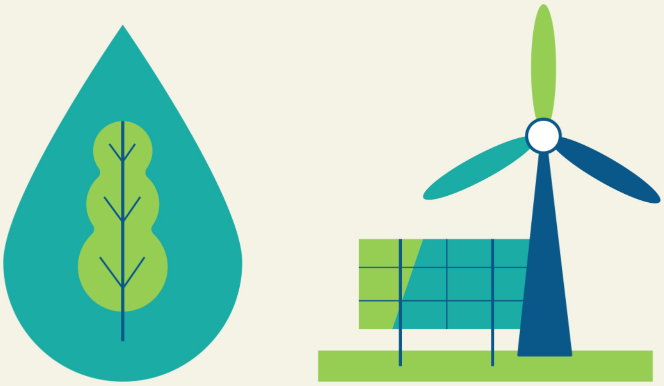
ICAO

INTERNATIONAL CIVIL AVIATION ORGANIZATION

REPORT ON THE FEASIBILITY OF A LONG-TERM ASPIRATIONAL GOAL (LTAG) FOR INTERNATIONAL CIVIL AVIATION CO_2 EMISSION REDUCTIONS

Appendix M5 Fuels Sub Group Report



ICAO COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION
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APPENDIX M5

LTAG-TG FUELS SUB-GROUP REPORT

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EXECUTIVE SUMMARY

In 2019, at the 40th Session of the ICAO Assembly, ICAO Member States requested the Council to explore the feasibility of a long-term global aspirational goal (LTAG) for international civil aviation. To address this request, CAEP formed the LTAG Task Group (LTAG-TG) to provide technical analyses of future international aviation CO_2 emission trajectories out to 2070 with the airframe technologies, aviation operations and alternative fuels associated with these varying future scenarios. This included evaluations of the technical readiness and attainability along with required costs and investments related to the implementation of these scenarios, as well as the potential impacts that scenarios may have on future aviation growth. To accomplish this technical analysis, the LTAG-TG created four sub-groups: Technology (TECH), Operations (OPS), Fuels (FUELS) and Scenario Development (SDSG). These groups investigated ways to reduce CO_2 emissions through (1) aircraft technology, (2) operations and (3) fuels. Each sub-group developed a collection of scenarios that capture the potential for future improvements that reduce CO_2 emissions. Traffic forecasts were developed by the Forecast and Economic Analysis Support Group (FESG) and integrated analyses were conducted by the Modelling and Databases Group (MDG). These forecasts reflect the impact of the COVID-19 pandemic on both short-and long-term recovery in international aviation.

The following report addresses the results of FUELS, including fuel categorization, methodology development and assessments of readiness and attainability. FUELS developed three fuels scenarios: F1, F2 and F3, which represent varying levels of introduction of both drop-in and non-drop-in fuels that could reduce the life cycle GHG emissions from aviation. For the purpose of the LTAG analysis, drop-in fuels are referred to as LTAG-SAF if they come from renewable or waste feedstocks and LTAG-LCAF if they come from petroleum. This distinguishes them from similar terms being used for the purposes of CORSIA. Non-drop-in fuels included electricity, liquefied gas aviation fuels (ASKT) and cryogenic hydrogen (LH_2). LH_2 was the only non-drop-in fuel included in the detailed analyses, and it was limited to consideration under scenario F3.

F1 represents the low end of potential GHG reductions from fuels (LTAG-SAF and LTAG-LCAF), where fuel production technologies with high attainability and readiness are considered. Technologies enable the use of waste gases for LTAG-SAF production but are limited to the most economic sources. Low incentives exist for LTAG-SAF and LTAG-LCAF production. F2 represents the middle range of potential GHG reductions from fuels (LTAG-SAF and LTAG-LCAF), where fuel production technologies with medium attainability and readiness are considered. Technologies enable the expanded use of waste gases for LTAG-SAF production. Broader electrification of ground transportation and Carbon Capture Utilization and Storage (CCUS) and increased incentives for LTAG-SAF and LTAG-LCAF impact LTAG-SAF and LTAG-LCAF production. F3 represents the high end of potential GHG reductions from fuels (LTAG-SAF, LTAG-LCAF and non-drop-in fuels), under which advanced fuel production technologies with low attainability and readiness are considered. Increased technologies exist to enable the use of both waste and atmospheric gases for LTAG-SAF production. Economy-wide deep decarbonization with extensive electrification of ground transportation and Carbon Capture Utilization and Storage (CCUS) impact LTAG-SAF and LTAG-LCAF production. Sufficient hydrogen production exists to enable cryogenic hydrogen use in aircraft. Unlike F1 and F2, F3 requires significant changes to both energy and airport infrastructures to enable the use of non-drop-in fuels. In this scenario, both advanced technologies and intensive infrastructure development, with the support of large incentives, lead to widespread use of low GHG fuels in aviation. These fuels scenarios were combined, as appropriate, with scenarios from TECH and OPS, as their use require modification both at aircraft as well as airport levels. These combined scenarios were reviewed for consistency and referred to as Integrated Scenarios (IS) with three main scenarios: IS1, IS2 and IS3.

These results are summarized below for the MID traffic forecast from MDG. Additional sensitivity analysis results for LOW and HIGH traffic forecasts are provided in §4.

Fuels Scenario Results for MID Traffic Forecast

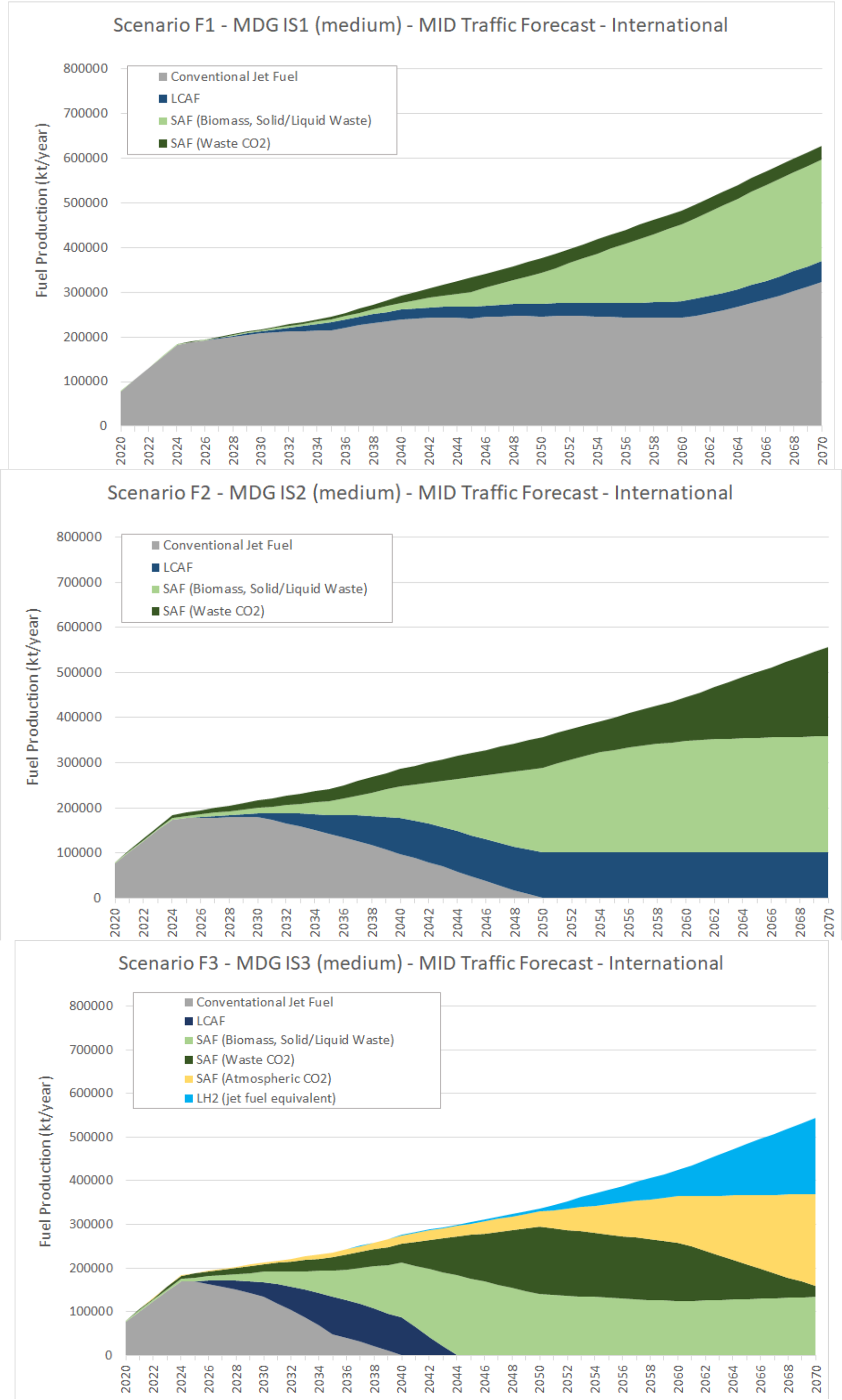

Figure 0.1 - F1, F2 and F3 MID traffic forecast fuels results from top to bottom

The top chart in Figure 0.1 shows the breakdown of future fuel supply across fuel categories for F1. Under F1, the fuel types included are conventional jet fuel, LTAG-LCAF, LTAG-SAF from biomass, solid and liquid wastes and LTAG-SAF from waste CO_2. 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. In 2070, conventional jet fuel drops to roughly half of total international jet fuel demand with LTAG-LCAF and LTAG-SAF supplying the remaining half. LTAG-SAF represents 40% of total supply in 2070, with 90% of that supply from LTAG-SAF produced from biomass and solid/liquid wastes.

The middle chart in Figure 0.1 shows the breakdown of future fuel supply across fuel categories for F2. Under F2, the fuel types included are conventional jet fuel, LTAG-LCAF, LTAG-SAF from biomass, solid and liquid wastes, and LTAG-SAF from waste CO_2. 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. In 2070, LTAG-SAF produced from biomass and solid/liquid wastes supplies slightly below half of projected international jet fuel demand, LTAG-LCAF drops to roughly 20% total international jet fuel demand and LTAG-SAF from waste CO_2 provides the remaining third.

The bottom chart in Figure 0.1 shows the breakdown of future fuel supply across fuel categories for F3. Under F3, the fuel types included are conventional jet fuel, LTAG-LCAF, LTAG-SAF from biomass, solid and liquid wastes, LTAG-SAF from waste CO_2, LTAG-SAF from atmospheric CO_2, and LH_2. As discussed in greater detail in the main body of this appendix, LTAG-SAF from atmospheric CO_2 and LH_2 were only included in F3. In 2050, LTAG-SAF supplies 96% of international jet fuel demand with the remaining 4% of conventional drop-in jet fuel demand replaced by non-drop-in demand (LH_2). LTAG-SAF from waste and atmospheric CO_2 supplies over half of the drop-in demand. In 2070, non-drop-in demand grows to roughly one-third of all international jet fuel demand. LTAG-SAF from waste and atmospheric CO_2 supply greater than 40% of total international jet fuel demand, representing over 60% of drop-in demand. LTAG-SAF from biomass and solid/liquid wastes supplies the remaining quarter of total international jet fuel demand.

Fuel Mix Emissions Reductions

To demonstrate the impact of the projected alternative jet fuel supply scenarios on future CO_2 emissions, an Emissions Reduction Factor (ERF)[1] was calculated for each respective fuel scenario and traffic forecast at three selected timeframes: this represents the reduction in GHG emissions achievable with the use of alternative fuels, in comparison with conventional fossil fuels. Table 0.1 summarizes the overall ERF values for the fuel mix under each fuel scenario (F1, F2 and F3) for the MID traffic forecast for three selected years: 2035, 2050 and 2070. Results reflect the effects of varying usage levels of alternative aviation fuels in accordance with projected fuel volumes and fuel burn demand. Combining the projected jet fuel supply mix with

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[1] $ERF = 1 - LC_{\text{fuel mix}}/LC$
Where $LC_{\text{fuel mix}}$ is the lifecycle emissions value of the fuel mix and LC is the baseline lifecycle emissions value for conventional jet fuel, equal to 89 gCO_{2e}/MJ. This ratio is multiplied by 100 to give the ERF values in terms of percent reduction compared to baseline conventional jet fuel.

estimated GHG lifecycle values for each fuel type provides total estimated CO_2 emissions per scenario.

Table 0.1 Emissions Reduction Factors for F1, F2 and F3 for MID Traffic Forecast

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

1 BACKGROUND

The Fuels sub-group was tasked with gathering and analysing data from internal and external sources to develop in-sector emissions reduction scenarios, for identified fuel categories out to 2070. The Fuels sub-group had two co-leads organizing this effort, focused on three identified LTAG fuel categories: Sustainable Aviation Fuels (LTAG-SAF), Lower Carbon Aviation Fuels (LTAG-LCAF), and non-drop-in Fuels. Both LTAG-SAF and LTAG-LCAF are drop-in fuels. LTAG-SAF is further subdivided into four categories by carbon feedstock source: biomass, solid/liquid waste, waste CO_2, and atmospheric CO_2. The non-drop-in category is also subdivided into electricity, liquefied gas aviation fuels (ASKT), and cryogenic hydrogen. Additional expert sub-groups were formed to organize the work of each of the three high-level fuel categories. The overall structure of the Fuels sub-group is given in Figure 1.1.

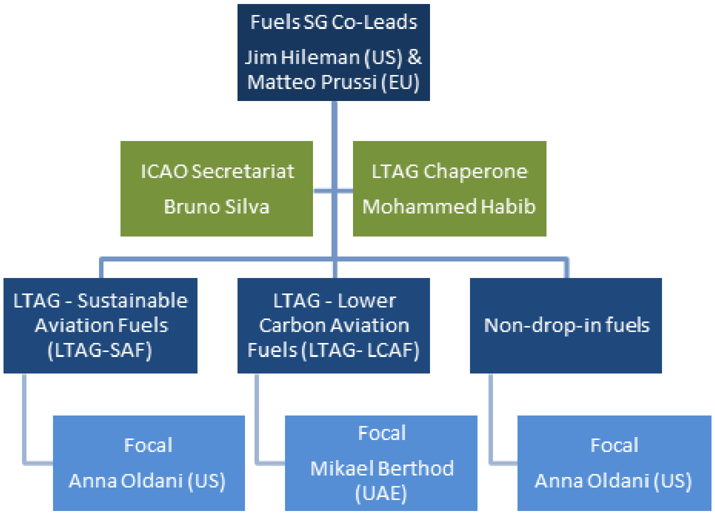

Figure 1.1 Fuels sub-group structure

This appendix provides information on the work of the Fuels sub-group analyses. The document begins with a description of the fuel categories followed by the methodology developed to assess the potential fuel volume projections and associated emissions reductions. The subsequent sections detail the final volume projections and the process by which the various fuel types are combined under each Fuels scenario to meet 100% of projected fuel demand. Additional reporting provides total greenhouse gas (GHG) emissions savings under each scenario across the timeline under evaluation. The appendix concludes with a discussion of the assumptions regarding the readiness and attainability of each fuel type with additional caveats to the analysis presented herein.

2 FUEL CLASSIFICATION

For the LTAG-TG analysis, the Fuels sub-group developed several fuel categories that cover expected drop-in and non-drop-in fuel alternatives to conventional jet fuel. Drop-in fuels are aviation fuels that are fully compatible with existing and legacy airframes and fueling supply infrastructure. These fuels do not require changes to existing infrastructure and can be used at the same operational safety and performance levels of current conventional aviation fuel within the limits specified by ASTM International. These fuels can directly supplement or replace today's petroleum-derived jet fuels. Table 2.1 presents the categorization of drop-in fuels with associated readiness and attainability criteria. Drop-in fuels for the LTAG analysis include sustainable aviation fuels (LTAG-SAF) and lower carbon aviation fuels (LTAG-LCAF).

Table 2.1 LTAG Drop-in Fuel Categorization

Fuel Category	*Fuel Name*	*Carbon source in fuel feedstock*	*Readiness Criteria*	*Attainability Criteria*
LTAG - Sustainable Aviation Fuels (LTAG-SAF)	**Biomass-based fuel**	Primary biomass products and co-products	1. ASTM approval process 2. Fuel conversion tech status 3. Systems available to produce low carbon energy carriers	1. Capital investment 2. Minimum fuel selling price 3. Land area 4. Water 5. Soil (residue extraction) 6. Biodiversity 7. Infrastructure for fuel transport to airport
	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		
LTAG - Lower Carbon Aviation Fuels (LTAG-LCAF)	**Lower carbon petroleum fuels**	Petroleum	1. ASTM approval process 2. Fuel conversion tech status 3. Systems available to produce low carbon energy carriers	1. Capital investment 2. Minimum fuel selling price 3. CCS capacity 4. Water 5. Infrastructure for fuel transport to airport

Sustainable Aviation Fuels (SAF) are the first category of drop-in aviation fuels. For the purpose of the LTAG analysis, Sustainable Aviation Fuels are referred to as LTAG-SAF. This is to distinguish the LTAG fuels analysis from the work concurrently being carried out by the Fuels Task Group (FTG). FTG are currently working to establish definitions for SAF lifecycle emissions values and sustainability criteria. The work in LTAG does not seek to pre-empt, override or challenge the outcomes of the FTG work program and efforts are taken to ensure the greatest consistency across these groups. For the purpose of the LTAG analysis, LTAG-SAF are drop-in aviation fuels that get the carbon in their fuel from renewable or waste resources. Definition of emissions reduction threshold or sustainability criteria for qualification as SAF were out of the remit of Fuels sub-group. For the LTAG analysis, LTAG-SAF are further categorized by carbon feedstock source: biomass, solid/liquid waste, waste CO_2 and atmospheric CO_2. Experts organized the four sub-level categories into two groupings to better approach the necessary evaluations. Sub-groups met bi-weekly throughout the fuels analysis process to develop fuel volume projections for biomass-, solid waste- and liquid waste-based fuels and separately for waste CO_2- and atmospheric CO_2-based fuels.

Production of drop-in fuels from biomass, solid waste and liquid waste requires a hydrocarbon source (feedstock) and a conversion process. Feedstocks for these fuels include a variety of renewable resources such as dedicated energy crops, municipal solid waste (MSW) and fats, oil and grease (FOG). These feedstocks can be processed via existing technologies currently approved by ASTM International under several annexes including hydroprocessed esters and fatty acids (HEFA), alcohol to jet (ATJ) and catalytic hydrothermolysis jet (CHJ), among others.

Production of drop-in fuels from atmospheric CO_2 and Waste CO_2 requires (1) a hydrogen source, (2) a CO_2 source, and (3) a conversion process for converting Hydrogen and CO_2 into jet fuel (and other products). A typology of the different combinations of processes considered under this class of fuels is shown in Figure 2.1. Many of the processes covered in Figure 2.1 rely on electricity, which, in many configurations, can be the most significant input (e.g. for production of hydrogen); therefore, many conversion pathways covered under this fuel class are commonly considered Power-to-Liquid (PtL) pathways.

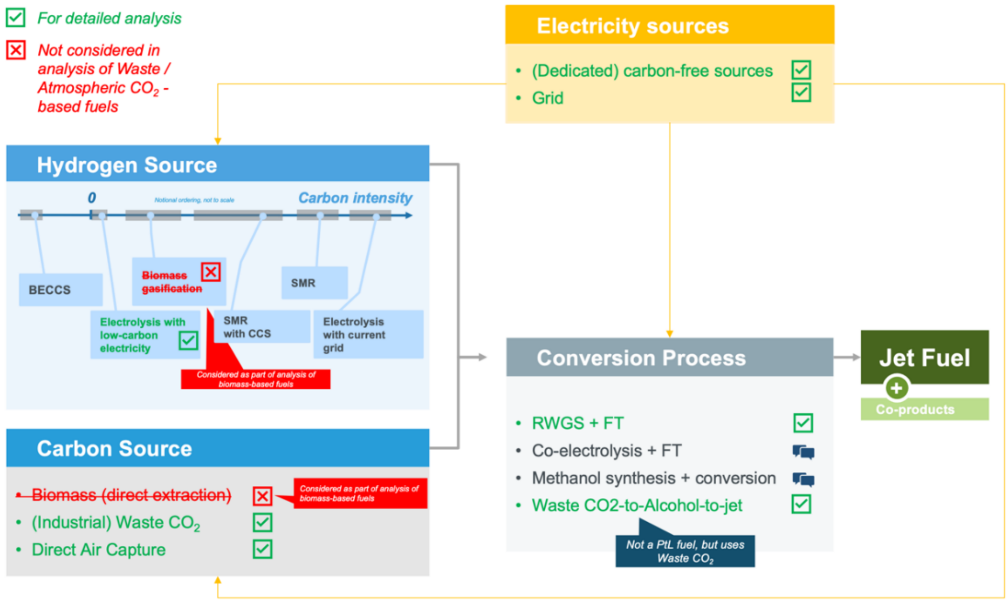

Figure 2.1 – Typology of fuels produced from atmospheric CO_2 and waste CO_2.

Lower Carbon Aviation Fuels (LCAF) are the second category of drop-in aviation fuels considered in the Fuel analysis. For the purpose of the LTAG work, they are referred to as LTAG-LCAF. Like

LTAG-SAF, there is a need to distinguish the analysis carried out in the LTAG work from the ongoing discussion with FTG. For the LTAG analysis, LTAG-LCAF is defined as a drop-in aviation fuel that get the carbon in their fuel from petroleum resources and demonstrates a well-to-wake carbon intensity of <80.1 gCO_2e/MJ. These reductions are achieved by applying greenhouse gas (GHG) mitigation technologies and best practices. Figure 2.2 shows the life cycle assessment (LCA) system boundary for LTAG-LCAF, with a breakdown of the feedstock and refinery elements, showing some of the technologies and best practices and where they could be applied.

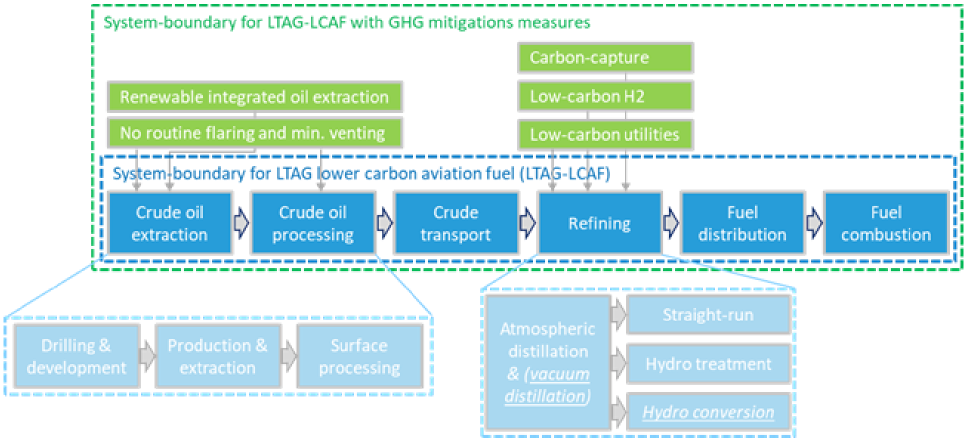

Figure 2.2 LCA system boundary for LTAG-lower carbon aviation fuel (LTAG-LCAF)

There are different opportunities to reduce the GHG emissions from the LTAG-LCAF supply chain and Figure 2.3 shows some examples of critical technologies that could contribute to the production of LTAG-LCAF. Those technologies include, but are not limited to, integration of renewable energy in operations, lower carbon hydrogen production, deployment of carbon capture and storage, minimization of flaring and venting emissions from upstream activities. Like LTAG-SAF, the total potential fuel volumes and associated emissions reductions from LTAG-LCAF will be calculated.

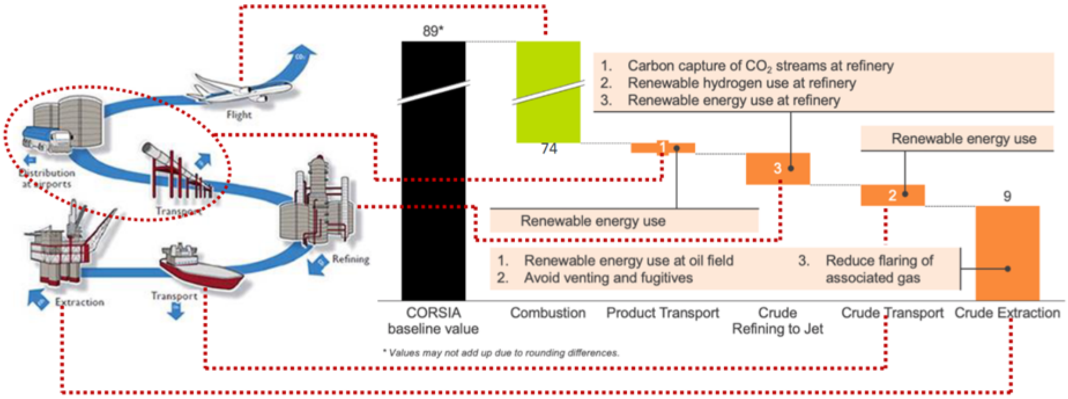

Figure 2.3 LTAG-LCAF supply chain with carbon intensity at the different LCA stages and GHG emissions reduction opportunities.

A hypothetical case of the carbon intensity of LTAG-LCAF production compared to the baseline is shown in Figure 2.4. Note that the implementation of abatement technologies and best practices will impact not only the carbon intensity of LTAG-LCAF, but also other co-products resulting in greater GHG emissions reductions overall. Refineries produce a wide range of products, and jet fuel accounts for <10% of a typical barrel of oil. In this study, only emissions reductions and investment costs allocated to the production of LTAG-LCAF are calculated.

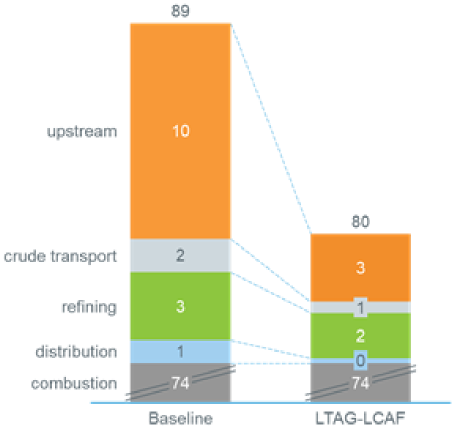

Figure 2.4 Example of an LTAG-LCAF production emissions profile compared to the conventional jet fuel baseline

Non-drop-in fuels are aviation fuels that require changes to existing and legacy airframes and fueling supply infrastructure. These fuels are not compatible with current aircraft and engine architectures and have unique safety and performance considerations as compared to current conventional aviation fuel. Table 2.2 presents the non-drop-in fuels categorization with associated readiness and attainability criteria. The LTAG analysis categorized three types of non-drop-in fuels: electricity, liquefied gas aviation fuels (ASKT) and cryogenic hydrogen (LH_2).

Table 2.2 LTAG Non-drop-in Fuel Categorization

Fuel Category	*Fuel Name*	*Carbon source in fuel feedstock*	*Readiness Criteria*	*Attainability Criteria*
Non-drop-in fuels	**Electricity**	Not applicable	1. Standards/regulations available to govern safety, handling, etc. 2. Technology available to produce energy carrier 3. Systems available to produce low carbon energy carrier	1. Capital investment 2. Minimum fuel selling price 3. Infrastructure for fuel transport to airport 4. Land area 5. Water
	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		

The **electricity** sub-category of non-drop-in fuels refers to the electrification of aircraft including both hybrid and fully electric airframes. For the purpose of the Fuels analysis, hybrid electrification systems do not create a significant charging load at the airport site. Such hybrid electric technologies are being evaluated for their emissions reduction benefits under the LTAG Technology sub-group (TECH). As they do not require significant changes at the airport level with regard to energy supply systems and only supplement conventional fueling processes, their impact from a fuels perspective is limited. Therefore, hybrid electric systems were not included in the Fuels sub-group analysis as these aircraft designs still rely on drop-in fuels to provide aircraft power and the electric systems are auxiliary to conventional power systems.

Liquefied gas aviation fuels (ASKT) are a sub-category of non-drop-in fuels which require changes to existing engines and airframe architecture. ASKT is included as a case study for applicability in remote areas with stranded hydrocarbon resources, such as arctic regions, due to its unique applicability and specific chemical features. It is excluded from subsequent analyses and scenario reporting. The case study can be found at the end of this appendix in Attachment C.

Cryogenic hydrogen (LH_2) is a non-drop-in fuel, which can be used in a dedicated aircraft fleet. LH_2 was evaluated by the Fuels sub-group for systems that use direct combustion of liquid hydrogen in gas turbine engines. Additional methods, such as hydrogen fuel cells, are not within scope of the analysis. From the Fuel sub-group standpoint, LH_2 uptake is defined by the availability of systems and technologies to be developed; therefore, the evaluations are being made in close coordination with the Advanced Concepts and Energy Storage (ACES) TECH ad hoc group, to ensure consistency across sub-group evaluations. Production of hydrogen (H_2) is modeled in accordance with the modeling used for Waste-CO_2 and Atmospheric-CO_2 based fuels. To increase the volumetric energy density, only hydrogen in liquefied form was considered, which requires an additional liquefaction step.

3 METHODS

The following section describes the methodologies developed to carry out the fuel production analysis for the various fuel categories. This includes the definitions of the fuel scenarios developed by the Fuels sub-group. These scenario definitions guided the analysis and provided the basis for sub-group experts to form the assumptions necessary to carry out the analysis.

3.1 Overarching Process

The Fuels sub-group followed a four step process to develop fuel production data: 1) scenario definition, 2) scenario development, 3) scenario alignment, 4) life cycle GHG emissions evaluations, 5) analysis of readiness and attainability, and 6) integrated scenario development. These steps are described in subsequent sections. Data gathering took place throughout the effort and was organized by three high-level fuel categorizations (LTAG-SAF, LTAG-LCAF and Non-drop-in). Data resources from both internal CAEP work and external literature and industry reports were evaluated and integrated into the analyses.

3.2 Deployment Scenario Definition

As a part of its work, the Fuels sub-group developed a high-level methodology to define a set of three deployment scenarios (low - F1, medium - F2 and high - F3), that reflect levels of emissions reductions representative of varying levels of readiness and attainability. These Fuels scenario definitions align with those of the overall integrated scenarios. Three Fuel scenarios, F1, F2 and F3, were developed to complement the IS1, IS2, and IS3 integrated scenarios.

Table 3.1 provides additional information on the details of each scenario and how the scenarios are aligned in the broader context of the integrated scenarios.

Table 3.1 LTAG Fuels Scenario Descriptions

	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

3.2.1 Fuels Scenario 1 (F1)

Fuels Scenario 1 (F1): F1 represents the low end of the range of potential GHG reductions from fuels (LTAG-SAF and LTAG-LCAF). In this scenario, fuel production technologies and certification processes are considered that have high attainability and readiness. Technologies do exist that enable the use of waste gases for LTAG-SAF production, however waste resource volumes are limited to the most economic sources. Additionally, low incentives exist for LTAG-SAF and LTAG-LCAF production.

3.2.2 Fuels Scenario 2 (F2)

Fuels Scenario 2 (F2): F2 represents the middle of the range of potential GHG reductions from fuels (LTAG-SAF and LTAG-LCAF). In this scenario, fuel production technologies and certification processes are considered that have medium attainability and readiness. Increased technologies exist to enable the use of waste gases for LTAG-SAF production, with expanded waste resource volumes. External economic trends that would impact LTAG-SAF and LTAG-LCAF production include broader electrification of ground transportation and Carbon Capture Utilization and Storage (CCUS). Additionally, increased incentives exist for LTAG-SAF and LTAG-LCAF production.

3.2.3 Fuels Scenario 3 (F3)

Fuels Scenario 3 (F3): F3 represents the high end of the range of potential GHG reductions from fuels (LTAG-SAF, LTAG-LCAF and non-drop-in fuels). In this, advanced fuel production technologies and certification processes are considered that have low attainability and readiness. Increased technologies exist to enable the use of both waste and atmospheric gases for LTAG-SAF production. External economic trends include economy-wide deep decarbonization with extensive electrification of ground transportation and Carbon Capture Utilization and Storage (CCUS). Sufficient hydrogen production exists to enable the use of cryogenic hydrogen in aircraft. Unlike F1 and F2, F3 would require significant changes to both energy and airport infrastructures to enable the use of non-drop-in fuels. In this scenario, both advanced technologies and intensive infrastructure development, with the support of large incentives, lead to widespread use of low GHG fuels in aviation.

3.3 Development of Deployment Scenarios

The next step of the analysis methodology regards development of scenarios. With the defined scenarios, Fuels sub-group experts developed potential fuel volumes and associated emissions reductions for each fuel category. These efforts address the readiness and attainability criteria as described in Section 2, within Table 2.1 and Table 2.2.

3.3.1 LTAG-SAF – Biomass- & Solid/Liquid Waste-based

The LTAG modeling of the production of fuels for biomass- and solid/liquid waste-based fuels builds off and further develops the work of the FTG Technology Production and Policy (TPP) group. The TPP group developed market diffusion models to model future SAF fuel volumes employing current knowledge on existing and announced SAF production facilities. The LTAG-SAF analysis carries out these models to 2070, aligning the FTG TPP scenarios with LTAG Fuels scenarios as appropriate. To estimate potential emissions reductions, the Fuels sub-group experts utilize feedstock projections, developed under the CAEP/10 Fuel Production Assessment (FPA). The FTG TPP group evaluated additional factors, such as oilseed cover crops and advancements in fuel production technologies, as a sensitivity case. The results of this work are incorporated in the lifecycle analysis (LCA) values for LTAG-SAF from biomass and solid/liquid waste as they impact potential GHG reductions from LTAG-SAF. Brief summaries of these FTG efforts as they relate to the LTAG-TG analysis are provided below. Detailed information can be found at the end of this appendix in Attachment A and Attachment B. Key reports include:

CAEPSG.20213.WP.020.7.en: *SAF Production Projections and Associated GHG Emissions Reductions*[2] - This working paper provides the work conducted by FTG on SAF production projections with their associated GHG emissions reductions. This report includes a description of the methodology, key results and a description of the "rules of thumb" developed to support the SAF production scenarios.

CAEPSG.20213.IP.005.7.en: *SAF Production Projections and Associated GHG Emissions Reductions*[3] - This information paper outlines the work on SAF production projections and associated GHG emissions. The paper includes detailed methodology description and results discussion.

For the LTAG-TG efforts, the FTG TPP work was employed to model future SAF production from the biomass- and solid/liquid waste-based fuel categories. This provides increased consistency across CAEP efforts. The TPP group employed a scenario-based approach to model short-term SAF production, selecting five scenarios to capture future production potential: *Low*, *Moderate*, *High*,

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[2] relevant excerpts are found under the link in Attachment A

[3] relevant excerpts are found under the link in Attachment B

High+, and *Max*. These scenarios vary with regard to maturity of production plans, product slate assumptions, and assumed success rate of future production announcements, among other factors. The Fuels sub-group evaluated the TPP scenario conditions and selected the scenarios which most closely aligned with the LTAG-TG Integrated and Fuels scenario definitions. F1 represents some incentives for SAF/LCAF production to level the playing field with ground transportation fuels and most closely aligns with the *Moderate* TPP scenario. The F2 scenario provides increased policy enablers for technology evolution to enable more widespread use of waste gases for SAF production as well as electrification of ground vehicles, which further increases SAF/LCAF availability for aviation. This scenario is modeled using the *High* TPP scenario. Finally, F3 represents economy-wide deep decarbonization and large incentives for low GHG fuels for aviation. This final scenario is best captured by the *High*+ scenario under the TPP modeling work.

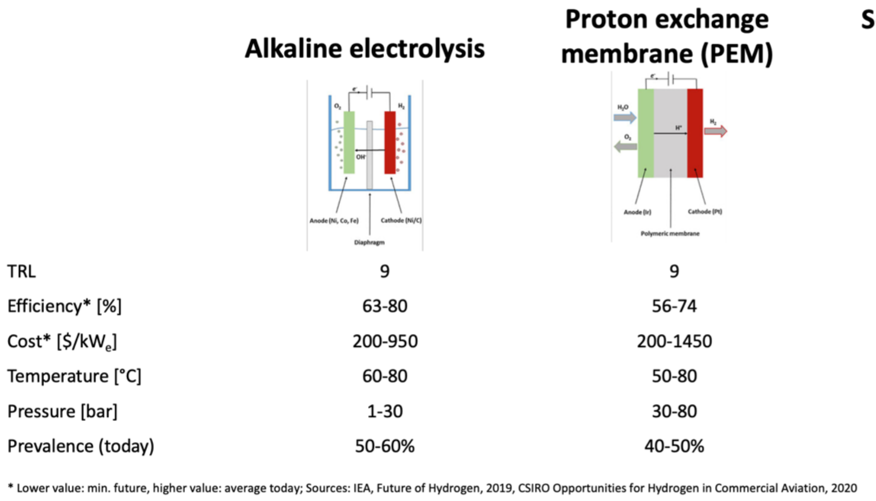
With the three scenarios thus defined, experts from Washington State University (WSU) worked closely with FTT TPP modelers from Hasselt University (UHasselt) to extend the market diffusion models out to 2070 for the purpose of the LTAG-TG work. Under each scenario, modelers carried out feedstock availability checks to ensure that projected volumes do not exceed potential feedstock resources. With these requirements satisfied, the WSU and UHasselt team was able to extend the short-term SAF production projections through to 2070 for the LTAG-TG effort.

3.3.2 LTAG-SAF – Waste CO_2- & Atmospheric CO_2-based

As mentioned previously, the Fuels sub-group experts developed a separate analysis for waste CO_2 and atmospheric CO_2 based fuels, as these fuels were not extensively evaluated under the FTG TPP work and have unique features, such as different feedstock limitations and production technology attainability. Factors such as broader economy wide de-carbonization impact the availability of waste CO_2 resources. Experts from Argonne National Laboratory (ANL) and Massachusetts Institute of Technology (MIT) led this portion of the fuels analysis. Following the fuel classification (see Figure 2.1), the modeling of the production of fuels produced from Waste CO_2 or Atmospheric CO_2 requires a definition of (i) the hydrogen production technology; (ii) the CO_2 capture technology (either from waste CO_2 streams or the atmosphere); and (iii) the fuel conversion technologies. In the following, the modeling of each step is outlined and an analysis of aggregate electricity demand for these processes is presented.

3.3.2.1 Hydrogen production

The analysis focuses on hydrogen production using water electrolysis. This is because, depending on different sources of electricity, this technology allows to model hydrogen production with a wide range of costs and lifecycle GHG emissions. Different electrolysis technologies exist as shown in Figure 3.1. Given the current prevalence and perceived scalability, the analysis uses assumptions which are consistent with proton exchange membrane (PEM) electrolyzers with an energy conversion efficiency of 70%.



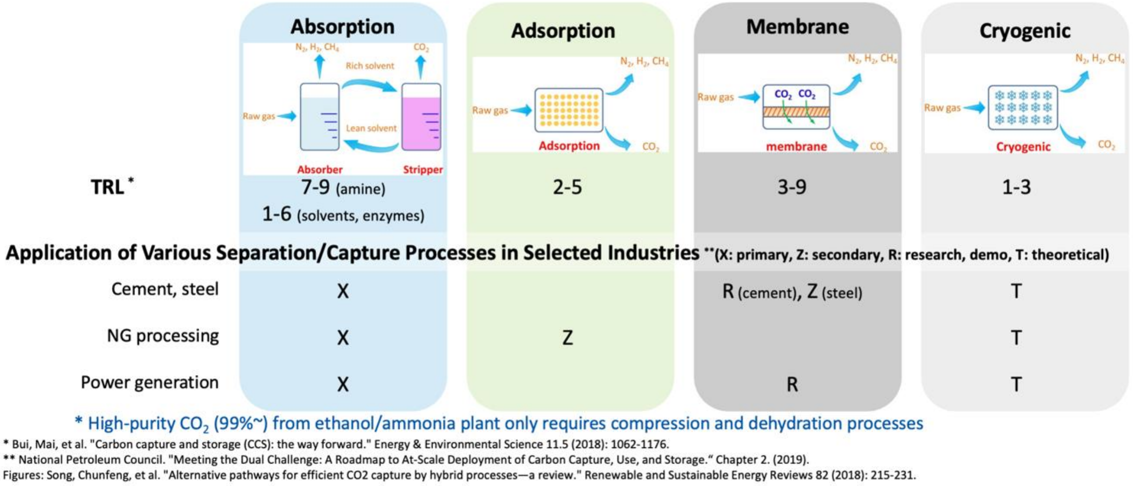
	Alkaline electrolysis	Proton exchange membrane (PEM)	Solid electrolyzer (SOEC)
TRL	9	9	6-7
Efficiency* [%]	63-80	56-74	74-90
Cost* [$/kW$_e$]	200-950	200-1450	500-4200
Temperature [°C]	60-80	50-80	650-1000
Pressure [bar]	1-30	30-80	1
Prevalence (today)	50-60%	40-50%	< 5%

* Lower value: min. future, higher value: average today; Sources: IEA, Future of Hydrogen, 2019, CSIRO Opportunities for Hydrogen in Commercial Aviation, 2020

Figure 3.1 – Electrolysis technologies

3.3.2.2 CO_2 capture technologies

For Waste CO_2 streams, different capture technologies are available, as shown in Figure 3.2. Absorption is the most applicable technology for the CO_2 capture at current technology levels. It is widely used for capturing waste CO_2. Adsorption, membrane, and cryogenic approaches are other technologies for CO_2 capture which are currently explored in research, demonstration, or theoretical studies. Combinations of two technologies are also an option for CO_2 capture (Song *et al.*, 2018). Here, the focus is on absorption technologies as a demonstrated technology which can be used under a broad array of circumstances.



	Absorption	Adsorption	Membrane	Cryogenic
TRL *	7-9 (amine) 1-6 (solvents, enzymes)	2-5	3-9	1-3

Application of Various Separation/Capture Processes in Selected Industries **(X: primary, Z: secondary, R: research, demo, T: theoretical)

	Absorption	Adsorption	Membrane	Cryogenic
Cement, steel	X		R (cement), Z (steel)	T
NG processing	X	Z		T
Power generation	X		R	T

* High-purity CO_2 (99%~) from ethanol/ammonia plant only requires compression and dehydration processes

* Bui, Mai, et al. "Carbon capture and storage (CCS): the way forward." Energy & Environmental Science 11.5 (2018): 1062-1176.

** National Petroleum Council. "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage." Chapter 2. (2019).

Figures: Song, Chunfeng, et al. "Alternative pathways for efficient CO2 capture by hybrid processes—a review." Renewable and Sustainable Energy Reviews 82 (2018): 215-231.

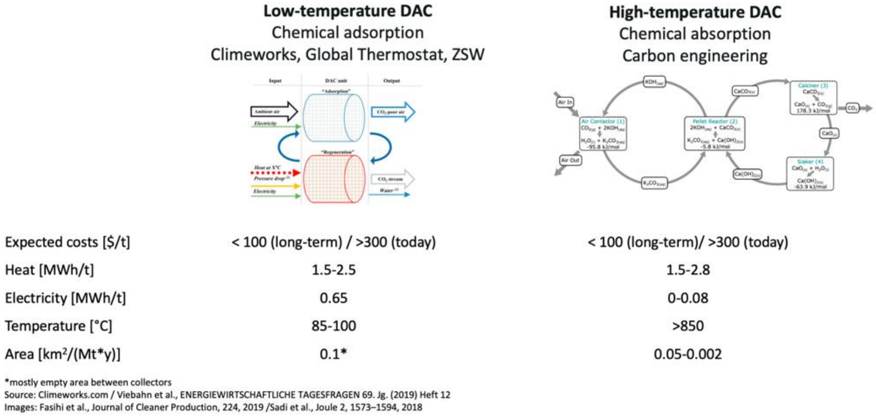
Figure 3.2 – Capture technologies for Waste CO_2 streams

Since the analysis considers waste CO_2 capture from ethanol production, ammonia production, iron and steel production, and cement production, the capture technology is adapted to each waste CO_2 stream. The modeling assumptions were taken from literature and are documented in Table 3.2. The analysis assumes heat integration of CO_2 capture and fuel conversion, which reduces natural gas requirements for waste CO_2 capture in the iron & steel and cement production processes.

Table 3.2 – Overview of waste CO_2 sources, CO_2 concentrations, associated electrical energy for capture, and available amounts

CO_2 source	**Purity level**	**CO_2 concentration [vol-%]**	**Capture technology**	**Capture energy [MJ/t] (electricity and compression)**	**Natural Gas requirements and/or heat integration [MJ/t]**	**Considered in Fuel scenario**
Ethanol	High	100	Purification	414.5	-	1-3
Ammonia	High	97.1	Purification	385.9	-	1-3
Iron and steel	Mid	23.2-26.4	Chemical absorption	511.4	4459	2-3
Cement	Mid	22.4	Chemical absorption	510.6	4441	2-3
Atmosphere	Low	0.04	Low-temperature chemical adsorption	2340	-	3

Atmospheric CO_2 can be captured through Direct Air Capture (DAC) using different capture technologies shown in Figure 3.3. In general, there are two types of DAC processes. Firstly, there are processes that operate at high temperatures (of several hundred °C) using chemical absorption to a sorbent such as calcium hydroxide or potassium hydroxide. Secondly, there are low-temperature processes that operate at around 100 °C using ammine-functionalized sorbents. The focus here is on low-temperature DAC technologies because of the possibility for integration with a heat source in the process. The Fischer-Tropsch conversion process, for instance, produces waste heat at > 200 °C and could be integrated to (partially) cover the heat demand of the DAC process. Such heat integration reduces the amount of additional energy required for CO_2 capture which improves emissions and costs. The electricity demand for CO_2 capture from DAC as used in the analysis is documented in Table 3.2.



	Low-temperature DAC Chemical adsorption Climeworks, Global Thermostat, ZSW	**High-temperature DAC** Chemical absorption Carbon engineering
Expected costs [$/t]	< 100 (long-term) / >300 (today)	< 100 (long-term)/ >300 (today)
Heat [MWh/t]	1.5-2.5	1.5-2.8
Electricity [MWh/t]	0.65	0-0.08
Temperature [°C]	85-100	>850
Area [km^2/(Mt*y)]	0.1*	0.05-0.002

*mostly empty area between collectors
Source: Climeworks.com / Viebahn et al., ENERGIEWIRTSCHAFTLICHE TAGESFRAGEN 69. Jg. (2019) Heft 12
Images: Fasihi et al., Journal of Cleaner Production, 224, 2019 /Sadi et al., Joule 2, 1573–1594, 2018

Figure 3.3 – Conceptual overview of DAC methods

3.3.2.3 Fuel conversion

Fuel conversion of H_2 and CO_2 (irrespective of source) is based on either the Waste-CO_2-to-Alcohol-to-Jet process (similar to the Lanzatech process) or a Fischer Tropsch (FT) process combined with the Reverse Water Gas Shift (RWGS) Reaction. The Waste-CO_2-to-Alcohol-to-Jet process was assumed for F1 (due to higher efficiency and lower cost compared to FT +RWGS processes)[4], while the FT process with RWGS is chosen for F2 and F3. The process assumptions considered in this analysis are documented in Table 3.3 and Table 3.4.

Table 3.3 Fuel shares in different scenarios.

	F1 [% of e-fuel]	**F2, F3** [% of e-fuel]
Jet fuel	70	41

Table 3.4 Demand for CO_2, H_2, and electricity in different scenarios and for different pathways.

	CO_2 demand [t CO_2/t e-fuel]		**H_2 demand** [t H_2/t e-fuel]		**Electricity demand** [MJ/t]	
	F1	F2, F3	F1	F2, F3	F1	F2, F3
Waste CO_2	6.80	3.68	0.634	0.518	36.324	26.89
DAC CO_2	-	3.68	-	0.518	-	28.81

3.3.2.4 Electricity demand of the combined fuel production process

As outlined in the previous paragraphs, electricity is required in all major process steps, including CO_2 capture, H_2 production, and conversion. The resulting electricity consumption for the different scenarios is summarized in Table 3.5. The electricity demand varies between scenarios, mainly due to different process assumptions. For example, electricity demand for electrolysis is lower in IS 2 and IS

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[4] ATJ was assumed for the calculation of potentials, while the FT process is used for the derivation of all other metrics.

3 as compared to IS 1 due to higher H_2 requirements in the Waste-CO_2-to-Alcohol-to-Jet process. For CO_2 capture, electricity demand for IS 2 and IS 3 is lower than for IS 1; however, natural gas consumption needs to be accounted for in IS 2 and IS 3 (0.09 MJ (NG) /MJ (fuel)) due to the higher heat requirements for capturing CO_2 from lower-concentration sources such as from cement production processes and iron & steel production.

Table 3.5 Electricity demand for fuel production from atmospheric CO_2 and waste CO_2 streams in the different fuels scenarios [MJ (electricity) / MJ (fuel)].

	F1 – *waste CO_2*	**F2 – *waste CO_2***	**F3 – *waste CO_2***	**F3 – *DAC***
Electrolysis	2.4	1.96	1.96	1.96
CO_2 capture*	0.06	0.04	0.04	0.06
Conversion	0.02	0.02	0.02	0.02
Total	**2.48**	**2.02**	**2.02**	**2.04**

* Weighted average of the electricity demand for capturing CO_2 from different sources.

3.3.3 LTAG-LCAF

For LTAG-LCAF, experts developed a detailed bottom-up approach to model the global jet fuel supply chain and a top-down approach to define three deployment scenarios for LTAG-LCAF for the considered timeframe by LTAG. Emissions reduction through the use of LTAG-LCAF results from the implementation of GHG mitigation technologies and best practices such as low carbon electricity use, control of methane leakages, minimization of flaring of associated gases, carbon capture of processes flue gases and use of low carbon hydrogen. The potential emissions reductions associated with LTAG-LCAF will be calculated for pathways that meet the reduction threshold of well-to-wake carbon intensity of <80.1 gCO_2e/MJ. Experts from the UAE and Saudi Arabia led this portion of the fuel analysis.

This Section will describe the models and assumptions used to determine the LTAG-LCAF fuel production potential across the three fuels scenarios presented in Section 3.2. The models and assumptions used were separated into feedstock production (crude oil production) and refining stages. Two different bottom-up engineering-based models were used to describe the variability in different processes across the supply chain.

“Upstream GHG emissions” represent all collective GHG emissions from exploration, drilling and development (including direct land use change), production and extraction, surface processing, and transport to the refinery entrance gate (i.e. well-to-refinery gate).

3.3.3.1 LTAG-LCAF Overall Models and Assumptions

Two recent studies have been used to model both global crude oil production and global crude oil refining GHG emissions. The studies below included a detailed analysis of emissions mitigation technologies and practices.

- (Masnadi *et al.*, 2018) *Science*: This study assessed the carbon intensity of ~9000 oilfields globally using the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) model, which was developed by Stanford University and used by California Air Resources Board for the implementation of the Low Carbon Fuel Standard. OPGEE was extensively peer-reviewed and, today, is the universal tool used for the assessment of GHG emissions from crude oil production. The Science paper maps the carbon intensity of 98% of global oil production in 2015 and estimates the potential emissions reductions from applying innovative technologies and best gas management practices.

- (Jing *et al.*, 2020) *Nature Climate Change*, 2020: This study analyzed the carbon intensity of global crude oil refining using The Petroleum Refinery Life Cycle Inventory Model (PRELIM), which was developed by University of Calgary and used to update the US Renewable Fuel Standard (RFS2) petroleum baseline carbon intensity. PRELIM is a bottom-up engineering-based model that captures the effect of wide variability in crude properties and refinery configurations. The study published in Nature Climate Change investigated the potential emissions reduction from various technologies.

Key results from both studies are shown in Figure 3.4 and Figure 3.5.

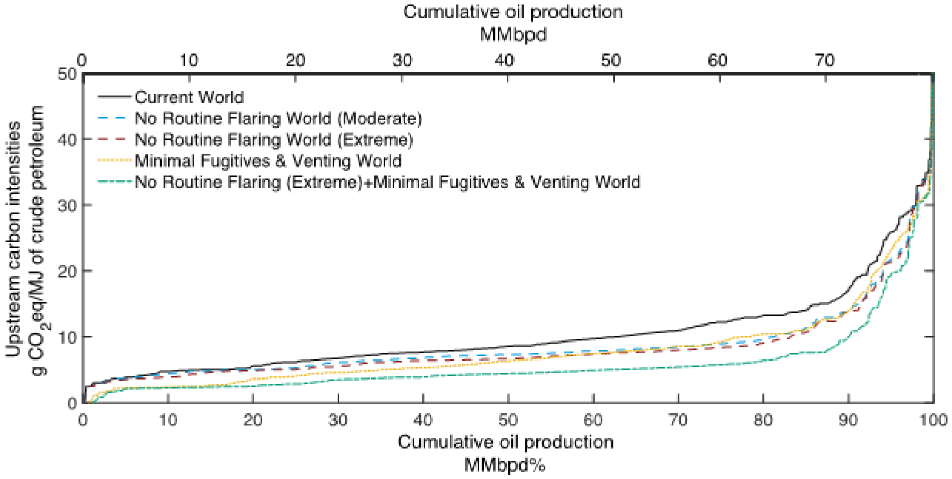


Figure 3.4 Global field-level upstream carbon intensity supply curve (Masnadi *et. al.*, 2018). This figure shows how the global CI supply curve reshapes as a result of different levels of gas management in upstream operations.

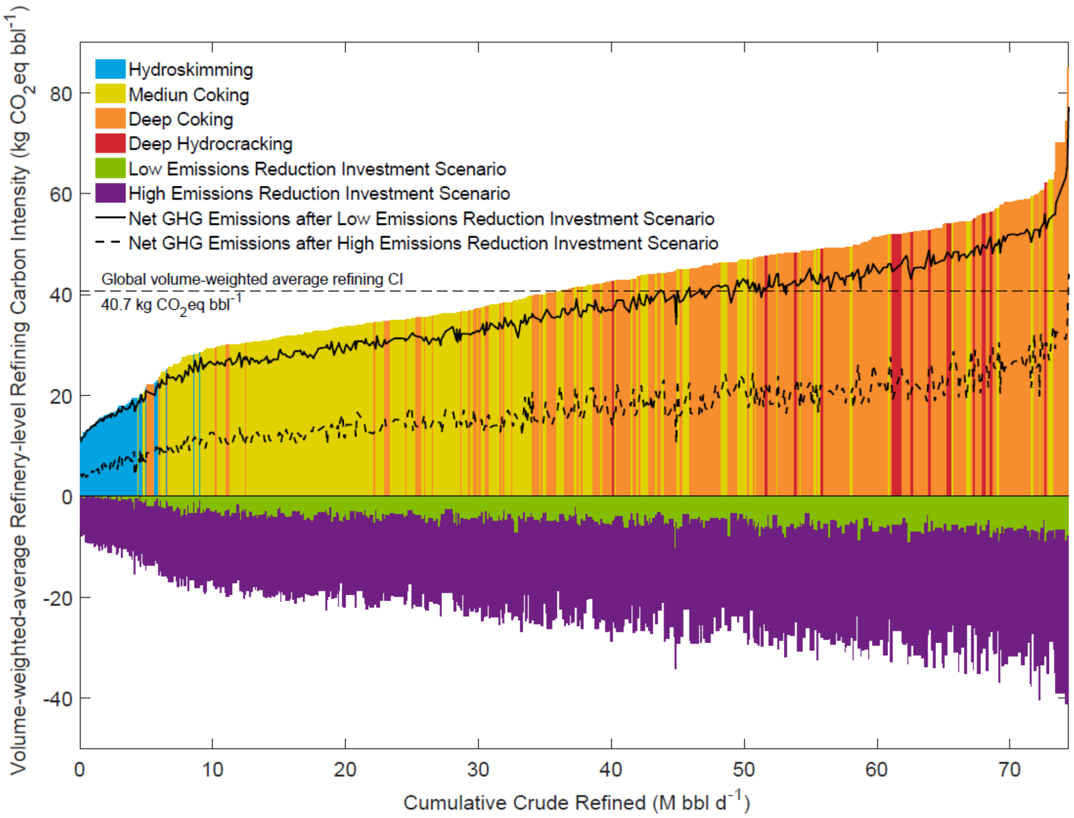


Figure 3.5 Global refinery-level crude oil refining CI supply curve. The figure shows the global distribution of refinery configurations and the emissions reductions from two investment scenarios (low- and high-investment scenarios) (Jing *et. al.*, 2020)

The overall methodology used to determine the LTAG-LCAF production under the three different fuels scenarios can be explained by the following steps:

1. Developing the current global jet fuel supply CI curve. This is referred to as the Baseline Merit Curve (BMC) with an average CI of ~89 gCO$_2$e/MJ of Jet. The carbon intensity of different engineering processes were modelled using the bottom-up models described in the two main studies used in this analysis. The carbon intensities of different LCA stages from different models were integrated for the representation of the complete jet fuel supply chain.
2. Identifying potential GHG emissions reductions technologies and best practices
3. Estimating Maximum Attainable Mitigation (MAM) by applying GHG emissions reduction technologies and recalculating BMC. This step was used to calculate the LTAG-LCAF maximum attainability.
4. Developing technology scenarios according to the LTAG Fuels Scenarios. This step was used to assess the LTAG-LCAF readiness under different scenarios.
5. Applying the technology map of each scenario and calculating the resulting scenario merit curve.
6. Propagating each scenario merit curve to determine the LTAG-LCAF volume and GHG emissions reductions by 2030, 2050, and 2070.
7. Estimating the associated cost of LTAG-LCAF production based on the abatement cost of each technology and its contribution to GHG emissions reductions.

3.3.3.2 Global Merit Curve Approach

To determine the LTAG-LCAF attainability, it is essential to understand the carbon intensity of global jet fuel production. This is an important first step because the various GHG emissions reduction technologies have variable impact in different regions depending on regional production processes, market dynamics, and feedstock availability. Previous studies (Masnadi *et al.*, 2018; Jing *et al.*, 2020) show wide variation in GHG emissions across the petroleum supply chain. By targeting primary emissions sources, the oil industry has the potential to save 56-79 $GtCO_2e$ up to 2100. LTAG-LCAF has the potential to contribute to the realization of this potential and could be a catalyst for wider implementation of GHG emissions mitigation measures.

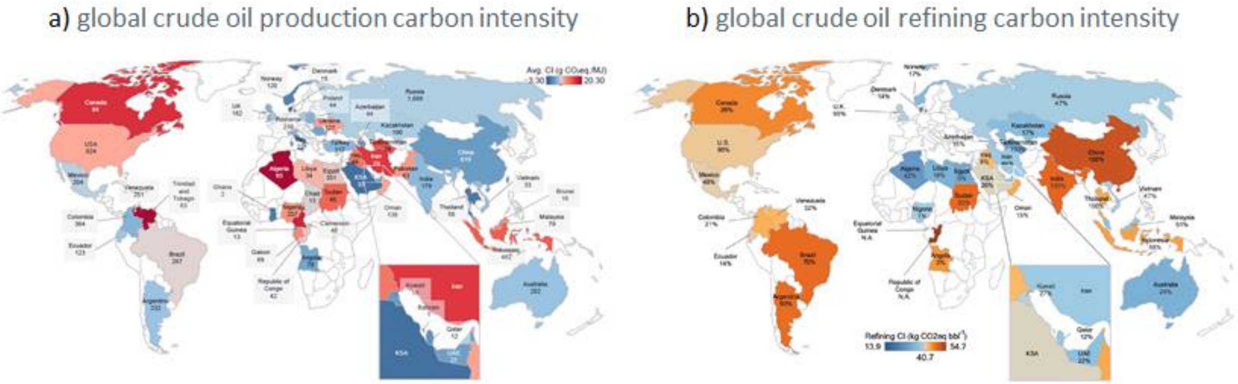


Figure 3.6 Global country volume weight average crude oil production and refining carbon intensity. Right map shows the refinery level carbon intensity in gCO_2e/MJ of crude, not petroleum products level. (Masnadi *et. al.*, 2018; Jing *et. al.*, 2020)

Using the abovementioned papers and Wood Mackenzie's refinery simulation model (PetroPlan) [WM], the GHG emissions of more than 400 refineries worldwide were modeled. As shown in Figure 3.7, the global jet fuel CI merit curve was generated as a baseline for the modelling of LTAG-LCAF production volume, GHG emissions savings potential, and cost.

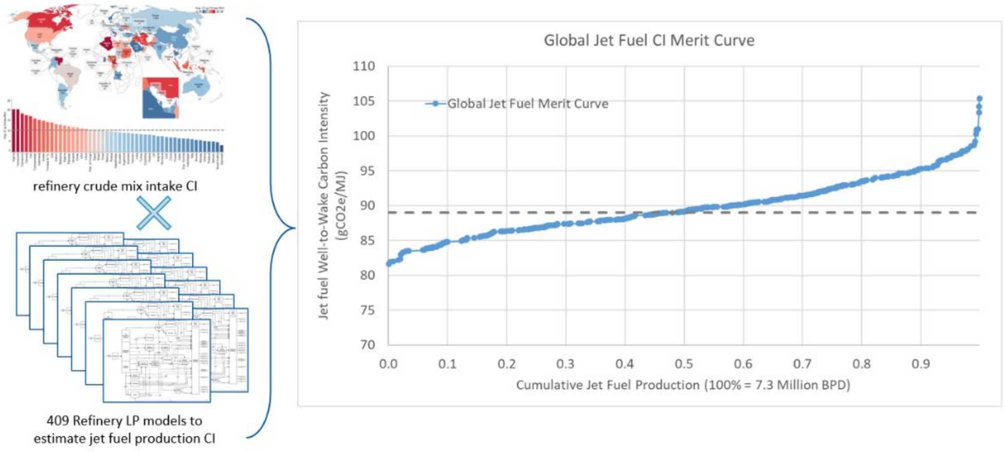


Figure 3.7 Generating an estimate global jet fuel carbon intensity merit curve

The allocation of refining GHG emissions to jet fuel production is performed using a process-level energy allocation method (Elgowainy *et al.*, 2014). The LTAG-LCAF combustion emissions factor was assumed to be 74 gCO_2e/MJ. The analysis of the global jet fuel CI resulted in an average of ~89 gCO_2e/MJ, which is consistent with the average CI of jet fuel used by LTAG to determine the GHG emissions savings of various fuel categories.

Merit Plots

The results shown in Figure 3.7 describe the distribution of the global jet fuel production volumes ranked according to their specific carbon intensity, referred to as the Baseline Merit Curve (BMC). Merit plots can be generated for each reference and scenario cases and can be mathematically described and fitted with the Beta probability distribution function. The Beta function captures the peculiar shape of the distribution and is easily adjustable to obtain the best fit. This will be of use when determining the projected volume by 2030, 2050 and 2070 for each IS scenarios, using the top-down approach.

3.3.3.3 Upstream GHG emissions reductions technologies

Minimize routine gas flaring: Gas flaring (burning) is a common practice in oil and gas production activities. If not economically sellable, associated gas co-produced with crude oil is either flared, reinjected, or vented (directly released to atmosphere). Gas flaring is the second biggest source of emissions and contributes to 22% of the global emissions from oil production. In order to minimize or achieve near-zero flaring intensity, the industry can adopt different technologies and practices as recommended by the International Energy Agency (IEA) (IEA 2019a). These include: increasing direct measurement of flared gas volumes, applying technologies that keeps gas in the reservoir, ensuring timely development of gas infrastructure, including gas utilization technologies in the design of new developments, and improving flaring efficiency.

The modelers assessed the potential of flaring minimization on the global jet fuel CI supply curve using a scenario in which flaring from global oil fields is limited to 20 standard cubic feet (scf) of gas flared per barrel of oil produced. This flaring rate represents the 5th percentile of the global distribution. Hence, existing oilfields have already demonstrated such low flaring practices. The implementation of such flare minimization technologies and practices reduces the global upstream carbon intensity of crude oil production by ~1.9 gCO_2e/MJ for petroleum-based jet fuel production.

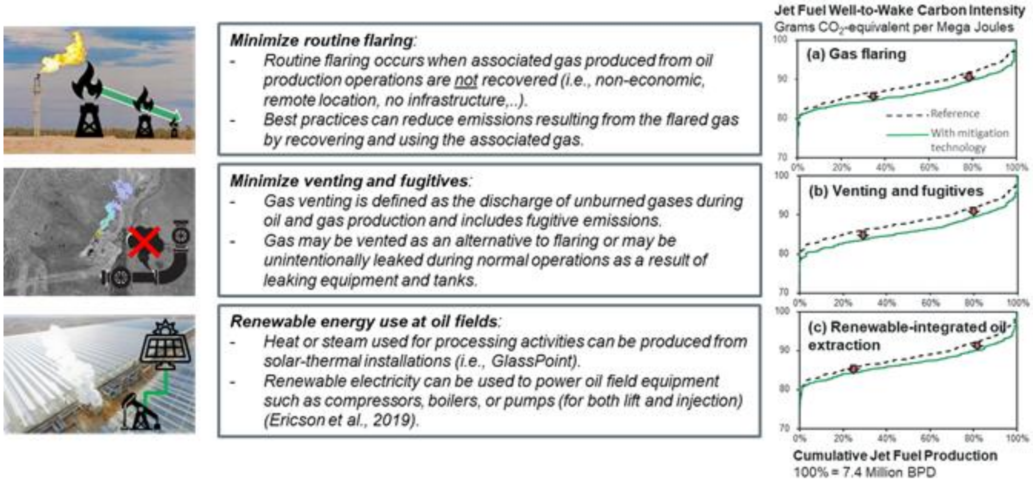
Minimize venting and fugitives: Venting and fugitive emissions can be a significant source of GHG emissions from oil production operations. These sources include (i) purposeful release of hydrocarbon gases (mainly methane) to the atmosphere during maintenance operations and other intermittent, infrequent activities; and (ii) non-purposeful emissions of hydrocarbon gases to the atmosphere commonly because of leaking equipment and tanks. In this LTAG-LCAF work, only venting and fugitive emissions associated with upstream operations (i.e. crude oil production) are considered. An example of key technologies to minimize venting and fugitive emissions is the application of Leak Detection and Repair (LDAR). LDAR programs are designed to identify and repair/replace leaking equipment to reduce or eliminate emissions, and provide accuracy, efficiency, flexibility, and a safe working environment while significantly reducing leaks and avoiding product losses from components.

The modelers assessed the potential of venting and fugitives' minimization on the global jet fuel CI supply curve using a scenario in which the sum of both planned and unplanned venting and fugitive emissions from global oilfields are limited to 0.2 gCO_2e per MJ of crude oil produced. This scenario is based on the 2015 reported venting and fugitive emissions from Norwegian oilfields. The minimization of venting and fugitive emissions from crude oil production to the level already achieved by Norway results in a global average CI reduction of ~2.4 gCO_2e/MJ for petroleum-based jet fuel production.

Renewable energy use at oil fields: Pumps and compressors used in crude oil production consume a significant amount of energy. On average globally, extraction pumps (i.e. downhole and water injection pumps) and compressors (i.e. gas injection compressors) consume 3% of oil barrel equivalent per barrel of oil produced. Converting oil well pumps and compressors to renewable and battery power will significantly reduce emissions from oil production.

Extraction of heavy oils by steam flooding (injection of steam into the oil reservoir) is very energy- and carbon- intensive. Solar-powered steam generators developed by GlassPoint[5] for heavy oilfields in Oman and California can provide substantial mitigation benefits. The deployment of this innovative technology in Oman is the largest of its kind and could reportedly save 300,000 tons of CO_2 emissions per year—equivalent to taking 63,000 cars off the road (GlassPoint, 2019).

To demonstrate the potential impact of renewable energy integration into oil extraction on the global jet fuel CI supply curve, the Oil Production Greenhouse Gas Emissions Estimator (OPGEE[6]) was used to estimate the global savings from: (i) shifting heavy oil extraction to solar-powered steam generators in regions with low seasonality and good economics of solar technology, and (ii) shifting oil well pumps and compressors to renewable and battery power. Renewable-integrated oil extraction could result in an average upstream carbon intensity reduction of 1.2 gCO_2e/MJ.



Minimize routine flaring:
- *Routine flaring occurs when associated gas produced from oil production operations are not recovered (i.e., non-economic, remote location, no infrastructure,..).*
- *Best practices can reduce emissions resulting from the flared gas by recovering and using the associated gas.*

Minimize venting and fugitives:
- *Gas venting is defined as the discharge of unburned gases during oil and gas production and includes fugitive emissions.*
- *Gas may be vented as an alternative to flaring or may be unintentionally leaked during normal operations as a result of leaking equipment and tanks.*

Renewable energy use at oil fields:
- *Heat or steam used for processing activities can be produced from solar-thermal installations (i.e., GlassPoint).*
- *Renewable electricity can be used to power oil field equipment such as compressors, boilers, or pumps (for both lift and injection) (Ericson et al., 2019).*

Figure 3.8 Summary of upstream technologies that can be applied for LTAG-LCAF production. Short descriptions of each technology are provided. On the right, the impact of technology implementation on the total jet fuel well-to-wake GHG emissions is shown.

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[5] GlassPoint is a company which delivers innovative low-cost solar energy to power industrial processes. It has developed and tested a technology that uses sunshine to produce zero-carbon steam by concentrating sunlight onto pipes containing water, which then boils the water to generate steam using curved mirrors enclosed in a greenhouse to protect against outside elements.

[6] OPGEE is an open source engineering-based model for the estimation of GHG emissions from crude oil production. The model was originally developed for California Air Resources Board (CA ARB) for the implementation of the Low Carbon Fuel Standard (LCFS).

3.3.3.4 Refining GHG emissions reductions technologies

Carbon capture and storage (CCS) is widely recognized globally as a critical technology to meet the GHG emissions reduction targets and remain in line with the Paris Agreement. CCS can be applied in both the industrial sector and power generation. This technology involves the capture of CO_2 from fuel combustion or industrial processes, the transport of CO_2 via ship or pipeline and its permanent storage in geological formations (IEA, 2019b).

[Additional details about carbon capture can be found in Section 3.3.2.2 about CO_2 capture technologies]

CCS technologies offer the potential to capture CO_2 emissions at the refinery level. Possible technologies include all three major CCS concepts (Romano *et al.*, 2013): post-combustion capture (e.g.: (Johansson *et al.*, 2013; Anantharaman, Roussanaly and Ditaranto, 2018)), pre-combustion capture (e.g.: (Weydahl *et al.*, 2013)), and oxy-combustion integration (e.g.: (Escudero, Espatolero and Romeo, 2016)).

For refineries, the number of separate point sources of CO_2 emissions is large and the composition of flue gases can vary significantly, with low CO_2 concentrations in many processes ((Romano *et al.*, 2013); (Bains, Psarras and Wilcox, 2017)). Depending on the processes covered in the carbon capture system, the shares of avoided CO_2 emissions can vary significantly (e.g. 20 to 85% of total refinery CO_2 emissions). In the LTAG-LCAF modelling, the key process that are part of the supply chain of interest, kerosene production, will be targeted for the deployment of CC at the refinery operations.

For the LTAG-LCAF modelling, the limited application of CC to refinery operations at the atmospheric distillation columns (sometime integrated with vacuum distillation columns) furnaces results in a significant GHG emissions reduction of ~1.3 gCO_2e/MJ for petroleum-based jet fuel production. There are potential additional reductions of ~1.0 gCO_2e/MJ if applied to other CO_2 sources (e.g. other furnaces, fluid catalytic cracker, etc.) at the facility. But due large uncertainties in terms of feasibility of the implementation of such flue gases gathering systems, and high associated cost, it is unlikely that LTAG-LCAF would be enough a driver to incentives such large application of CC at the refinery. Therefore, it was decided to ignore those additional GHG emission reduction from all fuels scenarios.

Due to lack of public data and the complexity of modelling the storage site required by CCS implementation, and potential market dynamic (i.e. CO_2 hub to store CO_2 from other economic actors). The storage component of CCS is not modelled in the study and hereinafter the analysis will refer only to carbon capture as CC.

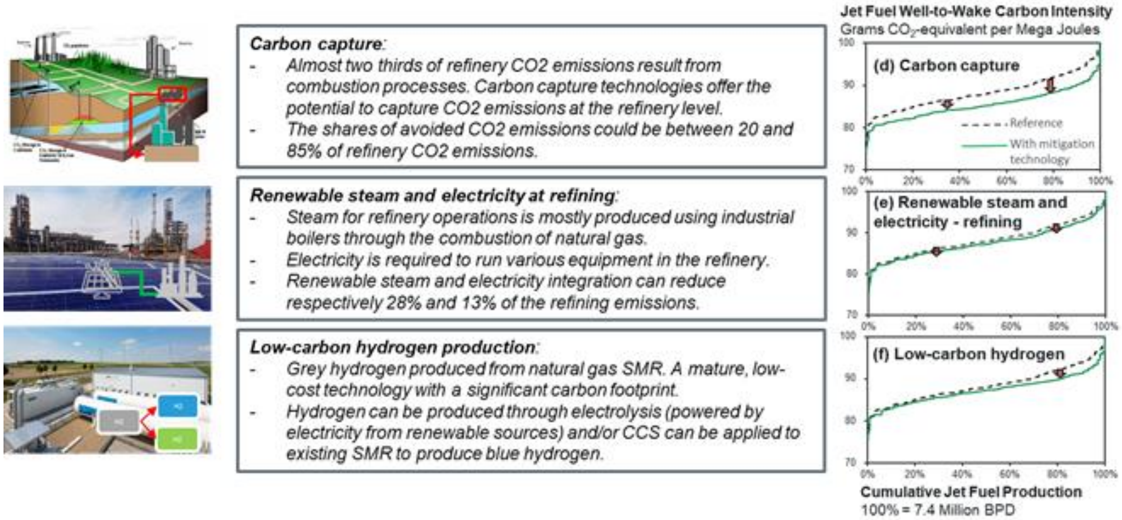
Renewable steam and electricity for refining: Steam for refinery operations is mostly produced using industrial boilers through the combustion of natural gas. Electricity is another important utility used by most, if not all, processing units in the refinery; it is critical to the functioning of various pumps across the refinery to ensure a continuous flow of intermediate streams. Based on the modelling of global refinery emissions, electricity and steam generation account on average for ~14% of the jet fuel refining carbon intensity.

The impact of renewable-powered steam and electricity generation for refinery operations on the global jet fuel CI supply curve was investigated. The generation of main refinery utilities via renewable sources would result in a global upstream carbon intensity reduction of ~0.7 gCO_2e per MJ of crude oil for the production of jet fuel.

Low carbon hydrogen production (blue and green hydrogen): Hydrogen is a critical component of refinery operations to remove sulphur and other impurities from refinery products and further convert the heavier gas oils to more valuable products. Refineries can produce a limited amount of hydrogen in the catalytic reformer of naphtha. Most refinery hydrogen today is produced via steam methane reforming (SMR) of natural gas which results in CO_2 emissions from the conversion process. Carbon capture can be retrofitted to the existing SMR and powered by renewable sources could lead to the production of blue hydrogen.

Another process that could be use is electrolysis. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyser. Electrolysis is a promising technology for hydrogen production from renewable sources. Hydrogen production via electrolysis can result in virtually zero GHG and criteria pollutant emissions. Further details are provided in Section 3.3.2.1.

The modelers assessed the potential of both low carbon hydrogen production, via use of CC and via electrolysis on the global jet fuel CI supply curve. Due to the uncertainty of which hydrogen source would be widely used by the refinery industry, a split of 50/50 was assumed in the modelling. Low carbon hydrogen production results in reducing the global jet fuel refining carbon intensity by ~0.6 gCO_2e per MJ of jet fuel, further contributing to the potential reduction in petroleum-based jet fuel life cycle emissions.


Carbon capture:
- Almost two thirds of refinery CO2 emissions result from combustion processes. Carbon capture technologies offer the potential to capture CO2 emissions at the refinery level.
- The shares of avoided CO2 emissions could be between 20 and 85% of refinery CO2 emissions.

Renewable steam and electricity at refining:
- Steam for refinery operations is mostly produced using industrial boilers through the combustion of natural gas.
- Electricity is required to run various equipment in the refinery.
- Renewable steam and electricity integration can reduce respectively 28% and 13% of the refining emissions.

Low-carbon hydrogen production:
- Grey hydrogen produced from natural gas SMR. A mature, low-cost technology with a significant carbon footprint.
- Hydrogen can be produced through electrolysis (powered by electricity from renewable sources) and/or CCS can be applied to existing SMR to produce blue hydrogen.

Figure 3.9 Summary of upstream technologies that can be applied for LTAG-LCAF production. Short descriptions of each technology are provided. On the right, the impact of technology implementation on the total jet fuel well-to-wake GHG emissions is shown.

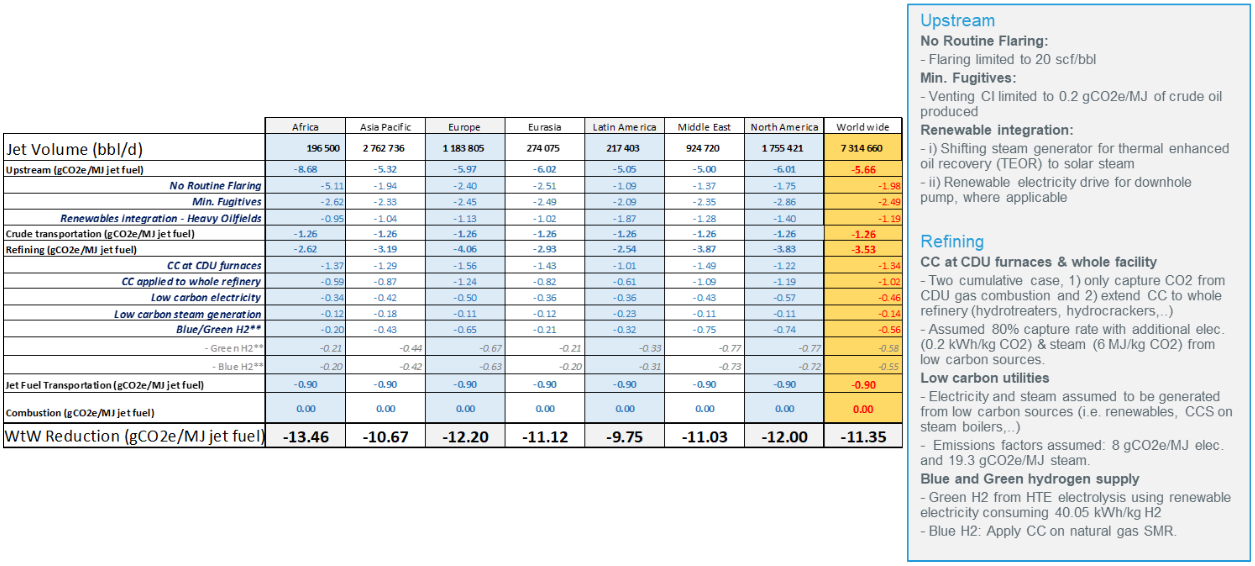
3.3.3.5 Other GHG emission reduction technologies

Crude oil transport: Crude oil mode of transport includes shipping (i.e. crude tankers), pipelines, rails, and barges. Crude tankers have globally the largest impact on the GHG emissions of crude transport (Yash Dixit, 2021). Measures to reduce crude tanker emissions will be used therefore as proxy for both this LCA stage potential CI reductions and stage abatement cost.

LTAG-LCAF distribution to the operators: Most jet fuel is produced from domestic refineries with, limited imports, resulting in trucking being the main mode of transport. GHG emissions reduction measure are assumed to be based on the deployment and use of fuel cells electrical vehicle, fuelled by green H2.

3.3.3.6 Maximum Attainable Mitigation (MAM)

Based on the detailed review of the GHG mitigation technologies and best practices, which can contribute to the production of LTAG-LCAF, each measure's maximum attainable carbon intensity reduction potential was determined. A list of possible measures and an assessment of the estimated maximum attainable mitigation (MAM) they can provide has been previously proposed and reviewed; they are summarised in Figure 3.10. For each measure, emissions reduction assumptions are adopted from (Masnadi *et al.*, 2018; Jing *et al.*, 2020) and by applying the emissions reduction to each element of the bottom-up models.



	Africa	Asia Pacific	Europe	Eurasia	Latin America	Middle East	North America	World wide
Jet Volume (bbl/d)	196 500	2 762 736	1 183 805	274 075	217 403	924 720	1 755 421	7 314 660
Upstream (gCO2e/MJ jet fuel)	-8.68	-5.32	-5.97	-6.02	-5.05	-5.00	-6.01	-5.66
No Routine Flaring	-5.11	-1.94	-2.40	-2.51	-1.09	-1.37	-1.75	-1.98
Min. Fugitives	-2.62	-2.33	-2.45	-2.49	-2.09	-2.35	-2.86	-2.49
Renewables integration - Heavy Oilfields	-0.95	-1.04	-1.13	-1.02	-1.87	-1.28	-1.40	-1.19
Crude transportation (gCO2e/MJ jet fuel)	-1.26	-1.26	-1.26	-1.26	-1.26	-1.26	-1.26	-1.26
Refining (gCO2e/MJ jet fuel)	-2.62	-3.19	-4.06	-2.93	-2.54	-3.87	-3.83	-3.53
CC at CDU furnaces	-1.37	-1.29	-1.56	-1.43	-1.01	-1.49	-1.22	-1.34
CC applied to whole refinery	-0.59	-0.87	-1.24	-0.82	-0.61	-1.09	-1.19	-1.02
Low carbon electricity	-0.34	-0.42	-0.50	-0.36	-0.36	-0.43	-0.57	-0.46
Low carbon steam generation	-0.12	-0.18	-0.11	-0.12	-0.23	-0.11	-0.11	-0.14
*Blue/Green H2***	-0.20	-0.43	-0.65	-0.21	-0.32	-0.75	-0.74	-0.56
- Green H2**	*-0.21*	*-0.44*	*-0.67*	*-0.21*	*-0.33*	*-0.77*	*-0.77*	*-0.58*
- Blue H2**	*-0.20*	*-0.42*	*-0.63*	*-0.20*	*-0.31*	*-0.73*	*-0.72*	*-0.55*
Jet Fuel Transportation (gCO2e/MJ jet fuel)	-0.90	-0.90	-0.90	-0.90	-0.90	-0.90	-0.90	-0.90
Combustion (gCO2e/MJ jet fuel)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WtW Reduction (gCO2e/MJ jet fuel)	**-13.46**	**-10.67**	**-12.20**	**-11.12**	**-9.75**	**-11.03**	**-12.00**	**-11.35**

Upstream

No Routine Flaring:

- Flaring limited to 20 scf/bbl

Min. Fugitives:

- Venting CI limited to 0.2 gCO2e/MJ of crude oil produced

Renewable integration:

- i) Shifting steam generator for thermal enhanced oil recovery (TEOR) to solar steam
- ii) Renewable electricity drive for downhole pump, where applicable

Refining

CC at CDU furnaces & whole facility

- Two cumulative case, 1) only capture CO2 from CDU gas combustion and 2) extend CC to whole refinery (hydrotreaters, hydrocrackers,..)
- Assumed 80% capture rate with additional elec. (0.2 kWh/kg CO2) & steam (6 MJ/kg CO2) from low carbon sources.

Low carbon utilities

- Electricity and steam assumed to be generated from low carbon sources (i.e. renewables, CCS on steam boilers,..)
- Emissions factors assumed: 8 gCO2e/MJ elec. and 19.3 gCO2e/MJ steam.

Blue and Green hydrogen supply

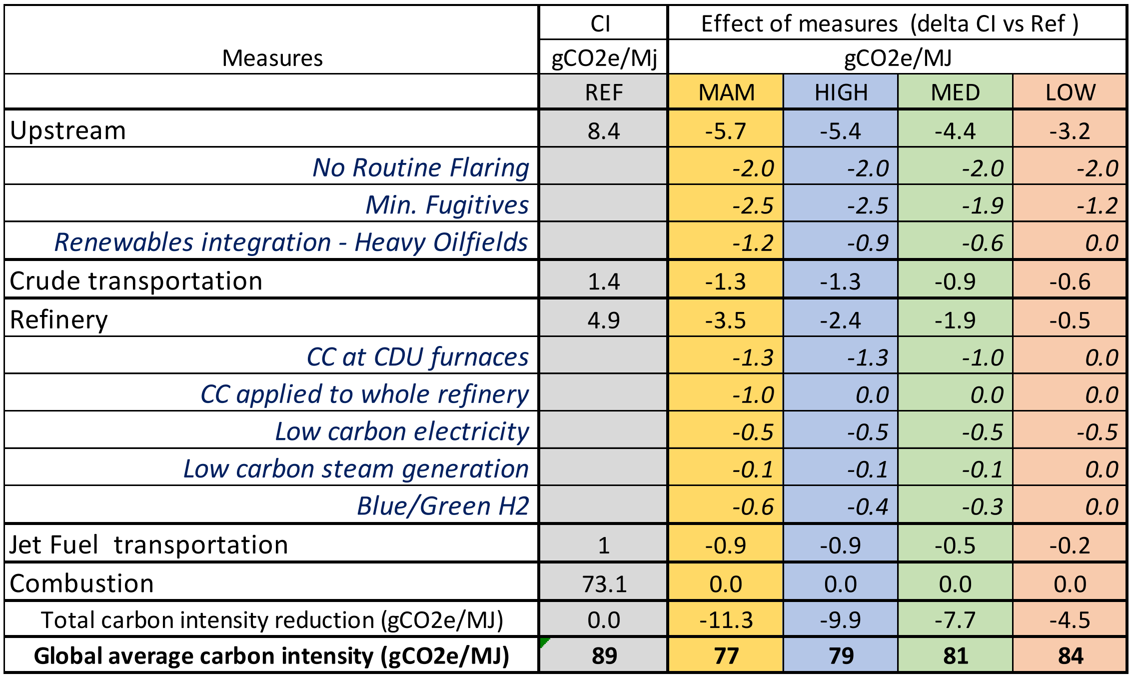
- Green H2 from HTE electrolysis using renewable electricity consuming 40.05 kWh/kg H2
- Blue H2: Apply CC on natural gas SMR.

Figure 3.10 Maximum Attainable Mitigation for each GHG emissions reduction technology with a regional breakdown. Because the GHG emission reduction potential was determined using bottom-up models, the MAM values of one technology can differ from one region to another (e.g. No routine flaring). In the right box is summarized the key assumptions used to determine each technology's CI reduction potential.

The MAM case is used to determine three cases with decreasing exploitation of the different measures and defined as High, Medium and Low cases, which correspond to the F3, F2 and F1 scenarios. Table 3.6 shows the summary of the expected carbon intensity reduction under each case. The following sections will provide additional explanations on how the values have been determined for each scenario.

Note that the resulting global volume-weighted average carbon intensity for each scenario represents the average CI for the whole jet fuel production and not the average CI of LTAG-LCAF under each scenario. LTAG-LCAF projected volume is determined as the portion of each scenario merit curve which demonstrates a well-to wake carbon intensity of <80.1 gCO_2e/MJ.

Table 3.6 Average Carbon Intensity of Jet fuel and contribution of mitigation measures. REF: reference case. No measures were applied. MAM: maximum attainable mitigation case. HIGH, MED, LOW Scenarios with a progressively deep application of the measures



Measures	CI	Effect of measures (delta CI vs Ref)			
	gCO2e/Mj	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**

3.3.3.7 Deployment of GHG emissions reduction technologies under different fuels scenarios

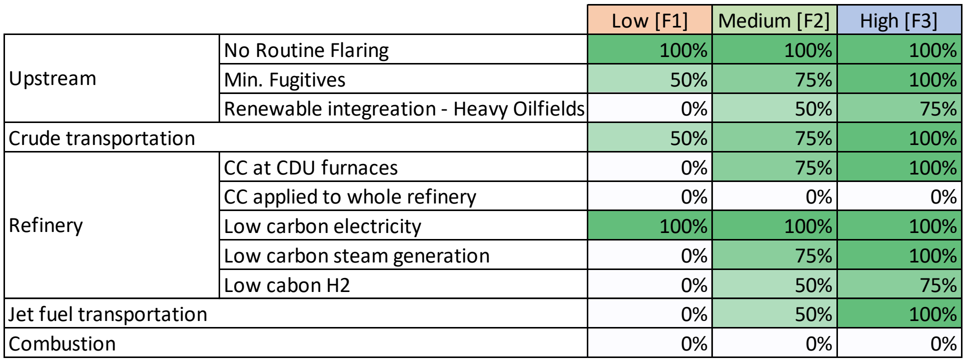
In the case of LTAG-LCAF, the different scenarios consider the deployment of key enabling LTAG-LCAF technologies as described in Table 3.7:

Table 3.7 Description of the LTAG-LCAF GHG emissions reduction measures deployment under LTAG Fuels scenarios.

Technology Scenario	**Description**	**Target**
Low	Low investment scenario based on quick wins and low-hanging fruit GHG mitigation technologies and practices: - Minimum flaring - Low carbon electricity use at refinery - Methane leakage detection and control measures in upstream operations	- 100% of target flaring rate (20 scf/bbl) - 100% of target electricity carbon intensity (8 gCO_2e/MJ of electricity) - 50% of target methane intensity (0.2 gCO_2e/MJ or Norway's methane intensity in 2015)
Medium	Moderate investment scenario that extends the low scenario by applying: - Methane leakage detection and control measures in upstream operations - Retrofitting carbon capture on the furnace stack of refinery crude distillation column - Partial low carbon steam use at refinery - Partial low carbon hydrogen use at refinery	- 75% of target methane intensity (0.2 gCO_2e/MJ or Norway's methane intensity in 2015) - 75% of target carbon capture efficiency (80% carbon capture rate) - 75% of target steam carbon intensity (19.3 gCO_2e/MJ of steam) - 50% of target hydrogen carbon intensity (combination of green H2 consuming 40.5 kWh/kg H2 and blue H2 applying CCS to SMR)
High	Reaching target emissions reduction for all technologies	- 100% of target

Table 3.7 shows how each LTAG-LCAF GHG emissions reduction measures are modeled under each Fuels Scenario. The technology deployment factors (%) describe the aspiration and barriers under each Fuels Scenario and each technology's readiness and attainability.

Table 3.8 Deployment of the various GHG emissions technologies under different scenarios described by their technology deployment factors (%)



		Low [F1]	Medium [F2]	High [F3]
Upstream	No Routine Flaring	100%	100%	100%
	Min. Fugitives	50%	75%	100%
	Renewable integreation - Heavy Oilfields	0%	50%	75%
Crude transportation		50%	75%	100%
Refinery	CC at CDU furnaces	0%	75%	100%
	CC applied to whole refinery	0%	0%	0%
	Low carbon electricity	100%	100%	100%
	Low carbon steam generation	0%	75%	100%
	Low cabon H2	0%	50%	75%
Jet fuel transportation		0%	50%	100%
Combustion		0%	0%	0%

As mentioned in Section 3.3.3.1, explaining the overall methodology, Table 3.8 will be applied to the global supply chain to provide a snapshot of the jet fuel CI merit curves under the different Fuels scenarios. The scenarios merit curve will be used to determine the LTAG-LCAF projected volume production under the different scenarios, and a time-propagation will be applied for 2030, 2050, and 2070. Given the time horizon of this study, it is essential to note the challenges/limitations in projecting the actual market dynamic and volumes.

3.3.4 Non-drop-in – LH_2

For Non-Drop-in fuels, Fuels sub-group experts worked in close coordination with the ACES ad hoc group of TECH. The electricity category was not deemed significant by ACES and Fuels sub-group experts as large scale fully electric systems are not anticipated to be of widespread use within the time frames under consideration. Experts from MIT led the LH_2 analysis, assessing airport fueling infrastructure, expected hydrogen volumes, and broader supply chain systems needed to support three main LH_2 scenarios.

Production of liquid hydrogen requires both the hydrogen production process as well as the liquefaction step. Furthermore, first order energy requirements were assessed for transporting hydrogen, which in the case of drop-in fuels are negligible (as can be seen e.g. for the value chain of crude oil transport to Europe ((Yash Dixit, 2021);(Christensen, 2020)).

Following the modeling in Section 3.3.2.1, ***hydrogen production*** was modeled using electrolysis. While no specific electrolysis process is defined, an energy efficiency of 70% was assumed, which is consistent with PEM electrolysis.

The ***liquefaction of hydrogen*** was assumed to show significant technical progress as outlined in (Aasadnia and Mehrpooya, 2018). This progress results in reductions in electricity requirements – starting at 10 kWh/kg in 2020 and reaching 5 kWh/kg in 2050.

The electricity demand for the **transport of gaseous hydrogen** via pipeline transport was assessed using the HDSAM model by Argonne National Laboratories (Argonne National Laboratories, 2015). It was found that the electricity for operating the compressor stations to be 0.02 MJ/MJ for a flow rate of 1500 t/d and a distance of 1000 km.

The sum of electricity requirements for LH_2 production are summarized in Table 3.9.

Table 3.9 Electricity demand for LH_2 production and transportation [MJ (electricity) / MJ (LH_2)].

	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**

3.4 Alignment of Deployment Scenarios

With the Fuels scenarios and methodologies to estimate the future production potential defined, the next phase of the analysis involved reviewing the various production assumptions to determine the appropriate approach for each respective scenario. As before, the LTAG-SAF efforts were split into two categories, biomass- and solid/liquid waste-based fuels and waste CO_2- and atmospheric CO_2-based fuels, as different methodologies were used to determine future fuel volumes. These efforts are described in the subsequent sections.

3.4.1 LTAG-SAF – Biomass- & Solid/Liquid Waste-based

As explained in previous sections, potential volumes of LTAG-SAF from biomass and solid/liquid waste were estimated using market diffusion models developed by the FTG TPP group. Market diffusion models are used to estimate the degree of entry of a new product or technology into the market, assuming that the new product entry is evolutionary. This new product replaces an older product while meeting the same needs. In this example, SAF replaces conventional, petroleum-based jet fuel. For the F1 scenario, the *Moderate* FTG TPP scenario was used wherein there is some policy level support for SAF production. While the FTG TPP model describes the *Moderate* scenario as not having level support for SAF production with ground transportation, given the limitations of the FTG TPP model scenarios and keeping in mind the desire to provide the greatest consistency across CAEP efforts, experts determined the most appropriate path forward would be to apply the model as it was defined and developed under the FTG TPP work and to note the assumptions used. For F2, the *High* FTG TPP scenario was employed to project future fuel volumes. The *High* scenario represents a level-playing field between SAF and ground transportation fuels. Finally, the *High+* FTG TPP scenario was used to model F3 future fuel volumes. This FTG TPP scenario represents a policy landscape with a SAF emphasis, as described under the F3 scenario description.

3.4.2 LTAG-SAF – Waste CO_2- & Atmospheric CO_2- based

The modelers estimated the potential volumes of synthetic jet fuel which is produced using CO_2 from gaseous waste CO_2 streams (e.g. in power stations or from cement production) or from the atmosphere (i.e. through Direct Air Capture (DAC)) out to 2070 considering three factors: (1) the size of future waste CO_2 streams under different scenarios; (2) the availability of CO_2 captured through DAC; and (3) the available renewable electricity for fuel production. Each of these three factors has the potential to limit the obtainable fuel volumes. In turn, for any point in time, obtainable fuel volumes for this fuel category were estimated through the following process:

i. Current and future availability of low-carbon electricity for jet fuel production (see Section 3.4.2.1) to power the process steps outlined in Section 3.3.1 was analyzed.
ii. Under IS 3 (Step (ii) is skipped under IS 1 and IS 2), future DAC scale-up (see Section 3.4.2.2) was analyzed and the amount of jet fuel that can be produced was determined, if (hypothetically) the CO_2 captured through DAC can be fully used for fuel production, using the process assumptions outlined in Section 3.3. If the resulting electricity demand exceeds availability of renewable electricity, the fuel production potential is reduced so that the maximum available electricity is not exceeded.[7]

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[7] Note that this step is relevant for IS 3 only since DAC is not available under IS 2. Step 2 is considered before Step 3 under IS 3, since the GHG emissions for DAC-based fuels are lower than for Waste CO_2-based fuels (see Section 4) and IS 3 relies on fuel prioritization driven by GHG emissions savings.

iii. Projected waste CO_2 streams (see Section 3.4.2.3) were analyzed and it was determined that the amount of jet fuel that can be produced if (hypothetically) all waste CO_2 can be used for jet fuel production, using the process assumptions outlined in Section 3.3. If the electricity demand for converting all waste CO_2 exceeds the residual renewable electricity availability after converting all CO_2 from DAC to fuel, the potential of fuel production from waste CO_2 will be reduced so that the electricity availability will not be exceeded.

3.4.2.1 Available renewable electricity

Electricity production scenarios are defined following the definitions of the Fuels scenarios. To focus on low-carbon fuels, the analysis of available electricity for jet fuel production primarily focused on renewable electricity sources and their scalability; the impact of other electricity sources and their impact on the lifecycle GHG emissions of fuel production is presented as a sensitivity analysis.

To model the availability of renewable electricity, three trajectories from the portfolio of IEA scenarios were used. Under F1, low systemic change and no large infrastructure adaptations were assumed, which was matched to IEA’s Stated Policy Scenario (IEA, Net Zero by 2050 – A Roadmap for the global energy sector, 2021). This scenario assumes that only power generation capacities are added which have already been committed. Under F2, increased systemic change and availability of technology was assumed. This was matched to IEA’s Sustainable Development Scenario (IEA, Energy Technology Perspectives, 2020), which is broadly consistent with the Paris goals limiting global warming to two degrees or less. Under F3, a net-zero emissions scenario for electricity production in 2050 was assumed, that is IEA’s NZE 2050 scenario (IEA, Net Zero by 2050 – A Roadmap for the global energy sector, 2021).

The IEA trajectories do not fully reflect the targeted alternative fuel production considered here. It was therefore assumed that the additional renewable electricity production, which can be made available, to vary over time, starting at 10% in 2030 and linearly increasing to 40% in 2060.

An overview of the available power generation for jet fuel production is plotted in Figure 3.11. It is noted that, according to Table 3.3, only a fraction of fuel output from the processes will be jet fuel. The available electricity will power the entire fuel production process, including all other products in the output slate, which reduces the jet fuel output in case of scenarios which are limited by the availability of renewable electricity.

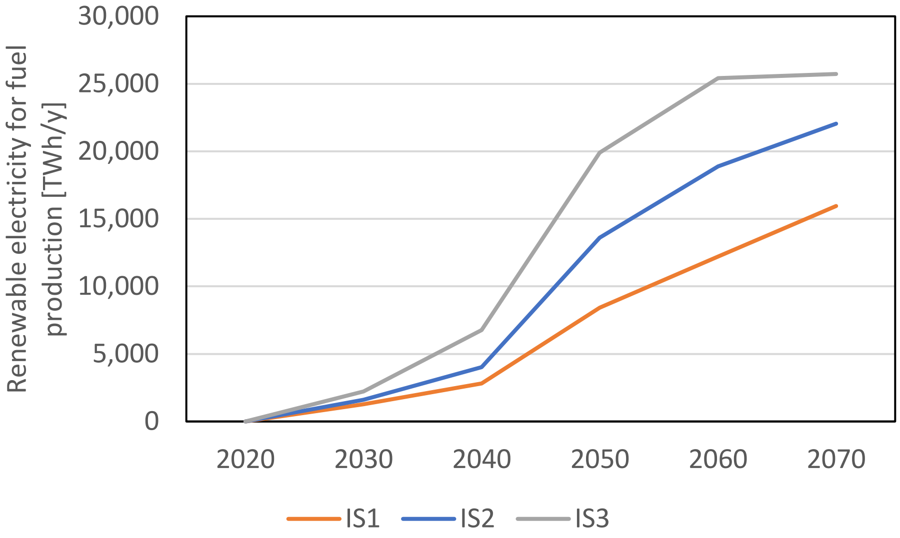

Figure 3.11 – Available renewable electricity for fuel production.

3.4.2.2 Direct Air Capture

Following the definition of the Fuels scenarios, DAC was assumed to be available under F3 only.[8] In addition, the scale-up of DAC capacity was limited in F3 following IEA's Net-Zero Emission 2050 scenario (consistent with the assumption of the stated electricity generation scenario). Since IEA's scenario does not represents the DAC installation for jet fuel production, additional DAC capacity [here: up to 50% above IEA's NZE 2050 level] was assumed to be installed for jet fuel production. The resulting availability of CO_2 from DAC over time is shown in Figure 3.12.

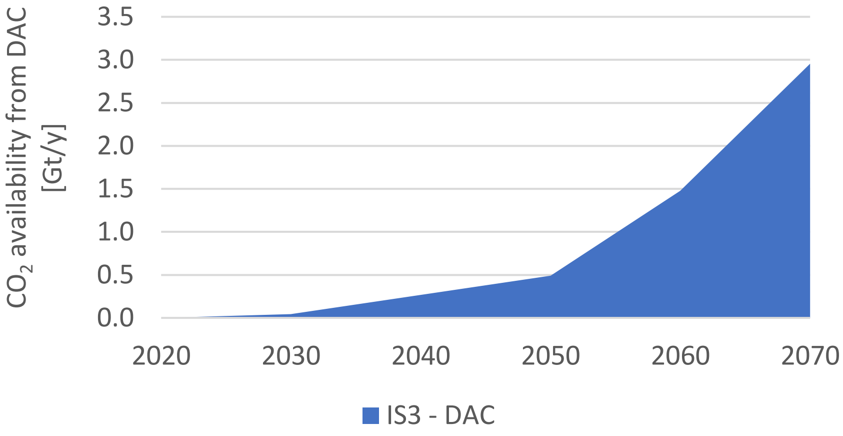

Figure 3.12 – Available CO_2 from DAC.

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[8] The sensitivity of these results have been analyzed against this assumption. Under IS 2, the fuel scenario is driven by avoidance cost. Since Waste-CO_2 based fuels have lower avoidance costs under IS 2 than Atmospheric CO_2-based fuels and Waste CO_2-based fuels already require all available electricity, this assumption is robust.

3.4.2.3 Waste CO_2 availability

The analysis considers waste CO_2 capture from ethanol production, ammonia production, iron and steel production, and cement production. These sources are included, as their emissions are often unavoidable, even under future decarbonization scenarios. CO_2 emissions from electricity production are not included because these emissions are considered to be avoidable.

The available CO_2 from waste CO_2 streams is determined based on sectoral production forecasts and carbon intensities for the industries under consideration. The trajectories are modeled as follows:

- Sectoral production forecasts of iron/steel, ammonia, and cement are taken from IEA's STEPS scenario, while ethanol production is estimated in IEA's SDS scenario.
- Carbon intensities of each product are 2.03 tons CO_2 per 10^3 gal of ethanol, 1.23, 0.49 – 0.54, 0.90 – 1.40 tons CO_2 per ton of cement, steel/iron, and ammonia, respectively.
- Assuming continued technology development, carbon intensities of cement and steel/iron, which account for 95% of the total available CO_2, are decreased linearly through 2070.

CO_2 from different subsets of waste CO_2 streams are assumed to be used under each of three fuels scenarios:

- Under F1, only CO_2 capture from ethanol and ammonia sources were considered as CO_2 capture from these sources is considerably cheaper than from the other sources (20-30 USD per tonne CO_2 for ammonia and ethanol vs. ~110 USD per tonne CO_2 for iron & steel and cement).
- Under F2, CO_2 capture from ethanol and ammonia sources, and from the production of iron and steel and cement, due to wide availability of waste CO_2 capture technologies, were considered.
- Under F3, the same sources as F2 are considered, but competition between carbon utilization (through producing jet fuel) and Carbon Capture and Storage (CCS), which is expected to be prevalent under F3, was modeled. CCS volumes are taken from (Paltsev *et al.*, 2021).

Figure 3.13 shows the availability of CO_2 from (industrial) waste streams for the three scenarios.

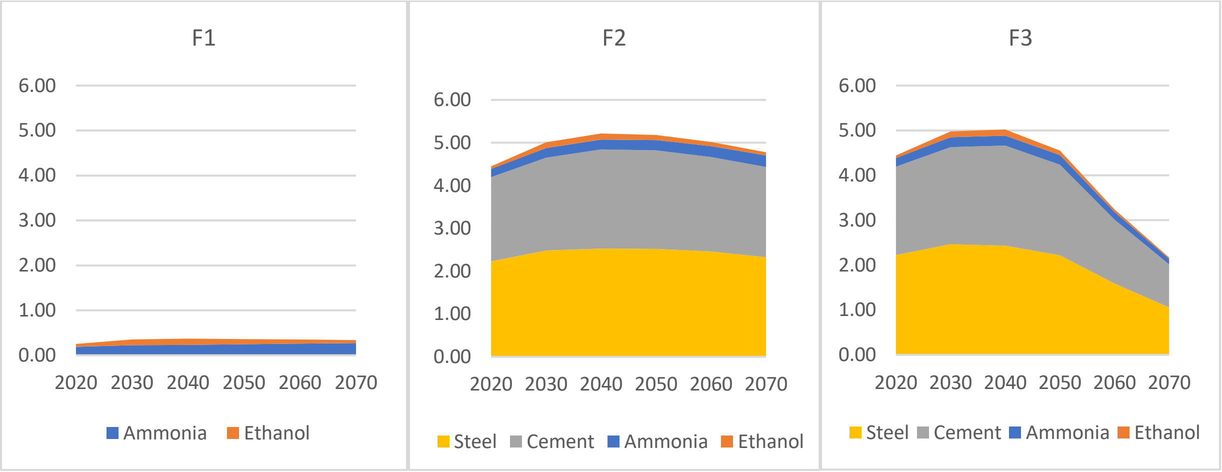


Figure 3.13 Net availability of CO_2 from waste sources and from the atmosphere in fuels scenarios 1-3

3.4.3 LTAG-LCAF

Figure 3.14 shows the global jet fuel production volumes' actual distribution according to their specific carbon intensity, referred to as the baseline merit curve (BMC). The previously described in-depth global supply chain analysis determined the merit plot for the reference case. In addition, the merit curves (including the IS cases) can be mathematically described and fitted with a probability distribution function.

The beta function captures the shape of the distribution well and can be easily adjusted to obtain the best fit. The use of the probability distribution function is explained due to limited available data required to develop diffusion models for each identified GHG emissions reduction technology and best practices by 2030, 2050 and 2070.

Therefore, a top-down approach was adopted, based on probability distribution functions, to determine the projected volume of LTAG-LCAF. Projected volume is determined by the deployment of the GHG emissions reduction technologies and practices and is defined as the fraction of the IS scenario merit curve, which demonstrates a well-to-wake carbon intensity <80.1 gCO_2e/MJ.

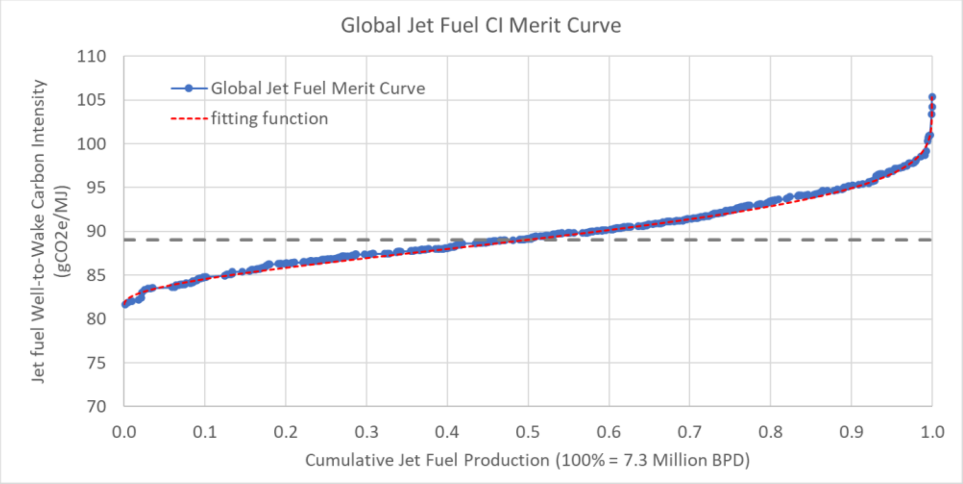


Figure 3.14 Global jet fuel production Baseline Merit Curve (BMC) with fitted probability distribution curve (red dotted line). The grey dotted line shows the global average carbon intensity of ~89gCO_2e/MJ of jet

A probability distribution model was applied to each IS merit curve from the technology scenario snapshot by fitting the curves. Allowing to perform the time propagation of potential attainable LTAG-LCAF projected volume under each technology scenario.

Under the Low and Medium technology scenarios, a limited volume of LTAG-LCAF can be offered to the market. Under the High scenario with expected high investment cost, the volumes of LTAG-LCAF offered to the market becomes significant. Overall, LTAG-LCAF will need large investments across the supply chain.

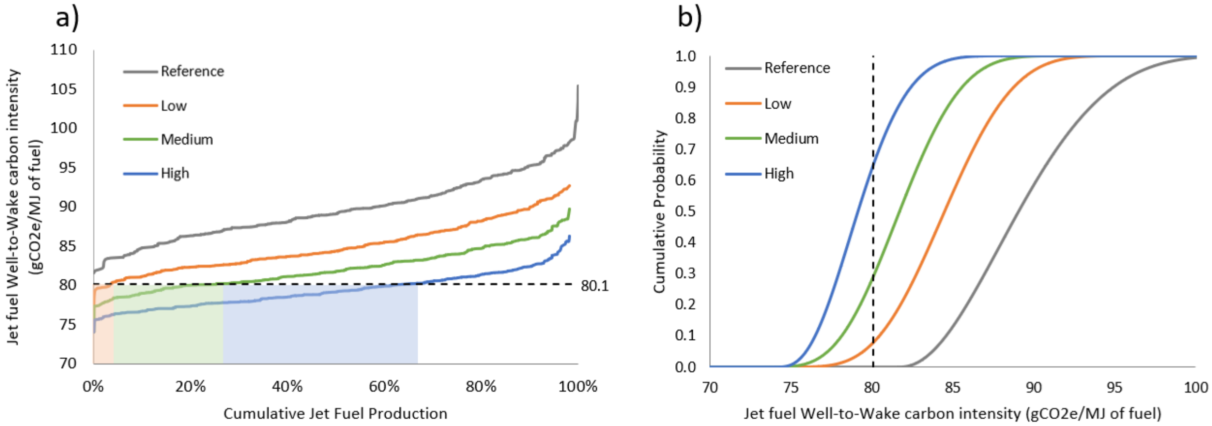


Figure 3.15 a) Fuels scenario global jet fuel well-to-wake carbon intensity based on detailed bottom-up models and b) corresponding cumulative probability of jet fuel carbon intensity which will be used to determine project volume of LTAG-LCAF. The black dotted line represents the CI threshold of 80.1 gCO$_2$e/MJ of Jet in both figures. In a), the colored boxes represent the projected volume of LTAG-LCAF as a share of the total jet fuel production.

Merit plots for the High, Medium and Low cases have been derived from the reference distribution applying the mitigation measures to a different extent, depending on the scenario and specific geographic area. Here below in Table *3.10*, as an example, is how the mitigation measures are applied in different geographic areas for the High case scenario and how this scenario global average carbon intensity reduction (-9.89 gCO$_2$/MJ of Jet) has been derived.

Table 3.10 - Assumed CI reduction of each GHG mitigation measure under the High scenario, breakdown by regions and measures.

		Africa	Asia Pacific	Europe	Eurasia	Latin America	Middle East	North America	**Averaged**
Jet Volume (bbl/d)		**196,500**	**2,762,736**	**1,183,805**	**274,075**	**217,403**	**924,720**	**1,755,421**	**7,314,660**
Upstream (gCO2e/MJ jet fuel)		**-8.44**	**-5.06**	**-5.69**	**-5.77**	**-4.58**	**-4.68**	**-5.66**	**-5.36**
	No Routine Flaring	-5.11	-1.94	-2.40	-2.51	-1.09	-1.37	-1.75	**-1.98**
	Min. Fugitives	-2.62	-2.33	-2.45	-2.49	-2.09	-2.35	-2.86	**-2.49**
	Renewables integration - Heavy Oilfields	-0.71	-0.78	-0.85	-0.77	-1.40	-0.96	-1.05	**-0.90**
Crude transportation (gCO2e/MJ jet fuel)		**-1.26**	**-1.26**	**-1.26**	**-1.26**	**-1.26**	**-1.26**	**-1.26**	**-1.26**
Refining (gCO2e/MJ jet fuel)		**-1.98**	**-2.22**	**-2.66**	**-2.06**	**-1.85**	**-2.59**	**-2.45**	**-2.37**
	CC at CDU furnaces	-1.37	-1.29	-1.56	-1.43	-1.01	-1.49	-1.22	**-1.34**
	CC applied to whole refinery	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
	Low carbon electricity	-0.34	-0.42	-0.50	-0.36	-0.36	-0.43	-0.57	**-0.46**
	Low carbon steam generation	-0.12	-0.18	-0.11	-0.12	-0.23	-0.11	-0.11	**-0.14**
	Blue/Green H2	-0.15	-0.32	-0.49	-0.16	-0.24	-0.56	-0.56	**-0.42**
Jet Fuel Transportation (gCO2e/MJ jet fuel)		**-0.90**	**-0.90**	**-0.90**	**-0.90**	**-0.90**	**-0.90**	**-0.90**	**-0.90**
Combustion (gCO2e/MJ jet fuel)		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
WtW Reduction (gCO2e/MJ jet fuel)		**-12.58**	**-9.44**	**-10.52**	**-9.99**	**-8.59**	**-9.43**	**-10.27**	**-9.89**

A specific time propagation pattern is defined for each scenario to fully implement all the scenario's measures. As shown in Figure *3.16*, for the High case, intermediate merit plots have been generated adjusting parameters of the distribution functions to describe the measures implementation over time and resulting carbon intensity reduction.

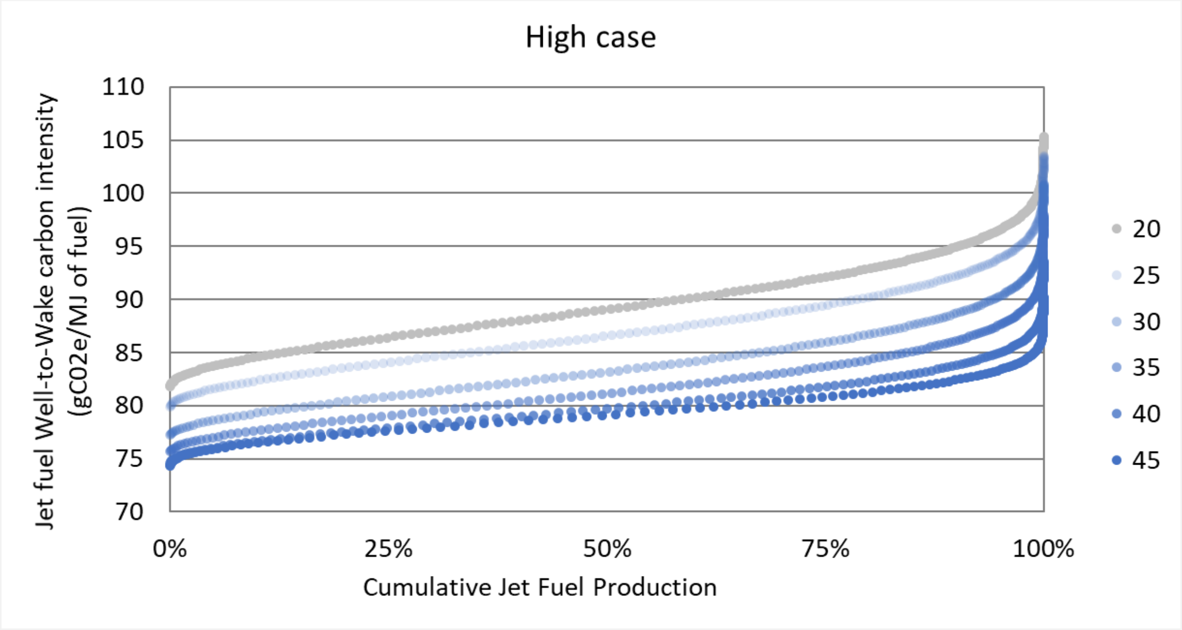


Figure 3.16 Evolution of the CI distribution with time for the High case

Under the Low scenario, the implementation of GHG mitigation measures will be limited, explaining the limited global average CI reduction of jet fuel production in Figure 3.17. However, the measures applied will likely be the ones having lower abatement costs. In addition, retrofitting of existing assets will be applied when possible. The exploitation of this set of measures is expected to span over the next 15 years.

In the High scenario, the global volume-weighted average well-to-wake carbon intensity reduction of jet fuel production will be reduced from 89 gCO_2e/MJ of jet to 79 gCO_2e/MJ of jet, all the available spectrum of measures will be applied. Assets will be retrofitted and reshaped, but as well new assets based on new technologies, with extensive utilization of renewable energy sources for utility consumption (electric energy, steam, process heat) will be put in operation. The exploitation of this set of measures is expected to span over the next 30 years.

An intermediate situation is foreseen for the Medium case with the global average CI of jet fuel production going from 89 gCO_2e/MJ to 82 gCO_2e/MJ and time span for application of 20 years.

3.4.4 Non-drop-in – LH2

For liquid hydrogen production, the analysis does not a priori assume fuel production to constrain the uptake of liquid hydrogen as a fuel. Instead, the fuel demand resulting from the hydrogen aircraft uptake under F3 was analyzed, which is not limited by fuel availability. The required electricity production was then calculated to compare the electricity demand to the electricity scenarios outlined in Section 3.4.2.1. Furthermore, the critical investment trajectories were quantified for LH_2 production and distribution infrastructure, which are associated with the vehicle uptake. The results of this analysis are presented in Section 4.

3.5 Lifecycle GHG Emissions

The following section describes the methods used to quantify the expected changes in lifecycle (LCA) values for the various fuel categories. For all fuels a lifecycle analysis was conducted that considered process steps “from well to wake”, i.e. including all emissions over the lifecycle of the fuel. This approach is consistent with the Core LCA work conducted in support of implementing the use of SAF into CORSIA. The results of these analyses are presented in Section 5.

3.5.1 LTAG-SAF – Biomass- & Solid/Liquid Waste-based

The Fuels sub-group used the TPP sensitivity analysis, CAEP12_FTG09_IP03: *Sensitivity Analysis on the GHG Emissions Savings of SAF Production Scenarios*, to model future changes in LCA values for the categories of biomass- and solid/liquid waste-based SAF. This work quantifies the effect of different future production environments, including increased use of cover crops (CC) and the effects of renewable energy (RE) usage for SAF production. Both elements are captured in the Fuels scenario definitions, and it was determined that a method for integrating these effects was needed. The Fuels sub-group reviewed the scenario definitions and established qualifiers to reflect the degree to which each element should be reflected under the three scenarios across the time frame under consideration. These qualifiers were then assigned a numerical weighting factor (WF) to reflect the degree to which each GHG reduction was included in the LCA value. A description of the qualifiers and associated weighting is given in

Table 3.11.

Table 3.11 SAF GHG emission factor qualifiers

Qualifiers	**Weighting Factor (WF)**
No	0
Limited	0.25
Moderate	0.5
High	0.75
Total	1

These qualifiers were then assigned across the three scenarios for three timeframes: 2035, 2050 and 2070. These results are shown in Table 3.12. The associated weighting factors were applied to the total GHG emission factors established through the TPP work (Table 3.13) and added to the base LCA values for each corresponding scenario (Table 3.14). The results of applying this approach are shown in Section 5.1.

Table 3.12 SAF GHG emission factor qualifiers assignments for Fuels scenarios

	F1			**F2**			**F3**		
Factor	**2035**	**2050**	**2070**	**2035**	**2050**	**2070**	**2035**	**2050**	**2070**
CC qualifier	limited	moderate	moderate	moderate	high	total	high	high	total
RE qualifier	limited	moderate	moderate	moderate	high	high	moderate	high	total
CC WF	0.25	0.50	0.50	0.50	0.75	1.00	0.75	0.75	1.00
RE WF	0.25	0.50	0.75	0.50	0.75	0.75	0.50	0.75	1.00

Where CC = cover crops, RE = renewable energy and WF = weighting factor

Table 3.13 FTG TPP total variation in GHG emission factors of SAF production (gCO_{2eq}/MJ) for cover crops and renewable energy scenarios

Scenario	**Cover Crops**	**Renewable Energy**
F1 (Moderate)	-6.8	-3.2
F2 (High)	-8.3	-3.4
F3 (High+)	-10.4	-3.7

Table 3.14 FTG TPP LCA SAF base values under different scenarios

Scenario	**2035 Base Values (gCO_{2eq}/MJ)**	**2050 Base Values (gCO_{2eq}/MJ)**
F1 (Moderate)	31.5	35.9
F2 (High)	32.2	35.3
F3 (High+)	33.9	35.2

3.5.2 LTAG-SAF – Waste CO_2- & Atmospheric CO_2-based

The CORSIA Core LCA approach was followed for LTAG-SAF from waste CO_2 and atmospheric CO_2, allocating emissions to products through energy-based allocation and by setting emissions for biogenic emissions, emissions from gaseous waste CO_2 streams, and emissions from CO_2 sourced from DAC to zero.

For the fuel production processes outlined in Section 3.3, electricity is among the most significant input factors. As such, it is important to consider the GHG emission intensity of electricity production in the analysis. In this analysis, the embodied emissions of electricity generation are accounted for, following the ISO standards of life cycle analysis. Literature values were applied ((Dolan and Heath, 2012); (National Renewable Energy Laboratories, 2012)), leading to a GHG emission intensity of 3.1 gCO_2e/MJ(elec) for wind energy and 11.1 gCO_2e/MJ(elec) for PV in 2020. These specific emissions are assumed to decline to 50% of their value until 2050, i.e. to 1.5 and 5.6 gCO_2e/MJ(elec), respectively. In addition, a sensitivity analyses was conducted using global average grid values for the GHG emission intensity of electricity. This step is considered to analyze the case that all electricity for fuel production is sourced from the grid. The global average grid composition in these analyses follows the scenario assumptions outlined in Section 3.4.2.1; that is: depending on the Fuels scenario under consideration, the grid was assumed to be decarbonized to different degree over time. The GHG emission intensity of electricity production from different sources was applied to obtain the global average grid GHG emissions curves as shown in Figure 3.18.

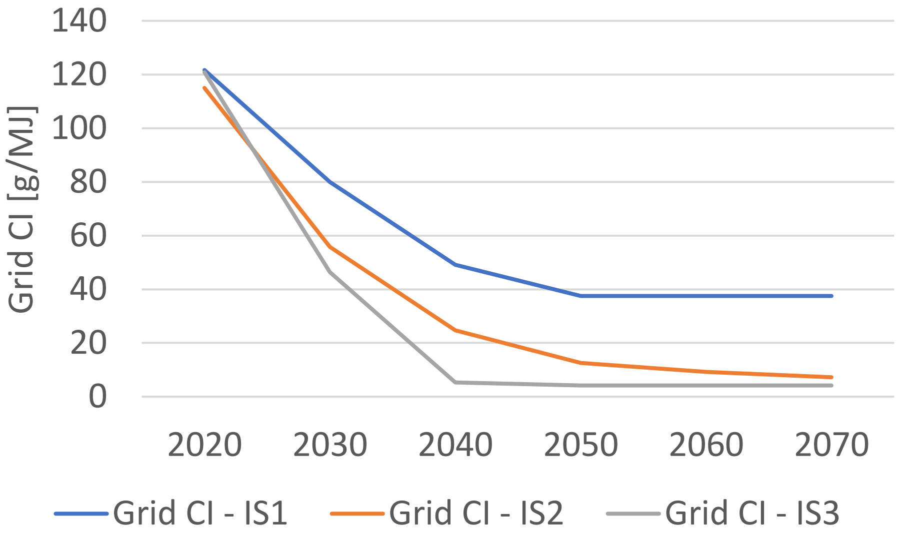
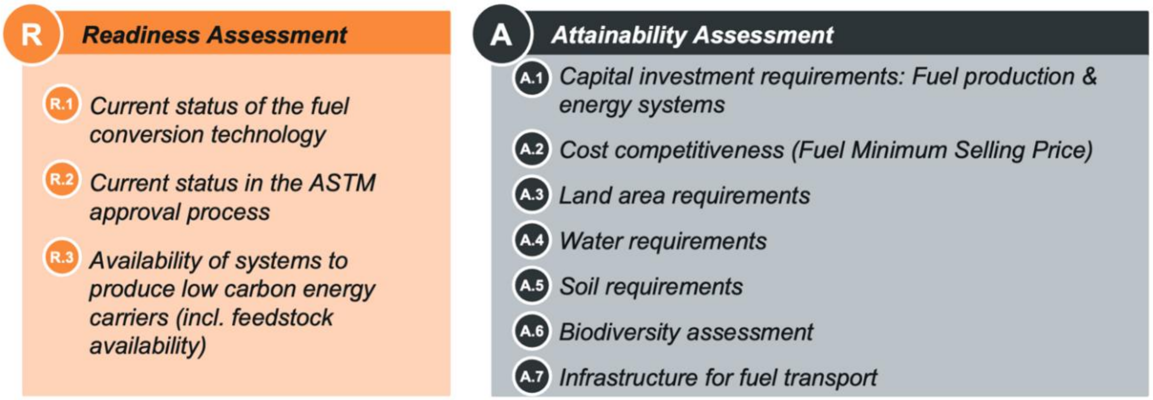


Figure 3.18 - Trajectories of grid carbon intensity. The selected scenarios correspond to IEA scenarios of different levels of ambition regarding the decarbonization of the grid (F1: IEA STEPS, F2: IEA SDS, F3: IEA NZE).

For ***other process steps***, including the transportation of the finished fuel, emissions are considered as calculated for CORSIA eligible fuels (using consistent assumptions for FT processes whenever applicable).

3.6 Readiness and Attainability Analysis

The attainability and readiness of drop-in and non-drop-in fuels were evaluated against a set of criteria, outlined in Figure 3.19 for drop-in fuels. A similar set of criteria was developed for non-drop-in fuels and is shown in Figure 3.20. These criteria were evaluated using input from international experts as well as external literature review. Additional analyses were conducted as needed. If applicable, such methods were outlined in more detail in the following subsections.



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)

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

Figure 3.19 - Readiness and attainability assessment criteria for drop-in fuels.

3.6.1 LTAG-SAF – Biomass- and Solid/Liquid Waste-based

The readiness and attainability assessment for LTAG-SAF from biomass- and solid/liquid waste-based fuels is embedded in the fuel production market diffusion models developed by FTG TPP. The market diffusion models implicitly incorporate various factors that reflect the overall readiness and attainability of these fuels. While not explicitly assigning values for each of the readiness and attainability elements, factors such as producer maturity and success rate reflect varying levels of readiness and attainability. For example, under the *High+* FTG TPP market diffusion model, which corresponds to the LTAG F3 fuel production case for LTAG-SAF from biomass- and solid/liquid waste-based fuels, these factors are set to reflect an implicit SAF policy landscape that has a SAF emphasis. To model this, facilities with varying maturity levels are given increased success rates over *Moderate*, *High* and *High+* models while increasing the jet fuel product slate ratio. This ratio starts from actual stated jet fuel product slate values or a low estimate under the *Moderate* scenario and increases to a high estimated jet fuel product slate ratio under the *High+* scenario.

3.6.2 LTAG-SAF – Atmospheric CO_2- and Waste CO_2-based

R.3 - Availability for systems to produce low carbon energy carriers:
The availability of waste CO_2 streams, DAC and renewable electricity is evaluated as described using the methods outlined in Section 3.4.2.

A.1 - Capital investments:
Investment costs are assessed on the basis of a literature review for specific investment costs. The resulting assumptions are documented in Table 3.15.

Table 3.15 – Investment assumptions for fuels produced from Waste CO_2 and Atmospheric CO_2.

Process step	**Specific investment costs**
Renewable electricity generation	PV: 1391-480 $/kW (2020-2050) Wind: 1436-525 $/kW (2020-2050)
Electrolysis	1000-450 $/kW (F1, 2020-2050) 840-200 (F2, 2020-2050)

	600-150 (F3, 2020-2050)
Carbon capture from waste gas	90 \$/(t/y) (F1) 450 \$/(t/y) (F2,3)
Carbon capture from DAC	730-2170 (2020) – 200-1350 \$/(t/y) (2050)
Conversion	410-4140 \$/kW

The specific investment costs are comprised of renewable electricity generation (PV, wind), electrolysis, carbon capture (from a waste stream (F1-F3) or from the atmosphere (F3)), and conversion. The cost for electricity generation depends on the technological maturity (F1: conservative, F2: average, F3: advanced). Furthermore, within each Fuels scenario, different locations for electricity generation are taken into account that define a minimum, an average, and a maximum of the capacity factor of the PV modules and the wind turbines. The capacity factor then defines the required installed power to produce the electricity needed for fuel production. The electrolyzers are sized to match the installed power of electricity generation to ensure compatibility with maximum power generation.

For each Fuels scenario, a minimum, an average, and a maximum estimate of investments costs is derived: in F1, the specific investment costs are 25.2-62.6 b\$/(t/y) in 2020 and 13.7-31.9 b\$/(t/y) in 2050, In F2, 18.5-45.5 b\$/(t/y) in 2020 and 8.3-18.7 b\$/(t/y) in 2050, in F3 for waste CO_2, 16.8-41.4 b\$/(t/y) in 2020 and 6.3-14.3 b\$/(t/y) in 2050, and in F3 for DAC, 19.1-45.1 b\$/(t/y) in 2020 and 7.8-16.2 b\$/(t/y) in 2050.

A.2 – Minimum Selling Price:

Minimum selling price (MSP) is calculated using spreadsheet techno-economic analysis models. Capital expenses, operating expenses and revenue streams from all products are utilized to estimate MSP of fuel distillates under a set of user-determined financial assumptions. All fuel distillate values are linearly related to jet fuel MSP using relationships developed by historical fuel cost data available on the U.S. EIA. Analysis variables include local operating costs (e.g. electricity and natural gas rates), financial variables (e.g. discount rate, loan details, inflation rate), and process options (e.g. feedstock type and price, facility scale, plant maturity), as well as resource specific availability of electricity (capacity factor). Capital costs are estimated using inside battery limit (ISBL) equipment costs that were determined from literature, Aspen modeling, and quotations. The ISBL costs were combined with ratio factors to estimate outside battery limit (OSBL) costs. The total capital investment, operating costs and financial variables are used in a cost-benefit analysis to determine the distillate MSP values that correspond to a net present value of zero. The following variables are used: levelized cost of electricity (varied in technological maturity (varied between fuels scenarios) and locations (varied within fuels scenarios)), of hydrogen cost (varies with cost of electricity and investment cost assumptions between scenarios), and of CO_2 capture cost (vary between technology and scenario). The fuel production cost thus have a minimum, an average, and a maximum value for each year and for each Fuels scenario.

A.3 – Land area

The land requirements for waste CO_2-based and/or Atmospheric CO_2-based fuel production is assessed specifically with regard to the land required for the installation of renewable electricity generation equipment, specifically PV and wind power. For this purpose, the specific land area requirements of electricity generation were multiplied by the total amount of electricity needed. Region-specific capacity factors are accounted for if necessary. The areas of the conversion facilities and those of direct air capture, where applicable, are smaller in comparison and can be accommodated on the areas of electricity production. Specifically, values of 2.9 - 72 m^2/(MWh*y)[9] (McDonald *et al.*, 2009) were used for wind energy and 6.3 m^2/(MWh*y) for PV[10].

A.4 – Water requirements:
The water requirements for PtL production using either waste CO_2 or DAC are determined by multiplying the amount of fuel by the specific demand of water for the single process steps, i.e. electrolysis, CO_2 capture, conversion. The specific water demand is 6-8 L/L jet fuel in F1, 4-7 L/L in F2, and 0-5 L/L in F3 (Mekonnen, Gerbens-Leenes and Hoekstra, 2015).

3.6.3 Non-drop-in – LH_2

The attainability and readiness of non-drop-in fuels is evaluated using the criteria as outlined in Figure 3.20. These criteria are consistent with the criteria for drop-in fuels presented in Figure 3.19, but contain some notable differences, e.g. as they look into the availability of standards and regulations, which are fully defined for drop-in fuels.
These criteria are evaluated using input from international experts as well as literature review. Additional analyses are conducted where needed. If applicable, such methods are outlined in the following subsections.

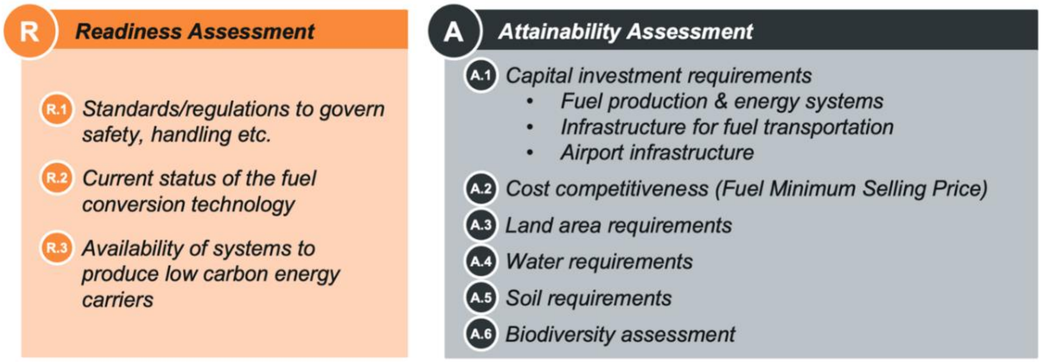


Figure 3.20 - Readiness and attainability assessment criteria for non-drop-in fuels.

R.3 - Availability for systems to produce low carbon energy carriers:
The availability of waste CO_2 streams, DAC and renewable electricity is evaluated following the approach outlined in Section 3.4.4.

A.1 - Investment requirements:
The investment costs of the pathways are determined by multiplying the specific investment costs for renewable electricity generation, electrolysis, and liquefaction (see Table 3.16) with the required demand for power or hydrogen. The investments are derived from a literature review. In F3, the cost of electricity generation per unit power declines with time. Power generation at different locations has different capacity factors. The generation of one megaton of fuel therefore requires different installed electrical power. Thus the specific and total investment costs change accordingly. This effect also

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[9] The lower end of the scale is the actually covered ground area and the upper end is the totally affected area around the wind park.
[10] Based on the assumption of 20% module efficiency, 40% land-use factor, 10% system losses, and 25% capacity factor.

defines the size of the electrolyzers that are sized to the maximum power output of the electricity generation system. The size of the gas storage is adjusted according to the capacity factor, as well, accounting for the fact that the liquefaction unit needs to run continuously. For the distribution of hydrogen, a 1000-km gaseous pipeline with a unit cost of 1.21 million USD per km was assumed.

Table 3.16 - Assumptions for derivation of investment costs

Process step	**Specific investment costs**
Renewable electricity generation	PV: 1391-480 $/kW (2020-2050) Wind: 1436-525 $/kW (2020-2050)
Electrolysis	F3: 600-150 $/kW (2020-2050)
Gas storage	1867 $/kg (2020) – 543 $/kg (2050)
Liquefaction	5.6*tpd^0.8*1.16*1.075*10^6 $
Transport of hydrogen	1.21 million $/km

tpd = tonnes per day

A.2 – Cost competitiveness

The minimum selling price for LH_2 is calculated using the investment costs outlined above and the operational costs of the fuel plant. The levelized cost of energy is then calculated with the annuity method by assuming a discount rate of 6% and a lifetime of 25 years.

LH_2 transportation costs are included as well. These costs are estimated from an automated analysis of airport layouts applying three different hydrogen supply schemes, i.e. truck-based refueling, remote hydrant refueling, and at-gate hydrant refueling.

A.3 Land area:

The land requirements for LH_2 production are assessed with regard to the land required for the installation of renewable electricity generation equipment, specifically PV and wind power. The specific area requirements for the electrolysis step are described in Section 3.6.2.

A.4 – Water requirements:

The water demand for the production of hydrogen is two-fold: i) chemical reaction via electrolysis and ii) use of electrical energy for electrolysis, liquefaction, and for desalination of seawater. The use of electricity leads to water consumption e.g. due to the use of water in the production and use of wind turbines and PV modules. The specific water demand is 21-24 L/kg in F3 (Mekonnen, Gerbens-Leenes and Hoekstra, 2015).

4 RESULTS - VOLUME PROJECTIONS

The following section presents the fuel production projections for each fuel category, giving both the unconstrained, full potential fuel volumes as well as the final fuel volumes constrained to meet 100% of aviation fuel demand. It should be noted that as the fuel projections extend into the future through 2070, the uncertainty associated with fuel production levels grows.

4.1 Integrated Scenario Development

To determine the overall potential fuel availability, the projected fuel volumes from each category were combined, according to their respective production scenarios, to form the F1, F2, and F3 scenarios. Further refinement ensured that the fuel volumes were combined in line with scenario definitions. This was particularly important for scenarios wherein the combined projected production of LTAG-SAF and LTAG-LCAF exceeded expected aviation fuel demand. The prioritization of fuel categories was developed in a transparent manner, accounting for the readiness and attainability of the fuels while ensuring they provide environmental benefit. For each scenario, fuels are selected in order to meet 100% of fuel demand.

In Section 4.2, fuel volume results are given for the unconstrained conditions. The unconstrained condition reflects the full potential before any ordering of fuels was applied. In Section 4.3, the constrained results are shown, providing the final volume assigned to ensure that the total fuel projected volume did not exceed expected fuel demand. For F1, the scenario prioritization emphasized low cost GHG reduction, and fuels were ordered by minimum selling price (MSP). For F2, selection prioritized cost effective GHG reduction, using marginal abatement cost as the ordering criterion given in units of \$/kg $CO_{2reduced}$. Under F3, the emphasis was on maximizing GHG reductions, and the fuel LCA value was used as the ordering criterion with lowest LCA value fuels prioritized. The results of this ordering process are shown in Table 4.1. Fuels were selected in the order shown, from top to bottom, until 100% of expected aviation fuel demand was met or all projected fuel volumes were exhausted, whichever occurs first. For the latter case, remaining expected aviation fuel demand was met with conventional jet fuel use.

Table 4.1 Fuel order per scenario with selection criteria

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

Note:

- *LTAG-SAF-DAC (Direct Air Capture) represents LTAG-SAF from atmospheric CO_2 and is not included under F1 or F2.*
- *Marginal Abatement Costs are given in units of US dollar per kg of CO_2 reduction*

4.2 Unconstrained Volumes

As described in Section 4.1, projected fuel volumes were evaluated against expected aviation fuel demand. In order to not exceed expected demand, additional constraints were applied to guide the ordering of fuel selection. The results that follow represent the unconstrained potential fuel volumes, prior to applying limits on fuel volumes. These unconstrained results are shown to demonstrate the full potential future fuel volumes from each of the fuel categories included under the LTAG analysis. The constrained results are shown in Section 4.3.

4.2.1 LTAG-SAF – Biomass- & Solid/Liquid Waste-based

The unconstrained volume potential of LTAG-SAF from biomass and solid/liquid wastes are summarized below in Table 4.2 and Figure 4.1. As described previously, these results employ the FTG TPP SAF production market diffusion models to project future SAF volumes out to 2070. The LTAG fuels scenarios: F1, F2 and F3 are aligned with the FTG TPP scenarios: *Moderate*, *High* and *High+*, respectively. These volumes were analyzed to ensure that they did not exceed expectations for feedstock availability in the given timeframes. Other constraints, such as electricity and water availability, were not considered to be limiting factors for the production of LTAG-SAF from biomass and solid/liquid wastes.

Table 4.2 Summary of unconstrained projected fuel volumes for LTAG-SAF from biomass and solid/liquid waste for selected years from 2020 through 2070

Volume [kt/yr]			
Year	**F1 LTAG-SAF biomass/waste**	**F2 LTAG-SAF biomass/waste**	**F3 LTAG-SAF biomass/waste**
2020	693	2,821	4,153
2025	1,707	7,571	12,651
2030	4,195	19,965	36,988
2035	**10,208**	**50,113**	**96,881**
2040	24,294	112,828	202,013
2045	54,991	209,138	310,371
2050	**112,523**	**305,031**	**374,999**
2055	195,138	366,897	401,924
2060	277,509	396,494	411,416
2065	334,604	408,635	414,568
2070	**365,012**	**413,293**	**415,603**

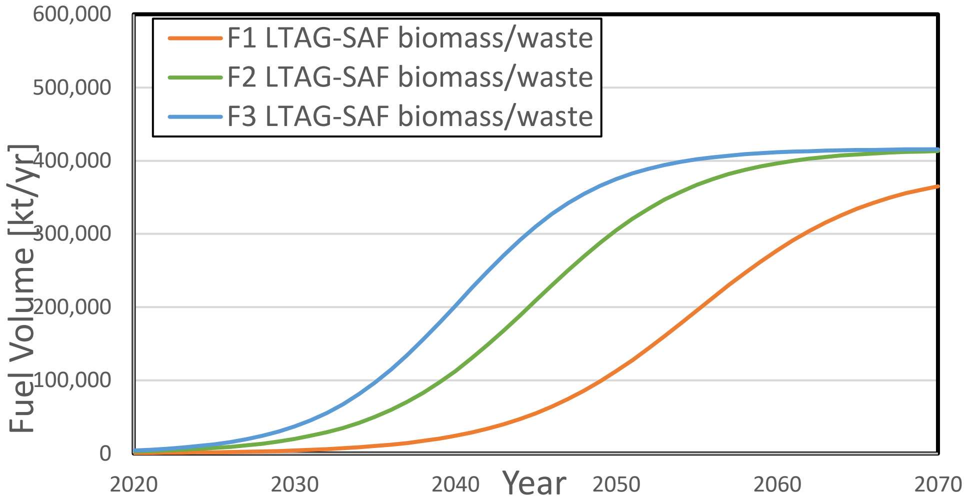


Figure 4.1 Unconstrained potential fuel volumes for LTAG-SAF from biomass and solid/liquid waste for F1, F2 and F3 from 2020 through 2070

4.2.2 LTAG-SAF – Waste CO_2- & Atmospheric CO_2-based

The unconstrained potential volumes of fuel produced by converting CO_2 from waste gases or the atmosphere is shown in Table 4.3 and Figure 4.2. The fuels scenarios allow for the use of different sources of CO_2 and therefore produce different volumes over time. In F1, up to 0.05 Gt/y can be produced from 2040 on (considering waste CO_2 from ethanol and ammonia only). In F2, the additional use of iron and steel and cement plants allows a scale-up to 0.3-0.35 Gt/y in the year 2070. In F3, a mix of fuel production leveraging waste CO_2 and atmospheric CO_2 reaches 0.35 Gt/y with an increasing share of DAC-based fuels over time as the availability of DAC scales up and Waste CO_2 streams decrease due to the increased use of CCS. Across the different scenarios and over the time frame under evaluation, the constraining factor, CO_2 resources or renewable electricity, varies. This constraining factor is indicated in Figure 4.3 for the three scenarios.

Table 4.3 Summary of unconstrained projected fuel volumes for LTAG-SAF from waste CO_2 (LTAG-SAF-CO_2) and atmospheric CO_2 (LTAG-SAF-DAC) for selected years from 2020 through 2070

Volume [kt/yr]				
Year	**F1 LTAG-SAF-CO_2**	**F2 LTAG-SAF-CO_2**	**F3 LTAG-SAF-CO_2**	**F3 LTAG-SAF-DAC**
2020	0	0	0	0
2030	24,670	24,637	28,404	5,018
2035	**38,745**	**43,049**	**49,736**	**17,495**
2040	52,820	61,461	71,068	29,971
2050	**51,200**	**207,577**	**244,593**	**54,924**
2060	50,380	287,985	210,968	164,771
2070	**48,480**	**336,195**	**39,170**	**329,542**

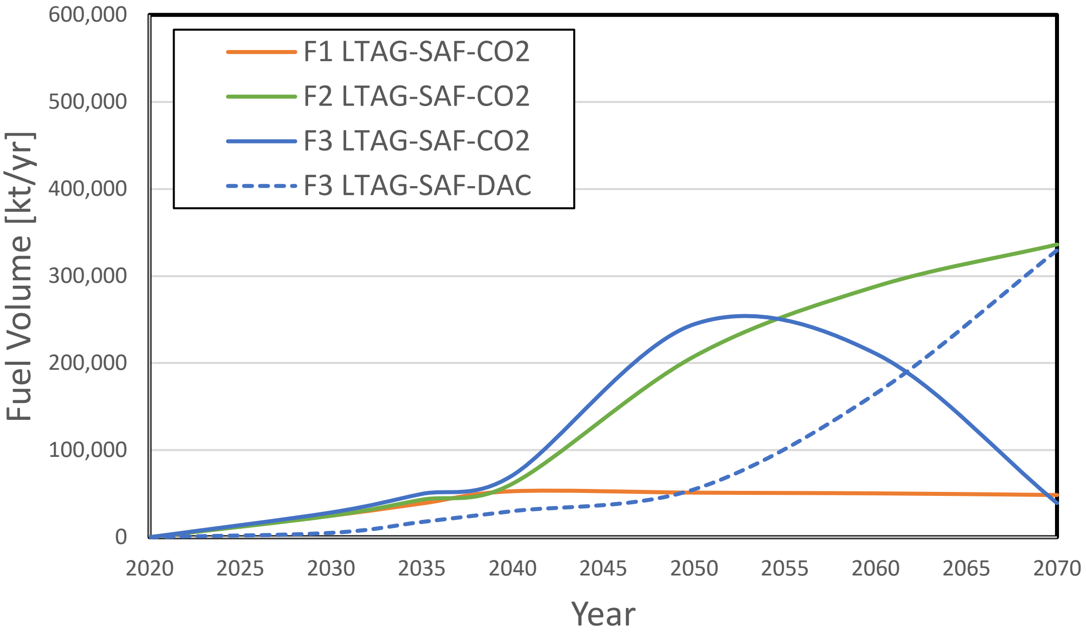


Figure 4.2 Unconstrained potential fuel volumes of LTAG-SAF from waste CO_2 (F1, F2) or additionally atmospheric CO_2 (F3) for F1, F2 and F3 from 2020 through 2070

Note: LTAG-SAF-CO_2 denotes LTAG-SAF from waste CO_2 and LTAG-SAF-DAC denotes LTAG-SAF from atmospheric CO_2 (direct air capture)

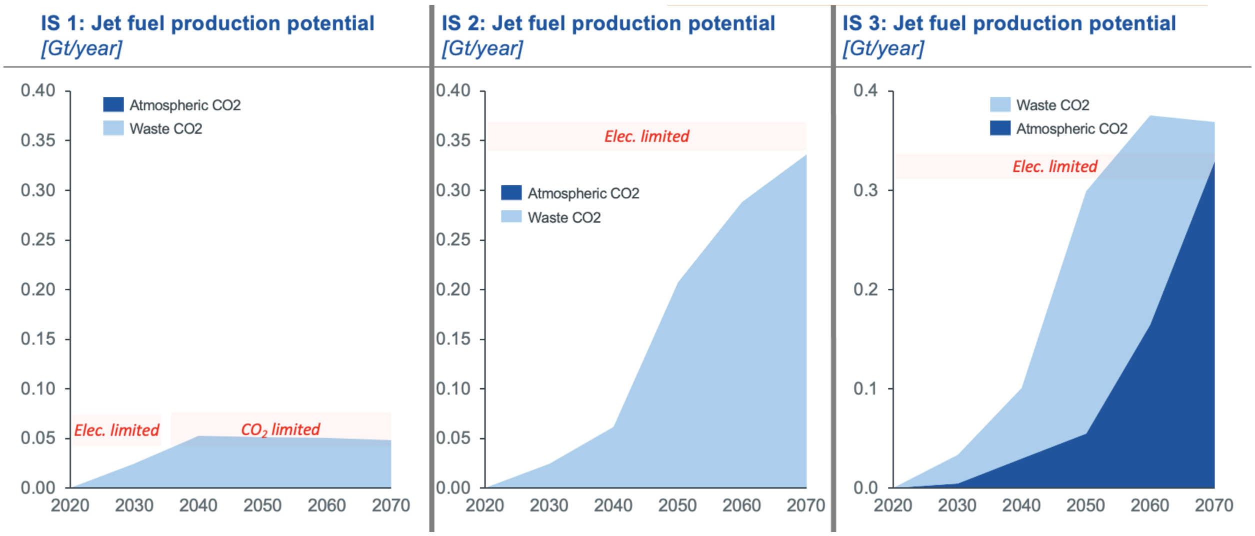


Figure 4.3 Production potential of PtL production in the three fuels scenarios using either waste CO_2 (F1, F2) or additionally atmospheric CO_2 (F3) with constraining factors (electricity or CO_2 resources) indicated

4.2.3 LTAG-LCAF

LTAG-LCAF unconstrained projected volumes are summarized in Table 4.4 and reported in Mt/y. The LTAG-LCAF fuel scenarios Low, Medium and High correspond to the F1, F2 and F3 scenarios. Projected unconstrained volumes are derived from the forecasted overall jet fuel consumption, applying the weight fraction corresponding to the portion of the scenario merit curves with a carbon intensity <80.1 gCO$_2$e/MJ of jet. LTAG-LCAF in the High (F3) scenario can reach up to 560 MT/year by 2070.

Table 4.4 Summary of unconstrained projected fuel volumes for LTAG-LCAF for selected years from 2020 through 2070

Volume [kt/yr]			
Year	**F1 LTAG-LCAF**	**F2 LTAG-LCAF**	**F3 LTAG-LCAF**
2020	0	0	0
2025	0	0	0
2030	4,853	14,439	54,917
2035	**29,076**	**67,907**	**137,779**
2040	34,881	130,160	240,817
2045	40,632	146,369	314,833
2050	**45,343**	**162,319**	**346,140**
2055	51,089	181,533	390,531
2060	57,800	200,748	435,780
2065	66,202	226,304	497,825
2070	**75,490**	**251,617**	**560,172**

Figure 4.4 shows the LTAG-LCAF unconstrained volumes, under the different Fuels scenarios from 2020 through 2050.

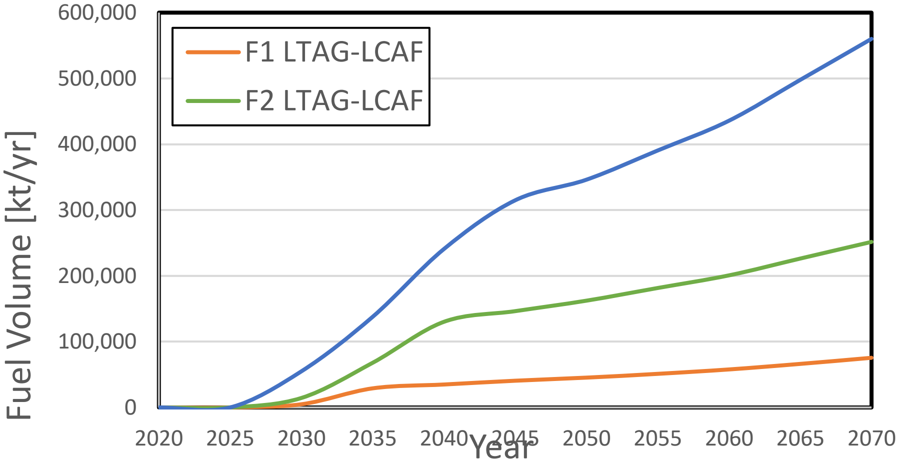


Figure 4.4 Unconstrained potential fuel volumes for LTAG-LCAF for F1, F2 and F3 from 2020 through 2070

4.2.4 Non-drop-in – LH_2

As outlined in Section 3.4.4, the analysis does not assume fuel production to constrain a priori the uptake of liquid hydrogen. Instead, the fuel demand resulting from the hydrogen aircraft uptake under F3, which is not limited by fuel availability, was analyzed. The resulting LH_2 demand trajectory under F3 is plotted in Figure 4.5. The hydrogen demand as projected by MDG starts in 2036, reflecting the entry into service of hydrogen aircraft, and rises to 6-9 EJ per year in 2070. The attainability of this scenario is evaluated in Section 6.4.

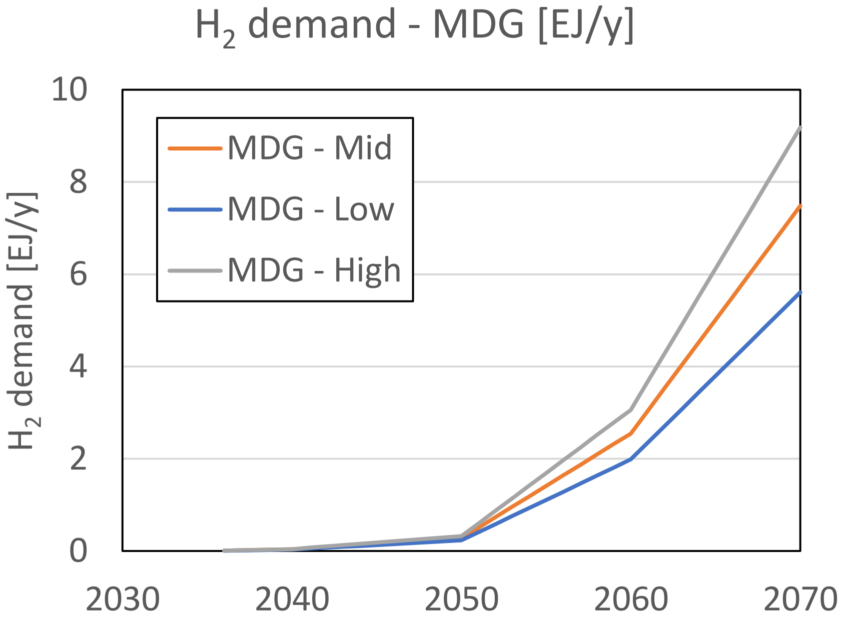


Figure 4.5 H_2 demand in F3 for ACA-T3 aircraft as modeled by MDG

4.3 Constrained Fuel Volumes

As described in Section 4.1, potential fuel volumes were constrained against expected aviation fuel demand, provided by FESG traffic forecasting and MDG integration. This ensured that projected fuel volumes did not exceed expected demand. FESG developed three traffic forecasts, LOW, MID and HIGH, which MDG then integrated with technology and operational improvements for each of the fuel scenarios that were modelled. This established nine scenarios, three traffic forecasts for each of the fuels scenarios: F1, F2 and F3. The Fuels sub-group then evaluated fuel volumes for each of these scenarios. The results that follow represent the constrained results to meet 100% of expected aviation fuel demand. Please note that in subsequent charts LH_2 is shown as demand of jet fuel displaced by hydrogen demand. The volumes shown in the charts and tables are not volumes of liquid hydrogen.

4.3.1 Low Traffic Forecast Results

The following three charts in Figure 4.6 display the combined fuel results for the LOW traffic forecast, starting with F1, followed by F2 and F3.

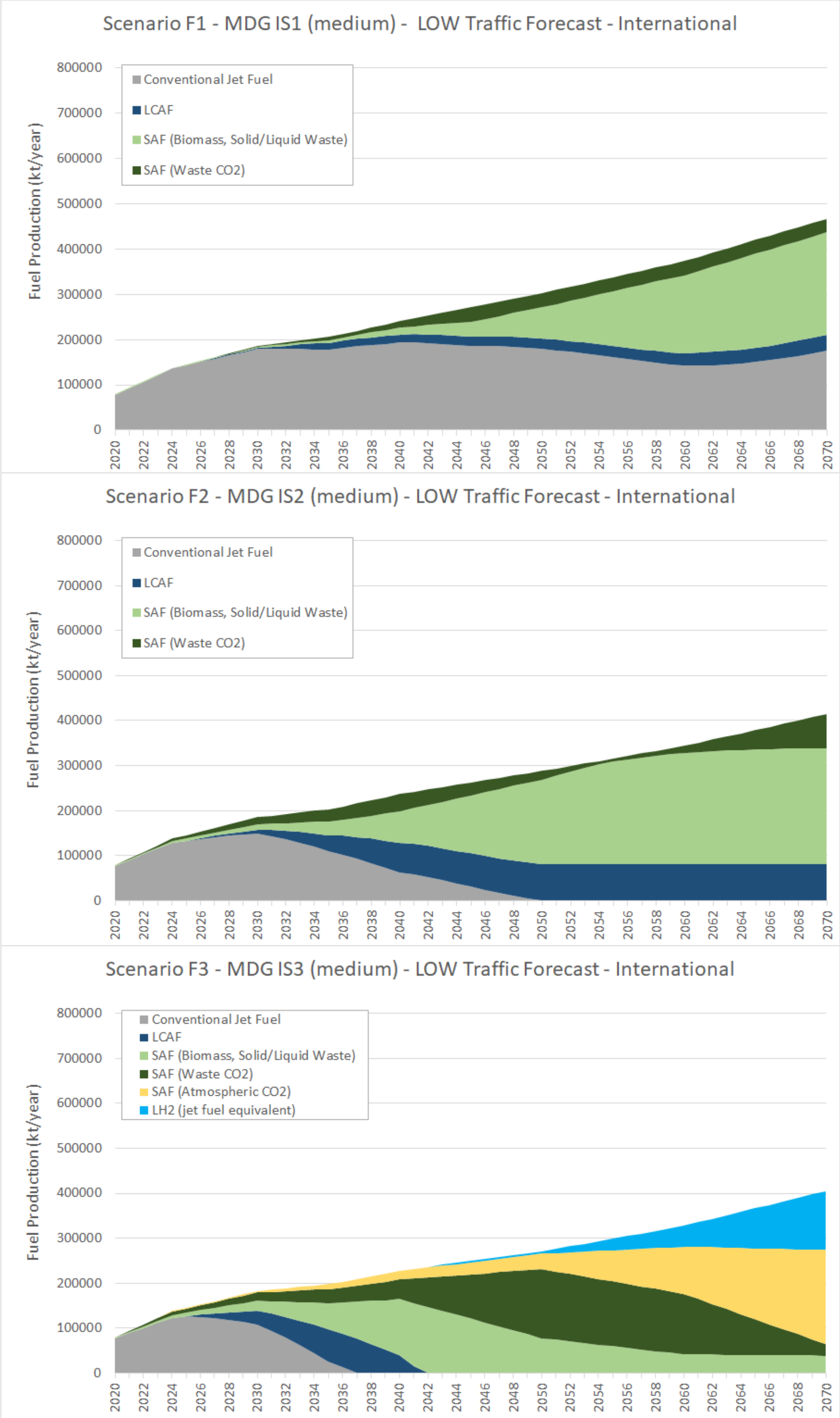


Figure 4.6 LOW traffic forecast results for F1, F2 and F3 scenarios

Table 4.5 provides the combined results to meet 100% of expected fuel demand under the LOW traffic forecast in 2035, 2050 and 2070. The table includes a breakdown of global and international volumes for each fuel category along with LCA values for each fuel category and the overall fuel mix.

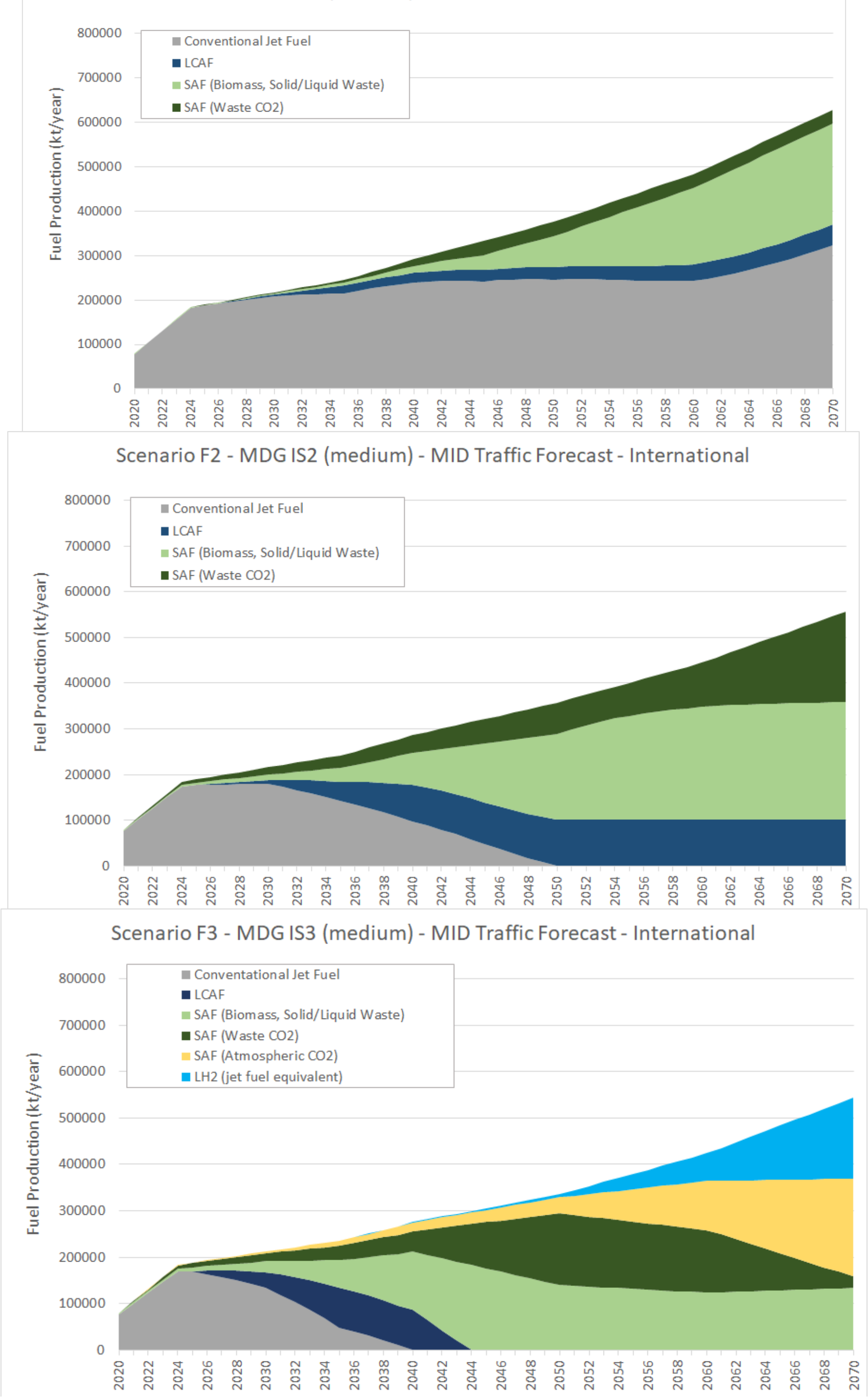
Table 4.5 Projected fuel forecast for LOW traffic forecast with global and international share and corresponding LCA values for fuel categories and the overall fuel mix

Volumes													
		F1				**F2**				**F3**			
Year		**Global**	**Share**	**Intl**	**LCA**	**Global**	**Share**	**Intl**	**LCA**	**Global**	**Share**	**Intl**	**LCA**
	Units	kt/year	%	kt/year	gCO$_2$e/MJ	kt/year	%	kt/year	gCO$_2$e/MJ	kt/year	%	kt/year	gCO$_2$e/MJ
2035	**Demand**	**334662**	**100%**	**205527**	**84.3**	**330258**	**100%**	**202856**	**68.5**	**321450**	**100%**	**197515**	**50.8**
	SAF-FTG	10208	3.1%	6269	29.0	50113	15.2%	30781	26.4	96881	30.1%	59528	24.2
	SAF-CO$_2$	10208	3.1%	6269	17.6	43049	13.0%	26442	16.7	49736	15.5%	30560	16.1
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	17495	5.4%	10750	12.2
	LCAF	24547	7.3%	15075	80.1	57331	17.4%	35215	80.1	116319	36.2%	71472	80.1
	SAF+LCAF	**44963**	**13.4%**	**27613**	**54.3**	**150492**	**45.6%**	**92438**	**44.1**	**280431**	**87.2%**	**172311**	**45.2**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.0%	0	8.6
	Jet A/A-1	289698	86.6%	177913	89.0	179765	54.4%	110418	89.0	41019	12.8%	25204	89.0
2050	**Demand**	**492139**	**100%**	**302850**	**67.7**	**467782**	**100%**	**288181**	**40.7**	**440448**	**100%**	**270791**	**15.1**
	SAF-FTG	112523	22.9%	69244	30.9	305031	65.2%	187917	26.6	123784	28.1%	77616	24.7
	SAF-CO$_2$	51200	10.4%	31507	18.3	31118	6.7%	19170	12.9	244593	55.5%	153367	12.5
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	54924	12.5%	34439	8.4
	LCAF	36774	7.5%	22629	80.1	131633	28.1%	81094	80.1	0	0.0%	0	80.1
	SAF+LCAF	**200496**	**40.7%**	**123380**	**36.7**	**467782**	**100%**	**288181**	**40.7**	**423300**	**96%**	**265422**	**15.5**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	17148	3.9%	5369	5.6
	Jet A/A-1	291643	59.3%	179470	89.0	0	0.0%	0.00	89.0	0	0.0%	0	89.0
2070	**Demand**	**752492**	**100%**	**466984**	**55.2**	**666820**	**100%**	**414567**	**33.3**	**655365**	**100%**	**404886**	**8.9**
	SAF-FTG	365012	48.5%	226521	30.1	413293	62.0%	256947	24.5	61086	9.3%	38922	21.1
	SAF-CO$_2$	48480	6.4%	30086	18.3	121894	18.3%	75783	12.9	39170	6.0%	24958	12.5
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	329542	50.3%	209973	8.4
	LCAF	56294	7.5%	34935	80.1	131633	19.7%	81837	80.1	0	0.0%	0	80.1
	SAF+LCAF	**469787**	**62.4%**	**291542**	**34.9**	**666820**	**100%**	**414567**	**33.3**	**429797**	**66%**	**273853**	**10.6**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	225567	34.4%	131033	5.6
	Jet A/A-1	282705	37.6%	175442	89.0	0	0.0%	0	89	0	0.0%	0	89.0

Global: International and domestic fuel burn demand
Share: Percent of total demand per fuel category
Intl: International only share of global fuel burn demand
LCA: fuel lifecycle value
SAF-FTG: LTAG-SAF from biomass and solid/liquid waste
SAF-CO$_2$: LTAG-SAF from waste CO$_2$
SAF-DAC: LTAG-SAF from atmospheric CO$_2$
LH2: shown are volumes of Jet A/A-1 displaced by hydrogen demand, these volumes do not represent liquid hydrogen volumes

4.3.2 Mid Traffic Forecast Results

The following three charts in Figure 4.7 display the combined fuel results for the MID traffic forecast, starting with F1, followed by F2 and F3.



Scenario F1 - MDG IS1 (medium) - MID Traffic Forecast - International

Scenario F2 - MDG IS2 (medium) - MID Traffic Forecast - International

Scenario F3 - MDG IS3 (medium) - MID Traffic Forecast - International

Figure 4.7 MID traffic forecast fuels results for F1, F2 and F3 scenarios

Table 4.6 provides the combined results to meet 100% of expected fuel demand under the MID traffic forecast in 2035, 2050 and 2070. The table includes a breakdown of global and international volumes for each fuel category along with LCA values for each fuel category and the overall fuel mix.

Table 4.6 Projected fuel forecast for MID traffic forecast with global and international share and corresponding LCA values for fuel categories and the overall fuel mix

Volumes													
		F1				**F2**				**F3**			
Year		**Global**	**Share**	**Intl**	**LCA**	**Global**	**Share**	**Intl**	**LCA**	**Global**	**Share**	**Intl**	**LCA**
	Units	kt/year	%	kt/year	gCO_{2e}/MJ	kt/year	%	kt/year	gCO_{2e}/MJ	kt/year	%	kt/year	gCO_{2e}/MJ
2035	**Demand**	**396399**	**100%**	**244999**	**85.0**	**391184**	**100%**	**241819**	**71.5**	**380753**	**100%**	**235459**	**56.3**
	SAF-FTG	10208	2.6%	6309	29.0	50113	12.8%	30978	26.4	96881	25.4%	59912	24.2
	SAF-CO_2	10208	2.6%	6309	17.6	43049	11.0%	26612	16.7	49736	13.1%	30757	16.1
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	17495	4.6%	10819	12.2
	LCAF	29076	7.3%	17971	80.1	67907	17.4%	41978	80.1	137779	36.2%	85203	80.1
	SAF+LCAF	**49492**	**12.5%**	**30589**	**56.7**	**161069**	**41.2%**	**99568**	**46.44**	**301890**	**79.3%**	**186690**	**47.7**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.0%	0	8.6
	Jet A/A-1	346907	87.5%	214410	89.0	230115	58.8%	142251	89.0	78863	20.7%	48769	89.0
2050	**Demand**	**606829**	**100%**	**375459**	**71.6**	**576830**	**100%**	**357319**	**39.0**	**542948**	**100%**	**335619**	**16.8**
	SAF-FTG	112523	18.5%	69620	30.9	305031	52.9%	188952	26.6	222599	41.0%	140324	24.7
	SAF-CO_2	51200	8.4%	31679	18.3	109480	19.0%	67818	12.9	244593	45.0%	154188	12.5
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	54924	10.1%	34623	8.4
	LCAF	45343	7.5%	28055	80.1	162319	28.1%	100549	80.1	0	0.0%	0	80.1
	SAF+LCAF	**209066**	**34.5%**	**129354**	**38.5**	**576830**	**100%**	**357319**	**39.0**	**522116**	**96%**	**329135**	**17.3**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	20832	3.8%	6485	5.6
	Jet A/A-1	397763	65.5%	246105	89.0	0	0.0%	0.00	89.0	0	0.0%	0	89.0
2070	**Demand**	**1009087**	**100%**	**627236**	**63.6**	**894638**	**100%**	**557177**	**30.4**	**878963**	**100%**	**543912**	**10.7**
	SAF-FTG	365012	36.2%	226887	30.1	413293	46.2%	257397	24.5	209298	23.8%	133636	21.1
	SAF-CO_2	48480	4.8%	30135	18.3	319026	35.7%	198688	12.9	39170	4.5%	25010	12.5
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	329542	37.5%	210411	8.4
	LCAF	75490	7.5%	46924	80.1	162319	18.1%	101092	80.1	0	0.0%	0	80.1
	SAF+LCAF	**488983**	**48.5%**	**303946**	**36.7**	**894638**	**100%**	**557177**	**30.4**	**578009**	**66%**	**369057**	**13.3**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	300953	34.2%	174855	5.6
	Jet A/A-1	520104	51.5%	323290	89.0	0	0.0%	0	89	0	0.0%	0	89.0

Global: International and domestic fuel burn demand
Share: Percent of total demand per fuel category
Intl: International only share of global fuel burn demand
LCA: lifecycle values given in units of gCO_2e/MJ
SAF-FTG: LTAG-SAF from biomass and solid/liquid waste
SAF-CO_2: LTAG-SAF from waste CO_2
SAF-DAC: LTAG-SAF from atmospheric CO_2
LH2: shown are volumes of Jet A/A-1 displaced by hydrogen demand, these volumes do not represent liquid hydrogen volumes

4.3.3 High Traffic Forecast Results

The following three charts in Figure 4.8 display the combined fuel results for the HIGH traffic forecast, starting with F1, followed by F2 and F3.

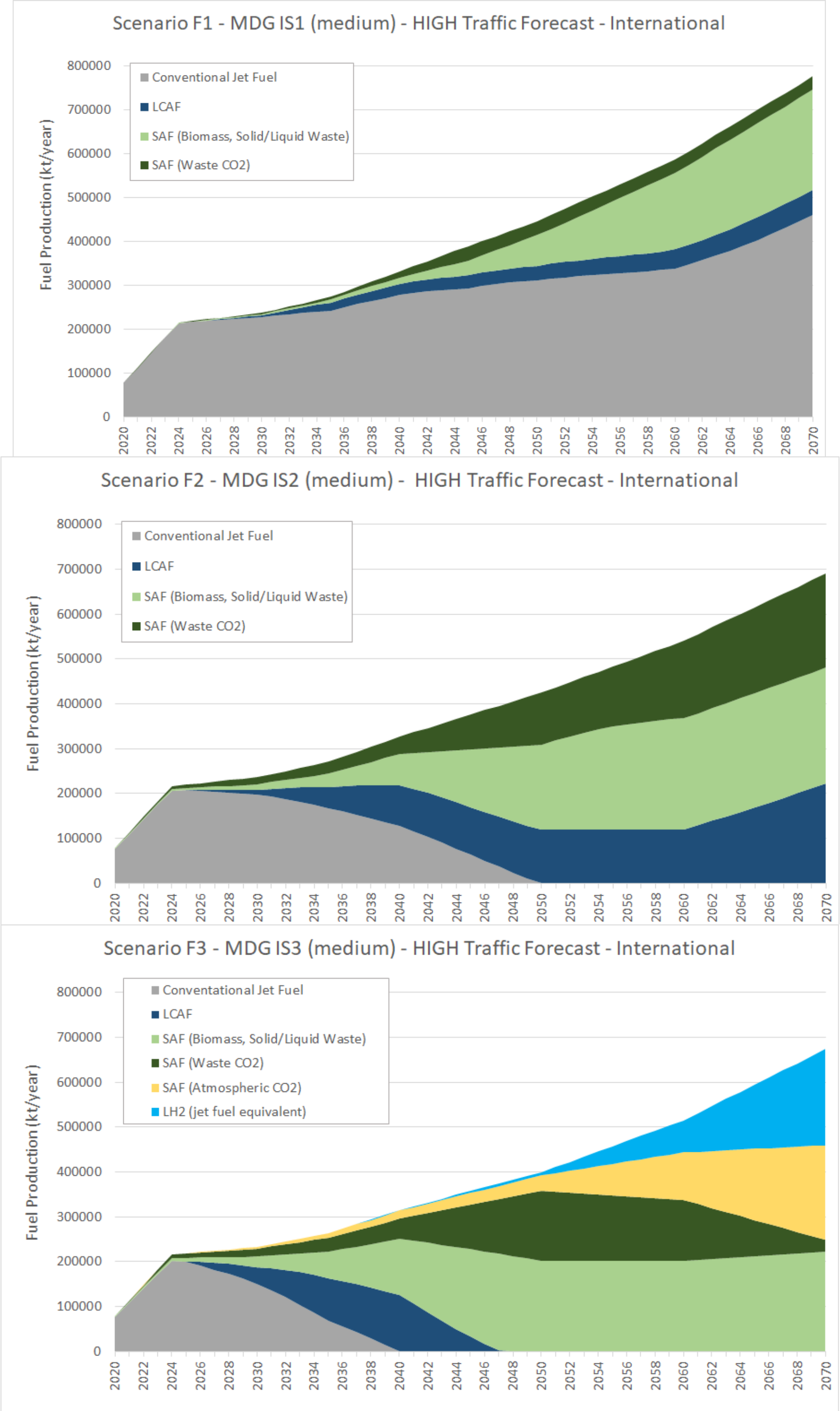


Figure 4.8 HIGH traffic forecast results for F1, F2 and F3 scenarios

Table 4.7 provides the combined results to meet 100% of expected fuel demand under the HIGH traffic forecast in 2035, 2050 and 2070. The table includes a breakdown of global and international volumes for each fuel category along with LCA values for each fuel category and the overall fuel mix.

Table 4.7 Projected fuel forecast for HIGH traffic forecast with global and international share and corresponding LCA values for fuel categories and the overall fuel mix

Volumes													
		F1				**F2**				**F3**			
Year		**Global**	**Share**	**Intl**	**LCA**	**Global**	**Share**	**Intl**	**LCA**	**Global**	**Share**	**Intl**	**LCA**
	Units	kt/year	%	kt/year	gCO$_2$e/MJ	kt/year	%	kt/year	gCO$_2$e/MJ	kt/year	%	kt/year	gCO$_2$e/MJ
2035	**Demand**	**445717**	**100%**	**274485**	**85.3**	**439854**	**100%**	**270925**	**73.2**	**428129**	**100%**	**263805**	**59.5**
	SAF-FTG	10208	2.3%	6286	29.0	50113	11.4%	30866	26.4	96881	22.6%	59696	24.2
	SAF-CO$_2$	10208	2.3%	6286	17.6	43049	9.8%	26516	16.7	49736	11.6%	30646	16.1
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	17495	4.1%	10780	12.2
	LCAF	32693	7.3%	20133	80.1	76356	17.4%	47031	80.1	154922	36.2%	95460	80.1
	SAF+LCAF	**53109**	**11.9%**	**32706**	**58.3**	**169518**	**38.5%**	**104413**	**48.11**	**319034**	**74.5%**	**196582**	**49.4**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.0%	0	8.6
	Jet A/A-1	392607	88.1%	241779	89.0	270336	61.5%	166512	89.0	109096	25.5%	67223	89.0
2050	**Demand**	**720775**	**100%**	**446819**	**74.2**	**685187**	**100%**	**425277**	**37.9**	**644798**	**100%**	**399309**	**17.9**
	SAF-FTG	112523	15.6%	69755	30.9	305031	44.5%	189324	26.6	320756	49.7%	202603	24.7
	SAF-CO$_2$	51200	7.1%	31740	18.3	187345	27.3%	116280	12.9	244593	37.9%	154495	12.5
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	54924	8.5%	34692	8.4
	LCAF	53858	7.5%	33387	80.1	192811	28.1%	119672	80.1	0	0.0%	0	80.1
	SAF+LCAF	**217580**	**30.2%**	**134881**	**40.1**	**685187**	**100%**	**425277**	**37.9**	**620273**	**96%**	**391790**	**18.4**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	24525	3.8%	7519	5.6
	Jet A/A-1	503195	69.8%	311938	89.0	0	0.0%	0.00	89.0	0	0.0%	0	89.0
2070	**Demand**	**1245978**	**100%**	**776893**	**68.3**	**1105406**	**100%**	**690636**	**38.9**	**1085545**	**100%**	**673859**	**11.7**
	SAF-FTG	365012	29.3%	227593	30.1	413293	37.4%	258217	24.5	348542	32.1%	223195	21.1
	SAF-CO$_2$	48480	3.9%	30228	18.3	336195	30.4%	210048	12.9	39170	3.6%	25083	12.5
	SAF-DAC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	329542	30.4%	211028	8.4
	LCAF	93212	7.5%	58120	80.1	355918	32.2%	222371	80.1	0	0.0%	0	80.1
	SAF+LCAF	**506705**	**40.7%**	**315941**	**38.2**	**1105406**	**100%**	**690636**	**38.9**	**717253**	**66%**	**459307**	**14.8**
	LH2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	368291	33.9%	214552	5.6
	Jet A/A-1	739273	59.3%	460952	89.0	0	0.0%	0	89	0	0.0%	0	89.0

Global: International and domestic fuel burn demand
Share: Percent of total demand per fuel category
Intl: International only share of global fuel burn demand
LCA: lifecycle values given in units of gCO$_{2e}$/MJ
SAF-FTG: LTAG-SAF from biomass and solid/liquid waste
SAF-CO$_2$: LTAG-SAF from waste CO$_2$
SAF-DAC: LTAG-SAF from atmospheric CO$_2$
LH2: shown are volumes of Jet A/A-1 displaced by hydrogen demand, these volumes do not represent liquid hydrogen volumes

5 RESULTS – GHG EMISSIONS SAVINGS

The following section provides results of the lifecycle GHG emissions analyses carried out as described in Section 3.5. These results specify the expected changes in LCA values for each of the evaluated fuel categories. The LCA values for the various fuel categories were combined with their respective constrained fuel volumes (shown in Section 4.3) to give an overall fuel mix LCA value, reflecting the weighted average LCA value of the fuel mix. This value was used to determine an overall Emissions Reduction Factor (ERF) for each of the fuel scenarios (F1, F2 and F3) at three time frames: 2035, 2050 and 2070. The CO_2 reductions from alternative fuel use were also computed, compared to using conventional jet fuel with an LCA value of 89These results are given in Section 5.5.

5.1 LTAG-SAF – Biomass- & Solid/Liquid Waste-based

The method for calculating the change in LTAG-SAF LCA values for biomass- and solid/liquid waste-based fuels was described in Section 3.5.1. The results of applying the methodology described above are shown in Table 5.1 below. These results are linearly interpolated to calculate the GHG emissions for the years between the selected time frames.

Table 5.1 LTAG-SAF lifecycle values for biomass- and solid/liquid waste-based fuels [gCO_2e/MJ]

Year	**F1**	**F2**	**F3**
2035	29.00	26.38	24.23
2050	30.91	26.55	24.67
2070	30.12	24.49	21.14

5.2 LTAG-SAF – Waste CO_2- & Atmospheric CO_2-based

The lifecycle GHG emission trajectories for drop-in fuels produced from atmospheric CO_2 or waste CO_2 for each Fuels scenario are shown in

Figure 5.1. Baseline values are given both for fuels produced exclusively with electricity produced from solar and PV and for fuels produced with average grid electricity, following grid scenarios as outlined in Section 3.4.2.1. The results show the fuels under consideration to have lower GHG emissions than conventional jet fuel only if dedicated low-carbon electricity is used and/or the grid is largely decarbonized.

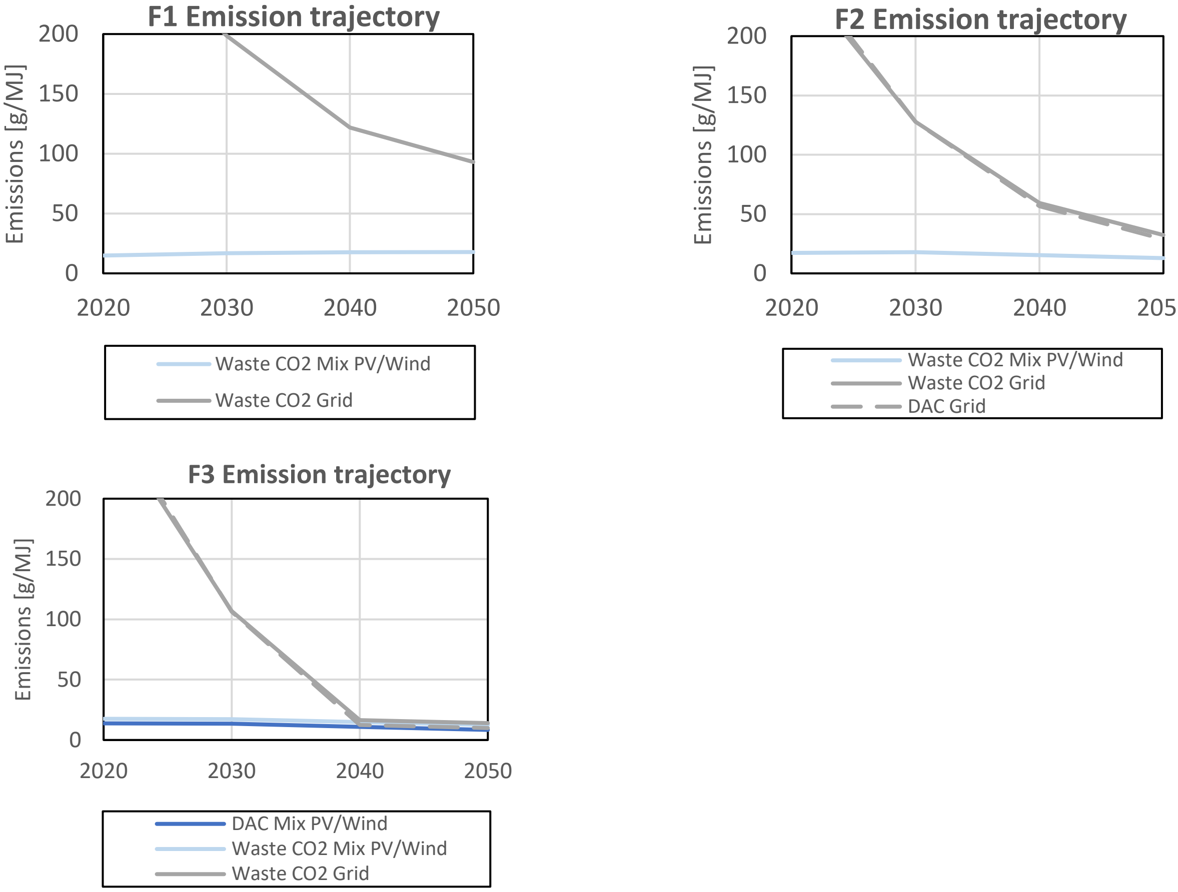


Figure 5.1 - Emission trajectories of PtL production in the three fuels scenarios using either waste CO_2 (F1: top, F2: center) or additionally atmospheric CO_2 (F3: bottom).

5.3 LTAG-LCAF

The well-to-wake carbon intensity of LTAG-LCAF was assumed to be 80.1 gCO_2e/MJ. This value was assumed to remain constant for the purpose of the LTAG analysis and, therefore, does not vary over the time period under evaluation.

5.4 Non-drop-in – LH_2

Based on the LH_2 production model and assumptions, the GHG emissions for LH_2 production were calculated over time. The results are shown both for LH_2 produced using solar and wind electricity as well as global average grid electricity, following grid scenarios as outlined in Section 3.5.2. The results are shown in Figure 5.2.

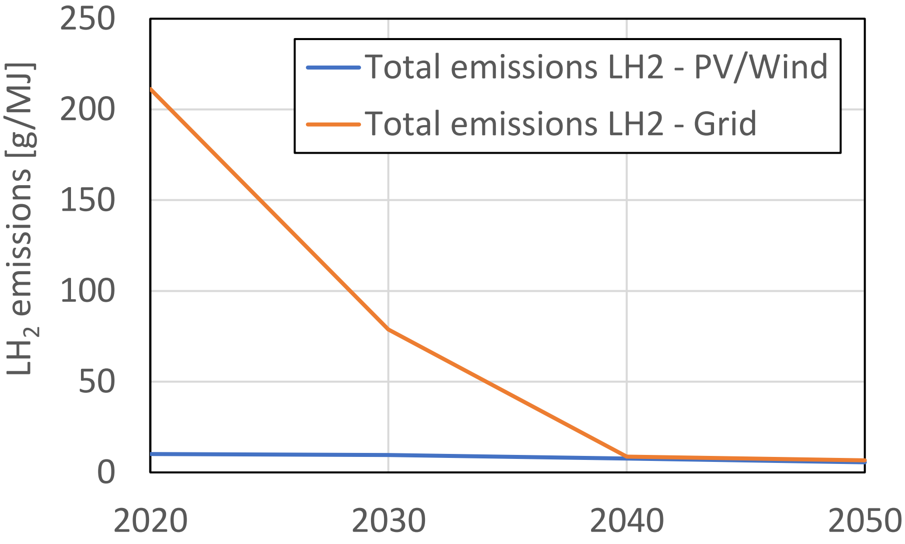


Figure 5.2 – Lifecycle GHG emissions of LH_2 production under F3.

5.5 Fuel Scenarios Emissions Reductions

To demonstrate the impact of the projected alternative jet fuel supply scenarios on future CO_2 emissions, the Emissions Reduction Factor (ERF) was calculated for each respective fuel scenario and traffic forecast at three selected timeframes. ERF is calculated as follows:

$1 – LC_{\text{fuel mix}}/LC$

Where $LC_{\text{fuel mix}}$ is the lifecycle emissions value of the fuel mix and LC is the baseline lifecycle emissions value for conventional jet fuel, equal to 89 gCO_2e/MJ. This ratio is multiplied by 100 to give the ERF values in terms of percent reduction compared to baseline conventional jet fuel. The following tables summarize the overall ERF values for the fuel mix under each fuel scenario (F1, F2 and F3) for each of the three MDG traffic forecasts: LOW, MID and HIGH. ERFs are shown for each fuel scenario (F1, F2 and F3) for three selected years: 2035, 2050 and 2070. Results reflect the effects of varying usage levels of alternative aviation fuels in accordance with projected fuel volumes and fuel burn demand.

Table 5.2 - Emissions Reduction Factors for LOW traffic forecast

Year	**F1**	**F2**	**F3**
2035	5%	23%	43%
2050	24%	54%	83%
2070	38%	63%	90%

Table 5.3 - Emissions Reduction Factors for MID traffic forecast

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

Table 5.4 - Emissions Reduction Factors for HIGH traffic forecast

Year	**F1**	**F2**	**F3**
2035	4%	18%	33%
2050	17%	57%	80%
2070	23%	56%	87%

The overall CO_2 emissions reductions from LTAG fuel improvements are calculated by subtracting the fuel mix lifecycle value under a given time frame and scenario from the baseline conventional jet fuel value of 89 gCO_2e/MJ. This difference is then multiplied across the total international fuel burn to give the total CO_2 emissions reductions. These values are shown in the tables (Table 5.5 to Table 5.7) below.

Table 5.5 - CO_2 Emissions Reductions for LOW traffic forecast [$MtCO_2$]

Year	**F1**	**F2**	**F3**
2035	34	147	268
2050	229	494	708
2070	560	819	1,151

Table 5.6 - CO_2 Emissions Reductions for MID traffic forecast [$MtCO_2$]

Year	**F1**	**F2**	**F3**
2035	35	150	274
2050	232	634	858
2070	565	1,159	1,511

Table 5.7 - CO_2 Emissions Reductions for HIGH traffic forecast [$MtCO_2$]

Year	**F1**	**F2**	**F3**
2035	36	152	276
2050	234	772	1,004
2070	570	1,229	1,845

6 RESULTS – READINESS AND ATTAINABILITY

This final step includes evaluation of attainability and readiness criteria including cost estimations and infrastructure requirements. Cost estimation work has been coordinated with the Cost Estimation ad hoc group (CEahg) under the Scenario Development sub-group (SDSG).

6.1 LTAG-SAF – Biomass- & Solid/Liquid Waste-based

Given that the facilities modeled under the FTG TPP market diffusions models are currently operating or announced plans, for readiness factor *R1: Current status of the fuel conversion technology*, the status of fuel conversion processes are assumed to be at operational levels, equivalent to a Technology Readiness Level (TRL) of 9, mature technology, with established production capability. For readiness factor R2*: Current status in the ASTM approval process,* the status was assumed to be an approved fuel annexed under ASTM D7566 and certified to be blended with conventional fuel as appropriate. The final readiness factor, *R.3: Availability of systems to produce low carbon energy carriers,* is incorporated through the fuel lifecycle analysis under the assumptions for the availability of renewable energy resources. It was assumed that the availability of these renewable energy resources varies with time and scenario, and these assumptions are reflected by adjusting the level at which additional reductions from renewable energy use are applied in fuel lifecycle values.

Regarding the attainability analysis, costs were evaluated for *A.1: Capital investment requirements* and *A.2: Cost competitiveness*. These values were coordinated with FTG TPP group experts and reflect the inclusion of cost savings from the repurposing of facilities and use of existing refineries when possible. Repurposing can reduce the outside battery limits (OSBL), or off-site costs, of a facility by assuming the repurposed site has standard infrastructure and supporting equipment, such as roads, buildings, power, water, etc., already in place. An additional repurposing case was run with the assumption that distillation equipment can also be repurposed, providing additional cost savings. Unlike other fuel categories, the capital investment per unit of fuel is expected to increase over time. Although there are learning curve improvements, i.e. going from pioneer plant to nth plant costs, and economies of scale that serve to reduce costs, overall, this fuel category will increasingly rely on more expensive feedstocks and pathways over time. The results of this analysis are shown in Figure 6.1. For *A.2: Cost competitiveness*, the Minimum Selling Price (MSP) of LTAG-SAF from biomass and solid/liquid wastes is expected to be roughly $0.90 -$2.00 per liter of fuel. This value varies depending on whether pioneer plant or nth plant assumptions are used, with additional reductions for repurposing of facilities with or without additional distillation equipment. The results of this analysis are shown in Figure 6.2. More information on the cost analysis can be found in the Cost Estimation appendix.

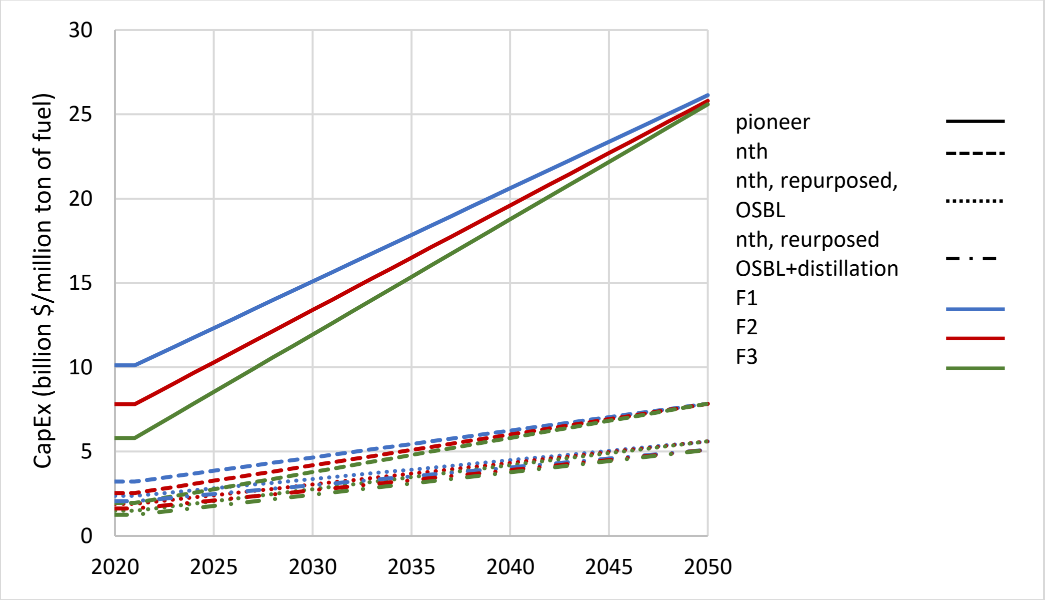


Figure 6.1 Projected capital investment (CapEx) for LTAG-SAF from biomass and solid/liquid wastes for pioneer and nth plant scenarios, OSBL = outside battery limit or off-site costs with or without distillation equipment repurposing

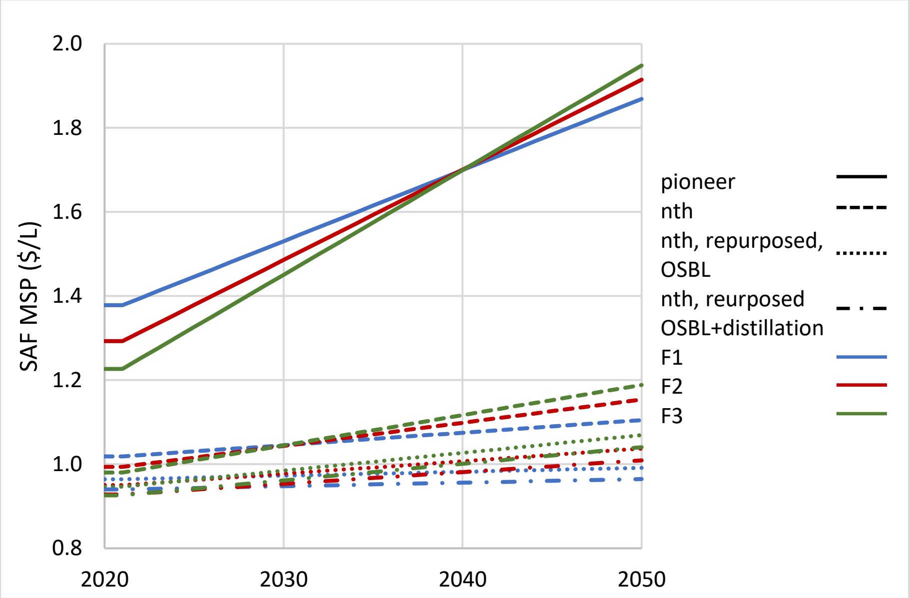


Figure 6.2 Projected minimum selling price (MSP) for LTAG-SAF from biomass and solid/liquid wastes for pioneer and nth plant scenarios, OSBL = outside battery limit or off-site costs with or without distillation equipment repurposing

For *A.3: Land area requirements*, *A.4: Water requirements*, *A.5: Soil requirements*, and *A.6: Biodiversity assessment*, a previous detailed scenario assessment of potential future SAF production indicated that there is an underlying technical potential for sufficient bio-based and waste feedstocks to exceed future anticipated jet fuel demand at least out to 2050, but that attainment of different levels of utilization within aviation will depend on policy, competition with other modes, and economic conditions (see Attachment A CAEPSG.20213.WP.020.7.en and Attachment B CAEPSG.20213.IP.005.7.en). Given the similar assumptions defined in the scenarios depicted herein, no significant feedstock limitations on attainability are expected. Finally, for *A.7: Infrastructure for fuel transportation*, as LTAG-SAF from biomass and solid/liquid wastes are drop-in, existing fuel transportation infrastructure can be used. It is also assumed that these fuels are approved to be blended as appropriate with conventional fuels, therefore no issues with fuel blending are anticipated.

6.2 LTAG-SAF – Waste CO_2- & Atmospheric CO_2-based

Readiness

R.1 – Current status of fuel conversion technology:

- *For H_2 production*, mature production technologies exist, including Steam Methane Reforming and electrolysis using renewable electricity (see details in Section 6.4). As the use of the technologies is scaled up, significant cost decreases are expected.
- *CO_2 capture technologies* have different levels of maturity, with carbon capture technologies from waste streams being proven technologies and Direct Air Capture being applied in first pilot plants. Significant advances and cost reductions are expected.
- For *fuel conversion*, established processes exist. Both the Fischer-Tropsch process with RWGS and the Waste-CO_2-to-Alcohol-to-Jet process are proven technologies.

R.2 – Current status in the ASTM approval process:

- Jet fuel produced through the Fischer-Tropsch process with RWGS and through the Waste-CO_2-to-Alcohol-to-Jet process are likely to be considered to have received ASTM approval under ASTM D7566 Annex A1 and Annex A5.

R.3 – Availability of systems to produce low carbon energy carriers (incl. feedstock availability):

- The uptake of the fuel volumes projected by LTAG-MDG in 2050 under scenario F1 requires expanding renewable power generation by 9% (for full fuel slate) or 4% (only jet fuel fraction) over the renewable power generation in IEA's STEPS scenario. Under F2, the renewable electricity production would have to be extended by up to 11% (full fuel slate) and 4% (only jet fuel fraction), as compared to renewable electricity generation as projected in IEA's more aggressive SDS scenario. Under F3, the generation capacities would have to be extended by 20% (full fuel slate) and 8% (only jet fuel fraction) as projected by the IEA NZE scenario (see also ***Figure*** 6.11).
- The LTAG-MDG fuel scenarios in 2050 leverage fuel production potentials from atmospheric CO_2 by 63% (F3 only) and Waste CO_2 based fuel potential by 62%, 13%, and 68% under F1, F2 and F3 respectively; the required electricity production in the fuel scenarios for international aviation approximately scale by these factors.

Attainability

A.1 – Capital investment requirements

- The specific investments needed to produce one megaton of PtL fuel per year are 18-63 billion USD in 2020 (over different scenarios), 11-48 billion USD in 2030, 9-38 billion USD in 2040, and 7-32 billion USD in 2050. The cost decreases result from technological progress. The specific investment costs are shown in Figure 6.3.

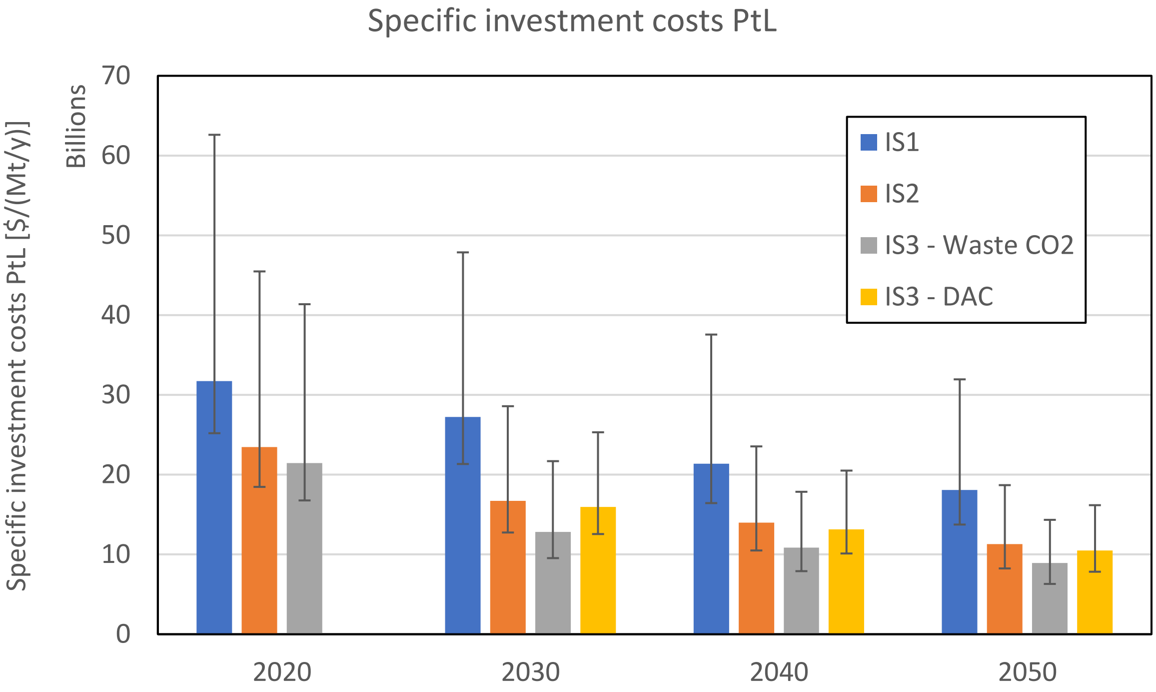


Figure 6.3 – Specific capital investment requirements (in bn USD) for jet fuel production in different scenarios.

- If the projected fuel volumes in the fuels scenarios from waste CO_2 sources and atmospheric CO_2 are to be reached, a total investment into fuel production of 1180-2700 billion USD are needed until 2050 under F1, 1880-4300 billion USD under F2, 3000-6850 billion USD under F3 using waste CO_2, and 790-1600 billion USD under F3 using DAC (not counting replacements of plants). However, only a portion of the resulting fuel output is jet fuel; by allocating the investment to the jet fuel fraction, the values are 550-1260 billion USD under F1, 770-1760 billion USD under F2, 1230-2810 billion USD under F3 using waste CO_2, and 320-660 billion USD under F3 using DAC.
- The required investments to reach the projected volumes are equivalent to an average annual investment over a 30-year timeframe, of USD 50-170 billion p.a. over 30 years (full slate) or 24-70 billion p.a. (jet fuel slate), depending on the scenario. This is on the order of 15-50% (full slate) or 7-20% (jet fuel slate) of the annual investment requirements under IRENA's Planned Energy Scenario (based on current plans and targets[11]).
- Waste CO_2 plants going out of service may be repurposed to produce fuel with a DAC unit. To this end, the necessary changes to the waste CO_2 plant are retrofitting a DAC unit and installing more electricity generation capacity upstream in the supply chain. These changes require 5.3-2.9 b$/(Mt jet fuel/y) (2020-2050) for the DAC unit and 0.5-0.1 b$/(Mt jet fuel/y) for the additional electricity generation capacity.

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[11] https://www.irena.org/financeinvestment/Investment-Needs

A.2 – Cost competitiveness

- Fuels from Waste CO_2 and Atmospheric CO_2 are found to currently be around 5 to 10 times as expensive as conventional Jet A (at current costs). These costs are largely driven by (i) the cost of H_2 production (25-50% of MSP), (ii) conversion costs (50-70% of MSP), and, for DAC-based fuels, DAC (37-45% of MSP).
- Due to expected significant reductions in all three major cost drivers, the PtL MSP is expected to decline by about 50% in all scenarios through 2050.

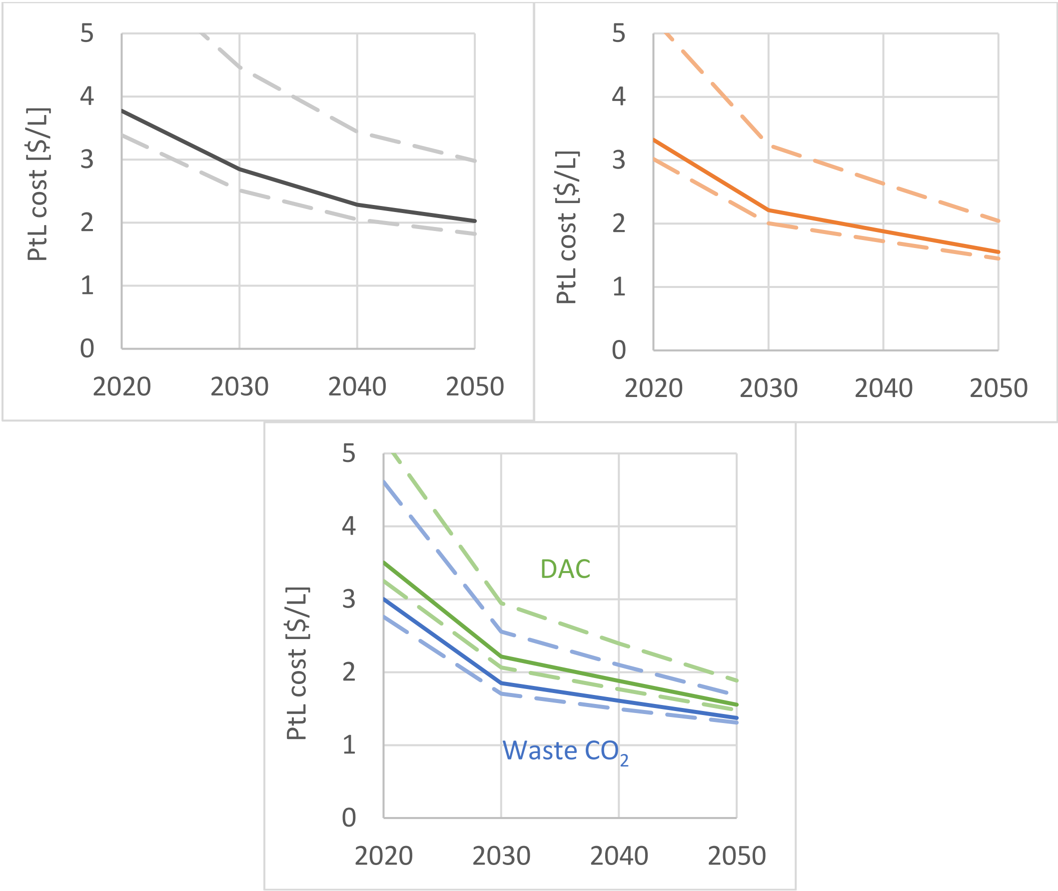


Figure 6.4 – Cost trajectories for fuels from Atmospheric CO_2 and Waste CO_2

A.3 – Land area requirements

- Power generation to support production of jet fuel in the fuels scenarios using waste CO_2 or atmospheric CO_2 will globally create land requirements of up to 170,000 km^2 for wind turbines and photovoltaic cells. This area is similar in size to the land area of New Zealand, but only a small fraction of a percent of the global land area. Considering that only a part of the full fuel slate is jet fuel, the overall total land area required in 2050 is up to 500,000 km^2. This area is comparable to the size of Spain.
- Note that any area covered with wind turbines can still be used for other purposes (e.g.: agriculture). In the following, both the totally affected and the actually covered land area are indicated.
  - F1: Total areas used (full slate) 2050
    - Overall area: 80,000 km^2

    - Actually covered area: 9,500 km^2
  - F2: Total areas used (full slate) 2050
    - Overall area: 166,000 km^2
    - Actually covered area: 21,000 km^2
  - F3: Total areas used (full slate) 2050
    - Overall area: 500,000 km^2
    - Actually covered area: 57,000 km^2

A.4 – Water requirements

- Production of fuels from waste CO_2 will require 5 to 9 liters of water per liter of jet fuel, depending on the specific water demand of the electricity source, the carbon conversion efficiency and the hydrogen demand. The largest water demand is attributable to electricity generation (50-60% of total demand) and electrolysis (40-50% of demand).
- Production of fuels from atmospheric CO_2 has the potential of only a small water demand; this is because DAC processes often also capture water from the atmosphere; the amount of water capture is potentially enough for running the electrolysis process.
- In F3 the water demand is 1540 billion liters *per year* in 2050 for the jet fuel share. The total demand (considering by-products) is 3750 billion liters per year. The latter is equivalent to three times the daily water use in the USA.
- The water demand can be met through desalination of seawater, with power demand ranging at around 0.1% of the total power requirements for fuel production through electrolysis.

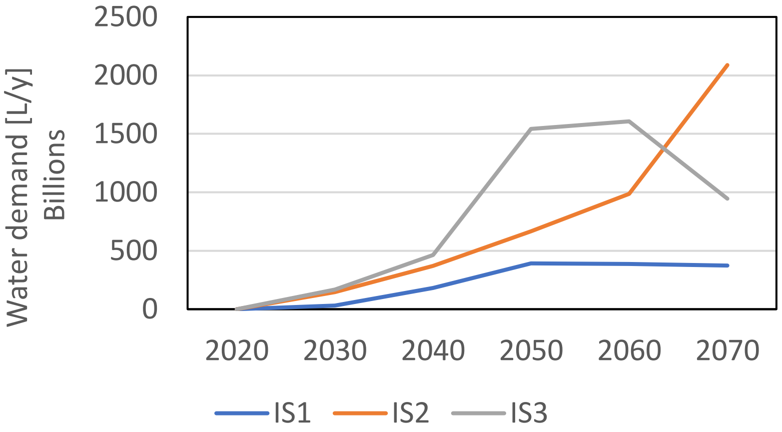


Figure 6.5 Water demand for jet fuel production in the three fuels scenarios. The numbers shown correspond to the water demand for the jet fuel share of the full fuel slate.

Note: In the figure IS1, IS2 and IS3 correspond to F1, F2 and F3, respectively

A.5 – Soil requirements

No significant hurdles for attainability expected.

A.6 – Biodiversity assessment

No significant hurdles for attainability expected.

A.7 – Infrastructure for fuel transportation

Existing fuel transportation infrastructure can be used.

6.3 LTAG-LCAF

LTAG-LCAF production depends on the deployment of GHG emissions reduction technologies and best practices. Given that the facilities modeled under the LTAG-LCAF are currently operating, the readiness and attainability were defined by the technology maturity and abatement costs of the different GHG emissions reduction measures.

Readiness

R.1 – Current status of GHG emissions reduction technologies:

- *Low carbon H_2 production*, mature production technologies exist, including Steam Methane Reforming and electrolysis using renewable electricity (see details in Section 6.4). As the use of the technologies is scaled up, significant cost decreases are expected.
- *CO_2 capture technologies* have different levels of maturity, with carbon capture technologies from waste streams being proven technologies with existing pilot plants that have deployed the technology for utility generation and hydrogen production (SMR) refinery subsystems. Significant advances and cost reductions are expected.
- *Gas management practices*, the technologies and practices that can prevent vented and fugitive emissions are well identified and, in most cases, considered mature. Captured gas can generate income, absorbing the required initial investments costs and the key barriers is to incentives the deployment of those abatement technologies.

R.2 – Current status in the ASTM approval process:

- LTAG-LCAF as the same fuel specifications as jet fuel and as such no additional ASTM approval is expected.

Attainability

A.1 – Capital investment requirements

- As shown in Figure 6.6, LTAG-LCAF will require the deployment of GHG mitigation technologies with a wide range in abatement costs, from \$6/tonCO_2eq to >\$200/tonCO_2eq. Some technologies are quite mature while others can see their abatement cost to be reduced as the technology becomes more mature and widely adopted.

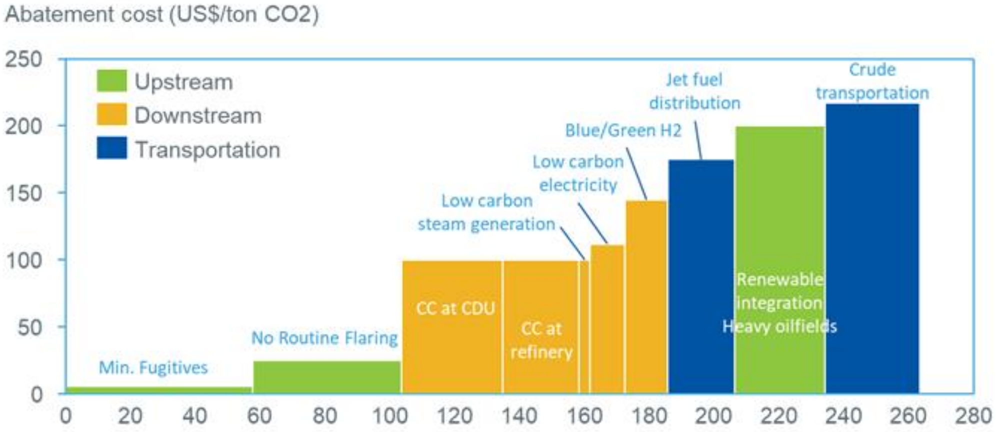


Figure 6.6 GHG emissions abatement potential by 2050 (MAM case) [MMt CO_2eq]

- *No routine flaring [Upstream]:* The abatement cost of $25/ton$CO_2$ is based on the requirement investment to end all routine flaring across the world. While this results in a higher abatement cost, it is important to keep in mind that the beneficial impact demonstrated through LTAG-LCAF are a fraction of the actual total GHG emissions reductions achieved through this measure. Such measure, in addition to capture all flared gas, will require to build the infrastructure to have sufficient capacity to utilize the gas. The current cost does not account for potential revenues from utilization of the gas.
- *Minimum fugitive emissions [Upstream]:* Abatement cost are determined by applying new technologies and best practices for upstream oil operations to minimize the release of methane in the atmosphere from venting and leakage. The considered technologies and practices include; i) the replacement of existing devices (e.g. use electric motors), ii) installation of new emissions control devices (e.g. install flares) and iii) the development and deployment of leak detection and repair processes (LDAR)

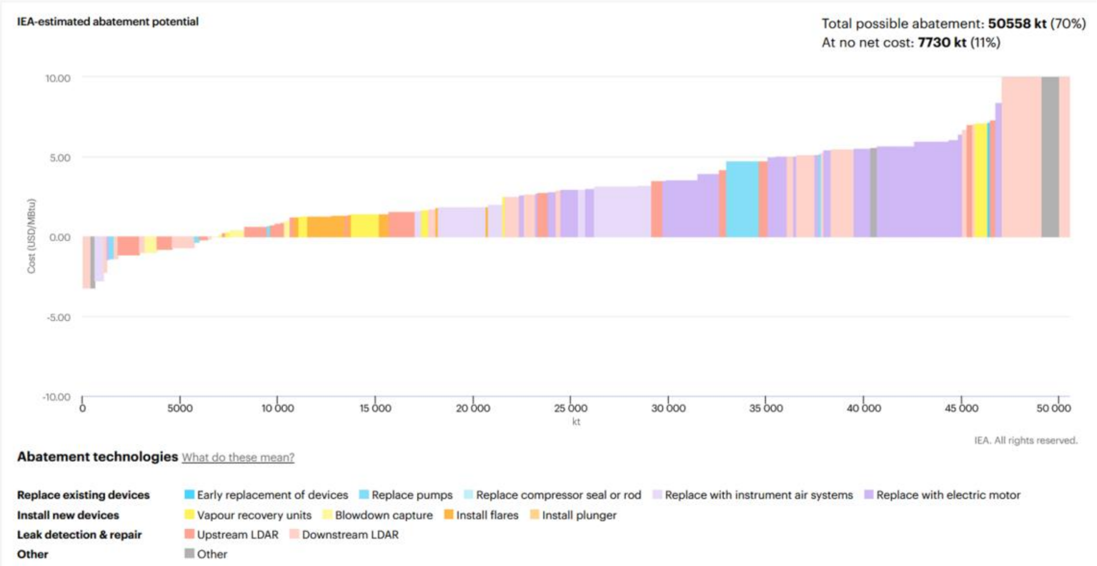
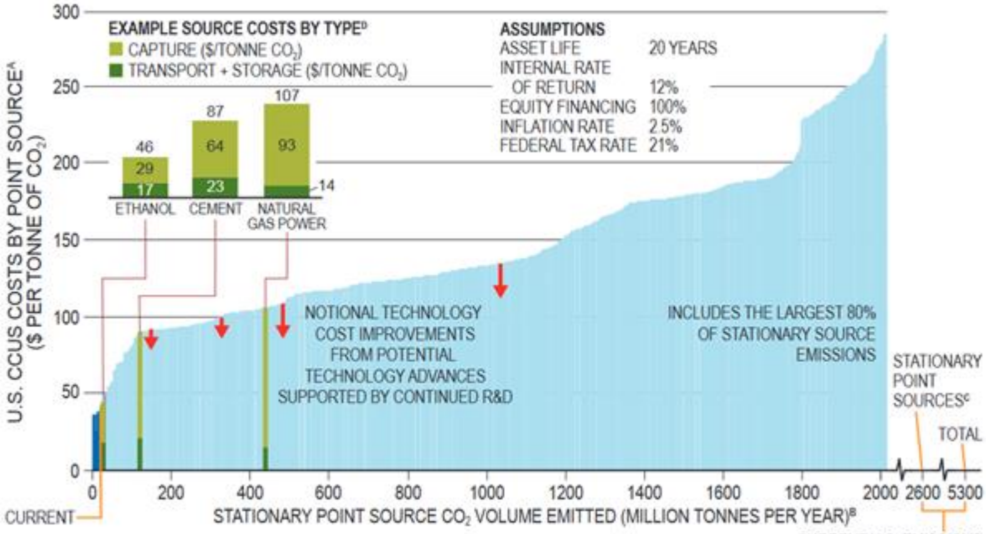


Figure 6.7 LTAG-LCAF abatement options to minimize methane emissions as reported by IEA

- *Renewable integration in heavy oil fields [Upstream]:* Deploying renewable energy sources (electricity and steam) to support oil production operations can be an effective way to reduce upstream emissions but require new infrastructure in remote areas or offshore operations.
- *Crude oil transport [Upstream]:* Effective emissions reduction can be achieved via i) optimization of supply chain to reduce the carbon footprint and/or ii) utilization of low carbon fuels on crude tanker (e.g. ammonia).
- *Renewable Electricity and Green H_2 [Refining]:* Refinery utilities generation can account for a large share of the refinery GHG emissions. Electricity can be purchased from the local grid, generated via gas fueled turbines and/or locally generated from renewable sources. Measure is exploited by energy production from renewable sources (solar + battery and wind + battery). Estimated abatement cost (Goldman Sachs, 2019) range between 85-139 $/t CO_2.

- *Jet fuel transportation & distribution:* Measure is deployed by utilization of fuel cells electrical vehicle, fueled by green H_2 electricity.
- *Carbon Capture in refinery operations [Refining]:* Carbon capture has the potential to drastically reduce refinery CO_2 emissions since an important source of emissions is from the process heat required by various separation and conversion process. The abatement cost will vary function of the CO_2 concentration in the flue gas and the installation of the infrastructure. As shown in Figure 6.8 the associated capture cost can vary and an abatement cost of $100/ton CO_2 was assumed.



Cost Curve Notes *(for Figures ES-13, ES-14, ES-16, ES-17)*:
A. Includes project capture costs, transportation costs to defined use or storage location, and use/storage costs; does not include direct air capture.
B. This curve is built from bars each of which represents an individual point source with a width corresponding to the total CO_2 emitted from that individual source.
C. Total point sources include ~600 Mtpa of point sources emissions without characterized CCUS costs.
D. Bar width is illustrative and not indicative of the volumes associated with each source.

Figure 6.9 U.S. CCUS cost curve showing capture, transport, and storage costs for the largest 80% of U.S. 2018 CO_2 stationary source emissions

A.2 – Cost competitiveness

Cost competitiveness for LTAG-LCAF can be evaluated by looking at the average abatement cost in $/t$CO_2$ which is determined based on different measures' abatement cost and weighted by their carbon intensity reduction contribution under each IS scenario. Estimated average abatement cost are 63, 87 and 95 [$/t$CO_2$] respectively for F1, F2, F3 scenarios.

A.3 – Land area requirements

Existing infrastructure can be used with retrofitting to install GHG emissions reduction technologies (e.g. CCS). No significant hurdles for attainability expected.

A.4 – Water requirements

No significant hurdles for attainability expected.

A.5 – Soil requirements

No significant hurdles for attainability expected.

A.6 – Biodiversity assessment
No significant hurdles for attainability expected.

A.7 – Infrastructure for fuel transportation
Existing fuel transportation infrastructure can be used.

6.4 Non-drop-in – LH_2

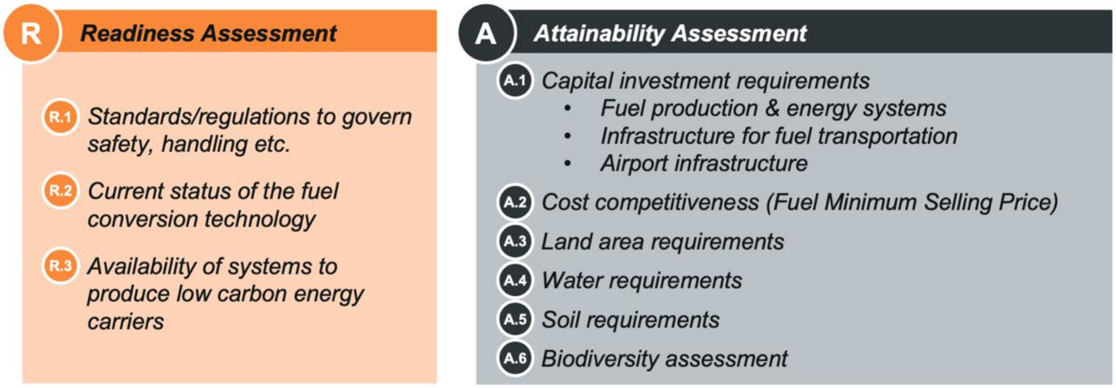


Figure 6.10 - Readiness and attainability assessment criteria for non-drop-in fuels.

Readiness

R.1 – Standards/regulations to govern safety, handling etc.:

- Standards exist which govern the use of LH_2 in industrial contexts as well as for vehicles. These standards regulate mostly hydrogen storage and distribution infrastructure (e.g. purging requirements, grounding, safety perimeters, proximity to other flammable liquids etc.).
- Existing standards do not capture the specificities of hydrogen use at the airport and in aircraft, i.e. close to terminal buildings, passengers boarding aircraft, and ground equipment, or at altitude.
- Safety equipment exists which can help mitigate some of the specific safety challenges of hydrogen.

R.2 – Current status of the fuel conversion technology:

- Mature production technologies exist for the production and liquefaction of hydrogen:
    - 95% of H_2 is currently produced from *Steam Methane Reforming (SMR)* at low cost, but with high GHG emissions; to reduce emissions, SMR can be combined with *Carbon Capture and Storage* (CCS) which reduces the cost advantage of SMR-produced H_2.
    - *H_2 from electrolysis* requires the use of low-carbon electricity to produce low-carbon H_2; costs are expected to decrease with lowering costs of renewable electricity, which could render H_2 from renewable electricity cost competitive with H_2 from SMR with CCS.
- Significant cost decreases are expected as more advanced technologies become available and production ramps up.

R.3 – Availability of systems to produce low carbon energy carriers:

- *Under the LTAG-MDG hydrogen scenario*, hydrogen uptake in 2040 and 2050 requires 0.06 EJ and 0.49 EJ [0.4% and 4% of year-2019 H_2 production] of LH_2. If the world transitions to a Sustainable Development Scenario (SDS) as described by the IEA, global H_2 production will increase by a factor of 4, thereby reducing the share of aviation H_2 to less than 1% of global H_2 demand.
- If produced from electrolysis with advanced technologies, the production of H_2 in the LTAG-MDG scenarios would require up to 135 GW of installed electric power in 2050. This is smaller than the annual addition of wind and solar power generation in 2019 (see **Figure** 6.11). If the world transitions as described in IEA's SDS, this power demand would account for 1% of global power generation from solar PV and wind.

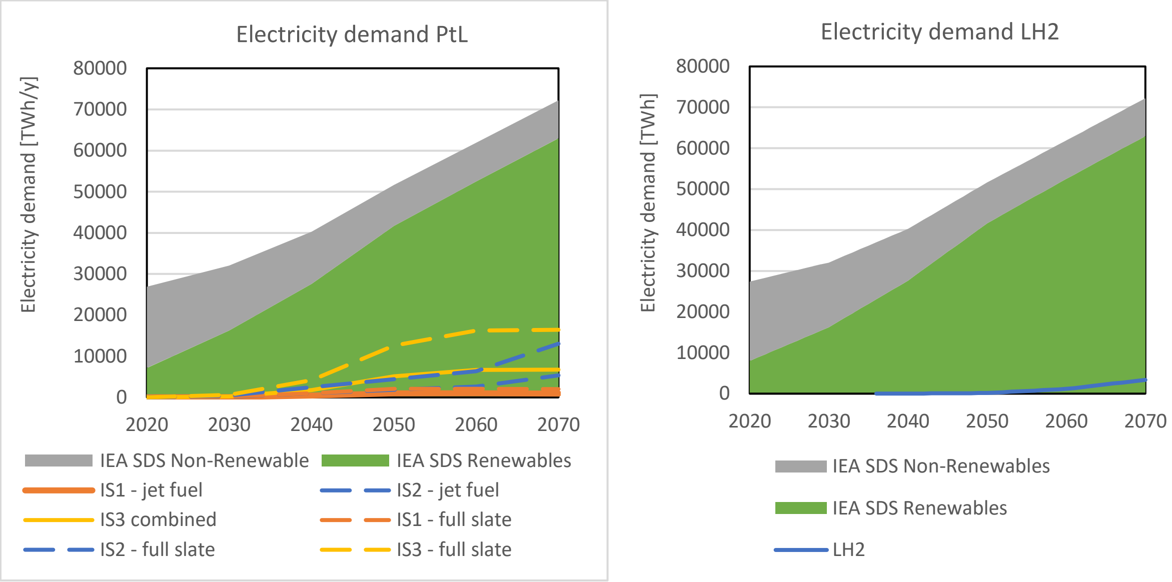


Figure 6.11 - Electricity requirements for PtL (full slate) and LH2 production in the context of electricity generation in the IEA Sustainable Development Scenario until 2070

Note: In the figure, IS1, IS2 and IS3 correspond to F1, F2 and F3, respectively

Attainability

A.1 – Capital investment requirements:

- The specific investment costs of LH_2 production under F3 are 24-37 billion USD per ton of liquid hydrogen in 2040, 16-25 billion USD in 2050 per ton of liquid hydrogen. The breakdown of specific investment cost is shown in Figure 6.12. The specific investment costs after 2050 are similar to the ones for 2050.

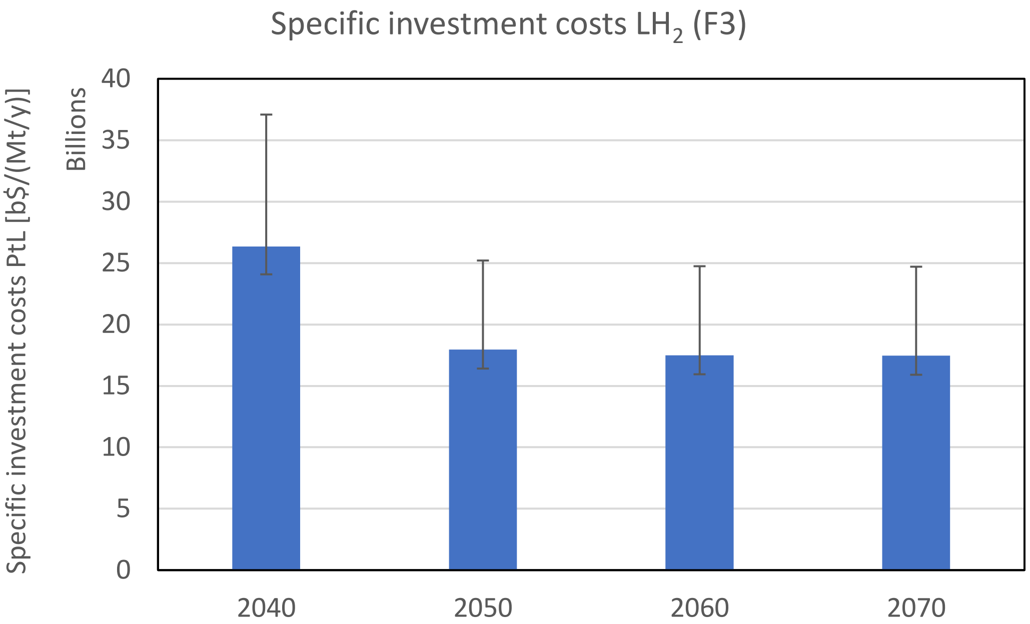


Figure 6.12 Specific investment costs for LH_2 production. These costs do not include the cost to produce the LH_2 aircraft. The specific investment costs after 2050 are assumed to be identical to the ones for 2050.

- Under the uptake scenarios, H_2 production with renewable electricity requires significant investments into fuel production of $52 billion until 2050 (up to USD 5 billion p.a. over 14 years) (see Figure 6.13). These investments are on the order of 1% of the annual investment requirements under IRENA's Planned Energy Scenario (based on current plans and targets).
- The investment required between 2050 and 2070 is significantly higher due to the increase in LH_2 uptake. Using the conservative assumptions of specific investment remaining constant at year-2050 levels, a total investment of 1010-1560 bn USD in fuel production infrastructure (including power generation) would be needed to meet the growing LH_2 demand in the aviation sector.

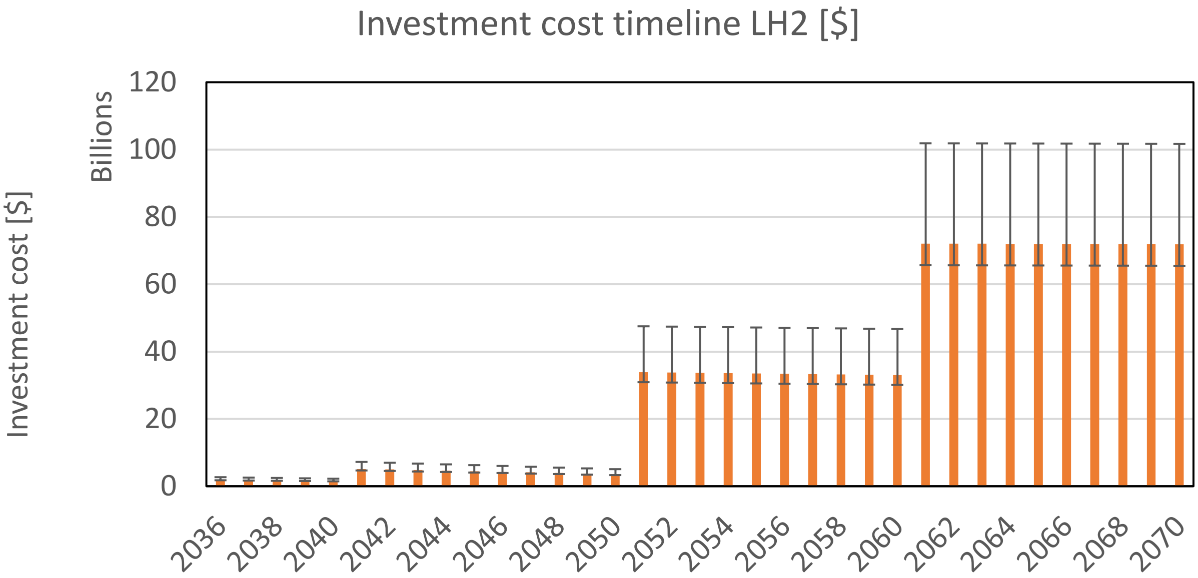


Figure 6.13 Required average investments into the LH_2 pathway to meet projected demands from MDG. The total investment accumulates to 1600 billion \$ until 2050. These numbers do not include the costs to create the aircraft infrastructure for LH_2.

- For airports, different LH_2 fueling systems are likely to be installed, with a global investment volume on the order of USD 100-150bn (USD 3-6 bn p.a. over 30 years). Airports will be required to operate LH_2 and Jet-A fueling systems in parallel, which causes additional challenges under existing H_2 standards.

A.2 – Cost competitiveness:

- Today, LH_2 from renewable electricity can be produced at around USD 7 per kg (~5 times as high as Jet-A on an energy basis). These costs are expected to decline by 40% as the cost of renewable electricity is reduced, efficiencies improve and capital costs for electrolyzers and liquefaction facilities come down.

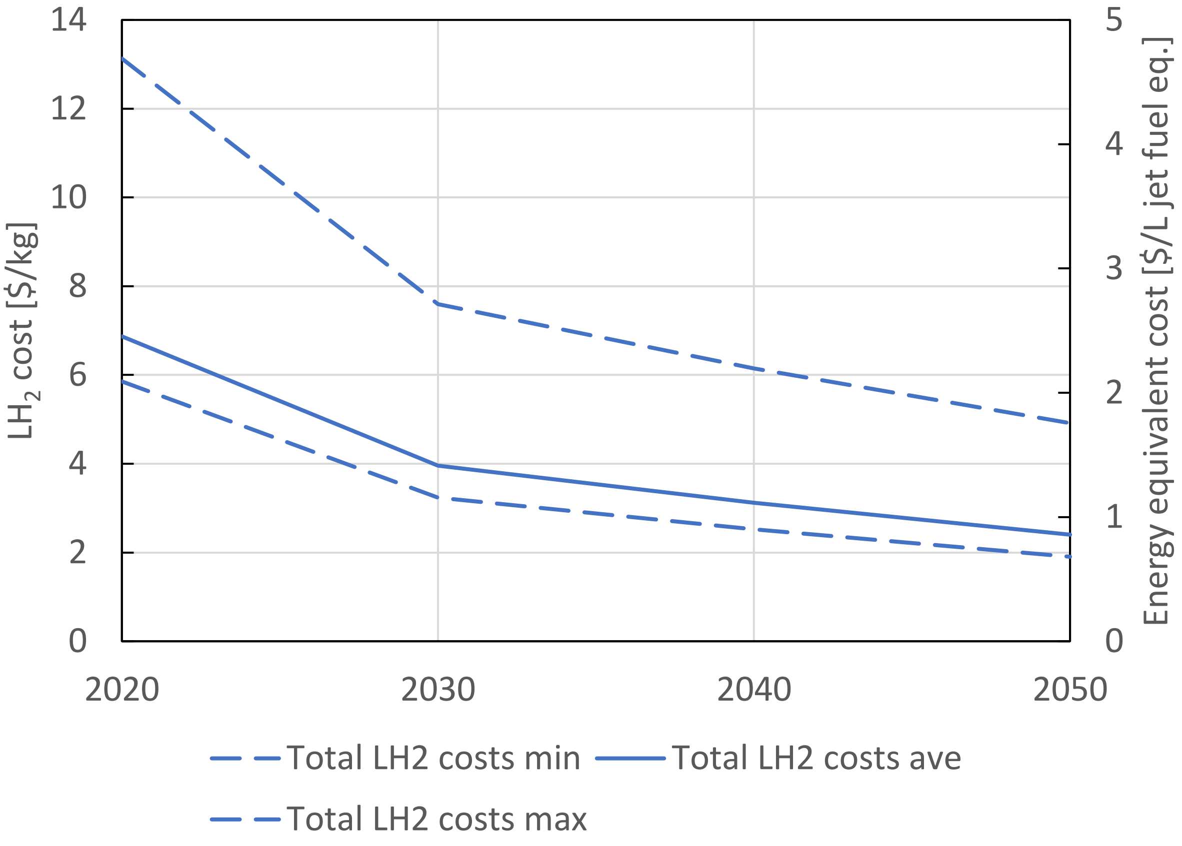


Figure 6.14 - LH_2 cost trajectory under F3.

- The price of LH_2 can increase through competition with other sectors for access to H_2 and renewable electricity. While other sectors can generally use H_2 in gaseous form, aviation users, under the LTAG analysis, require liquid (cryogenic) hydrogen. This additional requirement would increase hydrogen costs for aviation relative to other users.
- LH_2 logistics can add significant cost of up to USD 2 per kg, if transporting in gaseous form through pipelines (and liquefaction at the airport) is not possible and long-distance transport is necessary. However, short-distance transport or transportation of electricity to the airport can significantly reduce costs. If a pipeline for gaseous transport over 1000 km is used, the costs are 0.2 $/kg. If electricity is transported over 1,000 km, the costs implications on locally produced LH_2 are about 0.2-1.0 $/kg, depending on the capacity factor of electricity production.
- The cost of refueling at the airport is on the order of USD 0.03 – 0.10 per kg LH_2; indirect costs (impacts of fueling time on turnaround times and aircraft utilization) can be substantial if high transfer rates of LH_2 cannot be achieved and safety requirements do not allow loading and boarding to commence during fueling. With high transfer rates and pipeline- or tanker-truck-based fueling at the gate, the effects on turnaround times for shorter flights (<2,000nmi) are found to be on the order of 1% (on average); they are less than 0.1% if parallel boarding/refueling is allowed. For longer flights, parallel boarding and loading as well as achieving high transfer rates are essential to contain large impacts on turnaround times.

A.3 – Land area requirements:

- Power generation to support LH_2 will globally create land requirements of up to 140,000 km^2 for wind turbines and photovoltaic cells in 2070. This area is similar in size to the land area of Austria, but only a small fraction of a percent of the global land area.
- Note that area covered with wind turbines can still be used for other purposes (e.g.: agriculture).

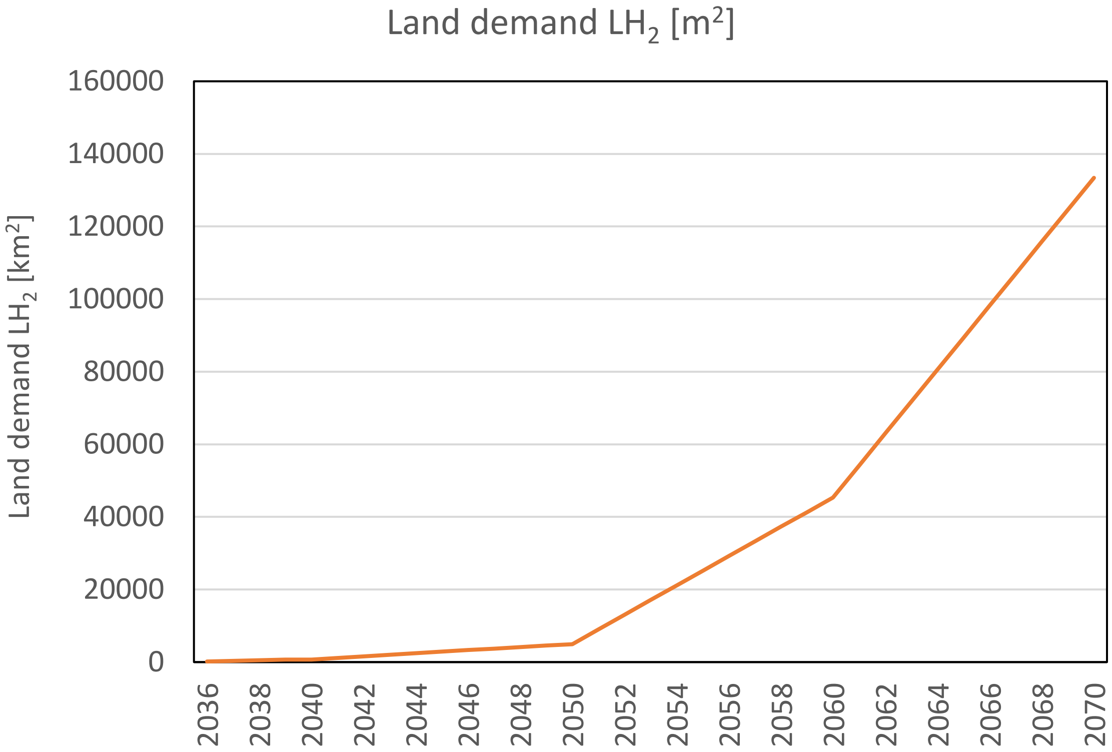


Figure 6.15 Land demand of LH_2 production.

A.4 – Water requirements:

- H_2 production from electrolysis (with renewable electricity) requires around 21-24 liters per kg H_2.
- The water demand reaches 60bn liters *per year* in 2050. This is equivalent to about 5% of the water use in the USA *per day*. The growth after 2050 occurs under fixed technological assumptions and is due to the increase in hydrogen demand.
- The water demand can be met through desalination of seawater, with power demand ranging at around 0.1% of the total power requirements for hydrogen production through electrolysis, including liquefaction.

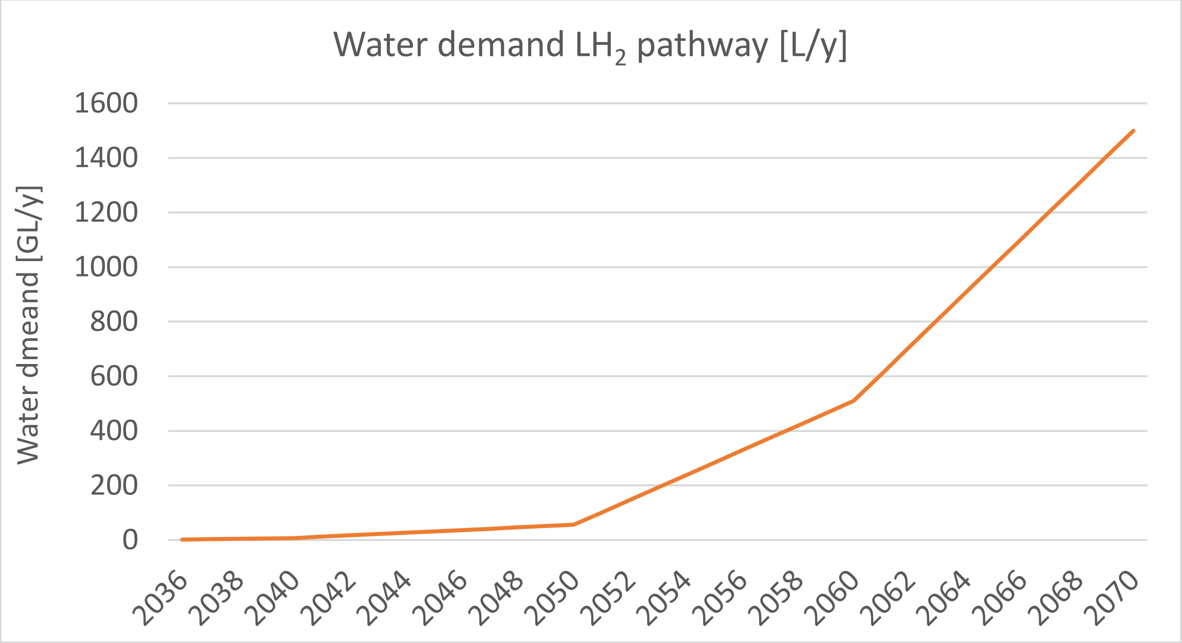


Figure 6.16 Water demand of LH_2 production.

A.5 – Soil requirements:
No significant hurdles for attainability expected.

A.6 – Biodiversity assessment:
No significant hurdles for attainability expected.

ATTACHMENT A TO APPENDIX M5

Working paper: SAF Production Projections and Associated GHG Emissions Reductions

Relevant excerpts from Working Paper CAEPSG.20213.WP.020.7.en are available from the link below:

https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM5_AttachmentA.pdf

ATTACHMENT B TO APPENDIX M5

Information paper: SAF Production Projections and Associated GHG Emissions Reductions

Relevant excerpts from Information Paper CAEPSG.20213.IP.005.7.en. are available from the link below:

https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM5_AttachmentB.pdf

ATTACHMENT C TO APPENDIX M5
ASKT Case Study

The following description has been provided by Artur Mirzoyan.

Condensed aviation fuel ASKT is a mixture of hydrocarbon gases propane and butane, in which higher hydrocarbon fractions up to C_{10} (decane) may be present in a relatively small amount. At negative temperatures, ASKT fuel has significantly better viscosity performance in comparison with petroleum aviation fuels. In addition, at negative temperatures, the low (below atmospheric) pressure of saturated vapors of ASKT fuel provides its operation in the same way as conventional fuels at plus temperatures, i.e. use it in fuel systems with open drainage (for example, locate it into the wing fuel tanks). At positive temperatures, it should be located in heat-insulated fuel tanks, or in high-pressure tanks (the saturated vapor pressure at $T= 450^{o}C$ is 0.5 MPa).

ASKT fuel has a higher low heating value and cooling resource in comparison with kerosene. Its density is about 600 kg/m^3.

The ground-based gas-fuel infrastructure for the production of ASKT fuel will be completed by 90-95% from mass-produced units and devices used in road transport and petrochemicals. The cost of production of ASKT fuel is comparable with the production of autopropane. There is no need to build new factories for ASKT fuel production. It can be produced from a wide fraction of light hydrocarbons (natural gas liquids NGL) obtained from associated natural and petroleum gases. There is no emission of carbon oxides during the production of ASKT from NGL. According to expert estimations, use of ASKT in propulsion systems, CO_2 emissions are reduced by 20-40%.

ASKT fuel belongs to the category of low-carbon fuels and could be used on almost any aircraft, primarily for regional transportation. After accumulating experience in the operation of such vehicles, which are entitled to be called "first-generation of gasaeroplanes", it will be possible to expand the scope of application of ASKT fuel to medium and long-haul aeroplanes, as well as to explore the most optimal solutions for creating second-generation of gasaeroplanes using cryogenic liquefied natural gas (LNG) and, then, the third generation of gasaeroplanes using liquid hydrogen (LH_2).

It should be noted that ASKT type fuel may have its own niche in the national economy system, if, under certain requirements, the required efficiency may be provided at lower specific costs. In the far future at certain conditions ASKT fuel may be applied for international aviation.

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