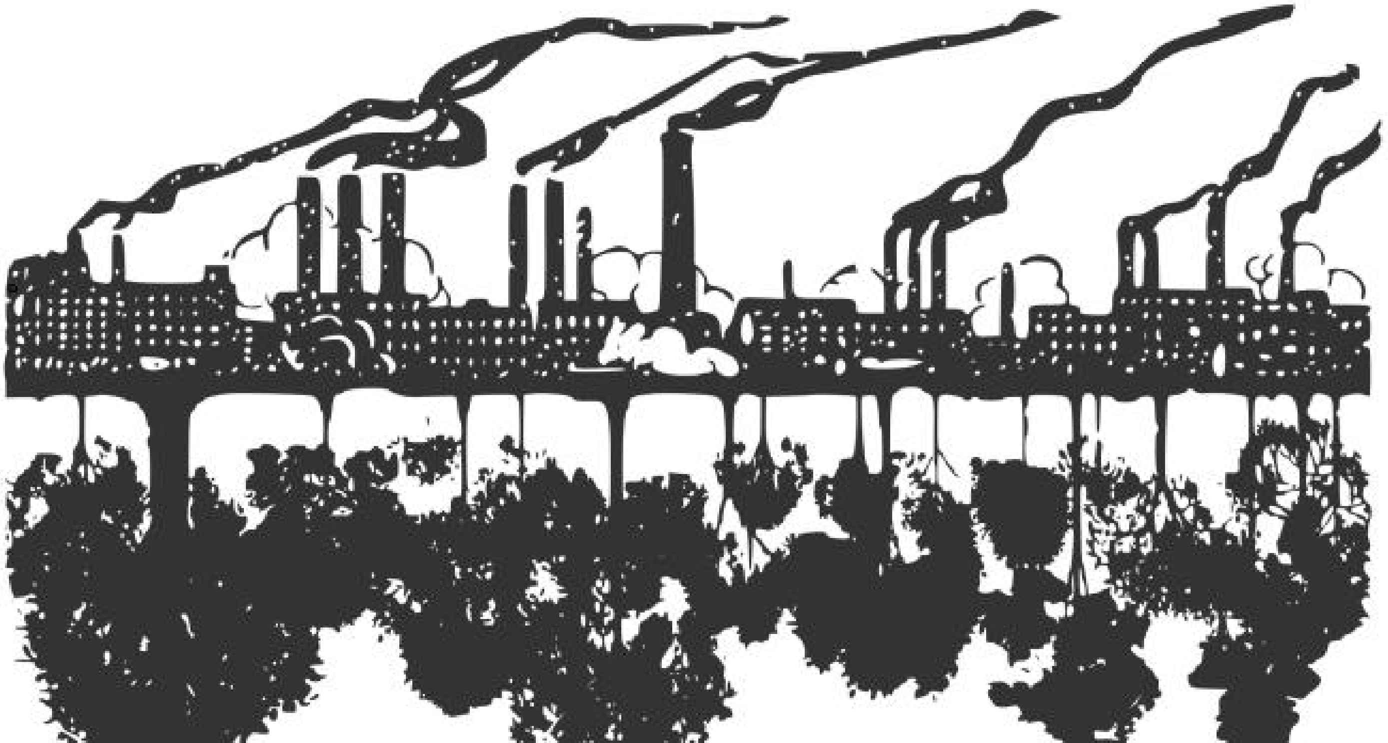
Last-ditch climate option, or wishful thinking?

Bioenergy with Carbon Capture and Storage

A report by Biofuelwatch



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For full references please go to http://www.biofuelwatch.org.uk/2015/beccs-report/

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Executive Summary

BECCS is the combination of bioenergy with Carbon Capture and Storage. It would involve capturing CO_2 from biofuel refineries or biomass-burning power stations and pumping it into geological formations. The concept is based on the assumption that large-scale bioenergy can be carbon neutral, or at least low carbon, and that sequestering some or all of the CO2 emitted from burning or refining it will render it carbon-negative. The International Energy Agency defines BECCS as "a carbon reduction technology offering permanent net removal of CO_2 from the atmosphere.

Various studies suggest that BECCS could in future remove as much as 10 billion tonnes of CO_2 every year. This idea has risen to prominence since the International Panel on Climate Change (IPCC), published their most recent Assessment Report in 2014. Most of the models considered by the IPCC suggest that keeping global temperature rises within 2^oC, will require BECCS, as well as rapid reductions in greenhouse gas emissions.

The urgency of the climate crisis does indeed require societies to drastically curb greenhouse gas emissions, as well as exploring credible means of removing some of the CO_2 already in the atmosphere. The question is, whether BECCS could ever be a credible means of drawing CO_2 from the air? For this to be possible, three conditions would need to be met: Firstly, one would need to show that the total greenhouse gas emissions associated with growing, removing, transporting and processing biomass for energy could be kept to an absolute minimum and that low carbon bioenergy can be massively scaled up. Secondly, BECCS technologies would need to be technically and economically viable, not just as small pilot projects, but on a very large commercial scale. And finally, long-term safe storage of CO_2 would need to be proven.

Biofuelwatch's report analyses the scientific literature and other evidence relating to relevant investments and policies in relation to each of these aspects.

Does the concept of large-scale carbon-negative bioenergy make sense?

Virtually all peer-reviewed studies about BECCS rely on the assumption that, subject to sustainability standards being in place, large-scale bioenergy will be at least close to carbon neutral. None of them discuss the large and growing volume of studies about the direct and indirect greenhouse gas emissions associated with bioenergy.

Evidence shows that existing policies which promote increased use of biofuels and wood-based bioenergy have had serious negative impacts, including on the climate. This is true for EU biofuels, too, despite the fact that sustainability and greenhouse gas standards are written into legislation: Direct and indirect emissions from land use change for biofuels are so high, that biofuels are commonly worse for the climate than the oil they replace. Wood-based bioenergy has led to increased forest degradation and destruction, and higher carbon emissions from land-use change associated with the expansion of industrial tree plantations. Large-scale removal of 'residues' from forests and agriculture depletes soil carbon and nutrients and harms future plant growth.

For carbon negative bioenergy to be possible, it would not be enough to keep bioenergy-related emissions down: Land-based ecosystems remove 23% of all the CO_2 emitted through fossil fuel burning and cement production. Damaging natural carbon sinks for the sake of trying to create a new, unproven artificial one through BECCS would be highly dangerous. Experience with bioenergy so far clearly demonstrates that the basic concept of carbon negative BECCS is a myth.

Are BECCS technologies viable and scalable?

Biofuelwatch's report looks at each of the proposed BECCS technologies in detail. Only one of them has ever been demonstrated: This involves capturing the highly pure stream of CO_2 from ethanol fermentation. It is highly unlikely to become commercially viable unless the CO_2 is sold for Enhanced Oil Recovery (EOR), i.e. to exploit otherwise unrecoverable oil reserves. One highly subsidised project involves pumping CO_2 from an ethanol plant into a sandstone formation, rather than using it for EOR. However, the CO_2 emissions from the fossil fuels which power the refinery, are higher than the amount of CO_2 captured and not even the owners of the ethanol plant call it 'carbon negative'.

"Advanced biofuel" production presents a significant opportunity for BECCS, according to the IEA, because it yields pure CO_2, which is much cheaper and easier to capture than the diluted CO_2 in power station flue gases. Yet the "advanced biofuels" technologies considered by the IEA are not, and might never become viable: nobody has found any way of producing net energy with them.

Capturing CO_2 from power stations that burn biomass has never been attempted. This report therefore examines the experience with capturing carbon from coal power plants. Only one commercial scale power plant project exists and it uses post-combustion capture.

An economic analysis shows that if the scheme was operating as intended, with CO_2 being sold to an oil company for EOR, it could still not break even financially over its lifetime. A Freedom of Information request revealed that the plant has been beset with serious problems: so little CO_2 has been captured that the operators have had to pay fines to the oil company for breach of their CO_2 supply contract. Two other technologies exist: oxyfuel-combustion and Integrated Gas Combined Cycle (IGCC) plants with carbon capture.

Oxyfuel combustion with carbon capture has been tested in pilot scheme and found to be highly costly and inefficient with current technical knowledge. IGCC plants are extremely expensive, complex, and failure prone. One IGCC plant with carbon capture is under construction but costs have spiralled from $1.8 billion to $6.4 billion, amidst long delays.

Studies about Carbon Capture and Storage (CCS) tend to assume that prices will come down over time. This is based on the belief in a natural 'learning curve' for all new technologies which inevitably reduces prices, provided enough initial funding is allowed. In reality, such 'learning curves' exist for some technologies but not for others and there is no evidence to suggest that CCS will ever become commercially viable.

The report concludes with an examination of the reliability of carbon storage. All existing commercial CCS projects, (apart from the one malfunctioning power station project), involve capturing pure CO_2 streams from industrial processes and using them for EOR. During EOR, around 30% of the CO_2 is directly emitted again. Once carbon emissions from the additional oil that is exploited are counted, EOR projects generally result in net carbon emissions – even if 70% of the captured CO_2 was to remain securely locked up.

There is a strong industry bias in many studies looking at how securely CO_2 can be stored underground, with much of the monitoring being conducted or financed by oil companies. There is now an increasing body of evidence that underground storage is far less reliable than CCS proponents hope.

The argument that we need BECCS seems no more convincing than an argument that we need carbon-sucking extra-terrestrials. The availability of large-scale carbon-negative BECCS appears no more credible than the existence of such extra-terrestrials. The only proven ways of removing carbon from the atmosphere involve working with nature, i.e. agro-ecology and the regeneration of natural ecosystems.

What is BECCS?

BECCS is the combination of bioenergy with Carbon Capture and Storage. The International Energy Agency (IEA) defines it as "*a carbon reduction technology offering permanent net removal of carbon dioxide (CO_2) from the atmosphere*". [1]

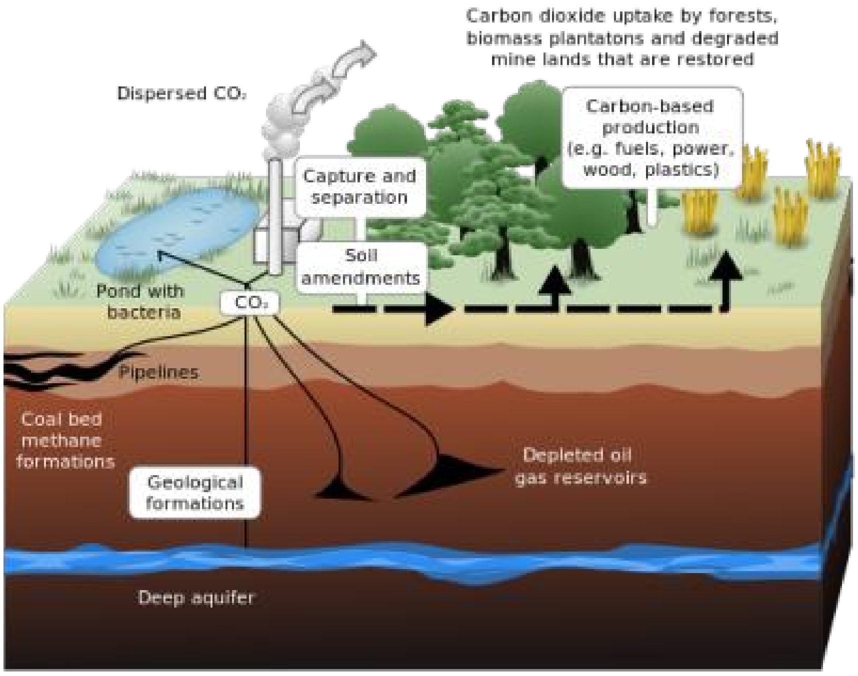
This graphic shows how US Department of Energy funded researchers imagine BECCS would work:

There would be three steps in any BECCS process:
1) Bioenergy production: This can refer to a biofuel refinery or to a power plant burning biomass to generate solely electricity or electricity plus heat. If carbon was captured and sequestered from a coal-power station co-firing biomass, then BECCS proponents would class the proportion of carbon captured from biomass as BECCS;
2) Carbon capture from this refinery or power plant;
3) Carbon sequestration in geological reservoirs: According to the International Panel on Climate Change (IPCC), [2] this includes injecting captured CO_2 into geological reservoirs underground and into partially depleted oil fields in order to extract oil which would be unrecoverable with conventional methods. This is a form of Enhanced Oil Recovery (EOR).

Research and development is also underway into using captured carbon to make products. Those advocating such work, such as the Clean Energy Ministerial [i] speak of CCUS, i.e. Carbon Capture Use and Storage. [3] However, if captured carbon is turned into non-durable products, such as biofuels, it obviously cannot be considered as carbon sequestration.

BECCS is commonly referred to as a 'negative emissions technology', although, as we discuss below, this is a highly problematic term because it implies that BECCS works and is scalable, and that it can indeed sequester carbon from the atmosphere – two unproven and controversial assumptions.

As discussed in detail below, the only BECCS-related technology that has ever been tested at any scale is CO_2 capture from conventional ethanol fermentation. It is far easier and cheaper to capture CO_2 from ethanol fermentation than from power plants. Most CO_2 captured this way so far has been sold to the foods of and drinks industries – to make fizzy drinks, dry ice (for food refrigeration) and bicarbonate of soda – which obviously cannot be classed as 'carbon sequestration'. One or possible two refineries have sold a small amount of CO_2 for Enhanced Oil Recovery (also discussed below), and one is part of a carbon sequestration trial funded by the US government. In each of those cases, the CO_2 emissions from fossil fuel use to power the refineries exceed the amount of CO_2 captured, which means that the process cannot be classed as 'carbon negative' by any definition.



Schematic showing both terrestrial and geological sequestration of carbon dioxide emissions from a coal-fired plant. LeJean Hardin and Jamie Payne

[i] The Clean Energy Ministerial has been formed by 24 governments accounting for around 75% of global greenhouse gas emissions.

A necessary technology? The IPCC and BECCS

The idea that BECCS can play a vital role in mitigating climate change has risen to prominence since the IPCC published their latest report, in 2014. According to their Synthesis Report:

"*Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a likely chance to keep warming below 2°C relative to pre-industrial levels) typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq in 2100 (Table SPM.1). Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and afforestation in the second half of the century. The availability and scale of these and other CDR technologies and methods are uncertain and CDR technologies are, to varying degrees, associated with challenges and risks. CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive (high confidence).*"

This is a startling yet confusing statement:

The IPCC is highly confident that we will need to use BECCS on a large scale from 2050 in order to keep global warming to 2^oC – and we may even have to rely on it to stabilise greenhouse gases in the atmosphere at a level which is more likely than not, to lead to higher temperature rises than 2^oC. Yet at the same time, there are challenges and risks, and we don't know whether BECCS will actually become 'available' i.e. viable, nor whether it can be scaled up. Elsewhere, [4] the report acknowledges that BECCS has never actually been tested at scale.

In short, we will need BECCS, yet it is a risky and uncertain technology and nobody knows whether it will actually work.

It is worth noting that the IPCC applies the same term - 'high confidence', to the finding that CO_2 emissions have lowered the ocean's pH, i.e. are causing ocean acidification, or to the finding that the Greenland ice sheet has lost some of its mass. Those findings are based on a large number of studies in which a wealth of observational data is analysed, i.e. they are derived from strong empirical evidence. The 'high confidence' about the 'need' for BECCS, on the other hand, is based entirely on computer modelling exercises.

In 2007, as soon as the IPCC published its last and began planning for its new 2014 report, they convened a meeting which called for new "Integrated Assessment Models" (IAMs), linked to "Representative Concentration Pathways". Those were to model emissions scenarios which would lead to different levels of global warming and which would represent different socio-economic pathways and technology choices. [5] They would not be policy recommendations, but they would inform policymakers about different options and their likely outcomes in terms of climate change. The 'IAM' teams created were asked to "*explore alternative technological, socioeconomic, and policy futures including both reference (without explicit climate policy intervention) and climate policy scenarios*". [6] There would be "*no overarching logic of consistency to the set of socioeconomic assumptions or storylines associated with the set of [pathways]*". The assumptions used in the modelled scenarios should be 'technically sound' but the hurdle for meeting this test was set extremely low: "Scientifically peer-reviewed publication is considered to be an implicit judgment of technical soundness".

Those running the models which were to inform the IPCC's report on climate change mitigation could thus use any assumptions about climate mitigation technologies, as long as those were backed up by a single peer-reviewed study, which could have been published in any journal whatsoever.

So the basis for the IPCC's 'high confidence' about the need for BECCS appears to be this:

1) Peer-reviewed studies exist which suggest that BECCS has the potential to offer negative emissions, i.e. to draw carbon out of the atmosphere;

2) The vast majority of the teams which undertook the Integrated Assessment Models requested by the IPCC decided to input 'negative emissions' from BECCS into their models in order to achieve a scenario which could keep warming within $2^{o}C$;

3) The authors of the IPCC's report therefore concluded that, based on those modelling assumptions, they could be highly confident that BECCS was necessary for keeping global warming to within $2^{o}C$.

The discrepancy between the high standard of empirical evidence required by the IPCC in relation to evidence on climate science and climate change impacts on the one hand, and the low standard of evidence related to climate change mitigation options could hardly be greater.

By comparison, the IPCC's 2007 report had also pointed out that various models for stabilising global temperatures rely on 'negative emissions' from BECCS but cautioned:

"*To date, detailed analyses of large-scale biomass conversion with CO_2 capture and storage is scarce. As a result, current integrated assessment BECCS scenarios are based on a limited and uncertain understanding of the technology. In general, further research is necessary to characterize biomass' long-term mitigation potential, especially in terms of land area and water requirements, constraints, and opportunity costs, infrastructure possibilities, cost estimates (collection, transportation, and processing), conversion and end-use technologies, and ecosystem externalities. In particular, present studies are relatively poor in representing land competition with food supply and timber production, which has a significant influence on the economic potential of bio-energy crops (an exception is Sands and Leimbach, 2003).*"

As we show in this report, scenarios relying on BECCS are currently based solely on a "*limited understanding of the technology*" just as they had been in 2007. Furthermore, in recent years, a large volume of peer-reviewed studies have been published which show that bioenergy is commonly associated with greater overall greenhouse gas emissions than equivalent amounts of energy produced from fossil fuels. [7] The main difference in 2014 was that the IPCC no longer regarded such a lack of understanding as a problem. The main difference in 2014 was that the IPCC no longer regarded such a lack of understanding as a problem. It appears that they had simply lowered the standard of evidence in relation to climate change mitigation.

From BECCS to Carbon Sucking Extra-Terrestrials: Do we really need ways of removing carbon from the atmosphere to stabilise the climate?

Climate models suggest that we need to stabilise CO_2 levels in the atmosphere at 450 ppm [ii] by the end of the century if we want to have more than a 50:50 chance of exceeding 2ºC of global warming since the industrial revolution. [8] The conclusions of those models are supported by evidence about climate changes in the Earth's past.

Nobody knows for certain what level of greenhouse gases in the atmosphere will lead to which level of warming. The bulk of the evidence suggests that a doubling of CO_2 levels in the atmosphere from a pre-industrial 280 ppm to 560 ppm would raise global temperatures by 2-4ºC, not accounting for a variety of potential 'feedback mechanisms' which could push temperatures up even further. However, this would only apply if concentrations of other greenhouse gases were not also rising. Once those greenhouse gases are accounted for, 2-4ºC is expected to be reached even sooner, i.e. at lower CO_2 concentrations.

CO_2 concentrations currently stand at 400 ppm and if methane and nitrous oxide, two very powerful, if shorter-lived, greenhouse gases, are added to the equation, then we now have equivalent CO_2 levels of 430 ppm, i.e. we are merely the equivalent of 20 ppm of CO_2 away from losing the 50:50 chance of keeping temperature rises within 2ºC. Yet since 2005, CO_2 concentrations in the atmosphere alone have risen by 21 ppm. [iii]

In fact, the situation may be even worse than those figures suggest:

Firstly, the 2ºC target is a political target; initially adopted by the European Council of Environment Ministers in 1996 and endorsed by the UNFCCC Climate Conference at Cancun in 2010. [9] Current levels of climate change are already deadly for many, especially, (but not only) in the global South. It is hard to see how the melting and changes under way in the Arctic and West Antarctica could be regarded as anything other than 'dangerous'. Evidence suggests that while global warming levels are so far in line with previous IPCC predictions, the increase in extreme weather events is much worse than predicted. [10] The hottest annual global temperature so far was recorded in 2014 – at 0.74ºC above the 1910-2000 average, [11] though air

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[ii] Note that this is wording is not entirely accurate: Climate models and the IPCC speak of CO2 equivalent (CO2e) levels of greenhouse gases, not just CO2. Because other greenhouse gas concentration have also been increasing – especially methane and nitrous oxide – 450 ppm CO2e levels are harder to achieve than 450 ppm CO2 levels.

[iii] See http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf, page 5 for the figure in 2005 (379 ppm of CO2).

temperatures over land that year were already 1°C above that average. 2015 is expected to set a new record. Betting on a further 'safe' temperature rise of more than 1.2°C seems reckless.

The 350.org campaign takes its name from a study by the former head of climate science at NASA, James Hansen, which concluded:

"*If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that*." [12]

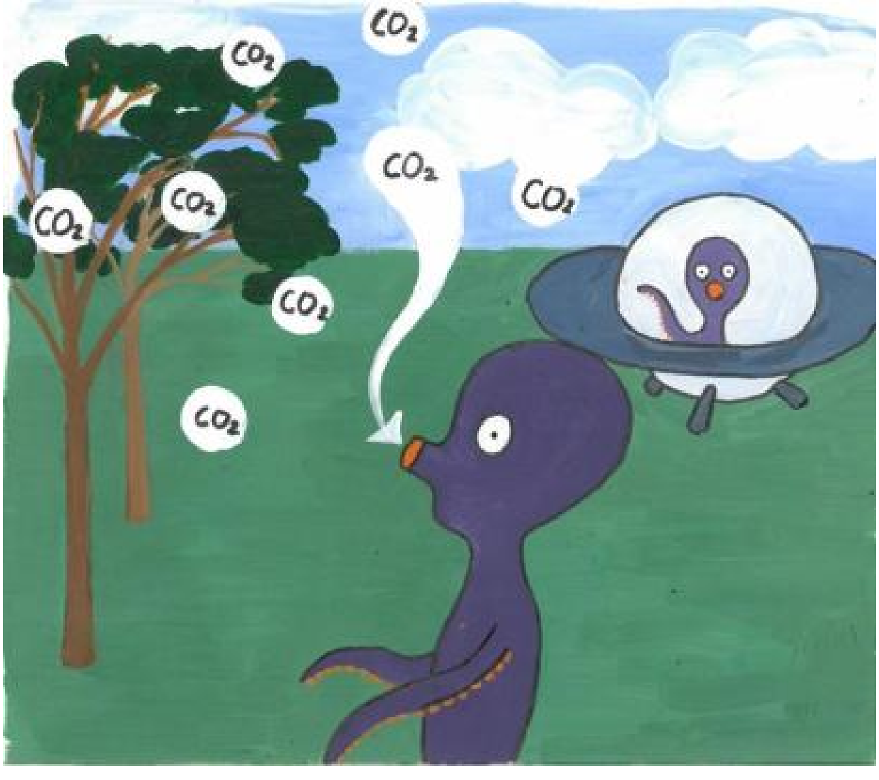
Clearly, the world would be a far safer place with 350 rather than the current 400 ppm of CO_2. This can't happen unless all CO_2 and other greenhouse gas emissions are rapidly phased out AND a substantial proportion of the CO_2 emitted since the industrial revolution could be removed from the atmosphere.

But this in itself is no more an argument for BECCS than it is an argument for the 'need' to invite carbon-sucking extra-terrestrials to Planet Earth.

Dangerously high CO_2 levels in the atmosphere require us to work for meaningful and applicable responses. We need to find real and proven ways of ending anthropogenic greenhouse gas emissions, i.e. of keeping fossil fuels under the ground, ending the destruction of ecosystems and the degradation of soils, and ending the emissions from agriculture. We do indeed need to find proven ways of removing some of the carbon emitted in the past from the atmosphere. Replacing industrial agriculture with agroecology and allowing degraded and destroyed forests and other ecosystems to regenerate or helping to restore them are proven ways of drawing down carbon.

Proposing sci-fi 'solutions' to the climate crisis, is irresponsible. As this report shows, the idea that we can contain global warming with large-scale genuinely carbon negative BECCS is hardly less science-fictional than the idea of carbon-sucking extra-terrestrials. To prove its possibility one would need to 1) demonstrate that it is possible to convert hundreds of millions of hectares of land to energy crops and use very large quantities of agricultural and forestry residues for bioenergy with zero or minimal direct and indirect greenhouse gas emissions from land use change, from soil carbon losses, from nitrogen fertiliser production and use. 2) that the technologies required for BECCS were both feasible and scalable, i.e. that BECCS plants could be expected to operate reliably and that they could offer energy balances which would make the process economically viable, without the need for linking it to Enhanced Oil or Gas Recovery, i.e. increased fossil fuel burning. And 3) that the CO_2 could be securely and safely stored over very long periods. Each of those assumptions is discussed in detail below. It becomes clear that right now, there is limited and inconsistent evidence about the long-term security of CO_2 storage – and no empirical evidence to back up any of the other assumptions that would need to be proven for BECCS to be considered as a safe and viable solution.

In short, there is no more empirical evidence that BECCS can help to contain global warming than there is evidence for the existence of carbon-sucking extra-terrestrials.



Carbon-sucking extra-terrestrials. Rhona Fleming

Does the concept of carbon-negative bioenergy make sense?

In 2013 (the most recent year for which estimates are available) an estimated that 9.9 billion tonnes of carbon (36 billion tonnes of CO_2) were emitted through burning fossil fuels as well as cement production. A further 0.9 billion tonnes of carbon was emitted through deforestation and other forms of ecosystem destruction. [13] Emissions of other greenhouse gases, including methane and nitrous oxide (the most important ones after CO_2), are not included in these figures. Of all the CO_2 emitted, 27% is quickly removed by the oceans, where it contributes to ocean acidification, a serious threat to marine life. 23% is removed by vegetation on land, and about 50% remains in the atmosphere.

The fundamental idea behind BECCS and other 'negative emissions technologies' is to create a substantial new 'carbon sink', in addition to the existing ocean and terrestrial carbon sinks.

The vast majority of studies addressing the greenhouse gas balances of bioenergy only consider actual emissions linked to bioenergy production – not the amount of carbon that would have been sequestered by natural vegetation and healthy soils in future, had those not been depleted or converted to monoculture plantations for bioenergy. Most relevant studies do account for fossil-fuel emissions (e.g. fossil fuels burned in a biofuel refinery, to make pellets, to transport biomass) and many studies also look at direct greenhouse gas emissions from logging and land-use change.

Some studies also consider emissions from indirect land use change especially in relation to liquid biofuels: Indirect land use change happens, for example, when bioenergy crops are grown on land formerly used to produce food or animal feed for livestock, with the knock-on effect that more land elsewhere is converted to grow the food or feed that has been displaced by biofuels.

Very rarely considered are other indirect impacts, although these can be substantial: For example, large bioenergy-related projects may be accompanied by infrastructure investments in roads, ports, or even river diversions, which can open up forests to loggers.

For bioenergy to be genuinely 'carbon negative', it would not be sufficient to capture and sequester an amount of CO_2 which exceeds all of the direct and indirect greenhouse gas emissions associated with growing, harvesting, transporting and processing the biomass. To accurately reflect climate impacts, it would also be necessary to include the loss of future carbon sequestration that results when forests are cut, ecosystems are converted to monoculture plantations, and when healthy soils are depleted. Nature, through plant growth and other processes provides the only real 'carbon sinks' that exist and has so far kept the rate of global warming to about half of what it would be. Destroying those natural 'sinks' in an attempt to artificially create a new (and unproven) one is highly nonsensical and destructive.

Where do the figures for the 'negative emissions' potential from BECCS come from?

We have not found a single study that calculates the potential for 'negative emissions' based on any type of life-cycle greenhouse gas assessment at all. Instead, such studies are based on the blanket assumption that all bioenergy is entirely carbon neutral, provided that basic sustainability standards are in place (e.g. no conversion of forests to bioenergy crops). Their authors thereby disregard a large and fast growing volume of peer-reviewed studies about the life-cycle emissions associated with different forms for bioenergy. [14]

The IPCC's 2014 Working Group 3 report on Mitigation of Climate Change does not discuss the lifecycle greenhouse gas impacts of bioenergy in relation to BECCS – although they do acknowledge that there is potential for significant emissions from land-use change and increased nitrous oxide emissions from greater fertiliser use as a result of bioenergy expansion. However, there is no detailed consideration as to how those or any other emissions would affect the viability of BECCS as a means to deliver 'negative emissions'.

One of the main references for the 'BECCS potential' figures considered by the IPCC is the 2011 report on BECCS by the International Energy Agency (IEA). [15] We therefore analysed the IEA's assumptions of the potential amount of biomass available for BECCS. The IEA figures regarding the global biomass potential rely on estimates from two different studies: One of those studies provided the IEA's estimate for the maximum amount of bioenergy that could be sourced from dedicated energy crops, provided strict sustainability criteria were in place. [16]

The other [17] was a preliminary assessment , from which the IEA took their estimates for the global potential for bioenergy from crop and forestry residues. However, the methodology from which those figures were derived was not described in that assessment, (i.e. the figures were simply cited in it, without showing where they came from).

Only the energy crop estimates thus appear to be based on a published peer-reviewed study. The authors of that study ran a model to calculate the maximum 'sustainable' biomass potential whilst accounting for land degradation, water scarcity and biodiversity protection. The authors' most conservative figures, which is the one which the IEA used, assumed that no forests and no nature reserves would be converted to bioenergy production, that energy crops would not be grown on severely degraded land, and that they would all be rainfed, not irrigated. Energy crops would, the authors assumed, only be grown on 'abandoned agricultural land' and natural grassland.

The 'sustainability' of converting either abandoned agricultural land or natural grasslands to bioenergy is very questionable.

As the authors of a report by the World Resources Institute explain:

"*Abandoned farmlands typically regenerate into forests, woodlands, or grasslands if left alone, which provide climate benefits that are already assumed and counted in climate change assessments. These benefits would be sacrificed by using that land for bioenergy.*" [18]

Moreover, most figures related to a global estimate of abandoned agricultural land, which could be converted to bioenergy, have been taken from a database set up by the Dutch government; which purports to provide global "*data on land-use patterns during the past three hundred years.*" [19] The Dutch environmental assessment agency providing the database has added this caution to their website: [20] "*Although databases of historical land use are frequently used in integrated assessments and climate studies, they are subject to considerable uncertainties that often are ignored.*" 'Uncertainties' seems quite an understatement in this context: Establishing historic changes in land use over 300 years for even a small region requires complex historical research. Plotting historical land use change back to the year 1700 would be a vast undertaking by historians worldwide, one that has never been attempted and would rely on many assumptions, due to lack of reliable data. Even establishing current land use requires detailed knowledge of local realities. Small farmers, pastoralists and other traditional communities, particularly in the global South, are at a particular risk from land-grabbing when the land they rely on is falsely classed as 'abandoned', wasteland, or 'marginal' and earmarked for conversion to industrial monocultures. [21]

Conversion of natural grasslands should not be considered lightly. Grasslands are highly biodiverse ecosystems. South Africa's grasslands, for example, which are heavily targeted for conversion to monoculture tree plantations, are home to more than 4,000 different plant species, as well as 15 endemic mammals and 10 globally threatened bird species. [22]

There are other problems with the study providing the IEA's energy crop potential figures:

For example, the authors decided to ignore all indirect impacts of bioenergy. While those can be difficult to track, they are certainly substantial.

Remarkably, one of the key assumptions for IEAs energy crop potential is that agricultural yields would grow by 12.5% between now and 2050. That is an extremely optimistic assumption given that the IPCC's latest report concludes with 'high confidence' that "negative impacts of climate change on crop yields have been more common than positive impacts" so far.

Assumptions about the availability of vast areas of 'abandoned agricultural land' and the sustainability of converting natural grasslands to bioenergy crops are thus highly problematic, as is the assumption that crop yields will rise continuously in the face of escalating climate change. Yet these assumptions are common to virtually all of the studies which purport to 'show' that a significant potential for 'sustainable' biomass worldwide exists.

Could large-scale climate friendly and sustainable bioenergy ever be possible?

Existing policies to promote the expansion of bioenergy use, including in the EU and US, have quite clearly had 'undesired' consequences: they have led, both directly and indirectly, to increased deforestation and forest degradation and to widespread biodiversity destruction. These policies have also led to increased greenhouse gas emissions from land conversion, soil carbon losses and greater fertiliser use, which has caused increased releases of nitrous oxide, a powerful greenhouse gas.

Use of agricultural and forestry residues for bioenergy, instead of, or in addition to, dedicated energy crops is widely proposed. Most optimistic bioenergy scenarios, including ones for BECCS, rely on all those sources combined. Yet there are serious problems with the concept that there are large quantities of forestry and agricultural residues available which can be burned without negative impacts.

Firstly, the type of agriculture which can reliably supply large quantities of 'residues' is that based on industrial monocultures, such as palm oil and sugar cane. Incentivising bioenergy from residues can be expected to push up the profit margins of oil palm and other plantation companies and thus the expansion of such plantations, including at the expense of forests.

Secondly, removing a large percentage of forestry and agricultural residues depletes soil carbon and soil nutrients and leaves soils more vulnerable to erosion and drying out. For example, one recent study finds:

"*Removing crop residues from the field led to average SOC [Soil Organic Carbon] contents that were 12 and 18% lower than in soils in which crop residues were retained, in temperate and tropical climates respectively.*" [23]

Thirdly, agricultural and forestry residues are widely used for other purposes: For example, agricultural residues are commonly used for animal feed or bedding and forestry residues are used, for example, to make panel board.

Finally, the definition of 'residues' is wide open to abuse. Some companies have found it easy to get away with referring to whole trees from clearcut natural forests as 'residues'. [24]

The concept of BECCS relies on the large-scale availability of carbon neutral or very low carbon bioenergy. As any examination of the real impacts of existing large-scale bioenergy shows, that concept is based on a myth.

Do the technologies needed for BECCS exist and are they scalable?

CO_2 can be captured from power station exhaust or flue gases as well as from ethanol refining, and it can be liquefied, transported and pumped underground. This means that it should, at least in theory, be technically possible to build a biomass power plant with carbon capture and storage. So far, however, nobody has attempted to do so and it thus remains unknown whether such a plant could be operated successfully and within acceptable cost limits – or, for that matter, within the range of costs predicted by the International Energy Agency. BECCS therefore remains technically, as well as economically, unproven. The sole exception is CCS involving carbon captured from conventional ethanol fermentation. And that, it appears, is economically viable only with large subsidies (for geological sequestration) or if the refinery is close to a partially depleted oilfield oil companies have invested (possibly with additional government subsidies) in extracting more oil with the help of CO_2 injections (discussed below).

False faith in learning curves: Why 'learning by doing' cannot be applied to every new technology and assumed as an inevitable pathway to affordability

In 1936, Theodore Paul Wright, an aeronautical engineer in the US, observed how greater experience was bringing down the cost of making aircraft. He plotted the number or aircraft built against the cost of producing each plane and found that whenever overall production doubled, the requirement and thus the cost for labour dropped by 10-15%. The reason for this price drop was that as companies gained greater experience with the process of building airplanes, they found ever new ways of making production more efficient.

His observation became known as Wright's Law or, the Technology Learning Curve, a concept that underlies much techno-optimism, including about the development of 'low carbon' energy technologies. Today, the name most widely associated with the idea that technologies become ever cheaper and more efficient when use is increased, is no longer that of Wright, but of Gordon Moore.

Moore was an electronic engineer who, in 1965, published an article called "*Cramming more components onto integrated circuits*". [25] Moore, rightly of course, predicted that integrated circuits would "*lead to such wonders as home computers*". He specifically predicted that by 1970, 65,000 units would be fitted on one chip, bringing the cost of each component down to one-tenth of what it was in 1965. He further predicted that the number of components on a chip (i.e. the power of computers) would at least double year on year for a minimum of a decade but very possibly beyond, bringing costs down at the same time. By 1975, Moore's "*Learning Curve*" predictions turned out to have been somewhat overoptimistic, [26] but the electronics industry was well on its way towards developing home computers. That year, Moore predicted that computing power would in future double every two years rather than annually. Progress has since slowed down and Moore himself acknowledged in 2005 that it could not continue forever. [27]

Gordon Moore was writing about one particular technology, but his optimistic forecasts, coupled with decades of real exponential progress in electronics has helped foster an optimistic view that, with enough effort, very steep Learning Curves are possible for virtually any technology. This belief continues to inform government policies, including in relation to energy technologies.

The notion that there is some universal 'law' about Technology Learning Curves which can be applied to the energy sector has been greatly boosted by the experience with solar PV. For several decades now, the unit cost of solar PV has been falling and efficiency has been rising, although the idea that this is solely due to a 'learning curve' has been disputed: Steep falls in raw materials, i.e. silicon prices, for example, have certainly played a role in reducing costs. [28]

Observing and plotting technological advances in particular industries and technologies is valid. Assuming that those can be translated into universal laws which apply to all technologies, on the other hand, is highly problematic. After all, while Moore's predictions about home computers came true, many other optimistic predictions about technologies have not. For example, nuclear energy has obviously never become 'too cheap to meter', despite what the Chair of the Atomic Energy Authority believed in the 1950s. [29] In fact, the cost of nuclear power remains so high that no nuclear plant has ever been built without large public subsidies, even though 505 such plants are in operation worldwide.

Misplaced faith in universal technology learning curves, however, influences government policies, including on energy technologies, and it also underpins a general techno-optimism that any technology will decrease in cost and increase in efficiency the more we use it.

In relation to Carbon Capture and Storage, the Global CCS Institute predictably claims that there is "*considerable scope for learning by doing*", i.e. that once enough CCS projects have been implemented, costs will come down. [30] The European Technology Platform for Zero Emission Fossil Fuel Power Plants, a public-private partnership set up by the European commission, is telling EU policy makers that CCS is "at the start of the learning curve, with huge capacity to reduce costs from technology refinements and economies of scale" – i.e. if enough subsidies are provided now, it will become much cheaper.

The operators of the world's only commercial-scale power station with CCS - a coal power station unit in Saskatchewan, boasted that opening a second CCS unit would already be 30% cheaper, [31] which would likely make it the steepest learning curve of any technology ever. However internal documents obtained by an opposition party in Saskatchewan reveal that operators have been misleading the public into believing the plant has been operating successfully so far, when this has not been the case (see below).

In the US, the government has had such faith in 'learning curve' predictions that it has made $6.9 billion in public funds available for CCS, with the aim of reducing the cost differences by 50% between a power plant with CCS and one without. A report by the US Congressional Budgetary Office, however, warned that $6.9 billion would be nowhere near enough to achieve that goal, judging by the 'learning curve' of a different technology to reduce emissions from power stations: The capture of sulphur dioxide.

In reality, nobody can credibly predict learning curves for any technology until those have been used on a large enough scale. But there are good reasons to be sceptical that CCS, including BECCS technology, could ever replicate the success story of, for instance, solar PV:

1) Capturing carbon from power plants and liquefying it so that it can be transported and pumped underground will always require substantial amounts of energy. This means that significantly more coal, biomass or whatever other fuel would need to be burned in a power plant to generate the same unit of energy, as would be the case without CCS. Higher energy and biomass costs in future could make carbon capture even more expensive, even if carbon capture were to become more energy efficient one day;

2) Because of these additional energy requirements, CCS will always be heavily dependent on direct or indirect subsidies – unlike, for example, solar PV, it can never become commercially competitive without such subsidies. This may well explain why companies have been highly reluctant to invest in CCS. And the costs of BECCS would, as shown below, almost certainly be even higher than those of coal power plants with CCS;

3) The technologies required for BECCS are highly complex. Some proposed BECCS pathways are based on gasification technologies which have been under development for many decades however there is no evidence of any learning-curve so far. This is discussed further, in the section about Integrated Gasification Combined Cycle power plants.

Which technologies are proposed for BECCS?

An in-depth report about BECCS published by the International Energy Agency (IEA) in 2011 [32] considers six technical options:

1) Co-firing biomass with coal in a conventional ("Pulverised Coal") power station and capturing the CO_2 from the exhaust gases before it is emitted through the smokestack;

2) Burning biomass in a purpose built biomass power station and, again, capturing CO_2 from the exhaust gases;

3) Burning, or rather gasifying, biomass together with coal in an Integrated Gasification Combined Cycle (IGCC) plant and capturing the CO_2 from the gas before it is in turn burned to generate electricity – this process is discussed in more detail below;

4) Gasifying biomass only in a purpose-built IGCC plant and capturing the CO_2;

5) Capturing CO_2 from the fermentation of ethanol: Here, the IEA has assumed that conventional or 'first generation' ethanol, which is made from sugar or starch (usually starch in cereals) would be phased out because most of it competes with food and that future ethanol plans with CCS would only use wood and other solid biomass. The carbon capture process itself would be the same whether the ethanol refinery is a conventional or an 'advanced' one using cellulosic biomass (i.e. solid biomass such as wood or corn stover);

6) Turning wood or other solid biomass into biodiesel using a technique called Fischer-Tropsch synthesis (briefly described below) and capturing CO_2 as part of that process.

If both coal and biomass are burned or gasified together in a CCS plant, the IEA would class only the carbon capture and sequestration from the biomass fraction as BECCS.

One option not discussed in the IEA report is a technology called 'oxyfuel combustion' with carbon capture. In the UK, a planning application for an 'oxyfuel' power plant burning mainly coal but with the possibility to burn up to 15% biomass is currently being considered. An article published in the New Scientist described it as "*the world's first power plant with negative emission*", [33] thanks to the co-firing of biomass with CCS. We therefore discuss this technology as well, although the planning documents for this proposed scheme contradict claims that it could be 'carbon negative. [34] One of the main corporate partners behind the scheme has since announced that they are pulling out, [35] making it most unlikely that this plant will be built.

Below we will discuss each of the technologies analysed by the IEA as well as CCS linked to conventional ethanol refineries and oxyfuel combustion with carbon capture in power stations. We will discuss them under four different headings:

a) Capturing CO_2 from conventional or advanced, cellulosic ethanol refineries;

b) Capturing CO_2 from 'advanced' biofuel refineries which turn solid biomass such as wood into a form of biodiesel;

c) Post-combustion carbon capture from power plants: This means burning biomass (with or without coal) and then capturing the CO_2, which is found in very diluted form in the exhaust gases. This covers the IEA's pathways 1 and 2 above;

d) Pre-combustion carbon capture from power plants: This covers the IEA's pathways 3 and 4, i.e. the gasification technologies for generating electricity;

e) Capturing CO_2 from an oxyfuel plant burning biomass (with or without coal);

As highlighted above, the world's only existing project involving carbon capture from bioenergy involves capturing CO_2 from corn ethanol fermentation. None of the other BECCS technologies has ever been tested. This means that we have to rely on what has been published about the experience with coal CCS plants, although all but one of those have only been small pilot schemes.

Capturing carbon from ethanol fermentation

Carbon capture from conventional ethanol plants

This is the only BECCS-related technology which has ever been demonstrated. Compared to capturing CO_2 from power plants, capturing it from ethanol fermentation is far simpler and cheaper.

During ethanol fermentation, microbes, usually yeast, convert biomass sugars into ethanol and CO_2. Around 765g of CO_2 are produced per litre of ethanol. This CO_2 stream is highly pure and this makes it easier to capture than the dilute CO_2 emitted from power plants. [iv] However, most of the carbon contained in corn will not be captured: Twice as much carbon ends up in the ethanol than in the CO_2 which is emitted during fermentation, and it is only practical to capture around 90% of the latter. Furthermore, a large proportion of the carbon in corn cannot be fermented at all.

Several ethanol refineries worldwide have been fitted with CO_2 capture equipment. A French company called Air Liquide sells ‘speciality gases’, including CO_2 used by food and drinks and manufacturing industries. They have built carbon capture and liquefaction plants attached to ethanol refineries in Austria, the UK and California. CO_2 capture equipment is also incorporated into a wheat ethanol refinery operated by Ensus in the UK. Five corn ethanol refineries owned by the US biofuels company POET have also had carbon capture equipment installed – and the above is not an exhaustive list of such schemes.

However, all of the CO_2 captured from these refineries is sold for commercial purposes rather than being sequestered. In particular, it is being sold to make fizzy drinks, to make dry ice for refrigeration and possibly also to make bicarbonate of soda. [36]

There are two schemes that involve CO_2 captured from ethanol refineries being sold for Enhanced Oil Recovery (EOR), i.e. to help pump more oil out of the ground. Enhanced Oil Recovery with captured CO_2 is classed as a form of ‘carbon sequestration’, including by the IPCC – although, as discussed below, this classification is highly questionable.
The two refineries from which CO_2 is being captured for EOR are owned by biofuel company Conestoga and are located in Kansas. Oil company Chaparral Energy captures and transports the CO_2 and uses it for EOR. These projects commenced in 2011 and 2013 respectively. [37] Both projects form part of the Regional Carbon Sequestration Partnership CCUS Activities initiative, which is financially supported by the US Department of Energy. One other project involving CO_2 capture for EOR from another corn ethanol refinery, this time in Nebraska is currently planned. [38]

Finally, there is one project involving CO_2 from a corn ethanol refinery in Illinois and injecting it into a large sandstone formation.

The Decatur ethanol CCS project: Is it carbon-negative?

This project involves capturing CO_2 from a corn ethanol refinery in Decatur, Illinois, which is operated by Archer Daniel Midlands (ADM). [39] ADM is the world’s second biggest grain trader and processor. The company has invested heavily in biofuels, especially in corn ethanol refineries in the US.

Between November 2011 and November 2014, almost 1 million tonnes of this captured CO_2 were pumped into the Mount Simon Sandstone formation. This first phase is being followed by a larger five-year demonstration project, during which time ADM have

[iv] Integrated Gas Combined Cycle (IGCC) power plants are an exception to this rule and are discussed below.

proposed that 1 million tonnes of CO_2 per year will potentially be captured and pumped underground.

The total cost of the two-phase project is $292.2 of which the US Department of Energy is paying a total of 71%.

ADM have never claimed that carbon capture and sequestration makes this corn ethanol refinery 'carbon negative' – they merely state that it reduces the carbon emissions from the refinery. [40] This is because all ethanol refineries in the US and most worldwide operate using natural gas (as this ADM refinery does) or even coal to run boilers and they also tend to import electricity. The resulting emissions from fossil fuel burning to provide energy for such refineries are greater than the maximum amount of CO_2 that can be captured from the fermentation vats [v] - and that is before fossil-fuel emissions related to the additional energy requirements for CO_2 capture and liquefaction are accounted for.

When fossil fuel emissions are linked to growing, harvesting and transporting corn, and emissions of the powerful greenhouse gas, nitrous oxide, (caused by the use of nitrogen fertilisers), are included, then the greenhouse gas emissions associated with a corn ethanol refinery are even higher.

And those are merely the emissions which US ethanol producers must legally account for under the Renewable Fuel Standard. The figures take no account of additional 'indirect' nitrous oxide emissions from fertiliser use, nor soil carbon losses from intensive corn production, nor carbon emissions from direct and indirect land use change, including displaced food and feed production.

The projects listed above which involve EOR (see below for a full discussion of EOR), will be even less 'carbon negative'.

Carbon capture from cellulosic ethanol refineries

As discussed above, it is technically possible to capture CO_2 from conventional ethanol refining, although the amount of CO_2 is likely to be less than that emitted from fossil fuel burning to power the refinery. [vi] The authors of the IEA's BECCS report assumed that current

Skyline of ADM plant in Decatur, Illinois. Dan

[v] See this calculation of greenhouse gas balances from a corn ethanol refinery with CO2 capture from fermentation: http://www.extension.umn.edu/agriculture/business/renewable-energy-bio-fuel/docs/umn-ext-reducing-life-cycle-greenhouse-gas-emissions-of-corn-ethanol.pdf. ADM's Decatur refinery has a natural gas boiler but note that the energy inputs and thus the fossil fuel carbon emissions will be higher than those presented in this study because their refinery uses wet milling. See http://www.arb.ca.gov/fuels/lcfs/012009lcfs_cornetoh.pdf for a comparison between dry and wet milling.

[vi] This statement is unlikely to apply to a sugar cane ethanol because ethanol production from sugar cane requires significantly less energy than that from starchy cereals such as corn. Furthermore, at least in Brazil, much of that energy comes from burning sugar cane residues. However, there is no carbon capture and sequestration (including EOR) project anywhere in the world linked to a sugar cane ethanol refinery. In 2009, the UN Global Environment Facility made a grant of $2.7 million (€2.52 million) available to what was to have been the first such schemes. However the project was cancelled (https://www.thegef.org/gef/project_detail?projID=4040).

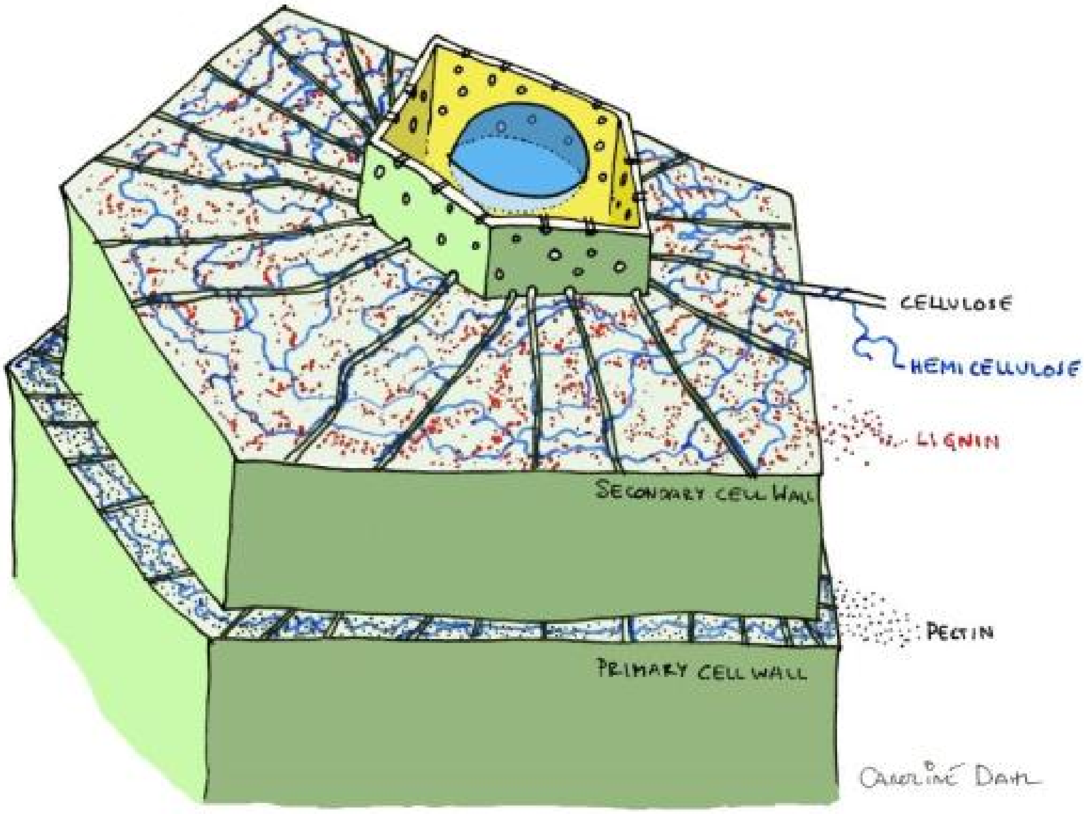
'first generation' biofuels, i.e. those made from sugar, starchy crops (mainly cereals) and vegetable oil, would be phased out in future and that BECCS would only be applied to 'advanced biofuel refineries'. Those would turn wood, agricultural residues and other solid biomass either into ethanol (called 'cellulosic ethanol') or into a form of biodiesel, with similar chemical properties as mineral diesel. [vii]

Cellulosic ethanol

Capturing carbon from cellulosic ethanol would be exactly the same process as capturing it from a conventional corn ethanol plant. Energy would be needed for capturing and compressing the CO_2 but it is the only BECCS-type technology that has been proven at a larger scale (i.e. at ADM's plant in Illinois, discussed above). Turning solid biomass into ethanol is perfectly feasible, too: The world's first cellulosic ethanol plant was opened as long ago as 1910 in South Carolina, by the Standard Alcohol Company. It operated for several years, before that plant and a second one in Louisiana were closed for 'economic reasons'. What the 'economic reasons' were seems quite obvious today: Given the technology available at the time, there was no way that the energy gained from burning the ethanol could have offset, let alone exceeded the energy put into producing that ethanol.

The reason for this is simple: Ethanol is alcohol and it is made through fermentation by microorganisms, usually yeast. During fermentation, yeast or other microbes convert simple sugars, i.e. glucose, fructose or sucrose into ethanol. Ethanol fermentation is most straightforward if the feedstock is sugar cane or sugar beet. If the feedstock is rich in starch – e.g. corn or other cereals – then it needs to be pressure-cooked first and then treated with an enzyme which splits the starch into simple sugars.

The sugars contained in wood, agricultural residues and other solid biomass, on the other hand, are not easily accessible to microbes. They are mostly found in complex chemical structures called cellulose and hemicellulose, which are closely interwoven with lignin. Lignin, which does not consist of sugars, gives



Plant cell showing primary and secondary wall. Caroline Dahl

[vii] Biodiesel has quite different properties from mineral diesel and can only be blended in limited quantities of around 10% without modifications to car engines.

plants their structure and rigidity and plays a crucial role in conducting water. Aggressive, energy intensive and costly treatment is needed in order to 'free' the sugars from plant cell walls and make them accessible to microbes. Another problem is that many of the sugars found in wood and other solid biomass have five carbon atoms,whereas glucose and fructose have six (and sucrose is made up of glucose plus fructose). Microbes which can ferment sugars with five carbon atoms cannot ferment ones with six carbon atoms and vice versa. Also, those microbes that can ferment five carbon sugars tend to be poisoned by ethanol, i.e. they can only survive in very dilute ethanol concentrations. The more dilute the ethanol is, the more energy has to be spent on boiling off the water to make it concentrated and usable.

So Standard Oil's cellulosic ethanol refineries would have needed a lot of energy in order to pre-treat the wood so that microbes could ferment a limited proportion of the sugars. And they would likely have ended up with very dilute ethanol and used a lot of energy to purify it.

More than a century later, and after many hundreds of millions of dollars of public subsidies have been spent on developing the technology, there is no evidence that anybody has succeeded in making cellulosic ethanol with a positive energy (i.e. actually gaining energy from the process). Today, much of the research and development focusses on the use of synthetic biology, or 'extreme genetic engineering', to engineer microbes which can efficiently break down the sugars contained in ligno-cellulosic biomass and others which can efficiently ferment all the different sugars to ethanol. This involves engineering complex new metabolic pathways, which goes far beyond the level and type of genetic modifications on which, for example, Monsanto relies for existing GMO crops. Studies suggest that a major breakthrough would be required, and remains a long way off. [41] The environmental risks of an accidental release of genetically engineered microbes capable of breaking down plant material and fermenting it into ethanol have never been thoroughly considered, but they could potentially be very severe. Also because of their very small size and rapid reproduction rates, 'secure containment' of engineered microbes inside an industrial refinery cannot be assumed. [42]

As of November 2015, there are eight supposedly commercial cellulosic ethanol refineries worldwide. One of them, in the US state of Iowa, was only opened at the end of October. For three of them – located in Brazil and Italy – no evidence about their actual production has been published. However, four of the cellulosic ethanol refineries (i.e. excluding one recently opened by DuPont), or: prior to 2015, are based in the US. The US Environmental Protection Agency, (EPA), publishes monthly and annual figures for total cellulosic ethanol production in the country. [43] According to those figures, 1.65 million gallons of cellulosic ethanol were produced during the first nine months of 2015. If the four refineries had operated at full capacity, they would have produced 45 million gallons during that period. This means that US cellulosic ethanol refineries have only been operating at 3.7% of their capacity. In spite of the fanfare accompanying opening of new cellulosic fuel production refineries, it is clear that successful commercial production of cellulosic ethanol remains highly elusive.

As it is highly uncertain whether commercial cellulosic ethanol production will ever be possible, capturing CO_2 from cellulosic ethanol seems even more unlikely: It would make it even more difficult to obtain any remotely positive energy balance, since carbon capture itself adds to the energy demands for production.

Carbon capture from 'advanced' biodiesel production based on gasification and Fischer-Tropsch synthesis

The second biofuel pathway which the IEA has identified as suitable for BECCS is Fischer-Tropsch synthesis of biodiesel. This process is fundamentally different to conventional biodiesel production – which does not lend itself to carbon capture. It results in a fuel that is chemically more similar to mineral diesel than conventional biodiesel. The process was developed by two German scientists, Franz Fischer and Hans Tropsch, in the 1920s. During World War II, Nazi Germany was operating nine synthetic diesel plants using this technology, albeit with coal, rather than biomass as the feedstock. But, as with cellulosic ethanol, the goal of operating such plants smoothly and with positive energy balances remains elusive, particularly when the feedstock is biomass, as opposed to natural gas or coal.

The first step of the process is biomass gasification, with a very high level of gas cleaning, resulting in syngas, which consists of carbon monoxide and hydrogen. As discussed in detail in Biofuelwatch's 2012 report on biomass gasification and pyrolysis, [44] producing such pure syngas from biomass gasification is a very difficult process. Those developers which have successfully operated such gasifiers have generally had to spend one or two years modifying plants and resolving problems. Fischer-Tropsch synthesis involves a series of catalytic reactions in which the carbon monoxide and hydrogen are converted to different hydrocarbons, including a synthetic (bio)diesel. Before those reactions can take place, CO_2 needs to be removed from the syngas so that it has the right composition for Fischer-Tropsch synthesis. According to the 2011 IEA report on BECCS, about 54% of the original carbon in the biomass could be captured this way – much more than the proportion of carbon that can be captured, for example, during ethanol fermentation.

If this process were ever to be scaled up and replace conventional biodiesel production then it would indeed be one of the easiest routes to BECCS. There are however, no indications of this happening. The technical challenges are formidable and energy losses during the process are substantial. There have been two 'flagship' research and development schemes for the technology in the EU. One of the schemes was undertaken by a company called Choren, which attracted investment from Daimler Chrysler, Shell and Volkswagen. After years of testing, Choren was unable to scale up the process to commercial production. They filed for bankruptcy in 2011. The other project is ongoing and involves a biomass gasification plant in Austria which was opened in 2001. [45] Since 2004, some of the syngas from the plant has been captured for Fischer-Tropsch synthesis. Millions of Euros of EU and Austrian subsidies have been spent on this. Now, 11 years on, the project is still nowhere close to selling any biofuels. Several other companies have dropped plans to invest in the technology. [viii] The US Department of Energy now focusses its Fischer-Tropsch synthesis research entirely on coal, not biomass. [46]

[viii] Especially Rentech and UPM.

Post-combustion carbon capture: Scrubbing CO_2 from conventional coal or biomass power stations

How does it work and what are the drawbacks?

With post-combustion carbon capture, around 90% of CO_2 is captured from flue gases (exhaust gases) after coal, biomass or other fuels have been burned. The CO_2 in flue gases is very diluted. Flue gases from conventional coal fired power stations may contain just 11% CO_2 [47] and CO_2 concentrations in biomass power station flue gases are even lower. [ix]

So far there is only one proven way of capturing CO_2 from flue gases and that involves the use of amines. Amines are a group of chemicals derived from ammonia, and one type has proven particularly suitable for CO_2 capture. During carbon capture, the flue gases are blown into a large tube or column containing amines; the amines react with the CO_2 and allow the other gases to pass through. The amine-CO_2 solution is then heated to 120°C, which releases the CO_2 from the amines. The amines are cooled and recycled – although over time they degrade and need to be replaced. The 'captured' CO_2 gas is then compressed so that it can be transported through pipelines to be pumped underground.

An additional challenge is posed by the fact that amines cannot effectively capture CO_2 from flue gases which contain more than a small trace of sulphur dioxide (SO_2), which means that costly equipment for capturing SO_2 may need to be installed, too, although once it has been installed, the energy requirement for capturing SO_2 is a small fraction of that needed to capture CO_2.

The National Energy and Technology Laboratory (NETL), which is part of the US Department for Energy, sums up the inherent problems with post-combustion carbon capture:

"1. The low pressure and dilute concentration dictate a high total volume of gas to be treated.
2. Trace impurities in the flue gas tend to reduce the effectiveness of the CO_2 separation processes.
3. Compressing captured CO_2 from atmospheric pressure to pipeline pressure (1,200-2,200 pounds per square inch) represents a large parasitic energy load." [48]

In short: It is a very expensive and energy intensive process. The US Department of Energy alone has spent tens of millions of dollars on research and development to find ways of capturing CO_2 from flue gases that require less energy but so far there has been no major breakthrough. [49]

[ix] Note that the overall amount of CO2 emitted from a biomass power station is almost always higher than that from a coal power station with the same energy output, largely due to lower conversion efficiency. Furthermore, a greater volume of biomass compared to the volume of coal needs to be burned for the same energy output.

Special drawbacks for posts-combustion carbon capture from biomass plants

The 'energy penalty' – i.e. the costs and the amount of energy needed for carbon capture would be even greater in the case of biomass power stations, according to the IEA's report on BECCS technologies:

• Burning biomass results in lower temperature heat than burning coal. This means that more biomass has to be burned to provide energy for carbon capture (since heat from the power plant is the energy source for the carbon capture);

• In general, biomass power stations are less efficient than coal power stations. This is why a unit of biomass electricity results in up to 50% more upfront CO_2 emissions than a unit of electricity from burning coal. [50] Therefore, in a BECCS plant, more CO_2 would need to be captured for each unit of electricity generated. This in turn means that more energy for carbon capture would be needed compared to the overall energy produced by the power station;

• A biomass power station would not normally be fitted with expensive equipment to capture sulphur dioxide (SO_2) because biomass contains much less sulphur than coal. Coal power stations commonly require such equipment (called Flue Gas Desulphuration) in order to meet legal air emissions limits. Flue Gas Desulphuration equipment is so expensive that across the EU energy companies are choosing to close down numerous coal fired power stations rather than fit this equipment to meet legal SO_2 standards. A BECCS power station, however, might well require Flue Gas Desulphuration because levels of SO_2 that are well within legal limits may still be far too high for carbon capture to work.

The Global CCS Institute – an international members' organisation set up to develop and support CCS – has published the results of a modelling exercise in which they have looked, amongst other things, at the energy penalty for different BECCS power station scenarios. [51]

Their report predicts that capturing CO_2 from a 76 MW biomass power station would reduce that power station's electricity output to just 49 MW and would reduce the efficiency from 36% [x] to just 23%. Since no BECCS power plant has ever been built, all such figures are based on mere predictions.

Health warnings

Community concerns about proposed CCS projects tend to focus on the fear of a sudden CO_2 leak: A CO_2 concentration of one-tenth of the volume of air is lethal and less than half that concentration is already toxic. [52] However, there is another, albeit less dramatic health risk associated with CCS and specifically post-combustion carbon capture which is generally overlooked: Toxic emissions from amines.

A fraction of the amines used during post-combustion carbon capture will be emitted into the atmosphere. Although amines themselves are not known to be toxic, they undergo complex chemical reactions and some of the compounds resulting from those are known to be highly carcinogenic. [53] The public health implications were serious enough for the Norwegian government to have suspended the country's flagship CCS project in 2011, pending more research. [54] It has since been cancelled for cost reasons.

A report by the Scottish Environmental Protection Agency into the health risks of amines from carbon capture [55] concludes that there are no legal limits for carcinogenic chemicals formed from amines, or at least not in the EU, that measuring concentrations would be very difficult, that "the environmental toxicity of many of the other individual compounds is not well understood" and that attempts to reduce

[x] 36% efficiency would in fact be very high for electricity-only biomass power stations that size. But if the efficiency without carbon capture was lower, the efficiency with carbon capture would be lower still than 23%.

SaskPower's Boundary Dam power station. Magnus Manske)

amine emissions could lead to more toxic waste water being produced.

Boundary Dam: Lessons from the world's only commercial-scale CCS power plant, which uses post-combustion carbon capture

What have we learned about post combustion CCS? In the Canadian province of Saskatchewan, the government-owned energy company SaskPower has built the world's first and so far only commercial-scale power plant unit with carbon capture. This CCS scheme is part of the four-unit Boundary Dam coal fired power station in Saskatchewan, owned by SaskPower. Once captured, the CO_2 is sold to an oil and gas company, Cenovus, where it is used for Enhanced Oil Recovery, i.e. for pumping more oil out of the ground.

SaskPower held their official ribbon-cutting event in October 2014, amidst great fanfare and international excitement. The whole project had taken "just" four years and cost overruns had (at that stage) amounted to "only" C$200 million (€140 million) - far less than the time and cost overruns experienced for example by the Kemper County CCS project currently under construction in the US. The energy industry magazine POWER pronounced the Boundary Dam CCS project the winner of their Power Station of the Year 2015 award, saying: "There was no debate among our editorial team when it came to selecting the most interesting and worthy project worldwide for this year's top award". [56]

The original power station unit from which CO_2 is now being captured had been built in 1969. Under Provincial legislation, it would have had to close in 2020 without carbon capture. But this was no simple retrofit of an old power plant unit. In fact SaskPower had previously sought to retrofit another larger power station with CCS but the feasibility study they commissioned showed that capturing carbon from such a retrofitted plant would use a full 40% of the whole plant's electricity, [57] making it economically unviable. SaskPower therefore decided to essentially completely rebuild the (smaller) Boundary Dam boiler unit, as well as building the carbon capture plant.

Boundary Dam's CCS unit should, after a full year of operation, have yielded valuable data to show how much energy a post-combustion carbon capture is really using up in a commercial setting and what the costs and economics are. Given that the Canadian government had given SaskPower a C$240 million (€168 million) grant for this scheme, and given that SaskPower themselves are publicly owned, one might expect that such data from the plant would be publicly available. It would, after all, be of vital importance for informing decisions about the merits and viability of CCS worldwide. Instead, SaskPower have been rather selective about the information they have released. The reporters of POWER Magazine (which granted SaskPower its top award of the year for the plant), were not allowed to take any photos of the carbon capture process itself, citing the "proprietary nature of the technology". SaskPower have said that 'early performance results' suggest that carbon capture is using 25% of the power station's energy, although they had originally expected it to be 32%, [58] but without actual data, this cannot be verified.

In October 2015, the opposition New Democratic Party obtained copies of internal memorandums through a freedom of information request [59] which seriously called into question the transparency and truthfulness of SaskPower and the provincial government about the operations of the plant. Far from "*exceeding expectations*" as SaskPower had told the media six months earlier, [60] the plant has been plagued by serious technical problems. Far from capturing 90% of CO_2 from the unit, SaskPower struggled to capture 55% throughout 2015, and the carbon capture unit was shut down for days and even weeks at a time. Memos also showed that the plant has never yet reached 'optimum performance'. SaskPower has already had to pay a C$12 million (€8.4 million) penalty to Cenovus for failing to supply the minimum amount of CO_2 they are contracted to deliver and they are expected to pay millions more this year. SaskPower is currently suing two contractors over the debacle, whilst one of those is, in turn, suing SaskPower. [61]

Yet even if the plant was operating as successfully as SaskPower had claimed, income from generating electricity, selling CO_2 to Cenovus and from selling sulphuric acid (obtained from capturing sulphur dioxide) would not have been enough over the 30 year lifespan of the plant to cover the costs of the investment put into this plant. This was the finding of an economic analysis commissioned and published by Community Wind Saskatchewan [62] - who of course had no idea that the real figures might be far worse than what the public had been told by SaskPower. In sum, the only experience of commercial-scale post-combustion carbon capture from a power station has so far been highly negative.

Carbon capture from a power plant with oxyfuel combustion

How does it work and what are the advantages and drawbacks?

As we have seen above, capturing the diluted CO_2 in exhaust or flue gases is costly and highly energy intensive. The purer the CO_2 stream, the less energy is needed for carbon capture. Also, capturing CO_2 that is already very 'pure' can be done through different methods, not just the amine method described above.

There is one way to significantly increase the concentration of CO_2 in otherwise conventional power station exhaust or flue gases: That is, to burn the fuel, i.e. the coal or biomass, with pure or almost pure oxygen rather than in regular air. Air consists of 78% nitrogen, 21% oxygen plus traces of other gases such as argon and carbon dioxide. Nitrogen is highly reactive (as is oxygen) and accounts for around 76% of the volume of power station exhaust or flue gases. [63] If most of the nitrogen is removed from the air and nearly pure oxygen is used for burning fuel then very little nitrogen will be found in the flue gas. There are three advantages for carbon capture:

1) The volume of flue gases which need to be cleaned up (to meet air emission standards) and from which CO_2 is captured is about 80% smaller than it would be if the fuel was burned with air; [64]

2) The flue gas consists mainly of CO_2 and water. The water and other impurities need to be separated out but this is simpler, cheaper and much less energy intensive than amine scrubbing of CO_2 from ordinary exhaust gases;

3) The gas leaves the turbine at a higher temperature than it otherwise would which can make power plants more efficient. [65]

In practice, burning coal or biomass with pure oxygen would not be feasible because fuel burns at much higher temperatures in pure oxygen. Boilers might not withstand those temperatures and also, high temperatures result in greater oxide of nitrogen (NO_x) emissions, which would either breach legal emission standards or require more costly equipment to clean up the flue gas. However, these problems can be addressed by capturing some of the exhaust gases and mixing them with the oxygen inside the boilers. Also, producing 100% pure oxygen would be prohibitively expensive and is not necessary.

Yet oxyfuel combustion has one serious drawback: Producing the oxygen – i.e. removing nitrogen from air – uses a great deal of energy. The most mature technology for doing so is called 'cryogenic oxygen production', a process first developed in the late 19th century.

In cryogenic oxygen production, air is first compressed and then passed through a water-cooled vessel to condense and remove the water it contains. The moisture-free air is then passed through an adsorber which traps trace gases, including CO_2, and which is regularly flushed clean. The 'cleaned' air is then put through a distillation process which involves splitting oxygen and nitrogen using high pressure and temperatures so low that oxygen turns into liquid (i.e. -183°C), [66] so that it can be separated and removed. The energy required for this process is provided by the power plant itself. This means that the power plant will have to expend a significant portion of its' power generation internally on oxygen purification process, plus a lesser portion on carbon capture.

The result is that (as with post-combustion carbon capture), more coal and/or biomass have to be burned for the same electricity output.

Other drawbacks include:

• Fuel burning at higher temperatures which puts stress on the boiler materials and requires more expensive ones to be used;
• A more inflexible and complex power plant design with multiple burners, and with the challenge of having to prevent any leakages which would allow air to enter the furnace. [67]

Special challenges for oxyfuel combustion of biomass

Compared to coal, larger volumes of biomass have to be burned to generate the same amount of electricity and biomass power stations are generally less efficient than coal power stations. This means that generating a unit of electricity from burning biomass under oxyfuel conditions would require more oxygen and thus more energy and costs for separating oxygen from air. This is an inherent disadvantage that cannot be overcome.

Furthermore, there is virtually no experience with oxyfuel combustion of biomass – none except for some very small-scale experiments. Oxyfuel combustion of coal, on the other hand, has been demonstrated in plants up to 30 MW in size. Coal and biomass are chemically very different and experience with one cannot simply be transferred to the other. Co-firing of biomass and coal under oxyfuel conditions has not yet been demonstrated on any significant scale either. It would therefore take significantly more research and development to build a BECCS plant with oxyfuel combustion compared to one burning coal.

Vattenfall's CCS pilot plant in Germany using oxyfuel combustion. SPBer

"Too expensive": Energy companies abandon oxyfuel CCS

There have been four demonstration projects in which coal was burned under oxyfuel conditions and carbon was captured but none of those are ongoing. [68] One demonstration was run by Vattenfall, one of Europe's largest energy companies and fully-owned by the Swedish Government. Vattenfall's oxyfuel project, based in Germany ("Schwarze Pumpe CCS project"), was meant to be the first step towards a large commercial oxyfuel CCS power station. But in May 2014, Vattenfall announced that they would no longer invest in the technology because "*its costs and the energy it requires make the technology unviable*". [69]

In the US a commercial-scale oxyfuel CCS power station scheme – FutureGen 2.0 - collapsed after the federal government had spent $202.5 million (€189 million) on it. FutureGen 2.0 would have seen an old coal power station unit retrofitted with oxyfuel combustion and carbon capture. The US government had pledged a total of $1 billion (€930 million) in subsidies, provided it could be up and running by 2015. The work proved significantly costlier and slower than foreseen and, crucially, no private investor came forward, i.e. no company showed any willingness to put their money into the plant. The failure of FutureGen 2.0 came on top of the failure of Future Gen 1 – an integrated gasification combined cycle (IGCC) coal power station with CCS that had been abandoned previously at a loss of $175.5 million (€163 million) to US taxpayers.

In the UK, planning permission is expected to be granted for a brand new 428 MW coal power station designed with oxyfuel combustion and CCS – the White Rose Project. However, few expect the plant to actually be built, after one of the main players, Drax Plc, announced that they were pulling out of the project. [70] The developers had been granted £50 million (€70.4 million) and expected at least another £450 million (€633 million) in public funding for the construction costs, as well as substantial year-on-year subsidies. Even with that level of public subsidies, Drax clearly decided that the project was financially too risky.

The White Rose Project had been billed as the "*world's first power plant with carbon negative emissions*" because of biomass co-firing. In fact, at least 85% of the fuel would have been coal, and the maximum amount of CO_2 that could have been captured would have been 90%. The planning documents claimed that biomass co-firing would further reduce carbon emissions from the plant – not that the plant could be carbon-negative. Drax, who were to operate the plant, already run a much larger power station which burns more wood than any other plant in the world and more coal than any other plant in the UK. Far from being climate-friendly, most of their biomass consists of wood-pellets imported from North America, at least some of which are from the clearcutting of carbon-rich and highly biodiverse southern US forests. [71]

Integrated Gasification Combined Cycle (IGCC) plants with carbon capture

How does it work and what are the advantages and drawbacks?

In theory, an IGCC power station – if it was operating entirely smoothly – should be the cleanest and most efficient [xi] way of generating electricity from burning coal or biomass. Furthermore, CO_2 capture from an IGCC plant should be simpler and less energy intensive than from a conventional power station using post-combustion carbon capture. CO_2 capture from IGCC plants is called pre-combustion capture, for reasons that become clear when looking at how such a plant works.

In an IGCC plant, the first step of the process involves 'pre-treating' coal or biomass so that it has the right consistency and moisture content. This generally means milling it to a fine powder and either adding

Kemper County coal IGCC power station with carbon capture, currently under construction. XTUV0010

[xi] Note that when speaking about efficiency in this report, we are looking solely at the efficiency of electricity generation. The most effective way of increasing any type of power station's overall efficiency is to capture heat and distribute it to nearby homes or businesses (i.e. to operate as a combined heat and power plant). A conventional power station with a steam turbine that supplies significant amounts of heat will be more efficient than an IGCC power station that supplies none. Focussing on electricity efficiency only, however, allows for the best comparison between different technologies.

moisture, or drying it (depending on the technology chosen). The pre-treated fuel is then pumped into a gasifier, i.e. a vessel where it is exposed to high temperatures with a controlled stream of nearly pure oxygen. An air separation unit is needed to generate the oxygen needed for the gasifier but the amounts of oxygen needed and thus the energy requirement for air separation are smaller than for oxyfuel combustion plants.

During gasification, most of the biomass is turned into a gas called "producer gas" which consists mainly of hydrogen and carbon monoxide but still contains many other trace gases and impurities. A small amount will be retained as char or ash. Producer gas is too dirty to be burned in gas turbines and thus has to be cleaned first. Gas cleaning is a highly complex multi-stage process involving different chemicals, used as solvents or adsorbents. [72] It includes scrubbing and filtering out particulates, hydrogen chloride and ammonia, reheating the partially cleaned gas and putting it through a reactor with a chemical which converts most of the sulphur compounds into hydrogen sulphide (which is subsequently removed), cooling the gas down again, removing most of the mercury with the use of another chemical ('adsorbent'). It also involves using nitrogen to remove more unwanted gas components, scrubbing the cleaned gas with solvents, compressing it, and recovering the sulphur in a separate Sulphur Recovery Unit (so that it can be sold and used). The cleaned gas is called syngas.

Once the gas has been so thoroughly cleaned, it can be used to power a gas turbine. The hot exhaust gas from that turbine is cooled down and passes through a steam generator which produces additional electricity through a steam turbine - which is why it is called a 'combined cycle'.

During the gas cleaning stage, carbon dioxide can also be captured. This needs a separate 'shift reactor' in which the carbon monoxide in the syngas is reacted with water to form hydrogen and CO_2. It also needs a CO_2 capture unit, using amines (discussed above under 'post combustion carbon capture) or possibly other methods. Because the concentration of CO_2 in syngas is higher than that in power station exhaust or flue gases, less energy is needed to capture it. Nonetheless, the amount of additional energy needed is still significant and will reduce the overall efficiency of the plant (i.e. result in more fuel being burned per unit of energy).

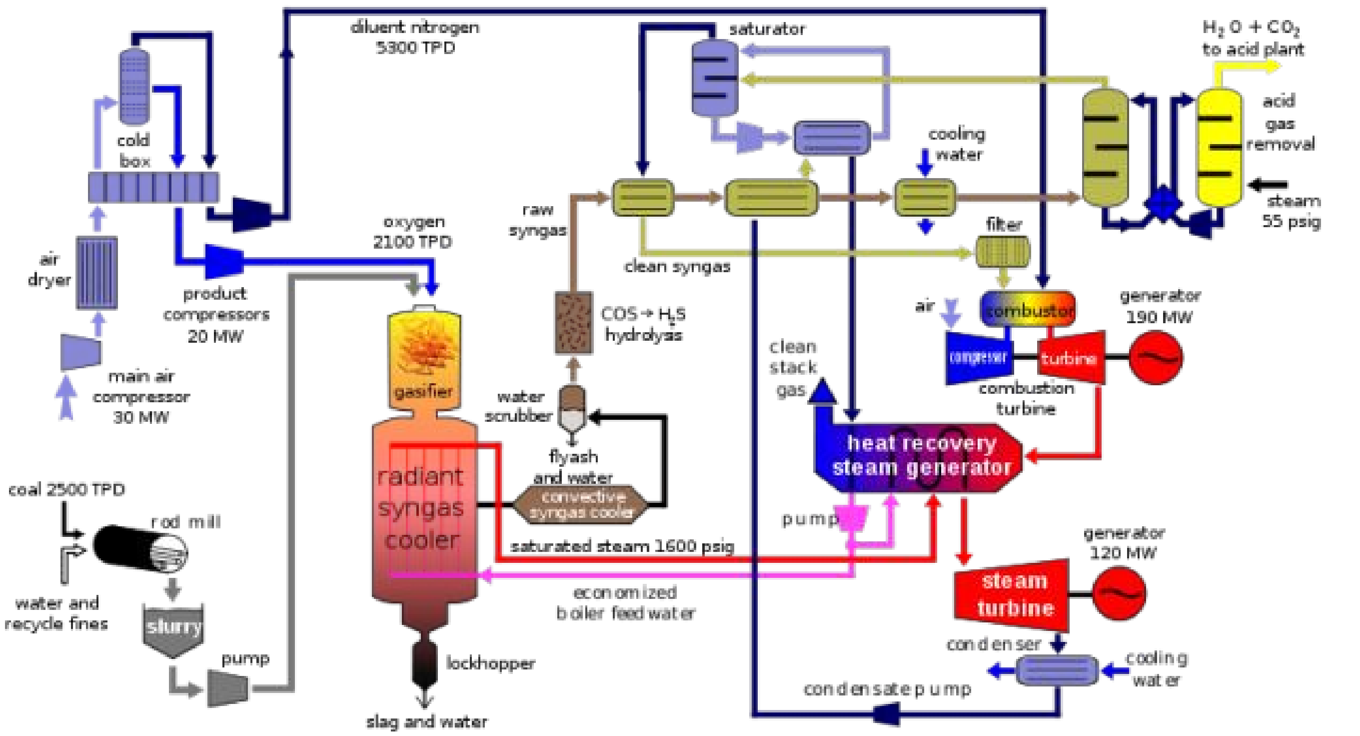


Image showing the complexity of the IGCC process. Stan Zurek

Clearly, IGCC power plants – especially ones with carbon capture are highly complex and complicated plants, and this complexity is their main drawback. IGCC plants have been developed since the 1970s. Although many improvements have been made to their design and much experience has been gained, such plants are fraught with operational problems and the solutions to problems commonly add yet further more complexity to the design and operation.

The experience with commercial-scale IGCC coal power station (without carbon capture)

A 2013 report by the International Energy Agency's Clean Coal Centre [73] looked at the experiences with seven coal IGCC plants, (none of them with carbon capture). Six of those plants continue to operate, one has been closed because the operators (Vattenfall's Dutch subsidiary, Nuon) decided that, after 15 years of commercial operation, the plant was too expensive to continue to run.

Five of the plants started operation in the 1990s and the largest of them is a 400 MWe coal power station in the Czech Republic (Vresova IGCC plant). Small carbon capture experiments were conducted at three of the IGCC plants and a CCS feasibility study has been carried out at a fourth.

Operators of each of these plants reported serious technical challenges, which they have had to overcome. The operators of the largest, the Vresova IGCC plant reported

"*a combination of high operating and maintenance costs, low conversion efficiency, lack of fuel flexibility, and limited capacity for load regulation. There is also a significant impact on the local environment.*"

Changing between different types of coal caused problems in all IGCC plants because the different types of coal (or for that matter biomass) have different properties and IGCC plants have to be adjusted quite precisely to specific types of fuel.

Typical problems include ash depositing inside the gasifier and piping, corrosion and cracking of vital parts of equipment, build-up of slag (a residue from coal or biomass gasification), blockage of hot gas filters, problems with keeping emissions of oxides of nitrogen (NO_x) low enough to meet legal limits, failures of filters used for cleaning the gas, salt formation which hinders the removal of sulphur, overheating putting strain on a turbine, water leaks, and ash blocking the waste heat boilers.

Operators have been able to address each of these problems as they have arisen – but it is the sheer number of different problems and recurrent problems that makes operating such a plant so expensive and generally unreliable. For example a coal-fired IGCC plant in Spain required 6,000 different modifications to the plant after it was built.

Shortly before this IEA report about coal-fired IGCC plants was published, the largest coal IGCC power station ever built (again without carbon capture) was opened by Duke Energy in Indiana. [74] It cost a full $3.5 billion (€3.27 billion) to build. 20 months after it was first commissioned, it had hardly ever operated at even half its capacity.

Will prices go down? Implications for the 'technology learning curve' model

The high complexity of such power stations has serious implications for the concept of a 'technology learning curve', which we discussed above:

Solar PV, which has seen a particularly steep and consistent decline in costs and increase in efficiencies, is based on a simple technology concept and improvements have been made largely through developing better materials. Those who installed solar PV panels twenty or thirty years ago would have been just as confident of it working as householders or businesses buying ones today – only today's solar panels will be cheaper and more efficient.

The 'learning' process for IGCC power stations is quite a different matter. Commercial-scale IGCC plants cost billions of dollars (or Euros) to build and literally thousands of different problems with different parts can arise. If an IGCC plant is optimised for gasifying one type of coal then settings will have to be modified for a different type of coal, or for co-gasification of biomass and of course for gasifying different forms of biomass. And running an IGCC plant with carbon capture will pose yet more challenges. So far, after decades of research and development of this technology, there are no signs that the cost of IGCC plants has started to come down. It is not inconceivable that IGCC plants – if many more were built – would follow the cost curve of nuclear power stations, which has been going up, not down. [75]

Carbon capture from IGCC plants

Carbon capture from IGCC plants has only been tried on a small pilot scale. In the pilot projects mentioned above, a small proportion of the coal-gas from existing IGCC plants was diverted for experimental carbon capture. Nobody has yet run an IGCC plant with full carbon capture. If carbon is removed from syngas (i.e. from the coal or biomass gas that has been cleaned up) then what is left is almost entirely hydrogen. An IGCC plant with maximum carbon capture would thus involve powering turbines by burning almost pure hydrogen. This has never been attempted at scale. A 2005 report about coal-fired IGCC plants, published by the Massachusetts Institute of Technology, cautioned:

"*It should also be noted that most of the other components in the plant such as fuel handling systems, the gasifier and the air separation unit will "see" different material flows through them in a plant with capture as opposed to a plant without capture. This is a complex issue which is currently not fully resolved.*"

Despite the almost complete lack of experience with carbon capture from IGCC plants, the US Government decided to award a $270 million (€252 million) grant [76] plus $412 million (€385 million) in tax credits [xii] to an electricity company (Southern Company) for building a large 582 MW IGCC coal power station which is to capture 65% of the CO_2 and sell it for Enhanced Oil Recovery. [77] "Success" would mean scaling up a new technology (i.e. running an IGCC plant with carbon capture) from virtually nothing to large commercial scale in one single go. But success remains a long way off.

Southern Company started building the plant in Kemper County, Mississippi in 2010. They had originally proposed to build it for a cost of $1.8 billion (€1.68 billion) but by the time the plant was approved, the cost estimate had risen to $2.88 billion (€2.69 billion). By November 2015, costs had risen to $6.4 billion (€5.98 billion) [78] and the plant's opening has been delayed to mid-2016. Construction costs continue to rise month on month. By comparison, using US government estimates, the capital cost of building a combined cycle gas power station without carbon capture would be around $534 million (€499 million). If the Kemper County plant was to ever work properly, its CO_2 emissions would be roughly equivalent to those of a gas power station with the same electricity output.

Southern Company could never have embarked on such a vastly expensive and high-risk project had it not been for a change in the law in Mississippi, made possible by a former state governor who had previously worked as a lobbyist for Southern Company. Under that law, the electricity company has been able to significantly raise rates, i.e. electricity bills in southern Mississippi in order to recoup their construction costs. Mississippi is the poorest state in the US and Kemper County is one of the poorest counties. Far from benefitting from the 'investment', residents have seen unemployment rise further. Unsurprisingly, other companies have been reluctant to invest in similar technology.

BECCS IGCC plants

Given the extreme cost overruns and delays at the Kemper County IGCC coal power project, it seems unlikely that other companies would want to follow Southern Company's example in the near future. Carbon capture adds a ream of new challenges to the already highly expensive, complex and challenging IGCC technology. Exchanging coal for biomass would add yet more challenges still. Biomass gasification results in a producer gas which is chemically quite different from that generated from coal gasification and therefore requires different treatment in order to produce a gas clean enough for burning to power a gas turbine. A previous Biofuelwatch report [79] looked in detail at the challenges and problems associated with biomass gasification, which would be the first stage in a BECCS IGCC plant.

The operators of one (now closed) IGCC plant, in Buggenum, Netherlands, succeeded in adding biomass to coal but for that they relied on torrefied wood pellets. Torrefied wood pellets are pellets which have been exposed to temperatures of 230-300oC in the

[xii] Note that the company has had to repay $130 million of those tax credits because of construction delays.

absence of oxygen, i.e. they are partially charred pellets. Torrefied pellets have various advantages for coal power station operators in particular [80] but they have one big drawback: A substantial amount of the energy contained in wood is lost during torrefaction – 10-40% depending on the temperature. This figure does not account for the energy required to heat the wood during torrefaction. Torrefaction itself remains technically challenging and an IEA report about that technology [81] states:

"*Depending on the reactor type, it can be a serious challenge to scale up torrefaction processes from pilot (typically 20-600 kg/h) to commercial scale*".

According to the IEA's 2011 report on BECCS:

"*The energy penalty for BIGCC [i.e. dedicated biomass IGCC] is not yet known. But the lower conversion efficiency of dedicated BIGCC together with the capture penalty results in a lower conversion efficiency than for co-gasification.*"

Compared to coal IGCC plants, biomass ones would be even less efficient.

Can we trust that CO_2 pumped into a geological reservoir will stay there?

How CO_2 is sequestered

Captured CO_2 may be injected into underground geological formations such as old oil and gas reservoirs or deep saline aquifers. The CO_2 is trapped in the pore spaces of these sedimentary rocks, and held in place by caprocks, which have very low permeability, and prevent the CO_2 migrating up through them and to the surface.

When CO_2 is not to be used for EOR or other purposes, but rather to be stored underground as a means of preventing it from reaching the atmosphere, after the CO_2 has been captured it is usually converted into a high-pressure, liquid-like form, called "supercritical CO_2", and subsequently injected into sedimentary rocks. Supercritical CO_2 is denser than gaseous CO_2, meaning that more can be sequestered into each geological reservoir. [82] Depending on the reservoir conditions, CO_2 can be stored as compressed gas, as liquid, or in a supercritical phase.

Various physical and geochemical trapping mechanisms are meant to prevent CO_2 from escaping to the surface and back into the atmosphere. [83]

Supercritical CO_2 may undergo a phase change due to changes in pressure and/or temperature after it is injected, but it will remain in a supercritical phase at depths below approximately 800-1000m, [84] with most of the injected CO_2 being mobile and free to move away from the injection well; either laterally, or up through the reservoir and towards the caprock.

The geological sequestration of CO_2 is achieved through a number of different trapping mechanisms that are determined according to the hydrodynamic, physical and chemical properties of the storage reservoir in question. These mechanisms are often summarised under 4 categories: Hydrodynamic trapping, residual trapping, solubility trapping, and mineral trapping.

1) Hydrodynamic trapping: Hydrodynamic trapping occurs when CO_2 is trapped in a supercritical state or as a gas under a low-permeability caprock. Once injected, the CO_2 plume will rise through the existing fluid in the formation (brine in the case of saline formations) until it reaches a caprock that prevents it travelling any further. CO_2 will then accumulate in the reservoir, to the extent that the caprock allows. Trapping in this manner is also referred to as structural or stratigraphic trapping. This trapping mechanism is the most important for CO_2 sequestration, and any storage site must be suitable for hydrodynamic trapping, as it prevents CO_2 escaping from the reservoir during the time required for other, slower trapping mechanisms to take effect.

Such traps are mostly found in reservoirs that have held oil and gas in the past, and their storage capacity mainly depends on the volume of the formation's pore space, i.e. microscopic gaps between the grains of the sedimentary rocks. Hydrodynamic trapping can also occur in saline aquifers that form parts of sedimentary basins, such as the Utsira formation in the North Sea.

2) Residual or capillary trapping: Residual or capillary trapping refers to CO_2 trapped in pore spaces within the formation, after injected CO_2 has been displaced by the existing brine. When CO_2 is injected into the reservoir, it displaces the brine, but when injection is stopped CO_2 moves up through the brine because of density differences between the two. The displacement of the CO_2 by brine leads to a significant quantity of CO_2 becoming trapped in small clusters of pores in the formation. This CO_2 is then trapped in an immobile phase, disconnected from the CO_2 that has migrated upwards through the brine.

3) Solubility trapping: Solubility trapping occurs when CO_2 dissolves into the water contained within the formation, until an equilibrium is reached. The solubility of CO_2 in water is dependent on the salinity, pressure and temperature of the water. The water in contact with CO_2 will become saturated, and gradually, more and more CO2 will dissolve into water which is further from the CO_2 plume. This process is extremely slow. It takes thousands of years for CO_2 to be completely dissolved in brine.

4) Mineral trapping: Mineral trapping occurs when CO_2 is incorporated via chemical reactions, into mineral and organic matter within the formation, in a stable mineral phase. Some of these reactions trap the CO_2 through the formation of carbonate minerals, whereas other reactions actually help the migration of CO_2. Mineral trapping processes will be dependent upon the structure, mineralogy and hydrogeology of the formation, and involve complex reactions and competing processes. Mineral dissolution is a very slow process as the reaction rates are usually very low, and mineral trapping would only occur over geological time scales. [85]

How could CO_2 leak once injected underground?

Numerous potential leakage pathways have been identified throughout the history of research into carbon sequestration. Of greatest concern is leakage from old wells, particularly onshore wells, where there is a risk that operators either plugged old wells insufficiently, or did not plug them at all. This is of particular concern in parts of North America where there are very high densities of oil production wells, and some were left unplugged following bankruptcy of the operators due to the 1986 oil crash. Unplugged, deeper wells penetrate many of the deeper formations currently used and thought to be suitable for CCS, which substantially increases the risk of leakage. [86]

Whilst the principle of the deep storage of CO_2 in geological formations over geological time scales is sound, and exemplified by natural CO_2 deposits, as well as oil and gas deposits, it is more likely to be human error that results in CO_2 leakage. On time scales appropriate for geological sequestration, the bulk of CO_2 sequestered in a properly chosen saline aquifer, for example, is unlikely to escape because of solubility trapping in the pore spaces of the formation. However, because of the diverse nature of geological formations, minor CO_2 leakage along faults, old production wells, or other pathways will persist and be difficult to seal completely by other trapping mechanisms, such as carbonate mineralisation. [87] Therefore, a poorly chosen site and well integrity issues are likely to represent the most significant risk to leakage.

A further issue concerning well integrity is how CO_2 reacts with water when it is injected underground and acidifies it. This can degrade well plugs which are generally made from cement. In cases where the cement used was not up to standard, corrosion and failure may occur when the acidified water comes into contact with it. This is a more common problem in older wells. For example, an analysis of well distributions in the Alberta basin's Viking Formation in showed that an injected CO_2 plume and the acidified brine that is thereby created, could encounter up to several hundred producing and old or abandoned wells. The Viking Formation is considered to be representative of mature North American basins, i.e. extensively explored and containing many oil wells. This represents a serious problem for carbon sequestration - if CO_2 storage takes place in formations such as this, where intensive exploration for oil has taken place, it could result in rapid leakage. [88]

Further studies have been conducted in other intensively drilled areas, such as the Wabamun Lake area of Alberta in Canada, and these show how large numbers of existing oil and gas wells can lead to complex leakage patterns, across multiple geological formations. [89] Other studies have shown that CO_2 gas can migrate rapidly from depth, and when established, flow paths are able to stay open, longer-term trapping mechanisms are not taking place rapidly enough to ensure containment. Under these conditions, CO_2 migration could occur rapidly, over large distances, and over long periods of time. [90]

Leakage from storage sites has been identified as a significant issue, but so too has the actual potential for geological storage at sites considered suitable for sequestration, with estimates of reservoir potential often being significantly reduced. A study published recently suggested that the chemistry of geological sequestration and the trapping mechanisms involved, are actually poorly understood. In particular, it showed that only a small fraction of the injected CO_2 is likely to be trapped through being physically converted to solid minerals, whereas previously it had been assumed that far greater proportions would be. [91] [92]

Some studies have attempted to assess the overall capacity for storage available in different regions as well as globally. Further studies have questioned the basis for assumptions of the storage capacity of geological sites, [93] but these assessments have come under heavy fire from proponents of the CCS industry and other academics in the field. [94] It seems that whenever a study is published, questioning some of the assumptions underlying CCS, it is met with a barrage of responses, rebuttals and counterarguments.

Has geological sequestration of CO_2 been successful?

Proponents of CCS are quick to claim that CO_2 storage at flagship sites is successful, effective, and safe. Three of the most significant storage projects to date are: Cenovus Energy's Weyburn Enhanced Oil Recovery site in Canada, BP and Statoil's Sleipner project in the North Sea, and the In Salah gas production site in Algeria, operated by BP, Statoil and Sonatrach. All three are heralded as examples of successful carbon sequestration, but have been surrounded by controversy regarding potential leakages.

Did CO_2 leak at Weyburn?

Cenovus Energy began injecting CO_2 into their Weyburn oil field in southeast Saskatchewan, Canada, in 2000. Weyburn is now recognized as the world's largest geological CO_2 storage project, and Cenovus state that 60% of the massive Weyburn oilfield is now undergoing CO_2 flooding. [95] At the time, Cenovus were buying CO_2 from a coal gasification plant, with the CO_2 piped over a long distance to the Weyburn field. In 2010, Cameron and Jane Kerr, farmers living near to Cenovus Energy's Weyburn EOR site, [96] enlisted the help of solicitors Ecojustice and Petro-Find, a small geochemical testing company, to get to the bottom of some unexplained phenomena on their farm. The Kerrs suspected that CO_2 was leaking from the Weyburn field, as they had experienced problems with animals dying on their land, and what appeared to be CO_2 bubbling up from water bodies on their land, whilst an oily film suggested hydrocarbon leakage had occurred.

The Petro-Find study

Petro-Find Geochem Ltd carried out a series of geochemical tests on the soils from the Kerr farm. Two studies were conducted, one in August 2010, [97] the other in February 2011. [98] Petro-Find used industry standard soil geochemical analysis and identified CO_2 and CH_4 anomalies on the site, in areas with significantly elevated levels of these gases. They also identified that the injected CO_2 and "leeching CO_2" were isotopically very similar, and used an old baseline value, from a previous monitoring report at Weyburn, that showed that biogenically sourced CO_2 on the site was significantly different, from both the injected CO_2 and the CO_2 that appeared to be leaking into the farm. However, no additional baseline or biogenic comparison was made.

Petro-Find's studies were unable to identify specific hydrocarbons or clearly identify the oily film from the water bodies. Nonetheless, it was assumed that the substance was a result of hydrocarbon seepage.

Petro-Find's reports concluded that CO_2 was definitely leaking from the injection site and into the Kerr's land. These results were publicised in a press release issued by Ecojustice on behalf of the Kerrs, which attracted a substantial media interest, and cast serious doubts on the success and safety of CO_2 injection at Weyburn.

Cenovus' "independent" study

In response to the Petro-Find reports, Cenovus commissioned Trium Environmental and Chemistry Matters, two consultancy firms specialising in geochemical analysis, to carry out a similar "independent" study on the Kerr farm. This study was published in November 2011. It conducted a similar analysis to the Petro-Find study, but came to the opposite conclusion. The main differences between the two studies were that Trium and Chemistry Matters found the injected CO_2 to be "ancient", (given that it was at the time CO_2 was being piped to the site from a coal gasification plant), and the higher than normal CO_2 concentrations on the Kerr farm to be "modern", and therefore biogenic in origin. This difference came about as a result of testing methodologies, where Trium and Chemistry Matters analysed for radioactive carbon isotopes, which Petro-Find didn't do.

Where Trium and Chemistry Matters had used the same analysis method as Petro-Find, their results were similar. However, Trium and Chemistry Matters also used additional "control" samples taken from a near-by farm that was quite a distance from the EOR area of injection. This showed that the control, the samples taken from the Kerr farm, and the injected CO_2, all had similar isotopic signatures. Trium and Chemistry Matters therefore concluded that the baseline figure in the paper that Petro-Find had sourced their figure from was incorrect. [99]

Trium and Chemistry Matters also identified the oily substance on the water bodies as being biogenic in origin, produced by phytoplanktion and cyanobacteria, and dismissed the idea that it was a hydrocarbon. Their report concluded unequivocally that their results showed that no CO_2 was leaking from the Weyburn injection site.

Rebuttal from the Weyburn injection monitors

The Petroleum Technology Research Centre (PTRC) issued two reports; one a rebuttal of the Petro-Find report, and another, a data review of the Trium study, a "document [that] provides a third-party review performed by "experts".

One of the main points of the PTRC's rebuttal was that the underlying geology and hydrogeology of the injection site showed, that if there was leakage, one would expect the CO_2 to be travelling in the opposite direction, away from the Kerr farm, and not, as Petro-Find had suggested, towards it. There were many other points of contention. PTRC validated the Trium and Chemistry Matters reports methodology and conclusions.

Starting in 2000, a consortium of companies and organisations, under the management of the PTRC, was monitoring the Weyburn site through the "independent" "IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project (WMP)". This monitoring project ended in 2012. Part of it included five soil gas surveys which were conducted between 2001-2005, 2 miles north of the Kerr property. This area was only comprised of about 5% of the total area of the Weyburn and Midale fields. Despite this, the PTRC referred to these soil gas surveys as being "extensive". [100] The PTRC was monitoring the Weyburn EOR project, on behalf of Cenovus, and received funding from the Canadian regional and national government agencies, as well as from the oil and gas industry. [101]

More industry studies

The International Performance Assessment Centre for the geologic storage of Carbon Dioxide, (IPAC-CO_2), was established in 2008 as a "*not-for-profit research and development organization*", to further the understanding and assessment of risk and performance in CCS. IPAC-CO_2 was created through the efforts of Royal Dutch Shell, the Government of Saskatchewan, and the University of Regina. The Government of Saskatchewan and Shell contributed $5 million each to launch the organisation. [102]

IPAC-CO_2's mission, as described on its website at the time, was to "*support the development, acceptance and commercialization of carbon capture and storage technologies as a safe and effective means of reducing CO_2 emissions by advancing geologic storage*." [103] Following their Weyburn study, IPAC-CO_2 developed the methodology they had devised into a "bi-national CO2 standard". [104] IPAC-CO_2 closed in 2013 amid reports amidst allegations of conflicts of interest and misspending of public funds, when the organisation was in its start-up phase. [105] Towards the end of 2013 IPAC-CO_2 was investigated for fraud. [106]

The IPAC-CO_2 study used a new "process based" methodology, designed specifically for the Weyburn study, and one that hadn't previously been used to monitor EOR or sequestration sites. The methodology utilised on this occasion was considerably different to previously used study techniques, which were considered to be industry standard practice at the time.

The authors of the IPAC-CO_2 report said that

"*soil gas monitoring might not have to be as complex and difficult as we had thought*" and that the old methodologies were costly and time consuming. Report authors, and IPAC-CO_2 scientists included researchers from the Universities of Texas and Edinburgh.

Too few sampling points, not rigorous enough

The first Petro-Find study had identified one particularly large anomaly in CO_2 concentrations on the Kerr farm, corresponding to one of the wetland areas, and they used this data as the basis for its conclusion that CO_2 was leaking from the Weyburn site. Despite this finding, neither the IPAC-CO_2 study, nor the Trium/Chemistry Matters study, took samples from the same location as the Petro-Find anomaly. The Trium/Chemistry Matters study avoided all of the wetland areas entirely, and the IPAC-CO_2 study, chose just 10 sample points, 5 of which were in the lowest CO_2 concentration area identified in the Petro-Find report. The other 5 were chosen in a line almost corresponding to the contour of the lower CO_2 concentration area, as identified by the Petro-Find study. The high concentration area was not sampled at all, even though the author of the IPAC-CO_2 study said

"*We've got some data from the Petro Find report, we know the area with high concentration of CO_2 and low concentration, so we've set up our gas sampling stations so that they span both of those areas. We start in low CO_2 and move sequentially to high CO_2 area and compare those analyses.*" [107]

In fact, the sampling points appear to have been selected to avoid what was thought to be the highest CO_2 concentration area, as based on the Kerr family observations and the Petro Find report.

The location of sampling points was one issue; another was the very small number of total sampling points The Petro-Find study took 25 samples for its first report, and 30 for the second, whereas IPAC-CO_2 chose only 10. The IPAC-CO_2 "process-based method" aimed to reduce time and cost for such studies.

Alternative interpretations?

In a comment on an NRDC website blog post, [108] Dr Schuiling, professor of Earth Sciences and Geochemistry at Utrecht University, says:

"*There is never a...dry CO_2 gas emission that forms so suddenly and so vehemently, in a non-volcanic environment. It is very implausible that it has no direct or more indirect connection to the injection of large volumes of gas in the underlying reservoir*."

In subsequent email correspondence, he elaborated on the implausibility of a sudden CO_2 gas release in a non volcanically active area. He remarked on the coincidence that it would occur in the same place as a major CO_2 injection that had begun a number of years beforehand, and described the phenomena as a "*geological miracle*", should the elevated CO_2 levels at the Kerr farm be unrelated to the EOR operations at Weyburn.

There is an obvious conflict in the Weyburn case where one set of consultants were commissioned by landowners who believed that CO_2 release was leaking onto their land, and the results of the study they commissioned confirmed this. Another set were commissioned by the industry, with a vested interest in the Weyburn project and CCS in general being successful, and reached the opposite conclusion. Nowhere, is there a suggestion, for example, that a mixture of the two interpretations could be correct - unusually high CO_2 levels through biogenic activity in organic rich, wetland areas in the summer, and some degree of leakage from old wells, or geological fractures.

It is also significant that the Kerrs were able to commission two geochemists from a local company with limited resources, and for less than $10,000 (€9,500), whereas the industry flew in experts from North America and Europe to conduct their studies, who even developed a whole new methodology to disprove the Petro-Find results. With such a response to the initial claims that CO_2 was leaking from the Weyburn field, there was presumably, very little the Kerrs, EcoJustice or Petro-Find would have been able to do. Indeed, Ecojustice accepted the alternative conclusions of the subsequent reports and issued a statement that the investigations into the impacts of

CO_2 storage at Weyburn were a "*win for all Canadians*", since they had taken place in response to public pressure. [109]

To summarise, the lack of independent assessment, conflicts of interest, combined with a lack of overall knowledge and understanding of the behaviour of CO_2 underground make the Weyburn case unresolved, inconclusive and troubling.

The Sleipner CCS Project

The Sleipner CCS project is the longest running in the world, and is a flagship demonstration project for proponents of CCS. Sleipner has been injecting approximately 1 million tonnes of CO_2 a year into a sub-seabed saline aquifer called the Utsira formation, since 1996. This followed the introduction of an offshore CO_2 tax by the Norwegian government. The CO_2 is captured from a facility that processes natural gas, and by early 2013, more than 14 million tonnes of CO_2 had been injected. [110] CCS proponents point to Sleipner as proof that CO_2 can be stored safely and permanently, and claim that the Utsira formation is large enough to hold all of Europe's emissions for many years to come.

However, Greenpeace highlighted how, in 2008, a leak from the StatoilHydro-operated project in the Tordis field, part of the Utsira formation, which showed that an understanding of the geology of the storage site was far from complete. [111] In this particular case, contaminated process water was being injected into the formation via a method designed to specifically create cracks in the reservoir, in order to increase its permeability. Several unexpected pressure drops were observed during injection, and injection operations were paused, only to be restarted again; even though the exact reason for the pressure drops was not identified. Careful monitoring and warning systems are required to be in place so that operators can identify possible leakages quickly, but, as Greenpeace reported, there were no such systems in place near to the location of the leakage, which was some 300 metres distant. As a result, it was not possible to determine how long the leakage had been occurring prior to its discovery. Once the source of the oily water and reason for the observed pressure drops was identified, injection operations ceased for good, and StatoilHydro estimated that 48-175 m^3 of oil had leaked from the storage formation.

Greenpeace rightly point out that:

"*if these so-called experts in the field cannot reliably inject processed water into a single underground formation, how can we assume that gigatonnes of CO_2 from thousands of coal fired power plants can be safely disposed of in prospective geological reservoirs across the globe?*"

Similar issues have occurred at other Utsira injection sites, such as at the ExxonMobil operated Ringhorne site, and another at the StatoilHydro operated Visund site. The Ringhorne field started production in 2001, and was injecting well cuttings and associated waste fluids into the Utsira formation. In February 2004, oily water was observed on the sea surface near the platform, and the leaked oil was found to be coming from the injection well. The Visund field started production in 1999, and involved injecting gas, as well as well cuttings and fluids into the Utsira formation. In 2007 there was unexplained activity in the seabed that involved cracking and/or other damage to the formation, which was probably related to the injections. [112]

At Sleipner, injected CO_2 has been migrating in the reservoir in an unpredicted manner, to the surprise of researchers. Initially, injected CO_2 was expected to rise gradually through the layers of the formation. However, seismic imaging showed that it was flowing almost immediately to the top of the formation instead. In 2006, a study found that the plume ascended 200m vertically through eight shale barriers in less than three years. [113] Another study conducted in 2014 stated that:

"*the plume flow behavior is not indicative of sealing shale barriers punctuated by faults, holes or penetrated by a high permeability chimney or sand injectite, and the means of CO_2 ascent is poorly understood.*" The study went on to say: "*If the laterally extensive shales had acted as seals, preventing the vertical migration of CO_2, the plume would have taken much longer to breakthrough, and its behavior would have been more akin to a 'zig-zag' distribution with lateral offsets resulting from the CO_2 tracking along the base of a barrier until encountering a hole through which to escape up to the next barrier, and then repeating this behavior.*"

This is an indication that the fate and migration of injected CO_2 is still poorly understood at Sleipner, some 10 years into the injection programme. [144]

Indeed, previous monitoring studies have revealed a large discrepancy between the amount of CO_2 injected and what was subsequently detected in seismic surveys. Researchers concluded that the discrepancy was inexplicable, possibly due to miscalculations in their modelling, or, potentially, leakage. [115]

As well as concerns over unexpected behaviour of CO_2 plumes and leakage from other sites in the Utsira, questions have also been raised over its CO_2 storage capacity. A study by the Norwegian Petroleum Directorate cast serious doubt on the ability of the formation to store significant volumes of CO_2, owing to the fact that the formation is relatively shallow, such that the injected CO_2 would not necessarily remain in a fluid or supercritical phase once injected. It concluded that

"*[...] it remains uncertain whether Utsira is suitable for large-scale storage of Europe's carbon emissions.*" [116]

It should be noted that US NGO, NRDC, produced a report similar to Greenpeace's on the Sleipner project, but concluded the opposite, claiming instead that reported leaks in the Utsira formation are not analogous to the Sleipner injection site, and that more recent studies that have downgraded the storage potential of the Utsira are simply part of the scientific process of refining and improving on these estimates. [117]

In a more recent development, an extensive, and previously unexplored fracture in the sea bed rock - the "Hugin Fracture", 25 km north of Sleipner CO_2 storage site was discovered and explored by ECO2, and reported on in October 2012. [118] This discovery was covered in a Nature article, [119] and immediately received rebuttals and responses from, amongst others, the Scottish Carbon Capture and Storage Centre. [120] Following the swift and negative response from other academic institutions, ECO2 has not published a report on its findings. Even if the Hugin Fracture presents no leakage risk to the Sleipner injection operations, it is significant that a report that is potentially damaging to the interests of the CCS industry has not been published at all.

Statoil maintain that there have been no major leaks from the Sleipner injection. However, as Greenpeace reported in 2008, several scientists have claimed that current technological limitations make this impossible to guarantee. The Greenpeace report quoted Peter Haugan, the leader of the Institute of Geophysics at the University of Bergen, as having said:

"*It's not possible to prove that all injected CO_2 is still there. There's no way of measuring the amount of CO_2 in the formation with sufficient accuracy using seismic mapping.*"

CO_2 sequestration at In-Salah

The In Salah CO_2 storage project at the gas-producing Krechba field in Algeria involved the injection of nearly 4 Mt of CO_2 into three wells between 2004 and 2011. The CO_2 was injected into the gas reservoir at around 1.9 km in depth. The site was chosen in part due to the thickness of caprock favourable for CO_2 storage. However, the porosity and permeability of the storage rocks were low, relative to other large-scale projects. There was no commercial incentive for CO_2 sequestration at In Salah, with an estimated $100 million (€93 million) cost to store the CO_2, and $30 million (€28 million) spent on the associated monitoring project. [121] This translates roughly as a cost to the operators of $30 (€28) per tonne of CO_2 stored.

A seismicity study at the site observed deformation of up to several centimetres above the injection wells, and added to previous work, that had concluded that CO_2 injection had activated a deep fracture zone near to one of the injection sites. This was several hundred metres wide and extended about 150m above the reservoir. The study found evidence that pre-existing fractures were opening in close proximity to the injection well during periods of high CO_2 injection rates, but that the injected CO2 was being confined to the fracture zone in the reservoir, rather than creating or reactivating shallower fractures and creating pathways for CO_2 to migrate to the surface.

There was also an indication that the fractures were closing as injection pressure reduced, and that the rate of seismic events dropped quickly after injection had stopped. The authors concluded that

"*It is reassuring to operators if seismicity can be controlled in this way*". [122]

Another study confirmed that:

"*It is clear that CO_2 injection has stimulated natural fractures at this location, and may have introduced new hydraulic fractures.*"

Despite the fact that the fractures had extended into the lower caprock, the report authors stated:

"*no leakage has been observed and all indications are that the CO_2 remains safely contained within the storage complex.*" [123]

To summarise, apparent early success appears to have been based not on understanding and control of the process by operators, but rather on pure luck. However, their "luck" did not last. An additional cause for concern at In Salah was leakage through old wells, especially since a lack of well integrity has long been recognised as the most likely leakage path at such storage sites. The closest, old or legacy well, to the injected CO_2 plume at In Salah was drilled in 1980. Satellite monitoring showed that the CO_2 plume from one of the injection wells was moving quickly towards it. When CO_2 arrived at the old well, it quickly migrated up it to the surface, and was detected by a leak through a valve. Less than a tonne of CO_2 was estimated to have leaked, and the leak was stopped the day after its discovery, with the well subsequently being fully decommissioned. [124] CO_2 injection was also stopped, until the old well had been fully decommissioned. [125]

The In Salah case highlights, in particular, how quickly CO_2 can migrate to the surface through old wells, especially in heavily explored oil and gas fields, and indeed how expensive CO_2 sequestration can be without the added financial incentive of Enhanced Oil Recovery (discussed further below).

Conclusion

The three case studies outlined above show how all of the predicted and most likely leakage paths for CO_2 sequestered in geological formations, have proved to be substantial issues in practice. At Weyburn, the potential for leakage through fractures and the many old wells punctuating the injection area has been hotly contested by industry and academia, which has resulted in no definitive answers. At Sleipner, serious questions have been raised about the level of understanding of the formation being used to sequester CO_2, and if the behaviour of CO_2 plumes is understood clearly enough, to justify the practice. At In Salah, CO_2 injection has been shown to increase seismic activity, as well as being a clear example of how quickly CO_2 can escape through old wells when it comes into contact with them.

A final issue is the monitoring of storage sites, and whether monitoring is in fact effective and reliable. Fundamentally, CO_2 must be stored underground on geological timescales – i.e. thousands of years. But monitoring of storage sites can only take place concurrently with CO_2 injection. Furthermore, the highly unpredictable nature of the movement of CO_2 in geological formations, and its effects on the surrounding features, even in the best understood and explored formations, has already been highlighted many times.

The CCS industry and academia are quick to jump on any studies or reports that question the long-term ability of geological formations to effectively sequester CO_2, there is therefore a danger that important data is not getting published, and claims that CO_2 storage is safe over long timescales, are going unchallenged.

Making money from captured carbon: Enhanced Oil Recovery

How EOR increases oil recovery

When a new oil field is first drilled, underground pressure in the oil reservoir forces oil to the surface. During this early stage, net energy gains from oil recovery are greatest. When 5-15% of the oil in a reservoir has been exploited, underground pressure drops to make this ‘primary recovery’ impossible. Once this happens, water is injected into the reservoir to create the necessary pressure and pumps may be used to recover the oil – a process that requires significant energy. This ‘secondary recovery’ stage works until around 35-45% of the reservoir is depleted. At that stage, pumping oil from the reservoirs becomes reliant on enhanced oil recovery (EOR). There are different EOR methods: Energy intensive injection of steam, in-situ burning of some of the oil in the reservoir to heat the surrounding oil, injection of detergents, microbial treatments (not widely used), and gas injections, including the use of natural gas, nitrogen and pure CO_2.

CO_2 injections reduce the viscosity of oil when they mix, and allow the oil to flow more freely. If oil companies can obtain cheap sources of pure CO_2 then CO_2 flooding is the favoured approach. This is highlighted by the fact that gas injections account for nearly 60% of US EOR projects, [126] and by the Oil and Gas Journal's 2014 EOR survey which describes

“*...CO_2's domination in current EOR projects as compared to steam injection.*” [127]

For the purpose of this report, we will refer to EOR as being synonymous with CO_2 flooding.

EOR currently allows a further 5-15% of oil in a reservoir to the exploited, which is equivalent to all ‘primary recovery’, or all of the easily recovered oil. This is therefore highly significant for overall oil production, and especially so in in regions such as the US where oil reservoirs are too depleted to allow for easier recovery methods.

Global use of EOR

EOR has been used since 1972, long before Carbon Capture and Storage was first proposed. With the advent of CCS, commercial use of captured CO_2 in EOR is has become widely seen as the main solution to offsetting the high costs of carbon capture and making it economically viable, especially in North America. In 2014 there were 136 CO_2 EOR projects in the US, producing some 300,000 barrels of oil per day. 175,000 tonnes of CO_2 was being used per day; 80% of which was sourced from natural CO_2 reserves, while the remaining 20% was sourced from industrial carbon capture. [128] In 2014, total onshore oil production was around 9 million barrels per day, 3.4% of that was extracted utilising EOR. [129]

This represents a considerable contribution to overall oil extraction, and it is claimed by the industry that vastly more oil could be accessed with adequate and cheap supplies of CO_2. The growth of oil production from EOR has been constrained in recent years, due to a lack of accessible and affordable supplies of CO_2. [130]

EOR is an important component of today's oil production in North America and, as far as the oil industry is concerned, it also has great potential to further expand production. An analysis commissioned by the US Department of Energy in 2014 projected potential oil resources recoverable with EOR could be up to 137 billion barrels, with 67 billion barrels economically recoverable at a price of $85 a barrel. These figures represent more than three times the current proven reserves in the US.

While the first ever EOR project used CO_2 separated from natural gas processing, most of the CO_2 used for EOR has come from natural reservoirs. These reservoirs are mostly found in the US, and have formed in geological formations similar to ones that contain oil and natural gas. However, the high cost of transporting and injecting CO_2 from the limited number of these reservoirs has restricted the use of EOR. Capturing 'anthropogenic CO_2' is thus of great interest to the oil industry, given that it would allow for CO_2 to be captured at more locations (keeping transport costs down), as well as offering the prospect of that CO_2 being available at low costs, thanks to government financial support for CCS.

The cheapest supplies of anthropogenic CO_2 can be obtained from capturing almost pure CO_2 streams, including from ethanol refineries. Carbon capture from power stations provides the largest potential source of CO_2, but that, as this report shows, it is a very long way from becoming technically and economically viable at commercial scale.

Carbon capture for EOR is thus being driven very much by the quest to exploit more oil from partially depleted reservoirs which requires a large continuous stream of cheap CO_2.

Another potential market for CO_2 streams from carbon capture is coal bed methane extraction with CO_2, which is also being explored. The rhetoric about carbon capture as a "*solution to climate change*" appears to be a prevalent PR strategy, mainly benefitting the oil industry in terms of providing false assurances that fossil fuels can continue to be used with impunity; as long as carbon capture is employed. Such a focus serves to meet the needs of oil companies as it promotes the supply of cheap CO_2 to enhanced oil and (potentially) gas extraction.

However, two caveats need to be made regarding the oil industry's interest in purchasing for CO_2 EOR:

Firstly, oil companies have only ever invested in EOR schemes using relatively cheap CO_2 sources and only ones located close to oil fields. Nearly all EOR involves oil fields under North American land areas. Transporting CO_2 to offshore oil fields, for example in the North Sea would be much costlier and there has been no meaningful commercial interest in doing so.

Secondly, in the current economic climate of low oil prices, oil companies are very reluctant to invest in new EOR schemes at all. Oil prices fell by 61% between June 2014 and November 2015 and many analysts believe they may fall further. [131] Most oil companies have reacted by slashing investment in order to protect dividends, even if this means sacrificing future oil production. [132] EOR projects are amongst many other oil industry investments that are being cut. [133]

How much CO_2 stays underground?

In order for EOR to work, a significant proportion of the injected CO_2 has to mix with the oil and is therefore brought back out of the well and onto the surface again. [134] CO_2 mixed with oil is then separated out, and can be re-injected. Separation is, however, an energy and hence carbon intensive process.

Various industry reports state that between one half and two thirds of the injected CO_2 returns back to the surface mixed with the produced oil. They claim that it is then separated once more and re-injected to minimise operating costs. [135] In theory, all of it could be re-injected to remain in the oil reservoir. In reality, CO_2 can escape into the atmosphere during various parts of the process, such as; leakage during transport (usually by pipeline), losses during maintenance related venting, unplanned, fugitive emissions from CO_2 returned through production wells, as well as potential leakage from the wells themselves. Oil industry estimates of onsite emissions of CO_2 from EOR projects are around 0.3 tonnes per tonne of CO_2

brought to the site. This means that 30% of the CO_2 piped to the EOR site will be directly emitted back into the atmosphere – even long-term secure storage of the remainder could be guaranteed. [136]

Typical values of oil recovery from CO_2 injection range between 1.1 and 5 barrels of oil for every tonne of CO_2 injected, although 1.1 is well below the amount typically assumed by industry. This means that significant volumes of oil become accessible through EOR, and therefore, that CO_2 injection is responsible for significant additional emissions from the oil produced and burned as a consequence of EOR.

A study looking at the life-cycle inventory of EOR emissions [137] calculated that between 3.7 and 4.7 tonnes of CO_2 are emitted for every tonne of CO_2 injected, and that active EOR fields currently inject and sequester less than 0.2 tonnes of CO_2 per barrel of oil produced. Therefore, in order to entirely offset the total emissions from the process, 0.62 tonnes of CO_2 would need to be injected and permanently sequestered for every barrel of oil produced. The authors of the study state that this could not be achieved with EOR operations alone, and that including all life cycle stages in the EOR process results in significant net emissions.

Another look at the Bounday Dam CCS project: How CCS with EOR increases emissions

SaskPower's Boundary Dam has been discussed above. The energy company had decided to proceed with its CCS project after entering into a 10-year agreement with Cenovus Energy the supply of CO_2 for Cenovus's EOR operation in the Weyburn oil field in Saskatchewan. Cenovus subsequently built a 66km pipeline from the power station to Weyburn. [138]

SaskPower claims that the power station is:

"capable of reducing greenhouse gas emissions by one million tonnes of carbon dioxide (CO_2) each year, the equivalent of taking more than 250,000 cars off Saskatchewan roads annually."

As has already been discussed, the Boundary Dam has been capturing far less carbon than originally intended. But would it have achieved such emissions reductions if had operated as intended?

The answer is no. SaskPower's claim rests entirely on the assumption that all of the captured CO_2 stays underground once injected, and that the emissions caused by the extra oil that is pumped out by Cenovus, are not the responsibility of the company or its power station.

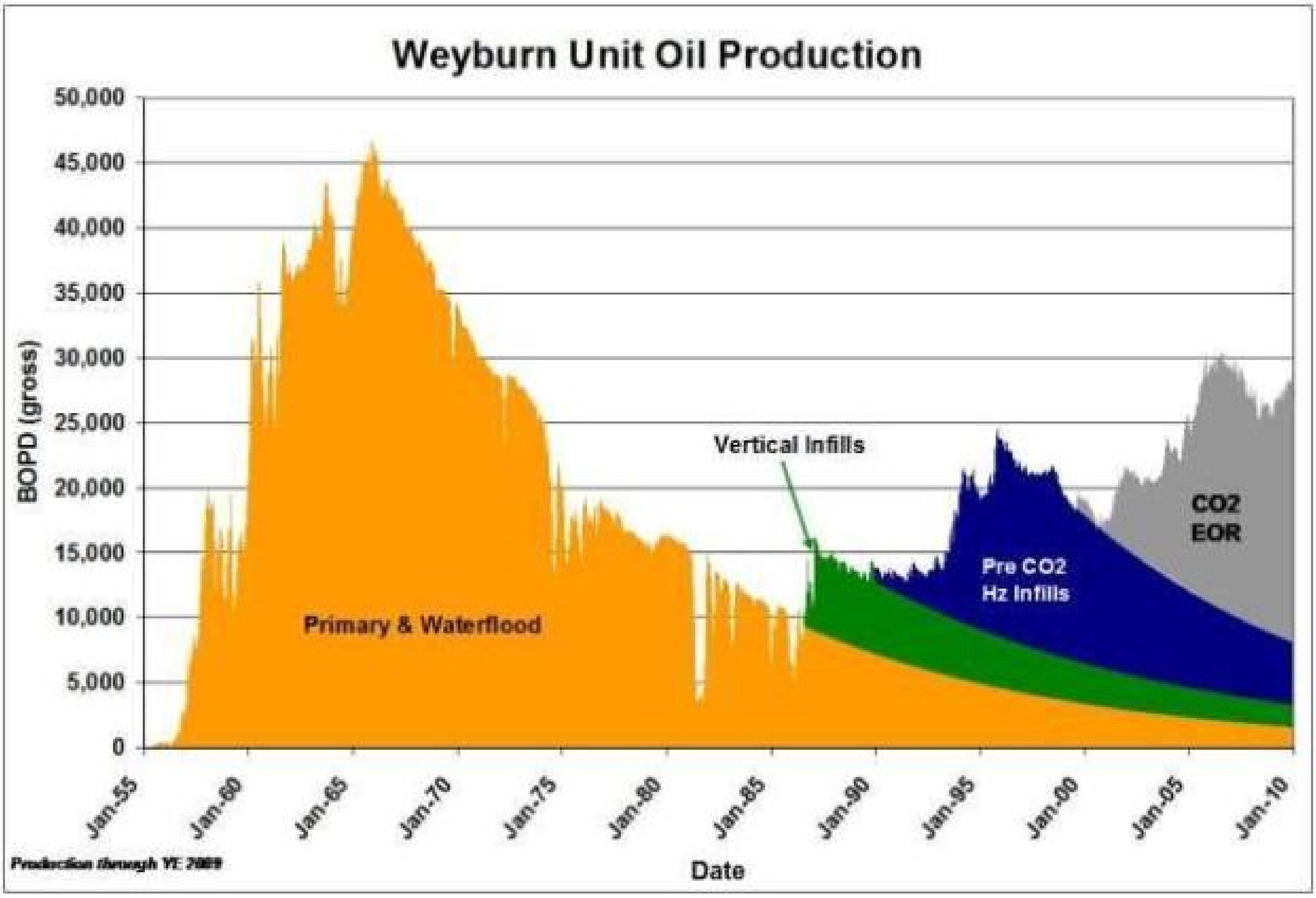
The Boundary Dam is supposed to generate 1.1 million tonnes of CO_2 a year, with 100,000 tonnes directly vented to the atmosphere, and the remainder captured. An analysis commissioned and published by Community Wind Saskatchewan [139] showed that there is an additional loss of around 300,000 tonnes a year of CO_2, in Cenovus Energy's processing of the CO_2 and crude oil mix, subsequent to EOR. That's around 400,000 tonnes of CO_2 lost to the atmosphere already.

Furthermore, the Boundary Dam's CO_2 is used to significantly boost oil production at the Weyburn field. Production at Weyburn peaked in the late 1960's prior to a sharp decline, which continued through to the late eighties. At that time the decline was halted and partially offset by infill drilling, water injection, and CO_2 injection. [140] [141]

Each tonne of CO_2 injected into the Weyburn field increases oil production by two to three barrels of crude oil, [142] with the Weyburn field currently producing about 16,000 barrels of oil per day. [143] One barrel of oil produces around 0.43 tonnes of CO_2 emissions when burnt. [144] If 1 million tonnes of CO_2 were to be piped to Cenovus for injection in one year, this would represent around 2.5 million barrels of oil produced, or 1.1 million tonnes of additional CO_2 emissions. The extra emissions from this oil production are, however, conveniently ignored by SaskPower.

When all emission source are considered, it becomes clear, that in reality, the Boundary Dam facility in no way decreases emissions, but rather increases them substantially. Whilst some 0.7 million tonnes of CO_2 may remain underground after injection in a year, around 1.5 million tonnes of CO_2 emissions will have been created during the overall process. That's not the equivalent of taking a quarter of a million cars off the roads, it's more like adding that many to the roads!

SaskPower are therefore misrepresenting the reality of the Boundary Dam's carbon impacts, and are selling this technology as beneficial, when it is in fact the opposite. Sadly, they can get away with such claims partly because the IPCC has classed EOR as a form of Carbon Storage, including it into climate mitigation scenarios despite the fact that, when considered on a life-cycle basis, it can increase rather than reduce carbon emissions.



Weyburn is one of the largest oil fields in Canada. This graph shows how oil recovery has been aided by CO_2 injection. Cenovus Energy Inc.

Turning captured carbon into 'useful products'

Hundreds of millions of dollars and Euros in public funds have been spent on developing 'useful products' made from captured CO_2. The German government made €100million available from 2010 to 2015 for research and development into of the material use of CO_2. [145] The US Department of Energy has made some of the $6 billion (€5.57 billion) funding for CCS Research and Development available for uses of captured CO_2, [146] and other governments, especially in Canada and Australia, have made further funds available.

Most of those uses cannot possibly be described as 'sequestration', or as potentially 'carbon negative'. For example, significant funds are going into feeding algae and bacteria with CO_2 rich exhaust gases so that they convert the CO_2 into biofuels. Of course it is then released into the atmosphere again as soon as the biofuels are burned – but that does not prevent companies and other proponents from describing those concepts as BECCS.

Biofuels made from algae & cyanobacteria [xiii] fed on CO_2-rich exhaust gases

After several decades and millions of dollars in government subsidies, commercial scale production of algae biofuels remains elusive. Many algae start-up companies are turning to production of other more profitable non-fuel products ranging from human and animal feeds to cosmetics, nutraceuticals and even drilling lubricants.

With the recent rising prominence of BECCS, algae enthusiasts point to the basic fact that microalgae absorb and require CO_2 for growth and some have jumped onto the bandwagon on BECCS, claiming that the processes they strive to develop would fit into the model of 'carbon negative bioenergy' - despite the fact that the captured CO_2 is to be burned and emitted again. For example, the Director of the US-based Algae Biomass Organization claims:

"*Capturing carbon from combustion of biogenic carbon does indeed provide a double carbon benefit to the atmosphere. But the best bang for the buck is delivered when, as in the case of algae-based carbon capture and utilization (CCU), that captured carbon is reused to produce yet more energy that substitutes for fossil fuels. Such a bioenergy with carbon capture and utilization approach (which I here christen BECCU) is a triple play for climate, absorbing carbon upstream, avoiding emissions at the power plant, and keeping fossil carbon stored for all time by substituting algae-based alternatives for fossil-derived fuels.*" [147]

The Algae Biomass Association in fact lobbied for and won support for "CO_2 utilization" as a viable approach under the Obama administrations "Clean Power Plan". Their success means that under the Clean Power Plan, states might claim to be reducing emissions from power generation by hooking up algae biofuel production facilities to the flue gas output of a coal, gas or other CO_2 emitting industrial plant. That is, if it works.

[xiii] Biofuels produced by cyanobacteria are generally referred to as 'algal biofuels'. Cyanobacteria are photosynthetic bacteria which live in water. They are responsible for many so-called 'algal blooms'. However, they are biologically different from algae.

To date there are no commercial facilities in operation, though millions of dollars have been spent on proof of concept trials many of which appear to have had little tangible results. Problems with the technology include:

The fact that algae are sensitive to some of the pollutants commonly found in flue gas emissions, including sulphur. It is therefore only theoretically applicable for some facilities, depending on the pollution controls that are in place, and fuel characteristics;

The fact that when algae are grown in open ponds, up to 40% are consumed by other microbes and by larger organisms and that strains which performs well for biofuel production can easily be outcompeted by other strains which can enter the ponds and which are less suitable for making biofuels; [148]

The fact that when algae are grown inside contained reactors, significant energy is needed to keep them at the correct temperature and to constantly adjust the growing conditions.

Much of the research into algal biofuels involves genetic engineering, with unknown but potentially very serious ecological consequences.

Just one company, LanzaTech, claims to be producing biofuels from CO_2-rich flue gases although they use bacteria that are not found in water. Lanza Tech's existing pilot and demonstration plants are based in China and Taiwan and there is no independent published information by which to judge their success.

A significant number of algal biofuels ventures, however have failed and none have achieved any commercial success.

Other companies are looking to use captured CO_2 utilisation projects for different short-term products such as bioplastics, bleach [149] or even fracking fluids. [150] A project led by the chemical corporation BASF for example has received €2.2 million in German government funding for trying to turn CO_2 and two different chemicals into sodium acrylate, a chemical used in nappies. [151] Another German-government funded projects saw Bayer (another chemical corporation) attempt to use CO_2 captured from a small carbon capture pilot project which linked to a coal power station owned by the energy corporation RWE [152] - this time for use in foam mattresses. And, as we have seen above CO_2 captured from some ethanol plants is captured and sold for fizzy drinks, dry ice and possibly bicarbonate of soda.

Some projects involve trying to incorporate CO_2 into more durable products – especially cement. These are not BECCS projects but, if successful, they could in theory use CO_2 captured from any power plant or industrial process – and especially from conventional ethanol fermentation.

Carbon-negative cement?

Cement production worldwide is responsible for around 2 billion tonnes of CO_2 emissions a year, both from the fuels burned to provide energy and as a result of the basic chemical process involved (calcination of limestone). [153] Incorporating captured CO_2 is one of the lines of research.

An article by Berkeley Energy & Resources Collaborative (based at Berkeley University in California) published in May 2015 was entitled "Carbon Negative Cement: Turning a Climate Liability into an Asset" – but it concluded that "none of these technologies is ready for mass market".

One of the companies involved is Calera Corporation, who obtained a $21.58 million (€20.10 million) grant from the US Department of Energy. This was for a small pilot project which involved that capturing some CO_2 from a gas power station and bubbling it through seawater so that magnesium hydroxide contained in the water reacts with carbon dioxide to form carbonates, used to make cement. [154] According to Calera, producing a tonne of concrete (which is made of cement as well as sand, gravel or crushed stones) would normally emit a tonne of CO_2 – but with their method, it would emit none and instead bind half a tonne of CO_2 captured from a power plant. [155] Ken Caldeira from the Carnegie Institute for Science was the first to publicly challenge Calera's claims, calling them "*backwards to the chemistry the rest of the world is accustomed to*". That chemistry, he pointed out, would require an alkaline to be added to the process Calera were describing. Calera's response revealed that they were indeed relying on alkalines such as sodium hydroxide, which are very energy-intensive to produce. Chemist Jerry Unruh [156] suggested that Calera's process would require significantly more energy than could be provided from the waste heat of power stations from which CO_2 was to be captured. He cited figures from a Calera patent application suggesting that 2.7 kWh of electricity would be required to produce enough sodium hydroxide in order to capture the CO_2 from 1 kWh of electricity. Calera, it seems, may not have found a route to 'carbon negative cement' after all.

Another start-up company, CarbonCure, has obtained a C$1.2 million (€840,000) grant from the Canadian federal government for directly adding CO_2 during the production of concrete, so that it forms carbonate ions which then react with calcium from cement to form a limestone-type material. CarbonCure works in collaboration with the global cement and aggregates corporation Lafarge. Their sister company Carbon Sense Solutions (who appear to have been taken over by CarbonCure), had obtained an undisclosed sum of funding from the Nova Scotia government for the same technology. [157]

Carbon Cure has entered into supply contract with various cement companies and they appear to be more successful commercially than other companies seeking to turn captured CO_2 into concrete. Unlike Calera, they do not claim that their technology renders cement production 'carbon negative'; they merely say that it reduces CO_2 emissions from cement production by up to 20%. [158] Nor do they invest in capturing CO_2: Although their promotional video shows carbon being captured from a power station smokestack and being used to reduce emissions from a cement plant, [159] they are actually purchasing it from a French company, Air Liquide. This is the same company that is purchasing and selling some CO_2 from certain ethanol refineries, although there are no indications that any of this is going to CarbonCure. Most of their CO_2 is captured from chemical industry processes which lend themselves to relatively cheap and easy carbon capture. [160] Using CO_2 captured from power stations render Carbon Capture's products more expensive.

CarbonCure's concrete appears to be the only CO_2 utilisation project which involves a durable product and appears to be technically and economically credible – though likely only with relatively cheap CO_2 sources, such as from ethanol fermentation. There are good reasons for being sceptical about CarbonCure's claims that their technology reduces carbon emissions from concrete production by up to 20%: The life-cycle assessments they present do not seem to account for carbon emissions associated with capturing and liquefying the CO_2. [161] Without those figures, it remains uncertain whether or to what extend Carbon Cure's technology reduces emissions at all. [xiv]

[xiv] Biofuelwatch sent a written query about this to CarbonCure but at the time of finalising this report has not received a response.

Technology: The missing piece in the debate about BECCS

In January 2015, researchers from the Tyndall Centre for Climate Research convened a workshop on BECCS in London for 18 'experts' drawn from industry, government, NGOs and, above all, academia. Participants were ask to comment on a range of different questions about BECCS and to indicate where they saw the greatest or the least uncertainties and risks. [162]

Concerns were raised about the impacts of bioenergy use at the very large scale that would be required for a meaningful BECCS programme, about whether a large-scale BECCS industry could deliver negative emissions, and above all about the implications of the land-use change required. Whether or not the technologies actually work and are viable, was not called into question:

"*The three key assumptions relating to CCS all broadly relate to technical aspects of the technology and the scoring reflects that there are not considered to be significant technical barriers to delivering CCS as a mitigation approach….There should be no technological show stoppers*".

Given that there has never been a successful CCS power station and that there is no evidence that anyone has ever managed to generate any energy at all from advanced biofuel production, let alone tried to capture carbon from it, such faith in the technology seems to be highly naïve, at best. Yet the 18 'experts' views are on part with the focus of virtually all peer-reviewed studies about BECCS.

For example, a peer-reviewed study about BECCS, published in 2017 [163] brushed off any questions about the viability of BECCS technologies, claiming:

"*While there are some technical constraints in running (BE)CCS plants over conventional fossil fuel plants, these issues seem not to be of overriding importance.*"

Similarly, a peer-reviewed commentary on BECCS, published in Nature Climate Change in 2014, [164] identified four uncertainties that would need to be resolved:

"*(1) the physical constraints on BECCS, including sustainability of large-scale deployment relative to other land and biomass needs, such as food security and biodiversity conservation, and the presence of safe, long-term storage capacity for carbon; (2) the response of natural land and ocean carbon sinks to negative emissions; (3) the costs and financing of an untested technology; and (4) socio-institutional barriers, such as public acceptance of new technologies and the related deployment policies.*"

The viability of what, after all, is acknowledged to be an 'untested technology' is not questioned. As for cost, the authors simply point to studies, including the 2014 IPCC report, which state that climate change mitigation would be more costly without 'negative emissions'. Yet the total lack of experience with BECCS technologies means that potential costs cannot be known. It would seem difficult to imagine a more expensive way of trying to mitigate climate than using BECCS if, for example, such plants built in future turned out to be as expensive as the Kemper County coal CCS project, i.e. if it cost some €6 billion for just over half a gigawatt of power station capacity. And since no commercial-scale power plant has ever been successfully run with CCS, one cannot credibly predict whether such plants could indeed operate smoothly in future. Furthermore, the authors of this article in Natura Climate Change, as well as authors of other BECCS studies, take it for granted that all CO_2 once pumped into an underground reservoir will safely remain there forever – another highly questionable assumption, as we have seen above.

Concluding reflections: The pseudo-science about BECCS

While we were working on this report, Indonesia's forests and peatlands were in flames in what an independent researcher has called *"the biggest environmental crime of the 21st century"* [165] and what the Indonesian meteorological institute has described as "a crime against humanity of extraordinary proportions". [166] Between July and October, around 100,000 fires had been recorded across Indonesian Borneo, Sumatra and on West Papua, more than half of them on peat. [167] Over two million hectares have been reduced to ashes, [168] including in national parks and in forests which had been the last refuges for endangered species such as orangutans. Indonesia's peatlands hold billions of tonnes of carbon and according to an initial estimate, over 1.75 billion tonnes of CO_2 [xv] will have been emitted by the end of the year as a results of the 2015 peat fires. [169] This is far more than the annual CO_2 emissions of Germany or Japan. Smoke inhalation has affected 48 million people and at least 500,000 cases of acute respiratory infection have been reported on just two of the three affected islands.

The ferocity of this year's fires is linked to an extreme El Niño event: El Niño is the warm phase of a natural pattern which sees the tropical eastern Pacific Ocean warm and cool irregularly over several years. El Niño years see higher global temperatures and bring droughts and flooding to different regions – in Indonesia, they are dry years. Climate change has turned El Niño years into 'record heat years', due to the background rise in global temperature. It is making extreme weather events more extreme still [170] and it may be making El Niño events themselves more frequent. [171] Climate change may well have contributed to the intensity of the 2015 fires, but most of the fires are being set deliberately to clear land, especially for pulpwood and oil palm plantations. Satellite images from the early weeks, showed that most of the fires of the fires were concentrated in the region with the highest palm oil concessions in Indonesia. [172] Oil palm and pulpwood plantation companies have for decades been digging drainage canals across peatlands, drying the peat up and thus making it easily flammable.

Why discuss Indonesia's peat fires in a report about BECCS? BECCS after all, remains no more than a proposal and, as we have seen, one most unlikely to ever become a reality.

Yet the fires in Indonesia are a horrifying illustration of all that is wrong with the idea that incentivising large-scale bioenergy, provided basic sustainability standards are written into law, will result in carbon neutral or at least very low carbon energy. This same idea, which also underlies the concept of BECCS, has been the rationale for bioenergy policies in the EU, North America and elsewhere. The basic premise behind all those policies and policy recommendations (including those emerging in the BECCS debate) is that we can sustainably convert vast areas of land to bioenergy crops and trees as well as remove huge quantities of agricultural and forestry residues from soils without emitting much or any carbon.

The EU's and other countries' policies to promote the use of biofuels and wood-based biomass have relied on the very same body of academic studies about the global 'sustainable biomass potential' which the IPCC and other bodies are citing in relation to BECCS.

[xv] This figure is for "CO_2 equivalents" and includes methane and nitrous oxide emissions from the fires.

EU biofuel policies, which were legitimised by 'sustainable biomass potential' studies, clearly bear some of the responsibility for the catastrophe in Indonesia: In recent years, Indonesia's rate of deforestation has shot up to become the world's highest, [173] and a 2013 mapping analysis by Greenpeace identified palm oil as the single biggest driver. [174] EU imports of palm oil for biofuels from Southeast Asia rose 365% between 2006 and 2012, accounting for 80% of the overall increase in EU palm oil imports for all purposes combined. [175]

A 2011 report published by the UN Food and Agriculture Organisation [176] showed that rising vegetable oil (including palm oil) prices in the late 2010s were driven primarily by the demand for biofuels. High palm oil prices and confidence in a growing market are prime incentives for plantation companies eager to clear more forests and drain ever more peat for new plantations – regardless of the cost to the climate, to biodiversity and to public health.

Although EU biofuels standards in theory 'prohibit' biofuels sourced through new deforestation or peat clearance from being subsidised or counted towards renewable energy targets, there is no evidence that those standards have ever been enforced. Even if they were, companies could easily sell palm oil destined for biofuels, from older plantations, linked to past, rather than new deforestation, and in turn burn more peat forests in order to establish new plantations to serve the existing markets. Nobody can say what proportion of this year's fires was due to biofuels, but even a minor share of the overall responsibility for the fires could translate into carbon emissions many times higher than those the EU officially set out to 'save' through biofuel use.

Indonesia's fires have by no means been the only disastrous impact of EU biofuel and wider bioenergy policies. [177] Yet, so far evidence of the real-world impacts of industrial bioenergy has failed to cause leading researchers and institutions to question the credibility of the academic conclusions about the potential for large-scale 'sustainable biomass' on which the policies were based. The IPCC has described a possible future increase in 'modern bioenergy' by 550% from current figures as their 'limited bioenergy' scenario. [178] In the same report, they included scenarios according to which BECCS could remove up to 5.45 billion tonnes of carbon (10 billion tonnes of CO_2) from the atmosphere every year. This would be the equivalent of 83% of both the existing global land and ocean carbon sinks combined.

Biofuelwatch's research into bioenergy and BECCS raises serious questions about the prevalent discourse on climate change mitigation, not just amongst policymakers but also amongst leading scientific institutions, including the IPCC. [xvi]

Why is the underlying premise of a large potential for sustainable, low or zero carbon bioenergy not being questioned when there is so much evidence that bioenergy policies meant to realise this assumed potential are contributing to environmental destruction and increased carbon emissions including, at least indirectly, from Indonesia's burning forests and peatlands?

Why do so many studies about the potential for 'sustainable bioenergy' (including for the purpose of BECCS) rely on sustainability standards as a supposedly credible key tool? Why could we not find a single study which attempts to test the hypothesis that sustainability standards can be effective against real-world evidence, in particular against the EU's mandatory biofuel sustainability and greenhouse gas standards, introduced in 2010? Robust testing of hypothesis against evidence lies at the heart of what is known as the 'scientific method' after all.

As this report shows, many other claims made about BECCS and other agencies, such as the IEA, appear far removed from any 'real world evidence' and critical examination.

For example, various studies state that BECCS is a cost-effective way of mitigating climate change, [179] as if this was a fact, even though none of the proposed BECCS technologies (except for a small amount of CO_2 capture from ethanol refining for sequestration and

[xvi] When discussing the IPCC in this context, it is important to be aware that there are three working groups: Working Group 1, which looks at the science of climate change is dominated, quite appropriately, by climate scientists. Working Group 3, which publishes the reports about climate change mitigation and adaptation, on the other hand, is dominated by economists, environmental managers and engineers. All references to the IPCC in this report refer to Working Group 3.

Enhanced Oil Recovery purposes) have ever been implemented, not even on a very small scale. [xvii]

Policy makers are being misled about the 'potential' for using bioenergy to scrub CO_2 from the atmosphere – and thus into believing that we can continue to burn fossil fuels, continue to achieve economic growth and yet still avoid the worst impacts of climate change. Some of those creating false hopes about BECCS are, predictably, fossil fuel companies such as Shell. However, the IPCC, the IEA and various academic institutes share some of the responsibility for such poor advice being given to governments and anybody else involved in developing climate-mitigation policies.

The IPCC's conclusion on BECCS and climate change mitigation are particularly disappointing in this context: The IPCC has for years played a vital role in defending the scientific consensus on climate change, [180] by demonstrating that that this is a real scientific consensus based on a wealth of empirical evidence against which models have been tested again and again.

Studies which portent to 'prove' that we can draw carbon out of the air with BECCS or other 'negative emissions technologies', by comparison, generally rely on computer-based models and untested assumptions rather than solid empirical data.

Questions as to whether different BECCS technologies are feasible are rarely explored in studies, and research into the safety of CO_2 storage is so closely linked to industry interests that much of it cannot be regarded as remotely independent.

In short, it appears that claims about BECCS – like other 'negative emissions technologies' are based on pseudo-science, coupled with corporate lobbying.

Even if BECCS may never become a reality, the claims about it are highly dangerous: Whether before or after the Climate Conference in Paris, we can ill afford false assurances about ways of removing carbon from the atmosphere – and we can ill-afford false assurances about the possibility of very large-scale industrial bioenergy either.

[xvii] As discussed below, ADM's capture of CO2 from ethanol fermentation at their Decatur plant has been referred to as BECCS by BECCS proponents, however we do not class it this way because ADM themselves do not consider the refinery to be 'carbon negative' since the fossil-fuel carbon emissions associated with their refinery exceed the amount of CO2 captured.