Beyond biomass?

Alternative fuels from renewable electricity and carbon recycling

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1. Executive Summary

Delivering deep decarbonisation in transport will require a mix of technologies and policy tools. Electrification is now widely understood to be at the heart of the vision for decarbonised road transport, but there's a large opportunity to deliver emissions reductions from lower carbon fuels both on-road during the transition, and in the longer-term for applications like aviation that are more difficult to transition away from liquid fuels. Alongside biofuels, recycled carbon fuels (RCFs) and renewable fuels of non-biological origin (RFONBOs) offer an opportunity to deliver such lower carbon fuels. RCFs are produced by using energy of fossil origin in waste materials that might otherwise be wasted or inefficiently utilised. RFONBOs are liquid and gaseous fuels produced using energy from non-biomass renewable sources such as wind and solar power. Much like advanced biofuels the technologies involved still need demonstration and commercialisation. Also similar to advanced biofuels there are sustainability and regulatory challenges associated with successfully ensuring that novel industries deliver real short- and long-term climate benefits. For both these technology families, there is now a tension between the desire to support immediate deployment and the desire to create a robust framework that will guarantee the benefits delivered.

This paper briefly reviews some of the pathways being considered for RCFs and RFONBOs. For RCFs, the pathways of most interest are bacterial fermentation of carbon monoxide in industrial off gases and liquid fuels from plastic waste. The most promising RFONBO pathway is synthetic fuel from renewable electricity. For both fuel types there are important lifecycle analysis issues that must be resolved, and clear evidence that not all pathways will deliver net climate benefits.

For RCFs, the main issues to consider are the displacement of existing energy recovery, and, for the use of waste plastics, the emission of carbon that would otherwise be semi-permanently sequestered in landfill. If the carbon combusted when RCFs are used would not otherwise have been emitted into the atmosphere, then there is little scope to deliver net climate benefits. Carbon buried in landfill should therefore be treated as sequestered for the purpose of analysing the climate impact of RCF production. It is important and appropriate to consider the associated environmental benefits of reducing the amount of material sent to landfill, but the value of improved waste management is separate from the value of reducing GHG emissions.

Where other energy recovery services are displaced by RCF production, the picture is more complicated – there may be opportunities to improve inefficient systems, or to replace lost power generation with low greenhouse gas (GHG) intensity renewables. Lifecycle analysis tools are well suited to assessing the net climate benefits of adopting these new fuel production systems. Under the European Union's recast Renewable Energy Directive (REDII), both RCFs and RFONBOs may be granted support by Member States to encourage production, but the Directive does not yet contain lifecycle analysis requirements for either family of technologies. It is important for the environmental integrity of European low carbon fuel policy that these issues are addressed effectively when lifecycle analysis requirements are developed in the coming years through "delegated acts" by the European Commission.

As well as setting lifecycle analysis rules the RED II calls for the Commission to establish a minimum GHG saving threshold for RCFs, just as the RED currently sets minimum GHG saving thresholds for biofuel and RFONBOs. If displacement emissions and combustion emissions are properly included in the assessment, there will be lower uncertainty about the emissions from RCFs than those of biofuels, and no major emissions terms outside the system boundary (in contrast to biofuels, which are expected to have significant indirect land use change emissions that are not directly included in the lifecycle analysis at present). The European Commission may therefore consider setting a lower minimum GHG saving threshold for RCFs than for biofuels.

For RFONBOs, the most important question for the regulatory treatment, and for the lifecycle analysis, is how and when to identify the electricity consumed as fully renewable. If net climate benefits are to be ensured, the most important aspect here is that additional renewable electricity capacity should be developed, rather than simply claiming renewable power that would have been generated anyway. The European Commission has an opportunity to set consistent requirements for assessing the renewability of the RFONBOs and their lifecycle GHG intensities in the coming decade.

2. Introduction and context

For the last ten years, the supply of alternative fuels in the European Union has been dominated by first generation biofuels (ethanol and biodiesel) produced from crops such as sugarbeet and wheat (for ethanol) and rapeseed and palm oil (for biodiesel), and to a lesser extent from waste and residual materials such as used cooking oil. The supply of these alternative fuels has been supported by Member States through various mandates, quotas, and tax incentives, offered under the common EU framework of the Renewable Energy Directive (RED, European Union, 2009). As we move into the next decade of EU climate policy, the Renewable Energy Directive has been recast (RED II, European Union, 2018), placing an emphasis on moving beyond first-generation biofuels. The strongest support will be for advanced biofuels produced from a lists of feedstocks specified in Annex IX of the Directive (for example agricultural residues), but there is also support for two categories of non-biomass-based fuels: recycled carbon fuels (RCFs); and renewable fuels of non-biological origin (RFONBOs). RCFs are fuels that are produced using energy of fossil origin that is carried in gaseous, liquid or solid waste streams. RFONBOs are fuels that are produced by converting non-biomass renewable energy (such as renewable electricity) into liquid or gaseous fuels.

Like other alternative fuel options, both RCFs and RFONBOs have characteristics that are appealing and also potential drawbacks. As these families of alternative fuel technologies receive more attention in the policy discourse, we can expect that competing and perhaps contradictory claims will emerge about the climate benefits of various pathways. In this report, we provide a brief overview of these novel fuels, focusing on the issues that emerge when trying to assess the potential climate benefits with lifecycle analysis (LCA). For RCFs, we include a brief review of LCA results from the literature. Additional background discussion on the LCA of RFONBOs can be found in Malins (2017b) and Searle & Christensen (2018).

While both fuel types are identified within the RED II, there are outstanding regulatory issues that will need to be resolved before the role of RFONBOs and RCFs in the EU's 2030 fuel mix will become clear. For RCFs, one important detail is that eligibility for support is at the discretion of Member States. The potential market for these fuels will therefore be dependent on whether all, most or only some Member States include RCFs in their RED II implementations. Both fuel types are also awaiting the publication of delegated acts by the European Commission – supporting legislation that fills in details left unresolved in the RED II. A delegated act (due by 31 December 2021) will set the LCA requirements for assessing climate performance of RCFs and RFONBOs. For RFONBOs, the delegated act will also clarify under which circumstances input electricity may be treated as entirely renewable. For RCFs, an additional delegated act (due by 1 January 2021) will impose a minimum GHG saving threshold. Until these delegated acts have been passed it will not be clear which pathways will be supported in the EU and which will not.

3. Recycled carbon fuels

There are two main families of fuel pathways identified as RCFs: fuel produced by utilising the energy in waste industrial gases, primarily carbon monoxide; and fuels produced by utilising the energy in waste plastics and synthetic rubber[1].

The concept of producing liquid fuels from waste carbon monoxide has been pioneered by the company LanzaTech. Some industrial flue gases contain carbon monoxide as a by-product. One example is steel manufacturing, in which carbon monoxide is used in the process and some inevitably remains unreacted and is discharged from the reactor. LanzaTech has developed a bacterial fermentation technology to convert this carbon monoxide (and hydrogen if available) into ethanol. The ethanol can be used directly as a transport fuel, or further processed into drop-in hydrocarbon fuels, for instance using alcohol-to-jet conversion technologies. For carbon monoxide based RCFs, the most appealing feature is that a low value energy carrier (carbon monoxide) is used to produce a much higher value and more flexible energy carrier (liquid fuels). It is important to recognise, however, that many steel plants and other industrial sites already recover energy from these flue gases by combustion for heat and power. If the flue gas is diverted to fuel production this energy will need to be replaced, potentially with fossil sources.

The idea of converting waste plastics into fuel is older, and has in the past been identified primarily as a waste management approach. While there are now some bio-based plastics available, the vast majority of plastics are currently manufactured using light hydrocarbons from oil or gas as the input feedstock. Much of the chemical energy from the oil or gas remains in the produced plastic materials, and thermo-chemical processes can be used to convert this energy into fuel. The most promising technologies that can be used to turn plastics into fuels are in essence the same as the technologies proposed for thermo-chemical biomass-to-liquids fuel production processes, for example[2]:

1. gasification to produce a hydrogen and carbon monoxide 'syngas' followed by Fischer-Tropsch (FT) fuel synthesis;
2. pyrolysis followed by upgrading of pyrolysis oil into transport-quality fuels.

For waste plastic based RCFs, the most appealing feature is the opportunity to generate fuels while reducing the amount of plastic waste needing to be disposed of with other methods (such as incineration or landfill). The downside of RCFs from waste plastic is that because the energy utilised is of fossil origin and the carbon in the fuels may otherwise have been sequestered in landfills, there may be no or limited net climate benefit.

1 Henceforth when we refer to 'waste plastics' it should be understood that waste synthetic rubbers are included.

2 As is the case with biomass-to-liquids, many technologies and combinations of conversion and fuel synthesis steps for RCF production are possible. In this report we focus on the technologies that we understand to be most likely to be commercialised in the short to medium term, but do not intend by doing so to imply any value judgment in favour of those pathways.

3.1. Assessing the (recycled) carbon footprint

LCA is a tool that can be used to assess and compare the GHG emissions and sinks associated with different fuel production pathways. LCA is already used within the Renewable Energy Directive to assess the GHG emissions associated with the processes required to produce biofuels. Biofuels must have a calculated lifecycle GHG intensity below a certain threshold (set with reference to the lifecycle GHG intensity of fossil fuels) in order to be eligible to receive financial support from Member State policies. There are a number of methodological choices that must be made when setting requirements for LCA, and one of the most fundamental is the setting of 'system boundaries'. The system boundary defines which of the GHG emissions and sinks associated with fuel production are to be included in the analysis. For example, indirect land use change emissions are considered outside the system boundary in the LCA requirements for biofuels.

For RCFs, one important system boundary question is whether the CO_2 released by fuel combustion is to be included in the reportable lifecycle GHG intensity value. For fossil fuels, the EU convention is that the combustion emissions are included, and they make up about 80% of the GHG intensity value set on petrol and diesel fuels. For biofuels, the EU convention is that combustion emissions are not included, on the basis that the carbon atoms in CO_2 released during combustion must previously have been absorbed by the growing plant from CO_2 in the atmosphere. If combustion emissions are counted in the lifecycle emissions of RCFs, then emission reduction would need to be achieved elsewhere within the system boundary if a significant net GHG saving is to be reported.

From the point of view of understanding net emissions changes, the central question to answer in determining how to treat the CO_2 released when recycled carbon fuels are burned is what would have happened to those carbon atoms if the fuel had not been produced. This alternative scenario can be referred to as the 'counterfactual'. If that carbon would otherwise have been expected to be reacted with oxygen[3] to make CO_2 and then been released, then combusting the recycled carbon fuel does not lead to a net increase in atmospheric CO_2 concentrations. If that carbon would otherwise have been expected to remain bound up in materials other than CO_2 (for instance remaining in the form of plastics) then combusting the recycled carbon fuel does lead to a net increase in atmospheric CO_2 concentrations.

It is important to distinguish between the potential climate benefits of RCFs and other environmental benefits that could be accrued relating to waste management. This is particularly important for waste plastics handling. In the case that non-biodegradable plastic waste would have been dispatched to landfill, the carbon in that plastic would have been sequestered semi-permanently.[4] Waste management benefits are not equivalent to climate benefits, and government policies generally value the reduction of GHG emissions from transport fuel more highly than the reduction of landfilling. Matheson (2019) reports average landfill fees in the OECD of about 40 € per tonne of material. If one and a third tonnes of plastic can be converted to one tonne of fuel (Benavides, Sun, Han, Dunn, & Wang, 2017) then avoiding that landfill fee would be worth about 60 € per tonne of fuel. This is much less than

3 Either through combustion or decomposition.

4 For example, one study on polyethylene film showed less than 0.2% by mass degrading to CO_2 over ten years in humid aerated soil if the sample had never been exposed to UV radiation, although degradation rates could be increased by UV exposure before disposal and by application of UV sensitisers (Albertsson & Karlsson, 1988)one without additive (PE.

the value of support for renewable fuels in RED – for instance credits under the UK Renewable Transport Fuel Obligation trade at prices up to 30 pence per litre, equivalent to over 350 € per tonne of synthetic diesel fuel supplied, about six times higher than the price signal from the landfill fee.

When providing additional policy support to RCFs by allowing them to count alongside low-carbon renewable fuels under the RED II, it would thus be consistent with existing policy priorities for the EU to require significant net carbon savings after the release of otherwise-sequestered carbon has been accounted for.

3.1.i) Flue gases

RCFs differ from biofuels and RFONBOs in that the energy being used to produce fuels comes from an originally fossil source. Consider the case of carbon monoxide in flue gases from the blast furnace at a steel plant. Carbon monoxide produced by the incomplete combustion of coke (purified coal) is required as a 'reducing agent' to produce iron from iron ore in a blast furnace by reacting away the oxygen in iron oxides. Some of this carbon monoxide fails to react with the iron oxides and leaves the blast furnace in the flue gas. This residual carbon monoxide could then be flared (combusted with oxygen in the air) and emitted as CO_2, combusted in a boiler to recover the remaining energy as heat and then emitted as CO_2, or diverted for use as feedstock in an RCF process such as LanzaTech's bacterial fermentation.

The carbon monoxide is clearly not a renewable energy source, and combusting the carbon monoxide leads to fossil carbon being released to the atmosphere as CO_2 – but that does not necessarily mean that RCF production would not be an efficient use for an available resource. In assessing the net climate implications of adding an RCF production step we must consider the counter-factual – is RCF production better or worse for the climate than the likely alternative disposition? If the carbon monoxide would otherwise have been flared with no energy recovery then the energy would have been entirely wasted, and RCF production is clearly a better use. In the case that the carbon monoxide would otherwise have been used as boiler fuel it is more complicated, and before coming to a conclusion about the climate implications of RCF production we must ask how efficiently the energy would have been recovered and what energy sources are available as alternatives to the boiler. If an existing energy recovery step is inefficient, or if that displaced energy could be replaced by low GHG intensity electricity, then there may still be a net GHG benefit.

3.1.ii) Waste plastics

Similar issues emerge when we consider the case of fuel production from waste plastics. Most plastics are made from oil and gas, and waste plastics still carry some energy from that oil and gas. When fuel is made from those plastics and later burned in a combustion engine, fossil carbon is released into the atmosphere as CO_2 just as surely as if the original oil or gas had been turned into fossil fuels. There may still, however, be cases in which fuel production from waste plastics could be climate friendly or otherwise environmentally justified. For example, some municipal waste is currently incinerated with no energy recovery. If a recycled carbon fuel production system allowed energy from those materials to be recovered, there would be no net additional CO_2 emissions from fuel combustion (the amount of CO_2 released to the atmosphere is unchanged from the counter-factual). If the plastic would otherwise be incinerated with energy recovery, then LCA can compare the efficiency of the two energy recovery systems, and consider the alternative sources of heat and/or power if incineration is reduced.

In cases where the counterfactual is included in the LCA, it is important that a realistic counterfactual is set. A producer cannot be permitted to simply assume that plastics would otherwise have been incinerated without energy recovery, supporting evidence must be provided. Setting a reasonable counter-factual will require considering regional context and the relevant policy environment (for instance if incineration without energy recovery was being made illegal, it should not be assumed in the counterfactual that it would continue).

RCFs could still be eligible to receive some government support even if LCA shows that they do not meet the GHG saving threshold to be counted towards REDII targets. Gate fees for landfilling already provide opportunities for waste plastics to be sourced at low or negative cost, and if government seeks to further reduce or eliminate landfilling the value from waste management policy may increase.

3.2. Treatment in published LCA approaches

3.2.i) Flue gases to fuel

One important consideration in lifecycle analysis of any type of alternative fuel is whether the supply of the feedstock responds to its demand. The two methodologies proposed by the European Commission (Edwards, Rejtharova, Padella, Wachsmuth, & Lehmann, 2020; Joint Research Centre, 2016) both develop the idea of the difference between feedstock resources that have an 'elastic' versus 'rigid' supply. A material has an elastic supply if the production of that material is expected to increase in response to increased demand – this applies to the primary crop feedstocks for many biofuels. A material has rigid supply if the production of that material is expected not to show any significant response to increased demand – this applies to most waste and residual feedstocks, whose supply is determined by demand for the primary product. For materials with an elastic supply, the guidelines require an assessment of the emissions associated with producing more of the material. For a material with a rigid supply, the European Commission guidelines require an assessment of any emissions associated with removing that material from its alternative use or method of disposal. Carbon monoxide in flue gas counts as material with a rigid supply because the rate of iron smelting is independent of demand for alternative fuel production, and therefore under these guidelines an assessment of the counter-factual use or disposal would be required.

One important element of the counter-factual assessment is setting the appropriate timeframe for data collection. In the LCA guidance for the Fuel Quality Directive, it was required that any displacement of electricity generation should be assessed based on recorded average GHG intensity of electricity in the relevant country two years prior to the assessment. Given that the electricity grid is being progressively decarbonised, this backward-looking approach would tend to overstate both any emissions penalty from increasing electricity demand from the grid and any emissions credit from increasing electricity supply to the grid. The Innovation Fund draft methodology, in contrast, requires a forward-looking approach by considering the expected GHG intensity of electricity production over the life of a project. This difference is important for cases where flue gas is diverted from existing energy recovery systems,

A formula to calculate the GHG intensity of a carbon monoxide fermentation process was published alongside the FQD guidance (Edwards, Padella, & O'Connell, 2017). For basic oxygen furnace (BOF) flue gas processing, if carbon monoxide would otherwise have been flared the calculation gives a GHG intensity of 19 gCO_2e/MJ. If instead the counter-factual included full energy recovery, based on the average EU grid GHG intensity at the time the GHG intensity of the RCF would be 89 gCO_2e/MJ. Assessment of the carbon monoxide to ethanol pathway by Handler, Shonnard, Griffing, Lai, & Palou-Rivera (2016) gave a similar result for the case that flue gas would otherwise have been flared, 31 gCO_2e/MJ. Searle, Pavlenko, El Takriti, & Bitnere (2017) present a result for an intermediate counter-factual, assuming 30% of flue gas (on average) diverted from flaring and 70% from low-efficiency energy recovery. These assumptions gave a GHG intensity of 26 gCO_2e/MJ. This analysis differs from the example calculations in Joint Research Centre (2016) by assuming lower efficiency of energy recovery in the existing boiler, and by considering natural gas rather than grid electricity as the replacement for displaced energy. The range in these results illustrates the sensitivity of calculated RCF GHG intensity to assumptions about the nature and GHG intensity of displaced energy in the counter factual.

3.2.ii) Waste plastic to fuel

The results reported by the various studies considered are dependent on the details of the technologies being assessed and the specific assumptions about the precise characteristics of the feedstock plastics, but nevertheless common themes emerge in the reported LCA results.

Firstly, the studies are consistent in attributing the emissions from combustion of plastic waste that would otherwise be landfilled to the energy recovery pathways. This can be done directly by counting the combustion emissions in the fuel lifecycle (e.g. Suresh, 2012) or indirectly by treating plastics in landfill as sequestered carbon in a counter-factual reference scenario (Edwards et al., 2020; Joint Research Centre, 2016). This is a fundamental difference between the LCA of RCFs from waste plastic and the LCA of biofuels, where it is conventional not to count the CO_2 emissions from fuel combustion[5].

Given that the CO_2 emissions from RCF combustion are about the same as those from conventional fossil fuel combustion, overall GHG savings compared to conventional fossil fuels are only reported for RCFs where some combination of the following is true:

1. RCF production replaces incineration without energy recovery, giving a credit for avoided emissions;
2. RCF production replaces incineration with energy recovery and:
    - RCF production is more energy efficient than a displaced system for incineration with energy recovery;
    - Reduced energy recovery from incineration will be compensated by increased production of relatively low GHG intensity energy (e.g. wind and solar power);
3. RCF production has lower associated upstream GHG intensity than a fossil fuel comparator.

5 The assumption being that the CO_2 released during combustion is cancelled out by CO_2 absorbed during plant growth.

As regards the first condition (displacement of incineration without energy recovery) the studies are consistent in reporting GHG savings. Given the process efficiencies considered in the literature substantial GHG savings (50-100%) should be reportable for such cases.

As regards the second condition, the results in studies that compare RCF production to incineration with energy recovery are sensitive to both the assumed efficiency of energy recovery at the incinerator and to the assumed GHG intensity of the alternative electricity supply. Benavides et al. (2017), which has a U.S. focus, finds that RCF production delivers climate benefits over energy recovery with incineration, but this result is predicated on a low efficiency of energy recovery from the incinerator (25%). Some regions will have much higher typical efficiencies on existing systems, especially for combined heat and power (e.g. Eriksson & Finnveden, 2009 reports 80% average energy recovery efficiency for Swedish facilities). Identifying cases where shifting waste plastics to RCF production will deliver climate benefits would require careful consideration of the efficiency of existing incineration systems and the likely adjustments to overall power generation if incineration with energy recovery is reduced in a given location. Decarbonisation of the electricity grid will tend to improve the climate performance of RCF pathways as compared to continued incineration with energy recovery. Where net GHG savings could currently be achieved by replacing incineration with energy recovery they may be relatively marginal, and will always be lower than for replacing incineration without energy recovery.

The third condition reflects whether it is more GHG efficient to produce transport fuels from waste plastics than from crude oil. Production emissions for RCFs from waste plastics should generally be lower than the average for fossil fuels (American Chemistry Council & RTI International, 2012; Benavides et al., 2017), although this will depend on the specific RCF process and on efficient process implementation. Delivering lower production emissions than are reported for conventional fossil fuels could result in modest reportable GHG reductions for RCF production even against landfilling as the counterfactual (up to about 10%) and would contribute to larger net GHG reductions for counterfactuals including incineration.

There is not an overall consensus in the literature about whether RCF production results in GHG savings against landfilling as a counterfactual. Benavides et al. (2017) and American Chemistry Council & RTI International (2012) both find modest emissions reductions compared to landfilling, but Alston & Arnold (2011) find a modest increase.

The lifecycle analysis studies of RCFs from waste plastic generally assume that plastic recycling rates are not affected – either the material processed is limited to non-recyclable plastic or to material that would simply not have been recycled. This reflects the EU waste hierarchy, under which material recycling should generally be preferred to energy recovery by RCF production. When considering increased RCF production as part of an overall EU policy of reducing the landfilling of waste, it is relevant to consider how the climate impacts of RCF production compared to recycling options. Recycling of efficiently sorted high quality material that can be recycled in a 'closed loop' replacing virgin polymers delivers much greater climate benefit than recycling of low quality mixed material that would be 'downcycled' to lower-value applications (Alston & Arnold, 2011; Huysman et al., 2015). Closed loop recycling can be expected to deliver much larger climate benefits than RCF production, but the climate performance of downcycling and RCF production are likely to be comparable. Determining whether RCF production has better or worse climate performance than downcycling in a given case would depend on the specifics of the systems being compared

3.3. Conclusions on lifecycle emissions of RCFs

For fuels produced from energy-carrying molecules in flue gas, the most important LCA question is the alternative disposition of that material. If the flue gas would otherwise be flared, RCFs produced from it will have a low GHG intensity. If energy would normally be recovered from that flue gas then the GHG performance of RCFs produced from that gas will be strongly dependent on the efficiency of the alternative energy recovery process, and on the GHG intensity of the likely replacement energy source.

For plastic to fuels pathways, several themes emerge fairly consistently from the studies considered. Firstly, if carbon atoms sent to landfill are treated as sequestered semi-permanently (which is generally physically correct), there is at best a modest climate benefit when plastic to fuel technologies are compared to landfilling. Secondly, when plastic to fuel technologies are compared to incineration with energy recovery, the outcome is strongly dependent on the assumed efficiency of energy recovery and the assumed GHG intensity of the energy source replaced. In general, moving resources from incineration with energy recovery to RCF production will not deliver large GHG savings. Thirdly, if plastics can be recycled back into similar materials replacing virgin plastic production then the climate benefit is much greater than from plastic to fuel technologies, but plastic to fuel technologies may not increase GHG emissions when compared to recycling of lower quality plastics into secondary materials, sometimes referred to as 'downcycling'. Finally, RCF production shows substantial climate benefit compared to incineration without energy recovery.

According to Bellona & Zero Waste Europe (2020) a larger quantity of plastic collected for recycling is currently downcycled than is recycled back into high quality plastic products. This suggests that in some cases RCF production could be an environmentally appropriate choice for plastics that are being separated but that are not suitable for recycling into high quality materials. In general, however, RCF production pathways would be at best marginally preferable in terms of net climate impact than other downcycling options, and therefore the net GHG savings from switching between downcycling options would be unlikely to meet any minimum threshold set for the RED II.

4. Renewable fuels of non-biological origin

The most promising family of fuel pathways identified as RFONBOs is based on the use of renewable electricity to produce hydrogen by electrolysis. This hydrogen can then either count directly as a RFONBO if supplied for transport use in fuel cell vehicles, or can be used as an input into chemical synthesis processes to produce fuels for internal combustion engine vehicles. Depending on the synthesis processes used the output fuel could be: methane for natural gas vehicles; ethanol for blending with petrol; drop-in substitutes for petrol, diesel or jet fuel; or other currently less commonly used energy carriers such as di-methyl ether (DME), methanol or ammonia. These renewable electricity-based fuel pathways are sometimes referred to as power-to-liquids (PtL), electrofuels, e-fuels or power-fuels (cf. Malins, 2017b). Other pathways to produce RFONBOs may be possible but are further from commercial operation, such as direct solar fuel synthesis[6].

For RFONBOs, perhaps the most appealing feature is the potential scalability. In principle, renewable energy can be produced much more efficiently in terms of factors like land requirements and water use by wind and solar power facilities than is possible for biofuel production. The enormous volumes of fuel consumed by modern society could therefore in principle for produced with fewer sustainability issues as RFONBOs than as biofuels. The biggest downside of RFONBO production is that energy is lost in the conversion from electrical to chemical energy, making RFONBOs less efficient than direct consumption of electricity for transport, and (at current electricity prices) very expensive to produce. There are also challenges involved with accounting for renewable energy in RFONBO production. Simple requirements to guarantee the use of renewable energy (e.g. that a RFONBO facility should only use electricity sourced directly from a specified renewable power plant) may lack the flexibility to support market deployment, but more flexible approaches (such as allowing renewability credits to be traded) could undermine the climate benefits of the industry if not carefully implemented.

4.1. LCA

By far the largest energy input to RFONBO production is the electricity used for electrolysis. At current efficiencies, over twice as much energy is input to producing a liquid RFONBO as is output in the fuel, and so the GHG performance of the RFONBOs is determined primarily by the GHG intensity assigned to that electricity. This can be seen in Figure 1, which provides indicative GHG intensities for RFONBOs produced with different sources of input electricity. On the left of the chart, we see that using 100% natural gas electricity would give a fuel GHG intensity of about 300 gCO_2e/MJ, more than three times higher than fossil petrol or diesel. Only by sourcing electricity solely from very low GHG-intensity renewables such as solar and wind could significant GHG savings be delivered (allowing a RFONBO to potentially meet the 70% GHG saving threshold set in the RED). In the chart, estimated emissions associated with construction of renewable power facilities have been included and so even wind and solar power are not shown as having zero GHG intensity. On the right of the chart, we see that even

6 Cf. https://www.bauhaus-luftfahrt.net/en/topthema/solar-fuels/

for a mix of renewable and fossil electricity (60% wind and 40% natural gas in this case) RFONBO production could still result in significant net GHG increases compared to conventional liquid fossil fuels.

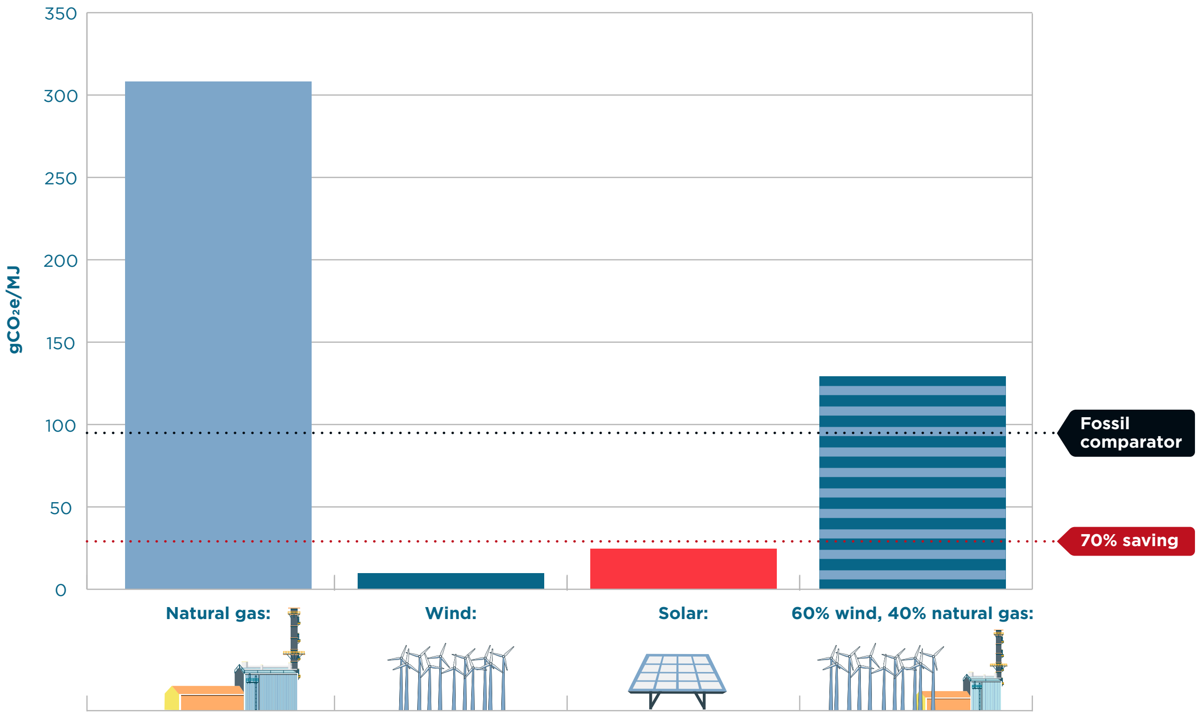

Figure 1. Indicative GHG intensity of RFONBO production for different electricity sources

Source: Malins (2017b) based on Edwards et al. (2013) with renewable electricity construction emissions from Edwards et al. (2020).

The fossil fuel comparator GHG intensity is shown as a grey line, and the 70% GHG saving threshold as a red line. Assumes 40% energy conversion efficiency of electricity into liquid fuel.

It can be seen from Figure 1 that any RFONBO hoping to get support under the RED would need to use more or less 100% low GHG intensity renewable power in order to meet the minimum GHG saving threshold of 70%. This naturally leads to the question of how it can be determined whether the electricity used can be treated as fully renewable. Power can be transported over great distances, and the power from many generating facilities, both renewable and fossil, can be combined and distributed through a single grid. This co-mingling of electricity means that it is not always obvious how we should assess the GHG intensity of a given kilowatt hour of electricity consumed from the grid. For a RFONBO plant that draws power from the grid, should that power be treated as having a grid average GHG intensity? Should we instead try to consider what additional electricity generation might be activated in order to meet additional demand from a RFONBO facility? Can we find a way to allow electricity from the grid to be treated as entirely renewable for a RFONBO plant even though the grid still includes fossil power?

There is not a single 'analytically correct' answer to these questions, but RFONBO production may not deliver climate benefits if the accounting system that is developed to assess renewability claims is not fit for purpose. If RFONBO production is increased without being accompanied by any additional renewable power generation[7] then net emissions across the system will be increased rather than reduced (Searle & Christensen, 2018), regardless of the LCA rules that are adopted for reporting. The RED II explicitly states that "there should be an element of additionality, meaning that the [RFONBO] producer is adding to the renewable deployment or to the financing of renewable energy."

Currently, the RED II presents three options to determine what fraction of the electricity input to a RFONBO process may be counted as renewable. Firstly, the facility may count a fraction as renewable based on the average share of renewable electricity generation in that country (based on two-year-old data). Secondly, the facility may count the electricity as wholly renewable if obtained by direct connection to a new renewable electricity installation without taking any power from the grid. Thirdly, the facility may treat the electricity as wholly renewable, "provided that it is produced exclusively from renewable sources and the renewable properties and other appropriate criteria have been demonstrated, ensuring that the renewable properties of that electricity are claimed only once." The detail of this third option will be laid out by delegated act.

While each of these options has a clear logic to it, using any of them as part of the LCA requirements would present challenges in terms both of guaranteeing the climate benefits of RFONBO production and of supporting the development of RFONBO projects. The first option, the use of average grid renewability, would mean that RFONBO projects could only be viable in countries with very high renewable electricity penetration in the grid (and possibly also countries with a grid dominated by a combination of renewables and nuclear). It also lacks any explicit requirement that additional renewable capacity should be added to meet demand from RFONBO plants. Effectively it is assumed that in a country with very high renewables penetration already, additional demand is also likely to be met with renewables, but this may not always be true.

The second option, requiring a direct connection to a renewables facility, provides a very clear association between the RFONBO plant and the renewable generation, but could implicitly require the adoption of less efficient operating practices. From a financial and resource utilisation perspective, it makes sense to maximise the operational hours for electrolysers, the most expensive single piece of equipment used in RFONBO production. If connected directly to a single wind or solar renewable power plant, however, an electrolyser could only be operated at full capacity when conditions were favourable. Electrolyser operation could be increased by building additional power production capacity, but that would imply either wasting some power generation in optimal conditions or exporting the excess electricity to the grid. Exporting to the grid would be the better solution, but it could become difficult to determine whether the RFONBO plant has brought additional renewable capacity into the system (good) or is simply using up some fraction of power production by a facility that could have been built for grid supply anyway.

The third option, finding a regulatory approach to allow electricity supplied over the grid to be treated as fully renewable, would enable the most efficient production modes but would be the most difficult to properly regulate. Under such an option, it would be possible to operate an electrolyser for a much larger fraction of the time than would be possible for a connection

7 Or additional utilisation of otherwise curtailed renewable power.

to a single generating facility, which would improve the economics of project development. It would allow projects to be constructed in countries with relatively low renewable penetration, unlike the first option. The capacity to deliver real emission savings under such a system, however, would be dependent on putting in place accounting rules that create a real drive for new renewable power project development matching additional demand from RFONBO plants. A more detailed discussion of the challenges in identifying electricity as renewable, and several options to implement this third option, are presented in Malins (2019) – including a discussion of the potential shortcomings of some possible approaches.

4.2. Economic challenges

Arguably the most fundamental barrier to expansion of RFONBO production in the near term is the high expected production cost, and the biggest contribution to the cost equation is the price of electricity as an input (Malins, 2017b; Searle & Christensen, 2018). Almost by definition, implementing effective mechanisms to require that RFONBO plants support additional renewable electricity generation is expected to increase the cost of electricity to producers, because it involves passing value through the supply chain to directly support capacity installations. It may seem to some that it is counter-productive to place additional costs on a prospective industry that is already confronted by a challenging business model, but the reality is that without ensuring that RFONBO production supports additional renewable capacity a RFONBO industry will not assist with climate goals.

It should be acknowledged that lower prices may be achievable by taking advantage of curtailment (electricity prices may be lower or even negative when more renewable power is being produced than the grid is able to dispatch). Utilising electricity generation that would otherwise be curtailed would be a true win-win – good on climate grounds and good on financial grounds. While the cost of electricity bought could be reduced in this way, curtailment normally only occurs for a small fraction of the time. As the grid develops in the energy transition, the bottlenecks in distribution that cause most curtailment may also be only temporary. Operating an electrolysis plant only during curtailment could reduce the input costs, but because such a plant would have less operational hours annual production would be reduced and capital costs increased per unit of fuel produced. There may be some opportunities to make such a business model work, but they are likely to be the exception rather than the rule.

There are also some renewable electricity projects, such as solar photo voltaic installations in the Middle East, that already claim to be able to deliver very low levelised cost of electricity production. Some analyses see RFONBO imports from such low-cost renewables locations as the most cost-effective way to achieve largescale deployment (Schmidt, Zittel, Weindorf, & Raksha, 2016). Even if renewable energy generation at low cost is possible in these locations, it should not be taken for granted that RFONBO production would be the preferred use for those resources. Any RFONBO industry would be competing with local power consumption, and with a range of other energy intensive industries that would value lower cost electricity. Overall, the high costs of RFONBO production seem likely to be a persistent issue for the medium-term, and are likely to prevent any large-scale deployment in the period to 2030.

5. Making the RED II work for RCFs and RFONBOs

5.1. Setting levels of support

The EU's energy transition is not simply a process of investing equally in every technology that could offer some environmental benefits – decarbonisation options need to be compared, and policy makers aim to provide the strongest support for options that both deliver near-term emissions reductions and that have a role in long-term decarbonisation. Policy makers set different levels of priority for GHG emissions reductions in different sectors, and different levels of priority for GHG emissions reductions and for waste management. These priorities result in quite divergent value signals for different technologies. For example, the value signal from RED for emissions reductions through transport fuels is of the order of ten times stronger[8] than the value signal from the Emissions Trading Scheme for emissions reductions in industry and power generation. Under the RED II, a sub-target for advanced biofuels and rules for double counting have been agreed that will provide a stronger value signal for advanced biofuels than either for first generation fuels or eligible RCFs and RFONBOS. It is appropriate that the net climate benefit of the development of specific RCFs and RFONBO pathways should be considered when deciding what level of incentive they should be eligible to receive. Setting the lifecycle assessment methodology, and the GHG savings threshold for RCFs, will identify which production models gain support under the RED II, and which shall only receive support (if any) from other policies. For example, even if an RCF is not rated as delivering net GHG savings, a producer of that RCF could still benefit from negative cost feedstock due to landfill fees.

It is important to set stringent eligibility criteria because policies like RED are designed to create competition between the different technologies available. There is a target of 14% for energy from renewables and RCFs in transport. Making a given novel fuel technology eligible to be counted means that it is in competition with other alternative fuels. Creating a stronger value signal for investment in one fuel can therefore weaken the value signal for investment in the others.

While the policy framework puts fuel technologies into competition with each other, it should also be acknowledged that there may be a degree of complementarity between technology pathways. For example, developing Fischer-Tropsch fuel synthesis technology in the context of plastic-to-fuels could help deliver cost reductions and technical innovations that could be used with biomass or with hydrogen from electrolysis. Developing pyrolysis technologies for waste plastics could support development of pyrolysis for waste wood. The fundamental challenge for the European Commission and Member States is to find a balance whereby rules to guarantee the climate performance of RCFs and RFONBOs are not so stringent that they prevent all project development, but are not so weak that a glut of fuel delivering minimal real climate benefits becomes a barrier to the development of real solutions.

8 ETS prices in the region of 25 €/tCO_2e compared to implied carbon abatement prices under RED in the region of 250 €/tCO_2e.

5.2. Considerations for the delegated acts under the RED II

It is common in European Union Directives for powers to establish additional rules, especially on technical issues, to be devolved to the European Commission[9] through the requirement to produce 'delegated acts'. The REDII calls for several delegated acts to be adopted, three of which are relevant to the regulatory treatment of RCFs or RFONBOs:

- Article 25 (2) calls for the adoption of a delegated act by 1 January 2021, "establishing appropriate minimum thresholds for greenhouse gas emissions savings of recycled carbon fuels through a life-cycle assessment that takes into account the specificities of each fuel."
- Article 27 (3) calls for the adoption of a delegated act by 31 December 2021 establishing a methodology by which RFONBO producers may report the electricity used as fully renewable.
- Article 28 (5) calls for the adoption of a delegated act by 31 December 2021, "specifying the methodology for assessing greenhouse gas emissions savings from [RFONBOs and RCFs], which shall ensure that credit for avoided emissions is not given for CO_2 the capture of which has already received an emission credit under other provisions of law."

The questions to be addressed in these delegated acts (GHG saving thresholds, renewability, and LCA requirements) are clearly closely related. For example, the choice of LCA methodology for RCF affects the decision about what GHG saving threshold would be reasonable, while the requirements for treating RFONBOs as fully renewable would be expected to inform the LCA of RFONBOs.

5.2.i) LCA methodology – RCFs

Probably the two most important decisions to be made in the LCA requirements for RCFs are how to deal with the use of inputs that have a rigid supply, and how to treat carbon atoms that would otherwise be sequestered in landfills. For inputs with a rigid supply, the ideas developed for the FQD and Innovation Fund present a reasonable basis to proceed. The emissions consequence of using inputs with a rigid supply is best assessed by considering the expected consequence of diverting that material from an existing use. Failing to consider these diversion emissions could result in significant investment being put into rolling out technologies that deliver no net GHG benefit.

For the diversion of energy carriers in flue gases, this means that the emissions associated with replacing any energy that would normally have been recovered ought to be assessed. Making this assessment requires making an assumption about the GHG intensity of the alternative energy sources available, in particular about electricity from the grid. The cleaner the alternative energy sources are, the lower the emissions attributed to diversion of the flue gas. In the FQD methodology, it was required that this GHG intensity must be calculated in a backwards looking way with two-year-old statistics. In the Innovation Fund, in contrast, project assessments are required to consider the expected future state of the EU energy system.

9 The European Parliament and European Council still have the power to reject a proposed delegated act, but unlike the process of agreeing Directives or Regulations they have no mechanism by which to amend a proposed delegated act.

Given that the EU's energy mix is being progressively decarbonised, the difference between backwards and forwards looking approaches to this question could be large. Novel RCF facilities will be long term investments, designed to produce fuel for the next two or three decades. There is little analytical reason to be excessively conservative in assessing the benefits of such projects by using only historical data on the GHG intensity of electricity – it is reasonable to assume that decarbonisation will move forward more or less as planned outside the transport fuel sector. If a new RCF project with significant electricity displacement would meet a given GHG savings threshold based on the expected GHG intensity of electricity three years in the future, it would meet that threshold across most of its operational life. Analogously to electric vehicles, the GHG performance of RCF projects with significant displacement emissions can be expected to improve further over time, on which basis it would be reasonable to consider a forward-looking approach in the LCA requirements.

For the use of waste plastic materials as feedstocks, the picture is perhaps slightly more complicated, as it may be less clear what the alternative fate of a given batch of material would be. Dependent primarily upon location, material may currently be destined for sorting and recycling[10], for incineration with or without energy recovery, or for landfilling. The amount of waste generated in the future and the disposition of that waste will be affected by European policy. The recently released EU Circular Economy Action Plan (European Commission, 2020) anticipates new measures to reduce the amount of non-recycled waste by half by 2030. RCF processes are identified in the waste hierarchy as "other recovery", being given a lower priority than material recycling options (European Commission, 2017). It is an explicit policy aim to reduce both landfilling and incineration without energy recovery, even without the further development of RCF technologies.

RCFs from plastics are most likely to be assessed with a significant GHG saving if the plastic is diverted from incineration without energy recovery. Where a producer wishes to claim such diversion, an assessment will be necessary informed by consideration of regional waste disposal norms – one could imagine undertaking such an assessment in a fashion analogous to sustainability assessment for biofuels. Such an assessment should include consideration of whether spare incineration capacity is likely to remain unused. If the plastic taken away from an incinerator input stream as feedstock for RCF production is simply replaced by diversion of more plastic from landfill elsewhere, then landfill would be the true counterfactual. In some cases, the knock-on effect on waste handling decisions could still be associated with increased or reduced emissions. For example, landfilling biogenic material results in methane emissions, whereas landfilling plastics does not. If plastics are sorted out of incinerator input streams and replaced in the incinerator by biogenic material, this could provide an indirect emission reduction through reducing methane formation in landfill. It will not always be possible to reliably predict such knock-on effects, but when establishing a counter-factual such possibilities should at least be considered.

As detailed in the literature review section above, it is normal in LCA (and physically accurate) that carbon in landfill should be treated as sequestered; following those precedents would imply that combustion emissions should be counted in the assessment of RCFs from plastics. Any non-climate environmental benefits from reducing landfilling ought to be framed in waste management terms rather than by artificially inflating the reportable climate benefits of RCF technologies.

As indicated in the review of previous LCA studies, the hierarchy of climate benefits between

10 With the residual part incinerated or landfilled.

incineration with energy recovery and RCF production is primarily dependent on the efficiency of the incinerator (and whether both heat and electricity are recovered) and the GHG intensity of alternative electricity production. Undertaking a diversion analysis for these materials using regional grid average GHG intensity would be a reasonable basis to identify locations where there may be a larger climate benefit from diverting resources to fuel production.

5.2.ii) GHG saving threshold – RCFs

In the RED II, minimum GHG saving requirements are imposed on biofuels from older plants (50-60%), biofuels from plants entering operation from 2021 onwards (65%) and for RFONBOs (70%). The thresholds set for these fuels serve at least three roles.

Firstly, requiring some minimum climate benefit is intended to avoid the case that significant resources are invested in fuels that deliver only modest benefits. All else being equal, the carbon abatement cost of using a biofuels with a 50% GHG saving is five times lower than that for using a biofuel with a 10% GHG saving, and so the policy can be made more efficient by limiting support to fuels that have poor climate performance.

Secondly, setting a threshold is a way to manage uncertainty about the real net climate impacts of using alternative fuels. There are uncertainties throughout the process of LCA, for example due to allowing the use of default values, because of limits to the precision of process data and because of uncertainty in modelling some emissions such as nitrous oxide from fertiliser application. Imposing a minimum requirement on expected benefit reduces the risk that some fuels may be worse for the climate than our modelling suggests.

Thirdly, setting higher minimum savings thresholds is one way to allow for the fact that some emissions terms may not be included in the regulatory LCA at all. For example, for biofuels grown on land that would otherwise be available for other crops or uses we expected significant indirect land use change (ILUC) emissions (cf. Malins, Searle, & Baral, 2014) but these are not included in the lifecycle assessment requirements of RED II. Similarly there may be indirect emissions associated with using resources that could be characterised as wastes, residues or by-products (cf. Malins, 2017a) but these are also not included in the regulatory assessment.

The first of these reasons to set a minimum saving threshold applies to RCFs just as much as to other alternative fuels. In contrast, *provided the LCA methodology adopted includes the knock on emissions from using inputs that have a rigid supply* there should be much less uncertainty about the real results than we see in the case of biofuels, and no major emissions terms left out of the LCA. This could justify adopting a lower threshold GHG savings requirement for RCFs than is required for biofuels.

5.2.iii) Renewability and LCA methodology – RFONBOs

The central question for LCA of RFONBOs is finding an appropriate basis to set the GHG intensity of input electricity. This is closely related to the assessment of the renewability of input electricity (electricity that is treated as renewable will generally also be assigned a lower lifecycle GHG intensity). The delegated acts setting the rules for treating input electricity as fully renewable and for the LCA of RFONBOs are due at the same time, and it might be expected that electricity that can be reported as 100% renewable in the one delegated act will be assigned the GHG intensity of 100% renewable electricity in the LCA in the other delegated act.

It has been discussed in previous papers (e.g. Malins, 2017b, 2019; Searle & Christensen, 2018) that robust rules for allowing electricity to be reported as fully renewable will be necessary if assurance is to be given that RFONBO projects taking power from the grid deliver net emissions reductions. Malins (2019) suggests that an approach could be built around power purchase agreements, whereby RFONBO producers would be required to have agreements in place to purchase power across the grid from identified renewable power suppliers. The use of such agreements does not in itself guarantee development of any additional capacity, especially given that renewable power producers may already be receiving government support through other mechanisms. A form of certification is suggested for renewable power that is produced without government support and without being counted towards existing targets (referred to as a 'guarantee of origin plus', GO+). Requiring RFONBO producers to purchase renewable electricity meeting such a certification requirement ought in most cases to imply that the RFONBO customer was supporting the operation of that renewable capacity.

Having established a system for assessing renewability, there are two cases that the LCA methodology for RFONBOs will need to address, firstly the case that all the input electricity to a facility meets the criteria to be treated as renewable, and secondly the case that only part of the input electricity meets the criteria to count as renewable.

In the first case, a fully renewable process, then the electricity input should be assigned the GHG intensity of the source renewable electricity. In the RED II LCA methodologies for biofuels and biomass, 'grey' emissions associated with facility construction are excluded from consideration. This simplification is informed by the expectation that for most bioenergy facilities those grey emissions will be small compared to other emissions sources. On this basis wind and solar power used in the biofuel or biomass supply chain have been treated as zero emissions. As noted in the draft methodology for the innovation Fund, in the case of renewable power facilities (particularly solar farms) construction emissions are relatively significant. It would therefore be appropriate for the Commission to consider whether some construction emissions should be assessed in the LCA of RFONBOs.

In the case that only part of the electricity input to a facility could be treated as renewable, a methodological decision must be made whether to assign a single average GHG intensity for both the renewable and non-renewable part of the produced fuel, or to allow the two output streams to be assigned separate GHG intensities. The latter approach would create the risk that a process could output a nominally renewable stream assigned a very low GHG intensity and therefore eligible for support, and a nominally fossil stream assigned a GHG intensity much higher than conventional fossil fuels but not subject to any GHG-related penalty. Perverse outcomes could be avoided by calculating a single average GHG intensity for all produced fuel.

It is already required in the RED II that the LCA methodology must ensure, "that credit for avoided emissions is not given for CO_2 the capture of which has already received an emission credit under other provisions of law." This implies that captured CO_2 that is already credited under the ETS could not then also be used as an input to produce 'carbon neutral' RFONBOs. Where CO_2 is captured for use in a RFONBO process no credit should therefore be given for reduced CO_2 emissions to the capturing plant. This may require protocols to be developed to ensure communication between the administrators of alternative fuels policy and of the ETS and other climate policies.

6. Conclusions

In this paper, we have discussed that the RED II provides an opportunity for novel fuel production technologies that take electricity, energetic waste gases and/or waste plastics as inputs – RFONBOs and RCFs. We have seen that the net climate benefits of producing such fuels is sensitive not only to the efficiency of the processes used, but to assumptions about counterfactual scenarios. For RCFs, that is primarily about determining the alternative disposition of the waste input, and in particular whether energy is already recovered from it. For RFONBOs, that is about showing that additional renewable electricity is generated to supply the process, rather than using existing capacity and leaving a deficit for other electricity consumers that will be met with fossil power.

Plastic waste is at the forefront of the public consciousness in recent years, and there is a renewed emphasis on increasing recycling. RCF production from plastics may be characterised as a form of recycling by some stakeholders[11], but it might better be understood as a form of 'downcycling', turning a once high-valued plastic material back into its lower value constituents. Downcycling may be the best option to deal with some plastic wastes, but does not preserve as much value or save as much energy as when like-to-like recycling is possible. Even where downcycling is an appropriate approach, including plastic-to-fuels or plastic-to-chemicals processes, there may be limited climate benefit. The value signal in climate policy, if measured per tonne of material used, is several times stronger than the fees set to discourage landfilling. We argue that including RCFs that offer little net climate advantage in incentives for renewable energy use would distort the market for other fuels and undermine policy objectives. It may be that new mechanisms to support RCF production as a waste management approach are appropriate, but that is outside the scope of renewable energy policy.

The increasing recognition that biomass resources are limited and inadequate to allow full transition of transport (or even a single mode such as aviation) to biofuels has led to increased interest in RFONBOs as a scalable long-term low carbon fuel option. The potential for RFONBOs certainly exists, but there is considerable risk that if not well-regulated then development of a RFONBO industry could end up supporting demand for fossil electricity and increasing net emissions in the short to medium term. The forthcoming delegated acts give the European Commission an opportunity to get ahead of this regulatory challenge and set rules that are workable but that also provide solid assurance that the public support invested is delivering real climate benefits.

11 E.g. https://www.neste.com/releases-and-news/circular-economy/neste-and-ravago-start-collaboration-enable-chemical-recycling-over-200000-tons-plastic-waste

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