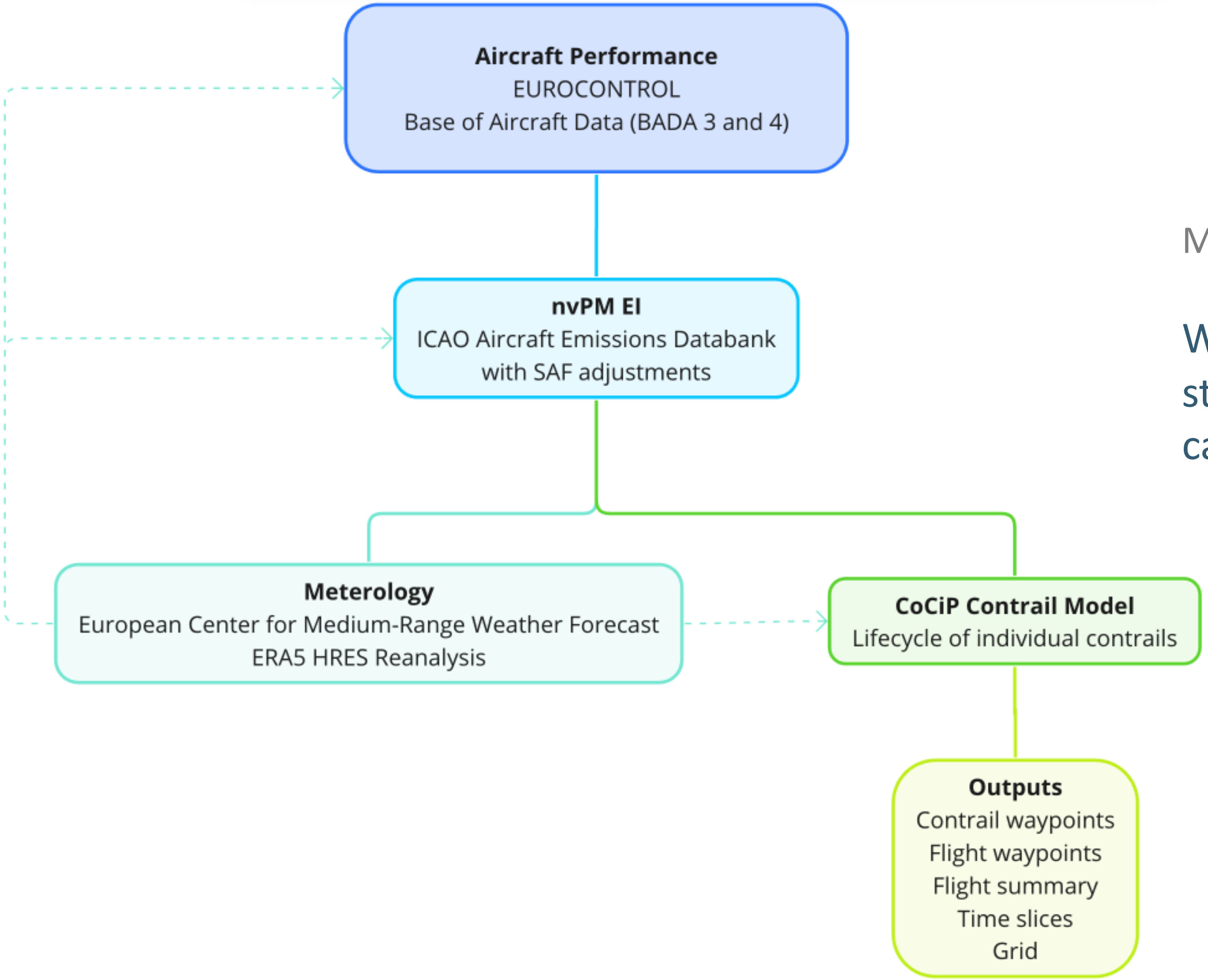
Overview Contrail Model



More details in Teoh et al., 2022.

We run the model for our SAF distribution strategies (including the baseline) to calculate the $EF_{contrail}$ change.

$EF_{contrail}$ Results

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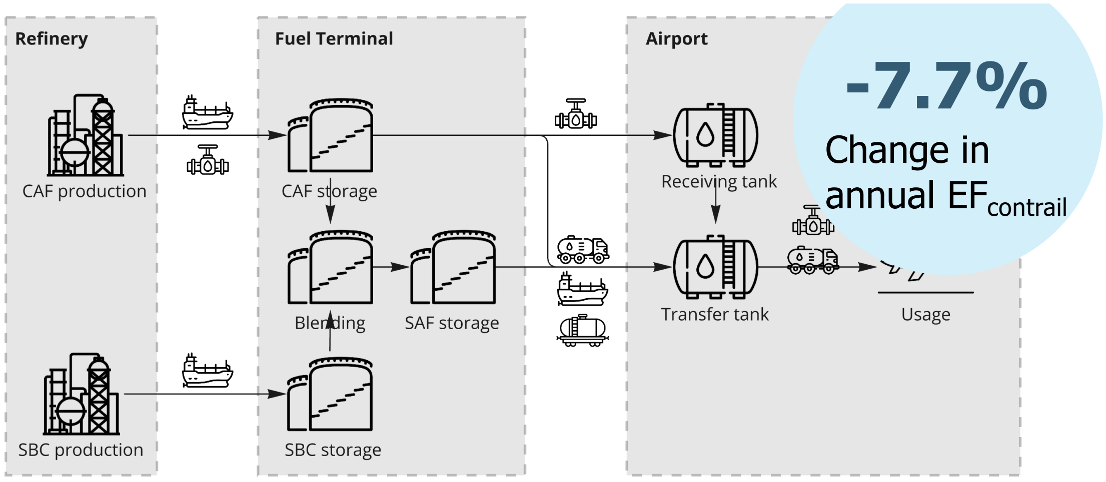
Baseline



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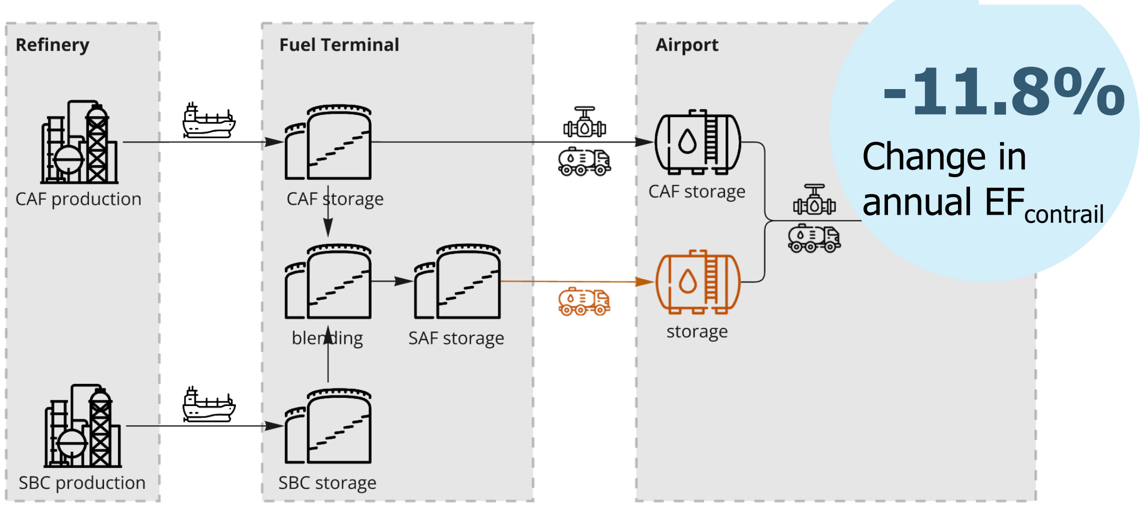
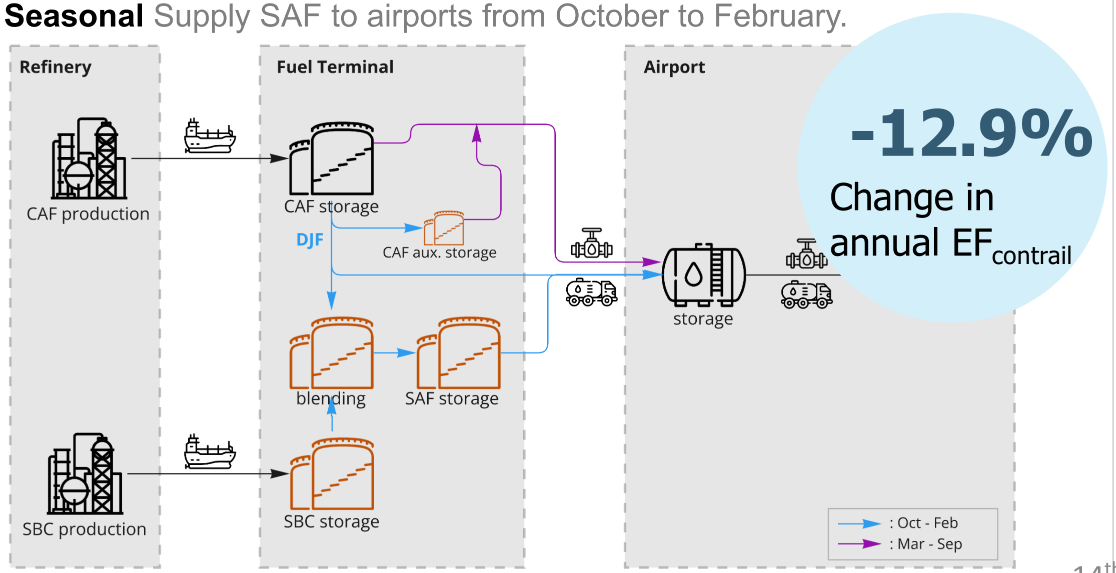


Seasonal Supply SAF to airports from October to February.



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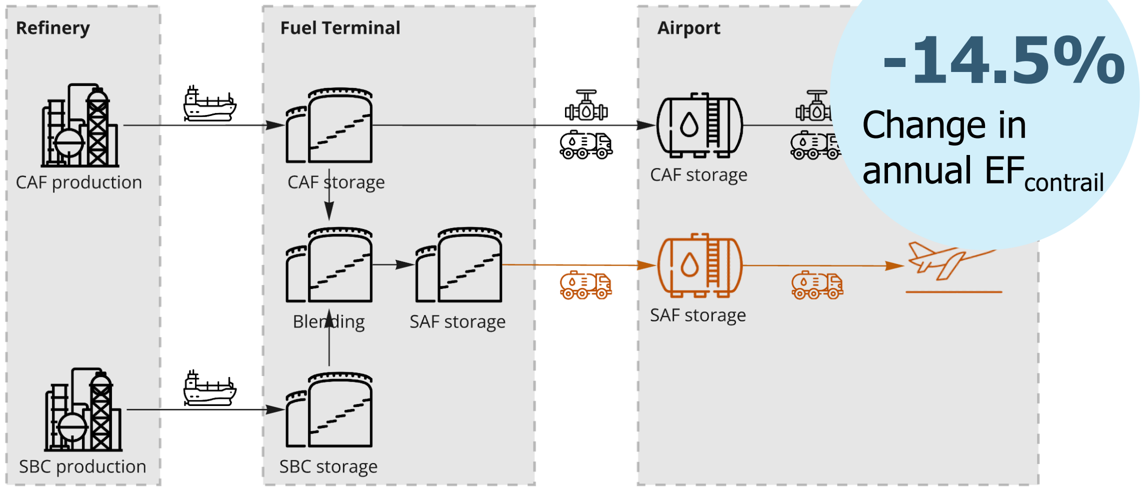

$EF_{contrail}$ Valuation

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Valuation of $EF_{contrail}$ in monetary terms:

(Teoh et al., 2022)

$$SC_{contrails} = m_{CO_2,eq} \times SC_{CO_2}$$

$100\ EUR/t_{CO_2}$

EU ETS projected for 2026-2030 for the EU

EF calculated for every scenario

0.42 to convert the contrail net RF to an ERF estimate

$$m_{CO_2,,eq} = \frac{EF_{contrail} \times \left(\frac{ERF}{RF}\right)}{AGWP_{CO_2,TH} \times S_{Earth}}$$

$S_{earth} = 5.101 * 10^{14}\ m^2$

$AGWP_{CO_2,100} = 2.78 \times 10 - 6\ J\ m^{-2}$ per kg $- CO_2$

Supply Chain | Blending | Opportunity

$EF_{contrail}$ Valuation

Baseline

GWP100-based estimate

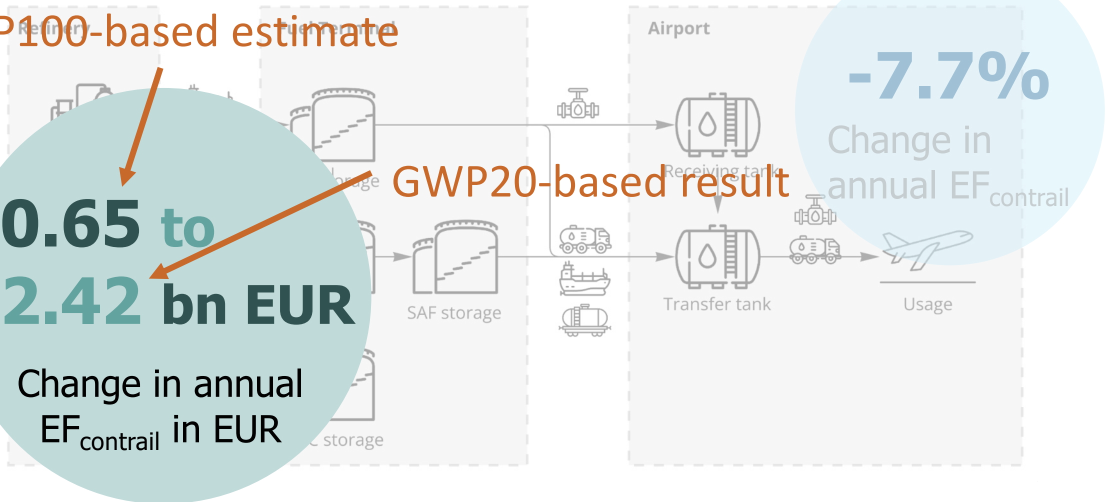
GWP20-based result

-0.65 to -2.42 bn EUR

Change in annual $EF_{contrail}$ in EUR

-7.7%

Change in annual $EF_{contrail}$



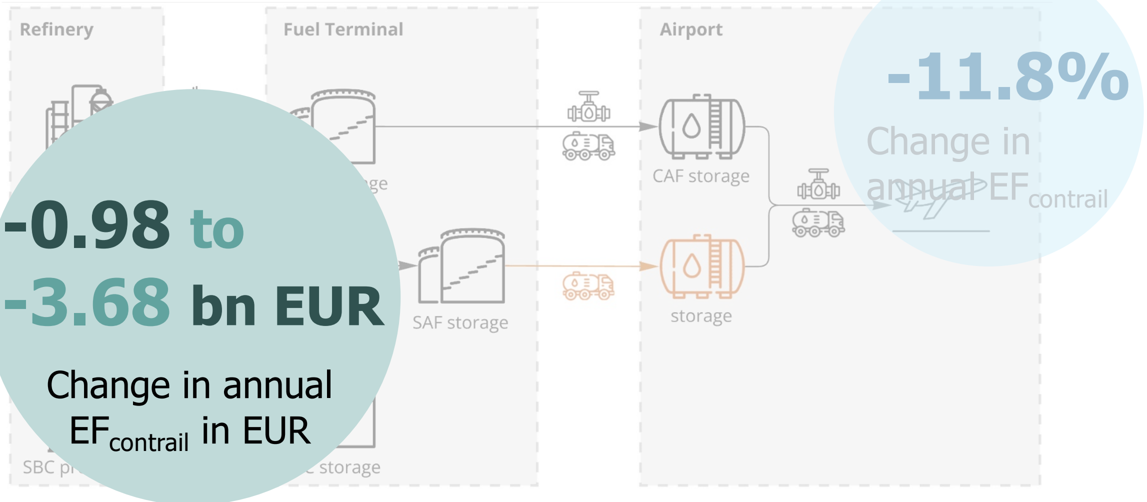
Diurnal Supply SAF to fights departing 1600 – 0300 UTC.

-0.98 to -3.68 bn EUR

Change in annual $EF_{contrail}$ in EUR

-11.8%

Change in annual $EF_{contrail}$



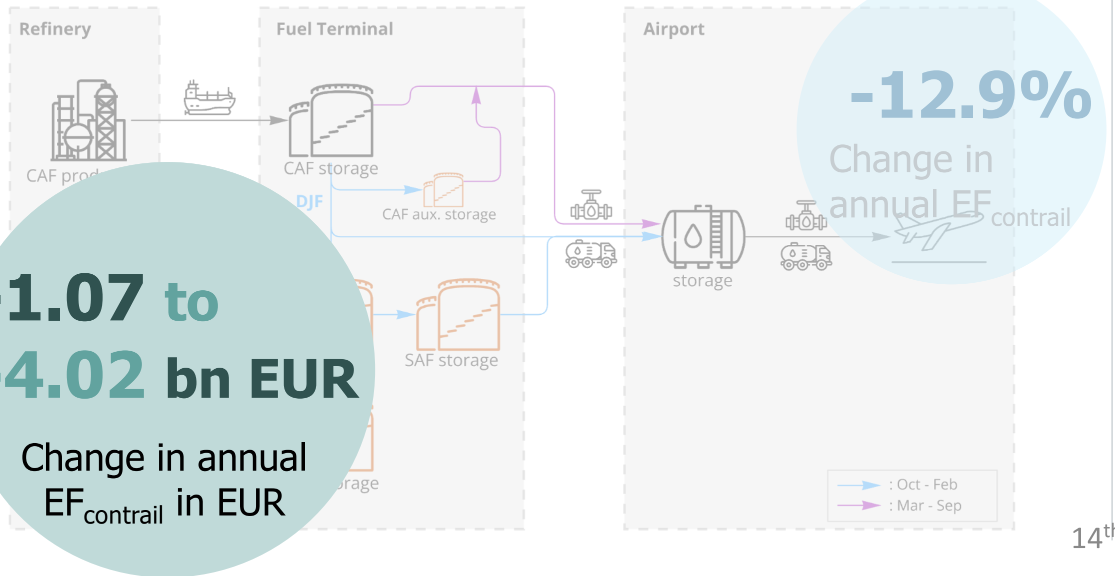
Seasonal Supply SAF to airports from October to February.

-1.07 to -4.02 bn EUR

Change in annual $EF_{contrail}$ in EUR

-12.9%

Change in annual $EF_{contrail}$



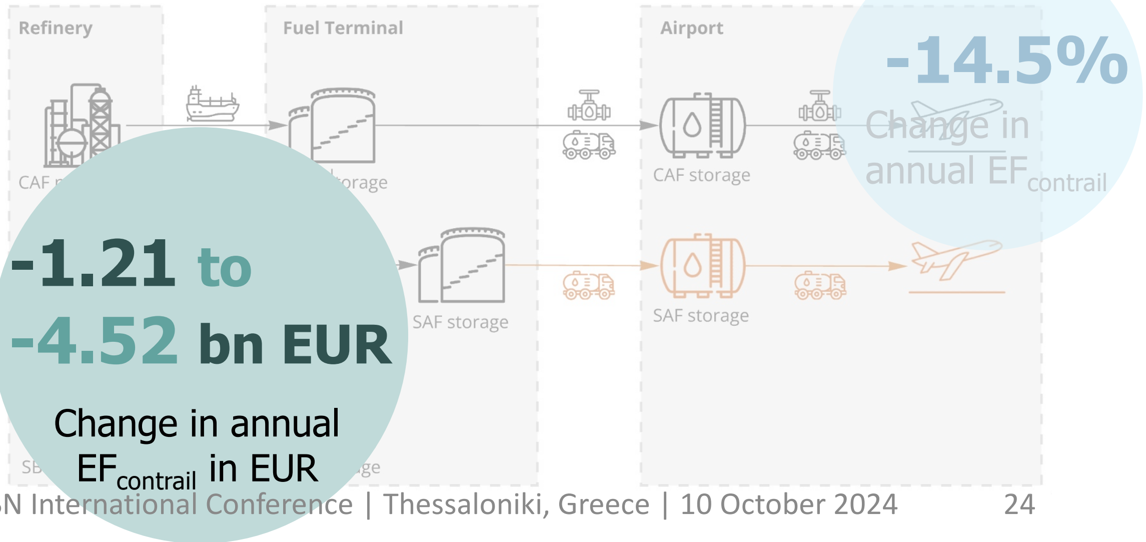
Diurnal and contrail forecasting Supply SAF to fights departing 1600 – 0300 UTC and forecasted to form at least 250 km of persistent contrails

-1.21 to -4.52 bn EUR

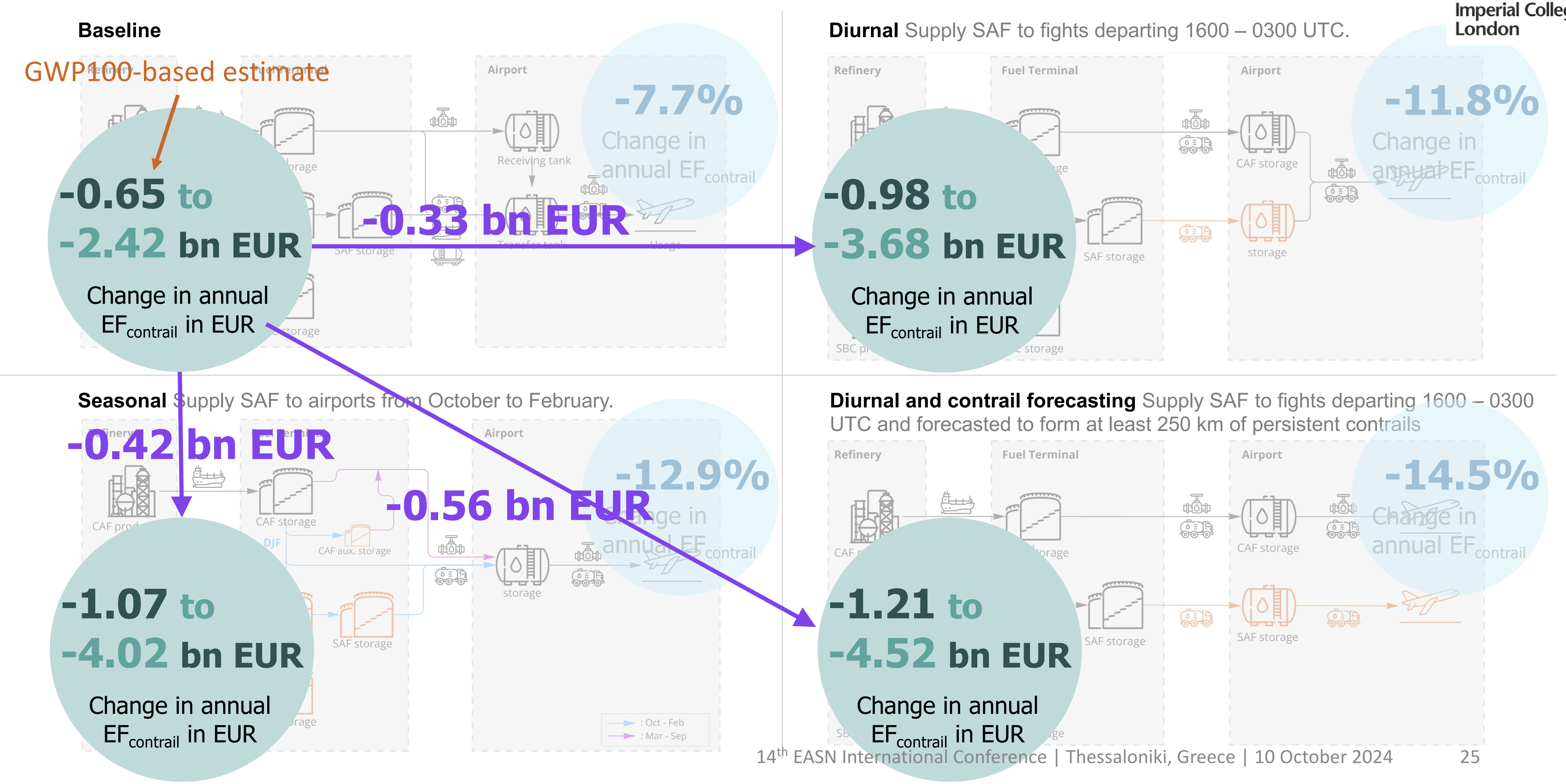
Change in annual $EF_{contrail}$ in EUR

-14.5%

Change in annual $EF_{contrail}$



$EF_{contrail}$ Valuation



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Overview Cost Model

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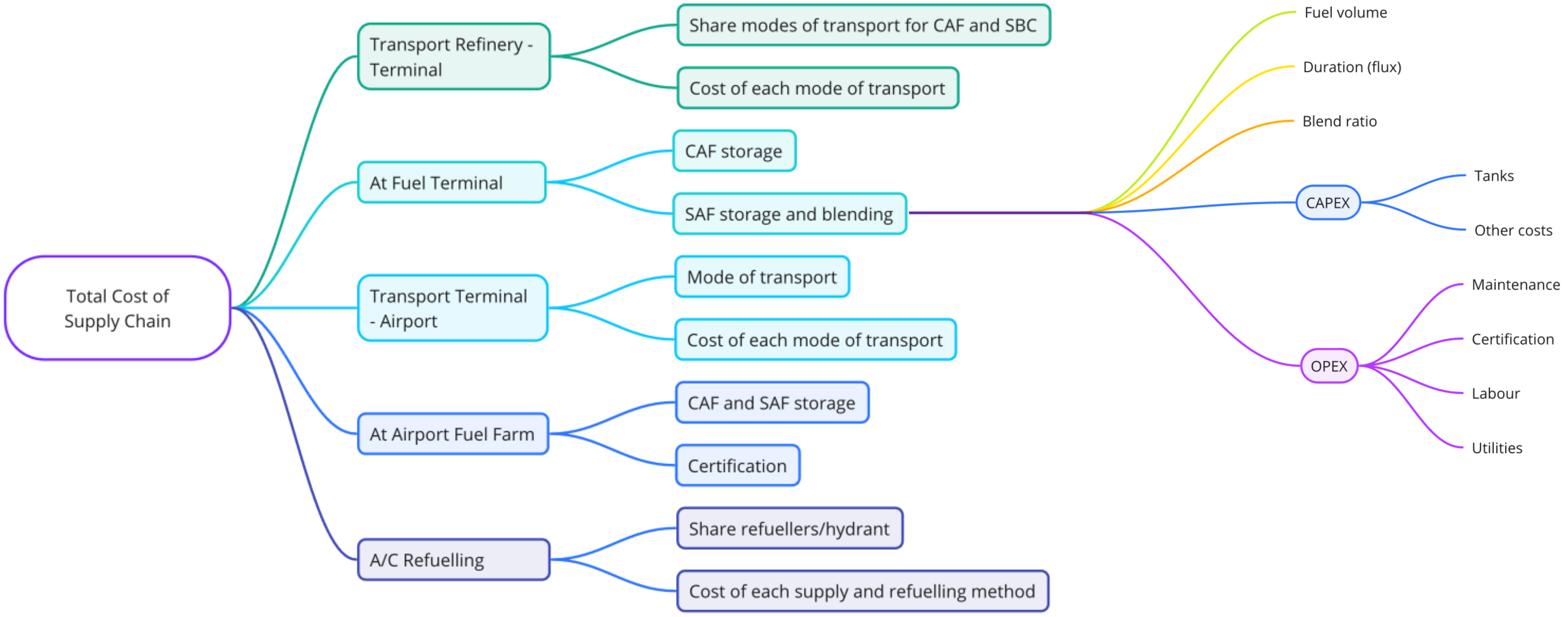

Supply Chain | Blending | Opportunity

Total Supply Chain Costs

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Annual supply chain cost (€ million)	Total costs	Additional costs relative to baseline strategy		
	Baseline	Seasonal	Diurnal	Diurnal + contrail forecasts
Transportation costs (Refinery to terminal)	635	0	0	0
Storage and blending costs at terminal	112	+87 (+78%)	0	0
Transportation costs (Terminal to airport)	1,959	0	+238 (+12%)	+238 (+12%)
Storage costs at airport	584	0	+338 (+58%)	+338 (+58%)
Fuel distribution at airport	43	0	0	+5 (+12%)
TOTAL	**3,324**	**+87 (+3%)**	**+576 (+17%)**	**+582 (+18%)**

Total supply chain costs for the baseline strategy, and the additional supply chain costs for the proposed SAF allocation strategies relative to the baseline strategy.

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Supply Chain | Blending | Opportunity

Cost–benefit comparison

Strategy	Cost-benefit comparison (€ million)
Seasonal	+341 (4.91)
Diurnal	-240 (0.58)
Diurnal + contrail forecasts	-20 (0.96)

- Cost-benefit comparison for the three targeted SAF allocation strategy relative to the baseline strategy.
- The cost-benefit comparison is evaluated using two different metrics:
  - Annual monetary benefits, estimated by subtracting the additional annualised supply chain costs from the annual monetised climate benefits (in € millions), with a positive value indicating a net benefit.
  - Benefit-to-cost ratio (presented in brackets).

Summary

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- The distribution of SAF involves numerous stakeholders along the supply chain.
- While the development of new policies should consider the existing supply chain constraints, it can also challenge it to accelerate the deployment of SAF.
- Blending is a complex operation.
- Targeted use of SAF could enhance climate benefits, but with an increase in supply chain complexity.
- We recommend a seasonal allocation strategy, where SAF is provided to all flights only between October and February, because its benefit-to-cost ratio is the highest (4.9) and is above one.

elisabeth.woeldgen@uhasselt.be