April 2016

A report by Biofuelwatch, in cooperation with Heinrich Böll Foundation

biofuelwatch

HEINRICH BÖLL STIFTUNG

Last-ditch climate option or wishful thinking?

Bioenergy with Carbon Capture and Storage

Report Authors: Almuth Ernsting & Oliver Munnion **Editor:** Rachel Smolker

Download the full report: **http://www.biofuelwatch.org.uk/2015/beccs-report/**

Contents

2 What is BECCS?
3 A necessary technology? The IPCC and BECCS
4 BECCS after the Paris COP
5 Removing carbon from the atmosphere to stabilise the climate: from BECCS to Carbon-Sucking Aliens
5 Does the concept of carbon-negative bioenergy make sense?
7 Could large-scale, climate friendly and sustainable bioenergy ever be possible?
8 Do BECCS technologies exist and are they scalable?
8 What technologies are proposed for BECCS?
11 Can we trust that sequestered CO_2 will stay put?
13 Making money from captured carbon: Enhanced Oil Recovery
15 Turning captured carbon into 'useful products'
16 Technology: The missing piece in the debate about BECCS
16 Concluding reflections: The pseudo-science around BECCS
19 References
20 BECCS Infographic

Preface

News about climate change is going from bad to worse: Last October, global warming breached the 1°C temperature rise barrier and has stayed above it for six months running. Carbon levels in the atmosphere are anything but safe and it is hardly surprising that the International Panel on Climate Change (IPCC) has been seriously looking at 'negative emissions', i.e. at ways of taking carbon already emitted out of the atmosphere again. But, as this report on Bioenergy with Carbon Capture and Storage (BECCS) shows, there is a dangerous trend to use the urgency of the climate crisis to justify unproven and potentially dangerous technological 'solutions'. One of the most hyped proposals for removing carbon from the atmosphere is BECCS, which would involve a massive global upscaling of bioenergy use, with CO_2 being captured from biomass combustion or biofuel production and then sequestered underground. According to the IPCC's latest report in 2014, most of their models and scenarios 'proved' that BECCS will be necessary for keeping global warming to within 2°C. Those who ran the models, however, simply input figures that assume that BECCS would indeed be carbon negative, without reviewing actual evidence about the technology – a circular argument.

This report summarises the key evidence that must be considered about BECCS. It looks at the overwhelmingly destructive impacts of existing large-scale bioenergy production and use and the implications of massively scaling it up, as would be required for a global BECCS programme. It examines the different technologies proposed for BECCS and shows them to be unproven, highly complex and thus failure-prone, and extremely costly. It also looks at evidence which shows carbon sequestration in geological reservoirs to be far less reliable than had been widely presumed. As the report concludes, BECCS is a dangerous diversion from the urgent and meaningful responses that the climate crisis requires.

What is BECCS?

BECCS is the proposed combination of bioenergy with carbon capture and storage (CCS), involving three steps:

• Bioenergy production: This can refer to a biofuel refinery or to a power plant burning biomass to generate electricity, or electricity plus heat, or a power station burning coal in combination with biomass, (in which case only the proportion of carbon captured from biomass would be classed as BECCS);

• Carbon capture from this refinery or power plant;

• Carbon storage in geological reservoirs: According to the International Panel on Climate Change (IPCC) [1] "storage" includes injecting captured CO_2 into geological reservoirs underground, as well as into partially depleted oil fields to force more oil from them (Enhanced Oil Recovery, or "EOR").

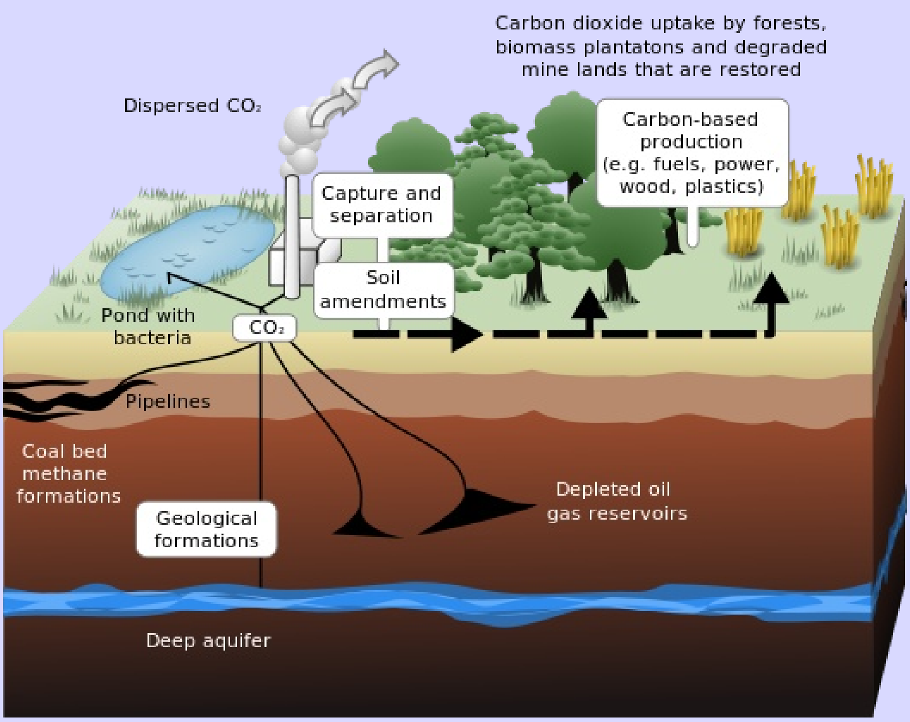
Research and development is also underway into using captured carbon to make various products, referred to as "carbon capture, utilization and storage" or "CCUS".

BECCS is commonly referred to as a 'negative emissions technology', based on the assumption that bioenergy is carbon neutral or very low carbon since all the carbon emitted from burning biomass will be taken up by new plant growth. It is suggested that capturing the CO_2 emitted from generating bioenergy and sequestering it will reduce the amount of CO_2 already in the atmosphere. This is a highly problematic concept because it implies that bioenergy can be virtually carbon neutral even when used on a large scale, that BECCS technologies work and are scalable, and that it can indeed remove and sequester carbon from the atmosphere.

BECCS remains a theoretical concept since no operational BECCS facilities exist anywhere in the world. There are only a small number of ethanol refineries from which some CO_2 is being captured – but these are not described as "carbon negative" operations, since it is openly recognized that the amount of CO_2 captured is smaller than the CO_2 emitted from burning fossil fuels to operate these refineries.

To prove that BECCS actually works, it would be necessary to show that 1) 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 and soil carbon losses, or from nitrogen fertiliser production and use; 2) that the technologies required for BECCS can operate reliably and 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 CO_2 can be securely and safely stored over very long periods.

As we show below, none of these has so far proven true.



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

[i] Pond with bacteria refers to the idea of cultivating (most likely) genetically engineered algae or cyanobacteria in ponds for biofuel production, and feeding them on CO_2 rich smokestack gases.

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 Assessment Report in 2014. According to their Synthesis Report, the great majority of "mitigation scenarios" which see global warming contained within 2°C involve emitting more CO_2 than is compatible with such a temperature limit in coming decades and then removing some of this CO_2 later this century through the use of BECCS as well as afforestation. The concept of emitting too much CO_2 and then removing some of it from the atmosphere is referred to as 'overshooting'.

On the one hand, the IPCC says that it is "highly confident" that we will need to use BECCS on a large scale from 2050 in order to keep global warming to 2°C. On the other hand, it acknowledges challenges and risks, and concedes that we don't know whether BECCS will actually become 'available' (i.e. viable), nor whether it can in fact be scaled up from being currently nonexistent, to fully effective and widely implemented. Elsewhere, the report acknowledges that BECCS has never actually been tested at scale. [2]

In short, we will need BECCS, yet it is a risky, unproven, currently nonexistent technology. Nobody knows if it will work. In fact a large and growing literature on the impacts of large scale bioenergy at the current relatively small scale, indicates that it cannot.

In 2007, the IPCC had called for new "Integrated Assessment Models" (IAMs), linked to *"Representative Concentration Pathways" to model emissions scenarios which would lead to different levels of global warming and represent different socio-economic pathways and technology choices. [3] The 'IAM' teams were asked to "explore alternative technological, socioeconomic, and policy futures including both reference (without explicit climate policy intervention) and climate policy scenarios"*. [4] 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 what does that actually mean? The standard was set extremely low: *"Scientifically peer-reviewed publication [even a single one, in any journal] is considered to be an implicit judgment of technical soundness"*.

The discrepancy between the high standard of 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. It stands in stark contrast even to their own approach to BECCS in 2007 when they concluded that there was only *"limited understanding of the technology"*.

The IPCC uses the term "high confidence" to report the finding that CO_2 emissions have lowered the ocean's pH, or that the Greenland ice sheet has lost some of its mass. Yet 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, a handful of questionable assessments of biomass availability, and incorrect assumptions about the climate impacts of bioenergy processes. Meanwhile, 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. [5] Instead of taking that body of literature into account, the IPCC appears to have simply lowered the standard of evidence.

An the context of the IPCC report, an Integrated Assessment Model (IAM) is a computer-aided model which combines modelling of physical climate change (i.e. forecasting temperature rises associated with different greenhouse gas concentrations) with modelling different policy and technology choices which would result in certain greenhouse gas concentrations and the likely range of warming associated with those. Modellers would thus assume that different technologies are 'high carbon', 'low carbon', 'zero carbon' and 'carbon negative' values and input the data accordingly.

As a result, IPCC conclusions about mitigation (upon which policies are based) rest precariously on the assumption that it is, or will be, possible to deliver negative emissions (i.e. to remove CO_2 from the atmosphere), mainly by using BECCS.

The fact that BECCS is indeed a dangerous distraction is immediately clear from the fact that "overshoot" is considered a manageable problem that can be later addressed. This further delays action, and provides fossil fuel industries with rationale to continue business as usual.

BECCS after the Paris COP

While not always referred to directly, BECCS is generally implicit in discussions where terms such as "net zero", "net negative" or "net neutral" emissions, are used – due to the fact that the IPCC has singled it out as the main such strategy. It is also discussed in the context of climate geoengineering as a featured technology for "carbon dioxide removal" (CDR). In the Paris Agreement, which was the outcome of the 2015 UN Framework Convention on Climate Change Conference of Parties, BECCS is not explicitly mentioned. There are, however, relevant references to the concept of 'negative emissions'. For example, Article 4 of the Annex states that Parties *"aim…to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century…"*.

The Paris Agreement further (II.21) *"invites the Intergovernmental Panel on Climate Change to provide a special report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways"*.

If this report presents BECCS as a viable carbon negative strategy, despite all the evidence to the contrary, it would create further impetus for companies trying to attract research and development funding as well as capital grants for BECCS projects. Even if the technologies might never become viable, governments including in the US have spent billions of dollars on ill-fated projects and technologies, including CCS projects (such as the failed Future Gen 2.0 and the failing Kemper County projects discussed below) and unsuccessful cellulosic and algal biofuel projects. [6]

Those funds should instead be directed to measures that are proven to genuinely reduce greenhouse gas emissions, such as energy efficiency, building and residential insulation and many others. The call for "negative emissions" has already spurred various initiatives to develop technologies, or at least to attract funding. The "Centre for Carbon Dioxide Removal", based at UC Berkeley, recently (April 2016) published a report "Philanthropy Beyond Carbon Neutrality". It calls on philanthropists to make 'near term grants for carbon removal' available, conflating proven and beneficial approaches such as agroecology with unproven and dangerous ones such as BECCS. [7]

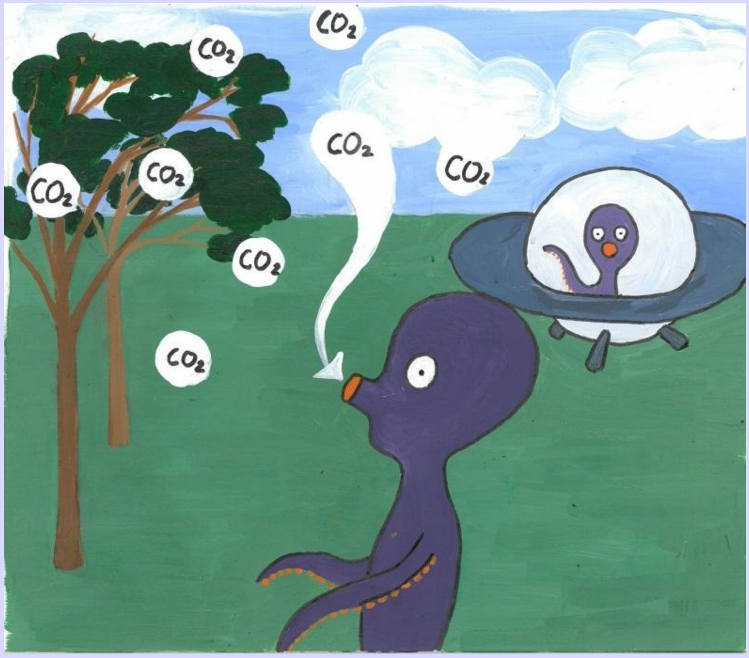
In "Vultures are Circling After Paris Agreement", Oliver Munnion critiques the report, stating *"interspersed with pearls of wisdom copied from various twitter feeds (including: "Removing CO_2 from the atmosphere is and can be valuable"), a decent analysis of the various CDR proposals, their value to climate mitigation, and scalability, is decidedly lacking."* [8]

IPCC claims about BECCS will continue to be used by the fossil fuel industry, arguing that its future 'availability' allows them to continue burning fossil fuels.

Removing carbon from the atmosphere to stabilise the climate: from BECCS to Carbon-Sucking Aliens

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 containing global warming to within 2°C of pre-industrial temperatures. [9] The conclusions of these models are supported by evidence on climate change in the Earth's past. CO_2 concentrations currently stand at 400 ppm and if methane and nitrous oxide are added to the equation, then we now have equivalent CO_2 levels of 430 ppm, with deadly consequences for many, especially in the global South. It is undeniably the case that greenhouse gas emissions must be rapidly phased out and that a substantial proportion of the CO_2 emitted since the industrial revolution must be somehow removed from the atmosphere.

This conclusion however is no more an argument for BECCS than it is an argument for the 'need' to invite carbon-sucking aliens to Planet Earth.



Carbon-sucking extra-terrestrials. Rhona Fleming

Does the concept of carbon-negative bioenergy make sense?

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 existing natural sinks are well proven across the Earth's history. Supporting them would mean putting an end to the destruction of ecosystems and degradation of soils, replacing industrial agriculture with agroecology and allowing degraded and destroyed forests and other ecosystems to regenerate. BECCS would do the opposite, by incentivising very large scale bioenergy, creating huge new demand for biomass and thereby destroying existing natural 'sinks' in an attempt to artificially create a theoretical, new and unproven one.

Many studies addressing the greenhouse gas balances of bioenergy only look at the direct emissions from fossil fuel burning linked to bioenergy production, e.g. fossil fuels burned to power a biofuel refinery, to make pellets, or to transport biomass. Some also account for emissions from logging, fertiliser use and land-use change for a particular consignment of bioenergy. Some studies, particularly about liquid biofuels, look at the emissions from certain indirect land use changes (for example, when bioenergy crops are grown on land formerly used to produce food or animal feed for livestock resulting in conversion elsewhere). The majority of indirect impacts however are virtually always ignored because they are difficult to quantify even though they may be substantial.

[ii] Note that this wording is not entirely accurate: Climate models and the IPCC speak of CO_2 equivalent (CO_2e) levels of greenhouse gases, not just CO_2. Because other greenhouse gas concentrations have also been increasing – especially methane and nitrous oxide – 450 ppm CO_2e levels are harder to achieve than 450 ppm CO_2 levels.

Also largely ignored are the climate impacts of "lost sequestration", that is, the loss of future carbon sequestration when forests are cut, ecosystems are converted to monoculture plantations, and healthy soils are depleted.

For bioenergy to be considered carbon negative, it would be necessary to capture an amount of carbon equivalent to all the direct and indirect emissions, in addition to the future lost sequestration resulting from ecosystem degradation.

This is highly improbable, so we must ask: where do the optimistic figures for the 'negative emissions' potential from BECCS come from? They are based on a blanket assumption that bioenergy is inherently low carbon, provided that basic sustainability standards are in place (e.g. no conversion of forests to bioenergy crops). The large and fast growing volume of peer-reviewed studies about the life-cycle emissions associated with different forms of bioenergy are ignored. [10]

The IPCC's 2014 Working Group 3 report on mitigation of climate change does acknowledge that there is potential for significant emissions, but refers to a 2011 report by the International Energy Agency (IEA) [11] for estimates of BECCS potential. The supposed potential is derived from two studies:

One is a preliminary assessment (not peer reviewed) from which IEA took their estimates for the global potential from crop and forestry residues. The authors do not describe their methodology in that publication. [12]

Although fossil fuel burning accounts for the bulk of global carbon emissions, researchers estimate that, historically, up to 200 billion tonnes of carbon have been lost through deforestation and other ecosystem degradation and destruction and soil depletion (see **http://www.grida.no/climate/ipcc_tar/wg1/pdf/tar-03.pdf**). Agroecology, ecosystem regeneration and ecosystem restoration could restore some of this carbon to soils and vegetation, though it could never sequester the carbon being emitted from fossil fuel burning today (and seeking to 'offset' fossil fuel emissions through agriculture and forests can never be justified). La Via Campesina and others are rightly highlighting the important contribution that peasant farming can make to combatting climate change. On the other hand, it is important be aware that terms such as 'ecosystem restoration' are routinely abused by industry interests to promote monoculture tree plantations at the expense of local communities, biodiversity, soil and water.

The second is a peer reviewed study from which the IEA took estimates for the maximum amount of bioenergy that could be sourced from dedicated energy crops. [13] The authors ran a model to calculate the maximum 'sustainable' biomass potential whilst accounting for land degradation, water scarcity and biodiversity protection. Their most conservative figures, used by the IEA, 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 they would all be rain-fed, not irrigated. Energy crops would, the authors assumed, only be grown on 'abandoned agricultural land' and natural grassland.

Yet, all indirect impacts are ignored, and remarkably, it is assumed that agricultural yields will increase by 12.5% by 2050 (even though 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.) Determining what land, globally, qualifies as "abandoned agricultural land", is highly problematic, as is the assumed 'sustainability' of converting either abandoned agricultural land or natural grasslands to bioenergy crops. Natural grasslands store large quantities of carbon, often in extensive root networks described as 'underground forests'. Converting them to plantations thus fuels climate change as well as biodiversity loss. These facts are ignored by the authors of the studies on which the IPCC relied for calculating the 'BECCS potential'.

In summary, the IPCC, like virtually all who purport to show a significant potential for sustainable biomass, relied on very improbable and unfounded assumptions from a couple of sources.

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. Nitrogen fertilisers are the main source of the powerful greenhouse gas nitrous oxide (N_2O). 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 of these sources combined. Yet there are serious problems with the concept that there are large quantities of forestry and agricultural residues available to burn without negative impacts.

Firstly, large and reliable quantities of 'residues' are generally only provided by industrial monocultures, such as palm oil and sugar cane. Secondly, removing too many residues depletes soil carbon and nutrients and leaves soils more vulnerable to erosion and drying. Thirdly, residues are widely used for other purposes already (animal feed or bedding and panel board manufacture, for example).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'. [14]

BECCS proponents tend to agree that there is a limit to the amount of bioenergy and thus BECCS that can be sustainable and low-carbon (or carbon negative in the case of BECCS). However, the assumed 'limit' is invariably many times greater than current global land and wood use for bioenergy, which is already associated with large-scale land-grabbing, loss of food and water sovereignty, forest and grassland destruction, soil and water depletion, and (in the case of biofuels) food price volatility, as well as the increased greenhouse gas emissions from land conversion, soil carbon loss and fertiliser use.

Communities in Maranhão, Brazil, have been fenced in by eucalyptus plantations for bioenergy. Ivonette Gonçalves de Souza

Biodiverse wetland forests are being cleared and turned into pellets in the southern US, due to UK biomass demand. Dogwood Alliance

Do BECCS technologies exist and are they scalable?

It is possible to capture CO_2 from power station exhaust or flue gases as well as from ethanol refining, to liquefy and transport captured CO_2, and to pump it underground. However, there are no operating pilot BECCS schemes, let alone commercial scale BECCS facilities, anywhere in the world. The only partial exceptions are a small number of projects involving carbon captured from conventional ethanol fermentation.

Ethanol fermentation results in an almost pure stream of CO_2, easier and cheaper to capture than the CO_2 found in much lower concentrations in power station flue gases. However, in each of these projects, less CO_2 is captured from ethanol fermentation than is emitted from fossil fuel burning to power the refinery, which means that they cannot possibly be 'carbon negative'. Furthermore, one of the projects depends on large subsidies (for geological sequestration), while others depend on sales of the CO_2 for use in "Enhanced Oil Recovery" (discussed below). Some ethanol refineries also capture CO_2 for sale in products such as carbonated beverages.

Some claim that BECCS could become technically and economically viable in the future with adequate investment and research. Such faith in a "technology learning curve" for BECCS appears extremely optimistic, given what we already know about the costs, energy demands and problematic technologies.

What technologies are proposed for BECCS?

Technologies for generating power from biomass and capturing CO_2 fall into the following categories:

• Capturing CO_2 from fermentation processes in conventional or advanced cellulosic ethanol refineries.

• Capturing CO_2 from cellulosic biofuel refineries, which turn solid biomass such as wood into a form of biodiesel using gasification and Fischer-Tropsch synthesis.

• Post-combustion carbon capture from power plants burning biomass (with or without coal), i.e. capturing CO_2 from the flue gases before they are emitted to the atmosphere.

• Pre-combustion carbon capture from biomass or biomass with coal power plants that use "Integrated Gasification Combined Cycle" (IGCC) processes: An IGCC plant involves heating solid fuel (e.g. wood) so that it turns into a gas, and then burning the gas to power both a gas and a steam turbine. The CO_2 would be captured from the gas before it is burned.

Capturing CO_2 from a facility using oxyfuel combustion to burn biomass (with or without coal): Oxyfuel combustion involves burning solid fuel in nearly pure oxygen rather

Skyline of ADM plant in Decatur, Illinois. Dan

than air. This results in a gas that consists mainly of CO_2 and water vapour, making it easier to capture the concentrated CO_2.

When biomass is burned with coal, only the fraction proportional to the amount of biomass being burned would be considered "BECCS". The only technology that has so far been tested with biomass at all is CO_2 capture from fermentation (a). We therefore have to rely on information from a few coal CCS facilities as an indication of how BECCS would operate if solid biomass, or wood, were to be used.

CO_2 capture from biofuel refining

Only one (corn) ethanol refinery, owned by Archer Daniels Midland in Decatur, Illinois, aims to actually sequester the CO_2 it produces. With most of the $292 million cost for the operation paid for by the U.S. Department of Energy, the facility has succeeded in capturing and pumping about 1 million tonnes of CO_2 into the nearby Mount Simon Sandstone formation, with a second phase demonstration project still apparently planned. The project has never been defined as "carbon negative" because, like most ethanol refineries around the world, fossil fuels are used to power the facility, which results in more emissions than could ever be captured from fermentation.

Capturing CO_2 from cellulosic ethanol fermentation would be similar in theory. However, efficient and therefore commercial production of cellulosic fuels remains highly elusive, in spite of decades of research and many hundreds of millions having been spent on research and development. In theory, CO_2 capture from biofuel production involving gasification and Fischer-Tropsch synthesis could be possible. The process results in a gas that consists mainly of water vapour, methane, hydrogen and carbon monoxide (CO). Once cleaned of impurities, this is called "syngas". During Fischer Tropsch synthesis, the carbon monoxide reacts with water to form more hydrogen as well as carbon dioxide. The CO_2 can then be captured, while the other molecules undergo more reactions in order to produce transport fuels. However, gasification and Fischer-Tropsch synthesis are highly complex and failure-prone technologies. Despite significant subsidies and investments, nobody has succeeded in operating a commercially viable biofuel refinery of this type to date.

Biomass combustion for electricity (or electricity and heat)

Post-combustion carbon capture involves capturing CO_2 from exhaust flue gases. The concentration of CO_2 in flue gases is very low, trace impurities reduce the effectiveness of the carbon capture equipment, and capturing (and compressing CO_2 for transport via pipeline) uses significant amounts of energy.

What can we learn from coal CCS experience? Canada's SaskPower Boundary Dam project, the first commercial scale post combustion CCS facility, after receiving C$240 million in government grants, was finally opened amid great fanfare in October 2014. Claims were made that the facility was operating splendidly, "exceeding expectations", and it won awards. However, it subsequently became clear that the facility has in fact never performed well at all, managing to capture only a small fraction of the CO_2 anticipated, and resulting in a much higher energy penalty than previously claimed. SaskPower has been forced to pay millions of dollars in penalties to Cenovus, the company they are contracted by to supply CO_2 for Enhanced Oil Recovery. [15]

Carbon capture at Boundary Dam was initially supposed to involve a 25% energy penalty. Recently, it has been reported that up to 31% of the energy the facility generates is used to power carbon capture and compression. [16] The energy penalty would be even higher for

SaskPower's Boundary Dam power station. Magnus Manske

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

biomass plants since they tend to be less efficient than coal power stations. A unit of electricity generated in a dedicated biomass power plant for example, results in up to 50% more CO_2 emissions than if generated from burning coal. [17] Since more CO_2 is released per unit of energy generated, even more energy is needed to capture the resulting CO_2, hence an even greater energy penalty can be expected for facilities burning biomass.

A report from the Global CCS Institute [18] predicts that capturing CO_2 from a 76 MW biomass power station, which would otherwise have a conversion efficiency of 36%, would reduce that power station's electricity output to just 49 MW, and would reduce efficiency to just 23%.

Oxyfuel combustion involves burning fuel with nearly pure oxygen, which results in a flue gas in which CO_2 is highly concentrated and thus easier and cheaper to capture. However, producing almost pure oxygen is energy intensive.

Some small demonstration coal oxyfuel facilities exist, but, as for most combustion technologies, biomass results in further inefficiencies. The notorious "FutureGen 2" project in the US would have involved oxyfuel CCS. Over $200 million in government subsidies were provided along with a pledge to invest over $1 billion, but due to slow progress, cost overruns and lack of interest from private investors, the project was abandoned.

Integrated Gasification Combined Cycle (IGCC) facilities would at least theoretically be among the cleaner and more efficient technologies. IGCC involves gasifying solid fuel, cleaning the gas and then burning the syngas to power both a gas and a steam turbine. However, the process is hugely complex, involving multiple elaborate stages, and reliable operation has been elusive. Attempts to resolve technical problems have made IGCC plants even more complex, expensive and failure-prone.

A few coal IGCC facilities have operated without CCS, but the addition of CCS only further complicates operations. This is because (just as with the Fischer-Tropsch technology described above) it involves reacting the carbon monoxide with water to form carbon dioxide and hydrogen and then capturing the carbon dioxide. This leaves almost pure hydrogen to be burned, something turbines have not been developed for. One (non-CCS) facility in Spain required 6,000 modifications after construction. Another non-CCS IGCC plant, the Duke Energy facility in Indiana (US), cost $3.5 billion to construct, and 20 months after it was commissioned, it had never operated at even 50% of its capacity.

That did not stop the US government from awarding a $270 million grant plus $412 million in tax credits to the Southern Company for construction of a 582 MW coal IGCC facility with CCS (with the CO_2 to be sold for Enhanced Oil Recovery). The Kemper Mississippi facility started construction in 2010 with costs estimated at $1.8 billion, but had ballooned to over $6.4 billion by November of 2015. At present, the facility is simply burning natural gas, without CO_2 capture.

An IGCC facility with CO_2 capture running on biomass, rather than coal, would therefore be technologically even less certain, less efficient and more costly.

Can we trust that sequestered CO_2 will stay put?

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 sedimentary rocks, and held in place by dense "caprocks". CO_2 can be stored as a compressed gas, liquid, or in a high-pressure liquid-like form called “supercritical CO_2”, depending on conditions. Mechanisms for trapping CO_2 include: [19]

1) Hydrodynamic trapping: This occurs when CO_2 is trapped under a low-permeability caprock (i.e. underneath a layer of hard, resistant rock). 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, or in saline aquifers that form parts of sedimentary basins, such as the Utsira formation in the North Sea.

2) Residual or capillary trapping: When CO_2 is injected into a brine (i.e. salt water filled reservoir), some remains trapped in an immobile phase, disconnected from the rest, which migrates upward.

3) Solubility trapping: This occurs when CO_2 dissolves into water contained within the resevoir, until an equilibrium is reached. It can take thousands of years.

4) Mineral trapping: Mineral trapping occurs when CO_2 is incorporated via chemical reactions, into mineral and organic matter within the formation. This is a very slow process that occurs over geological time scales. [20]

How could CO_2 leak?

Of greatest concern is leakage from old abandoned oil and gas wells, of which there are around 3 million in the US alone [21] Of particular concern are onshore wells that were not plugged, or which have cement plugs that are cracked. In parts of North America there are very high densities of oil production wells left unplugged following bankruptcies due to the 1986 oil crash. Unplugged wells penetrate many of the deeper formations currently used or considered for CCS. [22]

However, even if wells have been plugged with cement, the CO_2 that is injected into reservoirs dissolves in trapped salty seawater and turns it highly acidic. This acid water can cause the cement to corrode, crack and fail. Several hundred producing and old or abandoned wells could already be affected by acidified salt water. [23]

Further studies which have been conducted in other intensively drilled areas show that large numbers of existing oil and gas wells can lead to complex leakage patterns, across multiple geological formations. [24] CO_2 gas can migrate rapidly, over long distances and over long periods of time. [25]

The chemistry of geological sequestration and the trapping mechanisms involved, are in fact poorly understood. For example, it appears increasingly likely that only a small fraction of injected CO_2 is converted to stable solid minerals, whereas previously it had been assumed that far greater proportions would be. [26, 27]

Estimates of the overall capacity for CO_2 storage in different regions is also poorly understood and hotly debated. [28] Assessing the truth is challenging because studies that question assumptions about the viability of CCS are rapidly met with a barrage of responses, rebuttals and counter arguments, especially from industry proponents. [29]

Has geological sequestration of CO_2 been successful?

The three largest CO_2 storage projects to date are: 1) Cenovus Energy's Weyburn Enhanced Oil Recovery site in Canada, 2) BP and Statoil's Sleipner project in the North Sea, and 3) The In Salah gas production site in Algeria, operated by BP, Statoil and Sonatrach. All three have been heralded as examples of successful carbon sequestration, but are in fact surrounded by controversy.

Did CO_2 leak at Weyburn?

Cenovus Energy began injecting CO_2 purchased from the only coal-to-liquids gasification plant in the U.S and delivering it to the Weyburn oil field in southeast Saskatchewan, Canada, in 2000. The company states that 60% of the oilfield is undergoing CO_2 flooding (a method of Enhanced Oil Recovery discussed below). [30]

In 2010, Cameron and Jane Kerr, farmers living near Weyburn [31] reported some unexplained phenomena on their farm, including 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. The Kerrs hired Petro-Find Geochem Ltd to undertake studies, which concluded that CO_2 was in fact leaking from the injection site, [32] casting serious doubts on the success and safety of CO_2 injection. Cenovus in turn commissioned Trium Environmental and Chemistry Matters to carry out another study, which found no CO_2 leakage.

Beginning in 2000, a consortium of companies and organisations, under the management of the Petroleum Technology Research Centre (PTRC) had been contracted to do monitoring at the Weyburn site on behalf of Cenovus, with funding from Canadian regional and national governments and oil and gas industries. [33] The monitoring ended in 2012, and included just five soil gas surveys conducted between 2001-2005, 2 miles north of the Kerr property, comprising only about 5% of the total area of the Weyburn and Midale fields. [34] They issued two reports proclaiming that no leakage had occurred.

The International Performance Assessment Centre for the geologic storage of Carbon Dioxide, (IPAC-CO_2), was established in 2008 by Royal Dutch Shell, the Government of Saskatchewan, and the University of Regina. [35] They also did a study and also concluded no leakage had occurred. [36] Yet, in 2013 IPAC-CO_2 closed down amid allegations of conflicts of interest and misspending of public funds [37] and were subsequently investigated for fraud. [38]

The Sleipner CCS Project

Statoil, ExxonMobil and Total have been injecting up to 1 million tonnes of CO_2 a year, captured from a natural gas processing facility, into a sub-seabed saline aquifer called the Utsira formation, since 1996. The site is just above an oil field called Sleipner East, after which the project is named. By early 2013, more than 14 million tonnes of CO_2 had been injected. [39] 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 power plant emissions for many years to come.

However, a series of problems have occurred at injection sites along the Utisira formation: In 2004, oily water was observed on the sea surface near the ExxonMobil operated Ringhorne site. In 2007 unexplained activity in the seabed that involved cracking and/or other damage to the formation, was reported, probably related to the injections at the StatoilHydro operated Visund Field. [40] In 2008, an oil leak occurred from the StatoilHydro-operated project in the Tordis field, where contaminated process water was being re-injected.

At Sleipner, injected CO_2 was expected to rise gradually through the layers of the formation. However, seismic imaging showed that the plume ascended 200m vertically through eight shale barriers in less than three years. [41] Previous monitoring studies revealed a large discrepancy between the amount of CO_2 injected and what was subsequently detected in seismic surveys, potentially indicating leakage. [42] An extensive, and previously unexplored fracture in the sea bed rock - the "Hugin Fracture" was discovered 25 km north of Sleipner CO_2 storage site. [42, 44] That discovery was apparently buried following swift and negative rebuttal. [45] A 2014 study concluded that overall, the fate and migration of injected CO_2 is still poorly understood at Sleipner, some 10 years into the injection programme. [46] Meanwhile, questions have also been raised over just how much CO_2 can realistically be stored within the Utsira formation. [47]

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 million tonnes of CO_2 into three wells between 2004 and 2011. A seismicity study at the site indicated that CO_2 injection had activated a deep fracture zone (i.e. an area of naturally-occurring fractures that had previously not showed signs of movement) near to one of the injection sites that appeared to open during injection and subsequently close up after injection was halted. [48] Another study reported that the fractures had extended into the lower caprock, but that "no leakage had occurred." [49] Leakage did occur when CO_2 migrated to a nearby old well and leaked through the valve. [50] CO_2 injection was stopped until the well was fully decommissioned. [51]

A final issue regarding CO_2 storage is the monitoring of storage sites. Fundamentally, CO_2 must be stored underground on geological timescales – i.e. thousands of years. But monitoring of storage sites doesn't necessarily continue after CO_2 injection has stopped.

In sum, the answer to the question "will CO_2 injected into storage sites remain permanently sequestered" seems likely to be "No", at least in many or most cases. However it is difficult to assess results to date because of a) lack of understanding, and b) the role industry plays in challenging results that are unfavorable to their interests.

Making money from captured carbon: Enhanced Oil Recovery (EOR)

When a new oil field is first drilled, underground pressure in the oil reservoir forces oil to the surface, called 'primary recovery'. Secondary recovery involves pumping (which takes energy) and injection of water to create the necessary pressure. When about 35-45% of the reservoir is depleted, further extraction requires the use of EOR. EOR currently allows a further 5-15% of oil in a reservoir to the exploited, which is equivalent to all 'primary recovery'. It is therefore highly significant for overall oil production. EOR methods include energy intensive injection of steam, in-situ burning of some 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. In the latter, CO_2 injection is used in about 60% of EOR projects in the US. [52] Hereafter we refer to EOR using CO_2 flooding.

In 2014 [53] total onshore oil production in the US was around 9 million barrels per day, 3.4% of which was extracted utilising EOR. Industry claims that vastly more oil could be accessed with adequate and cheap supplies of CO_2. [54] The US Department of Energy in 2014 projected that potential oil resources recoverable with EOR could be up to three times the current proven reserves in the US.

CO_2 flooding for EOR has been used since 1972, long before Carbon Capture and Storage was first proposed. With the advent of CCS, commercial sale and use of captured CO_2 for EOR has become widely promoted as the main solution to offsetting the high costs of carbon capture, making it more 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 using around 175,000 tonnes of CO_2. 80% of that CO_2 was sourced from natural reserves, while the remaining 20% was sourced from industrial carbon capture. [55]

The high cost of acquiring, transporting and injecting CO_2 has restricted use of EOR in many areas. Capturing 'anthropogenic' CO_2 would allow for CO_2 to be acquired from more locations at lower 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

Carbon capture infrastructure at the Boundary Dam. SaskPower

ethanol refineries. Carbon capture from power stations provides the largest potential source of CO_2 but, as discussed above, is highly expensive and fraught with technical problems. Two important caveats need to be made regarding the oil industry's interest in purchasing CO_2 for use in EOR: 1) oil companies show little inclination to invest much in CO_2 capture themselves, and 2) EOR projects are amongst many other oil industry investments that are being cut as prices have recently fallen dramatically. [56]

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, which lowers its viscosity, that is, causing the oil to flow more easily. Between one half and two thirds of the CO_2 injected is subsequently brought back out of the well to the surface, mixed with the oil. [57] That CO_2 is then separated back out, an energy intensive process, and could be re-injected. [58] In theory, all of it could be re-injected to remain in the oil reservoir. In reality however, CO_2 can escape via leakage during transport (usually by pipeline), during maintenance related venting, through fugitive emissions from CO_2 returned through production wells, as well as potentially leaking from the wells themselves. Oil industry estimates indicate that about 30% of the CO_2 piped to an EOR site will be directly emitted back into the atmosphere. [59]

A study looking at the life-cycle inventory of EOR emissions [60] concludes that significant net emissions occur. Add to that emissions from oil produced as a result of CO_2 injection: Typical recovery from CO_2 injection ranges between 1.1 and 5 barrels of oil for every tonne of CO_2 injected.

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

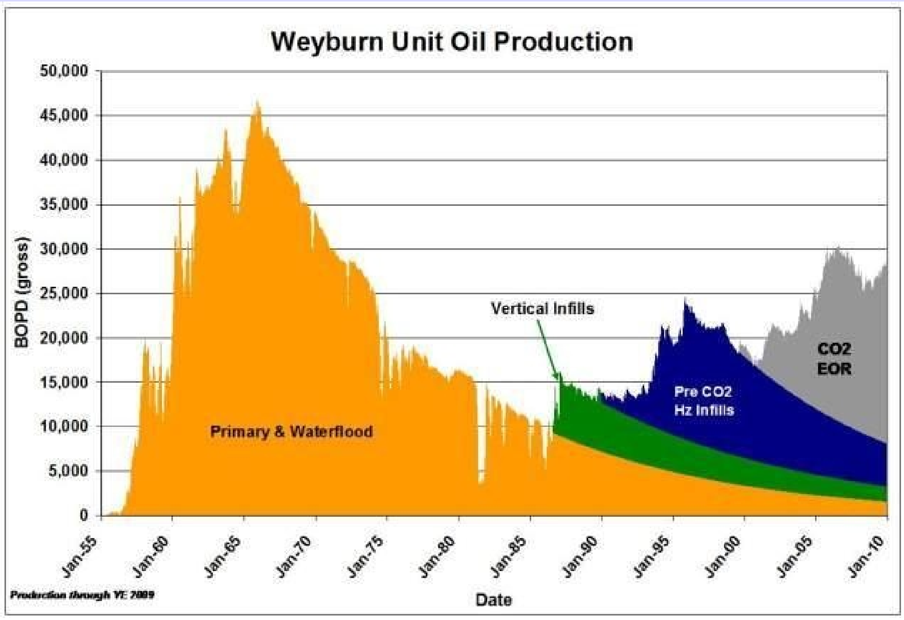
SaskPower is contracted to supply Cenovus Energy with CO_2 for use in EOR at the Weyburn oil field from their Boundary Dam coal power plant. The company claims that the power station is:

"...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 pointed out above, the facility has been capturing far less carbon than originally intended. But would it have achieved such emissions reductions if it 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. When all emission sources are considered, it becomes clear that the Boundary Dam facility in no way decreases emissions, but rather increases them substantially. We conclude some 0.7 million tonnes of CO_2 may remain underground after injection, but 1.5 million tonnes of CO_2 will have been created during the overall process.

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

The rhetoric surrounding carbon capture as a "solution to climate change" is essentially a PR strategy, providing false assurances that fossil fuels can continue to be used with impunity, while misrepresenting the true risks.



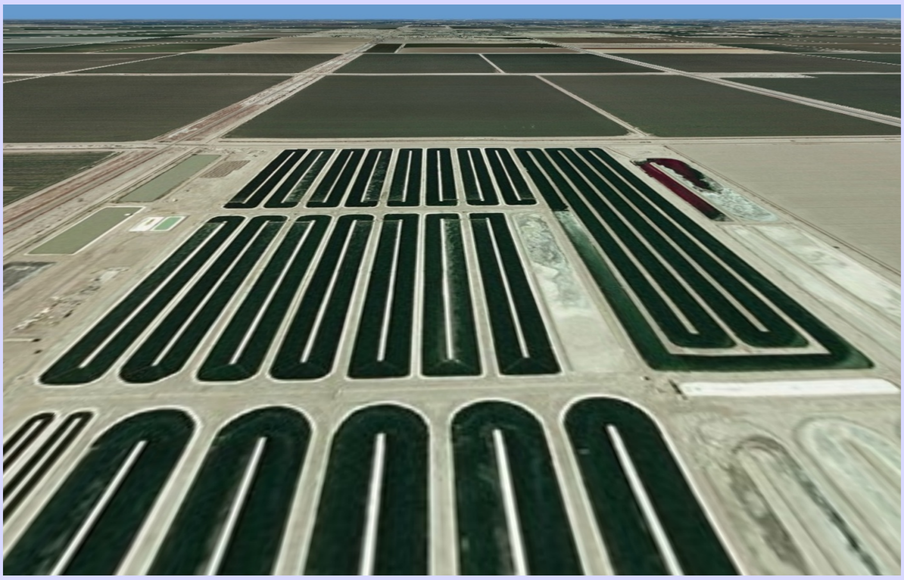
Weyburn is one of the largest oil fields in Canada. This graph shows how oil recovery has been aided by CO_2 injection. Cenovus Energy Inc.

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 €100 million available from 2010 to 2015 for research and development into the material use of CO_2. [61] 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, [62] and other governments, especially in Canada and Australia, have made further funds available.

Most of those uses cannot possibly be described as 'sequestration'. For example, significant funds are going into Research and Development to grow algae and bacteria fed with CO_2 rich exhaust gases so that they convert the CO_2 into biofuels. Of course the CO_2 would then be released into the atmosphere again as soon as the biofuels are burned – but that does not prevent the Algae Biomass Organization in the US from describing those concepts as BECCS (or "BECCSU", with the 'U' referring to 'use'). [63]

Synthetic biology is extreme genetic engineering. There is no universal definition but the term is used to describe novel genetic engineering techniques (including trying to build new genes and even organisms from scratch), as well as 'metabolic engineering', i.e. making substantial changes to an organism's metabolism. For more details, see **synbiowatch.org**.



Algal ponds such as this one in the USA, use algae to try to produce biofuels. Pacific Northwest National Laboratory

Other companies are looking to use captured CO_2 for different short-term products such as bioplastics, bleach [64] or even fracking fluids. [65] Some are even looking to use CO_2 in production of nappies [66] or foam mattresses.

Some projects involve trying to incorporate CO_2 into more durable products – especially 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). [67] Government-funded research and development has been looking at incorporating captured CO_2. However the only commercially viable cement product incorporating injected CO_2 is made by Carbon Cure, who merely claim that this process reduces the overall CO_2 emissions from their cement production by 20% - a long way from making it 'carbon negative'. [68] Carbon Cure have failed to respond to a Biofuelwatch query about their life-cycle calculations, hence even their "20% less CO_2" claims cannot be verified.

Several of the Research and Development projects on 'carbon capture and use' involve synthetic biology. For example, companies such as LanzaTech and Joule are genetically engineering algae and cyanobacteria to convert CO_2 directly into fuels.

Technology: The missing piece in the debate about BECCS

Having faith in BECCS as a technology seems at best highly naïve, 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. Despite this, whilst they may aknowledge potential concerns with land use change and the sustainability of biomass, virtually all peer-reviewed studies on BECCS blithely assume that technological obstacles can be easily overcome (see for example [69]). A peer-reviewed commentary on BECCS, published in Nature Climate Change in 2014, identified four uncertainties that would need to be resolved, [70] but never questions the viability of what, after all, is acknowledged to be an 'untested technology'. 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'. Judging by the costs of and problems associated with attempts to capture CO_2 from coal power plants, and the added cost of biomass (including the even greater energy need for capturing CO_2 from biomass compared to coal plants), it is difficult to imagine a more expensive way of trying to mitigate climate change.

Concluding reflections: The pseudo-science around 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"* [71] and what the Indonesian meteorological institute has described as *"a crime against humanity of extraordinary proportions"*. [72] Between July and October 2015, around 100,000 fires had been recorded across Indonesian Borneo, Sumatra and on West Papua, more than half of them on peat. [73] Over two million hectares have been reduced to ashes, [74] 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 [iii] will have been emitted by the end of 2015 as a result of the peat fires that year. [75] This is far more than the annual CO_2 emissions of Germany or Japan. Smoke inhalation was affecting 48 million people and at least 500,000 cases of acute respiratory infection have been reported on just two of the three affected islands. Most of the fires had been extinguished by rains in late December 2015, but by March/April 2016, fires were once more burning out of control in Sumatra and Borneo. [76]

Satellite images from the early weeks showed that most of the fires were concentrated in the region with the highest palm oil concessions in Indonesia. [77] 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.

Across Asia, high palm oil prices – and the expectation of continuing growth in demand – is leading plantation companies to clear ever more forests and peatlands. In recent years, Indonesia's rate of deforestation has shot up to become the world's highest, [78] and a 2013 mapping analysis by Greenpeace identified palm oil as the single biggest driver. [79]

Peat and forest fire in Kalimantan, Indonesia, December 2015. NASA

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

Forest destruction for palm oil plantations in West Kalimantan, Indonesia. Rainforest Action Network

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. [80] EU biofuel policies, which were legitimised by 'sustainable biomass potential' studies, clearly bear some of the responsibility for the catastrophe in Indonesia.

EU standards, at least in theory, prevent biofuels sourced from plantations and linked to recent deforestation from counting towards renewable energy targets. But they have done nothing to limit the incentives for forest destruction created by biofuel expansion, through higher palm oil prices. Indonesia's fires thus illustrate the deep flaws in the idea that, with the help of sustainability standards, one can increase global bioenergy use without triggering major destruction of ecosystems and the carbon emissions that accompany it. This is the same wrong idea that underlies the concept of BECCS, and has been the rationale for bioenergy policies in the EU, North America and elsewhere.

There is also no evidence that EU biofuels standards have even been enforced, which would in theory prohibit biofuels sourced through new deforestation or peat clearance from being subsidised or counted towards renewable energy targets. Even if they were enforced, companies could easily sell palm oil for biofuel production from older plantations, linked to past, rather than new deforestation, and in turn burn more peat forests to establish new plantations to serve the existing markets. Nobody can say what proportion of the fires were due to biofuels, but even a minor share of the overall responsibility for the fires could translate into carbon emissions many times higher than what 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. [81] Leading researches and institutions have also failed to question the basis for these policies – the credibility of academic claims made about the potential for large-scale 'sustainable biomass' – despite the clear evidence of the real-world impacts of industrial bioenergy. The IPCC has described a possible future increase in 'modern bioenergy' by 550% from current figures as their 'limited bioenergy' scenario. [82] In the same report, they included scenarios in 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.

The research highlighted in this report on bioenergy and BECCS raises serious questions about the prevalent discourse on climate change mitigation, not just amongst policy makers, but also amongst leading scientific institutions, including the IPCC. [iv] Why is the underlying premise of a large potential for sustainable, low or zero carbon bioenergy not being questioned? 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 that tests the hypothesis that sustainability standards can be effective against real-world evidence? Why does study after study state as "fact" that BECCS is a cost-effective way of mitigating climate change, [83] even though none of the proposed BECCS technologies (except for a small amount of CO_2 capture from ethanol refining for use in EOR) have ever been implemented on any scale? [v]

Policy makers are being misled about the 'potential' for using bioenergy to scrub CO_2 from the atmosphere. Thus, they are also being misled to believe that we can continue to burn fossil fuels, continue to achieve economic growth, and yet still avoid the worst impacts of climate change.

The IPCC, the IEA and various academic institutes share some of the responsibility for this. The IPCC's conclusion on BECCS and climate change mitigation are particularly disappointing in this context, given the key role that the IPCC has played in defending the scientific consensus on climate change. [84]

Claims about BECCS – like other 'negative emissions technologies' – are based on pseudo-science, coupled with corporate lobbying. Even if it is unlikely that BECCS will ever become a reality, the claims made about it are highly dangerous: we cannot afford false assurances about ways of removing carbon from the atmosphere, and we cannot afford false assurances about the feasibility of very large-scale industrial bioenergy either.

This report is a summarised version of Biofuelwatch's longer report, with the same title. The full report is available to download for free here: **http://www.biofuelwatch.org.uk/2015/beccs-report/**.

[iv] 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.

[v] As discussed previously, ADM's capture of CO_2 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 CO_2 captured.

References

[1] Carbon Dioxide Capture and Storage, International Panel on Climate Change, Special Report, 2005

[2] Climate Change 2014 Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, page 517

[3] http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html

[4] Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies, IPCC Expert Meeting Report, September 2007 http://www.iamconsortium.org/

[5] See for example the scientific studies listed at: http://www.biofuelwatch.org.uk/biomass-resources/resources-on-biomass/

[6] https://www.independentsciencenews.org/environment/biofuel-or-biofraud-the-vast-taxpayer-cost-of-failed-cellulosic-and-algal-biofuels/

[7] Philanthropy Beyond Carbon Neutrality report: http://static1.squarespace.com/static/54a2e4c1e4b043bf83114773/t/56f085628259b594db050f8e/1458603369594/Philanthropy+Report+Final+%28small+file%29.pdf

[8] http://www.geoengineeringmonitor.org/2016/04/vultures-are-circling-after-paris-agreement/

[9] Climate Change 2014: Synthesis Report Summary for Policymakers, International Panel on Climate Change

[10] See studies listed at: www.biofuelwatch.org.uk/biomass-resources/resources-on-biomass/, which are some of the studies related to biomass electricity.

[11] Potential for Biomass and Carbon Dioxide Capture and Storage, International Energy Agency, July 2011

[12] Hoogwijk et al. (2010), Global potential of biomass for energy, in Global Energy Assessment-Preliminary results, www.iiasa.ac.at/Research/ENE/GEA/index_gea.html

[13] Future bio-energy potential under various natural constraints, D.P. van Vuuren et.al, Energy Policy(37), 2009

[14] See for example www.biofuelwatch.org.uk/wp-content/uploads/DECC-open-letter-biomass-coal-april-2015.pdf .

[15] www.nytimes.com/2016/03/30/business/energy-environment/technology-to-make-clean-energy-from-coal-is-stumbling-in-practice.html?_r=0

[16] www.netl.doe.gov/research/coal/carbon-capture/post-combustion and http://www.nytimes.com/2016/03/30/business/energy-environment/technology-to-make-clean-energy-from-coal-is-stumbling-in-practice.html

[17] www.pfpi.net/carbon-emissions

[18] http://hub.globalccsinstitute.com/publications/biomass-ccs-study/overview-results

[19] http://www.bgs.ac.uk/discoveringGeology/climateChange/CCS/howCanCo2BeStored.html

[20] Mechanisms for Geological Carbon Sequestration.Dongxiao Zhang and Juan Song, Mechanics for the World: Proceedings of the 23rd International Congress of Theoretical and Applied Mechanics, ICTAM2012. 2014

[21] http://www.ieaghg.org/docs/General_Docs/Publications/Information_Papers/2014-IP27.pdf

[22] CO_2 leakage through existing wells: current technolgy and regulations. Ide, T. et al., presented at the 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway. 2006

[23] Leakage of CO_2 through abandoned wells: role of corrosion of cement. Scherer, G. et al. Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO2 capture project. 2005

[24] The Role of Existing Wells as Pathways for CO 2 Leakage 2010. Celia, M. Search and Discovery Article #80093. 2010

[25] Natural Leaking CO_2-charged Systems as Analogs for Geologic Sequestration Sites. Evans, J. et al., 2004

[26] Mechanisms for mechanical trapping of geologically sequestered carbon dioxide. Cohen, Y. and Rothman, D., Proc. R. Soc, 2015

[27] http://news.mit.edu/2015/carbon-dioxide-sequestration-doubts-0120

[28] Sequestering carbon dioxide in a closed underground volume. Economides, C. and Economides, M., Journal of Petroleum Science and Engineering, 2010

[29] http://www.eenews.net/stories/90472

[30] http://www.cenovus.com/operations/technology/co2-enhanced-oil-recovery.html

[31] http://www.cenovus.com/operations/oil/weyburn-third-party.html

[32] http://www.gasoilgeochem.com/reportcameron%20jane%20kerrfebruary2011survey.pdf

[33] http://dirtybusinessthefilm.com/2011/02/international-team-investigates-alleged-co2-leak-at-worlds-largest-carbon-storage-project/

[34] http://www.gasoilgeochem.com/reportcameron%20jane%20kerr.pdf

[35] http://www.zeroco2.no/projects/developers/ipac-co2-international-performance-assessment-centre-for-the-geologic-storage-of-carbon-dioxide

[36] http://dirtybusinessthefilm.com/2011/02/international-team-investigates-alleged-co2-leak-at-worlds-largest-carbon-storage-project/

[37] http://www.cbc.ca/news/canada/saskatchewan/regina-s-ipac-co2-to-close-march-31-1.1407789

[38] http://www.huffingtonpost.ca/2013/11/05/co2-capture-fraud-investigation_n_4219994.html

[39] http://www.statoil.com/en/TechnologyInnovation/NewEnergy/Co2CaptureStorage/Pages/SleipnerVest.aspx

[40] http://static.greenpeace.org/int/pdf/081201BRUtsira.pdf

[41] Calibrating reservoir performance with time-lapse seismic monitoring and flow simulations of the Sleipner CO 2 plume. Chadwick, R., et al., GHGT-8: 8th International Conference on Greenhouse Gas Control Tech, 2006

[42] Looking for CO_2 Buried at Sleipner: http://www.precaution.org/lib/looking_for_sleipner_co2.100727.pdf

[43] http://www.eco2-project.eu/newsarticles/items/north-sea-fracture-discovered.html

[44] http://www.nature.com/news/seabed-scars-raise-questions-over-carbon-storage-plan-1.14386

[45] http://www.sccs.org.uk/images/expertise/reports/working-papers/wp-2014-01.pdf

[46] The Sleipner storage site: Capillary flow modeling of a layered CO_2 plume requires fractured shale barriers within the Utsira Formation. Cavanagh, A. and Hazeldine, S., International Journal of Greenhouse Gas Control, 2014

[47] http://www.npd.no/en/Publications/Norwegian-Continental-Shelf/No2-2007/Carbon-containment-in-the-spotlight/

[48] The microseismic response at the In Salah Carbon Capture and Storage (CCS) site. Stork, A., et al., International Journal of Greenhouse Gas Control, 2015

[49] The In Salah CO_2 Storage Project: Lessons Learned and Knowledge Transfer. Ringrose, P., et al., Energy Procedia, 2013

[50] In Salah CO_2 Storage JIP: Site Selection, Management, Field Development Plan and Monitoring Overview. Wright, I., et al., Energy Procedia, 2010

[51] https://www.netl.doe.gov/publications/proceedings/10/rcsp/presentations/Tues%20am/Karen%20Cohen/Wright.ISG%20CO2%20JIP%20US%20DoE%20RCSP%20ARM%20Oct%205%202010%20Wright.pdf

[52] http://energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery

[53] http://www.eia.gov/forecasts/steo/report/us_oil.cfm

[54] http://netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Near-Term-Projections-CO2-EOR_april_10_2014.pdf

[55] https://www.iea.org/media/workshops/2015/sally/JohnHarju.pdf

[56] http://www.ogj.com/articles/print/volume-113/issue-4/special-report-capital-spending-outlook/companies-slash-capital-budgets-as-oil-price-drop-cuts-cash-flows.html

[57] Carbon Dioxide Enhanced Oil Recovery, National Energy Technology Laboratory, US Department of Energy, www.netl.doe.gov/technologies/oilgas/publications/EP/small_CO2_eor_primer.pdf

[58] www.sinoaustoil.com/irm/content/pdf/Sino%20Australia%20Oil%20and%20Gas%20Technical%20Information.pdf

[59] http://www.ico2n.com/wp-content/uploads/2013/06/Ico2n_EOR-Final-Report.pdf

[60] http://www.cmu.edu/gdi/docs/life-cycle-inventory.pdf

[61] www.dechema.de/dechema_media/ziel+des+foerderprojekts.pdf

[62] www.energy.gov/fe/articles/doe-selects-16-transformational-carbon-capture-technologies-projects-funding

[63] www.algaebiomass.org/blog/8567/why-bioenergy-with-carbon-capture-utilization-and-storage-beccus/

[64] http://skyonic.com/

[65] www2.buildinggreen.com/blogs/can-man-reinvent-concrete

[66] www.scotproject.org/images/BMBF,%202014,%20CO2%20utilisation%20project%20examples.pdf

[67] www.globalccsinstitute.com/insights/authors/dennisvanpuyvelde/2013/02/20/update-co2-capture-cement-production

[68] www.design-4-sustainability.com/case_studies/134-stronger-concrete-with-co2-injection

[69] The role of negative CO_2 emissions for reaching 2˚C—insights from integrated assessment modelling, Detlef P. van Vuuren et. al., Climatic Change, May 2013

[70] Betting on Negative Emissions, Sabine Fuss et.al., Nature Climate Change, September 2014

[71] http://jakartaglobe.beritasatu.com/opinion/erik-meijaard-indonesias-fire-crisis-biggest-environmental-crime-21st-century/

[72] http://jakartaglobe.beritasatu.com/news/bmkg-labels-indonesias-haze-crisis-crime-humanity/

[73] www.wri.org/blog/2015/10/indonesia%E2%80%99s-fire-outbreaks-producing-more-daily-emissions-entire-us-economy

[74] http://jakartaglobe.beritasatu.com/news/two-million-hectares-indonesian-forests-lost-fires-since-june/

[75] http://www.globalfiredata.org/updates.html

[76] http://news.mongabay.com/2016/04/companies-asked-pitch-indonesias-peat-restoration-drive-early-fires-flare-sumatra/

[77] www.wri.org/blog/2015/07/indonesia%E2%80%99s-forest-fires-reignite-threatening-protected-areas-and-peatlands

[78] http://news.mongabay.com/2014/06/despite-moratorium-indonesia-now-has-worlds-highest-deforestation-rate/

[79] Certifying Destruction: Why consumer companies need to go beyond the RSPO to stop forest destruction, Greenpeace, September 2013,

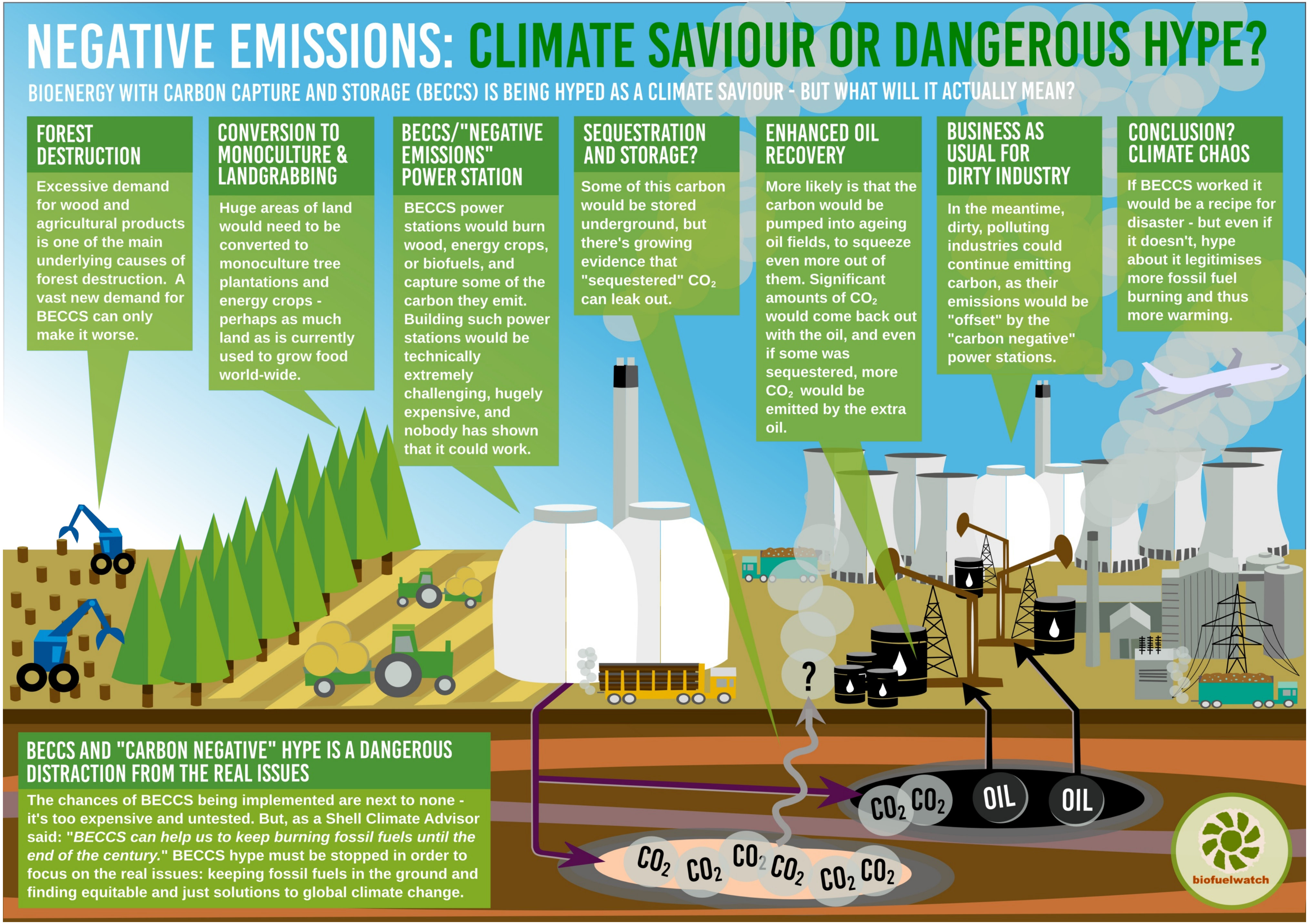
[80] The EU Biofuel Policy and Palm Oil: Cutting Subsidies or Cutting Rainforests, IvettaGerasimchuk and Peng Yam Koh, Global Subsidies Initiative and International Institute for Sustainable Development, September 2013

[81] Bioenergy Out: Why bioenergy should not be included in the next EU Renewable Energy Directive, by NOAH (Friends of the Earth Denmark), Biofuelwatch, Econexus, Global Forest Coalition, World Rainforest Movement, Rettet den Regenwald/ Rainforest Rescue, and Corporate Europe Observatory, September 2015, www.biofuelwatch.org.uk/wp-content/uploads/EU-Bioenergy-Briefing2.pdf

[82] Climate Change 2014: Synthesis Report Summary for Policymakers, International Panel on Climate Change

[83] See relevant studies listed here: http://hub.globalccsinstitute.com/publications/global-status-beccs-projects-2010/2-scientific-background-beccs

[84] www.realclimate.org/index.php/archives/2004/12/just-what-is-this-consensus-anyway/


NEGATIVE EMISSIONS: CLIMATE SAVIOUR OR DANGEROUS HYPE?
BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS) IS BEING HYPED AS A CLIMATE SAVIOUR - BUT WHAT WILL IT ACTUALLY MEAN?
FOREST DESTRUCTION
Excessive demand for wood and agricultural products is one of the main underlying causes of forest destruction. A vast new demand for BECCS can only make it worse.
CONVERSION TO MONOCULTURE & LANDGRABBING
Huge areas of land would need to be converted to monoculture tree plantations and energy crops - perhaps as much land as is currently used to grow food world-wide.
BECCS/"NEGATIVE EMISSIONS" POWER STATION
BECCS power stations would burn wood, energy crops, or biofuels, and capture some of the carbon they emit. Building such power stations would be technically extremely challenging, hugely expensive, and nobody has shown that it could work.
SEQUESTRATION AND STORAGE?
Some of this carbon would be stored underground, but there's growing evidence that "sequestered" CO_2 can leak out.
ENHANCED OIL RECOVERY
More likely is that the carbon would be pumped into ageing oil fields, to squeeze even more out of them. Significant amounts of CO_2 would come back out with the oil, and even if some was sequestered, more CO_2 would be emitted by the extra oil.
BUSINESS AS USUAL FOR DIRTY INDUSTRY
In the meantime, dirty, polluting industries could continue emitting carbon, as their emissions would be "offset" by the "carbon negative" power stations.
CONCLUSION? CLIMATE CHAOS
If BECCS worked it would be a recipe for disaster - but even if it doesn't, hype about it legitimises more fossil fuel burning and thus more warming.
BECCS AND "CARBON NEGATIVE" HYPE IS A DANGEROUS DISTRACTION FROM THE REAL ISSUES
The chances of BECCS being implemented are next to none - it's too expensive and untested. But, as a Shell Climate Advisor said: "*BECCS can help us to keep burning fossil fuels until the end of the century.*" BECCS hype must be stopped in order to focus on the real issues: keeping fossil fuels in the ground and finding equitable and just solutions to global climate change.
?
CO_2 CO_2 CO_2 CO_2 CO_2 CO_2
CO_2 CO_2 OIL OIL
biofuelwatch