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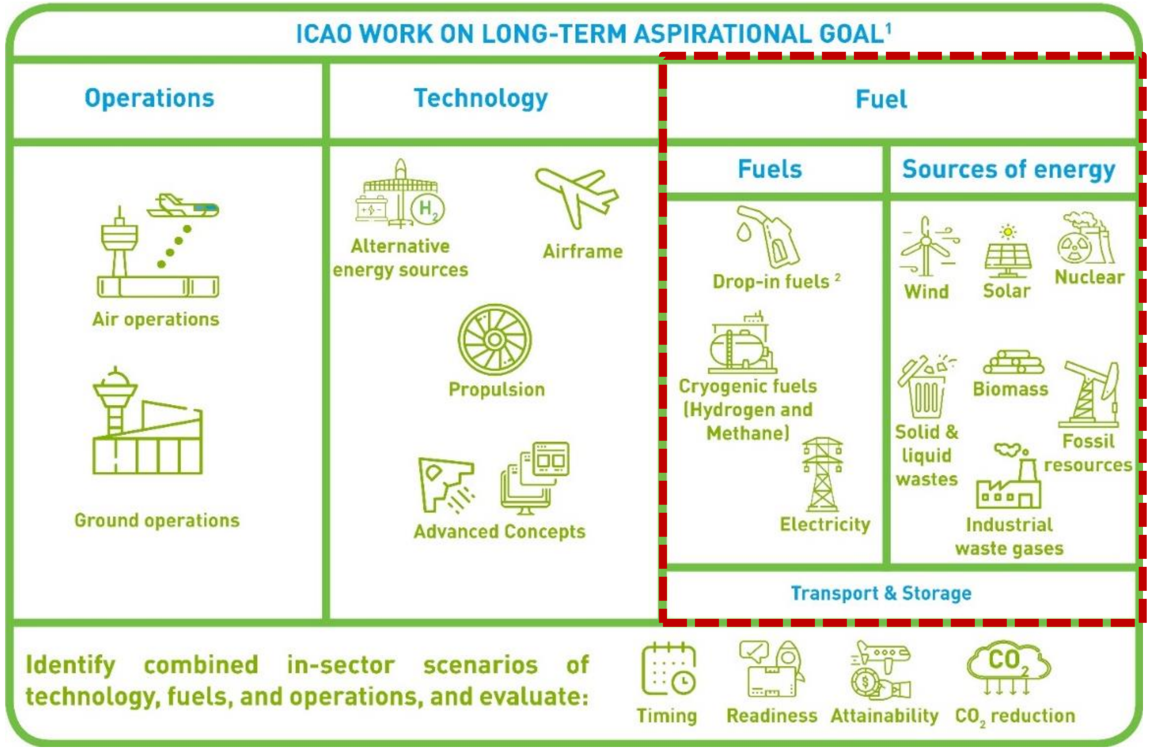
Summary of Fuels information from LTAG analyses

Background

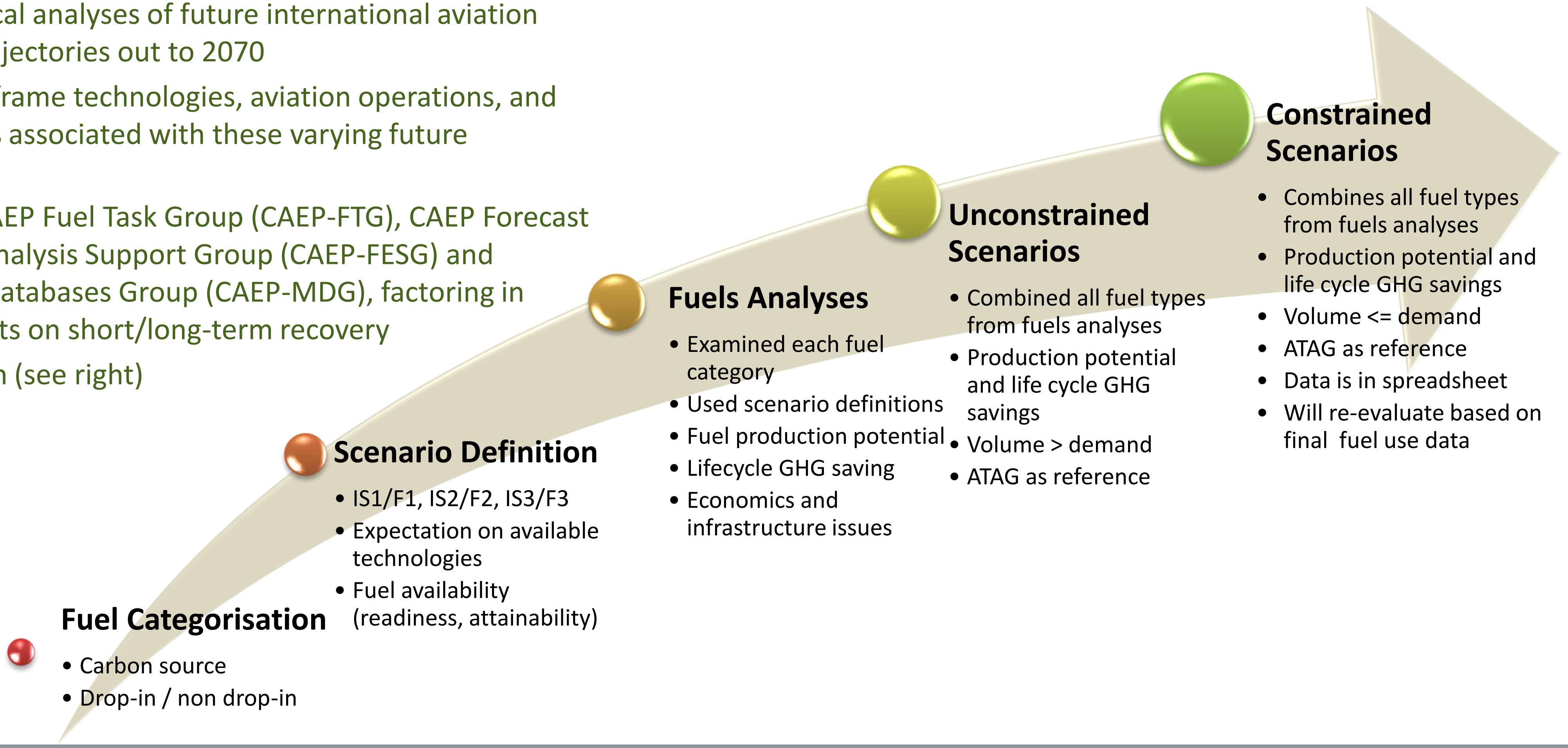
- ICAO Assembly Resolution A41-21 requested the Council to:
  - Continue to assess progress on the **development and deployment of SAF, LCAF and other cleaner energy sources for aviation** as part of the ICAO Stocktaking process
  - Convene the CAAF/3 in 2023 for **reviewing the 2050 ICAO Vision for SAF**, including LCAF and other cleaner energy sources for aviation
- ICAO's work on the LTAG provides useful information from the contribution of SAF/LCAF and cleaner energy sources



Fuels related information from the LTAG Report provide useful input to inform the review of the 2050 ICAO Vision

The LTAG approach to fuels

- Work on the LTAG was undertaken by the LTAG Task Group (LTAG-TG)
  - Provided technical analyses of future international aviation CO_2 emission trajectories out to 2070
  - Accounts for airframe technologies, aviation operations, and **alternative fuels** associated with these varying future scenarios
  - Supported by CAEP Fuel Task Group (CAEP-FTG), CAEP Forecast and Economic Analysis Support Group (CAEP-FESG) and Modelling and Databases Group (CAEP-MDG), factoring in COVID-19 impacts on short/long-term recovery
  - Overall approach (see right)



Presentation outline

1 – LTAG Fuels classification

2 – LTAG fuels scenarios

3 – Prioritization methodology

4 – Results – Volumes projections

5 – Results – GHG emission savings

6 – Analysis of fuel Readiness and Attainability

7 – Costs and investments associated with fuels scenarios

8 – Costs in context

1 – LTAG Fuels classification

Fuel classification

- Several fuel categories covering drop-in and non-drop-in fuel alternatives to conventional jet fuels are developed – crucial step as further assessments (fuel scenarios, volume projections, etc.) will be based off this categorization
  - **Sustainable aviation fuels (LTAG-SAF)**: drop-in aviation fuels produced from renewable or waste resources

Fuel Category	Fuel Name	Carbon sources in fuel feedstock
1. LTAG Sustainable Aviation Fuels (LTAG-SAF)	Biomass-based fuel	Primary biomass products and co-products
	Solid/liquid waste-based fuels	By-products, residues, and wastes
	Gaseous waste-based fuels	Waste CO/CO_2
	Atmospheric CO_2-based fuels	Atmospheric CO_2

Feedstocks include dedicated energy crops, municipal solid waste (MSW), fats, oil and grease (FOG), and can be processed via existing technologies (HEFA, ATJ, CHJ, etc.)

Requires hydrogen and CO_2 sources, and a conversion process. Many of such processes rely on significant electricity inputs, and are commonly considered Power-to-Liquid (PtL) pathways

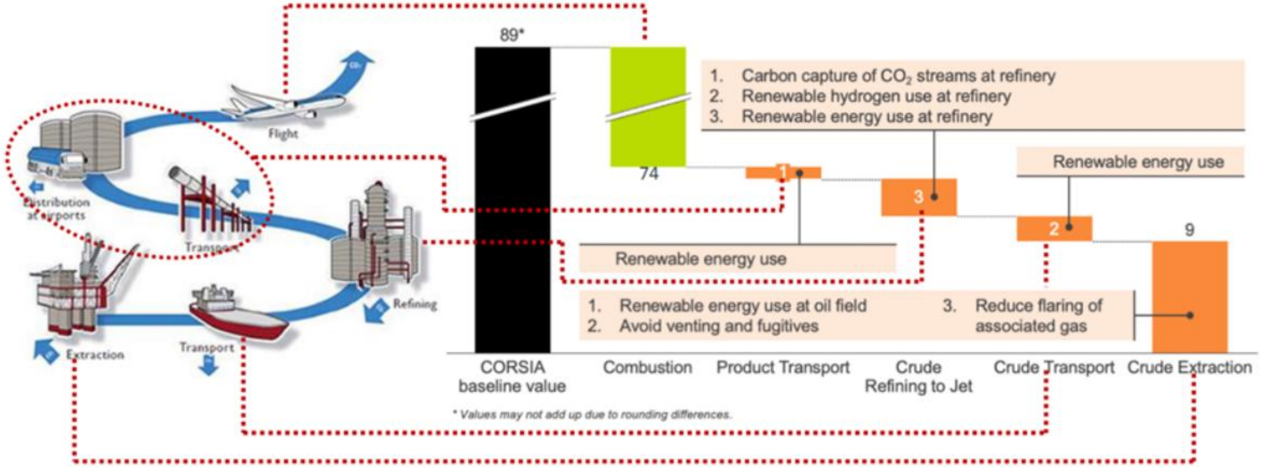
Fuel classification

- **Lower Carbon Aviation Fuels (LTAG-LCAF)**: drop-in aviation fuels that get the carbon in the fuel from petroleum resources, and demonstrates a well-to wake carbon intensity of <80.1 gCO_2e/MJ (10% below the life cycle emissions for conventional jet fuel)

Fuel Category	Fuel Name	Carbon sources in fuel feedstock
2. LTAG Lower Carbon Aviation Fuels (LTAG-LCAF)	Lower carbon petroleum fuels	Petroleum

Opportunities to reduce GHG emissions from the LTAG-LCAF supply chain include:

- Integration of renewable energy in operations
- Lower carbon hydrogen production
- Deployment of carbon capture/storage
- Minimization of flaring and venting emissions from upstream activities



Fuel classification

- **Non-drop-in Fuels**: Aviation fuels that require changes to existing and legacy airframe and fueling supply infrastructure.
  - These fuels are not compatible with current aircraft and engine architectures and have unique safety and performance considerations as compared with conventional aviation fuel

Fuel Category	Fuel Name	Carbon sources in fuel feedstock
3. Non-drop-in fuels	Electricity	Not applicable
	Liquefied gas aviation fuels (ASKT)	Petroleum gas, 'fat' natural gas, flare gas, and propane-butane gases
	Cryogenic hydrogen (LH_2)	Natural gas, by-products, non-carbon sources

Electrification of aircraft – including both hybrid and fully electric airframes. **Not part of LTAG-Fuels analysis (under LTAG-Tech).**

ASKT –LTAG-Fuels analyzed ASKT as part of case study for applicability in remote areas with stranded hydrocarbon resources. **Excluded from subsequent analyses and scenario reporting**

Not part of fuels analyses

Only LH_2 is considered under LTAG-Fuels scope - using direct combustion of liquid hydrogen in gas turbine engines. Additional methods (e.g. hydrogen fuel cells) not within LTAG-Fuels scope.

2 – LTAG fuel scenarios

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Fuel scenarios (F1, F2, F3) – Overall

- LTAG analysis was based on three fuel deployment scenarios: **Low – F1, Medium – F2, High – F3**
  - varying levels of readiness and attainability
  - Complementary to broader Integrated Scenarios IS1, IS2 and IS3, which also include technology and operational improvements

	MDG/FESG Baseline	LTAG-TG Scenarios		
	Integrated Scenario 0 (IS0)	**Integrated Scenario 1 (IS1)**	**Integrated Scenario 2 (IS2)**	**Integrated Scenario 3 (IS3)**
General Description	Projection of current technologies available in base year (through fleet renewal). No additional improvements from tech, ops and fuels. No systemic change – e.g. infrastructure changes to accommodate growth only.	**Low / nominal** Current (c. 2021) expectation of future available tech, ops efficiencies, fuel availability, costs. Includes expected policy enablers for technology, ops and fuels. **Low systemic change** – no ***substantial*** infrastructure changes.	**Increased / further** Approx mid-point. Faster rollout of future tech, increased ops efficiencies and higher fuel availability. Assumes increased policy enablers for technology, ops and fuels. **Increased systemic change** – limited infrastructure changes.	**Aggressive / speculative** Maximum possible effort: tech rollout, ops efficiencies, fuel availability, costs. Assumes max policy enablers for tech, ops and fuels. **High, internationally aligned systemic change** e.g. significant and broad change to airport and energy infrastructure.
Fuels (F)	No emissions reductions from low-carbon fuels (e.g. SAF).	**Low GHG reduction from Fuels (LTAG-SAF and LTAG-LCAF)**	**Mid GHG reduction from Fuels (LTAG-SAF and LTAG-LCAF)**	**High GHG reduction from Fuels (LTAG-SAF, LTAG-LCAF and non-drop-in fuels)**
		ASTM Intl develop methods to approve use of alternative jet fuels at blend levels above 50%.	ASTM Intl develop methods to approve use of 100% Synthesized Jet Fuel in existing aircraft and engines without any modification. This enables use of 100% SAF in all existing and new aircraft.	
		Ground transportation and aviation have level playing field with respect to alternative fuel use.	Electrification of ground transportation leads to increased availability of SAF as ground transport uses more electricity and less renewable fuels.	Economy-wide deep decarbonisation. Extensive electrification of ground transportation and widespread availability of renewable energy.
		Low incentives for LTAG-SAF/LTAG-LCAF production.	Increased incentives lead to reduced LTAG-SAF/LTAG-LCAF fuel cost for users.	Large incentives lead to widespread use of low GHG fuels for aviation.
		Technology evolution **enables use of waste (CO/CO_2) gases for LTAG-SAF**, **feedstock from a variety of settings** (e.g., oilseed cover crops), and **use of blue/green hydrogen** for LTAG-SAF/LTAG-LCAF production.	Technology evolution **enables widespread use of waste gases for LTAG-SAF**, **increased feedstock availability**, and **widespread use of blue/green hydrogen for LTAG-SAF/LTAG-LCAF** production. **Carbon Capture Utilization and Storage (CCUS) is in use.**	Technology evolution **enables widespread use of atmospheric CO2 for LTAG-SAF, further increases in feedstock availability, widespread use of CCUS**, and sufficient H2 exists to **enable use of cryogenic H2 use in aircraft**.
				Infrastructure developed to enable **use of non-drop-in fuels at airports** around globe

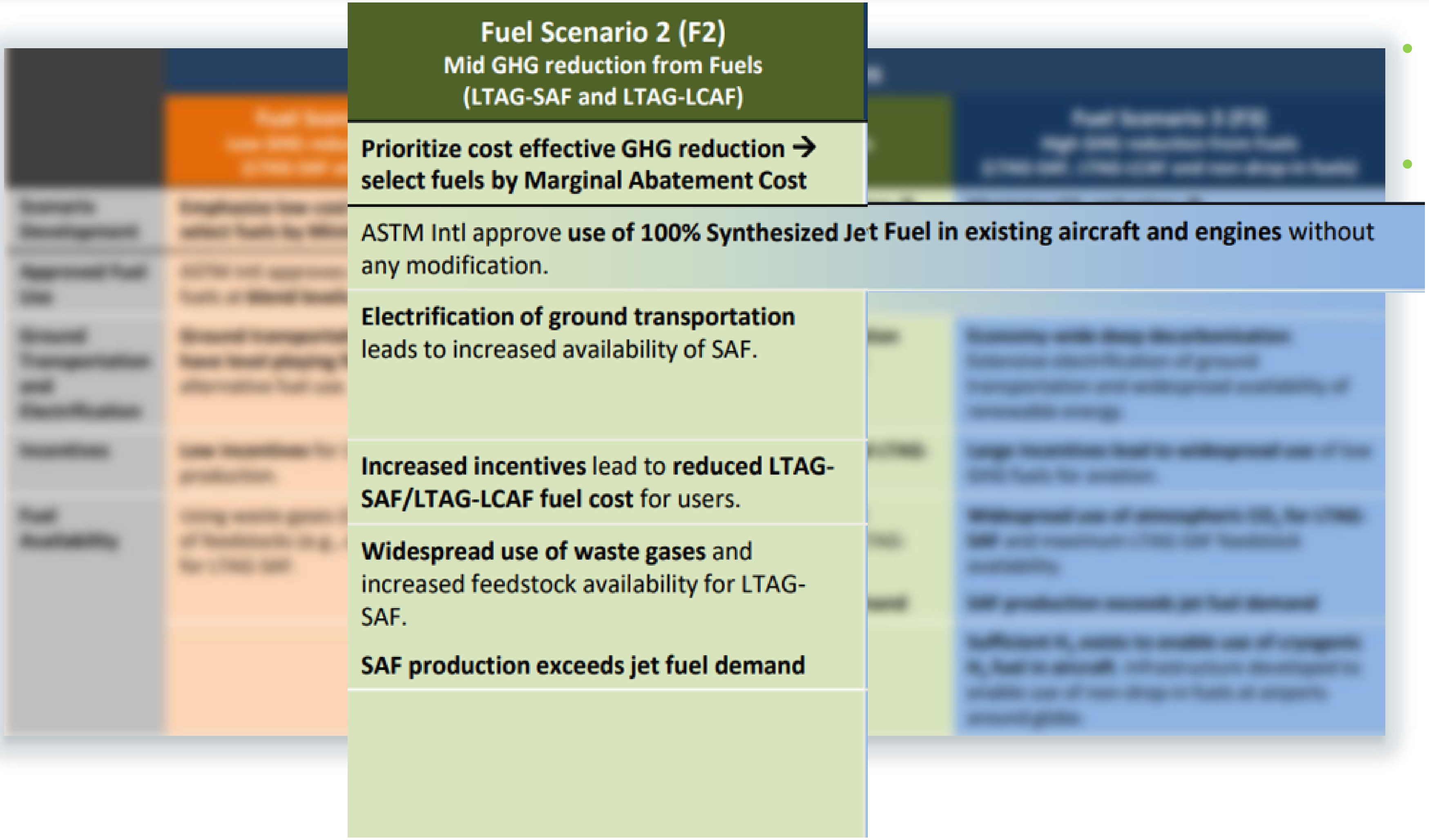
Decreasing readiness and attainability. Increasing aspiration

Fuels scenarios – Key descriptions

Fuel Scenario 1 (F1) Low GHG reduction from Fuels (LTAG-SAF and LTAG-LCAF)
Emphasize low cost GHG reduction → select fuels by Minimum Selling Price
ASTM Intl approves use of alternative jet fuels at **blend levels above 50%.**
Ground transportation and aviation have level playing field with respect to alternative fuel use.
Low incentives for LTAG-SAF/LTAG-LCAF production.
Using waste gases (CO/CO_2) and variety of feedstocks (e.g., oilseed cover crops) for LTAG-SAF.

- **F1** represents the **low end of the range of potential GHG reductions** from fuels (LTAG-SAF and LTAG-LCAF)
- Fuel production technologies and certification process that are considered have **high attainability and readiness**
  - Technology to enable the use of waste gases for LTAG-SAF production, but volumes limited to most economic sources
  - Low incentives for LTAG-SAF and LTAG-LCAF production

Fuels scenarios – Key descriptions



- **F2** represents the **middle of the range of potential GHG reductions** from fuels (LTAG-SAF and LTAG-LCAF)
- Fuel production technologies and certification process are considered that have **medium attainability and readiness**
  - Increased technologies to **enable to use of waste gases** for LTAG-SAF production, with expanded waste resource volumes.
  - Broader electrification of ground transportation and CCUS use
  - Increased incentives for LTAG-SAF and LTAG-LCAF production

Fuels scenarios – Key descriptions

Fuel Scenario 3 (F3) High GHG reduction from Fuels (LTAG-SAF, LTAG-LCAF and non-drop-in fuels)
Maximize CO_2 reduction → select fuels by Lifecycle Value
ASTM Intl approve **use of 100% Synthesized Jet Fuel in existing aircraft and engines** without any modification.
Economy-wide deep decarbonisation. Extensive electrification of ground transportation and widespread availability of renewable energy.
Large incentives lead to widespread use of low GHG fuels for aviation.
Widespread use of atmospheric CO_2 for LTAG-SAF and maximum LTAG-SAF feedstock availability. **SAF production exceeds jet fuel demand**
Sufficient H_2 exists to enable use of cryogenic H_2 fuel in aircraft. Infrastructure developed to enable use of non-drop-in fuels at airports around globe.

- **F3** represents the **high range of potential GHG reductions** from fuels (LTAG-SAF, LTAG-LCAF and non-drop-in fuels)
- **Advanced fuel production technologies and certification processes** are considered that have **low attainability and readiness**
  - Increased technologies to enable to use of waste and **atmospheric gases** for LTAG-SAF production, with expanded waste resource volumes.
  - Economy-wide deep decarbonization (electrification of ground transportation, CCUS)
  - Use of cryogenic hydrogen in aircraft
  - Significant changes to energy and airport infrastructure development to enable use of non-drop-in fuels.

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Assessing and aligning fuel deployment across scenarios (LTAG-SAF)

- **Taking into account the fuel scenarios, potential fuel volumes for each fuel category were assessed**
  - Factors in readiness and attainability criteria

Fuel Category	Fuel Name	Carbon sources in fuel feedstock
1. LTAG Sustainable Aviation Fuels (LTAG-SAF)	**Biomass-based fuel**	**Primary biomass products and co-products**
	Solid/liquid waste-based fuels	**By-products, residues, and wastes**
	Gaseous waste-based fuels	Waste CO/CO_2
	Atmospheric CO_2-based fuels	Atmospheric CO_2

- Supported by market diffusion models to model future SAF volumes (up to 2070) using current knowledge on existing and announced SAF production facilities
- Feedstock availability checks also done to ensure projected volumes do not exceed potential feedstock resources
- Five scenarios developed by TPP (low, **moderate**, **high**, **high+**, max) to capture future production potential
  - **Moderate** (**F1**) – Some incentives for SAF/LCAF production to level playing field with ground transportation fuels
  - **High** (**F2**) – Increased policy enablers for technology evolution to enable more widespread use of waste gases for SAF production, as well as electrification of ground vehicles, increasing SAF/LCAF availability for aviation
  - **High+** (**F3**) – Economy wide deep carbonization, large incentives for low GHG fuels for aviation

Assessing and aligning fuel deployment across scenarios (LTAG-SAF)

Fuel Category	Fuel Name	Carbon sources in fuel feedstock
1. LTAG Sustainable Aviation Fuels (LTAG-SAF)	**Biomass-based fuel**	**Primary biomass products and co-products**
	Solid/liquid waste-based fuels	**By-products, residues, and wastes**
	Gaseous waste-based fuels	Waste CO/CO_2
	Atmospheric CO_2-based fuels	Atmospheric CO_2

- For this sub-category, several processes to obtain fuel feedstock were defined and reviewed
- Size of future waste CO2 streams under different scenarios, availability of CO2 captured through direct air capture (DAC), availability of renewable electricity for fuel production were considered to estimate obtainable fuel volumes

	Waste CO_2 streams				Atmospheric CO_2
CO_2 source	Ethanol	Ammonia	Iron/Steel	Cement	Atmospheric CO_2
Considered in fuel scenario	F1, F2, F3	F1, F2, F3	F2, F3	F2, F3	F3

Assessing and aligning fuel deployment across scenarios (LTAG-LCAF)

Fuel Category	Fuel Name	Carbon sources in fuel feedstock
2. LTAG Lower Carbon Aviation Fuels (LTAG-LCAF)	Lower carbon petroleum fuels	Petroleum

- **Considered for F1, F2 and F3**
- A detailed **bottom-up approach used to model the global jet fuel supply chain** and a top-down approach to define the deployment scenarios for LTAG-LCAF based on the timeframe considered.
- **Emissions reductions acquired** through the following to meet well-to-wake carbon intensity of <80.1 gCO_2e/MJ, and its effects are modelled, based on max, high (**F3**), medium (**F2**), low scenarios (**F1**) (see right)
  - Low carbon electricity use
  - Control of methane leakages
  - Minimization of flaring of associated gases
  - Carbon capture of process flue gas
  - Low carbon hydrogen use
- As the measures are technology dependent, technology deployment factors (%) are then applied

Measures	CI gCO2e/Mj	Effect of measures (delta CI vs Ref) gCO2e/MJ			
	REF	MAM	HIGH	MED	LOW
Upstream	8.4	-5.7	-5.4	-4.4	-3.2
No Routine Flaring		*-2.0*	*-2.0*	*-2.0*	*-2.0*
Min. Fugitives		*-2.5*	*-2.5*	*-1.9*	*-1.2*
Renewables integration - Heavy Oilfields		*-1.2*	*-0.9*	*-0.6*	*0.0*
Crude transportation	1.4	-1.3	-1.3	-0.9	-0.6
Refinery	4.9	-3.5	-2.4	-1.9	-0.5
CC at CDU furnaces		*-1.3*	*-1.3*	*-1.0*	*0.0*
CC applied to whole refinery		*-1.0*	*0.0*	*0.0*	*0.0*
Low carbon electricity		*-0.5*	*-0.5*	*-0.5*	*-0.5*
Low carbon steam generation		*-0.1*	*-0.1*	*-0.1*	*0.0*
Blue/Green H2		*-0.6*	*-0.4*	*-0.3*	*0.0*
Jet Fuel transportation	1	-0.9	-0.9	-0.5	-0.2
Combustion	73.1	0.0	0.0	0.0	0.0
Total carbon intensity reduction (gCO2e/MJ)	0.0	-11.3	-9.9	-7.7	-4.5
Global average carbon intensity (gCO2e/MJ)	**89**	**77**	**79**	**81**	**84**

Average carbon intensity of jet fuel and contribution of mitigation measures

REF (Reference case with no measures applied), **MAM** (Maximum attainable mitigation), **LOW**, **MED**, **HIGH** (progressive deep application of measures)

Assessing and aligning fuel deployment across scenarios (Non-drop-in fuels)

Fuel Category	Fuel Name	Carbon sources in fuel feedstock
3. Non-drop-in fuels	**Electricity**	Not applicable
	Liquefied gas aviation fuels (ASKT)	Petroleum gas, 'fat' natural gas, flare gas, and propane-butane gases
	Cryogenic hydrogen (LH_2)	Natural gas, by-products, non-carbon sources

Not part of fuels analyses

- Only applicable in **F3**
- Airport fueling infrastructure, expected hydrogen volumes, broader supply chain systems assessed
- Hydrogen production was modelled using electrolysis – no specific electrolysis process defined, but an energy efficiency of 70% was assumed, consistent with proton exchange membrane (PEM) analysis
- Electricity demand for liquefaction of hydrogen and transport of gaseous hydrogen were also assessed.
- Sum of electricity requirements for cryogenic hydrogen production detailed below

	2020	2030	2040	2050	2060	2070
Electrolysis	*1.43*	*1.43*	*1.43*	*1.43*	*1.43*	*1.43*
Liquefaction	*0.3*	*0.25*	*0.2*	*0.15*	*0.15*	*0.15*
Transport	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*
Total	**1.75**	**1.70**	**1.65**	**1.60**	**1.60**	**1.60**

3 - Prioritization methodology

Prioritization methodologies

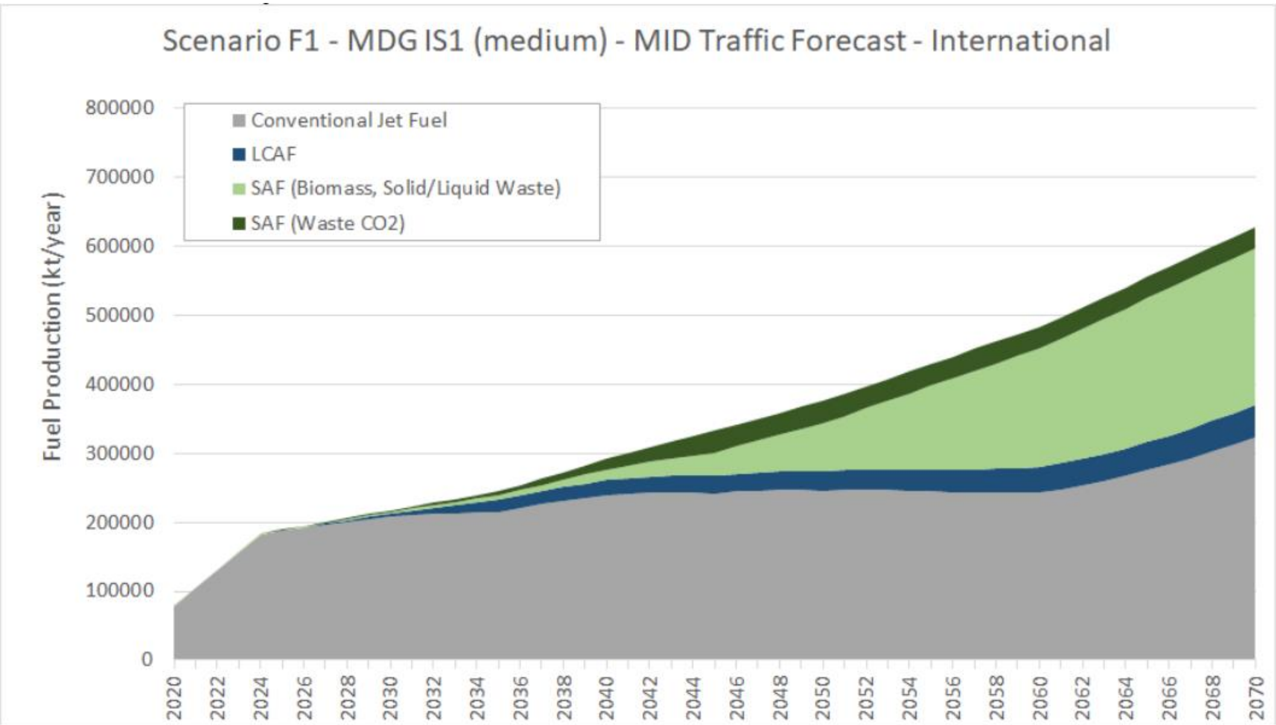
- **In determining the overall potential fuel availability, the projected fuel volumes from each fuel category were combined based on the scenarios definitions**
  - Ensuring combined fuel volumes were aligned with scenario definitions
  - **Prioritization of fuel categories** in scenarios where projected volumes (LTAG-SAF and LTAG-LCAF) **exceeded** aviation demand requires analyses to move from unconstrained to constrained fuel volumes to establish the production split between fuel categories
    - F1, prioritized low cost GHG reduction, with fuels ordered by Minimum Selling Price (MSP)
    - F2, prioritized cost effective GHG reduction using marginal abatement cost
    - F3, prioritized GHG reductions using fuel LCA values

F1	MSP [$/L]	F2	Marginal Abatement Cost [$/kg CO_{2red}]	F3	Lifecycle [gCO_2e/MJ]
LTAG-LCAF	0.52	LTAG-SAF-biomass/waste	<1	LTAG-SAF-DAC	8-13
LTAG-SAF-biomass/waste	0.9-2	LTAG-LCAF	<1	LTAG-SAF-waste CO_2	13-16
LTAG-SAF-waste CO_2	~2.5	LTAG-SAF-waste CO_2	4.3	LTAG-SAF-biomass/waste	21-24
LTAG-SAF-DAC	N/A	LTAG-SAF-DAC	N/A	LTAG-LCAF	80.1

4 – Results – Volume projections

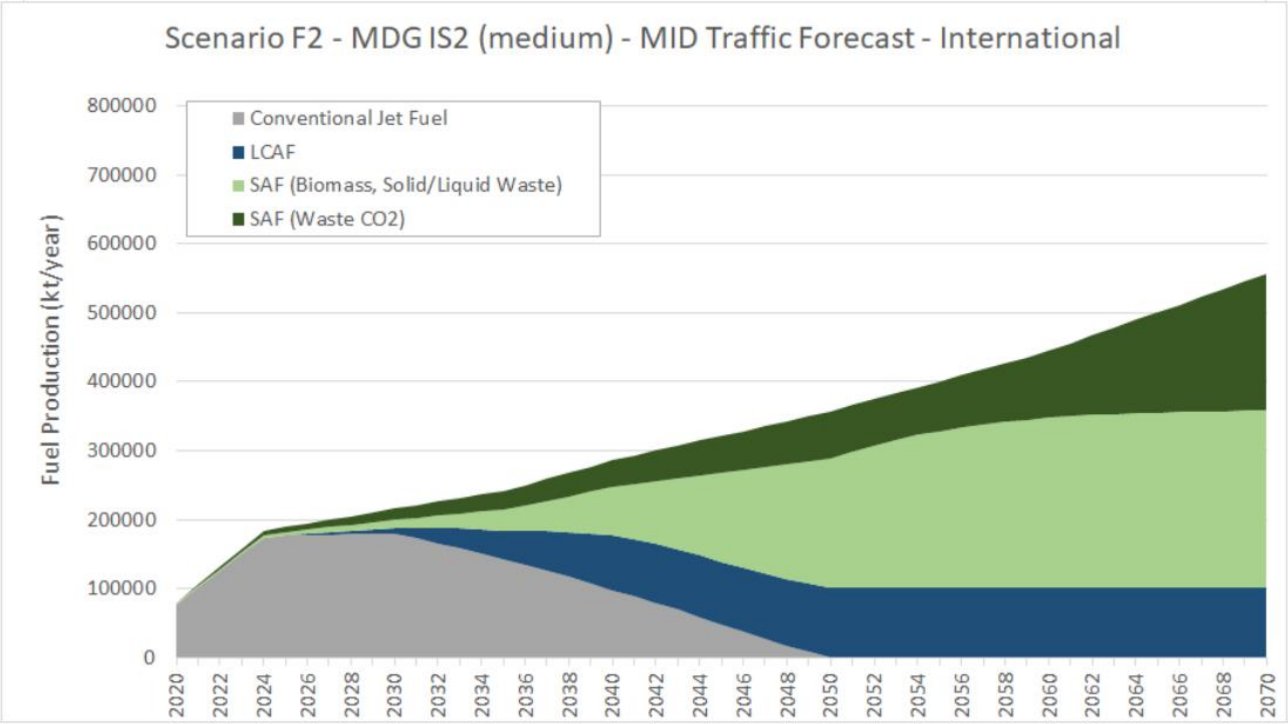
Combined fuel results based on MID traffic forecasts

- **Fuel use (supply / demand) for F1, F2 and F3 scenarios based on MID traffic forecasts**
    - **Under F1**, in 2050, conventional jet fuel supplies two-thirds of total international jet fuel demand with LTAG-LCAF and LTAG-SAF supplying roughly one-third of international jet fuel demand



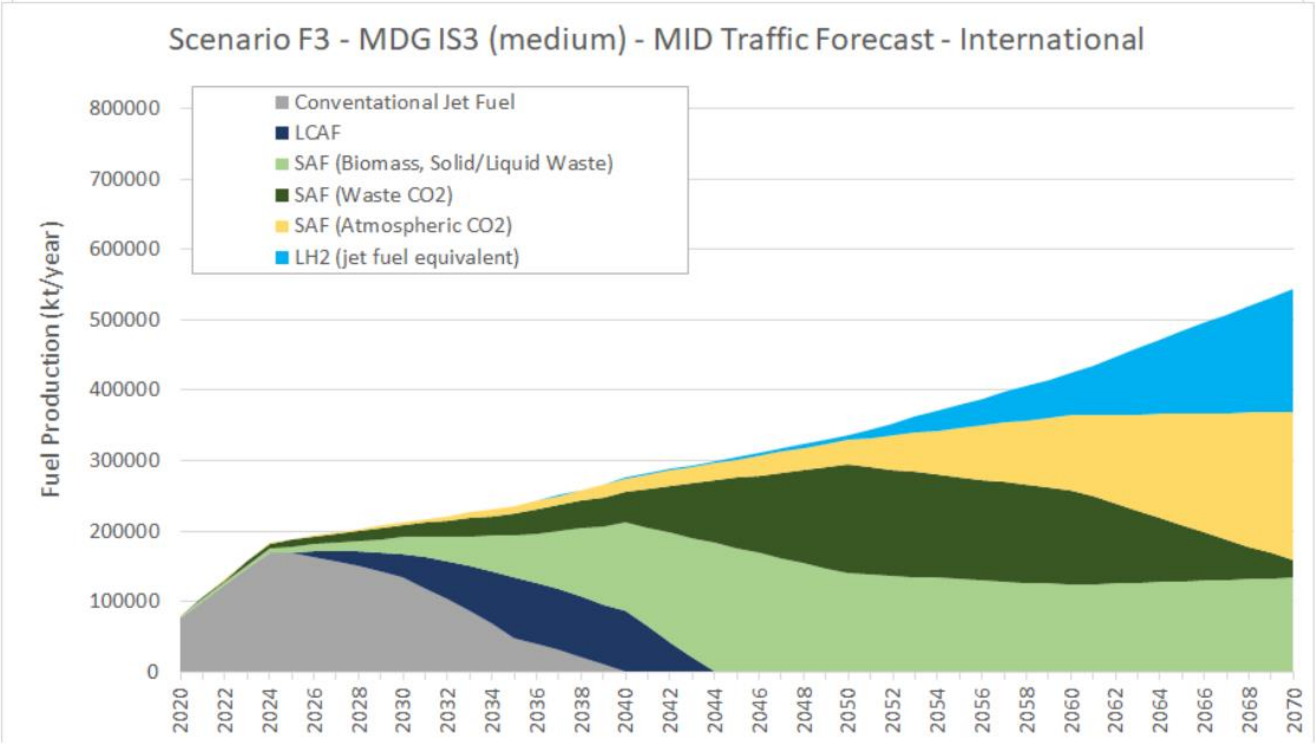
Combined fuel results based on MID traffic forecasts

- **Fuel use (supply / demand) for F1, F2 and F3 scenarios based on MID traffic forecasts**
  - **Under F2**, in 2050, LTAG-LCAF and LTAG-SAF supply 100% of international jet fuel demand with roughly two-thirds from LTAG-SAF, and one-third from LTAG-LCAF



Combined fuel results based on MID traffic forecasts

- **Fuel use (supply / demand) for F1, F2 and F3 scenarios based on MID traffic forecasts**
  - **Under F3**, in 2050 SAF production may well exceed international jet fuel demand
  - In 2070, non-drop-in demand grows to roughly one-third of all international jet fuel demand



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Aviation fuel production, by fuel category, by ICAO region

- **LTAG-SAF**
  - Production and uptake of LTAG-SAF will have regional variability
  - LTAG-SAF production dependent on feedstock availability
    - As economies decarbonize, availability of waste CO/CO2 from industrial processes will decrease
    - Regions may have limited biomass and solid/liquid waste resources
  - LTAG-SAF uptake will depend on regional incentives for low GHG fuels (tax credits, mandates for low GHG transportation fuels, etc.)
- **LTAG-LCAF**
  - Production of LTAG-LCAF dependent on key mitigation technologies, and its implementation across the jet fuel supply chain
  - Regional variations of market conditions and government incentives will determine the investment and uptake of LTAG-LCAF

5 – Results - GHG emissions savings

GHG emissions savings

- **Based on fuel production estimates in the F1, F2, and F3 scenarios and the calculated Life Cycle Assessment (LCA) values for each of the fuel categories, the potential GHG emissions savings was evaluated**
  - LCA values for each of the fuel categories combined to form a weighted average LCA value of the overall fuel mix
  - Value is used to determine an overall Emissions Reduction Factor (ERF) for each of the scenarios (F1, F2, F3) in 2035, 2050 and 2070.
  - ERF based on MID traffic forecast, indicating the **reduction in GHG emissions** compared to conventional fuel baselines, reflecting the use of LTAG-SAF, LTAG-LCAF, and non-drop-in fuels

Year	F1	F2	F3
2035	5%	20%	37%
2050	20%	56%	81%
2070	28%	66%	88%

6 – Analysis of Fuel Readiness and Attainability

Readiness and attainability considerations

- **What do readiness and attainability considerations within the LTAG-Fuels context mean?**
  - **Readiness**: the timeframe to which specific measures in fuels can be achieved (e.g. by 2030, by 2040, by 2050)
  - **Attainability**: if it is possible to implement a specific measure in terms of available resources, barriers, costs, location, etc.

		LTAG-SAF	LTAG-LCAF	non-drop-in fuels (LH_2)
Readiness criteria	R.1: Current status of the fuel conversion technology	X	X	X
	R.2: Current status in the ASTM approval process	X	X	
	R.3: Availability of systems to produce low carbon energy carriers (incl. feedstock availability)	X		X
	R.3: Standards/regulations to govern safety/handling etc.			X
Attainability criteria	A.1: Capital investment requirements	X	X	X
	A.2: Cost competitiveness.	X	X	X
	A.3: Land area requirements	X	X	X
	A.4: Water requirements	X	X	X
	A.5: Soil requirements	X	X	X
	A.6: Biodiversity assessment,	X	X	X
	A.7: Infrastructure for fuel transportation	X	X	

Readiness and attainability considerations

- **For LTAG-SAF – biomass & solid/liquid waste based drop-in fuel**

R Readiness Assessment

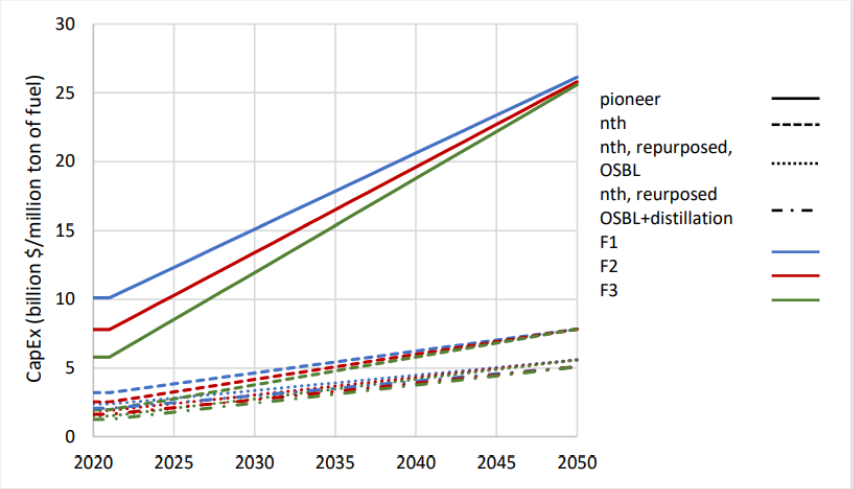
- R.1 Current status of the fuel conversion technology
- R.2 Current status in the ASTM approval process
- R.3 Availability of systems to produce low carbon energy carriers (incl. feedstock availability)

- **R.1:** Assumed to be at operational levels, equivalent to TRL 9 of mature technology with established production capability.
- **R.2**: Status assumed to be an approved fuel annexed under ASTM D7566 and certified to be blended with conventional fuel.
- **R.3**: Incorporated through the fuel lifecycle analysis under assumptions for the availability of renewable energy resources.

A Attainability Assessment

- A.1 Capital investment requirements: Fuel production & energy systems
- A.2 Cost competitiveness (Fuel Minimum Selling Price)
- A.3 Land area requirements
- A.4 Water requirements
- A.5 Soil requirements
- A.6 Biodiversity assessment
- A.7 Infrastructure for fuel transport

- **A.1:** Projected Capex for pioneer and n^th plant scenarios (see right) – capex per unit fuel expected to increase over time, due to reliance on more expensive feedstocks/pathways over time.
- **A.2**: MSP to be ~$0.90-$2.00 per litre of fuel
- **A.3-A.6:** No significant feedstock limitations expected. **A.7**: Existing fuel transportation infrastructure to be used.



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Readiness and attainability considerations

• For LTAG-SAF – waste CO_2 & atmospheric CO_2- based drop-in fuel

R Readiness Assessment

- R.1 Current status of the fuel conversion technology
- R.2 Current status in the ASTM approval process
- R.3 Availability of systems to produce low carbon energy carriers (incl. feedstock availability)

- **R.1:** For **H_2 production**, mature production technologies exist, and significant cost decreases expected as use of technologies is scaled up. For **CO_2 capture technologies**, different levels of maturity. For **fuel conversion**, established processes exist (Fischer-Tropsch, Waste CO_2 to Alcohol-to-Jet)
- **R.2**: Generally considered to have received ASTM approval under ASTM D7566 Annex A1 and Annex A5
- **R.3**: Uptake of fuel volumes under fuels scenarios requires expanding renewable power generation

A Attainability Assessment

- A.1 Capital investment requirements: Fuel production & energy systems
- A.2 Cost competitiveness (Fuel Minimum Selling Price)
- A.3 Land area requirements
- A.4 Water requirements
- A.5 Soil requirements
- A.6 Biodiversity assessment
- A.7 Infrastructure for fuel transport

- **A.1:** Specific investments needed to produce 1 megaton of PtL fuel per year are \$18-63b in 2020 (over different scenarios), \$11-48b in 2030, \$9-38b in 2040, and \$7-32b in 2050.
- In order to reach projected fuel volumes for waste CO_2 sources and atmospheric CO_2, total investment into fuel production of \$1180-2700b for F1, \$1880-4300b for F2, and \$3000-6850b for F3, and \$790-1600b under F3 using DAC (Direct Air Capture).
- However, as only a portion of the fuel output is jet fuel, by allocating the investments to the jet fuel portion, these values are expected to reduce.
- **A.2**: Fuels from waste CO2 and atmospheric CO2 are found to currently be around 5-10 times as expensive as conventional jet fuel: costs driven by H2 production, conversion costs, DAC.
- **A.3-A.4**: Land area requirements mainly for renewable power generation (e.g. wind turbines), but can be used for other purposes (e.g. agriculture)
- **A.5-A.7:** No significant hurdles on attainability expected

Readiness and attainability considerations

- **For LTAG-LCAF**:

R Readiness Assessment

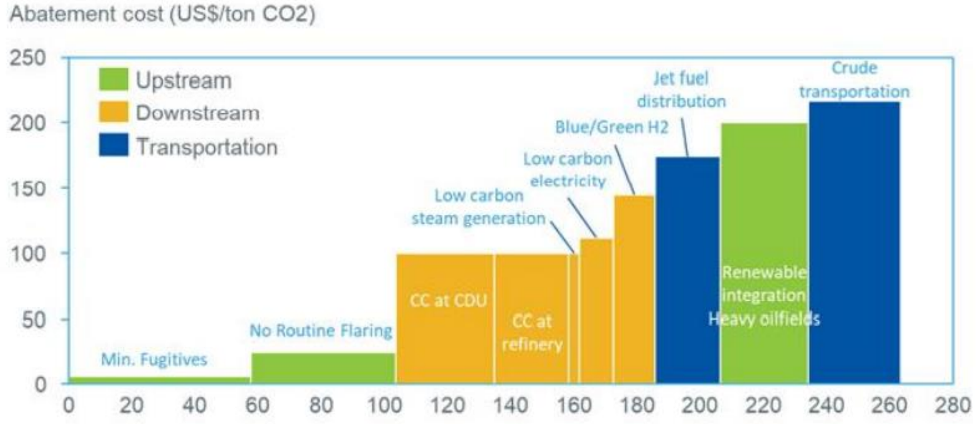
- R.1 *Current status of the fuel conversion technology*
- R.2 *Current status in the ASTM approval process*

- **R.1:** For **Low carbon H_2 production**, mature production technologies exist – costs decreases expected as use of technologies scale up. For **CO_2 capture technologies**, there are varying levels of maturity observed. For **Gas management practices**, technologies and practices are well identified and considered mature.
- **R.2**: LTAG-LCAF have the same specifications as jet fuel, and no additional ASTM approval expected.

A Attainability Assessment

- A.1 *Capital investment requirements: Fuel production & energy systems*
- A.2 *Cost competitiveness (Fuel Minimum Selling Price)*
- A.3 *Land area requirements*
- A.4 *Water requirements*
- A.5 *Soil requirements*
- A.6 *Biodiversity assessment*
- A.7 *Infrastructure for fuel transport*

- **A.1:** LTAG-LCAF will require the deployment of GHG mitigation technologies with a wide range of abatement costs, from \$6/tonCO_2e to >\$200/tonCO_2e.
- **A.2**: Estimated average abatement cost of \$63, 87, 95 [\$/tCO_2] respectively for the F1/2/3 scenarios
- **A.3-7**: No significant hurdles on attainability expected



Readiness and attainability considerations

- **For Non drop-in LH_2 (only applies to F3):**

R ***Readiness Assessment***

- R.1 *Standards/regulations to govern safety, handling etc.*
- R.2 *Current status of the fuel conversion technology*
- R.3 *Availability of systems to produce low carbon energy carriers*

- **R.1:** Standards exist which govern the use of LH_2 in industrial contexts, as well as for vehicles, which mostly regulate hydrogen storage and distribution infrastructure. Existing standards do not capture specifics of use at the airport and in aircraft (proximity to terminal building, passengers boarding aircraft, at altitude etc.). Safety equipment exists which help mitigate some specific safety challenges of hydrogen
- **R.2**: Mature production technologies exist for the production and liquefaction of hydrogen, and significant cost reductions expected in the future
- **R.3**: Share of aviation H_2 expected to be less than 1% of global H_2 demand if the world transits to IEA's Sustainable Development Scenario (SDS).

A ***Attainability Assessment***

- A.1 *Capital investment requirements*
  - *Fuel production & energy systems*
  - *Infrastructure for fuel transportation*
  - *Airport infrastructure*
- A.2 *Cost competitiveness (Fuel Minimum Selling Price)*
- A.3 *Land area requirements*
- A.4 *Water requirements*
- A.5 *Soil requirements*
- A.6 *Biodiversity assessment*

- **A.1:** Specific investment costs for LH_2 production under F3 are \$24-37b per ton of liquid hydrogen in 2040, \$16-25b in 2050
- For airports, different LH2 fueling systems are likely to be installed with a global investment volume on the order of \$100-150b – airports will be required to operate LH_2 and Jet-A fueling systems in parallel, which causes additional challenges
- **A.2**: Today, LH_2 from renewable electricity can be produced around \$7 per kg (~5 times as high as Jet-A on an energy basis) – expected to decline over time, but may face competition for its use by other sectors.
- **A.3-4**: Some land area and water requirements expected
- **A.5-6**: No significant hurdles for attainability expected

7 - Costs and investments associated with fuels scenarios

Projected costs/investments across scenarios

- **The LTAG costs and investments analysis included the following cost elements:**
  - Research and development (R&D)
  - Total capital investment (TCI)
  - Total feedstock costs
  - Total infrastructure cost
  - Minimum Selling Price (MSP) of fuels vs conventional jet fuel
- **The table below summarizes the results of investments/costs from fuel suppliers and airlines associated with the fuels scenarios**
  - For airports Costs and investments only relevant in IS3 ($125 billion related to fuel infrastructure for hydrogen)

	Costs and Investments for fuels suppliers (billion USD)			Costs and Investments for Operators (airlines)		
	IS1	IS2	IS3	IS1	IS2	IS3
SAF biomass-based fuels	480	1,200	950	300	1,200	1,600
SAF from gaseous waste	710	1,000	1,700	770	1,400	1,800
SAF from atmospheric CO2	-	-	460	-	-	600
LCAF	50	105	60	50	105	60
Hydrogen	-	-	55	-	-	10
Total	1,300	2,300	3,200	1,120	2,705	4,070

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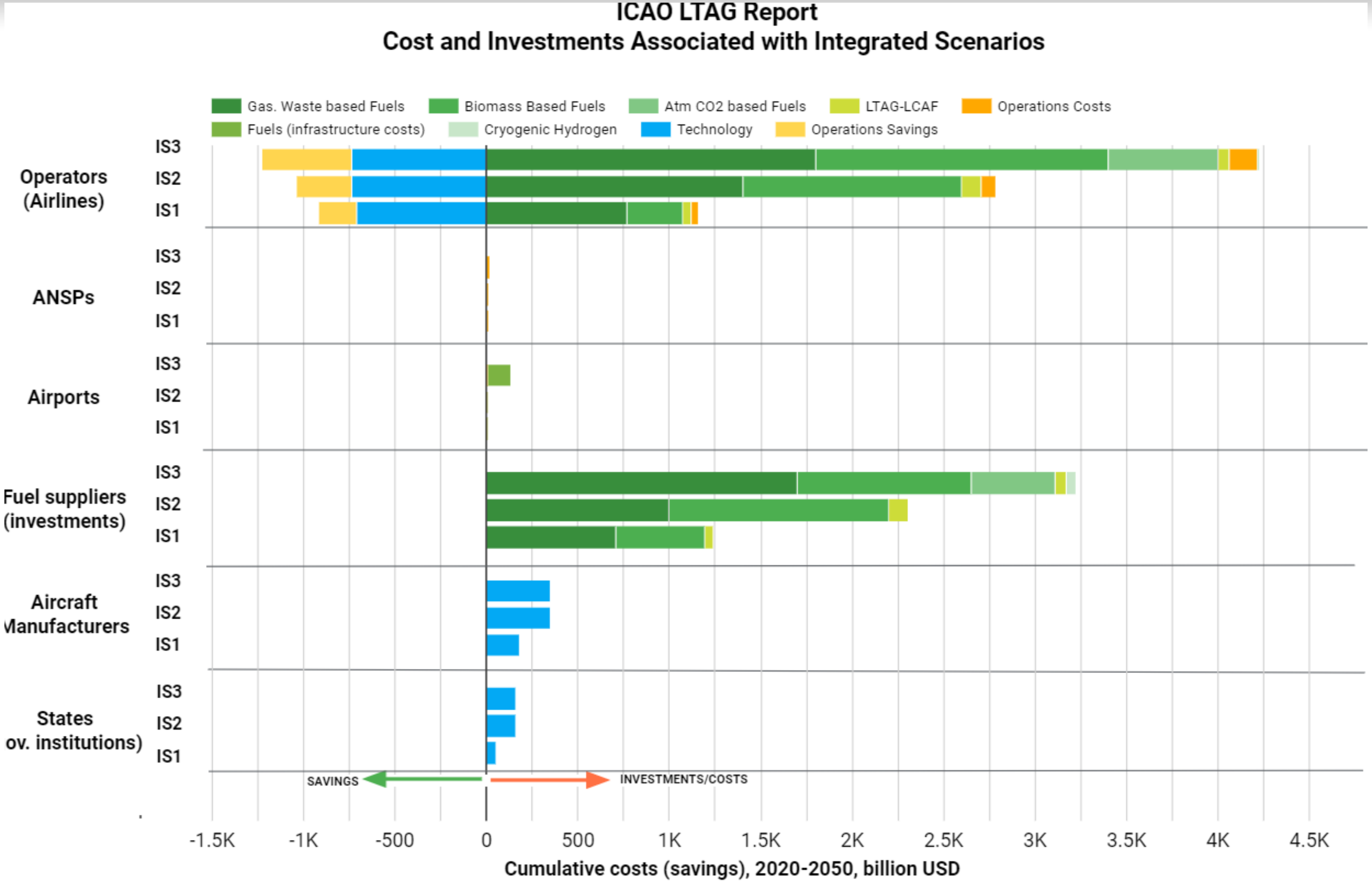
Projected costs/investments across scenarios

- **Summary results in graphical format**



`Note: Costs associated with scenario are not meant to be added towards a total cumulative cost. Costs and investments are displayed across a chain of stakeholders. Some investments from upstream stakeholders are passed on downstream in the form of incremental price of products (e.g. investments from fuel suppliers passed on to operators as part of Minimum Selling Price

8 - Costs in context

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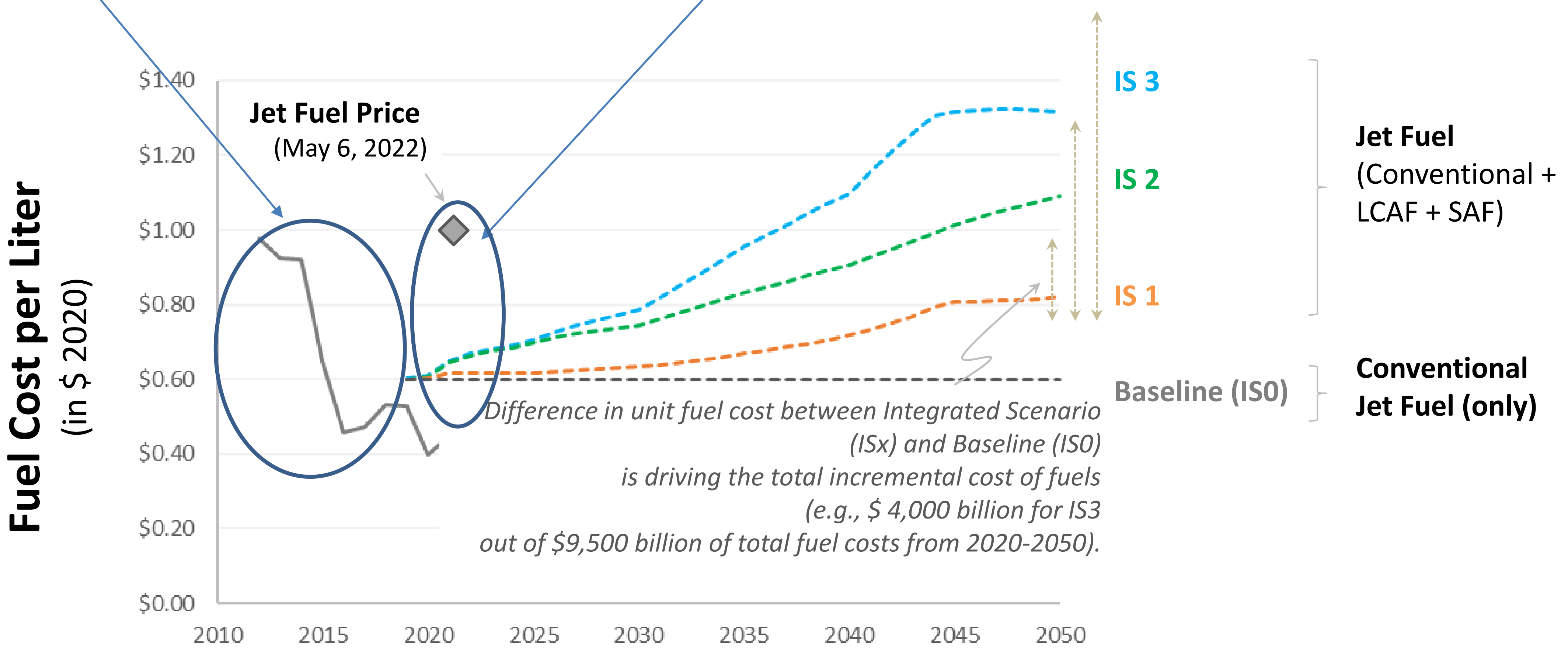
Unit Fuel Costs in Context of Historical Jet Fuel Costs

Over the last ten years, average cost of fuels varied from $0.40 to $1.00 $/L (a factor of 2.5×)

- LTAG baseline scenario assumed baseline fuel cost of $0.60 per liter.
- Jet fuel price has increased to about $1/L in May 2022



Total Cost of Fuels with underlying assumptions

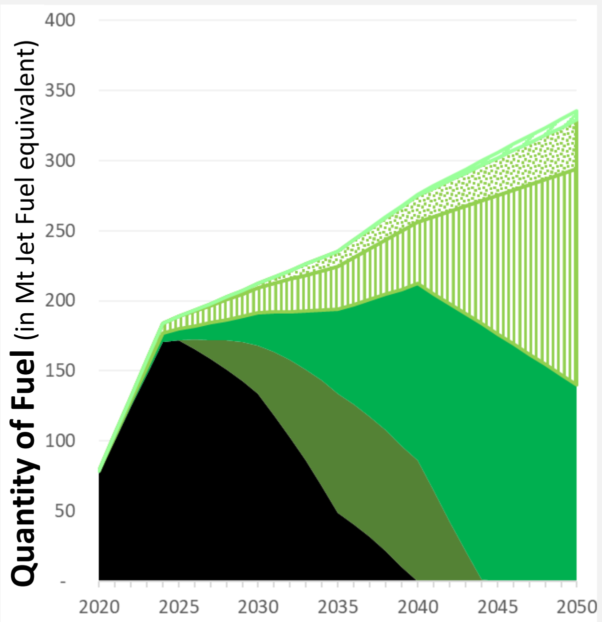
Illustrative LTAG Integrated Scenario 3

- 6% of incremental fuel costs would be borne in the 2020s and 69% in the 2040s.

Incremental fuel costs in context of Baseline fuel cost (at 0.60 \$/L)

Fuel Volumes

(by type of fuels 2020-2050)



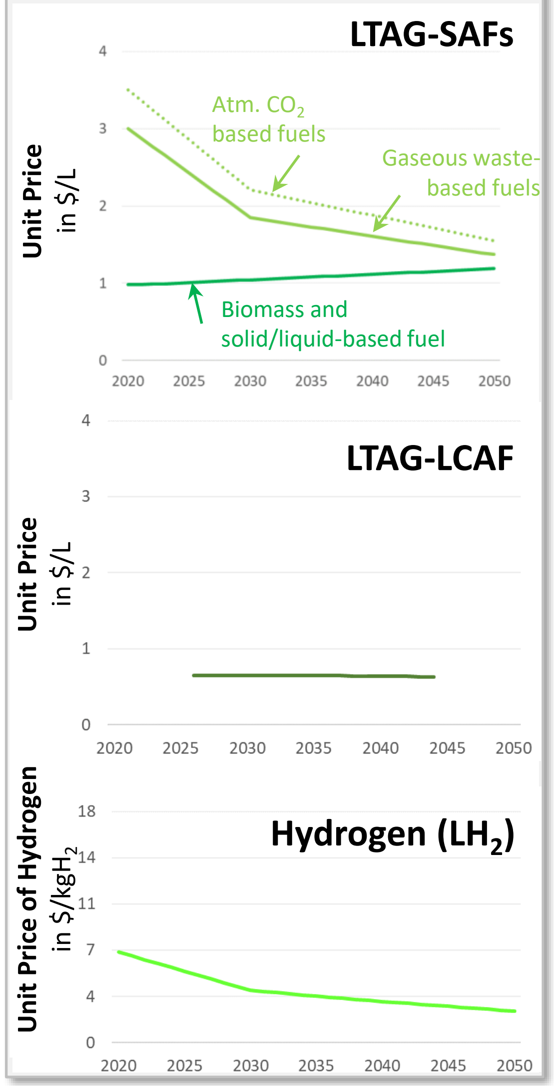
Legend:

- Non drop in fuels: Cryogenic Hydrogen
- LTAG-SAF Atmospheric CO2 based fuels
- LTAG-SAF Gaseous waste based fuels
- LTAG-SAF Biomass based fuel & LTAG-Solid/liquid waste based fuels
- LTAG-LCAF: Lower carbon petroleum fuels
- Conventional Jet Fuel

x

Unit Price of Fuels

(2020-2050)



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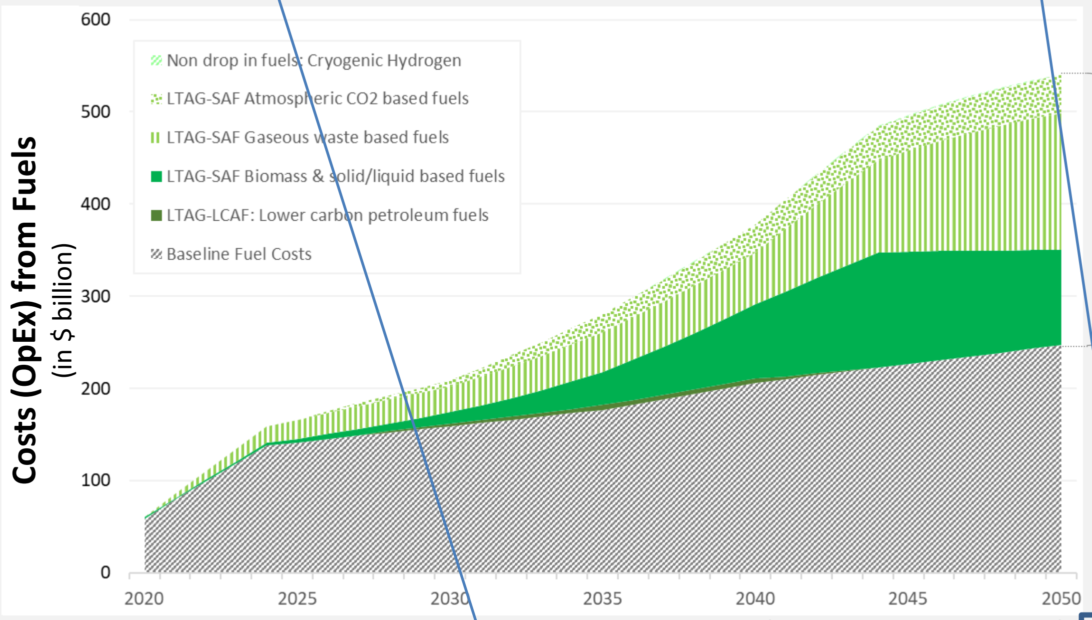
Total Cost of Fuels

(2020-2050)

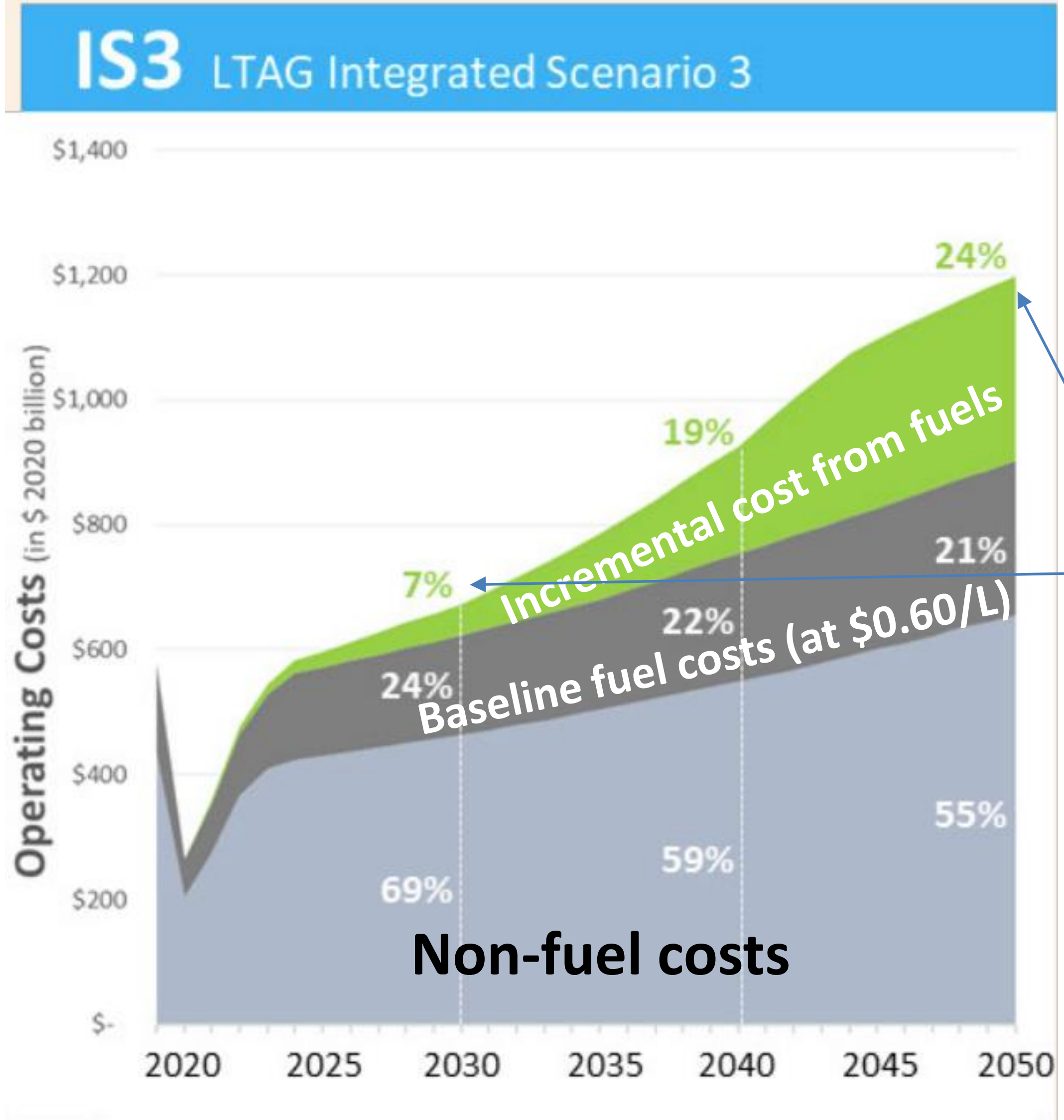


	2020s	2030s	2040s +2050	Total (2020-2050)
Incremental fuel costs	\$230 B (6%)	\$1000 B (25%)	\$2790 B (69%)	\$4020 B (100%)
Baseline fuel cost (at 0.60 \$/L)	\$1240 B (22%)	\$1770 B (32%)	\$2490 B (45%)	\$5500 B (100%)

Total: **\$9520 B**

† calculated as (Minimum Selling Price of SAF – Conventional Fuel costs) * Volume of SAF

Incremental fuel costs in context of operating costs



Under IS3, incremental costs of Fuels may represent 7% of total operating costs by the international aviation in 2030, and 24% in 2050

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Incremental costs per flight

Flight Distance *Illustrative Origin & Destination*		Incremental Cost* per Flight *(Incremental Cost* per Seat**)* *in 2030*	*in 2050*
Short *Haul Flight* 630 km *(≈10th percentile of int. aviation flights)* **Zurich** → **Amsterdam** *Switzerland* *Netherlands* *(LSZH)* *(EHAM)*	IS1	$ 130 *($0.8)*	$ 780 *($4.4)*
	IS2	$ 520 *($3.3)*	$ 1600 *($9.2)*
	IS3	$ 660 *($4.3)*	$ 2200 *($13)*
Average *Haul Flight* 2700 km *(average for international aviation)* **Montreal** → **Denver** *Canada* *U.S.* *(CYUL)* *(KDEN)*	IS1	$ 650 *($3)*	$ 3500 *($15)*
	IS2	$ 2600 *($12)*	$ 7200 *($31)*
	IS3	$ 3300 *($15)*	$ 10,000 *($43)*
Long *Haul Flight* 5800 km *(≈90th percentile of int. aviation flights)* **Singapore** → **Dubai** *Singapore* *UAE* *(WSSS)* *(OMDB)*	IS1	$ 1600 *($5)*	$ 8000 *($25)*
	IS2	$ 6600 *($20)*	$ 17,000 *($53)*
	IS3	$ 8300 *($26)*	$ 23,000 *($73)*

* *Costs in $ 2020 (adjusted for inflation).*
** *Seat equivalent including available seats for passenger, equivalent seats for freighters and 13 seats (default) for business jets.*

- **Under IS3, incremental cost from Fuels may represent an additional $3300 in 2030 for an average flight of about 2700 km, and $10.000 in 2050**
- **in a per seat context, this represents about $3 to $15 per seat equivalent.**

Incremental costs per passenger

Average
Passenger
Trip Length

Potential impact on ticket price*	in 2030	in 2050
IS1	$ 3	$ 13
IS2	$ 11	$ 28
IS3	$ 14	$ 38

** Proxy based on revenue per passenger, assuming an average 3% profit margin and 75% revenue from passenger (based on historical global averages from 2010-2019).*

- **From a passenger perspective, costs associated with IS3 could represent ≈ $14 to a ticket price in 2030, and ≈ $38 in 2050.**
- **While difficult to forecast, average ticket price may be on the order of $190–$200 in 2030.**


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