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CORSIA Lower Carbon Aviation Fuels: An Assessment of the Greenhouse Gas Emission Reduction Potential

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Abstract: Curbing aviation emissions is clear goal for the aviation sector, but it is a challenging task. At international level, the ICAO CORSIA initiative promotes the use of alternative fuels as a means to decarbonise flights. Among alternative fuels, lower carbon aviation fuels (LCAF) have been proposed under CORSIA. LCAF refers to a fossil fuel, which have been produced in a way that results in at least 10% lower lifecycle GHG emissions compared to a benchmark value. This paper analyses potential LCAF solutions for reducing GHG emissions of kerosene production and evaluates them relative to the ICAO baseline of 89.0 gCO_{2eq}/MJ of fuel. The study analyses the levers that can reduce GHG upstream emissions (emissions from crude oil production) and refining emissions as well. This study shows that no one lever can reduce emissions to a sufficient level to meet the requirement of being a CORSIA-eligible fuel, and therefore that the deployment of multiple levers needed. Since jet fuel comprises only around 10% of total refining output, the LCAF measures could support the implementation of large, high-abatement cost changes, such as refinery-wide carbon capture and storage that affects multiple fuels.

Keywords: sustainable aviation fuels; SAF; lower carbon fuels; LCAF; GHG savings; CORSIA

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1. Introduction

Aviation is a strong driver for modern economies, promoting social and regional cohesion. In recent years, the aviation sector has contributed to increased tourism, and stimulated economies. Global air traffic increased by more than two-thirds in the last 15 years to reach about 39 million flights in 2019. During the same time, the number of passengers more than doubled and the worldwide air freight traffic increased by half. At European level, in 2019, over 1.2 billion passengers travelled across the 500 airports of the region in 9.3 million flights. In 2019, commercial aviation emitted over 0.9 Gt CO_{2eq} globally, representing about 2% of global anthropogenic greenhouse gas (GHG) emissions and about 12% of the emissions from the transport sector. In Europe, the departing flights from Europe accounted for 5.2% of total GHG emissions in 2019 and 18.3% of transport sector emissions [1,2].

With respect to the consolidated trends of the last decades, the sector faced a disruptive phase, due to the strong impact of the COVID-19 pandemic. In 2020, flights decreased to just 4 million and emissions decreased by more than 50%. Following the recovery from the pandemic, it is expected that air traffic will gradually recover to its pre-crisis levels and the numbers of flights are foreseen to grow slowly until 2050 [2]. Regardless of the short-term effects of such a crisis, a growing concern exists for the increasing environmental impact of the sector [3].

In 2020, the European Commission (EC) adopted the Sustainable and Smart Mobility Strategy, which sets the objective to boost the uptake of sustainable fuels for aviation [4]. More recently, the EC launched the ReFuel EU aviation proposal, aimed at supporting the

EU aviation market to ensure a gradually increasing share of sustainable aviation fuels (SAFs) in Europe, limiting the detrimental effects on competitiveness [5]. The European Commission has proposed, in its ReFuelEU Aviation initiative, a blending mandate for the fuel suppliers to European Union (EU) airports, with minimum share of SAFs increasing to 5% in 2030 and to 63% in 2050. To achieve this mandate, approximately 2.3 million tonnes of SAF would be required by 2030 and 28.6 million tonnes by 2050. This mandate includes a sub-mandate for synthetic aviation fuels that should increase from 0.7% in 2030 to 28% in 2050 [2].

The Renewable Energy Directive 2018/2021 (RED II) set minimum targets in the EU for the use of 14% renewable energy for 2030. The proposed revision for the RED II (COM(2021) 557 final) as part of the Fit for 55 package calls for a 13% reduction of carbon intensity (CI) of the transport sector. To be eligible, biofuels used in transport must comply with the sustainability and GHG emissions-saving criteria laid down in RED II. The carbon intensity of a fuel is defined as the lifecycle of GHG emissions per unit of energy, i.e., gCO_{2eq}/MJ. According to RED II, in order to qualify as renewable energy source for aviation, biofuels must achieve an at least 65% reduction in their carbon intensity against the fossil fuel baseline of 94 gCO_{2eq}/MJ.

At international level, in 2016 the assembly of the United Nation's International Civil Aviation Organization (ICAO) agreed on the adoption of a global market-based scheme to limit international aviation CO_2-equivalent (CO_{2eq}) greenhouse gas emissions: the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [6]. CORSIA requires airlines to offset CO_{2e} emissions that exceed 2019 levels. On the basis of impact assessments and available scientific knowledge, CORSIA has been framed to allow offsetting either through credits or through the use of CORSIA-eligible fuels (CEFs).

CEF is a category comprising both sustainable alternative fuels (SAFs) and lower carbon aviation fuels (LCAFs). While SAFs are produced from low-carbon feedstocks, LCAF refers to a fuel from fossil sources, the production of which is able to displace at least 10% lower lifecycle GHG emissions against a certain benchmark value.

ICAO CORSIA developed a set of sustainability criteria for aviation fuels to qualify as CEFs that cover several themes, including greenhouse gases (GHG), carbon stock (for fuels produced before 1 January 2024), water, soil, air, conservation, waste and chemicals, human and labour rights, land use rights and land use, water use rights, local and social development and food security (for fuels produced after 1 January 2024). The CORSIA criterion for eligible fuels on GHG emissions requires a lifecycle emission reduction of at least 10% as compared to the baseline lifecycle emissions values for aviation fuels of 89 gCO_{2eq}/MJ using a lifecycle assessment (LCA) approach. [7]. CORSIA developed default lifecycle emissions values that may be used to claim emission reductions from the use of CEFs [8].

CORSIA produced guidance for sustainability certification schemes (SCS) for application of CORSIA sustainability criteria [9] and developed a methodology for calculating actual lifecycle emission values [10]. This is the first global LCA methodology agreement on the calculation of GHG emissions of aviation fuels. According to the methodology, a default lifecycle emissions value is a sum of a default core LCA value and a default indirect land use change (ILUC) value. The SAF pathways offer potentially significant GHG emission reductions in attributional lifecycle GHG emissions relative to fossil jet fuel [11]. The concept of LCAF and sustainability criteria are still under evaluation in CORSIA as its implementation poses many challenges both from a theoretical and practical point of view.

For the moment, sustainable aviation fuels are identified as one of the most important ways for reducing GHG emissions in the international aviation sector. A study [12] assessed the ways of controlling aviation carbon emissions, identifying improvements in aircraft aerodynamic efficiency, structural efficiency, air traffic management and the use of using alternative fuels as main determining factors.

Several studies have been conducted to assess the technical and economic feasibility of the production and use of SAFs and to assess the technical potential and GHG emissions that can be ensured by different pathways [13–15]. They have addressed the technologies to produce aviation biofuels, their potential to be upscaled and techno-economic perspectives, as well as the impact of SAF on sustainability. A study [16] assessed the current use of biofuels in aviation and the production potential of aviation fuels in the EU and the constraints related to costs and feedstock availability and competition with demand.

Prusi et al. [11] presented the lifecycle GHG emissions of sustainable aviation fuel pathways calculated following the CORSIA methodology. The GHG emission savings can be up to 94% when compared to petroleum-derived baseline jet fuel (and more than 100% when considering negative GHG emissions of ILUC contribution for some SAF pathways). This showed that many SAF pathways can play a major role in reducing the carbon footprint of the aviation sector. A study [15] concluded that the use of CORSIA-eligible fuels (CEFs) is beneficial to reducing the cost associated with CORSIA's offsetting requirement operational costs after considering the fuel cost, carbon pricing and GHG emission savings from reduction of different pathways.

A study [17] estimated the EU's technical potential for the production of LCAF considering the data on crude oil used in EU refineries, aviation fuel use and relevant carbon intensity reduction technologies. This showed that, even if LCAF could offer GHG saving opportunities, its possible impact is rather limited, especially when compared to the demand for the decarbonisation of aviation.

To deliver effective GHG reduction, LCAF should demonstrate additional GHG emissions reduction compared to reductions in emissions that are expected from the application of existing policies or trends in technologies and practices that occur regardless of any LCAF-related policy support.

Despite the expectation that fossil-based LCAFs contribute to the decarbonisation of the aviation sector, there is no study, to the knowledge of the authors of this paper, that counts the GHG emission reduction potential of LCAF. This is why this paper addresses the need to get a better understanding of the technologies and practices to achieve GHG emissions reduction. This study also addresses the need to quantify these reductions, model refinery emissions and analyse the conditions under which these reductions could be considered to be additional.

To reduce emissions from the production of aviation fuels this study identified several technologies that can be applied, contributing to reductions in both upstream (e.g., flaring reduction) and downstream (e.g., use of green hydrogen, renewable energy, carbon capture and storage, etc.) emissions of aviation fuels, which could result in LCAF. This paper identifies the potential LCAF technologies capable of reducing the GHG intensity of current fossil kerosene production. The technical potential for GHG savings of each technology is assessed independently and presented in a structured format that highlights the associated benefits and limiting factors. This is expected to significantly contribute to the existing body of knowledge on the potential role of LCAF for decarbonising the aviation sector.

2. Materials and Methods

2.1. LCA and Methodological Choices

Life cycle assessment (LCA) methodology is largely applied to determine the GHG saving potential of alternative fuels [6,18]. When applied to the use of these fuels in specific powertrains, LCA is usually down-tuned to the well-to-wheel (WTW) approach. WTW modelling includes so-called well-to-tank (WTT) [19] and tank-to-wheel/wake/wing (TTW) parts [20]. WTT emission intensity can be considered as the sum of individual contributions needed to convert a specific feedstock in a certain fuel, therefore encompassing downstream and upstream emissions. In the case of fossil feedstock, WTT includes crude oil production (upstream) and refining emissions. Figure 1 shows a diagrammatic representation of well-to-tank (WTT) and tank-to-wheel/wake/wing (TTW) emissions, respectively, along the fuel supply chains.

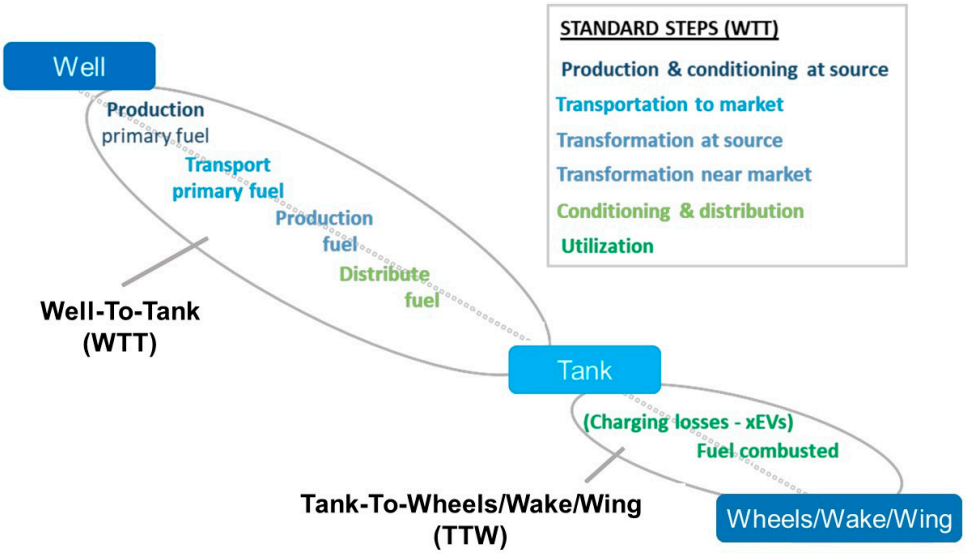

Figure 1. Well-to-wheel/wake/wing emissions for fuel supply chains.

The main contributors to upstream greenhouse gas emissions are:

- Energy use to get the oil out of the formation and for pre-processing before shipment;
- Fugitive emissions of methane from process equipment via seals, purges, etc.;
- Deliberate venting of produced gases, where it is considered uneconomic to collect them;
- Flaring as an alternative to venting, as well as flaring at start-up/shutdown or as a part of the pressure relief system.

The energy use in crude production is time- and location-dependent: EU refineries receive a mixture of crudes from different regions that have their own production characteristics, and this impacts upstream emissions. To determine the GHG intensity for fossil-derived kerosene it is needed to first properly characterize the crude feedstock. The physical properties of crude oil vary both by region and within a region, arising from differences in geology, operating factors and history. A review of the supply of crude to the EU and the GHG intensity of regional crudes supplying the EU [21,22] shows a substantial variation between different oil field countries that reflects fundamental differences in crude and the geology but also operational practices.

A refinery can be modelled by linear programming (LP). These kinds of models provide the distribution of energy and hydrogen supplies, allowing the overall GHG emission to be calculated as the sum of the individual contributions each multiplied by their characteristic GHG intensities. The refinery's GHG intensity is then calculated as the emission as gCO_{2eq} per tonne of crude input. For this study the functional unit is represented by the gCO_{2eq} per MJ of finished kerosene.

Given the goal and scope of this paper, a simpler refinery model was defined, with the specific target of focusing on looking at the various independent levers that could reduce the GHG of crude refining. In this paper, emission savings have been allocated on an energy basis; therefore, the GHG emission savings benefitted all refinery products. However, it could be argued that if the GHG savings rise because of LCAF incentives, then GHG emission savings should be attributed solely to the jet fuel (free allocation). As the differences in the results could be relevant, this raises the question about what an appropriate allocation methodology could be for the additional GHG savings arising from LCAF-specific incentives. For this study, energy allocation has been chosen as the ICAO document [11] states that energy allocation should be used to assign emissions burdens to all co-products in the system, this would apply to both LCAF and sustainable aviation fuels (SAF). This approach is also in line with the EU REDII GHG methodology for renewable fuels.

2.2. Production of Conventional Jet Fuel from Crude Oil

Crude oil currently provides a wide range of products such as gasoline, jet fuel, diesel, liquefied petroleum gas (LPG), fuel oils, lubricants and chemical feeds; the production of jet fuel is only a minor part of the overall production of a refinery. The distribution of the products depends mainly on the overall design of the refinery and the type of crude oil processed. The yield of jet-range kerosene is generally between 8% and 9% across a range of crude types, and used to make jet fuel, light heating oil and diesel. It is worth noticing the EU jet fuel consumption is approximately 55 to 60 Mtonnes/year, of which around 70% (40 Mtonnes/year) is made in EU refineries and the rest imported [21,23]. According to the Oil and Gas Journal Refinery Database, the EU and EEA has a total refining capacity of approximately 13.0 million bbl/day, corresponding to approximately 570 Mtonnes/year [24,25] in about 80 refineries.

A typical scheme of a refinery is shown in Figure 2. The highlighted process units are the main sources of materials used to make jet fuel from crude oil; note that not all refineries have all of these process units.

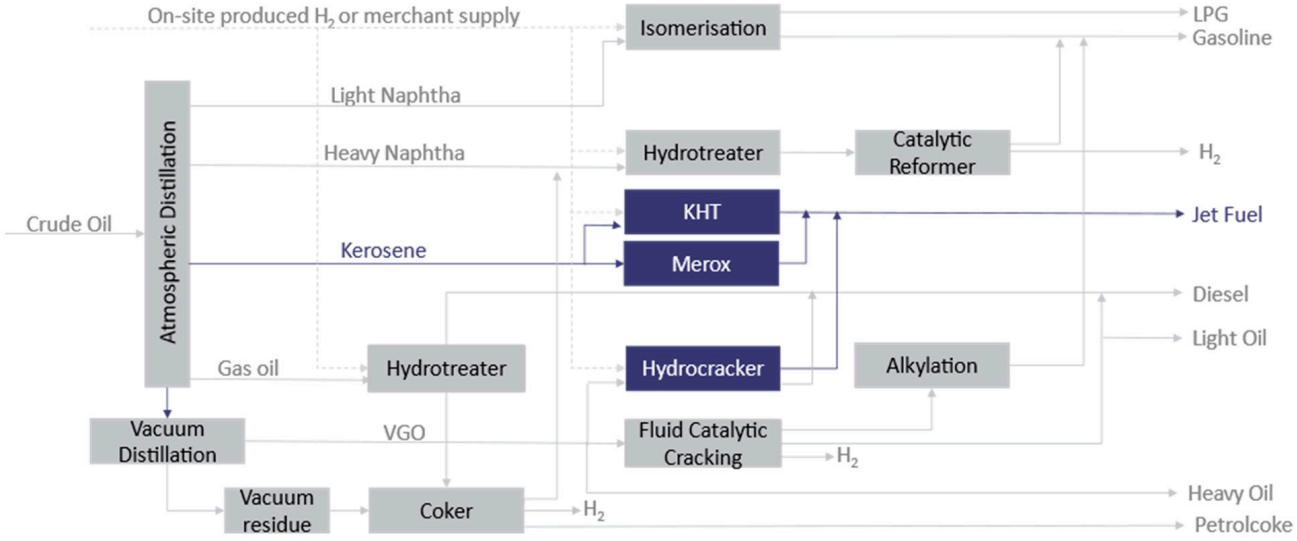

Figure 2. Flow diagram for a typical refinery.

2.3. The GHG Intensity of Conventional Jet Fuel

The WTW emissions detailed reported in Table 1 are based on the WTW Study v5 emissions, which have been prorated against the ICAO benchmark for jet fuel [26]; the refining emissions are in line with Concawe [27]. The disaggregated WTW emissions of diesel and gasoline were broken down by life-cycle stage [19]. From a WTW perspective, it is worth stressing that new technologies and practices for fossil jet fuel are unlikely to have a significant impact on TTW emissions: in principle, "low aromatics" jet fuel can be made from conventionally refined jet fuel using a high-severity aromatic saturation process, where aromatics are converted to cycloparaffins. These have a lower GHG intensity than aromatics, but a higher GHG intensity than the linear/branched paraffins in synthetic jet fuel. This treatment might reduce TTW emissions by roughly 1 gCO_{2eq}/MJ, but this would be counterbalanced by increased WTT emissions, thus the combustion emissions of 73.2 gCO_{2eq}/MJ are assumed. It is worth stressing that these kinds of evaluations are intrinsically affected by a wide variability.

In order to investigate the effect of specific modifications on crude refinement for jet fuel production, the total emissions have been divided into:

- Upstream emissions: Emissions from crude production, from process energy use, flaring of produced gas and methane emissions from venting and fugitive sources. These

are assumed to be independent of each other allowing the GHG intensity for the LCAF cases to be calculated simply by assuming a net reduction in upstream emissions.

- Refining emissions: Refinery GHG emissions, stemming from process energy use and from production of hydrogen, both of which are linked to the type and throughput of the process units within the refinery. These in turn depend on the type of crude-oil run by the refinery and the amount/properties of the products that the refinery is required to make. The supply of process energy includes refinery by-products (refinery fuel-gas; coke) supplemented by imports (natural gas; electricity; steam). Hydrogen is supplied partly as a by-product of catalytic reform to allow gasoline to be supplemented by imported hydrogen.

Table 1. WTW GHG emissions for gasoline, diesel and jet fuel.

Product WTW	Diesel (gCO_{2eq}/MJdiesel)	Gasoline (gCO_{2eq}/MJgasoline)	Jet Fuel (gCO_{2eq}/MJjetfuel)
Production at source (crude production emissions)	10.0	9.6	8.4
Transport to market	0.8	0.8	0.6
Transformation in market (refining emissions)	7.2	5.5	6.0
Distribution in market	0.9	1.0	0.8
WTT emissions	**18.9**	**16.9**	**15.8**
Combustion (TTW emissions)	73.2	73.3	73.2
WTW emissions	**92.1**	**90.2**	**89.0**

2.3.1. GHG Emissions from Upstream Activities

The values reported in Table 1 suggest that 9.4% of the WTW emissions occur from the upstream production of crude oil (production at source). There are three main sources of these emissions: (a) CO2 from combustion of fossil fuels to provide energy; (b) methane emissions, either from release of co-produced natural gas during well operations or from leakage of natural gas through valves and seals, and (c) CO_2 produced by flaring natural gas (e.g., for safety purposes). Table 2, which is based on IEA data [28], shows that the distribution of these factors is fairly consistent across a wide range of oil fields.

Table 2. Distribution of global aggregate CO2 emissions from upstream oil production.

% of GHG Emissions	TOTAL	Q1	Q2	Q3	Q4
Energy use	27	28	32	22	27
Flaring	14	14	7	19	14
Methane emissions	59	57	61	58	58

NOTE: the quartiles are defined in terms of absolute GHG emission intensity. Q1 = 40%, Q2 = 63%, Q3 = 83% and Q4 = 211% of the average intensity.

2.3.2. GHG Emissions from Downstream Activities

Table 1 suggests that 6.7% of WTW emissions occur mainly as CO_2 associated with downstream conversion of crude oil in refineries (transformation in market—refining emissions). The main sources of CO_2 are: (a) production of hydrogen from natural gas (or other hydrocarbons) to supply hydrotreating units; (b) provision of heat and motive power for process units by combustion of natural gas, refinery fuel gas or liquid fuels within the refinery; (c) combustion of coke deposited on the catalyst of fluid catalytic cracking (FCC) units; or (d) the activities of third parties supplying refineries with purchased power and steam. The EU aggregate distribution of these sources is shown in Table 3, derived from work by Concawe [29].

Table 3. Distribution of EU aggregate CO_2 emissions from Downstream Oil Refining.

Energy Source (EU Aggregate)	% of CO_2 Emissions	%
Manufactured H_2	19	19
Purchased natural gas	14	29
Purchased steam	4	
Purchased power	11	
Self-produced fuel gas	32	50
Self-produced liquid fuels	5	
FCC coke	13	
Other	2	2

2.4. Identification of Levers for Reducing GHG Emissions

Several technological levers could be adopted by EU refineries to produce lower carbon aviation fuels (LCAF). In order to assess the technical potential of reducing the greenhouse gas (GHG) intensity of jet fuel, each lever was considered in isolation. The three broad categories of levers that are considered split between upstream and downstream operations are listed below.

2.4.1. GHG Emissions Reduction from Upstream Activities

For what concern upstream emissions, they can be summarized as follows:

- Upstream energy efficiency improvements and use of renewable energy: IEA suggests that energy consumption represents approximately 27% of GHG of upstream emissions. These emissions could be reduced by:
  - Implementing energy efficiency improvements, e.g., by using better/newer equipment and energy management;
  - Replacing fossil energy with renewable power from the grid or generated locally or using renewable heat.

There is limited data on the subject of use of renewable heat and power in upstream crude oil operations; therefore, this study assumes the technical limit of 100% replacement of energy-related emissions with biogenic or renewable emissions, and thus a GHG reduction of 27% is assumed.

- Flaring reduction: Approximately 14% of upstream emissions arise from flaring operations. Factors for reducing flaring include [30]: better operational management, particularly during start-ups, shutdowns and upsets; flare gas recovery for re-injection as fuel or gas export; flare gas recovery for local conversion to syncrudes (e.g., a modular Fischer–Tropsch process). A complete ban on flaring is technically achievable, therefore the technical potential for GHG emissions reduction is 14%. There is a "Zero Routing Flaring by 2030" aspiration supported by the European Commission, oil majors and national governments, but specific targets and regulations vary between countries.
- Methane emissions reduction: Methane emissions are the main source of GHG emissions in upstream crude extraction and production. A weighted average of 59% of total emissions could be considered. Reducing methane emissions can be achieved by several actions: eliminating "economic" venting and replacing it with flaring; eliminating fugitive emissions, e.g., from seals and purges; improving operational practices to avoid gas release, e.g., during well completion. A complete reduction in these emissions is technically feasible; therefore, the maximum GHG reduction accounts for the 59% of upstream emissions.

Another option sometimes proposed for lowering crude upstream emissions is the use of CO_2 for enhanced oil recovery (EOR): CO_2-EOR involves the injection of liquid

CO_2 into the reservoir where it mixes with the crude oil, making it more mobile—typically primary and secondary production recover only 40% of the oil. CO_2-EOR is an energy-intensive operation but its own emissions can be captured and used. On the other hand, it also involves recirculation of huge amounts of CO_2 and poses the risk of substantial fugitive CO_2 emissions. Whilst CO_2-enhanced oil recovery (EOR) can be applied in crude production, there is significant uncertainty as to whether the potential can be achieved and if all identified CO_2 storage sites are feasible. This is less of an issue when the focus is purely on oil-recovery than it would be if the main aim of CO_2-EOR was refocused from oil recovery to CO_2 mitigation. There is uncertainty about the number of suitable sites (geology, well design), the ability to store enough CO_2 and the fugitive CO_2 emissions from storage sites [31–33]. As a result, CO_2-EOR was not considered further for the purposes of this paper.

2.4.2. GHG Emission Reduction Applied Refinery-Wide

At refinery level, there are several options for lowering GHG emissions, in particular:

- Refinery energy efficiency improvement: Refineries need energy for distillation, to drive endothermic chemical reactions and to power pumps, compressors, lighting, heating, etc. On average, the energy demand is broadly equivalent to 6–7% of the crude intake, but it could vary between 4–5% for a simple refinery and between 8–9% for a complex refinery with more energy-intensive processes [29]. Much of a refinery's energy demand is satisfied by burning refinery by-products such as fuel-gas and low-value oils. Changes in product demand and product quality regulation impact both the refinery process intensity and energy use. Historically, the average energy efficiency of the EU refining industry has been improving by around 0.5% annually, driven by a combination of energy costs, national energy efficiency programs and carbon costs (e.g., under the EU ETS). Many of the lower-cost opportunities may have already been implemented, leaving only the more challenging and expensive options. However, there is still potential for efficiency improvements by 2050; limited by refinery design and economical deployment, this study assumes that 22% improvement might be technically feasible by 2050 [29].
- Renewable energy use: There are several ways in which renewable energy might be used to provide power and heat in a refinery; for instance, imported fossil power could be replaced by imported low-carbon power, either through decarbonisation of the electricity grid or by a dedicated low-carbon power source. Imported natural gas or fuel oil used to provide fired heat could be replaced by low-carbon fuels (e.g., biogas, low-carbon hydrogen). Conventional heaters fired using hydrocarbon fuels could be replaced by electrical heaters using low carbon electricity. The technical potential for the use of renewable energy assumes that all energy inputs other than those linked to unavoidable self-produced gas and FCC coke are replaced by zero-carbon energy. The technical limit for the average EU refinery to reduce CO_2 emissions by using renewable energy imports is roughly one-third.
- Refinery Carbon Capture and Storage (CCS): Nearly all a refinery's direct CO2 emissions could be captured, but implementation is hampered by the wide range of CO_2 sources in a refinery. This leads to either a multitude of CO_2 capture plants and large amounts of CO_2 pipework, or a large amount of infrastructure to gather flue gases for a centralised refinery capture unit [29,34]. While 100% of refinery CO_2 emissions could be captured (including all of the emissions associated with running the capture plant), a lower level of CO_2 capture would be expected. The JRC report [19] considers that CCS reduces the GHG intensity of SMR hydrogen from 104 to 39.7 gCO_{2eq}/MJ H_2—70% mitigation. This paper considers two CCS lever cases: in the first case the refinery deploys site-wide CCS but continues to import hydrogen without CCS; in the second case the refinery has its own SMR unit that is included within the site-wide CCS; the providers of imported electricity and steam are assumed not to have CCS in both cases. These two cases lead to a 64% and 83% reduction in refinery CO_2 emissions,

respectively. The reductions in refinery emissions have been used to adjust the overall WTW emissions, leading to overall potential for reduction of 4.6 and 5.7 gCO_{2eq}/MJ jet fuel for the two CCS lever cases, or reductions of 4.0 and 5.3%, respectively.

- Large-scale low carbon hydrogen: Hydrogen is used extensively in refineries for hydrodesulphurisation and hydrocracking, so the demand depends on the type of refinery and sulphur content in the processed crudes. Hydrogen production currently accounts for around 19% of refining emissions, which is expected to rise to as much as 30% by 2030 due to growing demand for hydrogen. The opportunities for local production of low-carbon hydrogen include onsite electrolysis using imported low-carbon electricity and importing third-party low-carbon hydrogen produced either by (a) steam methane reforming (SMR) of natural gas with CCS or (b) electrolysis. SMR with CCS is a known concept, but despite the fact that SMR is the main route nowadays to hydrogen production [35], CCS continues to represent a huge barrier to widespread deployment for SMR with CCS. Renewable hydrogen production is rapidly getting momentum, driven by several policy initiatives [36], but several technical and non-technical barriers regarding its production are still yet to be overcome. The technical limit of this lever is the fraction of a refinery's hydrogen supply that is made on purpose, i.e., in an SMR. On average, this fraction is between 50–60% of the total hydrogen demand, which makes up 19% of total refinery CO_2 emissions. All on purpose hydrogen can be supplied as zero-carbon energy using either SMR with full carbon capture (100%) or electrolysis using renewable electricity. As a result, refined GHG emissions could be reduced by 19% compared to the base case. This reduction in refining emissions is applied to the full WTW distribution, showing an overall potential for reduction of 1 gCO_{2eq}/MJ jet fuel or 1.0%.

2.4.3. GHG Emission Reduction Applied Specifically to Kerosene Production at Refinery Level

Jet fuel production is a hydrogen-demanding process. Today, jet fuel is mainly generated in Merox or kerosene hydroreating (KHT) units plus a smaller fraction (perhaps 20%) from hydrocracking units (HCK). The hydrogen consumption of both KHT and HCK units depends on feed quality, unit design and operation. Alternatively, to typical refinery hydrogen supply (mainly obtained from catalytic reforming unit (CRU) or made by steam methane reforming (SMR) of natural gas), the use of low-carbon hydrogen can deliver significant benefits.

Decarbonising options of KHT hydrogen include a dedicated KHT-scale SMR with CCS, by replacing the natural gas feed to the main SMR unit with biogas, or by a dedicated electrolyser to produce "green" hydrogen using low-carbon electricity. It might also be possible to replace the gas used to provide process energy by low-carbon energy, for example biogas from anaerobic digestion, or in the longer-term, electrical heating using low-carbon energy.

The achievable GHG savings depend on the relative GHG intensities of green hydrogen versus fossil hydrogen. This assessment assumes that the hydrogen supplied to the KHT can be treated as SMR hydrogen, and thus is taken to have a baseline WTT GHG intensity of 104 gCO_{2eq}/MJ H_2. Hydrogen produced by SMR with CCS has a WTT GHG intensity of 39.7 gCO_{2eq}/MJ H_2 whilst electrolyser hydrogen with renewable electricity is assumed to have a GHG intensity of 9 gCO_{2eq}/MJ H_2. Clearly these savings have to be properly allocated to the whole final fuels pool, in proportion to the hydrogen consumed for its production.

As sulphur reduction becomes more and more important for aviation, alterative processes could be considered to lower the impact of this stage. Merox processing (to change the type of sulphur compounds) is a low-intensity liquid-phase process that does not consume hydrogen, but requires process energy for liquid mixing, stripping, etc. There is growing interest in lower sulphur jet fuel, which could constrain the potential for adopting Merox more widely. Therefore, it is highly unlikely KHT users would opt

to switch to Merox as a GHG reduction measure; thus, Merox is not examined in any further detail.

A potential alternative approach for removing sulphur is adsorption where a solid is used to separate sulphur compounds from liquid hydrocarbon. The solid adsorbent is then regenerated for reuse, leaving a high-sulphur stream for further treatment. An example of this is the Phillips S-Zorb process where a handful of commercial plants have been constructed for gasoline desulphurisation. In principle, the technology can also be applied to distillates such as jet, but—to date—no commercial plants have been built. A critical issue is adsorbent regeneration, in which S-Zorb is performed using hydrogen. S-Zorb requires one-third to half the amount of hydrogen that is necessary for kerosene hydrotreaters. However, the data also suggest that S-Zorb's energy consumption is approximately double that of the kerosene hydrotreater. On that basis, the GHG implications look broadly comparable with KHT.

2.4.4. Methodological Frame and Results Boundaries

For each of the identified levers, technical potential for GHG reduction was calculated, which assumes that a technology is used to its engineering and scientific limits. It is worth remarking that the technical potential for GHG reduction of each lever is calculated independently. Economic feasibility is not specifically addressed in this work, but only considered qualitatively to derive high-level commentary on the deployment of these levers.

3. Results

3.1. Upstream GHG Emissions Reduction Levers

Table 4 summarises the potential for GHG emissions reduction for each of the upstream levers. The results highlight that methane control has significant potential to reduce the GHG emissions of jet fuel by as much as 5.6% in comparison to the baseline of 89.0 gCO_{2eq}/MJ of fuel. Assuming there is no interdependency between the levers, implementing all three could theoretically result in an emissions reduction of 9.5% compared to the ICAO benchmark, this falls just short of the 10% reduction required to qualify as a lower carbon aviation fuel.

Table 4. Summary of the technical potential of upstream GHG emission reduction levers.

Product WTW (gCO_{2eq}/MJ)	Base Case	Energy Efficiency Improvements	Flare Reduction	Methane Control
Crude production	8.4	6.1	7.2	3.4
Crude transport to market	0.6	0.6	0.6	0.6
Refining	6.0	6.0	6.0	6.0
Product distribution	0.8	0.8	0.8	0.8
Combustion (TTW)	73.2	73.2	73.2	73.2
Total WTW	89.0	86.7	87.8	84.0
Technical potential for GHG reduction	-	2.6%	1.3%	5.6%

3.2. Refinery GHG Emissions Reduction Levers

The potential for mitigation offered from the identified levers was estimated and is reported in Table 5. The results indicate that deployment of CCS has the greatest emissions reduction potential, with refinery-wide CCS reducing WTW GHG emissions by 5.6% compared to the ICAO benchmark of 89 gCO_{2eq}/MJ.

Table 5. Summary of the impact of general refinery GHG reduction levers on jet WTW emissions.

Product WTW (gCO_{2eq}/MJ)	Base Case	Refinery Energy Efficiency	Renewable Energy	CCS Excl. H_2 Production	CCS INCL. H_2 Production	Low-Carbon H_2
Crude production	8.4	8.4	8.4	8.4	8.4	8.4
Crude transport to market	0.6	0.6	0.6	0.6	0.6	0.6
Refining	6.0	4.7	4.0	2.2	1.0	4.9
Product distribution	0.8	0.8	0.8	0.8	0.8	0.8
Combustion (TTW)	73.2	73.2	73.2	73.2	73.2	73.2
Total WTW	89.0	87.7	87.0	85.1	84.0	87.9
% technical limit for reduction	-	1.5%	2.2%	4.3%	5.6%	1.3%

3.3. Jet Fuel-Specific GHG Emissions Reduction Levers

As presented in Table 6, jet fuel-specific GHG emissions reduction levers make only a small difference to the overall WTW GHG emissions of jet fuel, less than 1.5% compared to the ICAO benchmark of 89 gCO_{2eq}/MJ, in all cases.

Table 6. Summary of the technical potential of jet fuel-specific GHG emission reduction levers.

Product WTW (gCO_{2eq}/MJ)	Base Case	SMR-CCS H_2 to KHT	Electrolyser H_2 to KHT	Renewable Power to KHT	Alternative Desulphurisation
Crude production	8.4	8.4	8.4	8.4	8.4
Crude transport	0.6	0.6	0.6	0.6	0.6
Refining	6.0	5.3	5.3	5.4	4.7
Product distribution	0.8	0.8	0.8	0.8	0.8
Combustion	73.2	73.2	73.2	73.2	73.2
Total WTW	89.0	88.3	88.3	88.4	87.6
% technical potential for reduction	-	0.8%	0.8%	0.7%	1.5%

3.4. Summary of the Potential GHG Emission Reductions

Considering the GHG emission reductions for each lever outlined in Table 7, it is clear that taking each lever independently, no single one can reach the required 10% reduction even if deployed to its maximum technical potential. When deployed together there is interdependency, which means the individual GHG reduction potentials cannot simply be added together.

Crude production represents approximately 50% of WTT emissions. The general indication is that methane control may have the greatest potential to reduce total WTW emissions compared to the ICAO benchmark, perhaps as much as 5.6%, as shown in Table 7. There are real opportunities across all three upstream levers with many of the operational techniques already well-established for energy efficiency, use of renewable energy and flare reduction.

Levers to reduce the refining contribution occur at two levels: (a) refinery-wide measures that in principle affect all refined products, and (b) kerosene-treating levers that affect only jet fuel production. These both include energy efficiency and improved technology measures, use of low-carbon hydrogen, use of low-carbon energy and CCS. Refinery-wide CCS has the greatest technical potential to reduce jet fuel WTW GHG by 5.6%, assuming 100% CO2 capture. Refinery-based kerosene treatment is less intensive than other refinery processes, so kerosene specific-levers generally have less impact on the jet fuel WTW emissions, e.g., perhaps less than 1.5% reduction.

Table 7. Summary of WTW emissions of jet fuel arising from each lever, and the percentage reduction compared to the base case (ICAO).

	Lever	WTW Emissions (gCO_{2eq}/MJ)	% Technical Potential for Reduction
	Base Case	89.0	-
Upstream levers	Energy use	86.7	2.6%
	Flaring reduction	87.8	1.3%
	Methane emissions control	84.0	5.6%
Refinery-wide levers	Energy efficiency improvements	87.7	1.5%
	Renewable energy	87.0	2.2%
	Refinery-wide CCS excl. H_2 production	85.1	4.3%
	Refinery-wide CCS incl. H_2 production	84.0	5.6%
	Use of low-carbon hydrogen	87.9	1.3%
Jet fuel-specific levers	Use of low-carbon hydrogen in KHT (SMR-CCS or electrolyser H_2)	88.3	0.8%
	Use of renewable power in KHT	88.4	0.7%
	Alternative desulphurisation	87.6	1.5%

4. Discussion

The presented results show that current options for mitigating fossil-based kerosene are not able to achieve the expected CORSIA impact (10% saving) when considered independently. There is no single LCAF technology that can reach the required 10% reduction even if deployed to its maximum technical potential. When deployed together, interactions do not allow for simply adding together the expected GHG reduction potentials. Some of the refining levers are not truly independent; for example, improved energy efficiency reduces the use of imported energy and thus reduces the opportunity for deploying lower-carbon energy. To address this, the levers should be applied sequentially, with levers being applied to the energy/hydrogen demand resulting from the application of its predecessor; this as determined based on industry and policy trends, which were triangulated with CO_2 abatement cost and technical feasibility in 2030. In particular: (i) energy efficiency; (ii) renewable energy; (iii) low-carbon hydrogen (blue and green); (iv) refinery-wide CCS.

Following refinery efficiency improvements, renewable energy is likely to be the next lever deployed fully. In addition to broad decarbonisation measures, the RED II targets renewable energy specifically, requiring it to make up about one-third of the electricity mix by 2030. These targets are currently under revision, and they will likely be increased. Progress in policies and technologies have caused sharply falling costs of renewable electricity, contributing to rising renewable electricity shares. However, by 2030 the EU-average grid mix will not be completely renewable (estimated GHG intensity of 71 gCO_{2eq}/MJ [19]); therefore, access to lower carbon-intensity electricity would require dedicated renewable electricity capacity.

Despite significant momentum behind green hydrogen production, demand looks poised to surpass supply by 2030 without significant innovation and scaling up of electrolysers. The EU Hydrogen strategy [36] is expected to contribute to the rapid increase of green hydrogen production and to overcome several technical and non-technical barriers. Thus, this EU Hydrogen strategy aims to achieve the installation of at least 6 GW of renewable-powered electrolysers in the EU by 2024, and 40 GW by 2030. This depends on the availability of low-cost renewable electricity. Several projects are being funded in the EU to ramp up hydrogen production [37]. Blue hydrogen is likely to have a significant role in satisfying the growing hydrogen demand due to lower costs compared to green hydrogen, abundant gas and pre-existing infrastructure. The Clean Hydrogen Partnership

(former Fuel Cells and Hydrogen Joint Undertaking (FCHJU)) has estimated that blue hydrogen could reach 10% of demand in industrial application by 2030 [38].

Despite large expectations for a significant contribution from carbon capture and storage (CCS) to decrease greenhouse gas emissions, the large-scale deployment of CCS deployment is lagging. Several technologies are available for carbon capture and different storage options are available (enhanced oil recovery—EOR, depleted oil and gas fields, saline formations, porous rock formations, deep ocean, etc.). A few pilot and demonstration CCS projects have been developed worldwide, such as Weyburn, Canada; Aquistore, Canada; or CO2CRC Otway, Australia, that have proven the technology to be technically feasible [39]. In Europe, several demonstration projects were announced, but most of them were cancelled in the last years. There are only two operating CCS projects in Europe, Sleipner and Snøvhit in Norway, where CO_2 captured is reinjected into the offshore natural gas fields [40]. Roll-out of CCS is being currently delayed by high capital cost, high energy consumption (on the carbon capture side) and thus high costs and a lack of demonstration of technology. Other aspects that hinder CCS deployment are related to the large scale needed and the available geological storage capacity. [39,41]. CCS also requires infrastructure to transport CO_2 and favourable storage conditions for wide-spread deployment, as CO_2 leakages and safety on the storage side are other aspects to consider. This is important for wide-spread deployment. Capturing all CO_2 in a refinery is challenging due to the number of CO_2 sources. By comparing the Clean Hydrogen Partnership's estimation of blue hydrogen accounting for 10% of refinery demand in 2030, it is likely that the degree of CCS deployment across the whole refinery will be smaller.

In general, and regardless CORSIA-related initiatives (e.g., LCAF), refineries are already expected to implement such technologies to reduce their carbon impact: historically, refinery energy efficiency has improved by 0.5% per year, and refineries will continue implementing efficiency improvement measures until 2030. In terms of upstream emissions reduction, a 20% reduction in upstream emissions could be assumed for 2030 on the basis of the trajectory set by the Oil and Gas Climate Initiative's (OGCI) target to reduce upstream emissions by 13% between 2017 and 2025. The 20% comprises the easier to implement and cheaper technologies or measures. Some measures for upstream emissions are still in early stages of development and are therefore unlikely to be available for widespread deployment in 2030. The extent of deployment of the both general refinery and kerosene-specific levers depends primarily on the availability and cost of low-carbon hydrogen, CCS and renewable electricity, which ultimately depend on the specific policy support level.

5. Conclusions

In this work, WTW emissions for the EU refinery base case presented were based on the JRC WTT v5 study but adjusted to align with the ICAO benchmark: WTW emissions comprise WTT emissions and TTW combustion emissions, which account for 18% and 72%, respectively. This approach allows for focusing on the application of GHG emissions reduction levers to the WTT emissions, namely the upstream oil production and refining steps. In this study, we identified the possible "levers"—technological measures that can achieve GHG reductions—in light of the possibility offered by CORSIA lower carbon aviation fuels (LCAF):

- Upstream emissions account for 53% of WTT emissions and comprise flaring, energy use and methane emissions. Of the three, methane emissions contribute most significantly to upstream emissions and therefore have the greatest potential for emissions reduction. There are a range of measures that can be implemented to reduce emissions, some of which relate to new technologies or use of low-carbon energy sources whilst others are more focussed on changes to operation management, e.g., elimination of economic venting of methane.
- Refining emissions account for 38% of WTT emissions. At this level, several actions can be considered for reducing emissions: energy efficiency improvements, renewable energy, low-carbon hydrogen and CCS, which in theory have the technical potential to

mitigate almost all of a refinery's carbon emissions; exceptions might include short-term flaring for safety reasons. Considering the technical potential of these levers, it was found that CCS has the greatest potential to reduce refining emissions but faces a number of technical and financial barriers to wide-scale deployment.

This study shows that no one lever can reduce emissions to a sufficient level to meet the requirement of being a CORSIA-eligible fuel (10% saving on WtW basis), and therefore that the deployment of multiple levers is needed.

The results suggest that the extent of deployment of both the general refinery and kerosene-specific levers depends primarily on the availability and cost of low-carbon hydrogen, CCS and renewable electricity. Since jet fuel comprises only around 10% of total refining output, the LCAF measures could support the implementation of large, high-abatement cost changes, such as refinery-wide CCS that affect multiple fuels.

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Abbreviations

CCS	Carbon capture and storage
CEF	CORSIA-Eligible Fuels
CI	Carbon intensity
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EC	European Commission
EOR	Enhanced oil recovery
EU	European Union
FCC	Fluid catalytic cracking
GHG	Greenhouse gas
ILUC	Indirect land use change
ICAO	International Civil Aviation Organization
KHT	Kerosene hydrotreating
LCA	Lifecycle assessment
LCAFs	Lower carbon aviation fuels
LPG	Liquefied petroleum gas
OGCI	Oil and Gas Climate Initiative
RED	Renewable Energy Directive
SAFs	Sustainable aviation fuels
SMR	Steam methane reforming
TTW	Tank-to-wheel/wake/wing
WTT	Well-to-tank
WTW	Well-to-wheel

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