

biofuelwatch

Carbon capture from biomass and waste incineration: Hype versus reality

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Abbreviations and technical terms

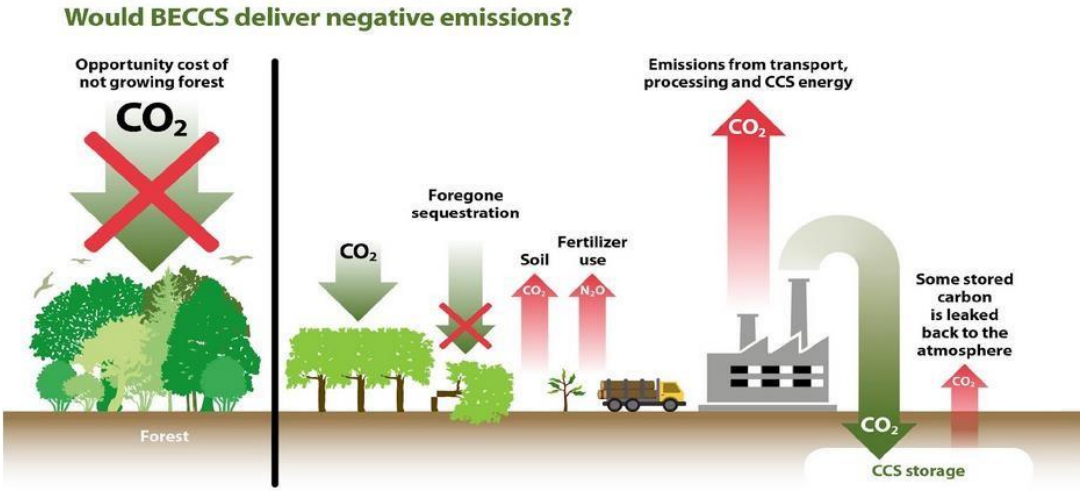
Abbreviation/Term	Definition
Amines	These are organic compounds that resemble ammonia (NH3) except that one or more of the hydrogen atoms is replaced with molecules consisting of carbon and hydrogen (i.e., hydrocarbons). There are many different types and uses of amines. One of them is absorbing carbon dioxide to form a soluble carbonate salt, from which it can be separated again using heat. This is the most common process used in carbon capture.
BECCS	Bioenergy with Carbon Capture and Storage
BECCUS	Bioenergy with Carbon Capture, Utilisation and Storage (see CCUS below)
CCS	Carbon capture and storage: "Storage" is defined as meaning either geological storage, for example in sandstone formations or depleted gas fields, or use for Enhanced Oil Recovery (EOR).
CCU	Carbon capture and utilisation: This involves using captured CO2 for example in the drinks and food industries (fizzy drinks, bicarbonate of soda, etc.) or in greenhouses.
CCUS	Carbon capture, utilisation, and storage: A term to cover both CCS and CCU
DACS	Direct Air Capture and Storage, which would involve removing some carbon dioxide directly from the atmosphere and storing it.
EOR	Enhanced Oil Recovery involves different methods to recover oil after an oil field has been partially depleted, all of them expensive and energy intensive. The most common type of EOR, used widely in the USA, is the injection of carbon dioxide into oil wells, to bring oil to the surface which would not otherwise be exploited.
R&D	Research and Development

1 Introduction

In 2016, Biofuelwatch, in collaboration with Heinrich Böll Foundation, published a report called "Last-ditch climate option or wishful thinking? Bioenergy with Carbon Capture and Storage"[1]. We looked at the concept of Bioenergy with Carbon Capture and Storage (BECCS) and the idea of it being 'carbon negative', i.e. a way to remove CO_2 from the atmosphere which, as we showed, is based on a false understanding of the role which forests and other ecosystems adversely impacted by bioenergy play in regulating the climate, including the carbon cycle.

In this new report, we examine primarily what has happened in the five years since 2016, although we also provide a short history of CCS and BECCS which did not form part of our previous report and which sheds light on technical obstacles and the framing of the debate today.

The fundamental problems with the concept of BECCS remain unchanged: Bioenergy has the largest land footprint of all types of energy, with solar PV converting around 30 times more of solar radiation per hectare into useful energy compared to trees or crops.[2] Procuring large quantities of biomass energy thus necessitates either logging more trees in forests, or converting more agricultural land or natural ecosystems to tree or crop plantations, both of which destabilise the climate and accelerate the extinction crisis. If it was possible to produce bioenergy with carbon capture on a large scale, those impacts would become even worse because carbon capture itself is highly energy intensive. Rather than discussing those fundamental concerns further, we include a list of some recent reports and articles for further reading at the end.



Source: fern.org/news-resources/six-problems-with-beccs-57/

The most important development unfolding in relation to BECCS and CCS in general is in the political arena: even though evidence of the persistent failure of CCS projects is mounting,[3] industry and government support for carbon capture and especially BECCS has grown. At the time of writing this report, oil and gas companies represented at UNFCCC COP27 are pushing for CCS to be included in carbon trading mechanisms.

They specifically want to see carbon credits for 'removals' in the case of BECCS, a term that, as shown in this report, has also been appropriated by several waste incineration companies.[4] And, at the end of November 2022, the European Commission is expected to publish a proposal for a new framework to certify carbon removal offsets in the EU, first announced in December 2021.[5] Clearly, CCS, including BECCS, is used by the fossil fuel

industry to divert attention from the impact of their business and to undermine policies that would restrict coal, oil and gas exploration and burning.

Actual, 'on the ground' developments related to BECCS have been modest, except for new, very large-scale plans for carbon capture from ethanol fermentation, together with associated CO_2 pipelines, in the USA.

There has been a growing number of pilot and demonstration projects involving carbon capture from biomass plants and waste incinerators in Europe and Japan. Carbon capture from waste incineration is increasingly framed as 'carbon negative' and a form of BECCUS[6], based on claims that a high percentage of the mixed waste they burn is of biogenic origin rather than coming from fossil fuels.

Proposals for commercial carbon capture from biomass and waste incineration are being progressed – the largest of all by Drax Group in the UK, however, as this report shows, there are good reasons to doubt that anybody has the technical know-how to make such projects work.

2 CCS and BECCS: A short history and overview of recent developments

History of CCS

The first recorded 'carbon capture' project was in Texas, where CO_2 removed from a fossil gas processing plant was captured and injected into the nearby Kelly-Snyder Oil Field to try and extract additional oil – a process now known as Enhanced Oil Recovery.[7] Injecting that CO_2 into the oil field proved a great success for the oil industry: today, 15 million tonnes of crude oil are recovered annually in the US using this method,[8] resulting in what could be more than 6 million tonnes of additional CO_2 emissions from fossil fuel burning to the atmosphere.[9] Today, 85% of CO_2 used for EOR comes from natural reservoirs and not from carbon capture.[10] Yet more than 70% of CO2 captured worldwide is currently used to pump more oil out of the ground,[11] showing how closely carbon capture is linked to fossil fuel industry interests.

The fact that the first CO_2 used for EOR came from a gas processing plant is often cited as evidence that carbon capture is a mature technology and that, with enough government support, it would be possible to capture unlimited quantities of carbon.12 This, however is simplistic.

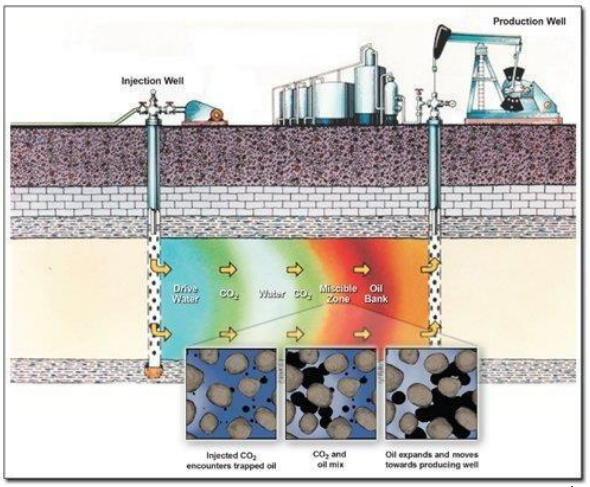
It is true that amines have been used since at least the 1930s to remove mostly hydrogen sulphide (H2S) but also CO_2 from fossil gas. This is called 'gas sweetening'. It is done to stop the highly toxic H2S being emitted, and to protect gas pipes from corrosion.[13] H2S itself is also a suitable gas for EOR,[14] and we can find no evidence as to whether the early, 1970s, carbon capture- EOR project actually involved pure CO_2, rather than a mixture of both gases.

These days, different methods are also used to capture CO_2 from gas processing plants, some of which are more energy efficient but cannot so far be used for carbon capture from power and heat plants.[15] The vast majority of the CO2 removed during gas purification is still vented into the atmosphere.

And although the sector with the largest number of commercial-scale CCS projects today is fossil gas processing,[16] actual carbon capture in such projects has been below expectations. The world's longest standing, as well as largest, CCS project involves carbon capture from a gas processing plant in Wyoming, USA (Shute Creek), developed for EOR (now classified as 'carbon storage').

> *"despite its improved performance over recent years, the plant has reached its capturing capacity target (about 75% of total CO_2 emissions) in only a few of those years. At all other times, the plant has fallen short, mostly by a wide margin."* (17)

The gas being processed at a particularly high CO2 content of 65%, making it easier and cheaper to capture. According to the Institute for Energy Analysis and Financial Analysis (IEEFA)[17]:



Recovery works, Source: energy.gov/fecm/science-innovation/oil-gas-research/enhanced-oil-recovery

Actual research and development of CCS as a supposed climate mitigation technology only started in the late 1990s, when Statoil, fully owned by the Norwegian government, started injecting CO2 captured from a gas processing plant into a geological formation (Sleipner project). The very first commercial-scale carbon capture from a power plant started in 2014 and remains the only one in operation today: Boundary Dam in Saskatchewan, Canada – a project beset with problems discussed in our 2016 report as well as in the IEEFA report referred to above.

Overview of CCS projects today

According to the latest, 2021, Status Report by the Global CCS Institute, there were 29 operational commercial-scale CCS projects worldwide in 2021.[16] 13 of those projects, involve capturing carbon from pure CO_2 streams, three of them from ethanol fermentation.[17] Capturing a pure CO_2 stream is far simpler and cheaper than trying to capture carbon from the flue gases of power and heat plants which contain a lot of different chemicals and pollutants.

73% of carbon captured is used for Enhanced Oil Recovery (EOR),[19] i.e., it is pumped into a partially depleted oil well in order to get more oil out of the ground than would be feasible without some form of EOR. Although most of the captured CO_2 is then reinjected and stored, the of amount additional CO_2 emitted by burning fossil oil that would otherwise have remained underground is far greater.

History of BECCS

With the exception of carbon capture from ethanol fermentation (discussed below), and a small number of experimental pilot projects, BECCS remains a purely theoretical proposition. As detailed in an article published by *Carbon Brief,* the first record of the idea of 'carbon negative' CCS with biomass comes from an email exchange between James Rhodes and David Keith in 2000.[20] Keith has since become one of the prominent researchers and proponents of climate geoengineering[21]. As the founder of the company Carbon Geoengineering, his main focus is now Direct Air Capture rather than BECCS. The following year, two people not linked the above, Michael Obersteiner from the International Institute for Applied Systems Analysis (IIASA) and Kenneth Möllersten, a Swedish researcher looking at opportunities for the pulp and paper industry to benefit from carbon trading, published a paper proposing BECCS (albeit with a different acronym). This 'partnership' is particularly interesting: on the one hand, BECCS is being investigated by pulp and paper companies looking for carbon credits. On the other hand, IIASA plays an important role in producing Integrated Assessment Models for the Intergovernmental Panel on Climate Change (IPCC)[22]. It is those models which have helped the concept of BECCS become prominent in the discourse on climate mitigation, where, including at the UN level, it is now being used by fossil fuel interest groups to undermine curbs on their practices. To this day, IIASA, claims that BECCS can remove carbon from the atmosphere and that such removals are necessary "on a huge scale".[23]

3 Technical and economic challenges of capturing carbon from biomass or mixed waste combustion

A good description of the fundamental problems with capturing carbon from power and heat plants is found on the website of an EU project funding R&D into alternatives to removing CO_2 with amine solvents, by far the best proven and most mature carbon capture method:[24] Its limitations include "high energy demand for regenerating the solvent and environmental problems such as volatile amine loss and reactor corrosion, which are not completely solved by using mixed amines rather than monoethanolamine (MEA)".

CCS, including BECCS, proponents commonly argue that the main barriers are not technological ones, but "of a socio-economic, political and institutional nature",[25] i.e. a lack of funding, including through carbon markets.

However, technological versus economic/political barriers is a false dichotomy. Thus, the world's only commercial power station with carbon capture, Boundary Dam in Saskatchewan, has been using 30-31% of the plant's energy to capture and compress CO2,[26] one of the main reasons why carbon capture from power and heat plants remains uneconomic. Problems such as amine degradation and corrosion (a problem reported by AVR in relation to carbon capture from their Duiven waste incinerator) push costs up further.

Capturing carbon from biomass and mixed waste combustion poses additional challenges compared to carbon capture from coal plants. A report from 2021, commissioned by the UK government,27 summarises the key challenges related to biomass plants, all of them involving impurities in the flue gases:

> *"Biomass retrofits and new-build also face additional challenges because of the impurities in the flue gas. While these will be at acceptable levels for emission to atmosphere, they may cause unacceptable consequences in the PCC unit, i.e. from particulates, SOx and NOx."*

Flue gases from the combustion of biomass, or for that matter mixed waste, have a different chemical composition than those from burning coal. Specific concerns raised in the 2021 report, in relation to biomass plants, are:

- Sulphur oxide (SO_x) emissions: In the absence of any mitigation, coal plants emit a lot more SO_x than biomass plants. For that reason, they have to be fitted with expensive equipment to remove such emissions, called Flue Gas Desulphurisation (FGD). However, SOx emissions from biomass plants are still high enough to cause amines to degrade or to allow them to be carried to other parts of the plant where they cause corrosion. We are not aware of FGD having been proposed for any of the biomass or waste incineration carbon capture projects listed below. Drax Group, who is proposing the largest-scale carbon capture project ever, is even planning to demolish existing FGD equipment first![28]

- Ash properties are different, which can affect amines degradation;
- Small particulate emissions: addressing amine degradation from small particulates may require adapting mitigation technology and the use of a more expensive one.

Finally, most biomass plants are less efficient than coal plants, which means that there is a larger amount of CO_2 to capture per unit of energy generated, which increases the so-called energy penalty, i.e., the amount of energy required for carbon capture and compression.

The biggest difference between carbon capture from coal and biomass or mixed waste, however, is that there have been decades of R&D into carbon capture from coal, yet very little in relation to biomass and mixed waste combustion. Overview of CCS projects involving biomass or mixed waste production

Why do we include carbon capture from waste incineration in a report about BECCS?

Each tonne of mixed waste that is incinerated emits between 0.7 and 1.7 tonnes of CO_2 in total (tinyurl.com/syhkuehb). However, under UNFCCC carbon accounting rules, CO_2 emissions from burning biomass are not accounted for in the energy sector. This extends to what is classed the "biogenic fraction" of mixed waste, such as food waste, paper and waste wood. In the EU and elsewhere, this accounting rule – or loophole – has led to mixed waste incineration benefitting from renewable energy subsidies and counting towards renewable energy targets, even though so-called biogenic waste is burned together with waste from fossil fuels. It provides a strong incentive against separate waste collections that are required for maximising recycling or, in the case of food waste, anaerobic digestion (a cleaner and more efficient form of energy generation for this type of waste). Furthermore, renewable energy subsidies for mixed waste incineration directly incentivise burning more plastic, which undermines waste reduction as well as recycling.

If proposals within UNFCCC, the EU and elsewhere to introduce carbon credits and offsets for 'removals', especially BECCS, are implemented, any waste incinerator operator wanting to take advantage of subsidies and carbon credits for CCUS would want to increase the biogenic content of the waste to more than 50% or even burn some virgin wood together with the waste to get over that threshold. It is therefore not surprising that some companies operating waste incinerators already speak about the prospect of becoming 'carbon negative'.

We searched data compiled by the Global CCS Institute, the International Energy Agency, including its Greenhouse Gas R&D Programme, as well as data from the Horizon Europe, the EU Innovation Fund, as well as undertaking broader web searcher to identify projects. We limited the search to projects with evidence of CO_2 having been captured from biomass plants or waste incinerator, regardless of the scale of carbon capture, and projects not yet implemented but which have attracted funding or for which subsidies have been applied for. We also included a proposed project by Marubeni and PT Pertamina which has not yet attracted funding, but which involves a Memorandum of Understanding and a finance plan involving carbon credits.

Unless we had found the answers already, we emailed each of the companies with an ongoing carbon capture project to ask how much CO_2 had been captured in the past 12 months, what the longest continuous period of carbon capture has been, and how much energy has been required to capture a tonne of CO_2.

Amager Bakke waste incinerator, Photo: Zero Waste Europe

Amager Resource Centre (ARC), Denmark (mixed waste)

ARC operates the Amager Bakke waste incinerator in the centre of Copenhagen. It opened in 2017 and, according to a 2019 report by Zero Waste Europe, it "*has been a technical and financial fiasco…, is double the size needed and [that] may need to import more and more foreign waste if it is to keep running.*"[29]

ARC and its carbon capture plans made headlines in the Danish media in September 2022, when the City of Copenhagen declared it was forced to give up on its goal of becoming 'carbon neutral' by 2025, a goal which, it transpired, had relied on CO_2 emissions from the Amager Bakke plant

being captured and stored. Apparently, ARC's efforts to attract subsidies for this had been unsuccessful.[30]

In fact, Copenhagen City's announcement simply exposes their prior 'carbon neutrality' announcement as mere hype in the absence of any credible plan, given that ARC has never been close to capturing half a million tonnes of CO_2 a year, a figure cited on its website.[31]

Having received over €4m from a Danish government R&D grant programme,[32] the company undertook small-scale tests between August 2021 and April 2022. In response to our questions, ARC informed us that "*the purpose of the campaign was not to capture a lot of CO2, but instead to demonstrate that it is actually possible to capture CO2 from a varying stream of gas from a waste-to-energy plant*". They further explained that they tested many different solvent configurations, usually for a period of just four hours. As part of the same government-funded R&D project, ARC is planning a further trial starting in autumn 2023, to test a smaller number of solvents, to capture as much as 4 tonnes of CO_2 and to compress that CO_2 so that it can be sold rather than being emitted again to the atmosphere.[33]

AVR Afalverking, Netherlands (mixed waste)

Duiven waste incinerator, Photo: Michielverbeek

AVR is a Dutch waste management company operating several waste incinerators which mix biomass (woodchips) with mixed waste. Backed by a €4.4 million Dutch government subsidy, AVR installed carbon capture equipment at its incinerator in the town of Duiven, Gelderland in 2019. In response to our query about the amount of CO_2 captured over the past 12 months, AVR pointed us to their 2021 Annual Report and said that the amount of energy required to capture and compress CO_2 was 'confidential'. According to that report, 42,470 tonnes of CO_2 were captured in 2021. Although less than the capture capacity of 60,000 tonnes, this is far more than has been captured from any other waste incinerator to date, assuming that Twence B.V. and Toshiba, both of which failed to respond to us or to publish their results, are not hiding record successes. However, the amount of carbon captured in 2021 was still only 10.6% of the plant's emissions and AVR reported problems with corrosion caused by the amine solvent in late 2021. The company did not answer our question about carbon captured during the twelve months up to October 2022, so we will have to wait for the next Annual Report to find out whether corrosion problems have significantly disrupted carbon capture.

All of the CO_2 is sold to greenhouses, which means that it is emitted back into the atmosphere. Furthermore, greenhouse horticulture in the Netherlands is a highly energy intensive sector, consuming 9% of all fossil gas burned in the country to grow flowers, fruit and vegetables out of season or unsuited to Dutch climate, much of it for export. Clearly, CO_2 capture to supply such greenhouses has no role to play in climate change mitigation.

AVR has applied for multi-year subsidies to install a much larger carbon capture facility at its plant in Rozenburg, South Holland. It seems highly problematic to us that the company will not and does not have to publicly disclose how energy-intensive its carbon capture is, nor how much carbon has been captured in recent months given that they are applying for a multi-million Euro subsidy.

Drax Group, UK (biomass)

Drax Power Station, Photo: Biofuelwatch

This is by far the most ambitious CCS project ever announced. Drax Group has applied for planning permission to capture at least 8 million tonnes of CO_2 from

two of its biomass power station units in Yorkshire, England by 2030. That CO_2 would be transported and pumped into a geological reservoir under the North Sea using pipelines that do not even have planning approval so far. By comparison, Norway's carbon sequestration sites under the North Sea have a combined capacity of 1.8 – 2 million tonnes a year – and the UK has no experience with carbon sequestration so far. The

amount of carbon Drax claims it will capture is equivalent to more than one-fifth of all CO_2 captured globally right now (most of which comes from pure CO_2 streams or gas processing).

Drax wants to capture carbon from two existing power plant units which are burning millions of tonnes of imported wood pellets every year. Drax's power station, which burns more wood than any other plant in the world, has been widely condemned due to impacts on forests, climate and communities.[34] Here, however, we focus on the credibility of Drax's claims, including their assertion that "the technology is proven".[35]

Up until now, Drax has carried out two small-scale carbon capture trial using different types of solvents. The first of those trials, involving a 'novel' solvent never used before by a startup company called C-Capture appear to have ended in failure.[36] The second trial also tested another new solvent, this one developed by Mitsubishi Heavy Industries Engineering (MHIEng), over a period of just 90 days. Drax captured a total of no more than 27 tonnes of CO_2. In response to questions, Drax stated: "*the aim of the trial was to not to prove operational reliability, as a pilot plant is not representative of a large-scale process in that regard.*" Nor, they confirmed, was the trial designed to learn how much energy would be required for carbon capture.[37]

Clearly, the prospect of a company being able to develop the world's biggest CCS project after capturing a mere 27 tonnes of CO_2 during 90 days of testing is far-fetched. Even more so when there is no other experience of capturing CO_2 from wood combustion to learn from.

So what is behind these unrealistic claims? Drax's current renewable energy subsidies – amounting to over €1.1 billion in 2021, are due to end in 2027. There is little prospect of Drax getting new subsidies without installing carbon capture equipment. Yet, under a current UK government proposal, Drax will not actually have to capture any or much CO_2 to then get further subsidies, guaranteeing long-term profits for the company.[38]

Hafslund Oslo Celsio, Norway (mixed waste)

Klemetsrud waste incinerator, Photo: Bjoertvedt, Wikimedia

Hafslund Oslo Celsio owns Norway's largest waste incinerator, Klemetsrud, in Oslo, following Fortum Oslo Varme's sale of their shares in the plant. Fortum Oslo Varme carried out two CO2 capture trials at the plant, using different types of solvents. The first one, in 2016, captured 376 tonnes of CO_2 over a period of 3,530 hours,[39] and the second, in 2019, captured 750 tonnes over 5,000 hours.[40] No information about the amount of energy required to capture the carbon was published.

Despite the modest amount of CO_2 captured during those trials, Hafslund Oslo Celsio has been awarded the equivalent of over €288 million to install carbon capture equipment with a capacity of 400,000 tonnes per year.[41] This is in addition to around €1.73 billion in public funding for a new CO_2 transport and sequestration project which would source any carbon captured at the Klemetsrud plant as well as from a cement plant.[42]

HVC Groep, Netherlands (mixed waste and waste wood respectively)

HVC Alkmaar waste incinerator, Photo: Reinier Sierag, Flickr

HVC Groep operates a number of waste incinerators as well as a waste-wood fired biomass plant in the Netherlands. Having received a government grant of €500,103,[43] HVC started carbon capture tests at its waste wood biomass plant in Alkmaar, North Holland, in 2018. The test or pilot facility has a capacity to capture 0.54 tonnes of CO_2 a day. When the project started, HVC said that the this would be sold to greenhouses.[44] However, no trial results have been published by either HVC or their project partners, the statutory research organisation TNO. The company failed to respond to our query.

Despite the lack of (or secrecy behind) any evaluation of the carbon capture trial, HVC hopes to get significant multi-annual subsidies for a much larger demonstration project to capture 45,000 tonnes of CO_2 a year for greenhouses. According to HVC, this could be applied either to the waste wood biomass plant or to one of their waste incinerator units, even though the company has never tested carbon capture on flue gases from burning mixed waste.[45]

Marubeni and PT Pertamina, Indonesia (biomass)

Acacia plantation for pulp and paper, Sumatra, Photo: Rhett A. Butler, Mongaba

In February 2022, the Japanese Marubeni Corporation announced signing a Memorandum of Understanding with Indonesia's state-owned energy company Pertamina to develop a BECCS project.[46] The project would be located at Marubeni's pulp mill, PT Tanjungenim Lestari, in South Sumatra and would presumably aim to capture carbon from the combustion of wood from Marubeni's nearby industrial acacia plantations. Both companies are looking to carbon credits for financing such a project.

We have included this proposal in the report for two reasons: Firstly, it shows how proposed carbon credits for 'removals' through BECCS are starting to translate into concrete project plans. And secondly, if implemented, this would be the first BECCS project in a country in the global South. It would be based at a pulp mill built against strong local protests over land conflicts in 1999/2000,[47] capture wood from acacia plantations, which in recent decades have been one of the two main drivers of rainforest destruction in Sumatra and, furthermore, it could create an additional demand for plantation wood to provide additional energy for carbon capture.

Öresundskraft AB, Sweden (mixed waste)

This is an energy provider and distributor owned by the municipality of Helsinborg in southern Sweden. In October 2022, the carbon capture company CO2 Capsol announced that Öresundskraft had started testing its carbon capture method at the Filbornaverket waste incinerator.[48] This is a four-month test programme subsidised by the Swedish Energy Agency. CO2 Capsol speaks of a potentially to eventually capture 210,000 tonnes CO_2 per year from the plant, but there are no concrete plans. CO2 Capsol's patented technology involves Hot Potassium Carbonate rather than amines, and it has never been used to capture carbon from power or heat plants at scale. It is discussed further in the section about Stockholm Exergi's BECCS project below.

Ørsted, Denmark (biomass)

Avedøre Plant, Photo: Orf3us, Wikimedia

Ørsted is a multinational energy company majority-owned by the Danish government.In 2017, the company, then called DONG Energy, announced that it would phase out burning coal in 2023.[149] Since then, Ørsted has replaced most of its coal- derived electricity with wind energy and most of its coal-based district heating with biomass, much of it in the form of imported woodchips and wood pellets from the Baltic States and elsewhere.

In June 2022, Ørsted announced plans to capture a total of 400,000 tonnes of CO_2 from two of its biomass plants: the Asnæs plant in Kalundborg and the Avedøre plant south of Copenhagen. The company has applied for some of the €108 million in future annual subsidies for CCS included in the Danish Climate Agreement for Energy and Industry.[50] Ørsted wants to sequester some of the captured CO_2 off the shores of Norway, as part of the sequestration project mentioned above in relation to the Hafslund Oslo Celsio project. The remainder is to be used for a Power-to-X "Green Fuels" project to make aviation fuel.[51] Neither sounds likely in the near term: the Norwegian carbon sequestration project, called Northern Lights, is to have a capacity to store 1.5 million tonnes of CO_2 a year from 2025. 800,000 tonnes capacity has been reserved for the two Norwegian projects,[52] and another 800,000 tonnes for future carbon capture from fertiliser production by Yara in the Netherlands.[53] Ørsted is also part of a consortium exploring potential carbon sequestration, called Bifrost,[54] which the Danish government is funding with around €10 million,[55] however, this remains in the early development stages. The "Green Fuels" project involves a technology never tried at scale anywhere in the world.

There is no record of Ørsted having undertaken any carbon capture trials and as discussed above in the section about Drax, no company has ever captured more than Drax's total of 27 tonnes of CO_2 from wood combustion.

In short, Ørsted has applied for large long-term subsidies in order to capture hundreds of

[1] The Danish coal phaseout has recently been delayed by the Danish government mandating Ørsted to keep two coal-fired and one oil-fired plants in operation until 2024 due to Russia's war against Ukraine.

thousands of tonnes of CO_2 in the absence of any experience with such a technology, in order to sequester carbon in hitherto non-existent geological storage sites and/or use it to make aviation fuels in a way nobody has ever demonstrated to be possible.

Resolute Forest Products, Canada (biomass)

Resolute Forest Products is a Canadian pulp and paper company. In North America, the company became well-known after responding to campaigns by environmental organisations including Greenpeace and Stand.earth against its logging practices with SLAPP suits for hundreds of millions of dollars. Most of Resolute's claims were dismissed by the courts in 2019,[56]and in 2020, the company was ordered to pay Greenpeace nearly $1 million in expenses.

In 2014, Resolute Forest Products became invested in a BECCS demonstration project.[57] In March 2019, it commissioned carbon capture equipment from CO_2 Solutions at its Saint-Félicien pulp mill in Quebec, with a capacity of 30 tonnes of CO_2 per day.[58] The project was part funded by the federal Canadian government and the Province of Quebec. The technology was based on a novel enzyme mix development by CO_2 Solutions as an alternative to amine solvents. Captured CO_2 was to be used in greenhouses rather than being sequestered, and a six-months trial was to be followed by commercial operation. At the end of the trial phase, the company reported an apparently glowing audit by the consulting and engineering company Tetratech.[59]

Yet CO_2 Solutions was not doing well. By January 2020, the company had been forced to sell its assets under bankruptcy proceedings.[60] Its carbon capture patents and the facility at the pulp mill were taken over by the Italian energy company Saipem, which invests mostly in oil and gas. Other than a Saipem webpage about the carbon capture trial, there are no indications that the project is continuing let alone being scaled up. We had no response to our email query to Resolute Forest Products which, in any case, is currently in the process of being taken over by the Indonesian pulp and paper giant APP under its global name Paper Excellence.[61]

In short, the millions of dollars of federal and provincial government subsidies have failed to yield even one peer-reviewed article, let alone any breakthrough as far as BECCS technology is concerned.

Stockholm Exergi, Sweden (biomass)

Stockholm Exergi is owned 50:50 by a private consortium and by the City of Stockholm and provides district heating and cooling and electricity for Sweden's capital. The company operates several biomass combined heat and power (CHP) plants and claims that its Värtan plant (KVV8) is Europe's largest biomass CHP plant. It burns woodchips.

Carbon capture tests using flue gases from the Värtan biomass plant started in 2019,

trialling patented Hot Potassium Carbonate (HPC) supplied by CO2 Capsol.[62] Those tests are supported with a grant from the Swedish Energy Agency.63 In response to our query, Stockholm Exergi informed us that the pilot unit has a capacity to capture one tonne of CO_2 per day, but that the amount captured is not recorded. The longest period of continuous operation of the carbon capture unit was two weeks. They further pointed us to a peer-reviewed article from 2021, according to which this carbon capture technology is not just less energy intensive than conventional amine solvents but could actually result in more heat being supplied using the same amount of fuel compared to operating a plant without carbon capture.[64]

A carbon capture method that made power and heat plants more and not less efficient would surely be the biggest breakthrough in carbon capture research and development ever. However, the history of CO2 Capsol's technology has been far from illustrious.

It was originally developed and patented by the Norwegian technology company Sargas, in collaboration with the Swedish Royal Institute of Technology, Massachusetts Institute of Technology and Siemens, adapting a process previously used for fossil gas sweetening.[65] In 2007 and early 2008, Sargas tested their technology on the same site, on flue gases from the then Värtan coal plant operated by Fortum Varme at the time.[66] At the start of the trial, authors from the Swedish research agency SINTEF and from Sargas predicted: "*On this basis it is supposed that the Sargas technology will be deemed commercially available within 2007.*"[67] It wasn't. The carbon capture trial on the coal plant was not extended, and no other company seems to have chosen to trial Sargas's HPC technology. Eventually, Sargas filed for bankruptcy and, in 2015, CO2 Capsol acquired the patents. It is now trying to revive this technology.[68]

Despite this history, and despite the fact that Stockholm Exergi has so far only carried out very small-scale, intermittent limited testing, it was awarded €180 million from the EU Innovation Fund in April 2022, in order to develop a commercial scale facility to capture 800,000 tonnes of CO_2 a year.[69] Furthermore, Stockholm Exergi is in a good position to attract additional funding under a new subsidies scheme for BECCS, set up by the Swedish Energy Agency.[70]

Stora Enso, Sweden (biomass)

Skutskär pulp mill, Photo: Papper, Wikimedia

Stora Enso is a multinational pulp and paper and timber company with its headquarters in Finland. There is long history of campaigns and protests against different Stora Enso activities, especially in South America, but also in

Europe. For example, in 2017, 56 travel, ecotourism and guide companies signed an open letter protesting against the felling of high conservation value forests in Sweden by companies including Stora Enso.

In 2020, forest activists in Estonia, spoke out against the company's destructive logging practices in their country.[71]

Stora Enso is the third company to trial carbon capture from biomass combustion at a pulp mill. It plans to start a trial at its Skutskär Mill in eastern Sweden in early 2023. For this it has been awarded EU funding,[72] as well as a research and development grant from the Swedish Energy Agency.[73]

Taihei Dengyo Kaisha, Japan (biomass)

Taihei Dengyo Kaisha is a construction company which also operates the Seifu Shinto biomass power station in Hiroshima. This is a medium sized, 7.1 MW, power station burning woodchips.[74] In December 2021, Mitsubishi Heavy Industries Engineering reported that they had received an order to instal the same type and scale of carbon capture unit trialled by Drax (see above) at the Seifo Shinto plant, to try and capture 0.3 tonnes of CO_2 per day.[75] The project commenced in August 2022.[76] We submitted a query regarding the progress of this project on the company's contact form on 10th October 2022, but did not receive any reply.

Toshiba, Japan (mixed waste and biomass respectively)

Saga City waste incinerator

Toshiba started studying carbon capture at the Saga City waste incinerator in Japan in 2013, installing a small capture facility with a capacity of 0.1 – 0.2 tonnes of CO_2 per day, using an amine solution.[77] It claims to have been operating a commercial carbon capture facility at that incinerator since 2016, capturing 10 tonnes of CO_2 per year. The carbon dioxide is used to fertiliser algae on a nearby microalgae farm, to produce anti-ageing skin cream, according to a blog article by the Global CCS Institute entitled *"Saga City: The world's best kept secret (for now)."*[78] The article's title seems apt, considering that no results from the original trials nor from the ongoing project appear to have been published anywhere. After an email query and a query sent via Toshiba's contact form about their Mikawa BECCS project (see below) failed to elicit a response, we did not try sending further queries about carbon capture in Saga City.

There is some evidence that carbon continues to be captured from that waste incinerator, namely a 2022 announcement about a research project into efficient soybean production with plans to use CO_2 from the waste incinerator.[79] How well the carbon capture plant is operating, how much CO_2 is actually being captured and how much energy it requires – all of this clearly remains a "best kept secret". What is certain, however, is that using CO_2 to grow algae or soybeans contributes nothing to climate change mitigation.

Mikawa Biomass Plant

This is a 50 MW electricity-only power station in Fukuoka, Japan, operated by Toshiba, which burns palm kernel shells (PKS). In 2019, eight environmental NGOs active in Japan published a joint statement on biomass energy in which they warned, amongst other things, that Japan allowed biomass energy from burning PKS to be subsidised even if PKS it burns from plantations for which, for example, tropical peatlands were drained. A paper published by Chain Reaction Research in 2021 shows that 70% of PKS burned in power stations in Japan comes from Indonesia and 30% from Malaysia. Beyond that, there is no traceability of PKS used for energy. It is clear, however, that subsidies for burning this residue translate into additional residues for oil palm companies in a region where palm oil is the single biggest cause of deforestation.

Palm kernel shells, Photo: Suhardiyoto Haryadi, Flickr

In October 2020, Toshiba announced that that "it has started the operation of a large-scale carbon capture facility at Mikawa Power Plant" and that "the new facility to commence operation will be

the world's first Bio energy power plant to be applied with a large-scale Carbon Capture and Storage (BECCS) capability."[80] Yet in September 2021, in a news update,[81] Toshiba referred carbon capture from the Mikawa biomass plant as a 'demonstration project' that ran from November 2020 until March 2021'. Future plans for carbon capture tests at the plant were mentioned, yet nothing has beenpublished about the results of the 2020/21 carbon capture trial, and two information requests from us remain unanswered.

Twence B.C., Netherlands (mixed waste)

Twence is a Dutch company that invests mostly in waste processing and incineration and in biomass energy projects. It operates one waste incinerator, in Hengelo in Overijssel. Twence commenced carbon capture trials at the Hengelo incinerator in 2014, in collaboration with the Dutch Association for Applied Scientific Research, TNO, using at least two different types of solvents provided by two different companies.[82] Furthermore, a new carbon capture and mineralisation technology has been tested to produce sodium bicarbonate used for scrubbing the plant's flue gases.[83] Since 2014, the capture capacity has been increased from 5 to 12 tonnes of CO_2 per day, with CO2 being sold to greenhouses. Although some research results, namely about solvent degradation and air emissions from amine degradation, have been published by the research organisation SINTEF,84 no information about the amount of CO_2 captured, about the continuity of carbon capture achieved, or about the energy requirement appears to have been published. Our query to Twence received no response.

Twence has been receiving EU subsidies for the carbon capture trial. In May 2022, solvent provider Aker Carnon Capture announced an order for a 100,000 tonnes per year CO_2 capture unit to be ready by the end of 2023. This willbe funded with a €14.3 million subsidy from the Dutch government.85

Compared to, say, Drax or Stockholm Exergi, Twence has spent significantly more time and efforts on carbon capture trials, and the proposed 'jump' from demonstration to commercial scale is less than three-fold – rather than thousands or even millions of times greater. Nonetheless, the lack of publicly available information about the success of the trials so far seems disappointing given the size of the public subsidy awarded. More concerning still is the fact that such large subsidies should be spent on a project with no other purpose than selling CO_2 for greenhouses which provides at best an economic benefit to the horticultural industry, but no benefit to the climate.

Veolia, France (mixed waste)

Veolia is a large European waste management company with its headquarters in France.

According to Veolia's French website,[86] the company is capturing CO_2 from the Sedibex waste incinerator in Le Havre, which has been part of a carbon recovery research project since 2009. According to that webpage, a commercial-scale carbon capture unit with a capacity of 12,000 tonnes of CO_2 per year was built after two years of testing from 2011 to 2013, and the CO_2 is, trucked to two industrial sites to produce additives for lubricants. However, there is no other information to be found to suggest that this is currently happening.

In 2015, Veolia had stated that it was going to decide the following year whether to invest in a carbon capture facility at Sedibex, following a trial.[87] No subsequent announcement appears to have been made.

Veolia is part of a joint venture with a carbon capture company, called Veolia Carbon Clean, however, its English webpage about carbon capture and 'negative emissions' makes no mention of the Sedibex plant.[88]

A query we submitted via Veolia's contact form received no response.

4 Hype around BECCS and carbon capture from waste incineration

The limited or non-existent progress of carbon capture form biomass or waste incineration does not prevent operators and other proponents from making sometimes extraordinary claims, which stand in sharp contrast to the actual status of carbon capture described in the previous centre. Here are some examples:

- Drax Group(who have so far captured a total of 27 tonnes of CO2):89

"The technology is proven, developers are bringing forward projects, and the most forward-thinking companies are actively seeking to buy removal credits from BECCS and DACS developers"

- Stockholm Exergi (who have undertaken small-scale carbon capture testing on a biomass plant using a technology never proven for capturing CO2 from power or heat plants)90

"BECCS is one possible way of slowing global warming and ultimately rebalancing the climate sustainably. Stockholm Exergi's calculations show that there is potential to capture 800,000 tonnes of carbon dioxide per year at our bio-cogeneration plant...Combine this with the rest of Stockholm and other companies' operations, the potential is even greater, amounting to two million tonnes per year."

- Ørsted (who have not even trialled small-scale carbon capture from biomass plants):91

"The Klemetsrud project has an impact beyond the city borders of Oslo. Bellona has worked with cities, industry, and the EU to show how CCS is necessary for rapid and deep decarbonisation"

- Bellona (environmental non-profit organisation with its headquarters in Norway, long- time proponents of CCS, including BECCS about Hafslund Oslo Celsius's announcement announced carbon capture plans from the Klemetsrud waste incinerator:[92]

"All of the CO_2 (from biogenic and fossil sources) in one waste energy facility could be captured, the plant would become CO_2-negative. It's not just the extra CO_2 that's removed, but also the CO_2 that was already in circulation. Active CO_2 is thus removed from the atmosphere instead of being recycled. Because carbon capture can lower the total amount of CO_2 in the atmosphere, the technology is considered one of the tools that can help effectively limit global warming in the short term."

- Amager Resource Centre (which has captured only a very small amount of CO_2 from its Amager Bakke waste incinerator so far):[93]

"The Plant is a shining example (literally) of a fully integrated CCS project where trash becomes treasure at the same time as helping meet international climate change targets…Global CCS CEO, Brad Page, says the Saga City Incineration Plant is one of the best global environmental stories that hasn't been told. 'If the rest of the world followed this model, climate change would quickly become a thing of the past. As such, the Saga City CCU story is unlikely to remain a secret for much longer."

- Global CCS Institute about the Saga City carbon capture project from waste incineration – a project that involves using captured CO_2 to grow algae for anti-wrinkle skin creams.[94]

"With carbon capture at the Asnæs and Avedøre CHP plants, we'll be able to capture 400,000 tonnes of carbon from 2025, which can be stored in the North Sea. This will contribute significantly to realising the politically decided climate target for 2025."

Carbon capture from ethanol fermentation

As we have seen above, the main challenges connected to carbon capture relate to the use of amine (or other, more novel) solvents. Ethanol fermentation results in a highly pure stream of CO_2.

Therefore, no solvents are needed for carbon capture.[95] This makes ethanol refineries attractive to proponents of BECCS, since no other type of carbon capture linked to bioenergy is anywhere close to succeeding at scale.

Why are ethanol refiners interested in carbon capture?

Ethanol producers have long captured and sold carbon dioxide, for example to make fizzy drinks or bicarbonate of soda, simply in order to get more revenues. For many years, they did so without calling it "BECCS" or relating it to the wider debates about carbon capture.[96] Indeed, a lot of businesses in the food and drinks industries depend on CO_2 captured from ethanol or fertiliser production.

Growing government support for CCS offers ethanol producers additional subsidies. This could become a potential lifeline for the industry in the USA, where ethanol output has been static since 2017 and may be in decline,[97] due to the fact that the 10% ethanol blending limit for conventional car engines has been reached and that electric vehicles are proving more attractive to customers than 'flex-fuel' cars that can burn more ethanol.

Especially in the United States, large sums of money are available to ethanol producers investing in carbon capture for Enhanced Oil Recovery or geological carbon storage. Government incentives include a highly lucrative tax credit, generous incentives under the California Low Carbon Fuel Standard, as well as millions of dollars of funding available through the Inflation Reduction Act and the Bipartisan Infrastructure Law of 2022.

Given all the above it is no surprise that the ethanol industry is indeed "banking on CCS". The Renewable Fuels Association in fact recommends that 90% of ethanol refineries implement CCS by 2050.[98]

Proposed CO2 pipelines in Iowa

Overview of CCS projects linked to ethanol refineries:

The 2021 Status report by the Global CCS Institute[99] lists three existing CCS projects involving ethanol refineries, two of them for EOR. The largest of those projects – discussed further below - has since been discontinued. 34 ethanol CCS projects are in the stage of "advanced development", all of them in the United States.

With or without EOR, the biggest capital expense in CCS involves new CO_2 pipelines. Summit Carbon Solutions, Navigator CO2 Ventures and Wolf Carbon Solutions, all of them focussed on carbon capture and sequestration, have partnered with the agribusiness corporation and ethanol producer Archer Daniel Midland (ADM) to build a vast network of pipelines to transport CO_2 from ethanol refineries scattered across thousands of miles in Iowa, N and S Dakota, Nebraska and Minnesota to storage sites in N Dakota and Illinois.

These proposals have been met with resistance from communities of landowners along the route, (not far from the contentious Dakota Access pipeline) who are fiercely opposing the construction.[100] There are serious concerns about the safety of constructing CO_2 pipelines close to populated areas.[101]

Why carbon capture from ethanol cannot be "carbon negative", let alone 'sustainable'

The largest CCS project linked to ethanol production to date has been the Illinois Industrial CCS project, with CO2 captured from ADM's corn ethanol refinery in Decatur. It has received $141.4 million in government support, yet captured just 12% of the plant's CO2 emissions, according to a report by the Institute for Energy Economics and Financial Analysis (IEEFA).102 The project stopped at the end of 2021.103 At full capacity, the project should

Protest against CCS outside California Air Resource Board hearing, June 2022, Photo: Gary Hughes

have captured twice the amount of carbon – which is still less than a quarter of the refinery's carbon emissions. The reasons why ADM captured just half as much carbon as planned have not been disclosed – another example of the widespread secrecy around the actual performance of carbon capture projects.

The reason why the project could have captured around one quarter of CO_2 emissions from the refinery at best is that emissions from burning fossil gas to provide heat and power to the plant far exceeded the amount of CO_2 emitted from ethanol fermentation. In fact, the energy required to separate CO_2 from water and compress it in order to be transported to the storage site via pipeline, required additional fossil gas to be burned.

Fossil fuels burned to power ethanol refineries are only part of the overall life-cycle greenhouse gas emissions from corn and other ethanol production. A well-publicised study, published in the science journal PNAS in February 2022, concluded that emissions from ethanol are up to 24% higher than those from burning petrol, once emissions from land use change and fertiliser use associated with the expanded demand for corn are accounted for.1[04]

Finally, most ethanol worldwide, and virtually all produced in North America and Europe, is made from cereals, mostly corn (maize) and wheat. As reported by the *New Scientist* in March 2022, the USA and Europe together are using 112 million tonnes of cereals a year to make ethanol. This is the equivalent of twice Ukraine's annual grain exports, the disruption of which by Russia's war of aggression has pushed global food prices and thus levels of hunger and malnutrition to record levels.[105]

5 Conclusions

Carbon capture technologies were developed by and for the oil and gas industry: they are derived from processes used for gas 'sweetening', i.e. removing poisonous hydrogen sulphide as well as carbon dioxide from fossil gas, which opens up otherwise unsuitable gas reservoirs to being exploited.

Carbon capture itself was first used in the 1970s or 80s, with the sole purpose of recovering fossil oil that could not have been accessed otherwise, a process called EOR. Today, 73% of all captured carbon worldwide is still used for EOR. The push for BECCS, too, is driven to a large part by fossil fuel interests, especially the desire to legitimise ongoing fossil fuel burning with hypothetical future "carbon removals".

While capturing carbon from (almost) pure CO_2 streams is straightforward, capturing it from power and heat plant poses far more technical challenges, is much more energy intensive, and, as a result, far costlier. Despite decades of R&D, there is only one power station, a coal plant in Saskatchewan, Canada, with carbon capture, used for EOR. Despite selling the CO_2 to recover more oil, the operators are expected to make net losses throughout the lifespan of this project.

Capturing CO2 from plants burning biomass or mixed waste poses additional challenges compared to doing so from coal plants and, crucially, there has been only minimal R&D into this. The most 'successful' of such projects has been AVR's carbon capture from the Duiven waste incinerator in the Netherlands, capturing over 42,000 tonnes of CO_2 in 2021. However, this was still only 10.6% of the plant's emissions and, furthermore, the operators reported problems with corrosion towards the end of the year. Finally, the CO_2 captured from the plant is used in greenhouses and thus ends up in the atmosphere anyway.

Claims by companies such as Stockholm Exergi or Drax Group that they will soon be capturing hundreds of thousands or even millions of tonnes of CO_2 a year stand in stark contrast to the very small scale of carbon capture by those companies so far. Clearly, developments of carbon capture from biomass plants and waste incinerators are driven first and foremost by government and EU policies and specifically subsidies. In the case of Drax Group in particular, there is clear evidence that vastly exaggerated claims about BECCS are made in an attempt to obtain long-term subsidies for 'business as usual' biomass burning, regardless of any actual carbon capture.

Financial incentives for investing in carbon capture from biomass and waste incineration could significantly increase as a result of carbon trading in so- called "removals" through BECCS, with developments under way in the voluntary carbon markets and proposed in the EU. An announcement by Marubeni to develop a carbon capture project at a pulp mill in Indonesia shows that the prospect of future carbon credits or offsets is already having an impact, this is an industry that has been a driver for rainforest destruction and land conflicts.

One sector that is genuinely looking at large-scale CCS linked to bioenergy is the ethanol industry in the USA. Corn ethanol producers are hoping that vast new subsidies for CCS could throw them a lifeline after ethanol expansion has been halted by a combination of the 10% blending limit (i.e. the limit to the amount of ethanol that can be used in unmodified car engines) and competition from electric vehicles. This is of serious concern because corn ethanol production has been shown to result in more lifecycle greenhouse gas emissions than the petroleum it replaces, and because it consumes a large share of cereals at a time of record food prices worldwide.

No carbon capture project involving biomass or waste combustion has been put forward without a guarantee of substantial subsidies. Moving from small capture trials to full-scale

CCS projects depends on much larger public funding for CO_2 pipelines and injection into geological reservoirs, especially if no EOR is involved. The latter applies to carbon capture from ethanol production, too.

Spending vast sums of public money on unproven and expensive carbon capture technologies diverts funding from proven and urgently needed solutions to the climate crisis, such as investment in energy conservation, including home insulation, in low-carbon renewable energy and heat pumps and, in the waste sector, investment in recycling and a move towards a circular, zero waste economy.

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