Cerulogy

Scrutinising the future role of alternative fuels in delivering aviation decarbonisation

Part 1 – lifecycle analysis

Dr Chris Malins and Dr Cato Sandford

September 2023

Acknowledgements

This work was supported by AEF. This report on issues in LCA is the second of a series of four reports on the role of alternative fuels in reducing the climate impact of aviation.

Disclaimer

Contents

Glossary

Alternative aviation fuel – aviation fuels not produced from crude oil, including aviation biofuels (biojet) and aviation e-fuels (e-jet). We do not include in this the category the fuels sometimes referred to as 'low carbon aviation fuels' (LCAF), a category that describes crude oil derived aviation fuels associated with some form of supply-chain emissions reduction.

Biofuels (including biojet) – fuels produced from biomass.

Carbon footprint – see GHG intensity.

Carbon intensity – see GHG intensity.

CORSIA – ICAO's Carbon Offsetting and Reduction Scheme for International Aviation.

Direct emissions – when we talk about direct emissions in the context of alternative fuels we are talking about the emissions that are within the control of operators somewhere in the supply chain for a given alternative fuel pathway. Note that this differs from the way that direct emissions are defined in company accounting under the GHG protocol, where direct include only emissions within the control of the company being assessed, and emissions under the control of third parties in the supply chain are characterised as indirect.

Downstream – processes that occur later in the supply chain (i.e. closer to the point at which a product is delivered to an end user).

E-fuels (including e-jet) – fuels produced from electricity be generating electrolytic hydrogen and synthesising it into hydrocarbons (or other fuel molecules).

Embedded emissions – the GHG emissions associated with the production of a material or energy stream used as an input for another process.

GHG – greenhouse gas.

GHG intensity – the GHG intensity of a fuel or of a process is a characterisation of the amount of carbon dioxide and other greenhouse gases that are released due to the production and use of the fuel or the application of the process. For fuels, in this report we express GHG intensity in terms of grams of carbon dioxide equivalent emissions (on a GWP100 basis) per megajoule of chemical energy in the fuel on a lower heating value basis. This unit is abbreviated to gCO_2e/MJ.

Indirect emissions – when we talk about indirect emissions in the context of alternative fuels we are talking about emissions that are generally outside the control of operators within the supply chain. This includes emissions from land use changes that are market driven and do not generally occur at the farms on which feedstock batches are actually produced and emissions (or GHG reductions) associated with displacement of materials out of existing markets. Note that this differs from the way that indirect emissions are defined in company accounting under the GHG protocol, where these sorts of market-mediated indirect emissions are normally treated as outside even Scope 3.

LCA – lifecycle analysis, the practice of assessing the full set of emissions associated with production, use and disposal of a product or service.

LCA score – for LCA of climate impacts, the LCA score is an indicator of the GHG intensity, determined not only by the characteristics of the fuel or process but by the rules of the LCA framework.

Physical CO2 emissions – in this series of reports, when we talk about 'physical CO2 emissions' we mean the CO2 emitted from a specified process ignoring lifecycle considerations and conventions such as zero accounting of biogenic CO2.

REFuelEU – the EU's regulation setting targets and rules for alternative aviation fuel use out to 2050.

Renewable Energy Directive (RED) – the EU's framework for supporting renewable energy, including renewable fuels in transport.

Renewable Transport Fuel Obligation (RTFO) – the UK's framework for supporting renewable fuels in transport.

Sustainable aviation (SAF) – see alternative aviation fuel (AAF).

Synthetic aviation fuels – hydrocarbon fuels certified for aviation use produced from non-oil resources (e.g. biomass, electrolytic hydrogen, natural gas, coal).

True emissions – when we say 'true emissions' in this report we mean the change in total global emissions (associated with a given action) that we could identify if we were omniscient and had perfect foresight – in practice, the true emissions are not known.

Upstream – processes that occur earlier in the supply chain (i.e. closer to the point of raw material extraction).

Summary

The discipline of lifecycle analysis (LCA) has become inseparable from alternative fuel legislation, with support under alternative fuel mandates in various jurisdictions made subject to reporting an LCA score that beats some threshold value. LCA of GHG impacts from a given fuel involves assessing the sum of all GHG emissions that are associated with the production of that fuel. LCA is a technical discipline built on carefully collected and documented data inventories, but assessing an LCA score does not produce a single precise value such as might be obtained for the mass or the energy content of a given fuel batch. Rather, LCA results are dependent on a number of subjective decisions. At the most fundamental level, this relates to deciding what we actually mean when we say that a GHG emissions is 'associated' with a production system. Different decisions about the scope and methodology for an LCA assessment can be taken depending on the goal of the LCA. It is possible to produce completely different LCA answers for the same batch of fuel based on differences in scope and methodology, both of which may still be correct on their own terms. For example, the LCA question 'what are the emissions associated with the processes required to grow feedstock for, produce, and distribute one million litres of biofuel?' may give a different answer to the LCA question 'what change in global net GHG emissions is expected if we increase the consumption of biofuels in a given jurisdiction by 1 million litres?'

The first of these two questions implies an 'attributional' approach to LCA analysis. The second implies a 'consequential' approach. Attributional LCA requires attributing each of the GHG sources and sinks in a system to some final product or service. For example, when assessing the GHG emissions from biofuel crop production in an attributional LCA we might identify the farm on which the feedstock sent to a specified biofuel processing plant was produced, and assess the GHG emissions from that farm and the GHG emissions associated with the inputs used on that farm. Most current biofuel regulations rely on attributional LCA to assess the emissions from cultivating and processing biofuel feedstocks. Consequential LCA of alternative fuel production differs in that it involves identifying the changes in GHG emissions in a system that are expected when demand for that biofuel increases. In a consequential framework, we might conclude that the GHG emissions from crop production at the farm that supplies a given biofuel plant are not actually indicative of emissions changes when demand increases – perhaps that farm would have produced exactly the same amount of feedstock in exactly the same way and just supplied it to a different market, and therefore that the change in feedstock production has been achieved by expanding agricultural area elsewhere ('indirect land use change') or by agricultural intensification – probably by a bit of both. Perhaps the production increase is not even the same crop that was supplied to the biofuel plant – e.g. we might conclude in consequential analysis that palm oil production increases to compensate for more rapeseed oil being turned into biofuel.

Attributional LCA questions are more narrowly defined and can be more precisely assessed, but attributional LCA scores may not be a useful indicator of the real consequences of expanding alternative fuel demand. In contrast, consequential questions are very broad – market responses to alternative fuel policy could spread out over the whole world – and there is always considerable uncertainty in modelling those sorts of impacts, but a good consequential result should be a better indicator of the consequences of expanding alternative fuel demand. The tension between the desire for the greater precision available from attributional approaches and the recognition that attributional analysis may completely miss important emission terms has led to the development of the idea of 'direct' and 'indirect' emissions. Emissions from cultivation of feedstock, processing feedstock, transport and distribution, and land use change at the farms that actually supply biofuel plants are all treated as direct emissions to be assessed attributionally. Land use change in the broader agricultural system and the results of displacing waste and residual feedstocks from existing uses are then treated as indirect emissions that can be assessed consequentially. Direct and indirect emissions intensity values can be combined into a 'hybrid' LCA score.

In the UK and EU it is normal to compare an attributional 'direct-emissions-only' LCA score for a biofuel with a fossil fuel comparator LCA score, and treat the difference between those scores as the 'carbon saving' delivered by the use of a given biofuel, often quoted as a percentage saving. This convention is problematic, because these percentage saving scores are not necessarily representative of the real net GHG impact that we expect from expanding a given biofuel production system. For example, there is a large body of evidence suggesting that increasing the consumption of biodiesel from commodity vegetable oils (palm, rapeseed, soy, sunflower) may lead to increases rather than reductions in net global GHG emissions. Nevertheless, producers and consumers of these fuels are able to state under the reporting rules of the relevant policies (the RTFO and RED)[1] that they deliver significant emission reductions. This dissonance is confusing both to the public and to policy makers who have only a superficial understanding of the issues involved.

In addition to the issues that arise from setting the scope and methodology for LCA, there are significant uncertainties and sources of variability even in attributional analysis that are often brushed over in the high-level discourse. EU and UK regulatory LCA rules also allow the use of default emission values for either the whole supply chain or for individual parts of it (e.g. cultivation, processing, transport). When taken together, these analytical challenges and options provided to reporting companies mean that any given reported LCA score should be understood as only an indicative estimate of what we think the in-scope emissions associated with a fuel pathway are likely to be, not as a precise scientific measurement of a fundamental property of the fuel.

A particular issue arises in the case of the LCA of e-fuels, because the overall LCA score is dominated by the assumption made on the GHG intensity of the electricity used. In most EU countries using electricity with the national average GHG intensity would result in e-fuels being produced that were much worse than the fossil fuels they replaced, and therefore some consequential thinking has been introduced into LCA rules for e-fuels. This is done by attempting to ensure that electricity used for e-fuel production is 'additional renewable' electricity, i.e. that additional renewable electricity is produced specifically in order to meet the electricity demand from e-fuel production. If this additionality requirement is satisfied, then we can conclude with a degree of confidence that the produced e-fuel is not associated with net GHG-increases across the wider economy. As in other aspects of LCA, however, there is a tension between the desire to simplify rules and make them more implementable and the desire for robustness.

Whichever LCA approach is used, the normal framing for LCA studies for bioenergy or for e-fuels is to start from the idea that a fuel production pathway could be 'carbon neutral' and to then assess any emissions that undermine that assumption of carbon neutrality. For biofuels, this stems from the accounting convention of counting CO_2 released by biomass combustion as a zero term in CO_2 emissions inventories. For e-fuels, it stems from the assumption that the CO_2 used to synthesise a fuel has previously been captured from either a point source or the atmosphere, offsetting any combustion emissions. An alternative way of thinking about the

---

[1] Renewable Transport Fuel Obligation and Renewable Energy Directive.

GHG impact of alternative fuel use is to ask the question the other way round. If the combustion CO_2 emissions for carbon-based alternative fuels are the same as the combustion emissions for fossil fuels, then we can challenge ourselves to identify exactly where in the system a CO_2 benefit is delivered, either by increasing a carbon sink or reducing a carbon source – this has been referred to as the 'additional carbon' framing. Within this framing, we can think of indirect land use change modelling (and other assessment of indirect effects) as a way to try to identify where additional carbon savings happen rather than as a way to identify indirect carbon emissions. Proponents of this framing argue that it is only rational to believe that alternative fuel use delivers net emission reductions if a robust additional carbon analysis has been used to identify exactly where the additional carbon is absorbed (or where a carbon emission that would otherwise have taken place has been avoided). For example, if we use corn as a biofuel feedstock then additional carbon could be identified if the rate of plant growth on existing farms is increased (i.e. if the rate of photosynthetic CO_2 absorption on the farm is increased) or if a new corn farm is established and delivers more photosynthesis than the pre-existing vegetation would have.

Looking at LCA and alternative fuels through the additional carbon framing brings out the parallels between GHG reductions from alternative fuels and GHG reductions from the type of land-based carbon offsets that might be used by airlines to comply with their targets under ICAO's CORSIA. Both for alternative fuels and for land-based offsets the GHG benefit is based on additional photosynthetic CO_2 absorption that can occur thousands of miles away from the airport where a plane might be filled with alternative fuel. In this sense, LCA is a way to treat GHG benefits accrued in the agricultural sector as in-sector emission reductions for aviation.

Overall, LCA should be understood as a tool that is limited and that can be misleading, but also as a tool that is useful and can give genuine insight about the expected GHG impact of switching to alternative fuels. There is a tendency for fuel producers to want LCA to be made as simple as possible, even if this undermines the precision or the usefulness of the results. There is a temptation for campaigners to discount concerns relating to practicality and consistency, even if those concerns are at least partly legitimate.

One response to these divergent priorities is to set different expectations between the regulatory LCA assessments that are required from fuel producers and more sophisticated LCA tools that can be used by governments when they undertake pre-or post-regulatory impact analysis. It is vital that policymakers should use consequential thinking and consequential LCA tools to identify the most important indirect emissions and to make sure that they are considered in policy development. Policies in the United States such as the California Low Carbon Fuel Standard provide examples of including estimates of indirect emissions (notably ILUC factors) in regulatory LCA, but it is still possible to recognise issues of indirect emissions even without directly using estimated emissions values in regulation. Currently, EU and UK policy do this by using ILUC analysis to inform the level of support offered to food-based fuels, by using displacement analysis to identify which lower value materials should be identified as wastes and residues and be offered extra incentives, and by building e-fuel requirements around the concept of additional renewable electricity. Where there is uncertainty about the magnitude of indirect emissions, policy makers can reduce the risk that policy is actively counter-productive by setting tighter thresholds on maximum allowable direct emissions, and by restricting the use of the fuels identified as having the highest indirect emissions risk.

1 Introduction

The world is at the start of a profound transition, moving from a period of complete reliance on fossil fuels to enable modern society to function towards a goal of almost complete decarbonisation of the economy. An important tool to enable this transition is to be able to identify the economic activities that are the most greenhouse gas (GHG) intensive, i.e. those that result in the largest carbon dioxide, or other GHG, emissions per unit of output, so that these activities can be changed or gradually eliminated. Quantification is the first step towards identifying activities that should be changed or eliminated, and which other activities should replace them.

When the activity in question revolves directly around burning a fossil resource, such as generating heat by burning natural gas at home or generating electricity by burning coal in a power station, the GHG intensity[2] of the activity is relatively clear – it is primarily determined by the quantity of fossil fuel combusted. Based on the quantity of fuel used and an analysis of its chemical carbon content it is possible to accurately assess how much carbon dioxide will be released. It is more complicated, however, to identify the 'carbon footprint' of activities that do not directly involve the combustion of fossil fuels, or that combine some amount of on-site combustion of fuels with the use of inputs that may have been energy intensive to produce.

In the language of carbon dioxide inventories for companies, these different types of GHG emissions are sometimes distinguished into three different 'scopes' as defined by the 'Greenhouse Gas Protocol'[3] (see also Figure 1):

- Scope 1 emissions are those that occur physically on premises or from company-owned machinery owned, for example CO_2 emissions from on-site fuel combustion for heat or power, CO_2 emissions from vehicles owned by the company, or fugitive emissions of other greenhouse gases such as nitrous oxide or hydrofluorocarbons.
- Scope 2 emissions are those that are associated with energy produced by a third party (such as an electricity supplier) and used by the company for an activity.
- Scope 3 emissions are those that are associated with all other aspects of the supply chain leading up to and following the activities of the company. This includes the production of inputs used by the company, the transportation of intermediate products by third parties, and use and disposal of the products made by the company.

---

[2] See the Glossary for a brief explanation of GHG intensity and the associated units.

[3] https://ghgprotocol.org/

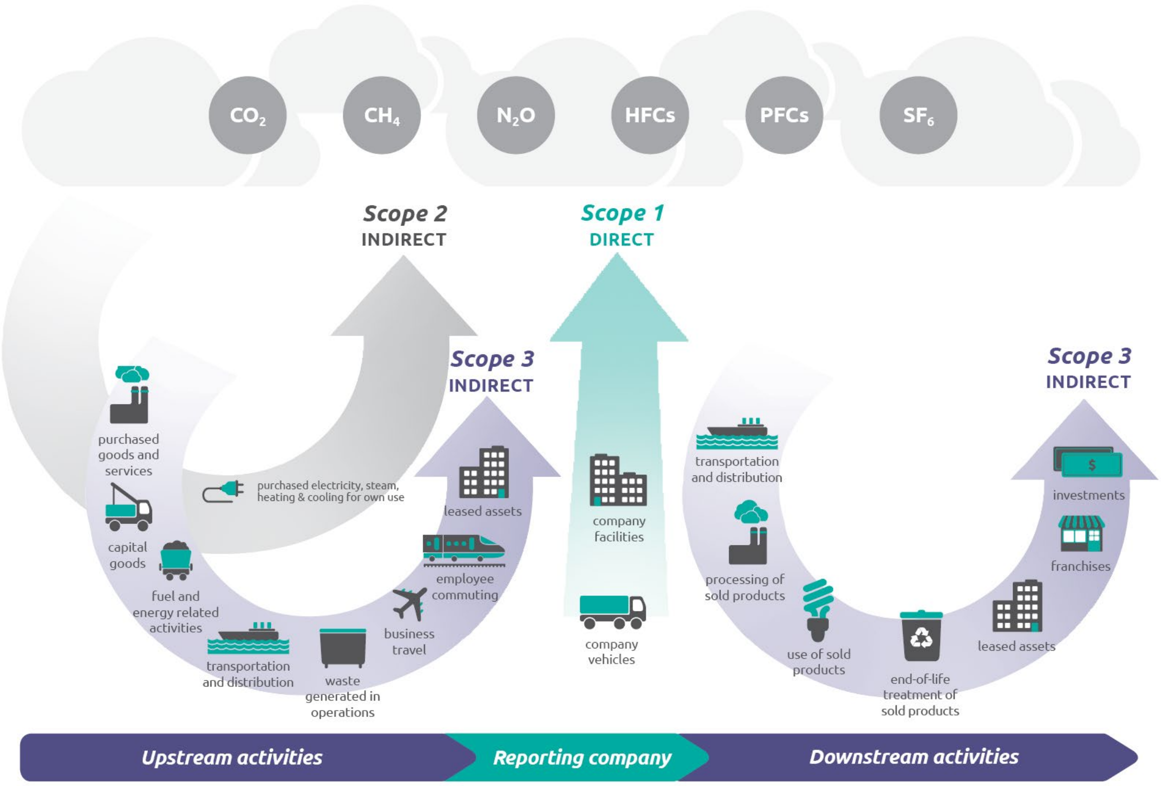

Figure 1 **Illustration of the three scopes of GHG emissions in the context of company emissions reporting**

Source: Greenhouse Gas Protocol (2013)

In this language, Scope 1 emissions are referred to as direct while Scope 2 and 3 emissions are referred to as indirect (although as we will discuss further below Scope 2 emissions and many Scope 3 emissions tend to be referred to as direct emissions in the context of lifecycle analysis). This system is in use for company reporting to the Carbon Disclosure Project. At the centre of 'inventory approaches' to GHG emissions is the idea of allocating each emission source and sink within a system to a specific entity, whether that should be a company or a country. Under the rules of the GHG protocol, every company and individual in the world could report their Scope 1 emissions and there would be no double counting – but every emission that is identified as a Scope 2 or 3 emission by one company or individual would be a Scope 1 emission for someone else.

Inventories are also vital within the Kyoto protocol and the activities of the Intergovernmental Panel on Climate Change. National emissions inventories allow compliance with national GHG emissions commitments to be assessed. Under these inventory rules, emissions from fuel combustion at factories in China are assigned to China's inventory, even if those factories are producing goods for export to some other country. One implication of this system of inventories is that countries can reduce their inventory emissions as they become more service oriented, and 'export' some of the emissions intensity of their economies abroad (cf. UK Office of National Statistics, 2021).

Scope 3 emissions can be the most important emissions to identify for understanding the GHG footprint of some companies, activities and indeed countries, but by their nature as indirect and distributed they are also more difficult than Scope 1 or Scope 2 emissions to measure and monitor, and the Carbon Disclosure Project notes that there may be considerable inconsistency in Scope 3 emissions reporting by companies (CDP, 2022). This calls for alternative methodologies that are focused on assessing the GHG emissions associated with given services or products across their whole 'lifecycle' from cradle (origination of materials and energy utilised) to grave (use and, where relevant, disposal).

Lifecycle analysis methodologies were developed in order to allow comparisons to be made on a consistent basis between the total environmental footprint of production systems and activities where the associated impacts may be widely geographically distributed. In the specific case of lifecycle analysis of greenhouse gas emissions, lifecycle analysis is intended to allow emissions associated with a product or activity to be identified and quantified 'from cradle to grave'. Once emissions have been assigned to different products, it enables those products to be compared – the implication being that using a product that has a lower lifecycle GHG emission score associated with it will do less harm to the climate. Setting a consistent methodology for the calculation of LCA scores is also intended to support greater transparency, as results (either for specific pathways or as averages across supplied fuels) can be disclosed to the public on a defined basis.

This type of lifecycle analysis has increasingly taken a central role in some parts of climate change policy and regulation, in particular in the field of alternative fuels. This reflects the fact that emissions associated with alternative fuel production and use are often widely distributed. When a 'conventional' fossil fuel is used in a transport application, most of the carbon dioxide associated with the production and use of that fuel is emitted from the vehicle. Take petrol for cars as an example. It can be shown that about 80% of the carbon dioxide emissions associated with using petrol in an internal combustion engine are emitted from the exhaust pipe of the car. The other 20% are split between the initial process of oil extraction (and could occur in any oil producing country in the world), the process of oil refining (normally, though not always, occurring at an oil refinery relatively near to where the car is used), and the transport and distribution of the fuel (e.g. shipping from the oil extraction site to the refinery, piping from the refinery to a distribution hub, trucking from the distribution hub to the petrol station).

For alternative fuels, the picture tends to be more complicated. In the case of biofuels, we can first consider the farm. Farming involves the use of seeds and agricultural chemicals (such as pesticides and fertilisers), all of which will have required energy to produce. The application of nitrogen fertiliser to fields results in the formation and emissions of nitrous oxide, a powerful greenhouse gas. Fuels are needed to run agricultural machinery such as tractors and combines. Carbon dioxide is simultaneously sequestered from the atmosphere by the plants as they grow. Once harvested, the plants need to be transported to a facility (such as an ethanol or biodiesel plant) where they are processed to produce molecules that can be used as fuels. We might also ask whether there is a 'carbon opportunity cost' from dedicating land to the production of fuels – couldn't that land also be reforested, for example? Lifecycle analysis tools have been developed in order to provide consistent bases to make assessments of biofuel production pathways and to assign GHG intensity scores to batches of biofuels, scores assigned in units of mass of CO_2 emissions (or equivalent GHG releases) per quantity of energy supplied as fuel[4].

---

[4] The standard unit in the EU is grams of CO_2 equivalent per megajoule of fuel.

There is no question that lifecycle analysis is a technical discipline that applies scientific knowledge and mathematical techniques to deliver answers. What can sometimes become obscured, however, is that by definition lifecycle analysis is not an exact and unambiguous science. Developing lifecycle analysis methodologies requires subjective choices, and therefore it is possible to have two different lifecycle analysis methodologies that are valid on their own terms but that would produce different results from assessing the same system. The GHG footprint of a fuel is not a fundamental physical property that can be precisely measured. RIf we change the rules, we can change the GHG footprint.

The absence of a single 'true' answer is not a flaw in lifecycle analysis – it is simply a feature of lifecycle analysis that emerges unavoidably from the fact that we have to make decisions about how emissions are allocated. In the language of emission scopes, we can think of LCA rules as setting a consistent standard for reporting a combination of emissions from Scopes 1, 2 and 3. Recognising that LCA results do not reflect an objective truth should, however, inform the way that we communicate about and interpret them.

This understanding can be particularly important in a regulatory context. Fuel regulations such as the Renewable Energy Directive (RED, European Union, 2018) and the CORSIA emissions offsetting scheme for aviation (ICAO CAEP, 2019) contain sets of rules for assessing the GHG intensity of the fuels supplied under those regulations. Companies supplying fuels within these schemes often quote their regulatory GHG scores as precise values, using them in marketing and in sustainability reporting. This is expected and even intended by the authorities that administrate these schemes, who want to create competition between operators to produce and purchase fuels that achieve lower GHG intensity scores. It can become problematic, however, when there are elements within the LCA rules that either have large associated uncertainties, or where the choice of rules is controversial.

For example, there is uncertainty around the nitrous oxide emissions that are associated with nitrogen fertiliser use in the production of agricultural feedstocks. There is also considerable variability in the rates of nitrogen fertiliser use per tonne of feedstock generated between farms and even between fields. If a regulatory calculation gives a GHG intensity score of 30 gCO_2e/MJ to a given fuel production pathway that relies on nitrogen fertiliser, then it would be more complete to say that "we believe that the average GHG emissions to produce a megajoule of this fuel are probably about 30 gCO_2e/MJ assuming that our characterisation of nitrous oxide formation from nitrogen fertiliser application is fairly accurate" than to say "producing a batch of this this fuel always emits exactly 30 gCO_2e/MJ". The difference in expected nitrogen-fertiliser-related emissions can be quite significant even when following standard practices. For example, Kim & Dale (2008) reported a difference by more than a factor of two between typical emissions for corn production in Linn Iowa versus Macon Illinois, two counties only 350 kilometres apart. If one considered differences between farms and fields with different tillage and nitrogen application practice, and the natural variability in nitrous oxide formation rates, the difference between lowest and highest emissions rates within a given area would be even greater.

The issue of indirect land use change, often abbreviated to ILUC, provides an even more problematic example. ILUC emissions (which are discussed in more detail below) occur when increased demand for agricultural materials causes agricultural expansion, which involves land clearance and loss of carbon stocks from vegetation and soils. Even if the specific field used to produce a batch of biofuel has not been recently converted, we can be confident that when a policy causes millions of hectares of land to be committed to growing biofuel crops, there is bound to be some agricultural expansion somewhere. ILUC emissions are potentially large – some estimates of ILUC emissions for some biofuel feedstocks are greater than the emissions associated with fossil fuel combustion (cf. Malins, 2019a). ILUC modelling can be used to estimate the expected magnitude of these emissions, but not all LCA frameworks include ILUC emissions. Of the two regulations mentioned above, CORSIA does include ILUC emissions in its LCA while the RED doesn't. When an important emission source is excluded from consideration under one methodology, it is clear that to report without context the score calculated under that methodology as factually true and complete is potentially misleading.

These problems are accentuated when companies go a step further and make a claim about the emissions saving delivered by using a given fuel by subtracting their regulatory LCA score from the regulatory LCA score for a substitutable fossil fuel. It is clearly unsatisfactory if the basis for claiming a '50% emission saving' is that another 50% of emissions have been treated as out of scope.

2 Choices and conventions in lifecycle analysis

If you've never thought in detail about lifecycle analysis, you might think that it is a simple, albeit time consuming, question of identifying the emissions sources and sinks all along the supply chain and adding them up. It may be surprising to realise that the results are shaped by numerous methodological decisions that need to be made all along the supply chain. Again, let us start by thinking about a crop-based biofuel production system and how we might characterise emissions that occur at the farm.

A basic question to address is how fuel suppliers will be asked to trace information from the farm up the supply chain. Will farmers be asked to record the exact rate of agricultural inputs used on each individual field, or only as an average for each crop, or could they be allowed to use average values across all crops produced by the farm? What sources of information can be used to identify the embedded emissions and chemical carbon content of any given input – is an organised system of lifecycle inventory data to be made available alongside the methodology, or must farmers find values by measurement or in the available literature? Is it proportionate to ask farmers to record farm-specific input data at all, or might we provide tables of default values associated with each crop, or perhaps at the level of the crop in a given region, or for a combination of a crop and a certain soil quality? Would farmers be asked to actively monitor nitrous oxide emissions from the field, or only to monitor the rate of nitrogen application to the field; or will nitrous oxide emissions be based on a default value for the crop and therefore independent of specific management choices made at a given farm? If we monitor the specific quantities of nitrogen fertiliser used on a given field, will we also trace that supply of nitrogen fertiliser to a specified supplier and require that the CO_2 emissions and nitrous oxide leakage from that fertiliser production facility should be monitored, or do we provide default values for fertiliser production emissions? If the emissions are to be specific to a given facility, should they reflect an average emission intensity over time or should they be assessed for the period in which a given batch of fertiliser was actually produced? If a plant was experiencing technical problems during a given period should they be considered in the assessment, or should the emission values only reflect operations at designed specifications? The same type of questions about the required level of detail in emissions tracking and reporting can be applied to every stage of the supply chain: use of on-farm machinery; application of pesticides; transport and storage of produced feedstocks; and so on.

It is easy to see that dozens of methodological decisions can quickly stack up even when considering just a single fuel supply chain, and that each of these decisions has the potential to affect the results of the calculation. Some of these choices may have only a minor effect on the final results; some could have a large effect. Some choices may have only a small effect in most cases but be more important for a few specific cases.

In order to provide an indication of good practice in the development of lifecycle analysis methodologies, the European Commission curates the European Platform on LCA and the International Life Cycle Data (ILCD) system (European Commission, 2012). The ILCD Handbook (Joint Research Centre, 2010) conceives lifecycle analysis as a bespoke iterative process, whereby a goal for the work is established and then on that basis the scope for the analysis is determined, lifecycle inventory data is gathered, the magnitude of the relevant emissions sources and sinks is established, sensitivity is investigated, and then the scope and model are fine-tuned further until a satisfactory outcome is reached. This active process of defining goals and exploring sensitivity contrasts markedly with the form of lifecycle analysis that is required by biofuel legislation, under which the goal and scope have already been defined (perhaps only implicitly) by the legislator, and where (in the EU and UK frameworks at least) a system of allowable default assumptions is available.

The ILCD handbook conceives the definition of a goal as the key first step of any lifecycle analysis. The first aspects to be considered in setting a goal for an analysis is: "Intended application(s) of the deliverables / results". In the case of lifecycle analysis of transport fuels, where the underlying goal is to establish the climate benefit that could be achieved by increasing alternative fuel supply, one way to state the intended application would be, "Comparative assertion of the overall climate change impact associated with production and use of renewable fuels (Option I) or fossil fuels (Option II) in the context of a mandate for the use of renewable fuels". In practice, however, practical considerations may be implicitly imposed on a lifecycle analysis framework in a way that alters the goal statement. For example, in a regulatory context the minimisation of regulatory burden is often considered important, and is one of the main reasons to provide default assumptions. We might then have to add to the goal statement a qualifier like, "…following a methodology that allows a result to be reported by someone without professional LCA experience with minimal commitment of time". This implied combination of goals that are not aligned implies that compromises will need to be made, whereby the quality of the result is balanced against the desire to make it simple to compute. A potentially conflicting goal in regulatory LCA is the desire to create an incentive for fuel producers to deliver marginal reductions in the GHG intensity of their fuel production systems, for example by greater energy efficiency or by reduced application of inputs. If producers are permitted to use defaults for certain values this can undermine or eliminate any incentive to improve performance on those parts of the process.

The compromises that are required in regulatory LCA therefore imply limitations, and indeed the second aspect that the ILCD Handbook says should be considered in setting goals is, "Limitations due to the method, assumptions, and impact coverage", stating that, "If the goal definition implies specific limitations of the usability of the LCA results due to the applied methodology, assumptions made or limited impact-coverage, such shall equally be clearly identified **and later be prominently reported**" (Joint Research Centre, 2010). In the context of regulatory LCA, this imperative to be open and explicit about the limitations in results comes immediately into conflict with the desire to use simple messaging when companies and regulators communicate about renewable fuel use – and indeed the desire to communicate positive messages. The average marketing professional would much rather make the statement that "Our fuel cuts greenhouse gas emissions by 80%" than the statement "Based on the regulatory LCA requirements of the RED, which allow the use of default assumptions in preference to actual supply chain data and which treat indirect land use change emissions as out of scope, we are permitted to report to the competent authority that our fuel has an LCA score which is 80% below the LCA score assigned to the comparator fuel". Similarly, the average politician would much rather say "Our biofuel policy delivered GHG savings equivalent to taking one million cars off the road" than say "Biofuel delivered under the biofuel policy reported LCA scores that were on average 60% below the LCA score assigned to the fossil fuel comparator, but given uncertainties in the LCA inventory data and the exclusion of some emissions sources from the scope of the analysis it is not currently possible to say with confidence whether the policy has delivered any net GHG benefit." In short, there is a predictable tension when LCA is used in a regulatory context between what is considered best practice in how to communicate about LCA results, and what the people actually deciding how to communicate LCA results want to say.

2.1 Scope

Scope is enormously important in emissions analysis, because setting the scope of an analysis is the basis for determining which emission sources and sinks should be counted and which might be excluded, and how these sources and sinks should be assessed. The ILCD Handbook places scope definitions for an LCA as the second stage of the process after the definition of the goals – the determination of the scope must be informed by the goals of the analysis. Scope includes setting the system boundary and defining the methodology for the analysis, such as whether inputs are rated based on average emissions for the input in question across the economy or based on a specific facility.

An example of a form of emission assessment with a very constrained scope is the EU Emissions Trading Scheme (ETS). Under the ETS, industrial facilities are required to monitor and report the GHG source and sinks that are within the spatial limits of a given installation, an approach comparable to Scope 1 reporting for company emissions. Under the ETS, facilities are not required to assess the GHG intensity of inputs brought from outside the installation for use in a process, nor of the production, construction or installation of buildings and capital goods, nor of the later use of the products produced at the installation. Emissions associated with processes upstream or downstream in the supply chain are either associated with a different facility under the ETS or fall outside the scope of the ETS entirely. Lifecycle thinking is different because it calls on us to consider those upstream and downstream emissions, and requires that an LCA should have a rather broader scope than this; but there is no single recognised choice for exactly what should be considered in-scope for a lifecycle analysis.

Some decisions are, however, common to all or almost all LCA frameworks used to assess alternative fuels. All LCA frameworks for fuels consider emissions from fuel combustion for energy at the fuel production site. They include emissions associated with fossil fuel combustion and for nitrous oxide releases associated with fertiliser use at farms – but in some frameworks this may be a notional 'typical' farm while others may encourage assessment of the specific farm at which a batch of feedstock is produced, and consequential frameworks (see below) may aim to assess only the farms that increase production when overall demand increases. The frameworks also include some characterisation of GHG emissions associated with the consumption of electricity or heat produced, and some characterisation of the emissions embedded in the production of non-energy inputs.

Similarly, some things are excluded from all or almost all LCA frameworks, or at least all of the regulatory ones. For example, to the best of our knowledge emissions from manufacturing farm equipment and capital goods for industrial installations are excluded from all regulatory LCAs and most other published biofuel LCAs. Albedo effects, whereby rates of warming are changed by the ability of the crop being grown to reflect sunlight back towards the sky, are only considered in a few academic studies. One justification for excluding an emission source is that it is expected to be small. For example, the emissions from constructing a barn that could be in place for thirty years may be small when amortised out over thirty growing seasons. Another justification sometimes used to rule emissions out of scope is consistency. For example, consider the case of undertaking a lifecycle analysis of a small pilot fuel production facility using a new technology. If you were to include the emissions from equipment manufacture they may be quite a large term, because equipment for a pilot project is likely to be bespoke and because it is likely to be in use for a much shorter period than commercial scale equipment, meaning the emissions would be spread over much less produced fuel. To include those emissions when comparing against a commercial scale system would mean that we would tend always to assess new technologies as having a higher GHG intensity than would be achievable after commercialisation, which could distort our decision making.

Sometimes a scoping decision is taken in one context because an emissions source is identified as negligible, but can then be exported to a different context where it may not be negligible. This may be done in ignorance (those implementing the scoping rules do not appreciate the difference in significance of a given emission source between cases) or can be justified by following principles of nominal consistency or fair treatment (we could say that, "we don't count emission X when we assess product Y, so we should also ignore it when we assess product Z"). For example, emissions from construction and capital goods are generally ignored in LCA of fossil power generation, because these emissions are expected to be negligible for a coal or gas power plant when they are divided across all the electricity that will be generated by that plant. This LCA choice can then be carried over and applied to renewable power generation with solar panels in order to be consistent, even though these emissions may be much more significant for solar panels – for example Schmidt et al. (2016) suggest a typical emission intensity value from manufacture and construction for solar panels of 27 gCO_2e/MJ[5]. Ignoring these emissions associated with solar panel production and solar farm construction simplifies the calculation, and might be seen as 'forward looking' because as the production of energy is completely decarbonised the emissions for producing new solar panels will also be reduced. Making this simplification allows us to refer to solar energy as 'zero carbon', but ignoring significant emission terms can distort the results of analysis in important ways. For example, in the case of the production of e-jet where a process may have only 50% energy conversion efficiency, treating solar energy as zero carbon would allow us to assess e-jet as having an LCA score close to zero, but treating solar energy as having a GHG intensity of 27 gCO_2e/MJ would result in e-jet from solar electricity an LCA score of at least 54 gCO_2e/MJ (doubling 27 gCO_2e/MJ because of the 50% efficiency, and then adding any other associated emissions sources).

There are also sources and sinks that are excluded from some major LCA frameworks but included in others. In the context of alternative fuels, the most important emissions in this category are indirect emissions such as indirect land use change (see also section 2.3.3). Indirect emissions are emissions that we expect to occur, but where there is a question mark about whether it should be considered fair to attribute them to a specific producer and that are often subject to considerable uncertainty.

2.2 Attributional versus consequential LCA

There is a fundamental distinction in LCA between two types of approach, which are referred to as 'attributional' and 'consequential' respectively, and these two approaches can lead to very different numerical results if applied to the same set of processes.

2.2.1 Attributional

Attributional LCA (which the ILCD handbook notes is sometimes also described as 'accounting', 'book-keeping', 'retrospective', 'descriptive', 'average' or 'non-marginal' LCA) identifies the emissions that are associated with the production of a given product within a system that is modelled as static, i.e. a system in which we do not treat anything as changing.

---

[5] The emissions intensity is a function both of the emissions involved in manufacture for a given solar panel and of the amount of electricity generated by that panel, and therefore will vary with the location, orientation etc. of a panel.

The philosophy of the attributional approach has much in common with the philosophy behind national inventory GHG accounting. In national inventory keeping if the UK stops producing steel, then the emissions from steel production are no longer attributed to the UK, even if a predictable consequence of the UK closing its steel works is that steel production increases elsewhere. Under attributional LCA, when wheat that would normally be supplied for livestock feed gets sent to an ethanol plant instead, we assess the wheat production process but don't consider what will replace that wheat in livestock rations.

Within the attributional paradigm, it is possible to base the lifecycle inventory on either specific data ("Company X supplied us with this input, and therefore we shall specifically assess the GHG intensity of Company X's process") or on average market data ("Company X supplied us with this input, but next week we might get it from Company Y instead, so we'll base our lifecycle inventory on the average GHG intensity to produce that input across all companies"). Market data could also be averaged at any geographical scale, for example we might calculate an average GHG intensity for wheat farmed in East Anglia, or in the whole of England, or in the whole of Europe. It might be averaged at a conceptual level, for example if we were committed to source only organic wheat we might look for an average GHG intensity for only organic farms in Europe. The ILCD handbook states that it is preferred to use producer specific data for a given input where the producer is known.

The development of a lifecycle data inventory for an attributional LCA is relatively well defined. Depending on the level at which the LCA practitioner decides to operate, it requires sourcing either specific data about actual use of energy and inputs and rates of emissions at specified facilities or gathering data about average use of energy and inputs and rates of emissions across some set of facilities. The acquisition of the relevant data may be obstructed by concerns of data confidentiality, and it is possible for data to be accidentally or purposefully misreported, but it is clear what the data requirements are.

Within attributional LCA it is sometimes necessary to allocate the emissions from all or part of a supply chain between multiple outputs. For example, a complex consisting of corn farms and an ethanol refinery might produce streams of: ethanol for fuel; distillers' grains for livestock feed; distillers' corn oil for biodiesel production; corn stovers for livestock forage and bedding; and carbon dioxide used in fizzy drinks. If all of the emissions from corn cultivation are allocated to the ethanol stream and none to the other streams, this might be considered to unfairly penalise the ethanol while allowing the other materials to be given an unduly favourable presentation as 'zero carbon'[6]. On the other hand, if large fractions of the emissions are allocated to low value products such as corn stovers this might lead to results that seem unduly favourable to ethanol, especially if the ethanol is being sold in a market where the GHG intensity has a value and the corn stover is sold in a market where the GHG intensity is ignored.

The output streams from a production system are therefore commonly divided between 'co-products' and 'residues' (cf. ICF International, 2015). Some systems also include an intermediate category of 'by-products', and output streams with no further use can be identified as wastes. Co-products are the output streams that have enough value to be considered the main aims of production, while residues and wastes are the output streams that are considered incidental, i.e. the total volume of output from these production systems is defined by demand for the co-products and is insensitive to demand for the residues. Emissions are then allocated between the output streams that are considered to be co-

---

[6] The idea of a zero-carbon stream of carbon dioxide might be a little counterintuitive, but what we mean is a stream of carbon dioxide to which we do not allocate any lifecycle production emissions.

products (i.e. ‘main aims of production’), while if the residues are supplied for an application where GHG intensity is relevant they are assigned zero embedded GHG emissions.

Emissions can be allocated based on a number of different parameters. Standard options are to allocate according to the mass of the co-products, according to the energy in the co-products or according to the economic value of the co-products. Each of these approaches has advantages and drawbacks. The main drawback of mass-based allocation is that mass is not necessarily a good indication of what the most important co-product is. For example, our ethanol refinery would produce more mass as distillers’ grains than as ethanol, but we generally understand that ethanol is the primary output and so it would seem odd to allocate less than half of the emissions from the system to the ethanol. The advantage of mass as a characteristic though is that it is very widely applicable – all of the possible output streams except heat and electricity have a mass, and therefore using mass might be seen as allowing consistent treatment of a wide variety of products. The advantage of energy allocation compared to mass is that often chemical energy content can be seen as a better proxy for which co-product is most important, especially when we are focused on renewable energy. Like mass, energy content is applicable to a wide range of products. Energy can be more difficult to use for materials than mass in practice, as it is more difficult to measure precisely – any material can be easily weighed, but not all materials have a consistent energy content. It is not appropriate for inert substances[7] but can be used for energetic outputs like heat, electricity or steam. It still may not, however, give a really good proxy for the actual relative value of two products, as it does not distinguish the utility of different sorts of energy (e.g. electricity is worth more per megajoule than low temperature heat, ethanol is worth more per megajoule than straw is). Allocation by economic value provides a basis to allocate emissions based on which co-products are actually considered the most important by the producers, and therefore is identified as preferable to energy or mass-based allocation in the ILCD handbook. The downside of economic value allocation is that prices change, it may be difficult to identify a single reference market price for a given product, and relative prices can sometimes diverge rapidly so that the allocation of emissions for a given process could change day to day.

The choice of allocation approach can make a significant difference to the emissions allocated to particular co-products. For example, Morais et al. (2010) presented LCA results for biodiesel production from soybean oil showing that the allocation of agricultural emissions to the biodiesel co-product (as opposed to the soy meal co-product) was two and a half times greater using value or energy allocation compared to mass allocation.

2.2.2 *Consequential*

Consequential LCA (which the ILCD handbook notes is sometimes also called ‘change-oriented’, ‘effect-oriented’, ‘decision-based’, ‘market-based’ or ‘marginal’) identifies the changes in emissions that occur across the economy as a result of some decision or change, for example the decision to increase the supply of biofuels. The ILCD handbook notes that “The consequential life cycle model is hence not reflecting the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain is modelled that is prognostizised [sic] along market-mechanisms, and potentially including political interactions and consumer

---

[7] So for example it does not provide a basis to allocate emissions to a CO_2 stream, and in principle one could have a process outputting gold as half of its product mass and would allocate no emissions to the gold!

behaviour changes." A consequential LCA assessment requires comparing emissions between two scenarios, one including the change of interest (e.g. an increase in biofuel consumption) and a counter-factual scenario in which this change does not happen.

Consequential modelling approaches require some basis to identify and quantify 'marginal' processes – i.e. the identifying of which processes will expand production of outputs in response to the given change. A simplified example can be constructed to illustrate this point. Imagine that a small country with no external trade has two ethanol plants labelled A and B. For this example, we will ignore feedstock and consider only the GHG intensity of the ethanol production process. In the baseline (the starting conditions before a change takes effect): Plant A has a GHG intensity of 10 gCO_2e/MJ, a production capacity of 10 thousand tonnes a year, and the capacity is 100% utilised; Plant B has a GHG intensity of 40 gCO_2e/MJ, a production capacity of 10 thousand tonnes a year, and the capacity is 50% utilised. Now, imagine that a government department decides to reduce its climate impact by sourcing 5 thousand tonnes a year of ethanol from Plant A, choosing Plant A because it has the lowest GHG emissions intensity for its process. In the attributional framing, if we used 'actual' data for Plant A we would conclude that our decision to consume 5 thousand tonnes of ethanol had an LCA score of 10 gCO_2e/MJ. On a consequential view, however, we would observe that Plant A had not been able to increase production to meet the demand for 5 thousand tonnes of ethanol. The only plant that had spare capacity was Plant B, so any marginal increase in production could only happen at Plant B. The additional demand from the government department would force an existing customer to switch from Plant A to Plant B[8]. We might therefore conclude on a consequential basis that our decision to consume 5 thousand tonnes of ethanol had an LCA score of 40 gCO_2e/MJ.

In the attributional system, the government department is able to claim a low LCA score of 10 gCO_2e/MJ by forcing another customer to accept switching to a higher LCA score but this does not reflect the net change in GHG emissions across the country. The actual net GHG emissions are four times more, 40 gCO_2e/MJ. In this simple example, focusing on attributional LCA results would have seriously misled the government department about the consequences of its decision. Plevin et al. (2014) argues that this type of outcome, where attributional results can be highly misleading, is not an occasional quirk of attributional LCA but is in fact a fundamental characteristic of attributional approaches, and that attributional LCA "is not predictive of real-world impacts on climate change, and hence the usual quantitative interpretation of attributional LCA results is not valid."

There is a clear argument that consequential LCA is the better suited discipline if the goal of an LCA is to establish what change occurs in emissions when government mandates the use of an alternative fuel. Why then are attributional LCA results often used when these questions are posed? One reason is that the philosophy of GHG emissions inventories has been firmly embedded in national climate policy by the implementation of the Kyoto protocol. Attributional LCA requires a focus on emissions that we might understand to be 'directly' related to a specific process or operator, which seems consistent with inventory thinking. In the example above with Plant A and Plant B, under the attributional system you can do business with Plant A and you can then assess the GHG footprint of that business based on Plant A's data alone.

The issue of attributional LCA failing to provide a useful characterisation of net changes across a system may also be mitigated somewhat in certain regulatory contexts. Imagine that we

---

[8] In a more sophisticated consequential LCA we would also ask whether the existing ethanol demand could be reduced by increased costs from competition.

added a ‘cap and trade’ rule to our simple example that limited the total combined emissions from Plant A and Plant B through an emission trading system. This regulatory system would change the consequential implications of the government department buying ethanol from Plant A, because Plant B would be forced to reduce its overall GHG intensity to be permitted to produce more ethanol (or Plant B would have to buy allowances from another party that delivers additional GHG reductions). Also, in the simple example above we assumed that the government department was interested in sourcing the lowest GHG intensity ethanol but implicitly assumed that the displaced customer of Plant A didn’t care. In a regulatory system where a cost is placed on lifecycle emissions (or equally where a defined incentive is provided for lower emissions) the government and other customers would compete for access to the output from Plant A, and in the longer term this would create a market driver either for Plant A to expand production or for Plant B to reduce the GHG intensity of its production. In this way, the use of attributional LCA results in a regulatory framework could be seen as creating a market context where reduced emissions would be a longer-term consequence. We still would not be confident that the assigned attributional scores reflected the real net emissions outcomes, but we could at least reasonably expect that the use of LCA in regulation was tending to push net emissions downwards.

The consequential approach requires you to gather information about companies with which you have no commercial relationship and that Plant A may not hold – knowledge about the status of the industry in the country, knowledge about Plant B’s GHG intensity. It takes us into the realm of emissions that are characterised as ‘indirect’ in the biofuels discourse, emissions that are not within the control of any actor in your own supply chain. The data for consequential analysis is not only potentially held by third parties, but the quantity of data required may be much greater than the attributional case. When assessing indirect land use change emissions on a consequential basis, for example, models are used that include simplified characterisations of the entire global economy – clearly a different data gathering proposition than asking a known farmer how much tractor fuel they used last year. Consequential analysis can also be seen as more subjective. Imagine that we added a Plant C to the example above, also with 5 thousand tonnes spare annual capacity. How would we decide whether Plant B or Plant C would be the one to increase production, or whether both would increase production and by how much? Consequential analysis requires developing scenarios for likely future outcomes, and while these can be informed and calibrated by knowledge about past outcomes, there are more ways for the LCA practitioner to impose elements of their world view on the results than there is when undertaking attributional analysis. Finally, consequential LCA is simply harder and more time consuming to undertake when done properly. Plevin et al. (2014) posits that it is entirely normal that when a new analytical methodology such as attributional LCA is first developed it will be presented with a full list of associated caveats (as the ILCD Handbook encourages), but that over time “the method itself takes on a truthlike character” as it moves from an academic exercise to an operational framework (Ehrenfeld, 1997). For all these reasons, it is not surprising that there is a tendency to invoke attributional results to answer questions that they are not well suited to.

2.2.3 Indirect emissions effects

Out of the tension between attributional and consequential LCA approaches, a compromise framing has emerged in the alternative fuels discourse in which emissions are split into the categories ‘direct’ and ‘indirect’. Direct emissions refers to the emissions that occur within the supply chain of a fuel production process and which it would be most possible for a fuel producer to exert some control over. The emissions normally assessed in attributional LCA schemes are generally identified as 'direct'. 'Indirect emissions' then refers to market mediated effects that occur beyond the supply chain of a given fuel production pathway. The most important examples of emissions that are treated as indirect are 'indirect land use change' (ILUC) emissions, emissions from displacement of by-products out of existing uses and avoided emissions from alternative forms of waste disposal. ILUC emissions occur if increased demand for agricultural feedstocks drive expansion in agricultural area and consequent reductions in land carbon stocks (Malins, Searle, et al., 2014). Emissions from displacement out of existing uses occur when materials that are in finite supply (i.e. materials for which production is not responsive to demand) are moved from one application to another and must therefore be replaced by some other material in the original application (Malins, 2017b). Finally, if a counter-factual form of waste disposal results in GHG emissions (for example the landfilling of biogenic waste, which results in methane emissions from anaerobic decomposition) then these can be avoided by taking that waste for biofuel use instead.

The division between direct and indirect emissions is reminiscent of, but not identical to, the division between attributional and consequential analysis. For example, ILUC is generally not included in attributional biofuel LCA, but it would be possible in principle to define some rules to allocate land use change emissions across all agricultural production in an attributional way. Conversely, the emissions categories treated as direct (agricultural emissions, processing emissions etc.) are all categories that would be considered in a comprehensive consequential LCA. Nevertheless, treating direct and indirect as two complementary categories of emissions allows a form of hybrid LCA logic to be proposed, whereby direct emissions are assessed using attributional LCA approaches and indirect emissions are assessed using consequential approaches. This framing has been adopted in a regulatory context in California's Low Carbon Fuel Standard and by the ICAO's CORSIA, wherein a traditional attributional LCA approach is used to characterise the emissions from biofuel feedstock cultivation, transport and processing into fuel, but a consequential approach is used to characterise the emissions from ILUC.

In these approaches, a single ILUC value is applied to all fuels in a given category, which may be defined simply by feedstock (as in the California system) or by feedstock and region of origin (as in CORSIA). Separate values are not calculated for every fuel producer because it is assumed that the indirect impacts of using an additional batch of feedstock will be similar irrespective or precisely where that feedstock was produced. Producers are therefore able to find the relevant ILUC values in simple look-up tables. An exception is provided under CORSIA for specific production systems in which indirect effects are expected to be 'avoided' – these systems are sometimes referred to as 'low ILUC-risk', and are allowed to report zero ILUC emissions.

A hybrid approach is also evident when the benefits of co-product production are assessed using the method of 'system expansion' rather than by allocating emissions to each co-product. In system expansion a credit is awarded based on the ability of a co-product to replace some other material, allowing less of that other material to be produced. There is also interest more recently in applying a consequential logic to estimate the indirect emissions that result from displacing a residual or waste material from an existing use, and this approach has been implemented in the GHG methodology for the EU Innovation Fund (European Commission, 2021) using the language of 'rigid' and 'elastic' inputs.

One obvious criticism of such a hybrid approach is that if attributional and consequential LCA are not suitable for the same types of question, then by combining them you are guaranteed to come out with an approach that is not the optimal way to deal with any specific goal for an LCA. The response to this would be that while such a hybrid LCA is built on a methodologically inconsistent foundation, each part of the hybrid LCA can tell you something that is relevant to decision making, and that it is preferable to either alternative: an attributional-only approach in which important emissions are missed; or a consequential-only approach that is too unwieldy to be accepted by policy makers and industry. Consider the case of biofuels produced from cultivated crops, and imagine that we want to learn something about each of three main lifecycle 'stages' for different biofuel pathways in order to make decisions that will reduce the overall GHG intensity of our biofuel use: stage 1 is the GHG intensity of the cultivation of the crop; stage 2 is the GHG intensity of the biofuel production process; and stage 3 is the GHG intensity of the associated indirect land use changes.[9] For stage 1, we take attributional LCA scores for the production of all the crops we are interested in. We know that these scores could be misleading because when we introduce demand for fuel from a given crop, we don't know for certain whether the market will actually increase production of that crop or of something else (for example we could find that we increase the consumption of wheat for biofuel, and then more corn is grown elsewhere to replace it in livestock diets). While we are not certain that our result is a good characterisation of the 'true' emissions consequences of deciding to use a given crop, we might hope that choosing to process the crop with the lowest attributional cultivation emissions improves our chances or delivering low emissions overall. At the processing stage, if we are considering a large expansion of biofuel production then we might imagine that the processing facility will be newly built because of the new biofuel policy, and in that case it may be justified to treat the attributional LCA score for processing as a proxy for the consequential emissions. Finally, we can take a score calculated in a consequential system for the indirect land use change emissions. If we have different scores for different crops, they provide an indication of which crop choice we expect to drive the least land use emissions. Adding those three numbers together might not be expected to give us a precise or accurate estimate of the 'true' consequential emissions of introducing a new biofuel mandate, but it does give us a score that tells us something relevant about which of a set of biofuel production pathways we would hope might give the best climate outcomes.

One can make a good argument that the results of a hybrid LCA that includes indirect land use change emissions are a better basis to discriminate between biofuel pathways than the results of an attributional LCA that ignores indirect land use change. Just as with an attributional-only LCA, however, there is a temptation to overstate the precision of such results. For example Transport & Environment (2021) includes the statement that it is an "inconvenient fact" that "palm biodiesel is on average three times worse for the climate than fossil diesel", a statement that is based on combining an attributional result for direct emissions with a specific and relatively high consequential result for indirect emissions (231 gCO_2e/MJ from Valin et al., 2015). While this is based on a fair characterisation of the hybrid result for palm oil biodiesel based on that particular analysis, presenting the comparison as a settled fact about relative climate impact is overstating the case a little. It turns out that producing a more simple, more categorical statement instead of a heavily caveated statement is just as appealing for those communicating the message that biofuels are problematic as it is for those communicating the message that biofuels are good!

---

[9] Here we ignore transport and distribution emissions for the sake of the example, as these tend to be less significant.

2.3 Making the difference – from GHG intensity to carbon saving %

In the preceding section, we often used the language of an LCA or GHG intensity 'score', rather than simply stating that a fuel would have a certain GHG intensity. Using the word score in this way is intended to gently remind the reader that an LCA result is a score calculated in accordance with a set of rules, rather than being a characterisation of a fundamental physical characteristic. And as with scores in sport, one of the reasons to generate LCA scores is to allow them to be compared, so that the pathway with the better score can be identified as the 'winner' from a climate change mitigation perspective. When the scores are given in units of gCO_2e/MJ the lower score is the winner, but in alternative fuel policy we are often interested not only in what the scores are for different alternative fuel pathways, but in how these compare to a fossil fuel alternative. We can then calculate a carbon saving % score:

$$\%\mathrm{GHG}_{\mathrm{saving}} = 1 - \frac{\mathrm{LCA\_score}_{\mathrm{alternative\ fuel}}}{\mathrm{LCA\_score}_{\mathrm{fossil\ fuel}}}$$

This predisposition to set some sort of fossil fuel comparator is natural enough, because if alternative fuels are being deployed as a part of climate change mitigation policy it makes sense that we would always want the alternative fuels to deliver GHG savings compared to fossil fuels. It seems fundamental that at the absolute minimum an alternative fuel should only be supported if we believe it has less climate impact than the current fossil option.

In both Europe and North America these comparisons have been given a central role in alternative fuel regulation because minimum requirements have been placed on the reportable GHG emission saving that a fuel should deliver in order to receive regulatory support. Minimum savings requirements are intended to a) reduce the cost of delivering climate benefits through the programme by excluding options that deliver very little benefit for a similar cost, and b) accommodate a certain amount of uncertainty about the true GHG impacts of each fuel pathway – if we think that a fuel is 50% better than fossil fuel but we have understated the true emissions by a third then we would still have some benefit. If we think that a fuel is 10% better than fossil fuel but we have understated the true emissions by a third, then we would be delivering no benefit.

It is obvious why these GHG saving percentage scores have been popular both as a regulatory tool and as a marketing claim, but adding a second LCA result to the calculation introduces an additional set of assumptions and uncertainties, and it also introduces the tacit assumption that when we increase the local supply of alternative fuel by one megajoule we consequently reduce the global supply of fossil fuels by one megajoule. The new assumptions and uncertainties are those that are associated with characterising the lifecycle GHG intensity of fossil fuel production. The largest part of the GHG footprint of fossil fuel use is from the process of burning the fuel itself, and those combustion emissions are known relatively precisely, so there is less uncertainty on fossil LCA values than there often is on alternative fuel LCA values. Nevertheless, there is a range in emissions from oil extraction depending on the nature of the oil well (cf. Malins, Galarza, et al., 2014) and from oil refining depending on the processes used and oil processed (cf. Abella & Bergerson, 2012). When strict numerical thresholds are imposed as 'minimum GHG savings' in a regulation, even a modest difference in the comparator value could make a large difference to the eligibility for support of a biofuel pathway. In the past, the biofuel industry has commissioned work to make the case that the marginal source of additional oil is likely to have a higher GHG intensity and therefore that the comparator value should be increased (van den Bos & Hamelinck, 2014), using a consequential argument in this context.

While the uncertainty in the appropriate level for the comparator value is not negligible, the assumption of one for one displacement of fossil fuel by alternative fuel is arguably more important. The basic theory of change for alternative fuel mandates is that by supplying alternative fuels to the market you achieve a corresponding reduction in the consumption of fossil fuels, thereby reducing GHG emissions from fossil fuel use. At the local level, this assumption of one for one displacement of fossil fuel by alternative fuel seems reasonably well justified. Biofuel mandates tend to impose slightly higher costs on drivers, and therefore one would expect that total local fuel consumption (in energy terms[10]) will either be unchanged or might be slightly reduced after the introduction of a mandate. Globally, however, this outcome is not obvious. A reduction in crude oil demand in one country will tend to marginally increase the availability and reduce the price of oil to other countries, potentially causing a rebound demand increase. Supply dynamics in the oil market are complicated by the role of OPEC (and OPEC+) in restricting supply, but for demand changes due to biofuel mandates to deliver net emission reductions at the global scale they must be matched by consequent oil production reductions somewhere. Research into this question of the global fossil fuel rebound using models has resulted in estimates that fossil fuel consumption is likely to rebound by between about 20% to 50%, although scenarios have been produced where the rebound is almost zero or as much as 90% (Malins et al., 2015). If at the global level one megajoule of alternative fuel replaces only half a megajoule of fossil fuel, then the fossil fuel comparator would need to be halved in order to characterise the net global emission change.

If these fossil fuel rebound results are taken seriously, it calls into question whether the standard regulatory practice of assessing a GHG reduction score to alternative fuels based on an assumption of one-to-one displacement is fundamentally misleading.

2.4 Understanding negative LCA scores

In both attributional and consequential LCA, it is possible to award a negative emission score to some particular product, and therefore estimate a GHG reduction of more than 100% when comparing to a fossil fuel comparator. Examples of potential negative LCA scores for biofuels could include:

- Biofuel crops associated with additional soil carbon sequestration;
- Tree plantations that increase sequestration in biomass on a given land area;
- Biofuels from wastes that are given an avoided emissions credit, e.g. biogas from manure;
- Biofuels for which a negative ILUC number is calculated in a consequential assessment;
- Ethanol where CO_2 released during fermentation is captured and stored.

In any of these cases a negative LCA score can be mathematically correct within the specific LCA framing, but it implies the counter-intuitive result that in such cases if we were to fly using those alternative fuels then we would reduce emissions more the further we flew.

---

[10] To the first approximation it can be assumed that one megajoule of alternative fuel moves a vehicle the same distance as one megajoule of fossil fuel.

The first thing to understand about such a result is that it is always based on the assumption that producing and using the fuel in question leads to at least one other GHG emissions benefit in addition to the displacement of fossil fuel use. From the point of view of inventory accounting, the additional GHG reduction beyond 100% is being delivered in another sector of the economy other than transport – maybe in the waste management inventory by avoiding methane emissions, or in the land use, land use change and forestry inventory by increasing soil carbon stocks or in the industrial inventory by delivering carbon capture and storage at an industrial installation. We could think of this as a sort of 'bundled offset' – buy fuel produced from short rotation coppice and get a free offset certificate for the carbon in the trees.[11] As we discussed above, it is fundamental to lifecycle analysis to consider a broader scope of emissions than are assessed under inventory systems like the ETS. In that context it is not innately surprising that if transport is going to be held accountable for some emissions in other sectors it might also be given credit for some emissions reductions in other sectors. Nevertheless, this idea of GHG reductions being bundled together and counted into the LCA of transport fuels becomes problematic in the context of policy that values emissions reductions in transport more highly than emissions reductions in other sectors.

Consider the example mentioned above of biogas from dairy manure, which is allowed to report a negative LCA score under California's Low Carbon Fuel Standard. This negative LCA score is based on a hybrid LCA in which a consequential assessment is made to identify the emissions that would be caused by the manure resource if it wasn't used for biogas production. The counter-factual in this part of the LCA is that the manure would be allowed to decompose anaerobically generating methane emissions, and therefore a large avoided-methane credit may be included in the LCA. The approved LCA scores for these pathways range from -135 to -530 gCO_2e/MJ. This implies that the GHG benefit from avoided methane emissions is up to 5 times greater than the GHG benefit from avoiding fossil fuel use. If one follows the logic of negative LCA scores to its conclusion, it implies that it is actually beneficial to the climate to take additional car trips using biogas fuel[12], even if the journeys are completely pointless. The further you drive the more biogas fuel you consume, the more biogas fuel you consume the more LCFS credits are generated by the supplier of the fuel, and the more LCFS credits are generated the more the proceeds from selling the credits can be invested into shifting manure resources from open slurry ponds into anaerobic digesters in order to capture the released methane. This is all logically consistent on its own terms, but looking at the issue only through the lens of fuel LCA might obscure alternative regulatory approaches. It should be fairly clear that asking people with natural-gas-powered vehicles to drive around in circles could not be the optimally socially efficient way of managing methane emissions from manure lagoons. If the emissions reductions that can be achieved by managing manure better are so great, this implies that there is a case for direct regulation of the sector rather than dealing with it through generous incentives from unrelated programmes.

Even excluding the possibility that direct regulation could be appropriate in a case like this, the assumptions behind the counterfactual in the LCA may start to break down if the value from the LCFS credits is so great that it distorts the market by discouraging farm operators from using other more-sustainable forms of manure management. The revenue from selling LCFS

---

[11] Note that because alternative fuels do not reduce exhaust CO_2 emissions and so even when fossil fuel displacement is identified as the sole basis for emission reductions from an alternative fuel some additional sink or reduced source outside the transport sector is still required in order for net emissions to be reduced; this is discussed in section 4.

[12] This requires having a car that runs on compressed natural gas, which is relatively common in some parts of the world, for example for taxis.

credits for manure biogas in California has been so generous that campaigners have become concerned that it has significantly skewed the dairy market in California in favour of large dairy herds for which manure biogas is most economically favourable – it has been suggested that manure is actually becoming more profitable than milk for these farms.[13] If the availability of credits fundamentally changes the market it might be necessary to periodically revise the consequential assessment of emissions avoidance.

Whether or not these sorts of bundled offsets distort other markets, they undermine the consistency of policies that assign different levels of priority to emissions in different sectors. Governments have recognised that emissions reductions tend to be more difficult/expensive to deliver in transport than in industry, and therefore the explicit or implied carbon price in transport policy tends to be higher than that in industrial policy. At the time of writing the value of a tonne of CO_2 avoidance by California industry under its cap-and-trade programme was about $30, while the value of a tonne of CO_2 avoidance in transport under the LCFS was about $80. It seems arbitrary to 'upgrade' the value of emissions reductions at dairy farms specifically by allowing them to be counted as transport sector emissions reductions.

The policy implications of negative LCA scores differ depending on whether value is directly dependent on the LCA score (as in California's LCFS) or whether the LCA score is used to demonstrate compliance with a threshold and value is based on quantity of fuel supplied (as in the UK RTFO). In markets such as the LCFS where highly negative scores can deliver large numbers of emissions reduction credits with high value, serious thought should be given to how those negative scores are assessed, and whether the amount of credit that is given for out-of-transport savings in transport policies should be capped somehow.

2.5 Temporality

The emissions associated with the lifecycle of a given fuel do not all occur at the same time. Even within Scope 1, it is possible that emissions associated with a given delivered batch of fuel occurred at different times – for example it is possible that one part of a batch was produced weeks earlier and has been held in a storage tank in the interim. When we expand the scope of a lifecycle analysis to consider the full set of emissions associated with a fuel production process, we may identify emissions sources or sinks that occurred years previously, or that will occur years in the future. We may also identify emissions that occur continuously over a period rather than at a single point in time. For example, emissions associated with building processing plants and machinery may have been incurred a long time prior to fuel production and use. On the other side, if wood is harvested from a stand of trees we may have a relatively immediate CO_2 emission associated with fuel combustion which is offset by a gradual sequestration of carbon over the following decades as the trees regrow.

There can also be cases in which an emission source or sink occurs in relation to an indefinite period of production rather than in relation to a specific quantity of production. This is true of land use change emissions. If an area of land is cleared to create a new agricultural field that will produce corn for ethanol, there is a one-off change in carbon stock due to that land use change, but it's possible that corn could be grown in that field for the next twenty years or for

---

[13] https://www.theguardian.com/environment/2022/feb/04/california-subsidies-biogas-dairy-cows-emissions-climate

the next two hundred[14]. If a peat swamp is drained to create new agricultural land, there is not only a one-off change in vegetative carbon stock on the land but persistent CO_2 emissions from peat decomposition that could continue for hundreds of years in the case of deep peat. Conversely, if a new stand of trees is established on bare land this can result in an increase in average land carbon stock as the trees reach their equilibrium carbon storage.

Lifecycle analysis must include rules for the way that these temporally distributed sources and sinks are added together, and for how emissions from one-off sources or sinks are allocated to the associated outputs. This includes deciding whether to weight earlier emissions more heavily than later emissions (given that the earlier emissions will be warming the planet for longer) and how to deal with the case that an emission source is offset by a corresponding sink several years later so that additional CO_2 is temporarily resident in the atmosphere causing heating. Accounting approaches have been developed that would allow the additional warming caused by temporary CO_2 emissions to be assessed including the use of a 'GWP_{bio}' factor (Baral & Malins, 2014; O'Hare et al., 2009), but these are not currently used in any regulatory context.

In the case of one-off emissions, it is normal in current lifecycle accounting approaches to 'amortise' them over a certain number of years. In EU biofuel accounting twenty years is used, so that when a one-off land use change emission occurs it is 'spread-out' in the LCA over the biofuel produced on that area for the next twenty years. In the U.S., a period of thirty years is used, with the result that land use change emissions are weighted less heavily in U.S. LCA than EU LCA.

Figure 2 provides an illustration from Baral & Malins (2014) of the way that different treatments of temporality can change affect conclusions about the climate performance of bioenergy systems. The three lines show the net CO_2-equivalent emissions over time for a system in which a wooded area is harvested for cellulosic ethanol, after which a short rotation coppice system with a 25-year harvest cycle is introduced. All three lines start with a large emission term associated with initial forest clearance. Emissions performance improves over time as more and more petrol is assumed to be replaced by the produced ethanol. The top line, shown in red, is a characterisation of the net emissions over time treating all CO_2 emissions as equal. For this example, the large initial emissions from land clearance create a substantial carbon debt, but it is paid back after about 175 years of operations, after which the system delivers a net carbon benefit. Note that a system with such a long carbon payback time would not be able to report any GHG savings under an LCA with an amortisation period of 20 or 30 years. The yellow line indicates the net GHG position if future GHG sources and sinks are discounted at a rate of 2% a year. Discounting is a standard practice in financial appraisals to reflect the greater value of receiving a given revenue/paying a given cost now versus in the future, but it does not have a direct physical meaning when applied to CO_2 emissions. Still, the fact that the net position remains permanently negative illustrates that if we prioritise near-term GHG benefits we should not develop bioenergy systems with long carbon paybacks. Finally, the blue line shows the net GHG position if we apply a GWP_{bio} term for temporary atmospheric residence of CO_2. This approach has a defined physical meaning, and it also extends the carbon payback period – it now takes about 275 years of harvesting to deliver any benefit.

---

[14] In practice crops are often grown in rotations, but for simplicity here consider only a continuous corn field.

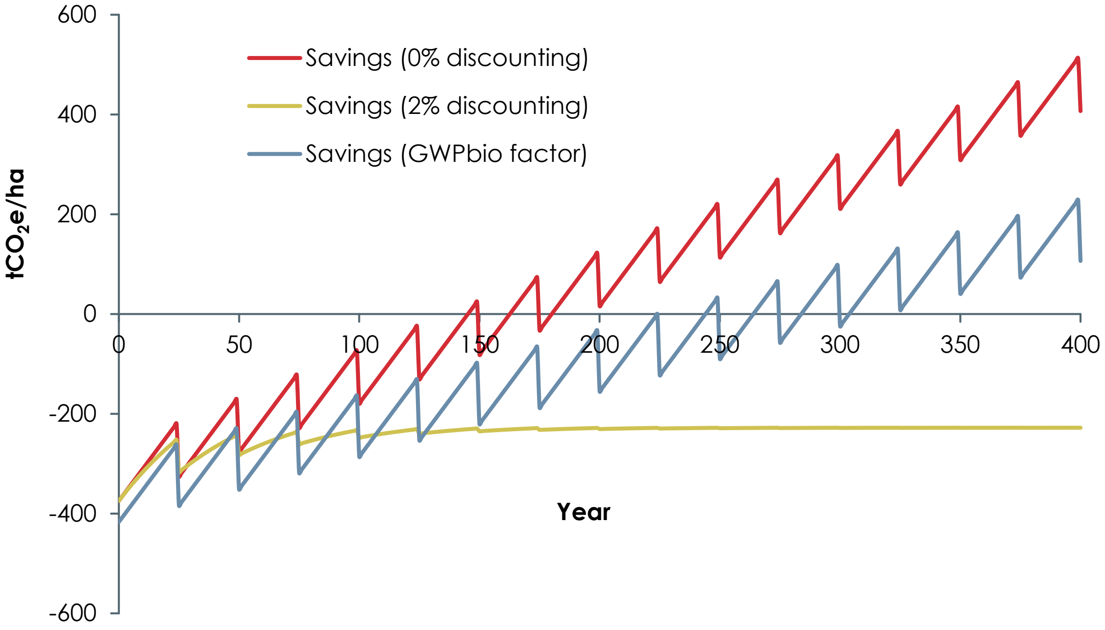

Figure 2 Cumulative emissions change from a system to produce cellulosic ethanol from farmed wood, under three different carbon accounting rules

Temporal concerns also enter GHG emissions accounting if we want to consider greenhouse gases and warming/cooling effects other than CO_2. Inventory accounting under the UNFCCC uses 'CO_2 equivalent emissions' for other greenhouse gases based on 100-year global warming potentials. These are values expressed in terms of the number of kilograms of CO_2 that would exert the same warming effect as a kilogram of the greenhouse gas in question over a period of 100 years[15]. For example, the IPCC's sixth assessment report estimates that a kilogram of methane emissions causes warming equivalent to 30 kilograms of CO_2 emissions over a 100-year period, but that, because methane's warming impact is front loaded, over 20 years its warming impact is equivalent to 83 kilograms of CO_2 emissions. Researchers have also developed other metrics such as the 'Global Temperature Potential' that could be used to compare the warming impact of different types of emissions. The choice of metric and of period affect the relative weights given to different greenhouse gases and other warming effects, and therefore will affect the results of an LCA.

2.5.1 *Timing in consequential analysis*

Issues of timing also become important in consequential analysis when defining counterfactual scenarios, as the construction of scenarios and counterfactuals can change over time. Consider, for example, the case of peat destruction as a form of land use change in Malaysia, which is important in assessing the expected ILUC emissions from oil palm expansion (as oil palms can be planted in drained peat soils). Miettinen et al. (2012) showed that peat loss in Sarawak province was being strongly driven by the oil palm industry, and that if it continued

---

[15] Global warming potentials can also be calculated on different time periods, but the use of 100 year values is normative in lifecycle analysis.

at that rate there may be no peat left by 2030. Full destruction of the peat swamps in Sarawak would be a highly environmentally damaging outcome, but if additional expansion on peat becomes impossible because none is left then peat destruction in Sarawak should no longer be part of an ILUC scenario after that point.

We can also consider an example in relation to the use of waste material as biofuel feedstock. In California's Low Carbon Fuel Standard, a large credit is given for avoided methane emissions when manure is used to generate biogas based on the counterfactual assumption that it would otherwise be kept in ponds that emit methane. If, however, legislation was introduced that banned these methane emissions, then it would no longer be appropriate to include them in the counterfactual scenario, and the biogas would lose the avoided methane credit. A similar case of a changing counterfactual emerges from the EU's rules for assessing the LCA score of recycled carbon fuels (fuels produced from fossil resources that would otherwise not be efficiently utilised). In cases where a material would otherwise be combusted for electricity generation, displacing it into biofuel use leads to a reduction in energy supply, and this can be included as a displacement emission in the LCA. Given that the EU's electricity supply is in the process of decarbonising, however, if that displacement emission is calculated based on an average GHG intensity for EU electricity generation it will get smaller over time. In that way, a recycled carbon fuel might start the decade failing to deliver threshold emission reductions but end the decade achieving them, even with no change in the process.

2.6 Non-CO_2 warming effects

Climate change is driven by greenhouse gases, gases that cause radiative forcing by trapping heat in the Earth's atmosphere. The most important of these is carbon dioxide of course, but other gases generated in smaller quantities such as nitrous oxide, methane and hydrofluorocarbons also cause radiative forcing, as does water vapour. Some gases such as hydrogen do not cause radiative forcing directly but can still contribute to climate change by affecting the atmospheric residence times of other gases (e.g. hydrogen can react with hydroxyl radicals that could otherwise play a role in destroying atmospheric methane).

In the specific case of aviation, the most important non-CO_2 warming effects relate to aviation's contrail induced cirrus cloud formation at altitude, though NO_x[16] emissions also have a significant impact. The inclusion or exclusion of the various non-CO_2 drivers of global temperature change is an important choice that must be made when setting LCA rules. Currently, most alternative fuel LCA frameworks consider three greenhouse gases – carbon dioxide, methane and nitrous oxide. This means that the aviation-specific effects relating to cloudiness and NO_x emissions are not included in the LCA calculations applied to aviation fuels.

A review for the European Commission (EASA, 2020) found that in 2018 these non-CO_2 effects accounted for two thirds of the net warming impact from aviation, with CO_2 from fuel combustion accounting for the remaining third, although there are large uncertainties in these values due to the complexity of the atmospheric physics involved (Figure 3). In the case of cloudiness, it should be noted that the rate of cloud formation is not determined only by the

---

[16] NO_x emissions do not directly cause warming but can generate a warming effect through interaction with ozone and methane.

jet engine exhaust but also by local atmospheric conditions on the plane's route, and therefore warming impact may vary significantly between otherwise similar flights.

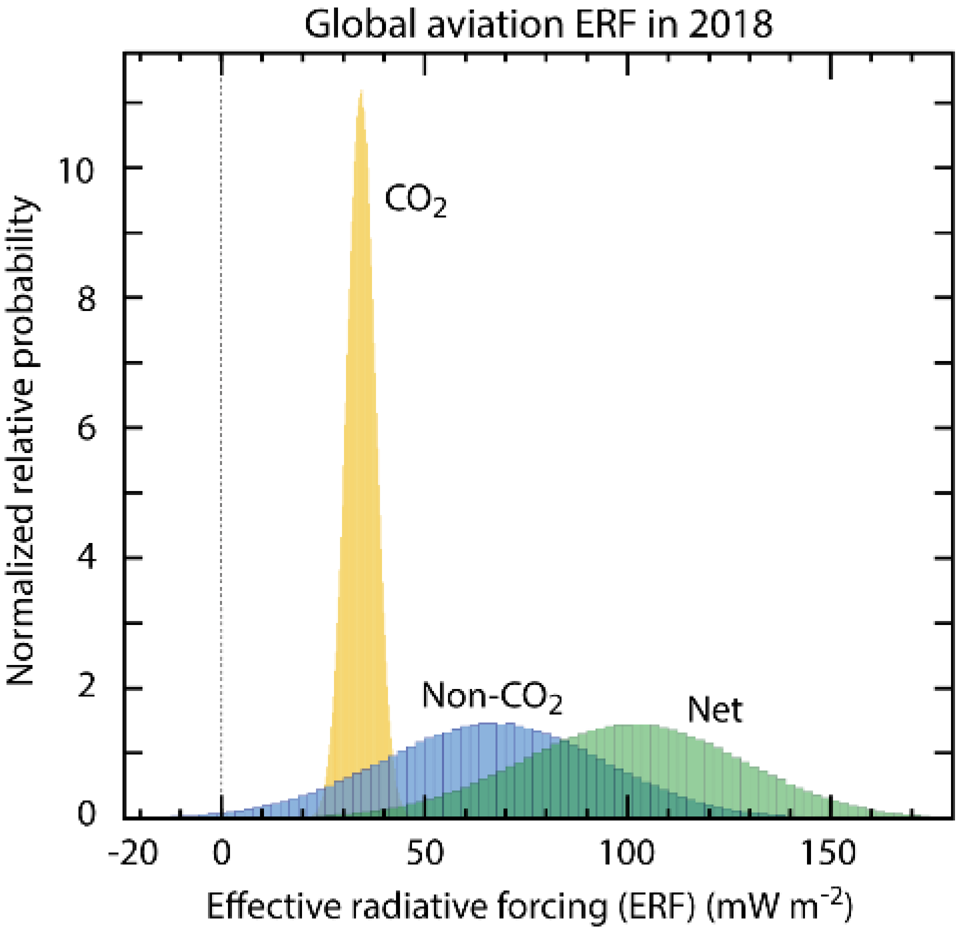

Figure 3 **Estimated probability distribution on the effective radiative forcing from aviation, disaggregated into CO_2 and non-CO_2 warming**

Source: Figure 7 of EASA (2020)

The impact from contrails and induced cloudiness is understood to be related to the soot particle number in jet engine exhausts, and this in turn is affected by the content of aromatic hydrocarbon molecules in aviation fuels (high aromatics content leads to higher soot particle numbers, which leads to increased warming due to induced cloudiness). Current synthetic aviation fuels, including biojet and e-jet, have very low aromatics content, and therefore it is believed that the use of synthetic fuels delivers an additional climate benefit (beyond reductions in lifecycle GHG intensity) due to reduced cloudiness. The precise relationship between aromatics content and the radiative forcing due to induced cloudiness is not yet firmly established, and is believed to be non-linear. EASA (2020) suggests that cirrus forcing could potentially be reduced by 50% by reducing aromatics content by 80%. This means that the overall climate benefit of using synthetic fuels in aviation is likely to be greater than the climate benefit of using the same fuel molecules in road transport. At present, it is not possible to run existing jet engines on zero-aromatics fuels, as the current standard for aromatic content has been assumed in engine design. In future, engines are likely to be made available that are able to operate with reduced or zero aromatics. As well as reducing aromatics through the use of synthetic fuels, aromatics could be reduced by adjusting fossil aviation fuel production processes at the oil refinery.

While there is a fairly clear consensus that non-CO_2 impacts are important and likely to be greater than CO_2 impacts in the medium term (i.e. on the order of decades), expressing cloudiness impacts in the standard units of CO_2 equivalent global warming potential introduces methodological challenges. For one, GWPs are generally presented in relation to mass of emission of a defined pollutant chemical. For aviation cloudiness there is no well-defined "tonnes of chemical X" that we can use as a functional unit for defining a GWP. Lund et al. (2017) suggests a GWP for contrail cirrus normalised to units of CO_2 emitted, giving a contrail cirrus GWP value of 3.1 over twenty years and 0.84 over a hundred years, while (Lee et al., 2021) gives slightly lower values of 2.32 and 0.63 over 20 and 100 years respectively. Assigning GWP values is practical and gives a good comparison point against CO_2 emissions, but most experts on non-CO_2 warming impacts are cautious about implementing regulations that use precise impact quantifiers based on evidence that is characterised by high levels of uncertainty.

The aviation industry is perhaps a little conflicted about advertising the non-CO_2 emissions benefits of alternative aviation fuels. The industry tends to emphasise the uncertainty in estimates of non-CO_2 warming impacts from aviation when it acknowledges them at all[17], and has used this uncertainty as a basis to argue against developing regulations to manage non-CO_2 effects or to hold aviation accountable for this warming. In this context there is little appetite from industry to offer any quantified regulatory recognition of non-CO_2 benefits from alternative fuels. On the other hand, producers of alternative fuels for aviation reasonably see the non-CO_2 benefit as a significant selling point. In particular, the extra non-CO_2 benefits provide a quantitative justification to prioritise the deployment of alternative fuels in aviation rather than in on-road applications. It is often stated by the aviation industry and by many policy makers that alternative fuels ought to be prioritised for aviation as aviation has few other medium-to-long-term options, but this argument is not enormously convincing for the next ten to twenty years. There are still more than enough diesel vehicles on the road to soak up any plausible level of alternative fuel production for the time being, and from a technology deployment point of view commercialising and building up alternative diesel production capacity is a perfectly reasonable starting point for building up the potential for jet fuel replacement in the longer term. Ignoring non-CO_2 effects, the GHG benefits of avoided diesel combustion are similar to those of avoided jet fuel combustion. Non-CO_2 effects could therefore provide a clear justification to support the aviation industry in calling for alternative jet fuel to be prioritised over other modes.

ICAO's Committee on Aviation Environmental Protection identified the recognition of non-CO_2 benefits from alternative aviation fuel as a potential policy tool to support alternative aviation fuels "as the understanding of the science evolves" (ICAO CAEP, 2022). In future, the possibility of including non-CO_2 benefits of alternative aviation fuels in LCA is likely to be a subject of discussion at ICAO and elsewhere.

---

[17] See e.g. https://www.iata.org/en/pressroom/dg-blog/european-politicians-need-to-get-real-about-aviation-and-environment/

2.7 Uncertainty and variability

At about the time that the first RED was being agreed, researchers from the EU's Joint Research Centre published a report (De Santi et al., 2008) which concluded that,

> *"The only major biofuels which we can say are likely to save greenhouse gas (considering indirect effects) are bioethanol from sugar cane from Brazil, compressed biogas and second generation biofuels. For 1st generation biofuels made in the EU it is clear that the overall indirect emissions are potentially much higher than the direct ones whilst they are unlikely to be much lower.*
>
> *"Indirect land use change could potentially release enough greenhouse gas to negate the savings from conventional EU biofuels. However, we do not know even roughly the magnitude of these effects. It depends critically on the policy and effectiveness of control in the regions of the world where the extra demand for crops will result in expansion of farmed area. Certification schemes help, but cannot expect to prevent the problem on a global scale."*

If one takes a step back, it might seem remarkable that a major climate policy should be adopted in the face of significant uncertainty about whether it would deliver a net climate benefit. One study (Ivetta Gerasimchuk et al., 2013) estimated that by 2011 the annual cost of the implied subsidies for biofuel production in the EU was of the order of €10 billion, divided between taxpayers and drivers – this is a costly bill for a policy that might be failing to deliver on one of its main promises. The main uncertainty identified by De Santi et al. is that regarding indirect land use change emissions, but (as noted above) there are considerable uncertainties associated with the relationship between the reportable regulatory LCA value and the true emissions intensity for any biofuel pathway, and indeed any biofuel batch.

Liska (2015) identifies two categories of uncertainty relating to biofuels. Parameter uncertainty relates to the spatial and temporal variability in important parameters required to accurately characterise biofuel production systems, and the fact that there is a lack of information relating to some of those parameter values and even relating to the character of the variability. Model uncertainty relates to the fact that any LCA model is an imperfect replication of a real system. Uncertainty and variability are fundamentally intertwined, and in practice when emissions values are adopted across time (i.e. when LCA values are fixed over multiple years) and across space (i.e. when multiple distributed fields or farms are assigned the same LCA scores or the same default inputs) parameter variability leads to uncertainty about how well the assigned score reflects real outcomes.

Some forms of uncertainty are reduced by considering aggregated results – for example using average values on key parameters could be a source of much more uncertainty when analysing outcomes at the field level (where variability is high) than at country level (where variability is lower). Other issues are more fundamental. (Liska, 2015) identifies nitrous oxide emissions, soil organic carbon change and indirect emissions as major areas of uncertainty, and these are all areas where it is conceivable that improvements in knowledge would cause a systematic shift (up or down) in our best estimates of lifecycle emissions across key fuel pathways.

In the specific context of indirect land use change modelling, Plevin et al. (2010) breaks out model uncertainty into two additional sub-classes in addition to issues of variability: epistemic uncertainty, and decision uncertainty. Epistemic uncertainty refers to fundamental lack of knowledge in relation to some things that are needed to undertake convincing land use change modelling. This includes a lack of knowledge about key model parameters and about functional relationships between processes. For example, economic models require parameters to be entered characterising the extent to which different products are substitutable, e.g. how readily demand for corn can be transmitted into demand for wheat, and there is no single, generally accepted value for such parameters. Similarly, modelling must make assumptions about how (and whether) increases in demand for a product lead to innovation and productivity improvement in the production systems for that product – these relationships are contentious. Any given economic model may include thousands of parameter values each of which could be contested with reference to the available econometric evidence and presumed relationships. Decision uncertainty refers to various subjective decisions about modelling approaches that must be taken once parameters have been established. This can include issues like the choice of crop aggregations or regional aggregations used in a model, the choice of the time horizon considered, whether a model should cover the whole economy or only the agricultural economy, and so on.

In general we hope that uncertainty can be reduced over time in areas of scientific investigation. In the case of biofuels, the understanding and characterisation of key processes may have improved, but important uncertainties still remain and it is unclear whether we are getting closer to the hypothetical true emissions answer. Further work for the European Commission (Laborde, 2011; Valin et al., 2015) on the indirect land use change impacts from EU biofuel policy have failed to resolve the basic question of whether we should believe that EU biofuel policy has delivered net climate benefits.

2.8 Regulatory applications – biofuel LCA in the EU, UK, CORSIA

While the academic and technical discussion of the relative merits of different LCA approaches will continue for the foreseeable future, inevitably the LCA systems that are applied in regulation tend to dominate the wider discourse. It is thus useful to briefly summarise the LCA rules currently in effect for alternative fuels supplied under rules set by the EU, by the UK, and by ICAO through CORSIA. We include a brief characterisation of the treatment of e-fuels – the assessment of lifecycle emissions for e-fuels is discussed in greater detail in section 3.

2.8.1 EU – the Renewable Energy Directive (and the UK Renewable Transport Fuel Obligation)

The LCA rules for alternative fuels supplied in the EU, including under the REFuelEU mandate for alternative aviation fuels, are defined in the RED. The rules under the UK RTFO are based on the RED rules and are still largely identical. The RED rules require either a feedstock level default LCA score to be adopted for each batch of biofuel supplied, or an attributional lifecycle analysis to be undertaken using the equation:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr},$$

The terms in this sum are, in order:

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualised emissions from carbon stock changes caused by land-use change;

e_p = emissions from processing;

e_{td} = emissions from transport and distribution;

e_u = emissions from the fuel in use;

e_{sca} = emission savings from soil carbon accumulation via improved agricultural management;

e_{ccs} = emission savings from CO_2 capture and geological storage; and

e_{ccr} = emission savings from CO_2 capture and replacement.

The last four terms are taken to be zero for most biofuel projects (both for crop-based and waste-based biofuels) – in-use CO_2 emissions are treated as zero under the biogenic carbon accounting convention (see section 4), while most projects will not claim increased soil carbon or be associated with CCU/CCS. The terms for extraction and cultivation of raw materials, for processing, and for transport and distributions are all to be assessed either based on actual data, or by using 'disaggregated' default values for these lifecycle stages that are given in RED, or in the case of extraction and cultivation may be based on regional average values. Default input data to be used is detailed in a report by the Joint Research Centre (Edwards et al., 2019), and there is a calculator tool available to help fuel producers with the calculations (BioGrace, 2017). An element of conservatism is introduced into the calculation by requiring suppliers to add 40% to the expected typical emissions from the processing stage if reporting the default value. Land use change emissions are to be assessed based on typical carbon stocks for relevant land types following rules in Commission Decision 2010/335/EU[18], with land use change emissions amortised over 20 years.

Indirect land use change and any other indirect effects are excluded from this LCA framework. Where processes output more than one co-product, emissions are to be allocated based on relative energy content (unless the output is identified as a waste or residue in which case no emissions are allocated to it up to the point of collection).

2.8.2 ICAO – CORSIA

Similar to the rules under the EU RED, the CORSIA framework allows operators to report either default values or to calculate 'actual values for their fuels following a defined methodology (ICAO, 2022). Unlike the RED, CORSIA requires suppliers to include a characterisation of ILUC emissions as part of their LCA scores. The ILUC emissions are based on estimates produced by ICAO using two models – 'GTAP' and 'GLOBIOM'. Where there is a significant disagreement between the two ILUC estimates the regulatory ILUC value is based on the lower of the two estimates. There is an option to avoid the use of an ILUC factor by getting low ILUC-risk certification.

Other than ILUC, the lifecycle stages to be considered under the CORSIA methodology are similar to those identified in the RED rules. The CORSIA rules delegate the responsibility for checking LCA scores to sustainability certification schemes, and is less prescriptive about the inventory data to be used than the RED rules are. As under RED, emissions are to be assigned

---

[18] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32010D0335

between co-products on an energy basis (but not to by-products, residues or wastes, which are assigned zero emissions up to the point of collection).

2.9 Defaults and cherry picking

In section 2 we discussed the importance of goal setting in lifecycle analysis, and how the use of LCA for regulatory purposes may require the introduction of simplifications and accommodation into the LCA approach – in short, that the optimal approach for an LCA with the goal,

> *Identify as accurately as possible the change in global net GHG emissions associated with increasing demand for a given biofuel pathway,*

will not be the same as the optimal approach for an LCA with the goal,

> *Provide a characterisation of the GHG emissions associated with the processes in a given fuel pathway, which can be used in a regulatory framework and that follows a methodology that allows the reporting of default emissions values at both the pathway and sub-pathway level.*

It is not 'wrong' that regulatory approaches should be different from the optimal approaches for policy analysis – but it is inappropriate if having made simplifications with a view to reducing regulatory burden those results are then presented as best possible estimates. The UK's Renewable Transport Fuel Obligation provides an example of a regulatory implementation of attributional biofuel LCA that is based on the LCA rules of the RED. As a compromise to allow results to be reported by fuel suppliers based on minimal administrative effort, they are given a degree of leeway to decide what level of data to use in their characterisation of their fuel supply chains (DfT, 2018). Suppliers may use default values accessible through a carbon calculator tool or through published spreadsheets, they may report detailed data characterising actual input use and emissions throughout their supply chain, and they may compromise by using a combination of default inputs and 'actual' inputs for different parts of the lifecycle[19]. For crop production, suppliers are allowed to use feedstock level average values, regional average values, or values specific to the source farm. The use of default values is somewhat limited in practice because not all default values are consistent with meeting the regulatory thresholds for minimum reportable GHG savings. If the default emissions estimate for a given pathway is too high, then a supplier is forced to improve the resolution of the data in order to report lower emissions and to be awarded certificates. In this way, the intention is that the burden of actual value reporting is only imposed as an effectively mandatory requirement on suppliers of fuels that are expected to have higher reportable LCA scores.

Allowing the selective use of default values and giving the choice of where to use defaults to fuel suppliers creates a potential problem of 'cherry picking'. Economic operators have an interest in reporting the lowest possible LCA score for their pathways, and receive no benefit from reporting a score that is more accurate but higher. Cherry picking occurs if suppliers report actual values only for those parts of the supply chain where performance is better than default. For example, if a particular biofuel pathway involved feedstock production that used lower than average rates of nitrogen fertiliser but feedstock processing that used more energy

---

[19] Although this is somewhat constrained (for example one may not report that no nitrogen fertiliser was used and then use a default value for crop yield).

than the default, the supplier might report actual data only for the farm. Suppliers may also be able to cherry pick the level of data to use if there are options for different tiers of default assumptions – for example, if regional average values for on-farm emissions are more favourable than either on-farm actual data or feedstock-level default values, it makes sense to report those regional values.

The potential for cherry picking of data can be managed somewhat through the use of conservative default values, i.e. default values for each lifecycle stage that are higher than the expected average. When defaults are made conservative there are fewer pathways that perform worse than the default, and more incentive for better performing pathways to report actual data. The RTFO and RED have a simple element of conservatism built in by inflating the default values for the fuel processing stage above the expected average value, but this does not affect the on-farm emissions calculations. Making default values less favourable also strengthens the role of the LCA calculation as a driver for the adoption of practices that reduce emissions. At any lifecycle stage, there are measures that feedstock producers and biofuel processors can take to reduce GHG intensity – this could be improving the efficiency of mechanised processes, using renewable energy instead of fossil energy, optimising the use of inputs etc. If adopting these improvements results in better treatment for a fuel under the regulatory framework, then producers are much more likely to adopt them. This role of attributional LCA acting as a driver for improved performance is strongest in regulations where the number of certificates awarded per fuel batch is proportional to the reportable GHG reduction delivered. This includes the RED implementations in Germany and Sweden, and Low Carbon Fuel Standards (LCFSs) in California, Oregon and British Columbia. Even if attributional LCA does not necessarily provide a good indication of the net emissions impact of increasing the use of a given fuel, it can be used to create incentives to make reductions in the GHG intensity of specific processes.

Another form of cherry picking (cherry picking of feedstock or produced fuel rather than cherry picking of data, which is sometimes referred to as fuel shuffling) can occur when a feedstock or fuel has two or more potential markets (e.g. food and fuel), and where only one of those markets is sensitive to GHG intensity. In an attributional system it makes sense for the batches of feedstock with the lowest reportable GHG intensity to be designated as biofuel feedstock, and the batches of feedstock with higher GHG intensities to be designated as food. Of the fuel produced, it is rational to supply the batches with the lowest reportable GHG intensity scores in jurisdictions that make the incentive proportional to reported GHG benefit, and the batches with higher reportable GHG intensities to jurisdictions where there is no reward for better performance.

Mass balance accounting[20] means that in a well-coordinated supply chain it will be possible to ringfence the most favourable LCA data from a production system for reporting under biofuel regulations, without having to actually interfere at all with any physical movements of feedstock. Consider, for example, two equal batches of palm oil that are produced in Indonesia by the same palm oil company and then trucked to the same port for shipping to Europe, and assume that when actual data is used in the LCA assessment under a regulatory system the first batch would be assigned a score of 15 gCO_2e/kg of palm oil and the second batch would be assigned a higher score of 45 gCO_2e/MJ. When the tanker shipping the palm oil arrives at Rotterdam, half of the palm oil can be taken off the ship and supplied to a biofuel

---

[20] Where it is not necessary to segregate the transit of a batch of feedstock/fuel through the supply chain from start to end.

plant and report feedstock emissions of 15 gCO_2e/kg, and the other half of the palm oil can be supplied to a food processor where the GHG intensity has no regulatory relevance.

3 Assessing the lifecycle emissions of e-fuels

While the considerations detailed in the previous chapter can be relevant to all forms of renewable fuel production, we focused on issues such as indirect land use change that are most relevant to biofuels. While the vast majority of alternative liquid transport fuels produced in the past has been biofuel, there is increasing interest (at the time of writing) in the potential of 'e-fuels'[21], meaning liquid fuels synthesised from electricity via the process of hydrogen production by electrolysis. A simple renewable e-fuel production system consists of a renewable power facility such as a windfarm or solar farm, an electrolyser unit producing hydrogen from electricity, and a fuel synthesis unit producing e-fuel from hydrogen. The fuel synthesis step could be based on Fischer-Tropsch synthesis of hydrocarbons or could be based on initial synthesis of a less complicated molecule such as methanol with the potential for further conversion to a drop-in liquid fuel – for aviation fuel, it is simply necessary that chemical processes are used that output fuel molecules that meet aviation fuel standards. There is also the option to produce ammonia, which is considered appealing as it can be combusted (or used in a fuel cell) without any exhaust emission of CO_2 and is being considered for shipping applications in particular (Malins, 2018).

Part of the perceived appeal of e-fuels is that many of the most significant sources of uncertainty in biofuel LCA are avoided – for example, in general there are no significant nitrous oxide emissions, minimal required soil disturbance and any indirect land use change emissions should be at least an order of magnitude lower because the rate of energy generated per area of land is an order of magnitude higher[22]. There are no annually or geographically varying rates of application of fertiliser and pesticides, and while there may be significant annual variation in power output at a given location there are no harvest failures and no crop rotations to take account of.

It can easily be demonstrated that the most important term in the lifecycle analysis of e-fuels is the GHG intensity that is attributed to the electricity used in the electrolysis process (Malins, 2017c), as this is by far the largest energy input (the additional energy required for the fuel synthesis step is relatively modest). Roughly speaking about half of the energy in electricity is converted into chemical energy in liquid fuel by an e-fuel process[23]. One implication of this is that both the GHG intensity per unit of energy and the cost per unit of energy are doubled going from the electricity input to the liquid fuel output.

In the case of fossil power, there is also an energy loss in the original process of power generation, and therefore the overall efficiency of a process to go from fossil fuel to electricity to e-fuels would be very poor. For example, the efficiency of electricity production from natural gas might be 40%. The GHG intensity of natural gas combustion is about 56 gCO_2e/MJ, and if electricity is produced from natural gas with an efficiency of 40% the output electricity

---

[21] These are also sometimes referred to as electrofuels, powerfuels, or (in the EU regulatory context) as RFNBOs (renewable fuels of non-biological origin).

[22] There is also no need to use high quality agricultural land for renewable power production.

[23] Perhaps a little less for currently available combinations of low temperature electrolyser and fuel synthesis technology and a little more for potential future pathways using high temperature electrolysis.

therefore has a GHG intensity of at least 140 gCO_2e/MJ[24]. This is already higher than the lifecycle GHG intensity of a liquid fossil fuel, for example the RED uses a value of 94 gCO_2e/MJ as the fossil fuel comparator. If this electricity is used to produce e-fuels with an efficiency of 50%, then the output GHG intensity of the e-fuel would be at least double 140 gCO_2e/MJ, i.e. at least 280 gCO_2e/MJ. That's about three times worse than the GHG intensity value on the oil-based fuels we would like to replace. Even at a 50:50 mix of natural gas power with zero carbon renewable power we would end up with an e-fuel that had a higher GHG intensity than a conventional liquid fossil fuel. This means that e-fuels only make sense as a climate change measure if the power used to produce them is not fossil based and has a very low associated GHG intensity. In the RED and the REFuelEU regulation, it is intended that low GHG intensity electricity should be guaranteed by requiring that the power for e-fuels is 100% renewable.

3.1 When can electricity be counted as renewable?

For many years the idea of renewability has been used semi-interchangeably with the idea of low climate change impact. Renewable energy production doesn't require burning fossil fuels[25], and therefore we expect that if energy is identified renewable it is low GHG intensity. This heuristic is generally pretty reasonable. Replacing coal power stations with solar farms, or natural gas boilers with heat pumps, makes a lot of sense from a climate change mitigation perspective. The idea of renewability becomes more complicated though when it starts to be treated as a tradable characteristic. In the consumer energy market, for example, it is now possible to commit to buying '100% renewable energy' and face similar prices to other non-renewable customers. The customers on these deals do not, however, only receive electrons that have flowed directly to their homes from the nearest wind turbine. Instead, these nominally renewable deals are managed through a system of tradable 'guarantees of origin' (GOs). A GO is a sort of certificate that can be claimed by the generator of each unit of renewable electricity, and which can then be sold on to an electricity supplier and eventually surrendered when a unit of electricity is supplied to a renewable energy consumer. It is a system that prevents electricity supply businesses from selling the same unit of electricity as renewable multiple times. It is a flexible system, because the power consumption and power generation associated with a given certificate do not have to happen at the same time, or even physically close to each other. The generation of GOs complements a range of other incentives and requirements for renewable power expansion. Historically, the value of GOs has been very small compared to the value that is needed to allow renewable power generators to compete with fossil power (Timpe et al., 2017) because GOs have not been a major revenue source for the renewables industry – GOs have simply been awarded to power generation that would probably have happened anyway due to other policy drivers. In short, under current market conditions signing up for a renewable tariff makes a modest contribution at best to driving the expansion of renewables[26].

---

[24] Other GHG emissions at the power plant, e.g. from natural gas leakage or from energy use for operations, would make the GHG intensity value even higher.

[25] At least not directly – there may well still be some fossil fuels used at points of the lifecycle of a renewable energy system.

[26] Although there is some sign that GO prices have started to become more relevant in the EU, https://www.newpower.info/2023/02/guarantee-of-origin-price-rise-could-fund-major-investment-in-renewables/

In the consumer market, knowing that the electricity that you buy as renewable is pretty much the same as the electricity that your neighbour buys as non-renewable may be a little disappointing, even more so when you know that your green tariff may have made little contribution to getting new power capacity deployed. In the e-fuel market, however, treating the wrong electrons as renewable would be disastrous. Given that there is already an excess of GOs available at low prices, e-fuel producers could buy GOs to claim that the electricity they consume is renewable at low cost without changing the underlying electricity mix, and in particular without pulling additional renewable electricity capacity into the system. We could therefore expect that in practice a lot of the electricity used for e-fuels was effectively fossil power, and that this would mean that net emissions would go up rather than down as e-fuel production increased (Malins, 2019b) – hardly a successful climate measure. This shortcoming of the GO system is acknowledged by the European Commission – it's simply not what GOs were designed for.

If the existing system of GOs is not fit for showing the renewability of e-fuels, what other options are there? The great attraction of GOs, and their great drawback in this context, is that they allow power supplied over the grid to be treated as renewable irrespective of when renewable power is actually being generated. One option would be to go to the opposite extreme and say that renewability simply cannot be transmitted across a fossil-powered grid – an e-fuel facility would need to be directly connected to a renewable power generator in order to count as renewable. The use of a direct connection is a more convincing demonstration of e-fuel renewability than the use of GOs would be, but even so this solution may be problematic.

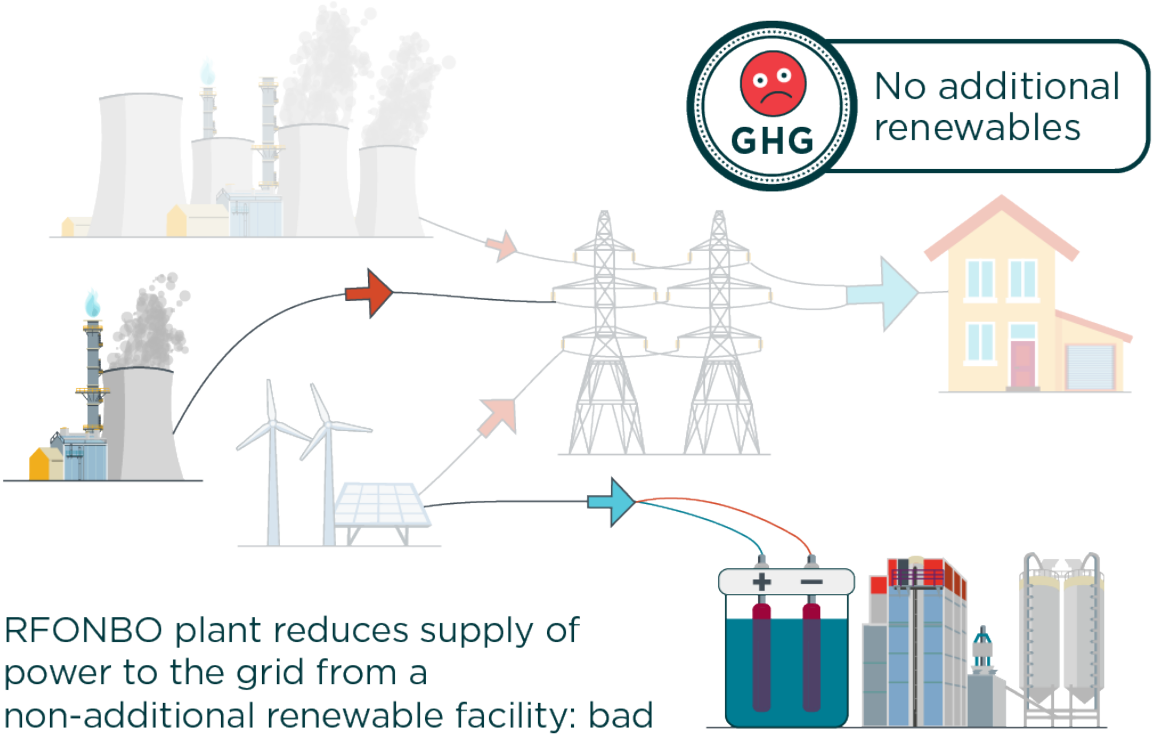

Figure 4 **Schematic of an e-fuel facility displacing renewable power from the grid**

Source: ICCT

The problem is simple enough to conceive (Figure 4). Imagine that a wind farm is currently supplying renewable power to the grid, thereby avoiding carbon emissions from fossil power. An e-fuel plant is constructed next to the wind farm, and the wind farm is disconnected from the grid in order to supply 100% renewable power to the e-fuel producer. There is no question that the power used to run the e-fuel plant is renewable in origin – it is not connected to any non-renewable source. But because there is now a shortfall on the grid that could be filled in by fossil power, a consequential LCA would tell us that the effective GHG intensity of our produced e-fuel is determined not by the windmill that the plant is connected to, but by the GHG intensity of whatever the power source is that replaces the wind farm. Even if there is a mix of fossil and renewable power to replace our disconnected windfarm there's a serious risk of increasing rather than reducing net emissions with our 100% renewable e-fuels.

3.2 Additional electricity

Adopting a consequential LCA perspective on e-fuels allows us to identify that in order for the use of renewable electricity for e-fuel production to be meaningful it must be additional renewable electricity – not simply renewable electricity displaced from an alternative use. The importance of the use of additional electricity for e-fuels is recognised by the adoption by the European Union in early 2023 of rules (European Union, 2023) laying out the requirements on the electricity that may be used to produce e-fuel under the RED. These rules dictate when electricity on either a direct connection to a renewable plant or a connection to the grid may be treated as being fully renewable.

For direct connections, the risk described above that existing renewable power facilities could be displaced from the grid in order to power e-fuel plants is managed by requiring that the power facility comes into operation not more than three years before the e-fuel facility. For e-fuel facilities running on grid power, there are several cases in which the rules allow the power to be treated as renewable:

1. The grid in that bidding zone is at least 90% renewable and the e-fuel facility does not run for more hours in the year than a number of hours consistent with the renewable fraction in the grid. This limit on hours operational is predicated on the idea that e-fuel producers will try to operate as much as possible possible when the grid is powered only by renewables, as the price of power is cheaper during these periods.
2. If the average calculated GHG intensity of power in that bidding zone is no more than 18 gCO_2e/MJ, the e-fuel producer has a power purchase agreement with producers of renewable power, and the power is consumed at roughly the same time and either within the same or a neighbouring bidding zone as it is produced.
3. If power is only taken from the grid at times when renewable power supply would otherwise be curtailed.
4. If the e-fuel facility has a power purchase agreement with a renewable power facility that came into operation not more than three years earlier than the e-fuel facility, the e-fuel facility used power at about the same time as it is generated and either within the same or a neighbouring bidding zone as it is produced, and the renewable energy facility did not receive any other government support in the form of operating aid or investment aid.

This final condition, relating to whether a renewable power facility has received other financial support from the government, is intended to preclude the case that the government should provide support to renewable power generation and then this capacity should immediately be diverted to e-fuel production instead of being supplied to reduce the GHG intensity of power in the wider grid.

These ideas about additionality will be even more important in the context of a potential international trade in e-fuels. The energy transition must be global if the worst impacts of climate change are to be avoided. There is no point in the European Union investing to import e-fuels from overseas that are produced at the expense of opportunities to decarbonise local grids. Malins (2017c) estimated that replacing half of the EU's 2050 aviation fuel demand would take about 880 TWh of electricity. According to data reported by the EIA (U.S. EIA, 2023), this is more than current total electricity consumption for the whole of Africa (700 TWh). With a potential for electricity demand on such a large scale it is not hard to see that there is a risk that renewable power investments intended to supply e-fuels to Europe could end up competing with investments to supply electricity for use in other parts of the world.

4 Where are the savings – finding the additional carbon

There is a simplification baked into the UNFCCC's carbon accounting regime ever since the Kyoto protocol that biomass combustion or decomposition should be treated in industrial emissions inventories as if it resulted in no carbon dioxide emissions. This is, of course, not physically true. Burning wood or other biomass releases CO_2 just as surely as burning coal or burning oil. The adoption of this simplification reflects the idea that carbon released by biomass combustion was absorbed from the atmosphere in relatively recent history (within the year for an annual crop, within a few years for a perennial crop, perhaps within tens or hundreds of years for trees, and up to thousands of years ago for some peat). Carbon absorption and release by plants is understood to be part of a carbon cycle, and releasing carbon from biomass into the atmosphere could be thought of as not changing the total amount of carbon in the biosphere, as opposed to carbon released from fossil fuel combustion which adds to the total amount of carbon in the biosphere. This leads to a discourse that systematically distinguishes 'fossil carbon' from 'biogenic carbon', although underneath these distinctions once CO_2 is emitted to the atmosphere it has the same warming effect no matter where it came from.

The problem with this framing is that it starts to break down if the carbon cycle from atmosphere to plants and back again gets out of balance and starts to become a net carbon flow from plants to atmosphere. It is certain that any carbon in a plant today was absorbed from the atmosphere via photosynthesis at some point in the past, but what is less certain is whether any carbon released from a plant today will be absorbed by another plant sometime in the future. To put it another way, if you cut down and burned a tree today but planted a new tree tomorrow and tended that tree to maturity, then you could demonstrate that the initial CO_2 emission was eventually paid back. If, however, you cut down and burned a forest today and replaced it with farmland tomorrow there is no guarantee that you would ever return to the net carbon position you started at. Most people would take it as obvious that cutting down a forest and burning it for energy would not generally be an ecologically positive thing to do, but under the rules of the IPCC inventory system an industrial power generator can do exactly that and report zero CO_2 emissions even if they have no plan to replant the area with new trees.

As it turns out, emissions from the loss of biomass and soil carbon due to land use change are pretty significant. One accounting of CO_2 emissions since 1850 (Friedlingstein et al., 2020) estimates that land use change emissions account for about a third of total anthropogenic emissions since 1850 – on this accounting cumulative post-1850 land use change CO_2 emissions weren't overtaken by cumulative fossil fuel CO_2 emissions until 1978, and annual fossil fuel CO_2 emissions didn't exceed annual land use change CO_2 emissions until 1950.

It is not that the IPCC framework ignores these land use change emissions entirely – they are simply accounted in a different inventory, the land use, land use change, and forestry (LULUCF) inventory. If trees are cut down for fuel, that is accounted as a LULUCF emission instead of as an industrial emission – and if the trees grow back then that carbon sink is also accounted in the LULUCF inventory. In terms of tracking global CO_2 emissions this system of inventories is somewhat workable. The convention of accounting biomass related emissions as zero at the point of emission becomes a problem, however, when there are very different levels of regulatory oversight of industrial emissions as compared to LULUCF emissions. Policies like the

EU Emission Trading Scheme put a cost on CO_2 emissions and require careful monitoring of those emissions, but EU ETS treats biomass combustion as a zero-emission activity. That means there is no CO_2 cost under the ETS to burning biomass – and because forests and farms are not regulated under EU ETS, there is also no cost imposed if net sequestration is reduced by increased biomass harvesting. EU policy makers would say that there are other instruments in place to manage LULUCF emissions – but this doesn't change the fact that there is an imbalance in the financial incentives; there is a potential advantage to individual companies of harvesting biomass for heat and power, or of replacing natural systems with farms to meet biofuel driven demand for crops.

The convention of treating biomass combustion as a zero emission activity has been internalised within much of the policy debate as what DeCicco (2009) refers to as the 'renewability shortcut', the idea that biomass energy is at some fundamental level carbon neutral. In the carbon neutrality view of bioenergy, biomass is to be treated as a zero-carbon resource and biogenic carbon is treated as a different species than fossil carbon. In this view, attributional lifecycle analysis can be used to identify fossil CO_2 emissions that are incidentally associated with the processes required to cultivate biomass and turn it into usable forms of energy (e.g., biofuels), but this can be seen as a sort of afterthought. This way of conceptualising the bioenergy industries can lead to a considerable mental resistance to the idea that bioenergy may not be a climate solution – even when LCA results are presented that suggest that the 'incidental' CO_2 emissions in a bioenergy supply chain add up to as much as the GHG intensity of a fossil fuel, the underlying idea of carbon neutrality can still have a hold.

The key to the renewability shortcut is that you act as if you started tracking carbon flows before a given piece of biomass grew. If you start a notional carbon inventory before the carbon in any piece of biomass was first absorbed, then any future emission only serves to cancel out that initial sequestration. If you change that framing so that you only start the notional inventory after a given piece of biomass has been grown, however, you draw a different set of conclusions. Imagine that we have a stand of mature trees and cut them down for bioenergy. This leads to a CO_2 emission, and this will only be offset if the stand of trees grows back to its original size. In this framing, carbon neutrality is conditional on future growth, not taken for granted because of past growth. In fact, when we look at the problem from this perspective the act of replacing fossil fuel with biomass fuel is not positive in itself – the CO_2 released per unit of energy from burning trees is similar to (and in fact a bit more than) that from burning coal. Rather, cutting down the stand of trees is climate positive because it creates an opportunity for additional carbon sequestration through new plant growth[27]. In this simple example it is this additional tree growth that is the basis for identifying what Searchinger (2010) refers to as additional carbon – an additional flow of carbon from the atmosphere to the biosphere that would not otherwise have taken place.

The additional carbon framing challenges us to move beyond the renewability shortcut, treat CO_2 as CO_2 without reference to biogenicity, and identify where exactly an additional carbon sink (or reduced carbon source) is delivered by a given biofuel policy. Consider now the case of production of biojet using an alcohol-to-jet (AtJ) process with corn as the feedstock, and assume that we open a new AtJ plant next to an existing area of corn farming where feed corn is grown for livestock. Assume that the year the AtJ plant opens we grow more or less the same amount of corn that we grew in the previous few years, but now supply that corn to the AtJ plant. Given that we produce the same amount of corn as normal there is no additional

---

[27] We'll ignore for now whether the trees could have continued to sequester carbon if they had not been cut down.

carbon sink on the existing farmland. The ethanol replaces jet fuel, but combusting biojet releases the same amount of CO_2 per unit of energy as combusting fossil jet, so there is no reduced CO_2 flow in the exhaust of the jet engine – some oil can remain in the ground, but this doesn't deliver any direct GHG benefit if the CO_2 emission from fossil fuel combustion is replaced by CO_2 from biojet combustion. The use of biojet only reduces net GHG emissions if there is either a reduced CO_2 source or an enhanced CO_2 sink somewhere else in the wider economy beyond the farm and the exhaust from the plane.

The change in our system we are yet to account for is that the corn from our fields is no longer available to its previous users – this brings us back to the ideas developed in the context of indirect land use change modelling about how the system reacts to increased biofuel demand. Perhaps elsewhere in the system somebody expands another farm to add a new field of corn. The carbon absorbed as that new corn grows can be identified as additional carbon sequestration from the atmosphere, but it will be offset if is carbon lost due to clearing the land. In general the CO_2 emitted during land clearance will be much more than can be absorbed in a year by a corn crop, so a land expansion outcome doesn't provide an expectation of net carbon neutrality. Additional carbon thinking therefore forces us to confront the opportunity cost of using agricultural land in a way that we don't need to if land is treated as a free resource in a regulatory LCA framework. Alternatively, perhaps the crop is not replaced – if the reduction in the supply of corn means that fewer animals are raised, and less meat is produced, then the accompanying reduction in animal and human respiratory emissions is a reduced CO_2 source, and this reduced source could contribute to carbon neutrality for our biojet fuel (Searchinger et al., 2015). This outcome is positive from a climate perspective, but problematic if these reductions and food and feed consumption are a sign of reduced food security (Malins, 2017a). Finally, it is possible that if the new demand raises corn prices then other farmers will find ways to improve their productivity, and deliver additional carbon sequestration by growing more corn on areas that are already farmed. This could also help take us closer to carbon neutrality.

In fact, following additional carbon thinking to its logical conclusion can be thought of as being equivalent to doing indirect land use change modelling, except that instead of using a model to find a positive emission term that we can add to a starting point based on zero combustion emissions, in the additional carbon framing we would start from the combustion emissions of a unit of biojet and then identify a CO_2 credit that we could subtract by considering the additional carbon sinks/reduced sources.

In the renewability shortcut mindset, we say that bioenergy is fundamentally climate neutral at the point of use but that we should consider associated emissions sources. In the additional carbon framework we say that bioenergy has no fundamental carbon benefit at the point of use, but that it may be associated with additional carbon sinks or reduced sources. In the first view we identify fossil fuel substitution as the basis for reporting a climate benefit – in the second framing we identify enhanced plant growth and reduced respiration as the basis for reporting a climate benefit. If considered comprehensively with a consequential LCA mindset, the two analytical frameworks become mathematically identical, and the answers would meet in the middle.

4.1 E-fuels and additional carbon

For hydrocarbon e-fuels, we can also ask the additional carbon question, though with a simpler answer. As with biofuels, e-fuel combustion results in the same physical flow of CO_2 to the atmosphere that you would get from fossil fuel combustion, so there is no direct benefit in terms of exhaust CO_2 emissions. The answer must therefore relate to the source of carbon for the e-fuel production process.

If the carbon for the fuel synthesis is sourced by direct air capture of CO_2, that is an additional CO_2 sink and that provides a basis for identifying net carbon neutrality for the pathway when this sink is offset against the combustion emissions in the jet engine. Similarly, if the carbon for the fuel synthesis process is delivered by capturing CO_2 that would otherwise have been emitted from an industrial point source, then that is a reduced CO_2 source and that could also provide a basis for identifying net carbon neutrality. Wherever the CO_2 comes from, it is important that the benefit of capturing the CO_2 should only be counted once. For direct air capture, that means that if the CO_2 benefit is allocated to the biojet then the direct air capture operator should not also be allocated emissions credits under any other system. For CO_2 capture from a point source, that means that if the CO_2 benefit is allocated to the biojet then the industrial facility shouldn't also be able to claim reduced emissions, for example under an emissions trading scheme. From an accounting point of view, we would treat it as if the CO_2 had been released to the atmosphere by the industrial facility and then immediately captured from the atmosphere and supplied to the biojet facility. This question of allocating GHG benefits is important, because there will inevitably be a desire to count a benefit both from the operator capturing the CO_2 and the biojet producer using the CO_2, but to count it as a benefit for both would be double counting and lead to distorted incentives and inaccurate CO_2 inventories.

In the context of commitments to deliver net zero CO_2 emissions by 2050, this practice of transferring the right to claim a CO_2 benefit from one sector to another is controversial with some commentators. It is argued that if all CO_2 sources ought to be eliminated then the industries associated with the point sources need to reduce their emissions to zero, which can only be done by eliminating the source entirely or by capturing 100% of the emitted CO_2 and storing it permanently. The EU has recognised these concerns by placing a time limit on the period for which the benefits from CO_2 capture can be transferred to e-fuels – after 2041[28] e-fuels cannot be given credited for avoidance of CO_2 emissions from other sectors unless the CO_2 was of biogenic origin.

Note that whether the CO_2 is captured from the atmosphere, from an industrial fossil point source or from a biogenic source, the net GHG emission reduction occurs outside of the transport sector and is then assigned to the transport sector under the accounting rules, allowing airlines (or other alternative fuel users) to claim in-sector emissions reductions. In this sense the use of e-fuels could be thought of as a constrained form of emissions offsetting.

4.2 Additional carbon and regulation

In the regulatory context, the existing inventory and lifecycle analysis frameworks are firmly embedded in policy thinking and implementation, and there is little prospect that lifecycle analysis approaches for biofuel based on the renewability shortcut will be replaced by new approaches based on the identification of additional carbon. Additional carbon thinking can therefore perhaps more usefully be seen as a mental discipline that provides a more complete understanding of exactly how an alternative fuel policy delivers net climate benefits. In the case of biofuels, if we are uncomfortable about the idea that part of the climate benefit is

---

[28] 2036 in the case of CO_2 from power plants.

predicated on reduced animal and human respiration then this could be a sign that biofuel policy should be refocused into areas where the additional carbon can be more clearly identified as a sink rather than as an avoided source. This is actually exactly what the European Union is trying to do with its biofuel policy. The current RED caps support for food-commodity feedstocks and includes enhanced incentives for biofuels produced from waste resources that have limited alternative uses and for biomass production systems that have potential to deliver additional biomass growth on-site – whether by replacing less productive systems with fast growing biomass crops or by introducing new cover crops and inter crops to existing crop systems.

5 The out-of-sector hunt for in-sector emission reductions

Aviation has not been a trailblazer when it comes to climate action. In the Kyoto system international aviation and international shipping have their own GHG emissions inventories, and therefore emissions from international aviation have historically been addressed outside of national emissions targets. Instead, the International Civil Aviation Organisation has been given responsibility for developing international measures to reduce the GHG emissions from aviation, and for supporting the aviation industry to achieve the industry and ICAO's stated 'aspirational' goal to reach net zero emissions by 2050[29]. As international flights collectively use more fuel than domestic flights, action by ICAO is central to reducing aviation emissions.

As discussed above, the system of emissions inventories under the Kyoto system has a very simple assignation of responsibility for emissions. In national inventories, each country is taken as responsible for the fossil fuel combustion and land use change emissions within its borders, irrespective of whether some of that combustion or land use change happened in service of consumers elsewhere. By the same token, the aviation emissions inventory includes emissions from all the fuel combusted in aeroplanes on international flights. The most obvious way to reduce emissions in the aviation inventory would therefore be burning less fuel.

There are three basic ways to reduce fuel burn. Firstly, you can try to make aircraft more efficient in the way they use fuel. ICAO already recognises improvements in aircraft technology through an aeroplane CO_2 standard (ICAO, 2023a). Fundamentally new aviation technologies like electric passenger aircraft could deliver greatly reduced emissions, although battery weight will mean that range is likely to be confined to a few hundred kilometres for the foreseeable future. Secondly, operational improvements can be made to reduce the fuel burn associated with flying existing routes. This could include things like improving air traffic control management so aircraft have to circle less while waiting to land, and optimising the size of aircraft working on each route (ICAO, 2023b). Finally, some people could simply fly less than is currently expected. Given that aviation use is growing rapidly, there is little prospect of reducing the total number of journeys taken globally, but various things could be done reduce the rate of aviation growth, from personal action ("flygskam") to frequent flyer levies to taxing aviation fuel. Aviation demand management is something of a dirty phrase in the aviation industry – the airlines hate the idea for fairly obvious reasons, and ICAO has a fundamental tension on the subject of demand growth as the first aim stated in ICAO's charter is to "Insure the safe and orderly growth of international civil aviation throughout the world"[30]. One can even find such notables as the Director General of the International Air Transport Association (IATA) making the rather specious claim that individual passengers flying less doesn't affect aviation emissions because the planes will just fly anyway with fewer passengers (IATA, 2022). While it is pleasing to see the industry embracing a consequential LCA outlook on this point at

---

[29] https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx; https://www.icao.int/Newsroom/Pages/ICAO-welcomes-new-netzero-2050-air-industry-commitment.aspx

[30] Although an argument could be made that growth has to be environmentally sustainable in order to be considered "safe and orderly".

least, the argument is not entirely convincing – we can safely anticipate that fewer passengers will lead in due course to fewer flights.

Reducing aviation activity in any of these ways will reduce the CO_2 physically expelled by jet engines, but these measures (short of implausibly strict demand management measures or an extraordinary breakthrough in battery-weight technology to enable electric passenger aircraft) cannot deliver large enough benefits to deliver the required reductions in total CO_2 emissions by 2050. ICAO therefore identifies two further measures to deliver the rest of targeted emissions reductions: offsetting through the CORSIA market-based measure and 'sustainable aviation fuels' (Figure 5). These measures will not reduce the CO_2 physically emitted as aircraft fly, but can reduce 'net' GHG emissions by delivering savings elsewhere that can be 'offset' against the physical emissions from fuel combustion.

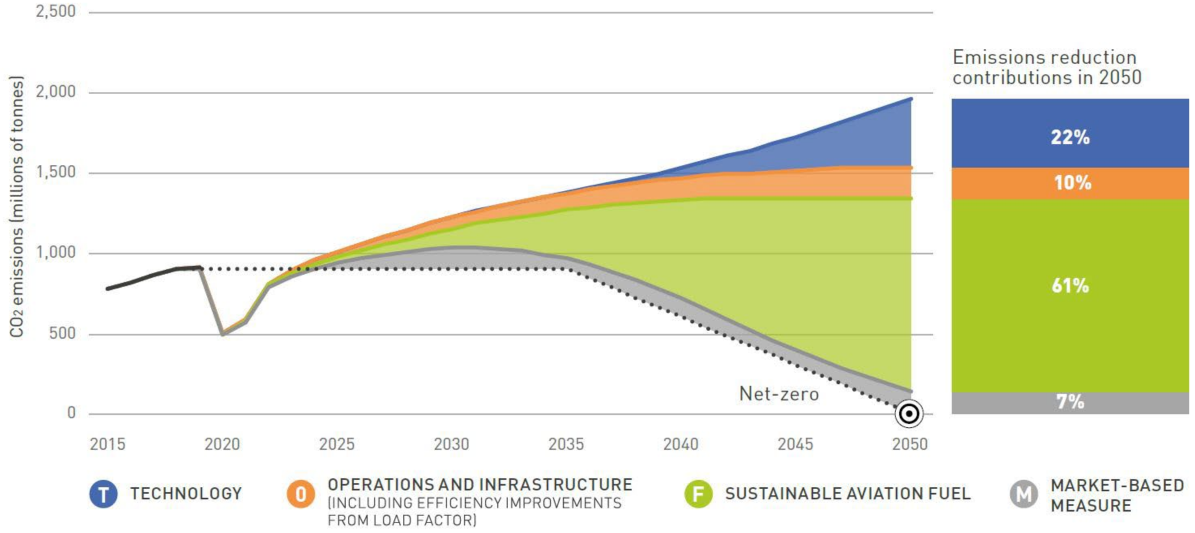

Figure 5 **'Waypoint 2050' characterisation of the path to carbon neutral growth**

Source: https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/; scenario 1 is shown.

Offsetting refers to the practice of paying for the rights to claim emissions benefits from measures taken in other sectors (and perhaps in entirely different geographic locations). An airline could buy offset credits representing a thousand tonnes of avoided CO_2 emissions achieved in another sector and use them to 'cancel out' a thousand tonnes of emissions from aviation fuel combustion. Offsetting is controversial in the environmental movement for a number of reasons. Firstly, offsetting can be seen as a sort of special pleading for aviation. Other sectors of the economy are asked to reduce their emissions directly and are regulated with instruments such as cap and trade schemes and carbon taxes. It can be seen as unfair to allow aviation (which can be seen as something of a luxury product predominantly used by relatively well-off people[31]) to claim carbon neutrality based on paying for low-cost emission reductions in other sectors, while other industries are expected to reduce their emissions directly at greater cost. Secondly, there are questions about the long-term relevance of an offsetting model – as humanity brings net CO_2 emissions towards zero, there will be fewer and

---

[31] Cf. https://www.carbonbrief.org/richest-people-in-uk-use-more-energy-flying-than-poorest-do-overall/

fewer ‘excess’ emission reductions that can be sold to other sectors. Finally, and perhaps of most immediate practical importance, there are longstanding concerns about the robustness of many offsets. These include carbon leakage (e.g. protecting one area of forest only for the area next door to be cleared instead), impermanence (e.g. a group of trees is planted as an offset but are destroyed in a forest fire twenty years later), vintage (that carbon reduction credits generated many years in the past should be used to cancel out aviation emissions happening today), additionality (activities like renewable energy expansion that would happen anyway for commercial reasons are registered as offsets and used to ‘greenwash’ aviation) and flat out fraud (such as accusations that refrigerant companies were producing excess quantities of high-GWP hydrofluorocarbons with the sole purpose of destroying them again for carbon credits[32]).

What is certainly true is that aviation has, correctly, seen offsetting as a very cheap way to claim carbon neutrality. CORSIA will rely on the purchase of carbon credits from voluntary carbon markets, and for the time being the prices of these credits are at least an order of magnitude below prices for carbon avoidance in cap-and-trade schemes. A snapshot of prices reported by www.carboncredits.com on 25th April 2023 showed the EU ETS price (€93 per tCO_2e) to be a healthy 61 times higher than the price of CORSIA eligible credits (€1.52 per tCO_2e[33]). Transport decarbonisation credits (such as RTFCs in the UK and LCFS credits in California) normally trade for even more than EU ETS credits. In the past, emissions reductions through offsetting in aviation have often been presented as a stop gap measure, an option to deliver ‘carbon neutral growth’ for a limited period while in-sector emission reductions are ramped up. Given that offsets currently present excellent value for an aviation sector keen to burnish its green credentials, it would be unsurprising if there is appetite to extend the use of offsets for as long a period as possible (CORSIA is currently due to end in 2035, but it is clear that the industry will need to rely on offsets or removals out to 2050 to achieve net zero).

The CORSIA scheme does not only allow compliance through the use of offsets. Airlines can also register GHG savings from the use of alternative aviation fuels, provided the fuels meet some sustainability criteria. Currently these relate only to climate change (reportable lifecycle GHG intensity and not using biomass from land converted from high carbon stock status) but from 2024 they will cover a broader set of sustainability principles.

Under CORSIA, the reportable GHG saving from the use of a batch of alternative fuel will be calculated based on a lifecycle GHG intensity value, rather than simply being based on the convention of treating emissions from biomass combustion as zero in the aviation inventory. This is an important detail, as it marks a methodological departure from the basic principles of UNFCCC inventory accounting and allows a degree of discrimination in rating different biofuel pathways. CORSIA’s LCA framework is similar to that used under the California Low Carbon Fuel Standard, because it couples an attributional LCA requirement for direct emissions with a consequential LCA requirement (based on computable equilibrium modelling) for land use change emissions.

While the LCA framework goes much further than just treating biofuels as zero carbon, and even has consequential elements, it is still built around the renewability shortcut. Alternative fuels are treated as if they have zero CO_2 emissions from combustion, which allows alternative fuel use to be characterised as an in-sector emission reduction for aviation in the same way that improved aircraft efficiency or operational improvements are. If we instead look at some

---

[32] https://www.energyintel.com/0000017b-a7bb-de4c-a17b-e7fbe90c0000

[33] Converted from $1.67 per tCO_2e quoted price at 0.91 € to the $.

example alternative fuel pathways through the additional carbon lens, we get a rather different picture – a picture in which alternative fuels might be seen as having a very similar character to some emissions offsets.

Take a corn ethanol-to-jet pathway where aviation fuel would be produced from corn starch. As was discussed above in section 4, the physical CO_2 emissions coming out of the jet engine are basically unchanged and so there can only be a net climate benefit if we identify somewhere else that CO_2 sequestration from the atmosphere is increased or CO_2 release to the atmosphere is reduced. The prime candidate for additional carbon sequestration is that we might be able to marginally increase corn productivity through additional investment. The prime candidate for reduced carbon releases is reducing human and animal respiratory emissions by reducing food and feed intake. From this viewpoint, the use of corn-based aviation fuel is actually a rather complicated implied offsetting scheme to grow more corn while selling less of it for food and feed use, and the benefit is not delivered in the air as the fuel is burned but diffusely throughout the agricultural economy.

We could also consider a cellulosic biofuel pathway, such as jet fuel produced via gasification of corn stovers (residues of corn agriculture). If the rate of corn stover removal is managed to avoid negative impacts on soil carbon formation then a counterfactual scenario in which the corn stover would have decomposed in the field if not collected for bioenergy could be justified, and therefore in this case the additional carbon comes from avoiding the CO_2 source caused by corn stover decomposition. The CO_2 benefit is not delivered as the fuel is burnt but when the corn stovers are transformed into a liquid fuel and decomposition is avoided. The GHG benefit in this case is predicated on the idea that the carbon would otherwise be released through decomposition, and therefore the CO_2 benefit would be reduced if that assumption was not valid. This is a particular concern for forestry residues that consist in part of large pieces of wood such as branches and tree stumps. In those cases, the counterfactual scenario could be gradual decomposition and carbon loss over years or decades, in which case it could be many years before a change to bioenergy use delivered any net CO_2 benefit.

The additional carbon sink or reduced carbon source could be entirely geographically removed from the use of the produced biojet fuel. One could easily imagine a case in which:

- corn stover is gathered for biofuel feedstock at farms in Iowa in the U.S., delivering a 'credit' for avoided decomposition emissions;
- the corn stover is aggregated to a local biomass-to-liquids plant and processed into a mix of hydrocarbon fuels;
- the kerosene molecules in the fuel output were exported to the EU as biojet to be supplied under the REFuelEU mandate;
- the fuel was eventually burned in on a flight to India somewhere between Schiphol and New Delhi. An avoided emission delivered at a farm in Iowa ends up getting counted as an emission reduction for a flight half a world away.

In the case of an e-fuel, the additional carbon is delivered when CO_2 emissions from a point source are reduced by carbon capture or when a new CO_2 sink is created by capturing CO_2 from the atmosphere. Some analysts (e.g. The Royal Society, 2019) and the Climate Change Committee (CCC, 2020) have noted that from a lifecycle emissions perspective capturing CO_2 for e-fuel production delivers a similar net CO_2 emissions benefit as capturing an equivalent amount of CO_2 for storage (CCS) and continuing to use fossil fuels in the air. The aviation industry could buy offsets from CCS projects and it would deliver 'additional carbon' in the same way that e-fuel production does. If the cost and energy requirements of e-fuel production remain higher than the cost of CCS offsets plus fossil fuel consumption, this will pose an important conceptual challenge to the alternative fuel market in aviation, as it is likely that there will be considerable pressure to follow a less costly offsetting route. Synthetic fuel production has some marketing appeal because it allows CO_2 capture to be ‘laundered’ into aviation as an in-sector emission reduction, but this is unlikely to be enough to resolve this argument in the longer term. If a strong benefit from synthetic fuels on non-CO_2 warming can be clearly demonstrated, this would provide an additional reason to follow the synthetic fuel decarbonisation pathway.

6 The role and limitations of LCA in supporting aviation decarbonisation

In this discussion paper we have presented the reasons for undertaking LCA and the limitations inherent in LCA, both at the theoretical and the practical level.

A selective reading of the recent history of the use of LCA in the context of biofuels might lead one to question whether the discipline is able to identify which alternative fuel pathways will deliver net climate benefits. Analysis has been produced that questions whether either 13 years of the RED in Europe of 16 years of the Renewable Fuel Standard 2 in the U.S. have actually delivered any net climate benefit for the considerable financial support provided. This is despite both programmes setting nominal minimum GHG saving requirements on the biofuels used. If it is unclear whether we can trust those regulatory results to give a useful answer on the most fundamental question, one might ask whether all of this LCA has had any value at all.

Part of this disconnect arises because of the persistent desire by regulators, industry and commentators to use LCA results in a way that is not fully consistent with the LCA design. In Europe, the RED requires that reportable GHG reductions are calculated by subtracting an attributional LCA score for an alternative fuel from an attributional LCA score for a fossil fuel. The results of these calculations are quoted as an indicator of the impact of the policy, but as we discussed above this is not necessarily true. A fully consequential LCA would be a more appropriate analytical approach to answer questions on the net benefits of the policy. The reporting of purported GHG emission saving results based on attributional analysis is so ingrained in the biofuel discourse and community that it is unlikely that this habit can be broken, but civil society organisations can play a role by:

- Challenging government to undertake better-framed impact analysis using consequential tools when new policies are introduced;
- Challenging government to undertake more sophisticated analysis of the net benefits delivered by existing policies when they are reviewed and renewed;
- Demanding that government should consider adding hybrid elements to regulatory LCA to provide some characterisation of the most important ‘indirect' effects (e.g. ILUC factors and displacement emissions) .

In the United States, the EPA did integrate consequential elements (indirect land use change and a consequential assessment of on-farm emissions changes) into the LCA modelling for the Renewable Fuel Standard (RFS). A lack of confidence that corn- and soy-based biofuels have delivered benefits is therefore not explained by the use of attributional tools for a consequential question but by the uncertainty that inevitably exists around how well the modelling frameworks were designed and whether the chosen parameters reflect best knowledge (for example Malins (2012) provided a detailed critique of model elements in EPA’s provisional palm oil analysis). There is also uncertainty, that exists irrespective of how well the model was specified, about whether observed outcomes are consistent with modelled expectations (e.g. Wright et al., 2017). One predictable consequence of the range of uncertainties associated with consequential modelling is that different analysts draw different conclusions about whether specific estimates are likely to be under- or over-estimations of true emissions (see e.g. Scully et al., 2021; Spawn-Lee et al., 2021). Another predictable consequence is that groups already committed to advocate in favour of a given alternative fuel pathway will want to amplify the results of studies that support their view, and that groups already committed to advocate against a given alternative fuel pathway will want to amplify the results of studies that support the counterview.

When we focus on uncertainty in LCA, and on the challenges involved in building policy on a contested knowledge base, it might seem tempting to discard either the more contentious elements of LCA results, or even the whole exercise. This would be premature. Notwithstanding their respective limitations, both attributional and consequential LCA can provide important insight about alternative fuel production pathways.

Perhaps the most basic function of attributional LCA is to identify pathways that are very unlikely to deliver climate benefits. If the attributional LCA score for a given biofuel production process is higher than the attributional LCA score for a fossil fuel, it would be quite surprising to find that a more comprehensive consequential LCA ascribed benefits to increasing the use of that pathway. Attributional LCA can then be thought of as providing a basis for a sort of pre-selection of alternative fuel pathways that are promising and that are worth analysing with other tools.

Another role of LCA as a regulatory tool becomes apparent in regulatory systems such as the California LCFS and the German implementation of RED where value is given to improved LCA scores. In these systems, there is a defined financial incentive to improve the real efficiency of production processes. These improvements represent real GHG reductions even if we cannot be confident about whether the headline LCA score is a good reflection of reality. It is important though that the opportunities to add value by improving production systems are not overwhelmed by opportunities for cherry picking of either data or supply chains, as in general it will be much cheaper to implement cherry-picking strategies than to make real changes.

LCA is certainly subject to significant uncertainties, but results from existing LCA frameworks can be combined with other available evidence to add confidence when drawing conclusions about which alternative fuel production pathways are likely to be better or worse. We can accept that our knowledge lacks precision without being forced to believe that it has no merit. For example, Malins (2019a) provides a review of complementary evidence from both consequential LCA and other forms of analysis that suggest that palm oil based biofuels are associated with a particularly high risk of land use change emissions. Equally, there are cellulosic biofuel pathways based on residues for which both attributional analysis and ILUC estimations fairly consistently suggest low GHG intensity.

LCA results can also be used as a basis to identify problems that need to be resolved, either in legislation or by technological development. If LCA shows that a given biofuel pathway is associated with excessive nitrous oxide emissions, we know that better management of fertiliser application would be important to improve that pathway. ILUC analysis has been used to show that the use of vegetable oils for biofuels may drive significant land use change emissions, and this has informed efforts by the EU to pivot away from a vegetable-oil-based biodiesel industry. In the case of e-fuels, we can use LCA results in a simple way to demonstrate that it is important that the electricity consumed should be renewable and additional if net GHG reductions are to be delivered, and this provides an impetus to make sure that the rules on electricity sourcing and the regulatory LCA requirements are adequate to guarantee additional renewable electricity as an outcome.

6.1 Making use of LCA as alternative aviation fuel use increases

As alternative aviation fuel use grows, it seems reasonable to assume that LCA scores will be at the heart both of the regulatory process and the discursive context. Fuels that are not assigned relatively low LCA scores will struggle to gain market share, either because of failing to meet threshold values or because fewer credits will be given to lower performers. Fuels that achieve low LCA scores under the rules of a given regulation will be marketed as climate solutions even if there is evidence of significant emissions that fall outside of the scope of the LCA. In truth, however, it will generally be more accurate to say that if Fuel A has a better LCA score than Fuel B it ***suggests*** that Fuel A ***may*** be more useful as a climate mitigation tool rather than ***proving*** that Fuel A ***is*** more useful as a climate mitigation tool. If the scope of the LCA includes all of the significant emissions that could be characterised as indirect (e.g. in a hybrid LCA), then we might decide that it is likely that the hierarchy of LCA scores is correct. If we know that the scope of the LCA excludes important indirect emissions, then we will probably conclude that we can draw no conclusions without additional information.

Based on the discussion in this paper, we propose three overarching principles for good practice in the use of LCA in fuel regulations:

1. To the extent possible, LCA should provide some characterisation of all important emissions associated with expanding the use of an alternative fuel pathway. It may be necessary to use consequential analysis to identify 'indirect' emissions that are likely to be significant. Having identified them, it may be appropriate to adopt a hybrid LCA approach (e.g. through adding ILUC factors or displacement emissions for rigid impacts), even in the face of uncertainty, in order to ensure that those emissions are reflected in regulatory decision making.

2. Favourable or unfavourable LCA scores should not be the end of the process of impact analysis. Where scores are very favourable, government should undertake complementary analysis to identify and sense check the assumed sources of additional carbon, and to explore sensitivities and identify any circumstances that could make those scores less favourable. Where scores are unfavourable, government should undertake further analysis to the validity of the result and explore what actions are available to improve performance.

3. Policy making should recognise that LCA scores are not the be all and end all of assessing the climate impact and long-term potential of a fuel pathway. It is appropriate to adjust the levels of support available for different fuels (e.g. through double counting or eligibility for sub-targets) based on complementary evidence and analysis.

Participants in the policy debate around alternative fuels in aviation should be alert both to the value of LCA and to its limitations. LCA has played an important role in the development of the road biofuel sector, and has been used to exclude some problematic biofuels from policy support, such as palm oil biofuels being effectively excluded from credit generation under the California LCFS. The environmental community should continue to advocate that LCA results inform regulatory decisions, whether through direct integration with thresholds and proportional credit award or by informing more qualitative decisions about which categories of fuels receive which level of support. It is equally important to call for ongoing assessment of the quality of the LCA scores we have, and to identify areas in which a specific LCAs could be delivering misleading outcomes – in particular by being attentive to issues of indirect emissions.

7 References

Abella, J. P., & Bergerson, J. A. (2012). Model to investigate energy and greenhouse gas emissions implications of refining petroleum: impacts of crude quality and refinery configuration. *Environmental Science & Technology*. https://doi.org/10.1021/es3018682

Baral, A., & Malins, C. (2014). *Comprehensive carbon accounting for identification of sustainable biomass feedstocks. January*. http://www.theicct.org/comprehensive-carbon-accounting-identification-s

BioGrace. (2017). *BioGrace version 4d*. BioGrace. http://www.biograce.net/content/ghgcalculationtools/recognisedtool/

CCC. (2020). *The Sixth Carbon Budget - Aviation*. www.theccc.org.uk

CDP. (2022). *Relevance of Scope 3 Categories by Sector - CDP Climate Change Questionnaire*. https://cdn.cdp.net/cdp-production/cms/guidance_docs/pdfs/000/003/504/original/CDP-technical-note-scope-3-relevance-by-sector.pdf

De Santi, G., Edwards, R., Szekeres, S., Neuwahl, F., & Mahieu, V. (2008). *Biofuels in the European Context: Facts and Uncertainties*. 0. https://doi.org/10.2788/69274

DeCicco, J. M. (2009). *Addressing Biofuel GHG Emissions in the Context of a Fossil-Based Carbon Cap*.

DfT. (2018). *Renewable Transport Fuel Obligation Guidance Part Two Carbon and Sustainability*. *April*, 147.

EASA. (2020). *Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)*. https://www.easa.europa.eu/en/document-library/research-reports/report-commission-european-parliament-and-council

Edwards, R., O'Connell, A., Padella, M., Giuntoli, J., Koeble, R., Bulgheroni, C., Marelli, L., & Lonza, L. (2019). Definition of input data to assess GHG default emissions from biofuels in EU legislation - Version 1d. In *JRC Science for Policy Report EUR* (Vol. 28349). Publications Office of the European Union. https://doi.org/10.2760/69179

Ehrenfeld, J. R. (1997). The Importance of LCAs—Warts and All. *Journal of Industrial Ecology*, *1*(2), 41–49. https://doi.org/10.1162/JIEC.1997.1.2.41

European Commission. (2012). *International Life Cycle Data system* . European Platform on LCA | EPLCA. https://eplca.jrc.ec.europa.eu/ilcd.html

European Commission. (2021). *Innovation Fund (InnovFund) Call for proposals. Annex C: Methodology for GHG Emission Avoidance Calculation*.

European Union. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, *2018*(L 328), 82–209. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

European Union. (2023). Commission Delegated Regulation (EU) of 10.2.2023 setting out detailed rules for the production of renewable liquid and gaseous transportation fuels of non-biological origin. In *Official Journal of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM:Ares(2022)3836651

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneth, A., Arora, V., Bates, N. R., … Zaehle, S. (2020). Global Carbon Budget 2020. *Earth System Science Data*, *12*(4), 3269–3340. https://doi.org/10.5194/ESSD-12-3269-2020

Greenhouse Gas Protocol. (2013). *Corporate Value Chain (Scope 3) Accounting and Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

IATA. (2022, December 21). *European Politicians Need to Get Real About Aviation and Environment*. https://www.iata.org/en/pressroom/dg-blog/european-politicians-need-to-get-real-about-aviation-and-environment/

ICAO. (2022). *ICAO document 07-CORSIA Methodology For Calculating Actual Life Cycle Emissions Values* (Issue June). https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20June%202022.pdf

ICAO. (2023a). *Climate Change Technology Standards*. https://www.icao.int/environmental-protection/Pages/ClimateChange_TechnologyStandards.aspx

ICAO. (2023b). *Operational Measures*. https://www.icao.int/environmental-protection/pages/operational-measures.aspx

ICAO CAEP. (2019). *CORSIA Eligible Fuels – Life Cycle Assessment Methodology* (Issue June). https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

ICAO CAEP. (2022). *Guidance on potential policies and coordinated approaches for the deployment of sustainable aviation fuels*. https://www.icao.int/environmental-protection/Documents/SAF/Guidance%20on%20SAF%20policies%20-%20Version%201.pdf

ICF International. (2015). *Waste, Residue and By-Product Definitions for the California Low Carbon Fuel Standard*. http://www.theicct.org/waste-residue-byproduct-defs-calif-lcfs

Ivetta Gerasimchuk, Richard Bridle, Tom Moerenhout, Tara Laan, Chris Charles, & Elisa Asmelash. (2013). *Biofuels—At What Cost? A review of costs and benefits of EU biofuel policies*. https://www.iisd.org/publications/report/biofuels-what-cost-review-costs-and-benefits-eu-biofuel-policies

Joint Research Centre. (2010). *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition*. European Commission - Joint Research Centre. http://bookshop.europa.eu/fr/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf

Kim, S., & Dale, B. E. (2008). Effects of nitrogen fertilizer application on greenhouse gas emissions and economics of corn production. *Environmental Science and Technology*, *42*(16), 6028–6033. https://doi.org/10.1021/ES800630D

Laborde, D. (2011). Assessing the land use change consequences of European biofuel policies. In *International Food Policy Research Institute (IFPRI)* (Issue October). European Commission. Specific Contract No SI2. 580403

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., … Wilcox, L. J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*. https://doi.org/10.1016/J.ATMOSENV.2020.117834

Liska, A. J. (2015). Chapter 10. Eight Principles of Uncertainty for Life Cycle Assessment of Biofuel Systems. *Sustainable Biofuels*, 243–268. https://doi.org/10.1515/9783110275896-014/HTML

Lund, M. T., Aamaas, B., Berntsen, T., Bock, L., Burkhardt, U., Fuglestvedt, J. S., & Shine, K. P. (2017). Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics*, *8*(3), 547–563. https://doi.org/10.5194/ESD-8-547-2017

Malins, C. (2012). *Comments of the ICCT on EPA palm oil pathway NODA*.

Malins, C. (2017a). *Thought for Food - A review of the interaction between biofuel consumption and food markets*. Cerulogy. http://www.cerulogy.com/food-and-fuel/thought-for-food/

Malins, C. (2017b). *Waste Not, Want Not: Understanding the greenhouse gas implications of diverting waste and residual materials to biofuel production*. Cerulogy. http://www.cerulogy.com/wastes-and-residues/waste-not-want-not/

Malins, C. (2017c). *What role is there for electrofuel technologies in European transport's low carbon future ?* (Issue November). Cerulogy. http://www.cerulogy.com/electrofuels/power-to-the-people-what-role-is-there-for-electrofuel-technologies-in-european-transports-low-carbon-future/

Malins, C. (2018). *What role for electromethane and electroammonia technologies in European transport's low carbon future? June*.

Malins, C. (2019a). *Risk management - Identifying high and low ILUC-risk biofuels under the recast Renewable Energy Directive* (Issue January). http://www.cerulogy.com/palm-oil/risk-management/

Malins, C. (2019b). *What does it mean to be a renewable electron?* https://theicct.org/publications/cerulogy-renewable-electrons-20191209

Malins, C., Galarza, S., Baral, A., Brandt, A. R., & Howorth, G. (2014). *Crude oil greenhouse gas emissions calculation methodology for the Fuel Quality Directive*. http://www.theicct.org/crude-oil-GHG-calculation-methodology-fuel-quality-directive

Malins, C., Searle, S. Y., & Baral, A. (2014). *A Guide for the Perplexed to the Indirect Effects of Biofuels Production*. *September*, 1–166. http://www.theicct.org/guide-perplexed-indirect-effects-biofuels-production

Malins, C., Searle, S. Y., & Pavlenko, N. (2015). *Assessment of the scale of potential indirect emissions due to higher oil use*. https://www.theicct.org/sites/default/files/publications/Indirect_emissions_oil_use_201510.pdf

Miettinen, J., Hooijer, A., Tollenaar, D., Page, S. S. E., & Malins, C. (2012). Historical Analysis and Projection of Oil Palm Plantation Expansion on Peatland in Southeast Asia. In *Indirect Effects of Biofuel Production* (Issue 17). International Council on Clean Transportation.

Morais, S., Martins, A. A., & Mata, T. M. (2010). Comparison of allocation approaches in soybean biodiesel life cycle assessment. *Journal of the Energy Institute*, *83*(1), 48–55. https://doi.org/10.1179/014426010X12592427712073

O'Hare, M., Plevin, R. J., Martin, J. I., Jones, a D., Kendall, a, & Hopson, E. (2009). Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. *Environmental Research Letters*, *4*, 024001. https://doi.org/10.1088/1748-9326/4/2/024001

Plevin, R. J., Delucchi, M. A., & Creutzig, F. (2014). Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers. *Journal of Industrial Ecology*, *18*, 73–83. https://doi.org/10.1111/jiec.12074

Plevin, R. J., O'Hare, M., Jones, A. D., Torn, M. S., & Gibbs, H. K. (2010). Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science and Technology*, *44*(21), 8015–8021. https://doi.org/10.1021/es101946t

Schmidt, P. R., Zittel, W., Weindorf, W., & Raksha, T. (2016). *Renewables in Transport 2050 - Empowering a sustainable mobility future with zero emission fuels from renewable electricity*. Ludwig Bölkow Systemtechnik GmbH (LBST).

Scully, M. J., Norris, G. A., Alarcon Falconi, T. M., & MacIntosh, D. L. (2021). Carbon intensity of corn ethanol in the United States: State of the science. *Environmental Research Letters*, *16*(4). https://doi.org/10.1088/1748-9326/abde08

Searchinger, T. D. (2010). Biofuels and the need for additional carbon. *Environmental Research Letters*, *5*(2), 024007. https://doi.org/10.1088/1748-9326/5/2/024007

Searchinger, T. D., Edwards, R., Mulligan, D., Heimlich, R., & Plevin, R. J. (2015). Do biofuel policies seek to cut emissions by cutting food? *Science*, *347*(6229), 1420–1422. https://doi.org/10.1126/science.1261221

Spawn-Lee, S. A., Lark, T. J., Gibbs, H. K., Houghton, R. A., Kucharik, C. J., Malins, C., Pelton, R. E. O., & Robertson, G. P. (2021). Comment on 'Carbon Intensity of corn ethanol in the United States: state of the science.' *Environmental Research Letters*, *16*(11), 118001. https://doi.org/10.1088/1748-9326/AC2E35

The Royal Society. (2019). *Sustainable synthetic carbon based fuels for transport*. https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/sustainable-synthetic-carbon-based-fuels-for-transport/

Timpe, C., Seebach, D., Bracker, J., & Kasten, P. (2017). *Improving the accounting of renewable electricity in transport within the new EU Renewable Energy Directive*. Transport and Environment. https://www.oeko.de/fileadmin/oekodoc/Improving-accounting-of-renewable-electricity-in-transport.pdf

Transport & Environment. (2021). *Why is palm oil bad?* https://www.transportenvironment.org/challenges/energy/biofuels/why-is-palm-oil-biodiesel-bad/

U.S. EIA. (2023). *International electricity consumption statistics*. https://www.eia.gov/international/data/world/electricity/electricity-consumption

UK Office of National Statistics. (2021, November 1). *Emissions embedded in trade and impacts on climate change*. https://climate-change.data.gov.uk/articles/emissions-embedded-in-trade-and-impacts-on-climate-change

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlík, P., Forsell, N., & Hamelinck, C. N. (2015). *The land use change impact of biofuels consumed in the EU - Quantification of area and greenhouse gas impacts* (Issue 2015). European Commission.

van den Bos, A., & Hamelinck, C. (2014). Greenhouse gas impact of marginal fossil fuel use.

Wright, C. K., Larson, B., Lark, T. J., Gibbs, H. K., Salmon, J. M., Gibbs, H. K., Clark, C. M., Lin, Y., Bierwagen, B. G., Morefield, P. E., Leduc, S. D., Clark, C. M., Campiche, J. L., Bryant, H. L., Richardson, J. W., Wright, C. K., Larson, B., Lark, T. J., & Gibbs, H. K. (2017). Recent grassland losses are concentrated around U. S. ethanol refineries. *Environmental Research Letters*, *12*(4), 044001. https://doi.org/10.1088/1748-9326/aa6446