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Supply and sustainability of carbon offsets and alternative fuels for international aviation

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ABSTRACT

International aviation produced an estimated 490.4 million tonnes (Mt) of carbon dioxide emissions in 2013, about 1.5% of global CO_2 emissions from fossil fuel combustion that year, and as the role of aviation in the global economy expands, those emissions are expected to rise, to 682–755 Mt by 2020 and 1223–1376 Mt by 2035. The International Civil Aviation Organization (ICAO) has set a global aspirational goal that the industry's growth from 2020 onward be "carbon neutral" in terms of net CO_2 emissions. This paper focuses on two means to achieving this goal: the use of alternative fuels and a global Market-Based Measure (MBM) that would allow airlines to offset some of their emissions. We examine the potential supply of carbon offsets and of jet fuel alternatives from different biofuel pathways, and consider both climate benefits, and potential sustainable development impacts. We find that in 2020–2035, carbon offsets from project types for which there is high confidence in environmental integrity, and which also advance sustainable development goals, could yield emission reductions of around 3.0 Gt CO_2e, or 70–90% of ICAO's projected demand for emission reductions of 3.3–4.5 Gt CO_2e. Including project types with medium confidence in environmental integrity would expand the potential supply to 4.6 Gt CO_2e. Further expanding eligibility to project types with neutral development impacts would increase supply to 5.1 Gt CO_2e. Jurisdiction-scale REDD+ programmes could add another 2.4 Gt CO_2e of offsets. The potential supply of alternative jet fuels is subject to greater uncertainties, but we estimate that 0.1–0.3 Gt CO_2e of emissions could be avoided by using biofuels produced with little or no land-use change impacts and backed by strong sustainability certification schemes. Our analysis shows that ICAO can apply high environmental and sustainable-development standards to both carbon offsets and alternative fuels without compromising its 2020 "carbon neutral" goal.

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1. INTRODUCTION

International aviation produced an estimated 490.4 million tonnes (Mt) of carbon dioxide emissions in 2013, about 1.5% of global CO_2 emissions from fossil fuel combustion that year (IEA 2015a).[1] As the role of aviation in the global economy expands, international aviation emissions are expected to rise. Passenger bookings nearly doubled from 2004 to 2015, to 3.5 billion, and they are expected to rise to 6.63 billion by 2032 (IATA 2015a; ATAG 2014). Air freight flights are forecast to nearly triple, from 1.6 million in 2010 to 4.4 million in 2040 (ICAO 2013a). The International Civil Aviation Organization expects international aviation emissions to rise to 682–755 Mt by 2020 and 1223–1376 Mt by 2035 (ICAO 2013).[2]

The 191 ICAO Member States have agreed on a global aspirational goal that the industry's growth from 2020 onward be "carbon neutral" in terms of net CO_2 emissions. ICAO has identified several measures to achieve this: aircraft technology and operational improvements, alternative fuels, and a global Market-Based Measure (MBM) that would begin operations in 2020. Final approval of the MBM is expected at the 39th ICAO Assembly, to be held in Montreal on 27 September–7 October. Based on early drafts, it is expected that the MBM will provide for the purchase of emission permits and offsets from other sectors and companies.[3]

The eligibility criteria set by ICAO for both alternative jet fuels and carbon offsets will be critical to ensuring the environmental integrity of these measures and the achievement of the carbon-neutral goal. Both rely on indirect emissions reductions, and both entail risks. This paper examines how carbon offsets and alternative fuels can contribute to achieving ICAO's emissions stabilization target. We look at cumulative emissions for the period 2020–2035, and consider both climate benefits, and potential sustainable development impacts. Our goal is to inform the discussions in the lead-up to the ICAO Assembly.

1.1 The challenge of reducing aviation emissions

Greenhouse gas emissions from aviation have been a concern for at least two decades, but reducing them has proven challenging. The Kyoto Protocol calls for Annex I Parties (developed countries) to "pursue limitation or reduction" of emissions from aviation, working through ICAO (UNFCCC 1997 Article 2.2). In 2008, seeing little progress under ICAO, the European Union adopted legislation to include emissions from all flights from, to and within Europe in its Emissions Trading System (EU ETS). In 2012, the EU granted a temporary exemption, until 2017, for flights departing or arriving outside the EU, to allow ICAO sufficient time to develop its own emissions reduction plan. In October 2013, the ICAO Assembly resolved that ICAO and its Member States and airlines would work together to achieve a global aspirational goal of "carbon neutral growth" in international aviation from 2020.

As part of this process, ICAO established a series of working groups to develop proposals for the MBM. A draft resolution text has already been published to inform the negotiations, but the

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[1] Readers should note that this paper, like the political debate it is meant to inform, focuses entirely on emissions from *international* aviation. Global data on emissions from domestic aviation (flights within countries) are less readily available; however, the International Energy Agency estimates that in 2013, domestic and international aviation emissions combined amounted to 2.5% of global CO_2 emissions, and in 2040, domestic aviation will account for about 36% of total aviation emissions (IEA 2015b, p.127).

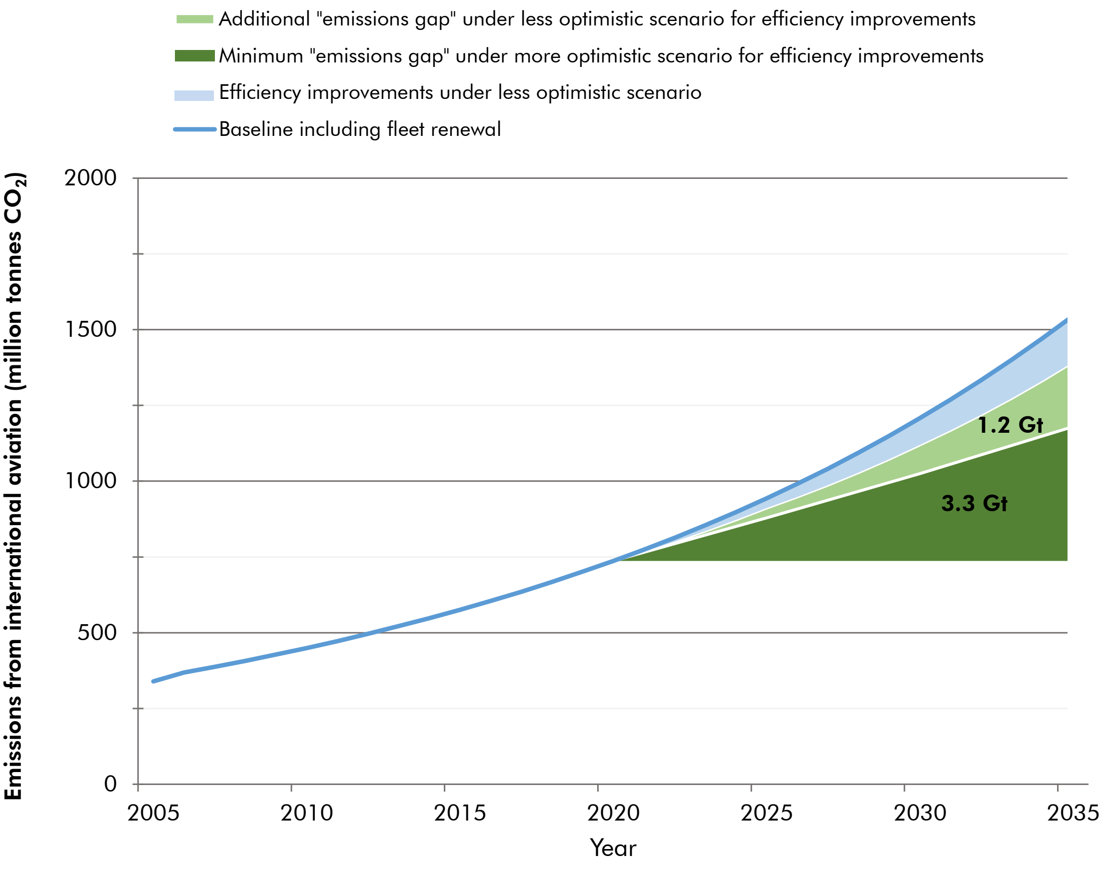
[2] ICAO is a specialized UN agency established in 1944 to manage the administration and governance of the international civil aviation sector. See http://www.icao.int. The emission projections reflect the range of possible reductions from technology improvements and operational efficiency under ICAO's central demand forecast.

[3] For an overview of the process, see: http://www.icao.int/environmental-protection/Pages/market-based-measures.aspx.

detailed rules that will govern offset and biofuel eligibility are being developed on a confidential basis within ICAO's Committee on Aviation Environment Protection.

The extent to which ICAO will need to rely on market-based measures and alternative fuels to meet its goal depends on two main factors: how fast international aviation grows, and how much improvements in aircraft technology and operations can reduce fuel use. ICAO's most recent projections estimate the "emissions gap" at 443–596 Mt per year in 2035 – the range between ICAO's most optimistic and least optimistic scenarios for technical improvements (ICAO 2016).[4] Based on these estimates for 2035 and the 682–755 Mt CO_2 range previously projected for total emissions in 2020 (ICAO 2013b), we estimate that ICAO's cumulative demand for offsets in 2020–2035 would be 3.3–4.5 billion tonnes (Gt) CO_2e, as shown in Figure 1. For reference, that is roughly equivalent to the Netherlands' or Pakistan's total greenhouse gas emissions in 2012.[5] These projections reflect a central estimate of a 4.6% annual growth rate in passenger and freight air travel (ICAO 2013b).

Figure 1: Projected cumulative ICAO demand for offsets, 2020–2035, in Gt CO_2



Data sources: ICAO (2016; 2013b).

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[4] ICAO's projections of efficiency improvements are based on compliance with air traffic control management systems, such as Next Generation Air Transportation System (NextGen) and Single European Sky ATM Research (SESAR), 1.5% per year fuel efficiency improvements for new aircraft, and 5–9% gate-to-gate fuel burn efficiency improvements (depending on route). ICAO's least optimistic scenario, which is more consistent with current trends in the aviation industry, assumes annual fuel efficiency improvements of 0.96% in 2010–2015, and of 0.57% per year in 2015–2050.

[5] Emissions data from the CAIT Climate Data Explorer: http://cait.wri.org.

1.2 Evaluating offsets and alternative fuels

As noted above, the MBM is likely to provide for the purchase of carbon offsets from other sectors of the economy. A carbon offset is a reduction in GHG emissions at one source or location made to compensate for emissions that occurred somewhere else. Under formal carbon offset programmes, such as the Clean Development Mechanism (CDM), Verified Carbon Standard (VCS), and the Gold Standard, a tradable offset "credit" is generated for each tonne of CO_2 equivalent that is abated by eligible GHG-reducing activities. These credits can then be purchased and retired by parties, such as airlines and ICAO Member States, to formally offset their emissions and contribute to achieving emission reduction goals.

Offsets can be produced through a wide variety of activities that reduce fossil fuel combustion and the resulting CO_2 emissions, or that avoid emissions of CO_2 or other GHGs from agriculture, industry and other sectors; reforestation and afforestation projects, which create carbon sinks, can also generate offsets. Typically, for a GHG reduction to be considered valid as an offset, it must meet criteria related to the eligibility of the activity that produced it and quantification and verification of the emission reduction.

Offset programmes apply standards and oversight to ensure such criteria are met. However, different types of mitigation activities can differ markedly in how well or easily they can produce GHG reductions that meet all criteria.

For this analysis, we have grouped offset project types by their ability to meet the quality criteria. All else being equal, higher confidence can be placed in the validity of offsets from project types that can more easily meet these criteria. As shown in Table 1, we also classify project types according to their potential for promoting multiple sustainable development goals: social, environmental, or economic benefits beyond simply reducing GHG emissions.

Table 1: Eligibility criteria for offset and fuel types for evaluating potential supply

Eligibility criteria	**Emission reductions**		**Sustainable development outcomes**	
	For offsets: Environmental integrity	For alternative fuels: Relative emission reduction potential	For offsets	For alternative fuels
Explanation	For offsets, relative confidence that claimed GHG reductions associated with a type of mitigation activity can meet essential criteria for offsetting emissions.	For fuel types, the relative performance of a given fuel pathway and feedstock in terms of reducing emissions compared with jet fuel.	For offsets, the expected relative contribution of a mitigation activity to broader sustainable development objectives.	For fuel types, the level of expected sustainable development co-benefits that could arise from fuel production and usage.
Relative rankings	Higher confidence Medium confidence Lower confidence	Lower range of emission reductions Upper range of emission reductions	Potential benefits Neutral effects Potential risks	

Alternative jet fuels can be derived from a range of bio-based feedstocks, including plant oils, starches and sugars, and trees and grasses. They may be purposefully grown on lands dedicated to biofuel feedstocks or derived from wastes and residues. These feedstocks may be processed through one of several processing methods ("pathways"), resulting in a "drop-in" fuel that very closely resembles kerosene-based jet fuel. The emission reductions from this substitution are typically defined on a life-cycle basis that accounts not only for emissions from fuel combustion, but also land use and other GHG impacts in recovery and extraction; transport of raw materials; refining and processing, and transport of the fuels (Stratton et al. 2010).

Emission reductions from biofuels vary by production pathway, feedstock, and fuel produced. The impacts of biofuel production on land use are of particular concern, as in some cases, the resulting emissions from land use change can fully negate the GHG benefits of replacing jet fuel with a biofuel. Our analysis draws on the biofuels literature to show the potential emission reductions from each alternative jet fuel feedstock and production pathway, and group them into "upper range" and "lower range" based on their relative performance. With regard to sustainable development outcomes, the main concern is whether ICAO can have confidence that specific feedstocks and production pathways are associated with sustainable development benefits beyond GHG emission reductions, and not with negative impacts (e.g. reducing food security or displacing rural populations). Several biofuel certification schemes have been established to ensure social and environmental sustainability; we review those schemes to evaluate the depth and breadth of coverage that each provides.

In the section that follows, we examine the potential use of offsets in the MBM; Section 3 then looks at alternative jet fuels. Both follow the same format: first, we define how the emissions reductions and sustainable development outcomes of each is assessed and how different types are classified; then we present our assessment of the available global supply. Section 4 synthesizes our findings and presents some options that ICAO may wish to consider.

2. CARBON OFFSETS

The purpose of the global Market-based Measure (MBM) is to close the gap between ICAO members' actual emissions from aviation, and 2020 emission levels, to achieve the goal of ensuring that all growth beyond 2020 is carbon-neutral. As noted in the introduction, based on ICAO estimates of 2020 emissions and of the gap to be filled in 2035, we estimate that ICAO's cumulative demand for offsets in 2020–2035 would be 3.3–4.5 Gt CO_2e, or about 0.2–0.3 Gt CO_2e annually on average.

There are two ways, in principle, to offset aviation emissions. One is to purchase and retire *allowances* issued under a variety of emissions trading systems, such as the EU ETS. The other is to purchase and retire *carbon offset credits*. Although retiring allowances can be an effective method for offsetting emissions,[6] the supply of allowances is limited by the very design of the ETS, and the terms of their use would need to be negotiated with the issuing entities. Thus, for this study we focus on carbon offset credits. Airlines are likely to have much freer access to offsets, as a variety of offset programmes exist to serve multiple markets, and in principle there is no limit to the number of credits they can issue. Moreover, the environmental integrity of carbon offsets can vary greatly, so the integrity of a MBM may hinge on the integrity of the offsets it allows to be used. Our analysis has two objectives:

1. To determine what a realistic global supply of carbon offsets could be in 2020–2035;
2. To determine whether ICAO can still meet its carbon-neutral growth goal if it limits carbon offset use to only those credits with higher integrity, defined in terms of both emission reductions and sustainable development benefits.

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[6] See Kollmuss and Lazarus (2010) for a discussion of issues associated with using allowances as a means to offset emissions.

There is no global system to evaluate the integrity of offsets, nor are there universal standards to do so. Each carbon offset programme establishes its own criteria, and then validates and certifies activities that meet those criteria, usually at the level of individual projects (e.g. a wind farm or a reforestation project). Common criteria, which we discuss further below, typically involve standards for quantification, verification and eligibility. However, different types of activities can differ markedly in how well or easily they meet these criteria. It is cheaper and easier to accurately measure and quantify the amount of methane destroyed by a flare at a landfill, for example, than the amount of carbon sequestered by a forest in any given year. For this analysis, we have grouped different offset activities, or project types, according to how easily they can meet fundamental offset criteria. All else being equal, higher confidence can be placed in the validity (or "environmental integrity") of offsets from project types that can more easily meet these criteria.

Some kinds of offsetting activities can produce social, environmental or economic benefits beyond GHG emission reductions – such as improving energy access or farm productivity. Others may have negative effects, such as displacing people, disrupting livelihoods, or destroying habitats – even if they still reduce GHG emissions. For this study, we have grouped project types according to their potential contributions to multiple sustainable development goals. Limiting offset purchases to categories of projects with a greater potential for co-benefits can help maximize the value of offsetting and contribute to a range of positive social and environmental outcomes.

After classifying offset project types based on these two criteria, we evaluate the potential future supply of offsets in each category, to determine how projected ICAO demand for offsets matches up with the likely availability of high-quality offsets.

2.1 Defining the relative environmental integrity of offset project types

The "environmental integrity" of an offset refers to how well it substitutes for a GHG reduction that would otherwise be made by the entity using the offset. Full environmental integrity is achieved when there is no difference in total net GHG emissions whether the entity procures an offset or reduces its own GHG emissions directly. To ensure environmental integrity, the providers of an offset must:

1. Demonstrate that the activity producing the offset is "additional";
2. Accurately and comprehensively quantify the effects of the activity on GHG emissions;
3. Regularly monitor and verify the activity and its effects;
4. Demonstrate an exclusive claim to the activity's GHG reductions; and
5. Guarantee the permanence of the activity's GHG reductions.

Below we explain each of the requirements in more detail. We also explain why some activity types may be able to meet them more easily than others. In all cases, it is the carbon offset programmes' responsibility to ensure that offset credits meet their standards. This generally entails providing mechanisms and procedures for independent verification of GHG reductions, certifying those reductions, and issuing offset "credits" that can be sold to buyers.

We focus primarily on requirements 1–3, because different project types have inherently different challenges and risks related to meeting these criteria, notwithstanding the rules and methodological requirements of carbon offset programmes. For requirements 4 and 5 (ownership and permanence), on the other hand, carbon offset programmes can ensure that these criteria are consistently met regardless of project type *if they adopt appropriate* *safeguards*. Where ownership and permanence concerns arise, ICAO may need to evaluate whether appropriate safeguards are in place.

Additionality

The *sine qua non* of an effective offset is that it be *additional* to any GHG reductions that would have occurred in the absence of demand for offsets. Activities that reduce GHGs may occur for a number of reasons: for example, a company may invest in energy-efficiency upgrades simply to save on electricity costs; a power plant may reduce emissions to comply with government regulations. When GHG reductions from these activities are counted as offsets, the act of purchasing them does nothing to actually change global emissions; total emissions would have been lower if the purchasers had reduced their own emissions instead. For a GHG reduction to be additional, demand for offsets must be a decisive factor in enabling the emission reduction activity. If a company or power plant did a major retrofit that would be infeasible without the sale of offsets, for example, the resulting GHG reductions would be considered additional, as they would not have occurred otherwise.

Though in principle, additionality is a simple concept, in practice it can sometimes be difficult to apply. All carbon offset programmes have rules and methodological procedures for making such determinations. However, none of these procedures is flawless, and one of offset critics' greatest concerns is that programmes certify too many GHG reductions as additional when they are really not.[7]

One way to reduce the risk of certifying non-additional offsets is to restrict eligibility to activities or project types that have a high likelihood of being additional. To put it in statistical terms, the chance of getting a "false positive" (certifying a non-additional project as additional) is much lower if a test is applied to a population with very few "true negatives" (actual non-additional projects). Although there are few activities (if any) that we can designate as categorically additional, or categorically non-additional, Table 2 offers some "rules of thumb" that we apply in Section 2.2 as one factor to help classify project types as higher-, medium- or lower-confidence with respect to environmental integrity.

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[7] See, for example, Schneider (2009a) or Lazarus and Chandler (2011a).

Table 2: 'Rules of thumb' for characterizing a project type's additionality risk

All else being equal, a project or activity type is likelier to be additional if…	All else being equal, a project or activity type is likelier to be non-additional if…
• The activity is not common practice • There are few or no reasons for undertaking the activity aside from generating GHG reductions • The activity produces no revenue streams apart from carbon offset sales • Carbon offset revenues are sufficient to cover the full costs of undertaking the activity	• The activity is common practice, or is considered "business as usual" in many contexts • There are often multiple compelling reasons for undertaking the activity, including cost savings or revenue generation from sources other than carbon offset sales • Other revenue streams associated with the activity are often significantly larger than the potential revenues from selling offsets • Potential carbon offset revenues cover only a small fraction of the activity's overall cost
Examples: • Destruction of N_2O from nitric acid production, in the absence of any legal mandate to do so; • Collection and flaring of ventilation air methane at operating coal mines.	Examples: • Construction of large-scale, fuel-efficient coal or natural gas power plants; • Fuel-switching projects where fuel cost savings exceed potential carbon offset revenues; • Large-scale wind energy projects (where regulatory and market conditions are favourable); • Transportation infrastructure projects (where total costs vastly exceed potential revenue from carbon offsets).

Quantification certainty

Environmental integrity also requires that the number of offset credits issued must not exceed actual GHG reductions. In general, the more uncertainty there is about how much an activity has actually reduced emissions, the less confidence we can have in the environmental integrity of the resulting offsets. It is possible to compensate for uncertainty by adopting conservative assumptions (that tend to undercount actual reductions), and most carbon offset quantification standards do this. But there are limits to how conservative one can be without undermining offset revenues and reducing incentives, so most standards strike a balance.

Three kinds of uncertainty can affect the quantification of offset GHG reductions:

- *Baseline uncertainty:* Offset reductions are quantified against a counterfactual baseline, which is an estimate of what GHG emissions *would have been* in the absence of the activity. For some types of activities, there are numerous plausible alternatives for what could have otherwise occurred, each with a different emissions profile. Where identifying a discrete and "most likely" alternative is difficult, uncertainty about baseline emissions – and therefore GHG reductions – will be relatively high.
- *Measurement uncertainty:* Some quantification uncertainties can arise simply because of challenges in measuring and monitoring emissions, or the processes that give rise to emissions. Projects that destroy methane, for example, can employ gas meters to accurately measure the amount that is destroyed. Projects that reduce fertilizer use in agricultural settings, by contrast, generally have to rely on complicated biogeochemical modelling to determine reductions in N_2O emissions.

- *Unintended indirect effects:* Activities that reduce GHG emissions at one source or location can sometimes have unintended effects that cause emissions to increase elsewhere. The classic example is protecting a parcel of forest and preventing emissions from logging, only to see the logging displaced to adjoining forest areas. Significant "leakage" effects can occur with many types of activities, including in the agriculture and bioenergy sectors.[8] Most offset quantification standards attempt to account for these kinds of effects, but because they are often difficult to observe, the actual volume of leakage can be subject to significant uncertainty.

For this analysis, we have factored these possible types of quantification uncertainty into our assessment of the relative confidence we can have in the environmental integrity of different project types. Project types that, because of their nature, have higher levels of inherent uncertainty will be ranked lower in terms of confidence.

Monitoring and verification

Closely related to quantification uncertainty are uncertainties that can arise from challenges in monitoring and verifying the performance of an emission-reducing activity. Projects can differ markedly in how easy it is to collect data to monitor their performance and outcomes. They can also differ significantly in how easy and cost-effective it is to review and verify monitoring data. Monitoring and verification challenges will track closely with difficulties in measurement uncertainties. For our analysis, we consider these two together in classifying the relative confidence in environmental integrity for different project types.

Exclusive ownership claims

For an offset to have environmental integrity, it cannot be counted more than once in service of an emission reduction claim. Double-counting and doubling-claiming can arise in many different situations.[9] A clear violation occurs if the same GHG reduction is used more than once as an offset, as could occur if two different programmes issued offset credits to the same project. Double-counting can also occur, however, if a GHG reduction used as an offset is also counted by another entity for meeting a separate GHG emissions goal. For example:

1. Double-counting will result if a GHG reduction at a power plant is used as an offset, but is also counted towards meeting a regulatory obligation (e.g. under a cap-and-trade programme);
2. Double-counting may also result if a GHG reduction is sold as an offset to a foreign purchaser, but is also reflected in a country's national inventory as contributing to the country's GHG reduction goals.

Different project types may have different risks for double-counting. It is easier to establish an exclusive claim to a GHG reduction at facilities one owns or controls, for example, than to a reduction that occurs elsewhere (as can happen, for example, when a renewable energy project displaces GHG emissions at power plants elsewhere on a grid). Carbon offset programmes, however, generally have rules and safeguards in place to ensure that double-counting and double-claiming are avoided, and that offset credits represent an exclusive claim to a reduction. For this reason, we have not tried to distinguish between project types based on double-counting and ownership concerns. However, from ICAO's standpoint, it may still

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[8] Leakage of emissions reductions from biofuel production and use, arising from indirect land use change, is discussed in detail further below in relation to sustainable alternative fuels (Section 3).

[9] For a full exploration of potential double-counting issues, see Schneider et al. (2015).

be worthwhile to scrutinize whether the safeguards established by different programmes are sufficient to address all possible circumstances where double-counting or double-claiming may occur. This is particularly true where countries have established GHG reduction commitments (e.g. under the Paris Agreement) and are still elaborating rules for how and when GHG reductions may be "transferred" to foreign parties.[10]

Permanence

When a tonne of CO_2 is emitted into the atmosphere, it can stay there indefinitely.[11] GHG reductions to offset those CO_2 emissions thus need to be "permanent" as well. This presents a challenge for mitigation activities that either sequester carbon or attempt to preserve terrestrial reservoirs of carbon, including reforestation, forest management, and various kinds of forest and soil conservation activities. Carbon stored in terrestrial systems can be emitted (back) to the atmosphere, effectively reversing any GHG reduction benefit.[12] This can occur, for example, if a forest used for offsets is affected by natural disturbances such as fire or disease, or if it is later harvested intensively.

Although reversibility is primarily a concern only for carbon sequestration and storage activities, like ownership concerns it can be addressed largely through rules and safeguards established by carbon offset programmes. A full exploration of these safeguards is beyond the scope of this analysis, but existing programmes generally take two approaches:

1. *Temporary crediting:* Under the UN Clean Development Mechanism (CDM), afforestation and reforestation projects are issued temporary credits. After a certain period of time (which varies depending on different options), offset credits issued to these projects will effectively expire. The party using these credits must then replace them, either with additional temporary credits, or with permanent credits from other project types. The advantage of this approach is that it effectively guarantees permanence. If a reversal occurs, a project will no longer be able to offer more temporary credits after existing ones expire, and holders of the credits must find permanent replacements. The drawback of this approach, in the eyes of many critics, is that it puts forestry and other carbon-storage credits on a different financial playing field, where purchasers effectively "rent" reductions rather than buying them.
2. *Insurance buffers*: All other offset programmes that allow terrestrial carbon storage projects insure against the risk of reversals by establishing a buffer reserve. Under this approach, a certain percentage of credits issued to each forest project (or to a jurisdiction, in the case of REDD+ programmes) is set aside in a buffer managed by the programme on behalf of all projects. When a reversal occurs at a project, it is compensated for by retiring credits out of the buffer. Most programmes effectively distinguish between reversals caused by natural disturbances (which are compensated) and those caused by human activity (for which landowners are usually

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[10] Article 6, Paragraph 5, of the Paris Agreement, for example, expressly forbids countries from claiming emissions reductions that have been officially transferred to another country, but leaves open questions about how such transfers can be reconciled with each country's nationally determined contributions.

[11] Some of the CO_2 in the atmosphere is slowly absorbed by carbon sinks, but about 40% of human-caused CO_2 emissions since 1750 are still in the atmosphere (IPCC 2014).

[12] Technically, a "reversal" occurs anytime GHG emissions are reduced below baseline levels and then subsequently rise *above* baseline levels. Although this can in theory happen with many types of activities, it is primarily a significant risk only for mitigation activities that sequester or store carbon in terrestrial reservoirs, such as forests and soils, which are subject to human and natural disturbances. (It may also be a significant risk for carbon capture and storage in geologic reservoirs, although this risk is harder to quantify.)

> held liable). The advantage of this approach is that, from the purchaser's standpoint, carbon storage credits are no different from any other type of credit (they cannot expire or be revoked). The disadvantage is that it is not a failsafe way to guarantee permanence; large reversal events, or events occurring far in the future,[13] may not be effectively compensated for.

Because existing carbon offset programmes (including REDD+ programmes – see below) have mechanisms to manage permanence where it is a concern, we have not factored reversal risks into our classification of project types by environmental integrity. That said, reversibility introduces a major factor affecting the potential worthiness of certain mitigation activities as carbon offsets, and ICAO may wish to closely scrutinize whether existing mechanisms to manage reversibility are truly sufficient.

2.2 Applying environmental integrity criteria to classify project types

As noted above, we have evaluated the relative environmental integrity of different offset project types based on how easily a typical project can meet criteria for additionality, quantification certainty and verifiability. This assessment considers *inherent* distinctions among project types, regardless of the quality of any standards applied to determine additionality, quantify GHG reductions, and verify project activities. We classify project types according to whether we have "higher", "medium" or "lower" confidence in their environmental integrity based on these inherent distinctions.

Several points should be kept in mind when interpreting the results. First, our rankings are relative. In principle, it is possible for *any* of the project types to generate truly valid carbon offsets – even those classified as having "lower" confidence for environmental integrity. At the same time, all carbon offsets are subject to at least some uncertainty.[14] We are confident that this uncertainty is *relatively* low for project types in which we have "higher" confidence for environmental integrity. Similarly, we are confident in the higher risks associated with project types classified as having "lower" confidence for environmental integrity. Within the "medium" category, however, there is a fairly wide range of relative uncertainty, and the dividing lines between "higher", "medium" and "lower" are not sharp or absolute.

Second, these rankings provide only a first-order screen for environmental integrity. Even project types classified as having "higher" confidence in environmental integrity can produce bogus carbon offsets if they are not subject to rigorous standards and procedures for additionality, quantification and verification. Further gradations of offset "quality" are possible based on the quality of the standards applied, and the rules and oversight mechanisms of carbon offset programmes. Regardless of any eligibility screens applied to project types, ICAO should fully vet existing programmes and ensure that offset credits are issued according to rigorous rules and procedures that are acceptable to it and its stakeholders.

Third, the rankings reflect a combined assessment of additionality and quantification/ verification concerns. Ratings on these criteria do not always correlate. There are some project types for which GHG reductions are relatively certain and easy to quantify, for

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[13] Several programmes limit liability for human-caused reversals to a finite period, e.g. 100 years, thus necessitating future policy interventions to compensate for ongoing reversal risk. It is also difficult to predict how well buffer reserves will function over the long term.

[14] Aside from possible measurement errors, some uncertainty is unavoidable because offset GHG reductions are quantified against a counterfactual scenario (a projection of "what would have happened otherwise") that cannot be directly verified and can never be 100 percent assured.

example, but for which additionality risks are relatively high (e.g. efficiency upgrades at fossil-fuelled power plants). For other project types, additionality concerns may be lower, but quantification uncertainties are higher (e.g. destruction of N_2O from adipic acid production). Both project types are classified as having "lower" environmental integrity. However, for some purposes ICAO might wish to consider these criteria separately – for example, excluding all project types with high additionality risks, but applying a more lenient approach to quantification risks (which are the primary concern in the agriculture, forestry and land use sectors, among others). We have not explored these kinds of possible distinctions in our rankings or supply analysis.

With these caveats in mind, we grouped project types as follows:

- *Higher confidence in environmental integrity:* These are project types with both low additionality risks and high relative quantification certainty. Project types that fall in this category must generally:
    - Meet all the criteria for having a high likelihood of additionality in the first column of Table 2;
    - Involve emissions that can be very accurately measured and quantified;
    - Have low baseline uncertainty;
    - Have low or zero risk of leakage effects;
    - Involve activities that can be directly and easily monitored and verified.

  Various types of GHG destruction projects typically meet these criteria (e.g. destruction of ventilation air methane at coal mines; destruction of HFC-23 emissions; destruction of N_2O emissions from nitric acid production). These project types have no other revenue streams, have costs that can be covered by carbon offset revenues, have high quantification certainty (because gas quantities can be directly and accurately metered or precisely determined), have no leakage effects (because they do not involve any market or activity displacement), and can be easily verified.

- *Medium confidence in environmental integrity:* These are project types where typically:
    - Many individual projects may be additional, but additionality is often context-dependent and challenging to determine; and/or
    - Measurement difficulties, baseline uncertainties, leakage effects and/or verification challenges make quantification relatively uncertain.

  A wide range of project types fall in this category, including most project types involving renewable energy and energy efficiency. Energy sector projects, for example, typically benefit from other revenue streams (either energy savings for efficiency projects, or direct revenue from energy sales for supply-side projects) and may be common practice in some contexts. In addition, although the performance of these kinds of projects can be directly monitored, they often reduce GHG emissions by displacing activity at other sources that can be difficult to monitor (e.g. power plants connected to an electricity grid). Because of this, baseline emission uncertainties can be significant. Leakage effects may also be a concern depending on the context (e.g. "rebound" effects associated with energy savings).

  Because of the higher levels of uncertainty involved (for additionality and/or quantification and verification), ensuring valid carbon offsets from these project types requires rigorous application of stringent standards and procedures. The actual environmental integrity of these project types can depend greatly on the tests used to determine additionality, the methodologies used to quantify and verify GHG reductions, and the rigor with which these are applied in practice.

- *Lower confidence in environmental integrity:* These are project types with relatively high additionality risks and lower quantification certainty. Typically, either or both of the following will be true:
    - Projects of this type will meet all the criteria for having a high risk of non-additionality, in the second column of Table 2;
    - There are measurement difficulties, baseline uncertainties, leakage risks, and/or verification challenges that produce a much wider range of uncertainty around GHG reduction estimates than for other project types. Although many uncertainties can be addressed by applying conservative assumptions to reduce the risk of “over-crediting”, for these project types substantially reducing such risk (to put them on par with “higher” integrity project types) will often make the projects financially unviable.

  Typical project types in this category include supply-side energy efficiency projects (where fuel cost savings often produce favourable returns and can significantly exceed the value of carbon offset revenues), and a variety of project types in the agriculture, forestry and land use sectors (where quantification is frequently more challenging because of the measurement challenges and complex interactions associated with biological systems). For this category of project types, valid carbon offsets are possible only if stringent carbon offset standards are rigorously applied.

Table 3 provides a summary of these classifications. Table 4 provides a detailed summary of our assessment and classification of broad project types currently found in the CDM (by far the largest offset programme in the world), as well as some unique project types found in other offset programmes.[15] Our assessments were informed by a review of available literature as well as our own judgement and experience from working with various offset programmes. As in any such assessment, judgement calls were required, and there are many potential details and context-specific situations that our classifications may gloss over. The goal here was to indicate general tendencies for the purposes of a supply analysis, and the results should not be interpreted as a definitive verdict on the environmental integrity of each project type.

Table 3: Offset project type categories, based on confidence in environmental integrity

Category	Definition
Higher confidence	Based on information available, there is relatively high confidence in the additionality and limited concerns related to the quantification certainty of offsets from this project type
Medium confidence	Available information raises some possible additionality and/or quantification concerns, but reasonable confidence is possible with sound methodologies of offsets from this project type
Lower confidence	Available information suggests that offsets from this project type are more likely to be non-additional or are subject to significant quantification and verification challenges

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[15] In particular, the CDM only recognizes a limited set of project types in the forestry and agriculture sectors; programmes such as the Verified Carbon Standard recognize a much wider array of activities in these sectors.

Table 4: Classification of offset project types based on relative confidence in their environmental integrity

Higher confidence

Project type	Sub-types included	Additionality	Quantification certainty
CO_2 usage	Use of CO_2 biomass or industrial tail gases to replace fossil or mineral CO_2 in industrial applications	No major additionality concerns; use of waste gas CO_2 (from biomass or industrial tail gas) in industrial applications is generally more expensive than alternative options	No significant quantification concerns; CO_2 displacement can be accurately measured and quantified under conditions specified in the appropriate methodologies
Coal mine VAM	Ventilation air methane	Likely to be additional, CDM revenue makes up a large portion of return on capital investment. (Cames et al. forthcoming)	Potential perverse incentives to dilute methane in order to avoid regulation requiring abatement (China) (Cames et al. forthcoming)
HFCs	HFC-23	Likely to be additional; abatement is not common practice nor required by regulation in developing countries; there are no economic incentives to abate HFC-23/N2O aside from carbon revenues (Cames et al. forthcoming)	Risk of perverse incentives largely addressed in revised quantification approaches (Cames et al. forthcoming) Perverse incentive to avoid domestic regulation or international regulation (e.g. Montreal Protocol) (Cames et al. forthcoming)
N_2O from nitric acid	Nitric acid production	Likely to be additional; abatement is not common practice nor required by regulation. There are no economic incentives to abate nitric acid aside from carbon revenues (Cames et al. forthcoming)	Little risk of over-crediting now that baseline accounts for technological innovations that reduce N_2O production (Cames et al. forthcoming)
Landfill gas	Landfill gas flaring and utilization	High likelihood of additionality (Cames et al. forthcoming); carbon revenues are a large share of profitability and projects are not common practice	High measurement certainty for methane quantities captured and destroyed. Some potential for baseline uncertainties, but most can be addressed through methodological corrections. Where methane is utilized for energy generation, some uncertainties arise regarding baseline for displaced emissions.
Methane avoidance	Including manure management, waste water, industrial solid waste, palm oil waste, aerobic treatment of wastewater, composting	Likely or highly likely to be additional; carbon revenues are a large share of profitability and projects are not common practice	High measurement certainty for methane quantities captured and destroyed. Some potential for baseline uncertainties, but most can be addressed through methodological corrections. Where methane is utilized for energy generation, some uncertainties arise regarding baseline for displaced emissions.

Medium confidence

Project type	Sub-types included	Additionality	Quantification certainty
Methane from coal production	Coal mine methane, coal bed methane	Carbon offset revenue can make up a large portion of return on capital investment (Cames et al. forthcoming); however, technical hurdles for these projects are no longer significant; significant levels of business-as-usual methane usage at mines in some countries	Potential concerns related to increased mining and/or pre-drainage of coal mine methane, leading to over-counting GHG reductions (Cames et al. forthcoming)
Energy distribution	District heating, connection to isolated grid, other	Additionality may be unclear in many cases; projects may be capital intensive and it is not clear that carbon revenues would be decisive for investment decisions	May be some uncertainty about avoided baseline emissions, but generally no major concerns
Energy efficiency – households, cookstoves	Improved cookstoves	Additionality can generally be demonstrated on a programmatic basis	Significant uncertainty and potential for over-crediting due to approaches used to estimate reduction in biomass fuel used with improved stove, fraction of non-renewable biomass (i.e. emissions associated with LULUC from biomass source), emissions factors for wood-fuel used in baseline, and suppressed demand use of fossil fuels (Lee et al. 2013)
Energy efficiency – households, other	Solar lamps, lighting insulation & solar, appliances	Additionality can generally be demonstrated on a programmatic basis; for some initiatives, it may be hard to show that carbon revenues were a decisive factor Concerns related to lighting efficiency (e.g. replacement of incandescent bulbs with CFLs) where efforts were already becoming common practice with national and local support schemes (Cames et al. forthcoming) Fewer concerns in lower income countries with less regulatory support for energy efficiency improvements (Cames et al. forthcoming)	May be some uncertainty about avoided baseline emissions, but generally no major concerns
Energy efficiency – services	HVAC, air conditioning, street lighting, water pumping and purification, energy efficiency of public stoves, energy efficiency of public and commercial buildings	Concerns related to lighting efficiency (e.g. replacement of incandescent bulbs with CFLs) where efforts were already becoming common practice with national and local support schemes (Cames et al. forthcoming) Fewer concerns in lower income countries with less regulatory support for energy efficiency improvements (Cames et al. forthcoming)	May be some uncertainty about avoided baseline emissions, but generally no major concerns

PFCs & SF_6		Additionality depends on specific project activity and facilities involved. In some contexts, measures for reducing emissions may be cost-effective without carbon revenues (USAID 2014)	No major quantification concerns
Hydropower – small-scale		Can face greater investment hurdles than large hydro projects; may not be common practice; however, there may be concerns similar to other types of renewable energy projects in terms of whether carbon revenues significantly affect profitability	Methane emissions not as significant a concern for small (run of river) hydro projects; however, significant uncertainties related to displaced grid emissions and concerns that baseline may be set too high for renewable energy projects, leading to over-crediting (Spalding-Fecher et al. 2012)
Renewable energy: solar and mixed – small		Generally not common practice; however, there may be concerns similar to other types of renewable energy projects in terms of whether carbon revenues significantly affect profitability	Significant baseline uncertainties related to displaced grid emissions; concerns that baseline may be set too high for renewable energy projects leading to over-crediting (Spalding-Fecher et al. 2012)
Municipal solid waste	Gasification and/or combustion of municipal solid waste	Likely or highly likely to be additional; carbon revenues are a large share of profitability, and projects are not common practice	Potential uncertainties related to avoided baseline methane emissions Potential uncertainties related to displaced energy emissions (similar to renewable energy projects)

Lower confidence

Project type	Sub-types included	Additionality	Quantification certainty
Agriculture & land use	Irrigation, energy efficiency, alternative fertilizers, rice crops, avoided conversion of high-carbon soils, low-till/no-till soil carbon sequestration, improved nitrogen fertilizer management	For individual farmers, reductions (and carbon revenues) are often too low to plausibly overcome economic and behavioural barriers; programmatic approaches may alleviate some of these concerns; irrigation, improved fertilizer management, and energy efficiency measures can often pay for themselves (without carbon revenue), although barriers may prevent efficient investments in some cases	Quantification of net GHG reductions in biological systems is inherently more uncertain than for many other project types; diverse and uncontrolled implementation environments make measurement, monitoring, and verification more difficult; risk of reversal (i.e. non-permanent reductions) is a concern for all carbon storage projects
Biomass energy – industrial waste	Bagasse power, palm oil solid waste, black liquor, forest residues, sawmill waste, industrial waste, biodiesel from waste oil	With support schemes in many jurisdictions, biomass power is increasingly competitive with fossil fuels without carbon revenues (Cames et al. forthcoming) Carbon revenues do contribute significantly to profitability in some projects where methane emission reductions are claimed (Cames et al. forthcoming)	Risk of exaggerated claims from methane emissions from anaerobic decay of biomass (Cames et al. forthcoming)

Biomass energy – other	Agricultural farm residue, forest residue, and dedicated energy crop	Documented concerns related to the barrier and investment analysis approach to assessing additionality used for the majority of biomass power projects (Schneider 2009b; Haya et al. 2009)	Large over-crediting concern due to lack of assessment of land use, as well as direct and indirect land use change from collection of biomass feedstocks (Cames et al. forthcoming)
Cement	Use of blended cements, process and efficiency improvements	Choice of cement blends is often determined by institutional purchasing or regulatory requirements, over which carbon revenues may have little influence; higher-blend cements are also often cheaper than standard blends (Loreti Group 2008)	Reasonable quantification certainty is possible; no major inherent concerns
Energy efficiency – industry		Many industrial efficiency projects pay for themselves and are common practice. Carbon revenues are generally small relative to cost reductions from energy savings. The pool of projects for which carbon revenues would make a decisive difference is small relative to already cost-effective (BAU) investments, leading to a greater likelihood of "false positive" additionality determinations.	May be some uncertainty about avoided baseline emissions, but generally no major concerns.
Energy efficiency – own generation		Carbon revenues are small relative to cost reductions from fossil fuel savings, large uncertainties in ex-ante estimates of investment costs and fuel savings, common practice in many (though not all) countries and sectors. (Cames et al. forthcoming; Lazarus and Chandler 2011b) Documented concerns related to the barrier analysis and investment analysis approaches to assessing additionality used for the majority of iron and steel waste gas projects (Schneider 2009b; Michaelowa 2009; Rong et al. 2011)	Potential over-crediting: in existing facilities where it is difficult to assess actual use of waste heat under baseline, in greenfield projects high uncertainties in modelling of baseline waste heat production. (Cames et al. forthcoming)
Energy efficiency – supply side	Cogeneration	Many cogeneration projects offer both energy savings and revenues; carbon revenues are generally small relative to energy revenues and cost savings; the pool of projects for which carbon revenues would make a decisive difference is small relative to already cost-effective (BAU) investments, leading to a greater likelihood of "false positive" additionality determinations	Baseline determination can be complicated and site-specific

Energy efficiency – supply side	Other	Carbon revenues are small relative to cost reductions from fossil fuel savings, large uncertainties in ex-ante estimates of investment costs and fuel savings, common practice in many (though not all) countries and sectors (Cames et al. forthcoming; Lazarus and Chandler 2011b) Documented concerns related to the barrier analysis and investment analysis approaches to assessing additionality used for the majority of iron and steel waste gas projects (Schneider 2009b; Michaelowa 2009; Rong et al. 2011)	Baseline may be set too high resulting in over-crediting (Spalding-Fecher et al. 2012)
Forests – afforestation and reforestation	Project-level afforestation/reforestation (including mangroves)	Frequent challenges in determining baseline activity, which may be highly site-specific; timber revenue value often exceeds carbon value, making it difficult in some cases to determine how and whether carbon revenues were decisive in changing baseline activity	There can be significant baseline uncertainties; measurement and quantification of forest carbon is subject to higher uncertainty than quantification of emissions in other project types; diverse and uncontrolled implementation environments make measurement, monitoring, and verification more difficult; displacement of existing land uses may lead to significant leakage (e.g., clearing of neighbouring forests)
Forests – avoided deforestation and degradation	Project-level avoided deforestation and degradation		
Forests – improved forest mgmt	Project-level improved forest management		
Forests – agroforestry	Agroforestry	Some challenges in determining baseline scenario, which may be highly site-specific; projects frequently face socio-cultural barriers, however, which may bolster additionality arguments	High baseline quantification uncertainties; diverse and uncontrolled implementation environments make measurement, monitoring, and verification more difficult; risk of reversal (i.e. non-permanent reductions) in all carbon storage projects
Fossil fuel switch		Carbon revenues small share of profitability, significant uncertainties in assessment of investment barriers to fuel switching (Cames et al. forthcoming; Schneider 2009b) Concerns that new natural gas projects are likely common practice and non-additional (Bogner and Schneider 2011; Wara and Victor 2008)	Over-crediting concerns due to lack of accounting for upstream emissions from fuels (Cames et al. forthcoming)
Fugitive gases	Other	Many oil and gas sector fugitive emission reduction activities are cost-effective without carbon revenues; the financial value of preventing fugitive emissions (e.g., in terms of reduced fuel losses) often exceeds the carbon offset value, meaning that carbon offset revenues only have a marginal effect on investment decisions	Fugitive emissions can be subject to high quantification uncertainty; accurate measurement techniques, where feasible, can be expensive (USAID 2014)
Geothermal		Unconventional renewables face greater financial hurdles than other technologies, and thus more likely to be additional. However, likely limited impact of carbon revenue on profitability.	Significant baseline uncertainties related to displaced grid emissions; concerns that baseline may be set too high for renewable energy projects leading to over-crediting (Spalding-Fecher et al. 2012)

N_2O – adipic acid	Adipic acid	Generally likely to be additional where not required by regulation; no other revenue streams are available to incentivize project activity	Demonstrated potential for over-crediting when offset prices are high (Cames et al. forthcoming)
Hydropower – large		Common practice in many countries, limited impact of carbon market revenue on profitability, competitive with fossil generation without carbon revenues (Cames et al. forthcoming) Documented concerns related to additionality assessment in large-hydro projects (Spalding-Fecher et al. 2012; Haya and Parekh 2011; Bogner and Schneider 2011; Au Yong 2009; Schneider 2009b)	Methodological concerns, including exclusion of methane emissions. (Cames et al. forthcoming)
Renewable energy – solar & mixed, large		Solar and unconventional renewables (e.g., tidal energy) face greater financial hurdles than other technologies, and thus more likely to be additional. However, there may be concerns similar to other types of renewable energy projects in terms of whether carbon revenues significantly affect profitability.	Significant baseline uncertainties related to displaced grid emissions; concerns that baseline may be set too high for renewable energy projects leading to over-crediting (Spalding-Fecher et al. 2012)
Transport		In general, the mitigation cost of transportation projects ($/ tonne CO_2 reduced) is well above current and historical prices for carbon offsets, calling into question whether carbon revenues can be a decisive factor in incentivizing these projects (Millard-Ball 2008) For transport efficiency projects, fuel cost savings often (substantially) exceed carbon revenues from avoided emissions, raising similar questions about additionality (Findsen 2009)	High levels of uncertainty in quantifying avoided emissions from public transportation, mode shifting, and vehicle scrapping/retirement projects. Reasonable quantification certainty for efficiency upgrades (notwithstanding baseline/additionality concerns).
Wind		Carbon revenues have a limited impact on profitability, declining investment costs have made wind more competitive without carbon revenues, and wind power now a common practice technology in large developing countries (e.g. China, India) (Cames et al. forthcoming) Documented concerns related to the claim that wind is not common practice and the use of investment analysis in the assessment of additionality for wind projects (Spalding-Fecher et al. 2012; Bogner and Schneider 2011; He and Morse 2010; Wara and Victor 2008; Schneider 2009b)	Significant baseline uncertainties related to displaced grid emissions; concerns that baseline may be set too high for renewable energy projects leading to over-crediting (Spalding-Fecher et al. 2012)

2.3 Sustainable development outcomes of offset project types

Many offset activities have the potential to contribute to sustainable development goals, including the goals of the UN’s Agenda 2030 (United Nations 2015). Offset activities can provide direct and indirect economic, environmental and social benefits, such as creating jobs, improving air and water quality, expanding access to energy, and improving the welfare of communities in general. However, some offset activities also have the potential for negative impacts, such as displacing local communities, perpetuating economic disparities, causing pollution, or disrupting habitats. For this analysis, we also consider activities that continue reliance on carbon-intensive fuels, such as projects that merely increase the efficiency with which these fuels are used, to have a negative contribution to sustainability.

ICAO may wish to screen offset projects to ensure that they produce sustainable development benefits, or at a minimum avoid harmful effects. To assess sustainable development impacts, we evaluated the potential effects of different projects types related to the UN Sustainable Development Goals (SDGs – see Box 1). We also reviewed criteria established under various sustainable development certification standards that apply specifically to carbon offset projects (Table 5).

Box 1: The UN Sustainable Development Goals (2030 Agenda)

1. End poverty in all its forms everywhere
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3. Ensure healthy lives and promote well-being for all at all ages
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5. Achieve gender equality and empower all women and girls
6. Ensure availability and sustainable management of water and sanitation for all
7. Ensure access to affordable, reliable, sustainable and modern energy for all
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10. Reduce inequality within and among countries
11. Make cities and human settlements inclusive, safe, resilient and sustainable
12. Ensure sustainable consumption and production patterns
13. Take urgent action to combat climate change and its impacts
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Source: United Nations (2015)

Table 5: Sustainable development certification standards used to guide our assessment

Programme	Description
The Gold Standard	Established in 2003 by WWF and other international NGOs as a sustainability certification programme for CDM projects. It now also approves and issues credits for voluntary projects that adhere to CDM standards. All Gold Standard projects must adhere to the following set of sustainability requirements: do no harm; enhance sustainable development; involve all relevant stakeholders; deliver real GHG emission reductions; be compliant with all relevant laws and Gold Standard Principles; be transparent; and be continually and regularly monitored, reported, and verified. Only a limited set of project types are eligible for Gold Standard certification, which includes energy, afforestation/reforestation, agriculture and water-related project types. In 2015, 9.9 million voluntary market offset credits and 2.0 million mandatory market offset credits through the CDM were issued with Gold Standard certification (Gold Standard 2016).
The Climate, Community & Biodiversity Standards (CCBS)	Offers rules and guidance for project design and development. It does not verify carbon offsets and is used in conjunction with another offset programme. CCBS focuses exclusively on land-based bio-sequestration and mitigation projects and requires social and environmental benefits from such projects. The standards were developed by the Climate, Community and Biodiversity Alliance (CCB Alliance) formed by representatives from CARE, Conservation International, The Nature Conservancy, Rainforest Alliance, and the Wildlife Conservation Society. CCBS projects must identify all stakeholders and ensure their full and effective participation; recognize and respect customary and statutory rights; obtain free, prior and informed consent; assess and monitor direct and indirect costs, benefits and risks; identify and maintain high conservation values; and demonstrate net positive climate, community and biodiversity benefits. The offset programme VCS has partnered with the CCB Alliance and taken over management of the CCB Standards to streamline the process for registering VCS+CCB projects and issuing VCS credits tagged with the CCB certification label. In 2014, out of the 19.1 million credits transacted under VCS, 12.6 million credits were certified with CCBS (Hamrick 2015).
Social Carbon Standard	Developed by the Ecológica Institute (Brazil) in 1998 as a complementary standard to assess co-benefits of projects used in conjunction with an offset programme such as VCS. Unlike The Gold Standard and CCBS, it does not have firm requirements for certification; instead it is a framework that can be applied to any project type to plan, monitor and evaluate project co-benefits. Social Carbon certification requires that projects use a transparent and participatory method of monitoring project co-benefits based on indicators related to six sustainability resource areas: social, human, financial, natural, biodiversity or technology, and carbon. In 2014, about 1 million Social Carbon-certified credits were traded (Hamrick 2015).

We categorized offset project types as having potential benefits, mostly neutral effects, or potential risks for contributing to the SDGs, based on the following criteria:

- *Potential sustainable development benefits with certification:* These project types can directly contribute to people's socio-economic well-being, have positive environmental outcomes (e.g. biodiversity preservation), and/or help alleviate dependence on fossil fuels – and have low risks for adverse social or environmental impacts. A number of project types fall into this category, including various types of demand-side energy efficiency, small-scale renewables, public transit projects, certain types of methane avoidance, and forestry projects. For example, these project types can help reduce local pollution, provide access to clean energy (SDG #7), contribute to economic growth (SDG #8), help build sustainable communities (SDG #11), or enhance biodiversity (SDG #15).

Note that, while all project types in this category have the *potential* to contribute to sustainable development, even many "good" projects can be implemented in ways that are disruptive to local stakeholders, promote inequalities, harm the environment, or have other adverse consequences that are at odds with the SDGs. Certain kinds of energy infrastructure or forest projects, for example, may have environmental benefits, but can also be implemented in ways that are disruptive to local communities. Ensuring that such projects are socially beneficial requires oversight to ensure that they are developed responsibly, in consultation with local communities and other stakeholders. Such oversight can be provided through the application of sustainable development certification standards, several of which have been developed for carbon offset projects (see Table 6). Ensuring positive outcomes may require certification against one of these standards.

- *Neutral effects:* Project types are classified as having neutral effects if they do not have significant potential to contribute to SDGs, but likewise have low risk of causing significant social, environmental or economic harm, and do not encourage dependence on fossil fuels. Project types in this category primarily consist of various kinds of industrial gas destruction and avoidance activities, as well as activities that reduce process emissions (such as reducing calcination emissions in cement production).
- *Potential sustainable development risks:* Project types are classified as having potential risks if they are frequently associated with negative social, environmental or economic impacts. We include projects involving fossil fuel production or usage, or which otherwise encourage continued reliance on fossil fuels, in this category. Examples here include fossil fuel switching, supply-side energy efficiency improvements involving fossil fuels, and reductions in methane emissions from the coal, oil and gas sectors. These offset project types have the potential to conflict with the SDG #12, to phase out "fossil-fuel subsidies that encourage wasteful consumption". Also included in this classification are large hydroelectric projects, since many of these have had adverse social and environmental impacts related to displacement of local residents and environmental degradation that have been difficult to mitigate. In particular, large hydropower projects have the potential to conflict with SDG #1.4, to "ensure that all men and women, in particular the poor and the vulnerable, have … access to … ownership and control over land"; SDG #6.6, to "protect and restore water-related ecosystems"; and SDG #8.4, to "decouple economic growth from environmental degradation".

Table 6 summarizes the results of our assessment, and indicates which project types are included in each classification. It also indicates the primary SDGs that could potentially be advanced (or hindered) by each project type. [16]

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[16] Note that because we are evaluating offsets projects, all project types are considered as contributing to "climate action" (SDG #13), notwithstanding distinctions between types that advance clean energy vs. those that continue reliance on fossil fuels. We therefore have not separately checked project types against this SDG.

Table 6: Potential sustainable development impacts of offset project types

Project types	**Primary SDG(s) this project type can help advance (✓) or hinder (×)**																
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Project types with potential sustainable development benefits with certification																	
Agriculture		✓				✓		✓				✓			✓		
Biomass energy – all forms							✓		✓			✓					
Energy efficiency – industry			✓				✓	✓	✓			✓					
Energy efficiency – households (incl. cookstoves)			✓				✓	✓				✓			✓		
Energy efficiency – services			✓				✓	✓				✓					
Energy distribution							✓	✓	✓			✓					
Forestry						✓		✓				✓			✓		
Landfill gas			✓				✓		✓								
Municipal solid waste							✓		✓								
Geothermal			✓				✓										
Methane avoidance			✓			✓	✓	✓				✓					
Renewable energy – wind, solar, small hydro			✓				✓										
Transport			✓						✓	✓	✓						
Project types with neutral effects																	
Cement																	
CO_2 usage																	
HFC destruction																	
N_2O adipic acid																	
N_2O nitric acid																	
PFCs & SF_6																	
Project types with potential sustainable development risks																	
Coal mine methane							×					×					
Energy efficiency – own generation							×					×					
Energy efficiency – supply side							×					×					
Fossil fuel switch							×					×					
Fugitive gases							×					×					
Hydro - large	×					×		×									

Note: For a list of the SDGs, see Box 1.

2.4 Assessing REDD+ and other forms of 'scaled-up' (non-project based) crediting

Our environmental integrity rankings are meant to be applied at the project scale, because all current carbon offset programmes evaluate activities and issue credits at the level of individual projects (or in the case of CDM, also as "programmes of activities", which administratively combine multiple projects). Crediting at the project scale is likely to persist for the foreseeable future. However, there is growing international interest in establishing offset crediting mechanisms that recognize activities undertaken at much larger scales, such as across a whole economic sector or an entire country or subnational jurisdiction.

Of particular interest in this context are crediting mechanisms for reducing emissions from deforestation and forest degradation (REDD+).[17] REDD+ mechanisms are designed to credit GHG reductions that result from slowing and stopping deforestation and forest degradation across an entire jurisdiction, often involving millions of hectares.[18] Although few REDD+ programmes are currently at the stage of issuing credits, several are under development around the world, including participants in the UN REDD Programme and pilot programmes participating in the World Bank's Forest Carbon Partnership Facility. In addition, general rules and procedures for REDD+ programmes have been agreed under the United Nations Framework Convention on Climate Change (UNFCCC), and Article 5 of the Paris Agreement explicitly encourages the development of REDD+ programmes.

There are a number of advantages to addressing deforestation and degradation at a jurisdictional scale, including:

- A REDD+ approach can more effectively address the underlying drivers of deforestation, rather than simply displacing them in time and space. If implemented appropriately, REDD+ programmes can have a much more comprehensive and sustained effect on carbon emissions.
- Related to this, REDD+ programmes avoid much of the leakage risk that plagues project-scale approaches to forest conservation and management, especially where deforestation drivers are localized. This reduces some of the quantification uncertainty otherwise associated with forest sector offset projects.
- Due to economies of scale, REDD+ programmes can deliver GHG reductions much more cost-effectively and in much higher volumes than individual projects.

At the same time, some of the same concerns that arise for project-scale forest and land-use activities also arise in the context of REDD+. As with projects, one of the biggest methodological challenges for REDD+ programmes is establishing an appropriate baseline (or "reference level") for quantifying GHG reductions. Although much work has been done at the international level to develop guidelines for establishing REDD+ reference levels, estimates of baseline deforestation are often subject to large uncertainties, especially over the long run. Thus, *baseline uncertainty* is still a significant concern for REDD+ relative to other types of offset activities – particularly given the potential for high volumes of credits to be issued. In addition, although *measurement uncertainty* related to forest carbon emissions can

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[17] The "+" in REDD+ can refer to two things: (1) inclusion of forest carbon enhancement activities, such as reforestation and improved forest management, that remove carbon from the atmosphere rather than simply avoid emissions; and (2) the inclusion of environmental and social safeguards, along with measures to improve the livelihoods of people living in forested areas, in contrast to programmes that might focus narrowly on stopping deforestation without consideration of larger social equity concerns.

[18] Some programmes use the REDD+ label more broadly to refer to project-level as well as jurisdiction-scale activities. Here we use the label to refer exclusively to jurisdiction-scale activity to avoid confusion.

be statistically reduced by averaging over large areas – and techniques for estimating forest carbon emissions are steadily improving – the measurement uncertainty associated with REDD+ programme emissions is still greater than with offset activities such as industrial gas destruction projects, where emission volumes are directly and precisely metered.

With respect to sustainable development, REDD+ programmes offer similar promises of improvement over project-based forestry activities. Done well and with proper safeguards, REDD+ programmes have the potential to transform rural economies in ways that respect indigenous rights, reduce poverty, and provide sustainable livelihoods for people living in and near forests. Done poorly, REDD+ programmes could exacerbate economic disparities and political tensions, displace rural communities, and cause other adverse social and environmental outcomes. Much of the international deliberation on REDD+ programmes has focused on setting up social and environmental safeguards to avoid these kinds of negative outcomes. However, it remains to be seen how effective these safeguards may be in practice.

Because REDD+ programmes are still nascent, and they are qualitatively different from traditional project-based crediting mechanisms, we have not assigned them an explicit classification for environmental integrity or sustainable development benefits. Instead, we provide separate estimates of the volume of credits potentially available from these programmes if they move forward as expected. As with certain type of project-based forestry, land use, and agriculture activities, there may be policy reasons for ICAO to consider REDD+ credits. ICAO may wish to scrutinize the results from current pilot programmes before committing to this option, in terms of both environmental integrity and sustainable development safeguards.

Finally, there is some growing international interest in applying jurisdiction-scale offset crediting approaches to sectors besides forestry, including industrial and energy sectors. Article 6 of the Paris Agreement arguably leaves the door open for such approaches, even if it does not explicitly acknowledge them. “Scaled up” crediting mechanisms for other sectors, however, are much less developed than REDD+ programmes, and it remains to be seen what their methodological rules and requirements will be. For this analysis, we assume that scaled-up crediting in other sectors – should it be adopted – will not fundamentally change the relative rankings of environmental integrity for different types of activities. Instead, we take into consideration the prospect for higher credit volumes associated with this approach in our projections of potential supply.

2.5 Future global supply potentials of carbon offset credits

Our assessment of the global supply of carbon offsets looks at both supply that could arise from *existing* projects registered under currently established offset programmes (including the CDM), as well as supply from potential *new* projects (or scaled-up crediting mechanisms) that could be implemented in the future. Discussion of our approach and results for quantifying the supply of offsets from existing vs. future projects is included in the sections below.

Potential supply from existing and currently registered offset projects

We estimated the supply of offsets from existing projects based on the number of the projects currently registered under various programmes, and the volume of offsets expected to be generated from these projects. We considered projects under the CDM, Verified Carbon Standard (VCS) and The Gold Standard; Table 7 provides brief profiles of the three.

Our supply estimates include offset credits that could potentially be issued between 2017 and 2035. This assumes that credits issued prior to the initiation of the MBM could be banked and used by airlines (and that no major sources of competing demand for offsets will deplete the supply of credits issued between 2017 and 2020).

Table 7: Carbon offset programmes included in this assessment of potential supply

Programme	Description
Clean Development Mechanism (CDM)	The CDM was established under the Kyoto Protocol to allow industrialized countries to help meet their GHG reduction commitments through investments in mitigation projects in developing countries. The offsets generated through CDM projects are called "certified emission reductions" (CERs); to date, roughly 1.6 billion CERs have been issued. The CDM is by far the largest carbon offset programme in the world, and has established sets of standards (or "methodologies") for many different types of offset projects. CDM standards distinguish between large- and small-scale projects, and also include a mechanism for aggregating projects to streamline their evaluation and certification (referred to as "programmes of activities", or PoAs). Since the end of the first Kyoto Protocol commitment period in 2012, demand for CDM offsets has declined precipitously. However, many projects are still actively registered and continue to generate CERs. The CDM's sister programme, Joint Implementation (JI), certifies offsets from projects in countries with GHG reduction commitments under the Kyoto Protocol. Because of its smaller volumes and uncertainties about the future status of JI projects, we did not include JI in our supply estimates.
Verified Carbon Standard (VCS)	The VCS is the world's largest *voluntary* carbon offset programme. It mostly serves demand from buyers choosing to voluntarily offset their emissions outside of any regulatory programme (i.e., mostly corporations and individuals with their own voluntary GHG reduction targets). The VCS recognizes and applies offset standards from a variety of other programmes, including the CDM. The majority of VCS projects follow CDM standards. However, the VCS has also adopted its own methodologies for project types not found in other programmes, mostly in the agriculture and forestry, such as project-scale forest conservation and management activities. To date, the VCS has issued about 185 million credits (called verified carbon units, or VCUs).
The Gold Standard	The Gold Standard is the second-largest voluntary carbon offset programme with global coverage. It began as a sustainability certification programme for CDM projects, but it also approves and issues credits for voluntary projects that adhere to CDM standards.[19] It recognizes a more limited set of project types than the CDM (i.e., those considered to contribute most to sustainable development goals), and includes additional requirements for sustainability and stakeholder consultations. To date, The Gold Standard has issued about 47 million voluntary market offset credits (termed "voluntary emission reductions", or VERs).

We used the results from Cames (2015) for estimates of offset supply from registered projects under the CDM. Cames, however, did not include estimates of supply potential from CDM

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[19] Some project developers choose to apply CDM standards but sell credits into the voluntary market rather than the official CDM market. This has become more common since prices for CDM credits declined dramatically after the end of the first Kyoto Protocol commitment period in 2012.

PoAs. We applied the same estimation methods as Cames (2015) to quantify the volume of offsets expected to be generated under currently registered CDM PoAs. For VCS and Gold Standard projects, we applied the same methods, assuming these projects will generate credits at approximately the same rate as projects of the same type under the CDM. This assumption is reasonable given the similarity in methodologies and protocols used. Some existing offset projects are registered with both the CDM and either the VCS or Gold Standard. Projected supply from these projects is included in our supply estimates for the CDM.

Our analysis assumes that all currently registered projects will continue to generate offset credits based on historical issuance rates. However, two caveats on this assumption should be noted. First, future mitigation policies in countries where current projects are located could compromise their ability to continue to generate credits, especially over the longer term (see discussion below, under supply projections for future new offset projects). Current CDM policies allow projects to receive credits even if they are required by new laws or regulations, as long as the laws were established after the creation of the CDM. But these policies may not continue indefinitely.[20] Likewise, the host countries for these projects may wish to discontinue credit issuance in order to claim their GHG reductions for their own domestic goals. For this analysis, we assume that current CDM policies will hold for all existing projects, and that host countries will accommodate their ongoing credit issuance with mechanisms that transparently avoid double-counting.

Second, carbon offset markets have stagnated worldwide over the last few years. Flat to modest growth in the voluntary offset market and in some regional compliance markets (e.g. China, Korea, California) has been overshadowed by a deep fall-off in demand for CDM credits (Borkent et al. 2015). Under current market conditions, many CDM projects have ceased generating credits. It is possible that many of these projects could drop out of the market entirely, thus lowering future supply potential. However, so far we have not seen indications that projects are ceasing operation or deregistering in large numbers (some are in fact switching over to either the VCS or Gold Standard to sell credits in the voluntary market). Expectations of future demand, such as what could arise under the MBM, may be sufficient to keep these projects in the market. We have therefore not made any downward adjustments to our supply projections.

Finally, our analysis also considers the volume of offsets that are currently certified by a sustainability standard. We include only currently certified projects in our totals for project types classified as “potential benefits”. That is, we conservatively exclude uncertified projects, even though these projects could in principle seek certification in the future.

Potential supply from future new offset projects

As noted above, current market conditions have led to a retrenchment in offset project registrations and relatively low issuance rates for offset credits. Nevertheless, future growth in demand could spur new investment in offsets, leading to additional project registrations and new sources of credits under the CDM, voluntary programmes, regional programmes, and possible new international crediting mechanisms.

Estimating potential offset supply from yet-to-be-registered projects is subject to significantly more uncertainty than the prospective supply from currently registered projects. A whole range of technological, economic, policy and institutional factors could affect how many

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[20] See, for example, Spalding-Fecher (2013).

offset reductions are able to be generated and brought to market. One way to bind the potential supply of GHG reductions is to look at estimates of the reductions that will be needed globally to avoid a 2°C increase in temperature. The Intergovernmental Panel on Climate Change (IPCC)'s latest summary of modelling studies, for example, suggests that global reductions on the order of 24 Gt CO_2e *per year* (relative to "business as usual") may be needed by 2030 in order to stay on a 2°C pathway (Clarke et al. 2014). This suggests that the *potential* for GHG emission reductions is quite large, notwithstanding the challenges associated with actually achieving them.

There are many reasons to believe, however, that the future potential supply of *offset credits* will be much lower than the global technical potential for GHG reductions. At least four interrelated variables could significantly influence the potential future supply of offsets:

1. *Institutional capacity:* To be available for airlines to use, offsets must be quantified, verified and certified by established programmes. Required programmatic infrastructure includes an administrative body to, among other things, establish protocols, standards and eligibility criteria; review and approve projects or activities, train and oversee verifiers; issue and track the transfer and retirement of credits; and otherwise enforce programme rules and requirements. Administrative resources and staffing levels, along with the nature and complexity of applied standards, can be an important limiter on the number of offset credits that can be issued over time. In addition, offset programmes generally rely on third-party, independent verification bodies to help validate the conformance of projects with required standards and to verify the quantity of GHG reductions they achieve. The availability, capacities, and competency of these verification bodies can also significantly constrain rates of offset project registration and credit issuance.

2. *Future policies to reduce emissions and double-counting concerns:* Under the Paris Agreement, nearly all countries have pledged to reduce GHG emissions. In many cases, these pledges have yet to be translated into explicit policies and mitigation actions. Collectively, they also fall far short of what is needed to avoid a 2°C increase in global temperature. However, future GHG reduction mandates could significantly restrict the supply of potential offsets, which generally must consist of reductions that are voluntarily undertaken, not legally required, and not double-counted against a country's GHG mitigation goals. Depending on the nature of a country's policies, offsets may be effectively precluded even where the country could do more to reduce GHG emissions. For example, a clean energy target could set goals for domestic renewable generation that fall short of the country's theoretical potential – but until the target is reached, it may be untenable to declare that a particular installation is "additional" to the country's mandate and therefore eligible for producing offsets. Even where additionality is not a concern, issuing offsets may not be possible because the emission reductions would be double-counted. The CDM, for the most part, has never faced these constraints, because developing countries were not expected to undertake binding mitigation actions. After the Paris Agreement, the conditions under which offsets can be legitimately generated may be murkier and more constrained.

3. *Other sources of offset demand:* One big question coming out of the Paris Agreement is the extent to which countries will rely on market mechanisms, including offsetting mechanisms, to help meet their mitigation pledges. Article 6 of the Agreement contemplates the establishment and formal recognition of emissions markets, but their exact nature – and the level of countries' participation in them – are yet to be

determined. If a significant number of countries choose to rely on international offsetting mechanisms, or if they establish domestic offsetting programmes, their demand for offsets could compete with the airline industry's. This could effectively restrict the supply available to the airlines and drive up offset prices. At the same time, however, significant new global demand for offsets could encourage the development of more institutional capacity to process projects and issue credits (see #1). The establishment of a new global policy regime for offsets could also help clarify the conditions under which offsets can be validly generated in the context of domestic mitigation pledges (see #2). The airline industry could benefit from both of these developments. On balance, therefore, we think moderate levels of competing demand would generally enhance the potential supply of offsets available to airlines.

4. *The nature of future crediting mechanisms:* To date, offset programmes have largely pursued a model of crediting individual mitigation projects. Projects can vary greatly in size – and, under the CDM, may be combined for evaluation under larger PoAs – but the focus has still been on projects as the primary unit of evaluation and source of emission reductions. In the future, this may change. As noted above, international negotiators have contemplated the establishment of "scaled-up" crediting mechanisms that could, for example, credit GHG reductions across whole sectors of a country's economy. A relatively well-developed example is REDD+ mechanisms, which are being designed to credit national-level reductions in emissions from deforestation and forest degradation. The same concept could in principle be applied to other sources of emissions, including a country's energy or industrial sectors. Article 6 of the Paris Agreement arguably leaves open the door for such mechanisms, but much more work is required to determine how they would operate and be recognized. Without sufficient prospects for demand (see #3), they may never be realized. However, if such mechanisms are established, they could greatly increase potential offset supply and in theory overcome some of the institutional bandwidth issues that have limited supply in the past (see #1).

Table 8 summarizes these various factors and their expected effects on future offset supply.

Table 8: Factors driving the potential future supply of offsets

Variable	Effect on supply	Explanation
Institutional capacity (offset program bandwidth)	Limit	Future supply potential could be limited by the capacity of offsets programmes to process projects and issue credits.
Existing and new mitigation pledges and policies + double-counting concerns	Limit	Policies implemented worldwide to reduce GHG emissions under the Paris Agreement may reduce the remaining supply of potential reductions, and introduce double-counting challenges that could make counting GHG reductions as offsets untenable.
Competing demand for offsets	Limit or expand	New global demand for offsets (e.g. under new international market mechanisms) could compete with demand from the airline industry. However, this demand could also encourage development of offset program capacity and clarify rules for distinguishing potential offsets from policy-mandated GHG reductions.
New offsetting mechanisms	Expand	"Scaled-up" crediting approaches, including REDD+, could substantially increase potential supply and overcome historical institutional capacity constraints.

For this analysis we assume that there will be limited development of new international offsetting mechanisms, that mitigation pledges will cover GHG emissions in many high-value sectors, and that a significant portion of global demand for offsets will come from an ICAO MBM. One implication of the latter assumption is that the institutional bandwidth of offset programmes is likely be a primary determinant of future offset supply for ICAO, since there will be only modest exogenous demand to drive investments in their capacity. Thus, we estimated future potential offset supply (excluding REDD+ supply) using the following assumptions:

1. Institutional capacity will be the largest limiting factor on future offset supply. We modelled this by assuming that, starting in 2020, carbon offset programmes around the world could collectively (if responding to sufficient demand):

    - Register new projects at a rate equal to the highest annual average rate of project registrations under the CDM (about 3,000 projects per year, in 2012);
    - Issue credits to new projects at a rate equal to *twice* the highest annual rate of issuance under the CDM (about 700 million credits per year, which is slightly more than twice the number of CDM credits issued in 2012).[21]

    We assume that both of these potential limits could increase by 5% per year as programmatic capacities are expanded in response to demand. Under these assumptions, the maximum rate of credit issuance quickly becomes the binding constraint on offset supply. This constraint is expected due to challenges in ramping up administrative capacities to train, accredit and oversee project verifiers; review project verification reports, and issue credits, as well as potential limits on the abilities of verification bodies to ramp up their capacities and staffing levels to conduct verifications.

    In the face of high levels of demand, it is entirely possible that programmatic capacities could grow more quickly than we assume here; we therefore believe these basic assumptions provide a conservative constraint on the upper limits of supply availability.

2. The predominance of different project types that get implemented will largely mirror the proportions of project types that have been registered under the CDM to date, with some adjustments. Specifically, we assume that:

    - Projects involving HFC-23 destruction, and N_2O destruction at nitric and adipic acid plants, will be unavailable due to most countries regulating these emission sources.[22]
    - The *proportion* of projects in energy supply and distribution (including renewable energy projects), as well as demand-side energy efficiency, will be reduced by three-quarters due to a higher prevalence of mitigation pledges and policies throughout the world covering GHG emissions in these sectors. (This means that offset supply will be proportionally greater in non-energy sectors, subject to the bandwidth constraints in #1.)

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[21] This would be above and beyond any credit issuances to *existing* projects, estimated in the prior section.

[22] Compared with other industrial gases (and other sources of GHG emissions generally), these sources are administratively easy to regulate and mitigation is relatively inexpensive.

3. Demand choices from airlines will not significantly change the distribution of project types that are implemented. If airlines choose to restrict offset purchases to certain categories of offsets, then a greater proportion of investment could shift to those project types, increasing supply from those categories. However, we assume there will be moderate levels of demand for offsets from other sources (e.g., domestic and international emissions trading programmes), such that overall patterns of investment and supply (serving all markets) would be as described in #2. In other words, we assume credits issued to project types rejected by the airlines would be "picked up" by other markets, subject to the overall supply limits described in #1.
4. The number of credits issued to each new project registered would be roughly equal to historical rates of issuance under the CDM, specific to the project's type.
5. We assume there will there will be limited implementation of "scaled up" crediting mechanisms, other than REDD+.

Taken together, we believe these assumptions provide a conservative estimate of *potential* new offset credit supply from non-REDD+ sources over the 2020–2035 period.

To estimate potential REDD+ credit supply, we consulted various estimates in the available literature on REDD+. Lubowski and Rose (2013) cite a range of modelling studies suggesting *annual* credit supply potential in the range of 1.5–3.0 Gt CO_2e at a price of US$20–30/tonne. As the authors note, however, these estimates are almost certainly too high, because they do not take into account various kinds of transaction costs, implementation constraints and institutional barriers. A more recent study suggests a more realistic programmatic (i.e., jurisdiction-level) REDD+ supply potential in 2020–2025 of between 35 Mt CO_2e/year, for supply from existing REDD+ programmes, to around 325 Mt CO_2e/year, from more speculative programmes (Linacre et al. 2015). For the purpose of this analysis, we assume a conservative mid-range estimate of 150 Mt CO_2e/year on average over the 2020–2035 period, resulting in a cumulative potential supply of 2.4 Gt CO_2e.

2.6 Analysis of global future carbon offset supply potential

Our analysis suggests that the total cumulative global supply of carbon offsets in 2020–2035 could be as high as 28.8 Gt CO_2e. This includes about 11.6 Gt CO_2e that could potentially be issued to currently registered offset projects between 2017 and 2035, plus another 14.8 Gt CO_2e that could be issued to potential new projects between 2020 and 2035. An additional 2.4 Gt CO_2e of offsets could come from jurisdiction-scale REDD+ programmes over 2020–2035. These numbers reflect conservative assumptions about future rates of credit issuance, the capacities of carbon offset programmes to register new projects and issue credits, future development of international policy and crediting mechanisms (which may limit supply), and the potential volumes of GHG reductions that could be achieved by REDD+ programmes.

A potential supply of 28.8 Gt CO_2e would far exceed our projections of offset demand under an ICAO MBM in that time frame, 3.3–4.5 Gt CO_2e. However, setting aside the question of what other demand there might be for those offsets, there could be good reasons for ICAO to narrow down the offset supply by through its own eligibility standards. ICAO could choose to screen project types by relative confidence in their environmental integrity, by their expected sustainable development impacts, or both. Table 9 presents potential supply estimates using different combinations of these screens, based on the classifications and analysis described above. Table 9 also indicates which project types fall into each combination of possible screening criteria (i.e., higher, medium or lower confidence in environmental integrity, and potential benefits, neutral, or potential risks for sustainable development impacts).

Because REDD+ programmes are still nascent and have yet to fully demonstrate either the relative environmental integrity of their offsets or their potential sustainable development benefits, we have not included REDD+ supply in the screening options presented here. However, we conservatively estimate that REDD+ programmes could provide an additional 2.4 Gt CO_2e of carbon offsets in 2020–2035, should ICAO choose to recognize them.

Table 9: Total cumulative offset supply, 2020–2035, by potential environmental integrity and sustainable development screens (Gt CO_2e)*

		Environmental integrity confidence screens			**Totals**
		Higher confidence	**Medium confidence**	**Lower confidence**	
		A1	A2	A3	
Sustainable development screens	**Potential benefits**	Methane avoidance; landfill gas	Energy efficiency – households (incl. cookstoves); energy efficiency – services; hydro – small; mixed renewables – small; energy distribution; geothermal; municipal solid waste gasification/ combustion	Transport; wind – small; agriculture; biomass energy; energy efficiency – industry; forestry (afforestation, reforestation, avoided deforestation, improved forest management, agroforestry); mixed renewables – large; wind – large	**13.5** (5.5/8.0)
		3.0 (0.6/2.4)	**1.6** (0.8/0.8)	8.9 (4.1/4.8)	
		B1	B2	B3	
	Neutral effects	CO_2 usage; HFC-23 (revised methodology); N_2O nitric acid	PFCs & SF_6	Cement; fugitive gas – charcoal production; HFC 23 (old methodology); N_2O adipic acid	**1.9** (1.5/0.4)
		0.3 (0.3/0.0)	**0.2** (0.0/0.2)	**1.4** (1.2/0.2)	
		C1	C2	C3	
	Potential risks	Coal mine methane – ventilation air methane	Coal mine methane/ coal bed methane	Fossil fuel switch; fugitive gas; hydropower – large	**11.0** (4.5/6.4)
		0.3 (0.0/0.3)	**1.5** (0.2/1.2)	**9.2** (4.3/4.9)	
Totals		**3.6** (0.9/2.7)	**3.3** (1.0/2.2)	19.5 (9.6/9.9)	**26.4** (11.6/14.8)

** Numbers in parentheses indicate respective supply potential projections for currently registered and future new projects.*

***Numbers refer to plausible screening options that ICAO could apply to limit the eligibility of offset projects types.*

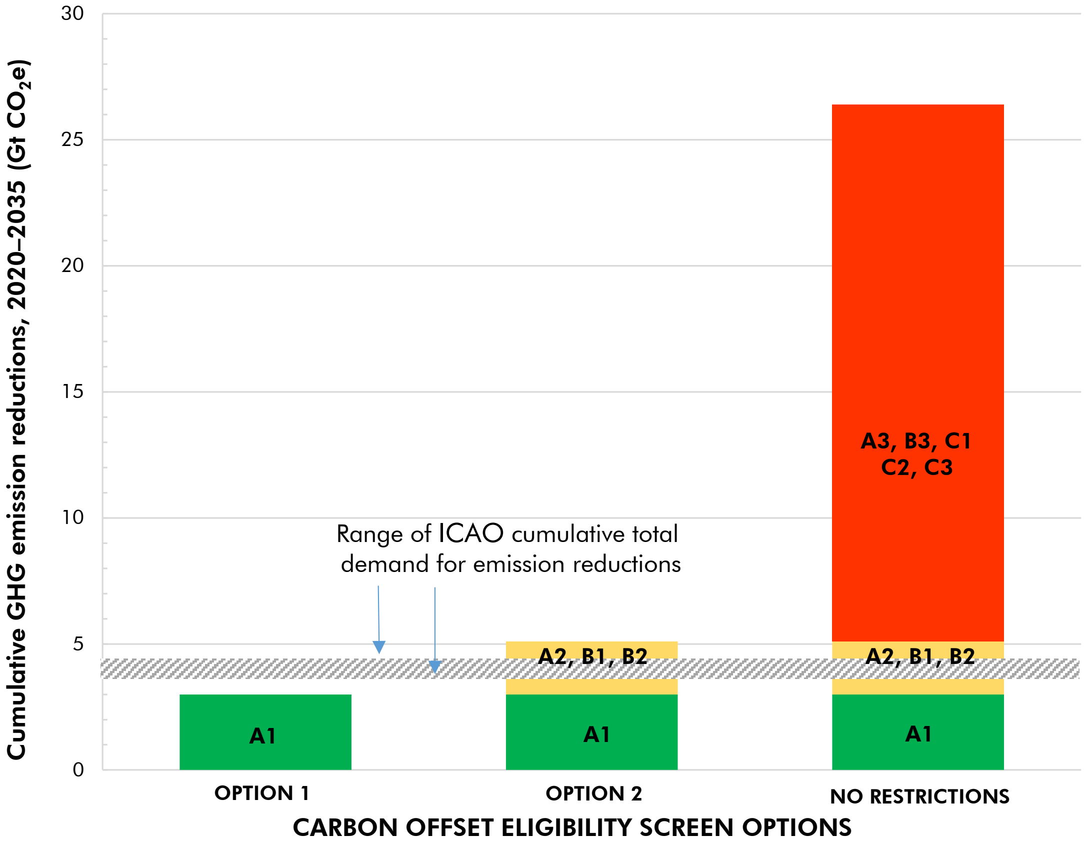
As stated at the top of this section, one of our goals was to determine whether ICAO can meet its carbon-neutral growth goal if it limits carbon offset use to only those credits with a higher promise of integrity, defined in terms of both emission reductions and sustainable development benefits. Table 9 suggests the answer is mostly yes, with some qualifications.

One option is for ICAO to restrict eligibility to project types for which there can be relatively high confidence in environmental integrity, and for which there are clear potential sustainable development benefits if certification standards are used (Option 1 in Figure 2). Under this option, only methane avoidance and landfill gas destruction projects would be eligible, and we estimate the supply potential over 2020–2035 at just 3.0 Gt CO_2e (A1 in Table 9). Thus, under this option, airlines would be unlikely to meet their expected offset demand from project-based offsets alone. However, demand could easily be covered if ICAO also includes REDD+ credits, even if other buyers compete for these same sources of offsets.

ICAO could expand eligibility to include project types for which there is medium confidence in environmental integrity or neutral sustainable development outcomes, but still exclude project types for which there is lower confidence in environmental integrity or that have potential development risks (Option 2 in Figure 2). Under this option, potential project-based offset supply would expand to 5.1 Gt CO_2e (A1, A2, B1, and B2 in Table 9), easily covering the airlines' projected demand for offsets under the MBM. Including REDD+ offsets would provide a large margin of additional supply, even in the presence of competing demand.

Given these projections, ICAO should not feel compelled to seek offsets from project types for which there is relatively low confidence in environmental integrity, or which pose risks of negative sustainable development impacts (including continued reliance on fossil fuels). Although there are multiple economic and policy considerations related to establishing a MBM, a selective approach to eligibility could yield significant gains for meeting the MBM's environmental goals and advancing sustainable development more broadly.

Figure 2: Total global cumulative supply of offsets, 2020–2035, by eligibility screening option (Gt CO_2e)



Note: See Table 9 for details on what is included in each category.

3. ALTERNATIVE FUELS

In the past two decades, biofuels have increasingly substituted for petroleum-based liquid fuels. Driven by blending mandates in place in dozens of countries, biofuels production has grown to constitute roughly 3% of the liquid fuels used for road transport worldwide (IEA 2015b). Biofuels have also been discussed and promoted as a low-carbon substitute for fossil-based jet fuel. The industry-led Sustainable Aviation Fuel Users Group (SAFUG), for example, has focused on accelerating development of sustainable aviation biofuels.[23] However, efforts to develop biofuels for aviation are still in their early stages.

Several bio-based jet fuel pathways – methods of production – are under development, relying on feedstock derived from plant oils, starches and sugars, or cellulosic materials such as trees and grasses. The feedstocks may be purposefully grown or derived from wastes and residues. They are then put through one of the processing pathways, resulting in a "drop-in" fuel that very closely resembles kerosene-based jet fuel (Stratton et al. 2010). These pathways include:

- *Hydro-processed esters and fatty acids* (HEFA), derived from fats and oils;
- *Fischer-Tropsch* (FT) process, in which fuels are synthesized from gasified biomass (Stratton et al. 2010);
- *Direct Sugar to Hydrocarbons* (DSHC), in which yeasts convert sucrose into an intermediate compound (farnisene) that can be upgraded into aviation fuel (Moreira et al. 2014); and
- *Pyrolysis*, which involves high-temperature conversion of cellulosic feedstock into synthetic crude oil that is subsequently processed into distillates such as jet fuel (Maniatis et al. 2013).

Three of these pathways, HEFA, FT and DSHC, are currently certified for use in actual commercial flights. HEFA has been used in thousands of test flights and demonstrations. FT fuels have also been used in many flights, but the FT fuels used thus far have been derived from fossil fuel feedstocks rather than biomass. DSHC fuel has been used in one flight,[24] and pyrolysis-based fuels are not yet certified for use.

3.1 Classifying alternative fuels by climate and development benefits

The different types of alternative fuels have different emission reduction benefits relative to conventional jet fuel, and their production can contribute more or less to sustainable development goals. Below we explain the definitions and groupings we use to classify alternative jet fuels by their climate and development benefits.

Defining the relative emission reductions of alternative fuel types

There is broad consensus that the GHG emission reductions resulting from the use of alternative fuels should be calculated on a life-cycle basis (IATA 2015b; ICAO 2011; Hileman et al. 2009). The life cycle includes recovery and extraction, transport of raw materials, refining and processing, transport of the finished product, and combustion (Stratton et al. 2010). In addition, any assessment of biofuel emissions must account for potential land use change associated with feedstock production (Cherubini et al. 2009), which may be either direct (dLUC) or indirect (iLUC). In some circumstances, emissions resulting from land use

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[23] See http://www.safug.org.

[24] See Air Transport Action Group (ATAG), "Passenger biofuel flights": http://aviationbenefits.org/environmental-efficiency/sustainable-fuels/passenger-biofuel-flights/.

change fully negate any emission reductions from substituting jet fuel with a biofuel. See Box 2 for further discussion.

Net emission reductions depend on the emissions associated with production, transport and conversion of the feedstock, inputs and the fuel itself, as well as any co-products. In addition, any land use change caused by feedstock production must be accounted for.

To put emissions reduction requirements for alternative fuels into context, we first examine the thresholds that have been defined by existing biofuel mandates and standards. As shown in Table 10, several mandates and standards set a threshold of about 50% for the emission reductions that a qualifying biofuel must meet. We therefore use this value as a rough benchmark for assessing the relative emissions benefits of different alternative fuels. As noted above, it is important to account for potential land use change impacts in these calculations, either by explicitly including those emissions, as is done in some standards (e.g. the U.S. Renewable Fuels Standard, the EU Renewable Energy Directive and the California Low Carbon Fuel Standard), or by ensuring that measures are taken to avoid land use change impacts (discussed further below).

Table 10: GHG emission reduction requirements for biofuels in existing mandates and standards

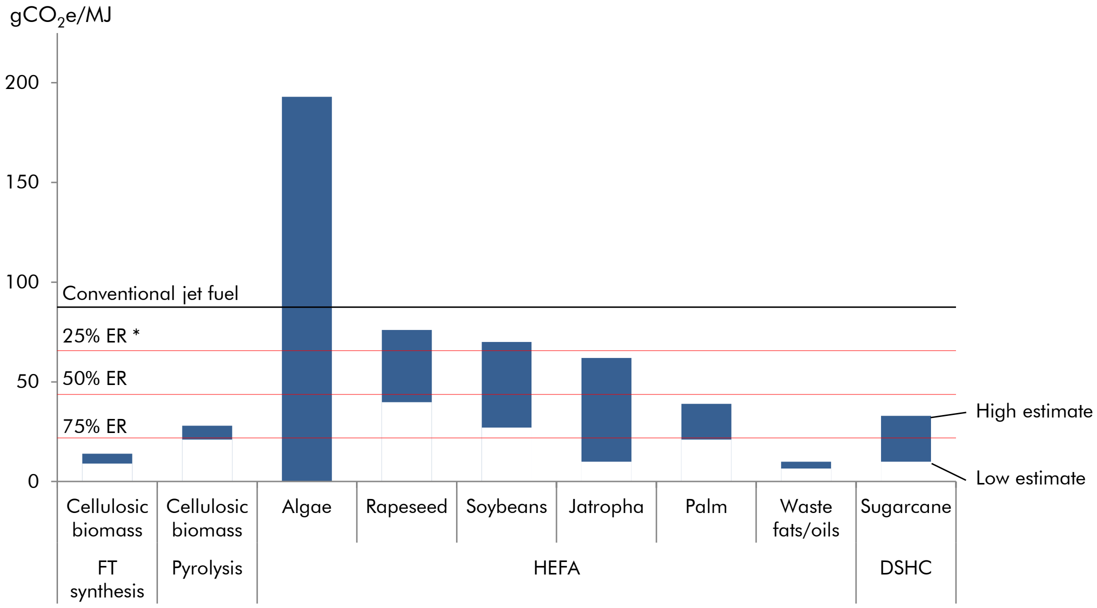
Mandate or standard	Minimum (life-cycle) GHG emission reduction requirements for biofuels	Comment
European Union Renewable Energy Directive (EU RED) [a]	35% initially 50% in 2017[b] 60% in 2018[b]	Originally did not include land use change, but prohibited production on land converted from previously high-carbon stock such as wetlands or forests. The Directive was amended in 2015 to require that fuel suppliers report "provisional mean values of the estimated indirect land-use change emissions from biofuels" (EU 2015, p.59).
U.S. Renewable Fuels Standard (as of 2007)	20%: first generation biofuels (corn ethanol) 50%: advanced biofuels (biodiesel and sugarcane ethanol) 60%: lignocellulosic fuels	The U.S. Environmental Protection Agency defines reductions for each pathway, explicitly including iLUC.
California Low Carbon Fuels Standard	Does not impose fuel specific limits, but requires 10% statewide reduction in transportation emissions by 2020.	California Air Resources Board (CARB) defines reductions for each pathway, explicitly including iLUC, but using a different methodology than RFS2.
Roundtable on Sustainable Biomaterials (RSB) standard	50%: will increase over time, but the schedule and magnitude of increases are not yet stated	Does not include iLUC. Requires operators to use data values from actual operation rather than defaults. Introduced a low iLUC risk module defining criteria and indicators for operators to avoid iLUC emissions.

[a] The EU RED is technically a meta-standard that allows regulated operators to use voluntary "qualifying standards" to demonstrate compliance. Currently, there are 19 qualifying standards, which must meet or exceed the EU's GHG reduction requirements (European Commission 2013).
[b] Applies only to new biofuel production facilities.

Several life-cycle analyses have been carried out to estimate the emission reductions achievable from different jet fuel feedstocks and pathways. Figure 3 shows the range of GHG emissions estimates for various alternative fuel pathways. With the exception of the DSHC entry, these results do not include land use change. The underlying data and sources are provided in Table 15 in the Appendix. The range of estimates for some feedstock-pathway combinations is very wide, and only three feedstock types – palm oil, waste fats/oils, and sugarcane – are fully above the 50% GHG savings benchmark. Others have low estimates that achieve the benchmark, but high estimates that do not. The HEFA-algae combination has the broadest range of estimates: from zero net emissions, to more than twice the GHGs associated with conventional jet fuel. The wide variation in GHG savings estimates for several alternative fuels is due to several factors, including systemic uncertainty in crop and fuel production as well as specific methodological choices made by the analysts (see Box 2).

Figure 3 also indicates that cellulosic feedstocks and associated pathways (FT and pyrolysis) can achieve larger emissions reductions relative to conventional jet fuel than most feedstocks processed through HEFA pathways, except for HEFA using waste fats and oils. However, to truly make a fair comparison we also need to consider land use change risks, which we explore in the next section.

Figure 3: Estimated GHG emissions from alternative feedstocks and pathways without considering land use change impacts



** ER = emission reductions. For data sources, see Table 15 in the Appendix.*

We group feedstock-pathway combinations into two categories to show roughly what level of emission reductions can potentially be achieved with each, based on the literature summarized in Figure 3:

- ***Lower range of emission reductions:*** This includes the less favourable (high) end of emission estimates for oilseed crops such as rapeseed, soybean and jatropha (assuming no land use change);
- ***Upper range of emission reductions:*** This includes fuels from waste, most cellulosic feedstocks (assuming no land use change), and sugarcane in the DSHC pathway.

The emissions profile of actual fuels may be quite different, based on the factors noted above and further discussed below; our classification is only indicative. Rigorous life-cycle analyses, including land use change, should be conducted to determine the emissions profile of an alternative fuel before it is put into use.

Box 2: Uncertainties in life-cycle estimates of biofuels' GHG emissions

Life-cycle analysis studies report a wide range of biofuel GHG emissions, as shown in Figure 2. The range reflects uncertainties in key assumptions as well as differences in accounting methodology, and system boundaries. Systemic uncertainty arises from unknown but bounded factors affecting feedstock production and processing such as crop yield, fertilizer inputs, and the source of energy used in processing. For example, in their analysis of multiple feedstocks and production pathways, Stratton et al. (2010) find that life-cycle emissions for a given feedstock can vary by 50 to 100% depending on crop yield assumptions.

Accounting methodology leads to variation in results for other reasons. Nearly all alternative fuel pathways yield multiple co-products in addition to the fuel itself. For example, oilseeds used as HEFA feedstocks yield seedcake, which can be used as feed, fertilizer or fuel. HEFA refining produces other hydrocarbon compounds, such as diesel, naphtha and bio-LPG. Cellulosic pathways yield combustible syngas that can produce heat and/or electricity (Elgowainy et al. 2012). Life-cycle analysis methodologies use different approaches to allocation, either based on inherent co-product characteristics (e.g. mass, energy, market value), or by considering the avoided impacts resulting from the displacement of other products by these co-products (substitution or system expansion). While discussing those methodologies is beyond the scope of this report, we raise the issue because the choice of methodology can lead to very different results. For example, Han et al. (2013) show that GHG emissions from soy-based HEFA vary from 30g CO_2e/MJ with mass-based allocation to 43g CO_2e/MJ with market-based allocation.

Lastly, choosing system boundaries can also affect results. One approach, called *attributional* life-cycle analysis, draws well-defined boundaries around the major inputs and processes required to produce a unit of biofuel and allocates impacts according to one or more methods described above. Another approach, called *consequential* life-cycle analysis, removes these boundaries and uses macroeconomic models to estimate the *indirect* impact of biofuel production on the broader economy by explicitly accounting for interconnections between markets. If large volumes of fuel are produced, the quantity of co-products would affect naphtha, diesel and/or LPG prices, leading to altered patterns of consumption and associated GHG emissions.

Consequential life-cycle analysis underpins iLUC analyses. For example, if oilseed crops are diverted to alternative jet fuel production, the global supply of edible oil would drop, leading to an increase in prices, which might motivate farmers to convert forests to oilseed plantations, driving potentially large losses of terrestrial carbon (and possibly harming biodiversity and/or food security). However, iLUC analyses are very sensitive to assumptions and input parameters, resulting in wide variation in estimates. Thus, the choice between attributional and consequential life-cycle analysis can result in very different estimates of GHG emissions, particularly if iLUC is included, as shown in Table 16.

Estimating and addressing land use change impacts

Common biofuel feedstocks are land-intensive, and as noted above, biofuel production can cause both direct and indirect land use change (dLUC and iLUC) that must be accounted for when assessing the GHG implications of substituting fossil fuels with biofuels. Both dLUC and iLUC have been discussed at length in other analyses.[25] Rather than provide a detailed overview, we will limit the discussion to the ways in which ICAO can select alternative fuel feedstocks associated with minimal land use change impacts in order to ensure emission reductions.

Direct land use change is relatively straightforward to observe and account for, because it occurs within the boundaries of whatever cropping system produces the feedstock, and changes in carbon stocks can be directly observed. In contrast, iLUC cannot be observed directly and requires sophisticated modelling to estimate (see, e.g., Wicke et al. 2012). These analyses apply a wide range of assumptions and modelling techniques, leading to widely varying estimations (see Table 15 in the Appendix) that are difficult to compare. Despite this difficulty, some regulators have used iLUC factors to set policies. For example, U.S.-based regulatory standards such as the RFS2 and LCFS have quantified feedstock-specific factors and incorporated them into GHG emission reduction calculations.

The EU RED originally lacked iLUC measures, but was amended in 2015 to include feedstock-specific factors for cereals, starch-rich crops, sugars and oilseeds (see EU 2015 and the Appendix to this document) and additional reporting of iLUC-related factors. The 2015 amendment also explicitly assigns a zero iLUC-factor to anything not explicitly included in the previous list. In addition, it creates incentives for algae- and waste-based feedstocks by crediting fuels derived from those materials at twice the rate assigned to biofuels from conventional feedstocks. However, the RED is not a standard in itself, but rather a meta-standard; the EU has identified 19 standards that aim to ensure that certified operators apply the RED's iLUC criteria. Of the 19 qualifying standards, only the RSB standard includes a detailed set of criteria to show that operators have minimized iLUC risk (RSB 2015). The RSB's approach to iLUC criteria could serve as an example for how to ensure that a given supply of aviation biofuels has a low land use change impact.

In order to minimize iLUC risk in biofuel production, the RSB guidelines encourage three broad approaches for sourcing feedstocks: increased yields (and counting only the fraction of production that comes from such increases), production on unused land, and use of wastes and residues. We review each briefly below in the context of likely alternative jet fuel feedstocks.

Increased yields: The higher the crop yields for a given biofuel feedstock, the smaller the amount of land needed for production. Globally, the yields of most commercial crops have increased over time. For example, globally, yields of grains and oilseed have increased by roughly 2% per year since the 1960s (FAOSTAT 2015). These increases are due to improved seed varieties; changes in sowing, harvesting and soil management; improved fertilizer applications; crop rotations; protection from weeds, pests and diseases, and improved pollination techniques, among other factors.

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[25] See, for example (Cornelissen and Dehue 2009; Melillo et al. 2009; Creutzig et al. 2012; Panichelli and Gnansounou 2015).

Grow feedstock on unused land: iLUC risk is reduced when feedstock is grown on land that was not previously used, so it does not displace other activities – it is the displacement of other activities that results in indirect effects. However, this category must be approached carefully, because land that appears to be unused may actually be used, at least periodically, by local people, particularly poor and marginalized populations (Baka 2014). The RSB guidelines address this with the following criteria:

- Land must not have been used for its provisioning services (i.e. for food, feed or fuel) during the three years preceding the reference date, as verified by interviews with the land owner or tenant and with other local people and authorities; or
- Land was only used for limited provisioning services[26] during the three years preceding the reference date, similarly verified.

The guidelines specifically note that land under *shifting cultivation*, a management system in which land may lie fallow for long periods of time, would not be considered "unused".

Using wastes and residues: Wastes can be low-iLUC feedstocks, if the waste stream was not previously used for other purposes. If the waste stream was previously utilized (e.g. burned as boiler fuel or applied to fields as fertilizer), then its diversion to biofuel production will leave a supply gap in the previous application, and filling the gap will result in indirect emissions. The RSB's low iLUC guidelines define a set of eligibility criteria for waste materials in order to ensure no indirect emissions result from their use (RSB 2013).

Table 11 presents our classification of different feedstocks under each production pathway, taking into account both net GHG emission reduction potential relative to conventional jet fuel, and land use change risks (dLUC and iLUC).

Table 11: Emission reductions and land use change impacts of alternative fuels by pathway and feedstock including a consideration of d/iLUC

Production pathway	Feedstock	Relative emission reductions w/o considering land use change impacts	Land use change impacts
HEFA	Algae	Greater than, roughly, or less than 50% Wide variation in life-cycle analysis results make it difficult to predict actual performance (see Figure 3)	Potentially large water and energy requirements Land use change risks are generally low
	Rapeseed	Roughly or less than 50% Non-land use change emission reductions vary depending on yields, inputs and allocation methodology	dLUC impacts are generally small or moderate depending whether crops are planted on existing farmland (drives iLUC) or on set-aside land iLUC estimates range from 33 to 66 gCO_2e/MJ (Table 16 in Appendix)
	Soybeans	Roughly or less than 50% Non- land use change emission reductions vary depending on yields, inputs and allocation methodology	Very high dLUC if natural forests or grasslands are converted iLUC estimates range from 20 to 66 gCO_2e/MJ (Table 16 in Appendix)

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[26] "Limited provisioning services" are defined as yielding 25% or less (by energy, protein content, or market price) of earnings or yield that would be reasonably expected from cultivation of the same crop(s) in normal conditions (RSB 2015 p.9).

Production pathway	**Feedstock**	**Relative emission reductions w/o considering land use change impacts**	**Land use change impacts**
HEFA	Jatropha	Roughly or greater than 50% Non- land use change emission reductions vary depending on yields, inputs and allocation methodology	dLUC impacts can range from net carbon sequestration if planting occurs on degraded land, to very high emissions if forests are cleared. No iLUC estimates have been done; risk depends on the type of land utilized
	Oil palm	Roughly or greater than 50% Non-land use change emission reductions are better than for other oilseed feedstocks due to lower inputs and high yields	Historically linked to very high dLUC due to conversion of peatlands and natural forests. However, dLUC can be small, or even negative if planted in land that has already been cleared. iLUC estimates range from 18 to 66 gCO$_2$e/MJ (see Table 16 in Appendix).
	Waste fats and oils	Greater than 50% Non-land use change emission reductions are high because impacts of feedstock production are attributed to primary product	dLUC impacts should be zero. iLUC impacts should be very low; however, if wastes were used in other processes, then risk of iLUC exists as markets react to change in supply of waste products.
FT synthesis and pyrolysis	Short-rotation woody crops	Greater than 50% Non-land use change emission reductions are 70–90%	dLUC can include carbon sequestration if planting occurs on degraded land or land previously used for annual crops. However, if planting replaces annual crops, then there is risk of iLUC. In addition, dLUC can be problematic if high-carbon grasslands or other native vegetation are displaced. iLUC estimates vary widely. One assessment estimates iLUC from SWRC planted in the EU ranges from 38 to 77 gCO$_2$e/MJ (Table 16 in Appendix). However, crops planted in tropical regions result in lower iLUC.(Cherubini et al. 2009).
	Grasses	Greater than 50% Non-land use change emission reductions are 70–90%	dLUC impacts can range from net carbon sequestration if planting occurs on degraded land, to very medium emissions if natural grasslands are cleared iLUC estimates for switchgrass range from 8 to 21 gCO$_2$e/MJ (Table 16 in Appendix)
	Crop or forest residues	Greater than 50% Non-land use change emission reductions are 70–90%	dLUC impacts should be zero. iLUC impacts should be very low; however, if wastes were used in other processes, then risk of iLUC exists as markets react to change in supply of waste products.
	Municipal solid waste	Greater than 50% Non-land use change emission reductions are not yet published, but should be similar to other waste-based feedstocks	dLUC impacts should be zero. iLUC impacts should be very low; however, if wastes were used in other processes, then risk of iLUC exists as markets react to change in supply of waste products.
DSHC	Sugarcane	Roughly or greater than 50%	Only one analysis of DSHC has been published and it includes d/iLUC. Results, including uncertainties in key parameters, indicate net emissions are 21 ± 11 gCO$_2$e/MJ (mean ± SD). With d/iLUC contributing between 11 and 17 gCO$_2$e/MJ (Moreira et al. 2014).

Sustainable development outcomes of alternative fuels

The focus of our sustainable development impacts analysis is whether ICAO can be confident that the production and delivery of alternative fuels provide development co-benefits beyond GHG emission reductions – or, at minimum, do not negatively affect development outcomes. There have been many efforts to define sustainability principles and criteria relevant for biofuel production (van Dam et al. 2010; ISO 2015). In this assessment, we consider existing biofuel sustainability schemes in the context of the SDGs in order to evaluate eligibility screening criteria under consideration by ICAO.

We can group feedstocks into several categories that have common characteristics with respect to sustainable development outcomes: annual crops (e.g. soy or rapeseed); perennial oilseed crops (e.g. oil palm and jatropha); perennial cellulosic crops (e.g. perennial grasses, forest residues, crop wastes or municipal solid waste) and waste materials (e.g. used cooking oil or tallow). No feedstock is inherently and unambiguously good or bad for sustainable development, though some are likely have fairly neutral impacts. For example, using waste products to make biofuels is unlikely to do harm, but will only yield development benefits if specific measures are taken (for example, encouraging socially inclusive supply chains). Little is known about the development impacts of perennial cellulosic crops, as they have only been planted in small areas, and neither positive nor negative impacts have been documented. Likewise, the potential impacts of algae-based biofuels are largely unknown, because production has not moved beyond the pilot phase.

In contrast, oilseed crops such as soy, oil palm and jatropha have many documented instances of negative social and environmental impacts, including conflict over land, risks to food security, and threats to biodiversity, soil fertility or water quality (Klink and Machado 2005; Koh and Ghazoul 2008; Sulle and Nelson 2009; Gomes et al. 2009; Gomes et al. 2010; McCarthy 2010; Carlson et al. 2012; Solomon and Bailis 2014).

Still, it is important to recognize that the crop itself is not inherently harmful. Indeed, some analyses suggest that the cultivation of common biofuel feedstocks such as soy and oil palm has made positive contributions to the livelihoods of the rural poor, particularly when government policies encourage smallholder inclusion or when smallholders have a degree of autonomy to decide how much to engage with agribusinesses (Sheil et al. 2009; Schneider and Niederle 2010; Koczberski 2007). Still, if the benefits are not evenly distributed, increased inequality and conflicts can result (Rist et al. 2010; Weinhold et al. 2013).

It is clear that far more than the feedstock used, it is the specific institutional arrangements and management practices involved that result in either negative, neutral or positive sustainable development outcomes. Numerous sustainability certification schemes have been introduced to try to ensure no harm is done and, in some cases, ensure sustainable development benefits. Some schemes are designed for specific feedstocks – such as the Roundtable on Sustainable Palm Oil (RSPO), Roundtable on Responsible Soy (RTRS), and Bonsucro (sugarcane) – while others cover multiple crops and production pathways – such as the RSB standards, the International Sustainability and Carbon Certification (ISCC), and the Biomass/Biofuel Sustainability Voluntary Scheme (2BSvs); see Table 12.

Other analyses have reviewed these and other biofuel certification standards and found dramatically different breadth and depth of coverage of sustainability issues (Diaz-Chavez 2011; Lee et al. 2011; Moser et al. 2014; Scarlat and Dallemand 2011; van Dam et al. 2010; Bailis and Baka 2011). Some standards focus mainly on ensuring emission reductions (e.g. 2BSVS and ISCC), while others include criteria and indicators requiring that biofuel producers expend some degree of effort to avoid negative social or environmental impacts (e.g. RSPO, RTRS, and Bonsucro). Finally, some standards include criteria requiring that feedstock or fuel production result in specific improvements under certain conditions. For example, the RSB requires that biofuel producers working in regions of poverty "contribute to the social and economic development of local, rural and indigenous people and communities" (RSB 2011, p.15) and "ensure the human right to adequate food and improve food security in food insecure regions" (p. 17).

Table 12: Sustainable development biofuel certification standards used to guide our assessment

Scheme	Description
Roundtable for Sustainable Biomaterials (RSB)	RSB is a global multi-stakeholder coalition promoting sustainability of biomaterials through a voluntary certification system. RSB has 93 member organizations from more than 30 countries, representing: 1) farmers and growers; 2) industrial producers; 3) retailers and blenders; 4) rights-based NGOs & trade unions; 5) civil society organizations including development, food security, smallholder indigenous peoples', or community-based; 6) environment, conservation and climate change organizations; and 7) intergovernmental organizations, governmental agencies, research/academic institutions, standard-setters, specialist advisory agencies, certification agencies, and consultants. The certification system itself consists of 12 principles covering all aspects of social and environmental impacts. The RSB is a member of the ISEAL Alliance and adheres to global codes of best practice for standard-setting organizations. It currently lists 17 operators with valid certifications on its website, including three involved in aviation fuel provision.
Roundtable on Sustainable Palm Oil (RSPO)	The RSPO brings together stakeholders from the palm oil industry to implement voluntary global standards based on eight principles. It has more than 2,800 members from across the supply chain, and certifies growers, palm oil mills, facilities and entire companies. About 21% of global palm oil production is now covered by RSPO certificates.
Bonsucro	Bonsucro is a global non-profit, multi-stakeholder organization promoting sustainability of sugarcane and related products with a voluntary certification scheme based on five core principles. It has more than 400 members from 32 countries, covering all aspects of the supply chain. To date, it has issued 51 certificates in four countries, covering nearly 4% of global sugarcane production.
Roundtable for Responsible Soy (RTRS)	RTRS is global civil society group that promotes responsible soy production, processing, and trade through voluntary certification. Its standard includes five core principles and membership consists of representatives from the soy value chain and major civil society organizations from around the world. It has 190 members and more than 80 certified operators.
International Sustainability and Carbon Certification (ISCC)	ISCC is a global certification scheme promoting sustainable bio-based feedstocks and renewables. It relies on third-party certification to show compliance with six core principles. It can be applied to bioenergy as well as food, feed and chemical products. It is one of the most popular schemes, with more than 10,000 certificates issued in 100 countries since 2010.
Biomass/Biofuel Sustainability Voluntary Scheme (2BSvs)	2BSvs is a voluntary certification scheme developed by French operators involved in grain production and biofuel supply to demonstrate compliance with criteria set by the EU RED. The scheme has five core principles aligned with the EU RED; to date, it has issued nearly 600 certificates.

Sources:
RSB: official website, http://rsb.org, and Participating Operators, http://rsb.org/certification/participating-operators/. RSPO: official website, http://www.rspo.org/about.
Bonsucro: official website, http://www.bonsucro.com. RTRS: official website, http://www.responsiblesoy.org, and Certified Producers Audit Reports, http://www.responsiblesoy.org/public-audit-reports/?lang=en.
ISCC: official website, http://www.iscc-system.org/en/iscc-system/about-iscc/iscc-in-short/. 2BSvs: official website, http://en.2bsvs.org, and Certified Operators Data Base, http://en.2bsvs.org/no_cache/economic-operators/certified-operators-data-base.html.

3.2 Future global supply potentials of alternative jet fuels

In the scenario that ICAO has deemed "most likely", about 3% of global jet fuel demand in 2020 – about 6.5–7.2 Mt – would be met by alternative fuels (ICAO 2013a, p.25). Because these jet fuels are currently a negligible fraction of the aviation fuel mix, and an equally small part of global biofuel production, it is difficult to determine whether the future supply is likely to meet that expectation. Using data from E4Tech (2014), we estimate the near-term supply, including production facilities that are either operating, under construction or planned, at 1.8 Mt per year. Looking further ahead, E4tech (2014) estimates that 3–13 Mt of alternative jet fuels could be produced annually by 2030.

There are few other studies for comparison. One paper, focused on supplying 2 Mt per year of biofuels for the EU aviation market by 2020, found it technically feasible, but "a question of politics and economics whether it will become a reality" (Maniatis et al. 2013, p.26). The IEA, meanwhile, envisions that the use of aviation biofuel "gains ground after 2025, accounting for 1% of total aviation fuels in 2040" (IEA 2015b, p.363).

Given that the alternative jet fuels market is just getting started, it is challenging to predict just how much fuel will be produced, from which feedstocks or through which pathways. The analysis we present below should thus be taken as an *illustrative estimate* of the range of potential emissions reductions that could be achieved in 2020–2035.

We start with the near-term production estimate of 1.8 Mt per year in 2020. Experience suggests that the biofuel industry can grow rapidly in response to policy signals such as the U.S. Renewable Fuels Standard or the EU Renewable Energy Directive. For example, U.S. ethanol and biodiesel production capacity grew by an average of 14% and 25% per year, respectively, between 2001 and 2015.[27] To estimate potential aviation biofuel supply between 2020 and 2035, we assume that aviation biofuel production capacity grows at a rate similar to ethanol's average growth over the past 15 years.[28] Taking 1.8 Mt per year as a starting point, 14% growth results in total production capacity of 14.4 Mt per year by 2035. This aligns with the upper limit of E4Tech's (2014) estimate of 3–13 Mt per year in 2030.

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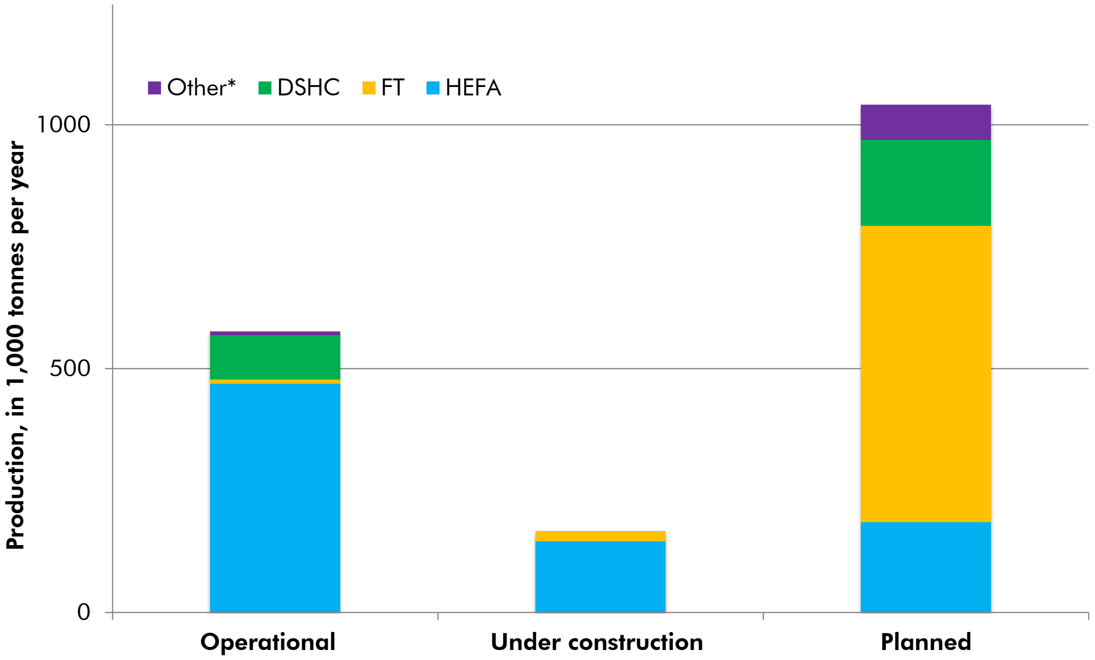
[27] Bioethanol growth rates are estimated based on data from the U.S. Department of Energy Alternative Fuels Data Center, http://www.afdc.energy.gov/data/10342, and the U.S. Energy Information Administration (EIA), http://www.eia.gov/petroleum/ethanolcapacity/. Biodiesel capacity growth is estimated based on historical data from Carriquiry (2007) and December 2015 data from the EIA Monthly Diesel Production Report, http://www.eia.gov/biofuels/biodiesel/production/.

We model past growth in U.S. biofuel production capacity as a simple exponential function: $Q(t) = Q(0)e^{rt}$ where Q represents output, t represents time (in years), and r is the annual growth rate. We acknowledge that exponential growth is unrealistic in the long term, but it can simulate short-term growth fairly well.

[28] This could be considered an optimistic upper bound, given that ethanol production from starch and sugar-based crops is a mature and widely used technology, and there were many fully commercial plants in operation prior to 2000. In contrast, the technologies required for alternative jet fuels are less mature, and there are very few commercial facilities currently operating.

Figure 4: Aviation biofuel facilities in operation, under construction, and planned as of mid-2014



** "Other" includes the "alcohol to jet" and "hydrotreated depolymerized cellulosic jet" pathways.*
Source: E4Tech (2014).

Emission reductions from alternative jet fuels

The magnitude of cumulative emission reductions that could result from the use of 14.4 Mt of aviation biofuel between 2020 and 2035 depends on the specific pathways and feedstocks used. As noted above, however, the industry is too young still to allow detailed predictions. Instead, to illustrate the potential, we created two stylized scenarios that define a range of possible outcomes and examine the implications of each. The first scenario assumes the industry relies on fuels in the lower range of emission reductions – using the HEFA pathway with lower-performing soy, rapeseed and jatropha, for example (see Figure 3); we assume that replacing jet fuel with these fuels reduces CO_2 emissions by 25%. In the second scenario, we assume the industry relies on fuels in the upper range of emission reductions – using the HEFA pathway with waste oils, FT or pyrolysis with cellulosic biomass, or DSHC with sugarcane; we assume that replacing jet fuel with these fuels yields average CO_2 reductions of 75%. If requirements are in place to ensure feedstocks are produced with little or no land use change (direct or indirect), and strong sustainability certification schemes are followed, we find that cumulative emission reductions in 2020–2035 would be 0.1 Gt CO_2e in the low-range scenario and 0.3 Gt CO_2e in the high-range scenario.

Table 13 summarizes our analysis.

Table 13: Cumulative emission reductions from biofuels, 2020–2035, based on total capacity in 2020 (see Table 18 in the Appendix for more detail)

Upper range of emission reductions		**Lower range of emission reductions**	
Pathway	Illustrative feedstock	Pathway	Illustrative feedstock
HEFA	Waste fats and oils	HEFA	Low iLUC risk rapeseed, low-performing algae
FT	Low iLUC switchgrass, maize-stover, bagasse, forest wastes or MSW		
DSHC	Sugarcane with no d/iLUC	DSHC	Sugarcane with minimal d/iLUC
Other	Low iLUC switchgrass, maize-stover, bagasse, forest residues, MSW	Other	Switchgrass with iLUC
0.3 Gt CO_2e		0.1 Gt CO_2e	

Implications of different feedstock-fuel pathway combinations

Each feedstock-pathway combination has different implications for emissions, land use, and sustainable development impacts. Thus, we examined the HEFA, FT, and DSHC pathways and related feedstocks more closely. We focused on these three because they are the only pathways that have ASTM certification; they have already been used by commercial airlines in demonstration flights, and collectively they represent 96% of the facilities that are currently operating, under construction or planned, as shown in Figure 4.

HEFA is the most commercially advanced pathway. It relies on hydro-processing, a mature technology that is commonly used in conventional petroleum refining (Stratton et al. 2010). HEFA biofuels are made from fats and oils, derived either from oilseed crops or waste. Waste fats and oils have advantages in that they are relatively low-cost and carry low risk of land use change impacts. However, the available supply of waste fats and oils is probably not enough to meet more than a fraction of projected alternative jet fuel demand. Data are difficult to find, but in the U.S., for example, 4.1 Mt of waste fats and oils were produced in 2014 (Brorsen 2015). If all of this were used, it could potentially meet ~60% of 2035 demand for HEFA feedstock and yield 15% of the projected 14.4 Mt of aviation biofuels in 2035. However, there are competing demands: in 2014, roughly 25% of the waste fats and oils produced in the U.S. were used as biodiesel feedstock, and the rest were used in other applications or exported (Brorsen 2015).

Oilseed crops face fewer supply constraints, but as noted earlier, crops such as soy and oil palm have been associated with large land use change impacts, as well as with negative impacts on sustainable development. In addition, the oil itself is relatively expensive, representing the most significant portion of biofuel production cost (Pearlson et al. 2013), which has led one group of analysts to conclude that the HEFA pathway is “economically unattractive for short to medium term deployment” (Mawhood et al. 2014, p.8). Other potential HEFA feedstocks include novel crops such as jatropha or algae. These remain at the very early stages of development and must overcome many challenges in order to be viable options (Quinn and Davis 2015; Edrisi et al. 2015).

The FT pathway relies on cellulosic feedstock, which, like fats and oils, can be derived from waste or from dedicated biofuel crops. Advantages of this pathway include the flexibility and wide availability of feedstocks. Cellulosic waste materials are ubiquitous and include agricultural waste, forest residues, and even some types of municipal solid waste. In addition, there is a wide range of grasses and fast growing trees that are suitable as dedicated cellulosic biofuel crops (UNCTAD 2016), and these crops lack the negative associations that common oilseed crops have. Cellulosic crops generally carry lower indirect land use change risk than oilseeds (See Tables 15 and 16 in the Appendix); some analyses even associate certain cellulosic feedstocks with negative iLUC (Valin et al. 2015; U.S. EPA 2010).[29]

However, the FT pathway also has several disadvantages. For example, although the technology is mature, very few commercial facilities exist and all are using fossil-based feedstocks and rather than biomass.[30] Thus, there is very little experience with biomass in this type of process. In addition, capital costs for FT facilities are higher than other alternative jet fuel options (Mawhood et al. 2014). Nevertheless, FT constitutes the largest segment of planned alternative jet fuel facilities expected in the near future (E4Tech 2014), indicating that considerable capacity for commercial biomass-based FT production may be coming online soon.

The DSHC pathway requires sugar-based feedstocks, which can be derived from a variety of crops, such as sugarcane, sweet sorghum or maize (Mawhood et al. 2014) as well as starches and cellulosic materials, although the latter require additional steps to be used in this pathway. The only feedstock currently used to produce DSHC fuels at a commercial scale is sugarcane (E4Tech 2014), so we focus here on that crop. Sugarcane has several advantages as a biofuel feedstock; it is grown throughout the tropics and delivers very high yields of biomass. In addition, most analyses find that sugarcane has a lower iLUC risk than common oilseed crops, although it is higher than cellulosic feedstocks (See Tables 15 and 16 in the Appendix). However, the existing DSHC process is inefficient; more than 26 tonnes of sugar are required to produce one tonne of jet fuel (Moreira et al. 2014). Therefore, despite sugarcane's high productivity, the DSHC pathway requires about as much land to produce a tonne of jet fuel as the HEFA pathway using soy oil (we explore land requirements in more detail below). In addition, while the literature is not as extensive as with the oilseed crops discussed above, there are instances in which sugarcane production has been linked to negative development outcomes (Selfa et al. 2014; Solomon and Bailis 2014; Glass 2012).

Whichever pathway and feedstock (or combinations of them) are used, producing biofuels to meet ICAO's demand will require millions of tonnes of new feedstock, and potentially large areas of land. Table 14 examines the relative impacts of different options, focusing on the feedstock and land required to produce 1 million tonnes (1 Mt) of alternative jet fuel.

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[29] When researchers find that a feedstock has negative iLUC, this means that the use of the feedstock results in net regrowth, rather than loss, of terrestrial carbon.

[30] See the National Energy Technology Laboratory website: http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/ftsynthesis.

Table 14: Feedstock and land areas required to supply 1 Mt of alternative jet fuel, compared with 2014 areas of feedstock cultivation

Pathway	Feedstock		Land needed (million ha)[a]	% of crop's cultivated area in 2014 [b]	Comments & key references
	Type	Amount (Mt)			
HEFA[c]	Fats & oils: Soy Rapeseed Oil palm Algae	2.0	4.2 2.1 0.4 0.04–0.06	4% 6% 2% NA	Assumes the production facility maximizes jet fuel output, producing 0.5 tonne aviation fuel per tonne of input fats or oils (Pearlson et al. 2013). Co-products include bio-LPG, propane, naphtha and diesel.
FT[c]	Cellulosic biomass: Switchgrass Maize stover Short-rotation woody crops Forest residues	22.3	2.2 6.0 1.2–2.2 NA	NA 3% NA NA	Some tropical grasses and short rotation woody crops are more productive and could result in lower land requirements. Assumes jet fuel represents ~25% of output. Co-products include 55% diesel and 20% naphtha by volume (Stratton et al. 2010).
DSHC	Sugars: Sugarcane	26.1	4.1	13%	Assumes 26.1 tonnes of sugar to produce 1 tonne of farnesane (Moreira et al. 2014).

The land required to produce 1 Mt of jet fuel ranges from 0.04 million ha using high-yield algae, to 6 million ha using maize stover (see Table 16 and its associated notes for an explanation of sources and assumptions). Among common oilseed crops, oil palm has the highest productivity and requires 0.4 million ha to produce 1 Mt of fuel. Rapeseed and soy are considerably less productive, requiring 5–10 times more land. Cellulosic feedstocks have similar land requirements as oilseeds, ranging from 1.2–6 million ha for 1 Mt of fuel. DSHC using sugarcane would require about 4 million ha.

To put these land area requirements into perspective, we compare them with the total cultivated area of each crop in 2014. We find that producing 1 Mt of aviation biofuel would require 2–6% of the planted area of common oilseed crops, 3% of global maize cultivation (using stover, not maize itself), and 13% of current sugarcane cultivation.

This analysis requires some additional caveats. First, each feedstock-pathway combination produces several co-products, so the cultivated areas estimated in Table 14 would provide more than alternative jet fuel. For example, most HEFA pathways result in a protein-rich seedcake that can be used as animal feed or fertilizer. HEFA and FT pathways co-produce diesel fuel and other hydrocarbons. DSHC and FT use some residues to produce electricity. Still, the land requirements are daunting, particularly when we consider that dLUC and iLUC must be minimized, if not avoided entirely, in order to achieve the desired emissions reductions and avoid other negative impacts from land use change.

3.3 Key considerations for ensuring GHG and sustainable development benefits

The amount of feedstock and land area required to produce large volumes of biofuels naturally leads to questions about environmental and social impacts. Meeting either the lower or upper range emission reductions presented in our illustrative examples above depends on avoiding land use change, particularly for oilseed feedstocks, which have been implicated as major drivers of land use change (Carlson et al. 2012; Richards et al. 2012; Barona et al.

2010). Land use change can also hinder sustainable development. For example, biofuel development can indirectly affect food security and biodiversity by increasing food prices and creating incentives to cut down forests for farmland. To achieve the desired emission reductions using biofuels produced through the HEFA pathway, millions of hectares of annual or perennial oilseed crops would need to be cultivated while avoiding land use change; the same is true of sugarcane in the DSHC pathway. All three of the options for avoiding iLUC described in the RSB's low iLUC guidelines – increasing yields, cultivating currently unused land, and using wastes and residues – would likely be needed, and still it might not be enough.

When we broaden our perspective and consider other dimensions of sustainability beyond those associated with iLUC, we face additional challenges. The sustainable development implications of expanding alternative fuel production depend on the type of feedstock and fuel pathways that are utilized. As we discussed in Section 3.1, feedstocks are not inherently unsustainable: much depends on the specific circumstances under which they are produced. Nevertheless, certain feedstock types, particularly oilseed crops, have been associated with negative impacts in many of the SDGs' thematic areas. Other feedstocks, such as algae and cellulosic crops, lack well-documented negative impacts, but these have not moved beyond the pilot stage of production.

If ICAO wants to ensure that aviation biofuels not only yield the promised GHG benefits, but also have positive impacts on sustainable development outcomes, the best approach is thus to require certification through one of the schemes outlined in Table 12. Most alternative jet fuels, at least in the next several years, are likely to be derived from feedstocks that carry at least some risk of land use impacts and other negative outcomes – and the amount of fuel involved means the impacts could be significant. The policies and standards that ICAO sets are thus crucial; indeed, ICAO could help build a more sustainable market.

4. CONCLUSIONS

ICAO is proposing that airlines achieve carbon-neutral growth after 2020 by relying on alternative jet fuels and offsetting their greenhouse gas emissions. However, both these approaches are subject to uncertainties about how well they reduce emissions and how they affect sustainable development outcomes. It is thus important for ICAO to establish credible guidelines for the tools that airlines will use to reduce emissions. Our analysis suggests that focusing on certain types of fuels and carbon offsets could bolster confidence in the GHG reductions they achieve, and also promote sustainable development – without compromising the airlines' or Member States' ability to meet ICAO's carbon-neutral growth target.

In principle, it is possible for any type of GHG reduction project to generate truly valid carbon offsets, as long as projects are subject to rigorous standards for additionality, quantification, and verification. However, certain kinds of projects have an easier time meeting these essential standards than others. These project types can deliver valid GHG reductions with relatively higher confidence. Carbon offsets that deliver high-confidence GHG reductions are not always the same ones that best advance sustainable development goals. Still, airlines could meet most of their carbon-neutral growth requirements even if they focus on offsets that do both. These offsets would primarily involve methane avoidance or destruction projects. We estimate such projects could yield reductions between 2020 and 2035 of around 3.0 Gt CO_2e, with about 20% of these reductions coming from existing projects and 80% from new projects. This amounts to about 70–90% of ICAO's projected demand for GHG reductions over the same period, which we estimate at 3.3–4.5 Gt CO_2e.

Offset supplies could exceed demand if eligibility were broadened to include a range of project types for which there is medium confidence in environmental integrity, and which still have strong sustainable development potential. This would encompass various types of energy efficiency and renewable energy projects, and would increase the potential supply to around 4.6 Gt CO_2e between 2020 and 2035 (30% from existing projects, and 70% from new ones). Further expanding eligibility to project types with neutral sustainable development impacts (mostly industrial gas destruction projects) would add another 0.5 Gt CO_2e to this total, increasing the supply to 5.1 Gt CO_2e.

Finally, an additional 2.4 Gt CO_2e of offsets could come from jurisdiction-scale REDD+ programmes over 2020–2035. Because REDD+ programmes are still nascent and have yet to fully demonstrate both the relative environmental integrity of their offsets and their potential sustainable development benefits, we have assessed them separately from other offset categories. With proper safeguards, however, including REDD+ programmes could help cement prospects for meeting ICAO's demand.

The potential supply of alternative jet fuels is subject to greater uncertainties. However, with appropriate restrictions to ensure that feedstocks are produced with few or no land use change impacts, backed by strong sustainability certification schemes, the international aviation sector could use biofuels to reduce its emissions while advancing sustainable development. We estimate near-term aviation biofuel production capacity (available by 2020) at 1.8 Mt per year; if the sector matched the average annual growth rate of U.S. bioethanol capacity in 2000–2015, 14%, it could produce 14.4 Mt per year by 2035.

The emission reductions achievable if the aviation industry builds up to 14.4 Mt of aviation biofuel in 2035 depend on the pathways and feedstocks used. To illustrate the potential, we created two stylized scenarios. The first assumes the industry relies on fuels in the lower range of emission reduction potential, which we assume reduce CO_2 emissions by an average of 25% relative to conventional jet fuel. The second scenario assumes the industry relies on fuels in the upper range of emission reduction potential, which yield average CO_2 reductions of 75%. The resulting cumulative emission reductions in 2020–2035 would be 0.1 Gt CO_2e in the low-range scenario and 0.3 Gt CO_2e in the high-range scenario; the latter is 9% of ICAO's lower projected demand for GHG reductions from 2020 to 2035.

It is important to bear in mind that the market for biofuel aviation fuels remains in its infancy, so growth in the market will be driven by a wide number of factors, including economic and technical feasibility, as well as the signals provided by ICAO itself in terms of what biofuel types are deemed eligible. At the same time, the much larger oil and biofuel markets will also drive change and compete with the aviation sector for feedstocks, production capacity, and consumers. That said, the signals that ICAO provides regarding biofuel eligibility and sustainability certification requirements could drive the biofuels market in a direction to achieve the emission reductions we have estimated.

In sum, ICAO can adopt high standards for both offsets and aviation biofuels and still meet its carbon-neutral growth goal. A selective approach to sourcing offsets and alternative fuels can ensure the achievement of real emission reductions and – in conjunction with third-party certification – help achieve a range of sustainable development benefits. Given the important contribution that airlines can make to climate change mitigation and sustainable development globally, the high profile of ICAO's efforts, and the important precedent these efforts will set for sectoral climate policies, it is vital for ICAO to ensure a robust and rigorous approach. Our analysis indicates that such an approach is entirely feasible, and could result in strong, positive environmental, economic and social outcomes.

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APPENDIX

Table 15: Life-cycle GHG data, including land use change, for different fuels

Fuel / pathway	Emissions (gCO_2e/MJ)	Compared with conventional jet fuel (%)	dLUC	iLUC	Source
Conventional jet fuel	87.5		No	No	Hileman et al. (2009)
HEFA-soy	35–70	-40%	No	No	Hileman et al. (2009)
HEFA-Jatropha	52	-41%	No	No	Han et al. (2013)
HEFA-rapeseed	52	-41%	No	No	Han et al. (2013)
HEFA-Camelina	44	-50%	No	No	Han et al. (2013)
HEFA-soy	38	-57%	No	No	Han et al. (2013)
HEFA-palm	32	-63%	No	No	Han et al. (2013)
Pyrolysis w/elec	28	-68%	No	No	Han et al. (2013)
Pyrolysis w/soil application	21	-76%	No	No	Han et al. (2013)
BTL-stover	10	-89%	No	No	Han et al. (2013)
FT-bagasse	9	-90%	No	No	Warshay et al. (2011)
FT-switchgrass	14	-84%	No	No	Warshay et al. (2011)
HEFA-palm	21–39 (28)	-66%	No	No	Warshay et al. (2011)
HEFA-Jatropha	36–52 (44)	-50%	No	No	Warshay et al. (2011)
HEFA-Salicornia	46– 52	-44%	No	No	Warshay et al. (2011)
HEFA-algae	64	-27%	No	No	Warshay et al. (2011)
HEFA-algae	- 21–1.5	-111%	No	No	Bauen et al. (2009)
HEFA-Tallow	10	-89%	No	No	Bauen et al. (2009)
DSHC-sugarcane	21 ± 11	-62 to -89%	Yes	Yes	Moreira et al. (2014)
HEFA-Jatropha	31.8– 45.1	-48 to -64%	No	No	Stratton et al. (2010)
HEFA-algae	14.1–193.2	121 to -84%	No	No	Stratton et al. (2010)
HEFA-palm	22.5–38.1	-64 to -74%	No	No	Stratton et al. (2010)
HEFA-soy	27.3–59.2	-32 to -69%	No	No	Stratton et al. (2010)
HEFA-rapeseed	39.8–76.0	-13 to -55%	No	No	Stratton et al. (2010)
HEFA-Jatropha	30–62	-29 to -66%	No	No	Bailis and Baka (2010)
HEFA-Jatropha	22–33	-62 to -75%	No	No	Bailis and Kavlak (2013)

Table 16: dLUC and iLUC factors estimated for various alternative fuel feedstocks (ranges indicate high and low estimates; parentheses indicate a baseline value)

Source of data	Sugarcane	Maize	Maize stover	Soybean	Palm	Rape-seed	Jatropha	Cellulosic[a]	Mix
EU (2015)	4–17 (13)	8–16 (12)		33–66 (55)	33–66 (55)	33–66 (55)			
U.S. EPA	4	25–104 (34)[b]	-10.4	32.2	46	33			
Stratton et al. (2010)				61.6–534[c]	12.7–676.4[d]	43.5[e]			
Lange (2011)				8–616[f]	-75–182[f]	-13–76[g]			
Yan et al. (2010)				169–845[h]		65–328[h]	28–142[h]		
Siangjaeo et al. (2011)					-52.9--40.5[i]				
Bailis and Baka (2010)							-27–101[j]		
Overmars et al. (2011)									30–204[k]
Plevin et al. (2010)		21–142[l]							
Fritsche et al. (2010)	-27–94[m]			72–168[n]	-88–180[o]	33–94[p]		22–92[p]	
CARB (2009)	38–57 (46)[q]	18–44 (30)[q]		27–51 (42)[q]				18	
Stratton et al. (2010)				81–774[t]	32–801[s]	38.4–52.6[r]			

[a] *Includes both short rotation forestry (Fritsche et al.) and switchgrass (CARB)*

[b] *Value in parentheses is the factor applied by RFS2 policy*

[c] *Assuming conversion from grassland (min) and forest (max).*

[d] *Assuming conversion from forest (min) and peatland rainforest (max).*

[e] *Assuming conversion from set-aside land.*

[f] *Assuming conversion from degraded grassland (min) and tropical rainforest (max).*

[g] *Canola in Germany, assuming conversion from degraded grassland (min) and grassland (max).*

[h] *Assuming conversion from grassland (min) and forest (max) in China.*

[i] *Assuming conversion from rubber plantation (min) and abandoned land (max).*

[j] *Direct LUC only, assuming conversion from degraded pasture (min) and shrubland (max).*

[k] *Biofuel consumptions in EU.*

[l] *This is the 95% probability range. The full range of estimates ran from 10-340 g CO_2e MJ^{-1}*

[m] *Ranges from degraded land (best case) to savannah (worst case)*

[n] *Ranges from grassland (best case) to savannah (worst case)*

[o] *Ranges from degraded land (best case) to forest (worst case)*

[p] *Ranges from cropland (best case) to grassland (worst case)*

[r] *dLUC only: assumes cultivation on set aside land. Range depends on yield.*

[s] *dLUC only: low end assumes high yield in logged over forest; high end assumes low yield in peat forest*

[t] *dLUC only: low end assume degraded grassland conversion with high soy yield; high end assumes rainforest conversion with low soy yields*

Box 3: Feedstocks and fuels credited with twice their energy content by the EU RED

Part A. Feedstocks and fuels, the contribution of which towards the target referred to in the first subparagraph of Article 3(4) shall be considered to be twice their energy content:

(a) Algae if cultivated on land in ponds or photobioreactors.

(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC.

(c) Bio-waste as defined in Article 3(4) of Directive 2008/98/EC from private households subject to separate collection as defined in Article 3(11) of that Directive.

(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex.

(e) Straw.

(f) Animal manure and sewage sludge.

(g) Palm oil mill effluent and empty palm fruit bunches.

(h) Tall oil pitch.

(i) Crude glycerine.

(j) Bagasse.

(k) Grape marcs and wine lees.

(l) Nut shells.

(m) Husks.

(n) Cobs cleaned of kernels of corn.

(o) Biomass fraction of wastes and residues from forestry and forest-based industries, i.e. bark, branches, pre-commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil.

(p) Other non-food cellulosic material as defined in point (s) of the second paragraph of Article 2.

(q) Other ligno-cellulosic material as defined in point (r) of the second paragraph of Article 2 except saw logs and veneer logs.

(r) Renewable liquid and gaseous transport fuels of non-biological origin.

(s) Carbon capture and utilisation for transport purposes, if the energy source is renewable in accordance with point (a) of the second paragraph of Article 2.

(t) Bacteria, if the energy source is renewable in accordance with point (a) of the second paragraph of Article 2.

Part B. Feedstocks, the contribution of which towards the target referred to in the first subparagraph of Article 3(4) shall be considered to be twice their energy content:

(a) Used cooking oil.

(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009 of the European Parliament and of the Council.

Source: EU (2015), Annex IX (reproduced verbatim, except for box heading and omitted footnote reference to the regulation cited at the end).

Table 17: Alternative jet fuel facilities operating, under construction or planned as of 2014

Process	Producer	Location	Status	Production capacity (tonnes/year)
HEFA	Neste	Finland	Operational	38,000
			Planned	38,000
		Singapore	Operational	160,000
		Netherlands	Operational	160,000
	UOP	USA	Operational	2,000
	ENI	Italy	Operational	62,000
	Dynamic Fuels	USA	Operational	47,000
	Darling Int. and Valero	USA	Under construction	90,000
	Alt Air	USA	Under construction	56,000
	Emerald Biofuels	USA	Planned	53,000
			Planned	94,000
FT	Haldor Topsoe	USA	Operational	350
	Syntroleum	China	Operational	1,400
	TRI	Canada	Operational	7,000
		USA	Planned	7,000
		USA	Planned	13,000
	UPM	Finland	Under construction	20,000
		France	Planned	37,000
	Red Rock Biofuels	USA	Planned	17,000
	Solena	UK	Planned	50,000
		Italy	Planned	50,000
		Australia	Planned	50,000
		Ireland	Planned	50,000
		India	Planned	150,000
		Turkey	Planned	50,000
		Germany	Planned	50,000
		Sweden	Planned	50,000
	Forest BTL	Finland	Planned	29,000
	Fulcrum Biofuels	USA	Operational	Demonstration
		USA	Planned	5,000
ATJ	Terrabon	USA	Operational	80
		USA	Planned	800
	Swedish Biofuels	Europe	Planned	5,000
	LanzaTech	China	Planned	40,000
DSHC	Virent	USA	Operational	< 10
	Solazymes	USA	Operational	50,000
	Amyris	Brazil	Operational	40,000
		Brazil	Planned	40,000
	LS9	USA	Operational	700
		USA	Planned	16,000
		Brazil	Planned	120,000
HDCJ	Allenotech	USA	Operational	Pilot
	KiOR	USA	Operational	7,800
		USA	Planned	23,000
	UOP	USA	Under construction	30
	BTG	Netherlands	Planned	3,500
Other	Licella	Australia	Operational	Pilot

Source: E4Tech (2014), Appendix A.

Table 18: Illustrative estimate of potential CO_2 emission reductions from aviation biofuels, 2020–2035, using low (25%) and high (75%) emission reduction fuels

Year	Amount of biofuels used (Mt)	Emission reductions (Mt CO_2)*	
		25%	75%
2020	1.8	0.6	1.7
2021	2.1	0.7	2.0
2022	2.4	0.8	2.3
2023	2.7	0.9	2.6
2024	3.1	1.0	2.9
2025	3.6	1.7	5.2
2026	4.1	2.0	6.0
2027	4.8	2.3	6.9
2028	5.5	2.6	7.9
2029	6.3	3.0	9.1
2030	7.2	3.5	10.4
2031	8.3	4.0	12.0
2032	9.5	4.6	13.8
2033	10.9	5.3	15.8
2034	12.6	6.1	18.2
2035	14.4	7.0	20.9
Cumulative total	**99.3**	**96**	**287**

** 25% and 75% emission reductions are defined on an energy basis, as in Figure 3. The results in this table are estimated with the following equation:*

$$ER = M \times f \times E \times LHV$$

Where:

M = the mass of fuel displaced (defined in the second column of the table)
f = fractional emission reduction (0.25 and 0.75 respectively)
E = emissions from conventional jet fuel defined in energy terms (88 gCO_2e/MJ)
LHV = the lower heating value of aviation biofuel (44.1 MJ/kg)

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