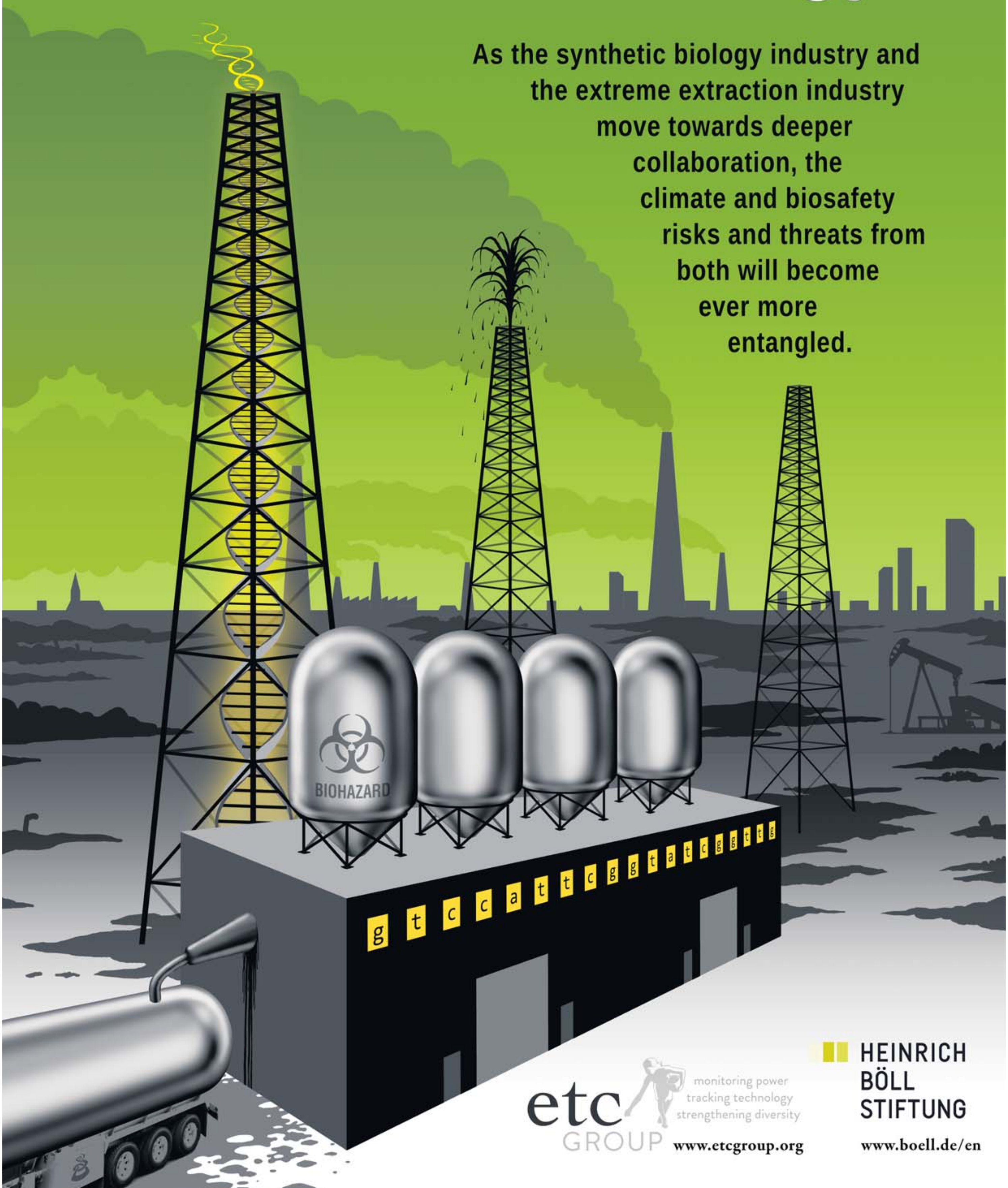
Extreme Biotech meets Extreme Energy

As the synthetic biology industry and the extreme extraction industry move towards deeper collaboration, the climate and biosafety risks and threats from both will become ever more entangled.



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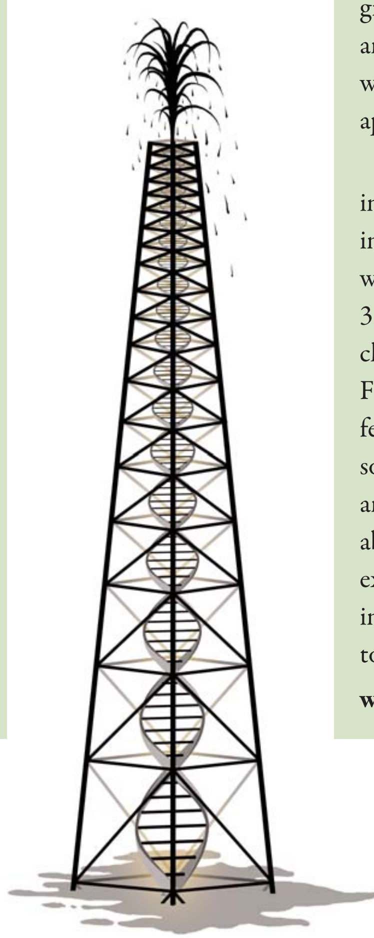

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Issue

The extreme genetic engineering industry of Synthetic Biology (Syn Bio) is rapidly shrugging off earlier pretensions that it might usher in a clean, green, post-petroleum future. Instead, many Syn Bio executives and start-ups are now trying to create alliances with fracking, oil and shale interests, which will actually increase the fossil–based extractive economy that has already brought planetary climate change and other ecological and social problems. New Syn Bio-enabled techniques of "gaseous fermentation" allow for natural gas to be transformed into fuels, chemicals, plastics and possibly even proteins, adding even more value to the gas coming from oilfields and frackfields and potentially making economical the 40-60% of global gas reserves currently lost or "stranded" (gas that is not currently economically recoverable). At the same time, fossil producers are becoming intrigued by the possibility that applying engineered microbes to existing wells and coal seams could enable them to access more of the 2 to 4 trillion barrels of oil in existing oil fields, oil that has been considered inaccessible. Pumping microbes into oilfields is a technological gamble that might expand global oil reserves by 150% if it pays off, and it could also liberate more gas from coal reserves. As the extreme biotech industry and the extreme extraction industry move towards deeper collaboration, biosafety risks and climate risks emanating from both will start to become ever more entangled.

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Actors

A rash of Syn Bio start-ups and more established biotech firms making fuels and chemicals are switching their feedstocks (the material the engineered bacteria eat) from biomass to natural gas; they have been encouraged and subsidised to do this by the US Department of Energy. More established companies in this "dash to gas" include Calysta, Intrexon, Coskata and Lanzatech. A leading bioplastic company, Natureworks, is also switching to a Syn Bio/gas feedstock plan. Meanwhile, nascent oil company interest in pumping engineered organisms into extraction sites appears to be led by BP and Du Pont, with smaller actors also pioneering the field. They include Craig Venter's Synthetic Genomics Inc., and California's Taxon Biosciences. There is less interest so far in applying Synthetic Biology to mine for non-fossil minerals, but this is still under development, with San Francisco's Universal Mining as the standout pre-commercial player.

Fora

At the nation-state level, the US Government's Department of Energy is actively convening and funding research work on Synthetic Biology for the benefit of the extractive fossil industries. However, no international policy discussion has yet taken place as to the implications of this shift towards supporting fossil fuel extraction in the SynBio Industry. In particular, the societal and ecological challenge of new biotechnologies propping up the aging fossil fuel industry has not been discussed in the vital context of climate negotiations. Despite this, in an on going process, the 194 parties to the UN Convention on Biological Diversity (CBD) have passed several precautionary international decisions urging proper regulation and assessment. The topic of Synthetic Biology returns to the CBD's SBSTTA (scientific and technical body) in April 2016.

Policy

Most urgently, a dialogue needs to get underway between movements opposing fossil fuel extraction and expansion (e.g. anti-fracking or anti-pipeline), and those tracking developments in biotech. Civil society organizations could recommend a moratorium on the environmental release and commercialisation of Synthetic Biology applications, which would include applications in the extractive industry sector. In climate negotiations, civil society and policymakers should be vigilant that neither the capture of stranded gas for Syn Bio transformation nor the use of MEHR (Microbially Enhanced Hydrocarbon Recovery) are misleadingly promoted as a climate solution, and moreover that the very considerable climate and biodiversity risks of these techniques are very clear to all parties.

Introduction

Modified Climates and Modified Microbes - Two Bad Ideas Find Each Other

A quarter century ago, in his groundbreaking book *The End of Nature*, ecological writer Bill McKibben pointed out that humans were now interfering with nature in two fundamental ways.[2] The prime subject of his book was that the burning of fossil fuels is altering Earth's atmosphere, creating an unnatural climatic state everywhere on the planet. The second "end of nature" was that humans were for the first time crossing natural species barriers, intentionally altering the genetic code of living organisms through genetic engineering.

"Why then does it (genetic modification) sound so awful? Because of course it represents the second end of nature. We have already, pretty much by accident, altered the atmosphere so badly that nature as we know it is over. But this won't be by accident – this will be on purpose."

- Bill McKibben, *The End of Nature*[1]

As the planet's atmosphere, now loaded with carbon dioxide to over 400 parts per million, inexorably warms towards a dangerous 2 degree centigrade average temperature rise, more and more civil society, climate scientists and governments are reaching the logical conclusion that only a serious phase-out and winding down of the global extractive fossil fuel economy can safely ward off dangerous climate change. Part of preventing fossil expansion means striking out any policies, proposals or technologies that would increase the extraction of fossil fuels, including new "extreme energy" approaches such as fracking, coal bed methane recovery, deep water drilling, shale oil mining and enhanced oil recovery. Given the planet's current warming state, developing and deploying these technologies, to intentionally increase the flow of fossil carbon from underground in order to deposit even more in the atmosphere, borders on the insane.

Today, while the uncontrolled risks of further fossil extraction are widely discussed, the technology to achieve McKibben's second "end of nature," genetic engineering, has been far less in the spotlight, even though it too has been rapidly accelerating. The transgenic techniques that he worried about in 1989 have now been superseded by a much more powerful platform of Synthetic Biology (Syn Bio) and extreme genetic engineering that permit laboratory technicians to quickly and flexibly edit and manufacture a wide range of artificial genomes, using living organisms. These techniques have evolved with such speed and depth of intervention that there are as yet few methods (to say nothing of regulatory bodies), with which to begin to safely assess their impacts on the natural genomes they will invade. Roboticised genetic engineering platforms now enable Syn Bio companies to generate tens of thousands of novel species at one go, releasing these constructs, whose effects on the evolution of Earth's lifeforms are completely unknown. This amounts to intervening in evolution itself at an unprecedented scale and speed.

And now, these two "end of nature" scenarios are becoming synergistic. As the multibillion dollar Synthetic Biology industry searches for viable products, new markets and new funding, a number of private companies and even some governments are seizing on the idea of using the extreme genetic engineering of Syn Bio to further extreme energy extraction in the fossil fuel economy. This is a potent and potentially lethal synergy; it combines the biosafety risks of synthetic biology with the climate risks of fossil fuel extraction.

The new alliance, unfortunately, makes excellent economic sense for the carbon majors,[3] that is, the large coal, gas and oil companies who have been most responsible for human-made climate change. These hugely powerful and wealthy multinational corporations must demonstrate to their investors their ongoing viability by continually overcoming geographic and technological barriers. One alarming feature of the current era of extreme energy is the increasing willingness of fossil companies to take on greater risks, including technological risks, to assure investors that all that carbon will keep on flowing. Turning to Synthetic Biology as a tool is consistent with this increasingly risky behaviour.

Turning to Synthetic Biology is consistent with the fossil industry's increasingly risky behaviour.

This report is intended to provide a first assessment of how the extractive industries are exploring ways to harness synthetic biology and to help policy makers, civil society and others act in a precautionary manner against the risks this may bring.

What is Synthetic Biology?

Synthetic biology, dubbed "genetic engineering on steroids,"[4] broadly refers to the use of computer-assisted, biological engineering to design and construct new synthetic biological life-forms, living parts, devices and systems that do not exist in nature. The term also refers to the intentional redesign of existing biological organisms using these same techniques. Synthetic biology attempts to bring a predictive engineering approach to the genetic engineering of biological life, using genetic "parts" that are thought to be well differentiated and which will have rationally predicted behavior in their new organism. It works also by "editing" genetic codes as if they were identical to the printed coded instructions used in, for example, mechanical engineering. While the field aims to make bioengineering predictable, it is still a very long way from that ideal. In fact, many geneticists and microbiologists (and even synthetic biologists in private) contend that this will likely never be possible. Biological lifeforms are highly dependent on context and environmental influences for their function, health and behaviour. They are fundamentally not like machines, which are far more separated from their surroundings, and many studies have demonstrated that it is very difficult to reliably treat any organism as if it were simple machinery.[5]

Some Definitions of Synthetic Biology:

"The overall aim of synthetic biology is to simplify biological engineering by applying engineering principles and designs — which emanate from electronic and computer engineering — to biology."

– Synthetic Biologists Jay Keasling and Chris Paddon, May 2014

"Synthetic Biology is a further development and new dimension of modern biotechnology that combines science, technology and engineering to facilitate and accelerate the understanding, design, redesign, manufacture and/or modification of genetic materials, living organisms and biological systems"

- Operational Definition developed by the Ad Hoc Technical Expert Group on Synthetic Biology of the UN Convention On Biological Diversity. Montreal, September 2015

Originally more of an investment term than a clearly delineated field, the catch-all name Synthetic Biology (or "Syn Bio") is now used to refer to a suite of second-generation genetic engineering techniques overtaking the classical genetic engineering methods (also known as transgenics) that originally brought genetically modified crops onto the market. To date, the commercial applications of the new Synthetic Biology have been in making biofuels and chemicals and in engineering living microbes, such as yeast and algae, so they will excrete synthetic versions of food, flavours, cosmetic and fragrance ingredients. This has included artificially producing vanilla flavour, sweeteners and essential oils such as patchouli and rose oil.[6]

Regulators are struggling to adjust to this new set of genetic techniques and to learn how to assess and control the proliferating number of products flowing from them. The term "Synthetic Biology" is now becoming formally defined in the European Union and at a United Nations level at the UN Convention On Biological Diversity.[7] In this report, we use this term (or its shortened form, Syn Bio) to describe biotechnology techniques now being applied that go well beyond classical genetic engineering, and we use it particularly when it is microorganisms that are being manipulated and deployed.

1 Bill Mckibben, *The End of Nature,* Random House 1989

2 *Ibid*.

3 See: www.carbonmajors.org

4 www.techcentral.co.za/synthetic-biology-genetic-engineering-on-steroids/30351/

5 Craig Holdredge, "When engineers take hold of life." *In Context,* The Nature Institute, www.natureinstitute.org/pub/ic/ic32/synbio.pdf

6 See: www.etcgroup.org/tags/synbio-case-studies

7 Current CBD process to define Synthetic Biology are archived here: https://bch.cbd.int/synbio

Fickle Rhetoric:

From Replacing the Petrochemical Industry to Servicing It

There was a time when those pioneering the field of Synthetic Biology presented themselves as opponents and challengers to the extractive fossil industries, and claimed they were part of the solution to the climate crisis. In 2008, before a power audience of tech CEOs and politicians, controversial genome entrepreneur J. Craig Venter claimed that, "We have modest goals of replacing the whole petrochemical industry and becoming a major source of energy,"[8] by which he meant they would be producing biological fuels from sugar, cellulose and algae transformed by synthetically engineered microbes. In the same year Venter told the BBC that, "the most important issues facing humanity right now is that we're taking billions and billions of gallons of oil and billions of tons of coal out of the ground and burning it and putting all that carbon in our atmosphere. And if the population doesn't wake up to the dangers of doing that and if we don't quickly come up with a replacements, we're going to have very serious consequences, not hypothetical ones in science fiction."[9]

Positioning Syn Bio firms as heroic green upstarts ready to disrupt the dirty fossil monopolies of the oil, coal and gas industries was a frame that other Syn Bio leaders were to repeat and reinforce continuously between 2007 and 2013. Alan Shaw, CEO of the Synthetic Biology biofuel company Codexis, claimed that his company's technology would, "enable the transition from an oil based economy to what is known as the sugar economy." And that, "biotechnology is a primary driver of this transition from a 20th century dependence on oil to what will be a 21st/22nd century dependence on sugar."[10] With approximately two thirds of Syn Bio investments flowing into biofuels and bio-based chemicals at that time, Synthetic Biology was increasingly presented as synonymous with a green-tinged post-petroleum economy – the so-called "bioeconomy" vision that might rid the world of fossil fuels.[11] It should be noted that even from a climate protection perspective, there were considerable problems with this bioeconomy approach. Extracting the biomass required for biofuels and bio-based chemicals involves significant land use change, which would most likely release carbon dioxide and deplete natural carbon sinks. Biomass removal from soils would also likely necessitate increased use of fertilizers because of lost soil fertility, and of course fertilizers can emit significant greenhouse gases in production and use.[12]

> ***"Biomass doesn't cut it... Carbohydrates are not a substitute for oil. I was wrong in that, and I admit it. That will never replace oil because the economics don't work. You can't take carbohydrates and convert them into hydrocarbons economically."***
>
> – Alan Shaw, CEO Calysta, formerly Codexis[15]

A few years later, however, even this somewhat shaky narrative has shifted, and the public rhetoric of how Synthetic Biology will supplant the oil industry has nearly evaporated. Today, Synthetic Biology CEOs are touting services to fossil extraction companies, or seeking to "add value" to fossil resources, rather than engaging in anti-petroleum posturing.

8 www.dailygalaxy.com/my_weblog/2009/04/gucci-genes--de.html

9 www.icis.com/blogs/icis-chemicals-confidential/2008/01/biology-will-replace-the-petro-1/

10 Shaw Alan, Clark General Wesley, MacLachlan Ross, and Bryan Paul. "Roundtable: Replacing the whole barrel of oil," *Industrial Biotechnology*, April 2011, 7(2): 99-110. doi:10.1089/ind.2011.7.099

11 Market Research Report, "Synthetic Biology: Emerging Global Markets," Bio066b, BCC Research, November 2011

12 For a discussion of the climate risks of biomass extraction in the bioeconomy including references, see ETC Group, "The New Biomasters – Synthetic Biology and the Next Assault on Biodiversity and Livelihoods," October 2010, p.19-21.

Shaw, who now declares that he was "wrong," and that his "sugar economy" vision was never really practical, is today the CEO of another Syn Bio company, Calysta, that turns fracked natural gas (methane) into liquid fuels and other products.[13] Edward Dineen, formerly CEO of Syn Bio biofuel company LS9, now heads Siluria Technologies Inc. Their technology uses synthetic viruses to convert methane into chemicals such as ethylene. Leading cellulosic ethanol company Coskata no longer uses any kind of sugar as a feedstock, only natural gas. Solazyme, a San Francisco bay area firm that raised billions of private, military and government dollars on the green rhetoric of creating algal biofuel, today makes most of their income selling drilling lubricants to the fracking industry.

In fact, even as Craig Venter was in 2008 lecturing the BBC on the climate dangers of taking oil and coal out of the ground, the ink was already dry on a deal he had made with BP: to use his company's microbes to increase the flow of fossil fuels from oil wells by exploiting the technique of Microbially Enhanced Hydrocarbon Recovery (MEHR).[14] Obviously, even though the rhetoric of the post-petroleum bioeconomy still hangs around the Syn Bio industry, far from replacing the fossil carbon companies, the synthetic biologists are increasingly hoping to be key players in the fossil fuel extraction economy.

The Allure of Fossils

So what changed their focus? In those few years, the Syn Bio industry has had to mature and diversify rapidly, constantly seeking new markets. As a growing field whose "killer app" is yet to be determined, it has very likely become more profitable to play nice with the richest companies on the planet than it is to posture about their demise.

In turn, those fossil carbon companies are seeing the benefits in leveraging the powerful technologies of synthetic biology for their own activities. This is not as new as it might first appear; in fact, the first patent on a genetically modified organism, the famous Diamond vs Chakrabarty case, was for oil spill clean-ups.[17] The extractive industries have always kept a close eye on developments (and opportunities) in biotech.

Probably the main reason for the shift is that the global energy story has changed since the early days of this industry, forcing Syn Bio executives to reorder what kind of "value proposition" (i.e., money-making product), they can offer to investors and clients. Back in 2008, high oil prices and growing talk of Peak Oil meant that in the face of these spiraling costs and for a brief window, biofuels could be pitched to investors as potential big moneymakers. With oil prices low again, that pitch is no longer convincing. There has also been the subsequent boom in natural gas enabled by hydraulic fracturing technologies (fracking), plus the opening up of shale gas deposits and coal bed methane seams. While the collapse in oil prices and the current gas boom have sidelined biofuels in the energy economy, these developments have also increased the pressures. Unconventional fossil resources, such as the heavy bitumen dredged from the Canadian tar sands, are expensive to mine and the players there are looking for ways to lower their costs through inventive technological efficiencies. For the newly struggling unconventional oil sector, as well as for the natural gas-producers with plentiful product on their hands, Syn Bio firms are repositioning themselves as attractive partners, offering potential breakthrough solutions to their every problem.

"The world seems to be finding more and more gas, so I feel very comfortable with the feedstock story here."

- Edward Dineen, CEO of Siluria, Formerly CEO of biofuel company LS9[16]

13 www.bloomberg.com/news/articles/2013-04-30/biofuel-pioneer-forsakes-renewables-to-make-gas-fed-fuels

14 http://www.syntheticgenomics.com/130607.html

15 Andrew Hearndon, "Biofuel Pioneer Forsakes Renewables to Make Gas-Fed Fuels," 30 April 2013, Bloomberg News. www.bloomberg.com/news/articles/2013-04-30/biofuel-pioneer-forsakes-renewables-to-make-gas-fed-fuels

16 *Ibid*.

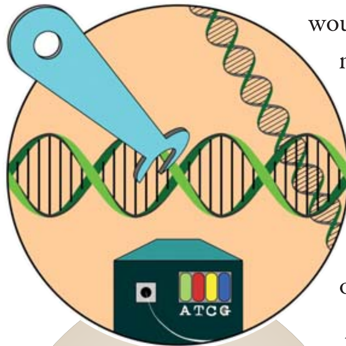
17 US Supreme Court decision, Diamond v. Chakrabarty, 447 U.S. 303 (1980)

How Might Syn Bio Help Fuel Producers and Extractive Industries?

Syn Bio may be used in the production, use and remediation of fossil resources. It also may be useful for recovering metals from ores. One way of conceiving of the activities of the Synthetic Biology industry that helps to partly explain the technology's usefulness to the "carbon majors" is to regard Synthetic Biology as a biological platform for transforming one carbon-based compound into another, using living organisms as the agent of transformation.

In some ways, it is a biological equivalent of what's termed the "cracking" of petroleum into other useful compounds; that is to say, the thermochemical process which gave rise to the entire petrochemical industry. In the early phase of the Synthetic Biology industry, the targeted material (termed "feedstock"), needed to feed the newly synthesized lifeforms, was the carbon found in biomass, that is, sugar and cellulose. Energy and chemical companies partnered with Syn Bio start-ups to explore options for producing liquid biofuels and "bio-based" chemicals. But for the fossil majors, whose core business is to produce and refine abundant and relatively cheap carbon, biological transformation of hydrocarbons (oil, coal and gas) instead of carbohydrates (plants), was always potentially more interesting.

This Syn Bio form of "cracking" provides a means of shifting petroleum refining from transforming petrochemicals via heat and chemistry techniques, to what might be called "bio-hacking" living organisms, which are genetically modified so they will release the chemical resources present inside fossilized hydrocarbons. Normal oil cracking requires operating big, expensive, energy-hogging refineries. Bio-hacking is lightweight, flexible and only needs a fermenter vat and a handful of reproducing microbes.



[The extractive industries] can now more cheaply upgrade the value of its extracted hydrocarbons, especially natural gas, by turning crude products into ready-to-use fuels, plastics, cosmetics and even food ingredients–all without the huge social, construction and operating expenses of running refineries.

This is the tastiest of the new "value propositions" that Syn Bio firms are now presenting to the carbon majors: it would mean that this gigantic industry can now more cheaply upgrade the value of its extracted hydrocarbons, especially natural gas, by turning crude products into ready-to-use fuels, plastics, cosmetics and even food ingredients – all without the huge social, construction and operating expenses of running refineries.

At the same time, engineering biological lifeforms to serve industrial purposes is being viewed as a potential new technological fix for dealing with other problems and inefficiencies present in the extraction, processing and disposal of both fossil and mineral resources. Theoretically at least, synthetic organisms, if properly designed, might help increase the flow of oil from existing reserves; produce drilling fluids; break down minerals and metal ores; and also help liberate natural gas. Theoretically (because despite decades of trying it has yet to be achieved), they could also be deployed in clean-ups, to break down persistent chemical pollutants or to sequester chemical wastes and gases such as CO_2. Syn Bio companies, hand in hand with the extractive industries, are exploring all of these approaches.

The rest of this report addresses the two most significant areas in which the Syn Bio industry is beginning to advance agendas around fossil fuels and mineral extraction more generally. They are:

Approach 1) **Biologically "refining" crude fossil fuels via "gaseous fermentation" to use as a feedstock for the production of refined or "drop-in" fuels, plastics, or food (especially methane and syngas).**

Approach 2) **Mining by microbe – direct extraction techniques.**

Approach 1

Methanotrophs and “Gaseous Fermentation”: Biologically “Refining” Fossil Fuels

For the past century, at the heart of all the power and success of the world's richest industry, the production of petrochemicals, are the processes known as petroleum “cracking” and associated “reforming” processes. Big thermo-chemical facilities refine crude oil or natural gas into different chemical fractions, that in turn are the building blocks of thousands of valuable compounds, from plastics to fertilizer and food ingredients, from cosmetics to textiles. These oil “crackers” are the familiar huge refineries that transform oil and gas into transport fuels as well as these higher-value products.

The research we're talking about here is trying to figure out if certain Synthetic Biology or other industrial biotechnology approaches might in the future be able to offer a cheaper, simpler and more flexible way to refine oil, coal and gas, with microbes replacing refineries. This prospect is being particularly explored for natural gas, since there exists a class of microbes, known as methanotrophs (methane-eaters), that are already able to consume methane (the key component of natural gas) as their food; in their digestion process it turns, normally, into methanol and then formaldehyde. Which means that, crudely put, they eat one chemical and poop out another, a talent of obvious interest to bioengineers.

By engineering the genetics of methanotrophs, synthetic biologists believe they can direct the conversion process, so that a methanotrophic bacteria might consume methane from oil and gas wells and then excrete a desired chemical for use in the manufacture of plastics, for example, or liquid fuel or food flavourings. This process is referred to as “gaseous fermentation.”[18] In essence it's a fermentation process, the way yeast organisms ferment sugars into beer, except in this case methane could be fermented into high-value chemicals such as jet fuel or plastics. Other approaches include converting methane or coal into syngas (a mixture of carbon monoxide, hydrogen and carbon dioxide) and feeding that chemical to engineered microbes.

A third approach would be to use engineered organisms to produce powerful enzymes (biocatalysts) that will react with methane to make new compounds.

Turning methane from natural gas into high-value ingredients using engineered organisms has a series of market and industry advantages:

1) Natural gas is currently a plentiful and relatively cheap “feedstock” (the food supply needed for the engineered microbes). If the process works, it might be more reliable than securing a source of biomass, like farm waste. It is also a concentrated market where, if any of the handful of oil and gas companies controlling these commodities adopted a product, the money to be made, and of course, the proliferation of the new, engineered microbes, would both be huge.

2) According to Calysta Energy, transforming methane to fuels is cheaper, requires less energy and is more efficient than biofuel processes. Sugar and biomass is only 40% carbon and so, theoretically, only about 30-40% of the feedstock can be transformed into, for example, a final biodiesel. Algae has an even lower carbon content. Syn Bio developers claim that since methane is 75% carbon, up to 59% of the feed can be converted into a biodiesel.[19] The founders of Industrial Microbes point out that carbon from methane is four times cheaper than from sugar.[20]

3) If synthetic biologists can viably refine natural gas into high-value products such as cosmetics, fuels or food ingredients, then the overall value of natural gas as a commodity increases. This would help justify higher extraction costs (e.g. for fracking, shale and coal seam gas), and encourage even more exploration and exploitation. And if coal can be turned into syngas or methane and then transformed into high-value products, then coal deposits would also become more tempting to exploit.

18 see for example http://calystaenergy.com/technology/gaseous-fermentation/

19 Josh Silverman, “BioGTL Platform for the Conversion of Natural Gas to Fuels and Chemicals.” http://calysta.com/pdfs/AIChE_final_33114.pdf

20 Yarrow Madrona, “Scientists Seek to Engineer Microbes to Make Simple Chemicals” Synapse http://synapse.ucsf.edu/articles/2015/01/09/scientists-seek-engineer-microbes-make-simple-chemicals

4) Most significantly, flexible biological transformation potentially addresses the problem of "stranded gas" faced by the oil and gas industry and turns it into both an industrial and public relations advantage. Stranded gas refers to gas that is not economical to capture and bring to market and so is routinely wasted – for example, the gas that comes off of offshore oil wells, gas fields that are too remote, or the "associated gas" that is produced as a by-product of oil production. Most of this is usually vented into the atmosphere or flared (burned), causing a great deal of atmospheric pollution. Estimates of remote or stranded gas reserves are huge and range from 40 to 60% of the world's proven gas reserves.[21] Because Syn Bio fermentation facilities can be relatively small and flexible, even highly portable, it may be possible to deploy them to capture stranded gas at its source, and turn it into a product such as a liquid fuel that is easier to ship, handle and sell. This is also a possible boon to fracking operations, which typically only extract a limited amount at each well and need to convert the gas into something that can be shipped out.

The industry of course presents making use of "stranded gas" as an environmental benefit, since the excess gas no longer will escape into the atmosphere or need to be burned. Vented methane is indeed a significant greenhouse gas, with 25-34 times the greenhouse impact of CO_2. But replacing flaring with Syn Bio conversion may have an even worse climate impact. This is because when the stranded gas is "upgraded" to fuels, those fuels will be burned, producing a great deal more CO_2 with a more serious climate impact than flaring methane directly would have (see Box below). Of course, methane flaring is itself a major problem – especially for communities near wells or extraction sites. U.S. Secretary of Energy Ernest Moniz has argued that such natural gas conversion technologies, "could be used in a distributed way to address natural gas flaring at oil wells, which we know is both a problem and an opportunity."[22] Moreover, turning stranded gas into a new income stream for oil companies would very likely give them yet another incentive to explore and drill oil and gas fields that would have otherwise been considered too marginal – again driving up fossil fuel use (and climate change) overall.

Definitions

Methanotroph - An organism that consumes methane as its principal source of carbon and energy.

Syngas – Synthesis Gas - a gaseous mixture of carbon monoxide, hydrogen and carbon dioxide produced by thermal treatment of coal and biomass (via the Fischer tropsch process).

Stranded Gas – Wasted and leftover gas from oil and gas fields that is not economic to collect for market.

Flaring and Venting – The process of burning off excess gas from indutrial extraction an d refining operations (flaring) or emitting it unburnt as methane into the atmosphere (venting).

Biomass - Living material, especially plant matter, collected for an industrial production process.

Biosafety – A term that refers to the innate and direct risks of organisms; often used at various governance levels, especially the UN, about direct risks of genetically engineered organisms.

5) Engineered strains of bacteria that convert methane or syngas into valuable products can also be fed with the methane from landfills or confined animal feeding lots. For public relations reasons, Syn Bio companies working in the methane-to-chemicals and methane-to-fuels sector often talk more about the prospect of capturing and transforming that kind of landfill gas as a "green" prospect, even though the area of fracked or stranded gas from oil and coal fields is a far bigger market.

21 "Stranded Gas Utilization—Methane Refineries of the Future," Report prospectus, Feb 2002, ChemSystems, San Francisco. See also Chabrelie, M.-F. and Rojey, A., "Prospects for Exploiting Stranded Gas Reserves," Presented at Gastech 2000, Houston, 14–17 November.

22 David Biello, "Can Methane Leaks from Fracking Be Turned into Valuable Gasoline?" *Scientific American,* March 5, 2014

23 "EIA voluntary reporting of greenhouse gases program fuel carbon dioxide emission coefficients," www.eia.doe.gov/oiaf/1605/coefficients.html

24 Kevin Bullis, "Biofuels companies drop Biomass and turn to Natural Gas," *Energy News,* Oct 30 2012. See also Chad A Haynes and Ramon Gonzalez, "Rethinking Biological Activation of Methane and Conversion to Liquid Fuels", *Nature Chemical Biology*. Vol 10, May 2014.

Methanotroph Biosafety Risks

Genetically engineering any organism may give rise to unpredictable and unforeseen effects, often not immediate; and the increased complexity of synthetic biology can only heighten these risks. Because such organisms can reproduce on their own and spread throughout the biosphere, releasing them into the environment (even if by accident) very much increases the dangers to natural plants, animals and microbes. Such risks may be acute, if an engineered methanotroph that produces these chemicals (which may be poisonous to all other lifeforms) is released into environments high in methane and finds an adaptive niche or fitness advantage, for example, if bio-engineered methanotrophs finds themselves in wetlands or soils with much rotted material producing methane in the soil. Some animals, like cattle, are also significant sources of methane, So if the methanotroph finds a niche in ruminants and reproduces, it may in a worst case scenario produce a substance such as car fuel or plastic within the animal - that could sicken other organisms or alter outputs of milk or meat. There may of course be many other unknown health and environmental implications.

Increasing climate risks

In discussions about methane as an energy source, methane is presented by the fossil industries as a "cleaner" and less carbon-intensive alternative to coal and oil. Unburned methane as a gas has a higher global warming impact than carbon dioxide. However, when burned, methane produces less CO2 per energy unit than any other type of fuel (including biofuels such as ethanol).[23] Biologically turning methane into fuels and other high-value products by fermentation may undo that advantage.

For a start, the process of fermentation includes its own energy costs and produces CO_2 during fermentation; plus methanotrophs are currently inefficient in transforming methane to fuels. The end product (for example, a refined, "drop-in" fuel that can be used immediately in cars or airplanes) will have a similar carbon intensity to existing oil-based fuels and when burned emit more greenhouse gases than unconverted methane. According to some analyses making a fuel from natural gas using methanotrophs is a process that will currently release more greenhouse-gas emissions than making fuel from conventional oil; this is because the production-related impacts must be factored in.

The REMOTE project (see below) is trying to overcome this problem of higher emissions but has not solved it yet.[24] But the deeper problem may lie in moving further into a methane-based economy. Un-burned methane has extremely high climate impacts. Accidental escape of methane from wells, fracking sites and distribution networks is a common fact of life already, and can only increase as new uses for methane vastly increase the size of the industry.

Syn-CCUS - Methane-based Syn Bio as 'Carbon Capture, Use and Storage'

The focus on capturing flared and vented methane to turn into fuels fits within fossil industry strategies to promote carbon capture technologies. The fossil industries are increasingly arguing for a "decoupling" of fossil fuel energy from greenhouse gas emissions - arguing that new technologies mean the world can continue to extract and consume carbon-heavy fuels while still reducing overall emissions. To argue this they are promoting technologies that barely exist and are still unproven. The prime technology promoted to advance this paradoxical proposal is Carbon Capture and Storage (CCS) – where waste CO_2 gases (e.g. from coal-fired power stations) are supposedly captured and sequestered into geological formations. However, achieving pure CCS would be enormously costly and to date there is only one CCS plant operational in the world. Increasingly fossil industry advocates are also promoting a different approach where rather than go to the expense of burying captured carbon emissions, they are instead "used" as a feedstock to make fuels, plastics, cement and other materials – thereby making a profit from the process. This approach is called "carbon capture use, and storage" (CCUS) – although in the case of conversion of waste gases to fuel there is no actual storage since the fuel still gets burned and carbon released to the atmosphere. Capturing methane and transforming to fuels using Syn Bio instead of flaring it is a perfect example of a carbon capture and use project. While this will be presented as a "green" benefit, it's a false solution that ultimately benefits the fossil industry and may lead to a net increase in atmospheric emissions, rather than a decrease.

Syn Bio Companies Get Gas

At this time, it appears there is something of a "dash to gas" within the Synthetic Biology industry, as a significant number of biotech players are clearly tooling up to use either methane or syngas as a feedstock for their synthetic organisms:

Calysta - Headquartered in Silicon Valley's Menlo Park, Calysta is the most visible company working to transform methane directly into fuels, food and other chemicals. Using their "BioGPS" bioengineering platform (Biological Gas-to-Chemicals and Biological Gas-to-Liquids), Calysta engineers microbial strains such as Methylococcus (a methanotroph) to feed on methane and produce a variety of compounds. The microbes are held in reactor vats that carry out "gaseous fermentation," the digestion described above. Calysta claims their Synthetic Biology platform can produce important classes of industrial chemicals, such as alcohols, esters, oxides and olefins, which would include liquid fuels.[25] Besides collaborations with the US Department of Energy through the REMOTE programme, and with US national energy labs (See Box below), Calysta has a 2.5 million dollar partnership with the leading bioplastic company, Natureworks, to produce Polylactic Acid (PLA) from methane instead of from corn starch.[26] This is still in a development phase, with both companies announcing in June 2013 that they had successfully developed bacteria able to convert methane into lactic acid (the precusor for PLA).

Calysta also has a "nutrition" arm headquartered in Stavanger, Norway, that grows microbes on methane as a base for fish and livestock feed. As they eat the methane, the microbes grow larger and larger. They are 70-72% protein by weight, so that material is harvested, dried and used to feed animals.

25 http://calystaenergy.com/materials-and-energy/materials/ . See also Josh Silverman, "BioGTL Platform for the Conversion of Natural Gas to Fuels and Chemicals." http://calysta.com/pdfs/AIChE_final_33114.pdf

26 Press Release, Natureworks, "Calysta Energy and Natureworks Annouce an R&D Collaboration to Transform Methane into the Lactic Acid Building Block for Bioplastics," June 18, 2013.

Calysta plans to introduce its FeedKind™ Aqua protein for the aquaculture industry in 2018, to be followed by commercial feed for the Scottish and Norwegian livestock industry.[27] Calysta claims that the microbes it uses for its animal and fish feed are "naturally occurring," rather than engineered, and will be marketed as "non-GMO" (as they must be, to find a market in the EU). Calysta now intends to build a multi-million dollar production facility for its methane-to-chemicals platform. The location is unannounced, but there is speculation, such as the following from *Biofuels Digest*: "Where will they build it? Next to a very cheap source of methane. Think: Brunei, the Emirates, Qatar, Saudi Arabia, or in a methane hot spot in the Bakken, Marcellus or Niobrara formations in the US or Canada."[28]

Intrexon - In the past few years, US-based Intrexon, headed by biotech billionaire Randal Kirk, has emerged as one of the most aggressive and fast-growing of the Synthetic Biology companies, purchasing a suite of smaller start-ups, which cover production of everything from engineered fish and apples to pharmaceuticals and fuels. Like Calysta, Intrexon boasts a "methane bioconversion platform." It also uses Syn Bio to engineer the genetics of methanotrophs, to produce fuels, chemicals and other high-value compounds, potentially including even pharmaceuticals. As they put it, "With new genetic circuitry we have enabled the methanotroph to upgrade carbon from its natural food source, methane (c3) to more valuable end products."[29]

27 "Here's how it works. Calysta develops non-GMO methanotrophs – these are little microscopic critters that eat methane as their energy source (just like we get carbon from ...the foods we eat). Like you, when they consume energy and food, they grow — in this case, making lots and lots of newly divided out methanotrophs. The cells are 70-72% protein by weight. That protein is harvested, dried, powdered, and distributed by BioProtein as a substitute for fish meal." www.biofuelsdigest.com/bdigest/2014/05/20/goodbye-fuel-from-food-hello-food-from-fuel/see also www.economist.com/news/science-and-technology/21649441-feeding-farmed-salmon-protein-made-methane-gas-guzzlers

28 Jim Lane, "Goodbye Fuel from food, hello food from Fuel," Biofuels Digest May 20th 2014. www.biofuelsdigest.com/bdigest/2014/05/20/goodbye-fuel-from-food-hello-food-from-fuel/

In particular, Intrexon has demonstrated its ability to produce two fuels: isobutanol and farnesene from methane. As well as a source for diesel fuel, farnesene is also a chemical precursor to a large range of common chemicals and natural products, including glues, cleaners, soaps, solvents, fragrances and many others. To commercialize its methane conversion technology, Intrexon formed a joint venture called Intrexon Energy Partners (IEP); and in March, 2014, IEP raised $75 million from its partners to help fund commercialization of its technology for fuels and lubricants.

Coskata - For several years Coskata was among the leaders in the race to produce cellulosic biofuels from wood chips and other forms of biomass, with General Motors, Total, the US government and several large investment firms providing many millions of R&D dollars. Today, however, Coskata bills itself as focused primarily on turning syngas into ethanol using its own engineered microbes. Coskata operates a semi-commercial facility in the heart of the Marcellus shale gas fracking region of Pennsylvania. Coskata has been converting natural gas into ethanol since 2012 and are forthright about the economic reasons for using SynBio to transform gas to fuels. They state: "With natural gas prices of $4/mmBtu, we expect to achieve unsubsidized production costs well below that of current transportation fuels such as gasoline, diesel and corn-based ethanol. In fact, even if natural gas prices were to increase to 4 times today's levels, we would still be competitive with current corn ethanol production costs. By utilizing natural gas as a feedstock, not only can we produce transportation fuels at a price that creates value for consumers, we can also build much larger plants, because we will not be limited by availability of biomass within a specific radius. By producing at industrial scale, we can have a material impact on transportation fuel supply in this country."[30]

…"Natural Gas is the New Sugar" touting the benefits of methane as a feedstock whose carbon is four times cheaper than carbon from sugar.

Coskata claims its process can also be used to produce ethylene from natural gas; ethylene is a precursor to various plastics.

Industrial Microbes - Established by 3 former employees of leading Syn Bio Biofuel company LS9, Industrial Microbes of Emeryville California is developing microbes that will turn a combination of both methane and CO_2 into Malic Acid,[31] a widely used industrial chemical used as a sour food flavouring. Like Calysta, the founders of Industrial Microbes proclaim that "Natural Gas is the New Sugar" touting the benefits of methane as a feedstock whose carbon is four times cheaper than carbon from sugar. In particular Industrial Microbes are pitching their process as a "carbon capture and use" approach because it will use CO_2 as well as Methane. The initial start-up money for the venture came from CCEMC (Climate Change and Emissions Management Corp.),[32] a quasi governmental and industry led funding body from Alberta in Canada (home of the highly polluting tar sands extraction). CCEMC are tasked with finding technological solutions for emissions reduction. Industrial Microbes also received some funds from the US Environmental Protection Agency.

Newlight - Newlight bills its technology as a "carbon-negative" production process for turning methane and greenhouse gases into plastic, for use in furniture and other applications. Unlike other Syn Bio companies, Newlight doesn't use a direct "gaseous fermentation" process to make its "air carbon" plastic, but instead uses an engineered biological catalyst (an enzyme produced from a bioengineered organism) that reacts with methane and air to produce the plastic, supposedly by drawing carbon out of both the methane and CO_2 in the air.

29 Intrexon News release, "Synbio company Intrexon and Dominion partner to commercialize bioconversion of natural gas to isobutanol in Marcellus and Utica Basins" 20 Aug 2015. www.greencarcongress.com/2015/08/20150820-intrexon.html

30 Jim Lane, "Coskata: Biofuels Digest's 2014 5-Minute Guide," March 25, 2014, *Biofuels Digest*.

31 See http://www.imicrobes.com

32 CCEMC/Industrial Microbes News Release, "Industrial Microbes Wins $500,000 Grant to Turn Greenhouse Gases into ValuableMaterials" May 2014.. www.imicrobes.com/news/2014%2005%2019%20Industrial%20Microbes%20CCEMC.pdf

Newlight has received various "green business" awards and claims to be, "working with Fortune 500 partners and brand name market leaders to use AirCarbon as a material to launch carbon-negative products across a range of market segments, including in automotive, electronics, construction, apparel, and others."[33] Their AirCarbon plastic is being used by leading US furniture producer KI to make chairs and other furniture for education, healthcare, government and corporate markets.[34]

Kiverdi - Kiverdi uses engineered organisms that turn methane into drop-in fuels, oils and custom chemicals, biomaterials and food additives. "Drop-in" fuels, as mentioned, can go into cars and pipelines without alteration, working in existing engines. They can also be carried over existing infrastructure, unlike ethanol, which requires modifications to the car and, along with bitumen, needs different carrying and handling infrastructure. While Kiverdi's public communications focus on capturing methane from "waste carbon" (e.g. landfills, straw, etc.) this also includes "stranded" gas. They are still in development phase, and are funded by US government.[35]

Lanzatech - Lanzatech, originally from New Zealand but now headquartered in the US, has for a few years been using engineered microbes to ferment "waste carbon gases" (syngas) from the steel industry, into more drop-in fuels and chemicals. The company is now also exploring applying its technology to transforming stranded gas from fracking facilities and coal mines into high-value products. Lanzatech received 4 million dollars from the US government's REMOTE programme (see Box below) to turn methane, via syngas, into fuel and chemicals. Lanzatech presents itself as a "carbon capture and reuse" company.[36]

33 Newlight, "Our Technology: Greenhouse Gas to Plastic." http://newlight.com/technology/

34 KI news release: "KI to Unveil World's First Carbon-Negative Chair Made with Revolutionary Thermoplastic AirCarbon at Greenbuild 2013," Nov 20th 2013.

35 Jim Lane, "Kiverdi: Biofuels Digest's 2015 5-Minute Guide," *Biofuels Digest,* May 11, 2015.

36 Jim Lane, "LanzaTech: Biofuels Digest's 2015 5-Minute Guide," *Biofuels Digest,* January 13, 2015.

...engineered viruses rearrange minerals to create a powerful catalyst that turns methane into new molecules of ethylene.

GreenLight Biosciences - GreenLight, a Boston-based Syn Bio company, received 4.5 million dollars of US funds from REMOTE (See Box) for its methane-to-chemicals programme. GreenLight uses a "cell-free" system; that is, employs synthetic genetic processes outside of the living cell, to create a bioreactor that can convert large quantities of methane to fuel in one step. Although GreenLight describes their company's vision as challenging the extraction of hydrocarbon fossil fuels, they also clearly see their system working at gas fracking sites. As Greenlight explains, "the process uses natural gas and wellhead pressure to generate the power needed to run the facility. Any carbon dioxide that is released in the process is captured, condensed and pumped back into the well to maintain reservoir pressure and reduce emissions. This technology could enable a scalable, mobile facility that can be transported to remote natural gas wells as needed."[37]

Siluria - Like other companies engineering biology San Francisco-based Siluria sells itself to investors and oil companies as able to turn natural gas into high value chemicals. In particular Siluria has perfected a process for turning Methane into Ethylene – probably the most widely used petrochemical available. What is different from other Syn Bio companies is that the core technology is not about gaseous fermentation but instead viruses are re-engineered to form tiny nanostructures that can act as very efficient catalysts in chemistry. The scientist behind the technology, MIT's Angela Belcher, is almost a rockstar in the world of nanobiotechnology for her work harnessing and programming microbes and bacteria. In this case engineered viruses rearrange minerals to create a powerful catalyst that turns methane into new molecules of ethylene.

37 GreenLight Biosciences, "Highly Productive Cell-Free Bioconversion of Methane," ARP-E description online at http://arpa-e.energy.-gov/?q=slick-sheet-project/cell-free-bioconversion-natural-gas

38 Forbes, "Upstart Siluria Technologies Turns Shale Gas Into Plastics And Gasoline" 14th April 2-14.- http://siluria.com/Newsroom/In_the_News?Upstart_Siluria_Technologies_Turns_Shale_Gas_Into_Plastics_And_Gasoline#0.

Siluria has received over 120 million dollars from investors including oil giant Saudi Aramaco and former Microsoft technology chief Paul Allen.[38] In April 2015 Silurian opened a demonstration plant in Texas, co-located with the facilitys of Braskem – a major Brazillian chemical manufacturer. That plant is already turning test batches of methane into ethylene and Siluria expects to start running commercial scale plants in 2017-2018.[39]

Zuvasyntha - Zuvasyntha is a newly created UK-based Synthetic Biology company that engineers microbes to transform syngas into higher value products. Syngas can be produced by methane methods or by gassifying coal or other sources. The company's first project is to create organisms which will convert syngas to 1,3-butadiene, for cheap, renewable rubber. Butadiene is important component in the production of rubber, plastics and copolymers such as acrylic.[40]

Knipbio - Knipbio is a Boston-based synthetic biology startup which has engineered methanotrophic bacteria for fish feed. According to Knipbio, their microbes are about 60 per cent protein, and have been genetically modified to closely match the protein needs of fish. "Instead of beer, we're brewing protein," says Larry Feinberg, the company's CEO. Knipbio's methane-brewed fish feed also contains the pigments commonly fed to salmon, but they claim that can be customized to suit different kinds of fish. The company seems to be particularly targeting salmon, which can efficiently convert a pound of fish feed into a pound of salmon. Salmon are currently fed mostly on soy, but Knipbio is saying that developing fish food from methane saves on land use: "In a 100-acre facility, we can equal the production of 10,000 acres of soy," Feinberg told National Geographic.[41] Knipbio are one of a handful of Syn Bio startups who are pitching their technology as a "solution" to unsustainable farming of protein.

Salmon are currently fed mostly on soy, but Knipbio is saying that developing fish food from methane saves on land use. Knipbio are one of a handful of Syn Bio startups who are pitching their technology as a "solution" to unsustainable farming of protein.

Arzeeda – Seattle-based Arzeeda corporation uses synthetic biology tools to design new enzymes. With one million dollars funding from REMOTE (see Box) Arzeeda is running a program to develop enzymes that can be used to transform methane into complex chemicals and liquid fuels through fermentation.[42]

MOgene – St. Louis-based MOgene green chemicals in Missouri, working with Sandia National Lab, received 2.4 million dollars from the US government's REMOTE programme (see Box) to engineer a cyanobacteria (blue-green algae) to efficiently turn natural gas into the fuel butanol using energy from the sun.[43]

39 Joe Fisher, "Methane-to-Ethylene Plant Comes Online in Texas" *Natural Gas Intelligence,* 6th April 2015. http://siluria.com/Newsroom/In_the_News?MethanetoEthylene_Plant_Comes_Online_in_Texas#2

40 "ZuvaSyntha: Recycling Cheap Carbon And Waste Into Commodity Chemicals" Synbiobeta 02/06/2015. http://synbiobeta.com/zuvasyntha-carbon-chemicals/

41 Tamar Haspel, "Finding ways to feed the fish that feed us," *National Geographic,* May 13, 2015. http://theplate.nationalgeographic.com/2015/05/13/finding-ways-to-feed-the-fish-that-feed-us/

42 http://arzeda.com

43 http://mogene.com

REMOTE (Reducing Emissions using Methanotrophic Organisms for Transportation Energy)

A common element across a number of companies and academic groups developing bioconversion of methane to fuels and chemicals is a 35 million dollar funding program by the US Department of Energy's ARPA-E (Advanced Energy Projects Agency). Known by the acronym REMOTE (Reducing Emissions using Methanotrophic Organisms for Transportation Energy), the focus of this program is to develop the means to capture "stranded gas" from fracking and other oil and gas extraction operations.[44] It would then be employed as a feedstock using Synthetic Biology and other biotechnology methods to convert that methane into fuels and chemicals.

The focus of the REMOTE program is to develop the means to capture "stranded gas" from fracking and other oil and gas extraction operations.

The "reducing emissions" part of the title is because the intention is that by capturing and using stranded gas for gaseous fermentaion purposes, ARPA-E hopes that will displace flared and vented gas. Additionally REMOTE hopes that new synthetic biology-based means to turn gas into liquid fuels can be developed that do not have the same heavy carbon-intensive outcomes as the means of conversion that already exist.

The program is administered by Ramon Gonzalez, a synthetic biologist from Rice University in Texas. In an interview about REMOTE, Gonzalez explained that the technologies the program intends to produce are particularly applicable to the booming fracked gas market, since they, "will support natural gas bioconversion facilities with low capital cost and at small scales, which in turn would enable the use of any natural gas resource, including those frequently flared, vented or emitted."[45]

44 http://arpa-e.energy.gov/?q=arpa-e-programs/remote

45 Mike Williams, "The clean, green gas of home" *Rice News*, Feb 6, 2014. http://news.rice.edu/2014/02/06/the-clean-green-gas-of-home-2/#sthash.HuRIJMM4.dpuf

If Synthetic Biology allows the oil and gas industry to make economic use of "stranded" gas that will increase revenues from coal seams, oil fields and fracking operations. Photo of gas flare (cc) Kristian Dela Cour

Approach 2

Mining by Microbe: Direct Extraction Techniques

At a time of significant change in the extractive industries, there is some interest by oil, gas and mining companies to explore Synthetic Biology and related areas of engineering biology for use directly at the extraction end of things. This is not new. A US government review of prospects for genetic engineering in 1981 identified applications in the oil extraction and mining sector for recombinant DNA – approaches that are still under consideration today.[46] While the authors of this report have not been able to identify current commercial utilisation of Synthetic Biology-engineered microbes to directly access oil, coal, gas and minerals, there is on going research including field trials towards applying new biotechnologies for extraction, particularly for shale oil and natural gas. Below are a few of the key areas.

MEHR – Microbial Enhanced Hydrocarbon Recovery (including MEOR, Microbially Enhanced Oil Recovery)

As the volume of oil production experiences a worldwide decline, oil companies are increasingly interested in how to increase production in existing oil wells. Most of the oil in a reservoir is in fact "residual" oil that is largely inaccessible because it is still locked up in the matrix of rock or minerals that comprise the oil field. Usually oil extraction at an oil field will undergo two or three distinct phases: The first is an initial primary phase of recovering the easily available oil, which gushes forth due to natural pressure of the reservoir. A secondary phase is where water might be pumped into geological formations to flush out additional oil reserves. Then there is a suite of tertiary recovery techniques, such as injecting CO_2, chemicals or using heat – in what is known as Enhanced Oil Recovery (EOR).

As new oil becomes harder to access, these secondary and tertiary oil resources become increasingly important. The US Government's Department of Energy estimates that only 10 per cent of oil is recovered in primary oil recovery phase, 10-20% is recovered in secondary recovery and that "tertiary" recovery can yield 40-60% more oil from a reservoir.[47] According to some estimates, this "residual oil" amounts to 2-4 trillion barrels of oil, which is around 67% of total oil resources.[48] Some of this amount may be counted in official estimates of existing oil reserves, depending on market conditions and available technologies; but probably most of it is not counted, so it constitutes a large additional oil resource waiting to be tapped. That residual oil is therefore the focus of intense technological attempts by the oil industry to unlock it, through various techniques known by that acronym, EOR. BP, for example, speculates that if they can increase recovery of oil in existing reserves by just 1%, that amounts to an additional 2 billion barrels of oil to sell. BP believes up to a 5% increase is achievable.[49]

The leading areas of interest for Enhanced Oil Recovery involve pumping gases and chemicals into oilfields. However, also gaining some interest is the use of microbes to coax these fossil resources out of the ground. This area of technological development is known as Microbial Enhanced Hydrocarbon Recovery or Microbial Enhanced Oil Recovery (MEHR or MEOR). Similar approaches are being pursued to increase the extraction of natural gas (Microbially Enhanced Gas Recovery), and also include Microbially Enhanced Coalbed Methane. It has been estimated that up to 50% of residual oil may theoretically be able to be recovered by MEOR.[50] If that were proven to be true, it would expand global oil reserves by 150 per cent.

46 "Impact of Applied Genetics - Micro-Organisms, Plants and Animals," US Government Office of Technology Assessment, April 1981.

47 see http://energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery

48 Presentation by Jimoh I.A., Rudyk S.N. and Sogaard E.G, "Microbial Enhanced Oil Recovery: A Technology Tool for Sustainable Development of Residual Oil," Aalborg University

49 "Energy Biosciences Institute Adds Microbially Enhanced Hydrocarbon Recovery Project," Green Car Congress 1st April 2009. www.greencarcongress.com/2009/04/energy-biosciences-institute-adds-microbially-enhanced-hydrocarbon-recoveryproject.html

50 Biji Shibulal *et. al,* "Microbial Enhanced Heavy Oil recovery by The Aid of Inhabitant Spore forming Bacteria: An Insight review," *The Scientific World Journal,* vol 2014; article id 309159.

The idea of MEHR/MEOR goes back to 1926, when US geologist C.E. Zobell began exploring the role that microorganisms play under the surface to release hydrocarbons (oil and gas) from rock. Zobell began identifying naturally occurring microbes that degraded oil and made it flow more easily. Since then, over 400 patents for MEOR/MEHR techniques have been granted, although few have gone beyond exploratory stages. One example is using strains of bacteria injected into oil wells, along with molasses or other nutrients. The microbes, nourished on these feedstocks, excrete the chemicals that will treat the oil; for example upgrading heavy oils to lighter oils, or simply excreting surfactants (soaps) to help wash the oil out of the rock. To date, more than 322 trials of MEHR have been reported, and oil companies including BP, Shell and Statoil, are increasingly investing in developing the microbial approach, which, if feasible, could potentially operate at a lower cost than other EOR approaches. At least one company, Statoil, is already using MEHR in its fields in the Norwegian Sea, but is not using engineered microbes.[51]

While the practice of MEHR/MEOR is mostly concerned with isolating, culturing and re-injecting existing strains of naturally occurring microbes, oil and gas researchers are increasingly interested in adding genetic manipulation to their company's MEOR/MEHR techniques. In October 2007, a workshop held in Berkeley's Energy Biosciences Institute (EBI) brought together 18 scientists and engineers from private companies and academia, and which also included a Canadian provincial funding agency, Genome Alberta. They met to develop a white paper setting out research priorities in MEHR.[52] The group included 4 scientists from oil giant BP, as well as a representative of Syn Bio company Synthetic Genomics Inc. While the top priorities established were simply to be better characterization of existing microorganisms to be found in oil and gas fields, the group also discussed Synthetic Biology research as holding singular promise. They wrote: "As the science progresses it may be feasible to use the tools of synthetic biology to improve the efficiency of MEHR." They gave specific examples, including engineering a single strain of microorganism that could carry out multiple-linked metabolic processes that in nature require several species working in collaboration. They also suggested Syn Bio could "improve" enzymes and make microbes better able to withstand the stresses of the subsurface environment – such as being able to survive with less nutrients.[53] This should be of particular concern for ecologists if it imparts a fitness advantage that lets the microbe persist and reproduce in the environment.

As well as using microbes as miners to actually extract oil from rock underground, researchers are also interested in using microbes as refiners to process and "sweeten" oil, either in situ underground, or after it has left the well. The idea here is to convert heavier oils such as "heavy crude," the bitumen of the tar sands, to lighter oils that are easier and cheaper to transport. The International Energy Agency reports that around 66% of remaining crude oil in reserves is classified as "heavy."[54]

Using Microbes to Stimulate Coal Bed Methane

Similar to the approach of MEOR is a field of activity referred to as Microbially Enhanced Coalbed Methane generation (MECoM) in which researchers are seeking to identify more methanogen microbes that can collaborate to turn coal into gas. These researchers then either introduce these microbes into coal seams or add nutrients to stimulate those that are already there. The discovery that around 20% of natural gas originates from microbes has led to increased interest in MECoM, with a handful of commercial companies beginning to carry out field trials of MECoM approaches since 2000.[55] So far, field trials appear to have only involved naturally occurring microbes; but at least one company, Synthetic Genomics Inc., has the intent (and a patent) to move towards possible genetically engineered ones. (see Box below).

51 Statoil Website, "Microbial enhanced oil recovery (MEOR)." http://www.statoil.com/en/TechnologyInnovation/OptimizingReservoirRecovery/RecoveryMethods/WaterAssistedMethodsImprovedOilRecoveryIOR/Pages/MicrobialEnhancedOilRecovery(MEOR).aspx

52 "Research priorities in Microbially Enhanced Hydrocarbon Recovery (MEHR)," Report of EBI MEHR Workshop, October 24, 2007, Energy Bioscience Institute of UC Berkeley.

53 Report on Project: "Bio-engineering High performance Microbial Strains for MEOR by Directed Protein-Evolution Technology," National Energy Technology Laboratory/US Department of Energy, December 2008

54 http://www.taxon.com/applications.php

55 Ritter, Daniel "Enhanced Microbial Coalbed Methane Generation: A Review of Research, Commercial Activity, and Remaining Challenges," *International Journal of Coal Geology,* 05/2015.

Commercial Research into Synthetic Biology for MEHR

Although we have not been able to identify any proven current or imminent commercial uses of Synthetic Biology for MEOR/MEHR or MECoM, the following research initiatives are underway and are relevant:

Synthetic Genomics / BP project

Synthetic Genomics Inc. (SGI) is the private synthetic biology company established by the controversial genome businessman J. Craig Venter. SGI exists to commercialise Syn Bio research emanating from an ostensibly non-profit outfit, the J. Craig Venter Institute, with which it shares facilities. In June 2007, oil giant BP took an undisclosed equity stake in SGI, accompanied by what was described as, "a significant, long-term research and development deal" between SGI and BP to explore Microbial enhanced hydrocarbon recovery (MEHR).[56] Although public details of the BP/SGI collaboration are sparse, the deal was to be in two phases, beginning with genomic profiling of the microbes found in oil and gas fields, including coal bed methane.[57] The profiling would be followed by field pilot studies of the most promising bioconversion approaches, and perhaps subsequent joint commercialization. At the time of the announcement, SGI president Ari Patrinos told Technology Review that SGI and BP were particularly interested in finding microbes that could upgrade heavy oils (like tar sands bitumen), making them lighter and less dense for transport, as well as deploying microorganisms that could convert coal seams into methane. The SGI/BP project was initially focused on characterizing naturally occurring microbes.

SGI and BP were particularly interested in finding microbes that could upgrade heavy oils (like tar sands bitumen), making them lighter and less dense for transport, as well as deploying microorganisms that could convert coal seams into methane.

56 Synthetic Genomics Inc. news release: "Synthetic Genomics Inc. and BP to Explore Bioconversion of Hydrocarbons into Cleaner Fuels," June 13 2007.

57 Emily Singer, "Building a Bug to Harvest Oil," *Technology Review*, June27 2007.

58 Synthetic Genomics Inc., US Patent no US8448702 B2, "Methods of enhancing biogenic production of methane from hydrocarbon-bearing formations."

However, a US patent on MECoM applied for by Synthetic Genomics in 2011 clearly claims ownership of a microbe for producing methane from coal: "wherein said microorganism expressing said enzyme is a synthetic microorganism." The patent's scope covers use of these microorganisms in a variety of hydrocarbon reserves, including "coal, peat, lignite, oil shale, oil formation, traditional black oil, viscous oil, oils sands and tar sands."[58]

EBI MEHR Project (BP sponsored)

In April 2009, the Energy Biosciences Institute (EBI) at the University of Berkeley, funded by BP, established a new program to develop Microbial Enhanced Hydrocarbon Recovery approaches, in collaboration with BP scientists and researchers from the Department of Energy's Lawrence Berkeley National Lab and the University of Illinois at Urbana-Champagne.[59] EBI is part of one of the leading Synthetic Biology hubs in the world. Besides monitoring and analysing existing microbial populations, it was reported that its project would develop a "model framework that future EBI researchers will be able to use for MEHR microbial engineering, [and] on-site biology manipulation." The program also established "natural subsurface laboratories" as test sites, including a newly drilled injection well located on the property of Archer Daniels Midland in Decatur Illinois.

Taxon Biosciences / DuPont

In April 2015, chemical and biotech giant DuPont acquired Taxon Biosciences of California – a biotech company specialising in manipulating microbiomes (communities of microbes). Taxon boasts several strands of development and application in the oil and gas field, including Microbial Enhanced Hydrocarbon Recovery.

59 "Energy Biosciences Institute Adds Microbially Enhanced Hydrocarbon Recovery Project," Green Car Congress 1st April 2009. www.greencarcongress.com/2009/04/energy-biosciences-institute-adds-microbially-enhanced-hydrocarbon-recoveryproject.htm

Their core technology is creating so-called "synthetic consortia" of microbes. They artificially combine together groups of microbes with specific functions, to make them cooperate in biologically processing oil, coal and other hydrocarbons. Taxon has on going work creating these "synthetic consortia," to inject into coal seams to transform coal to methane, as well as converting heavy oil to lighter oil, or degrading oil under the surface in order to more easily recover it.

"New microbes with enhanced properties to recover residual oil are currently in development. These discoveries offer the promise of converting non-economical oil fields into economical resources and extending the life of mature oil fields."

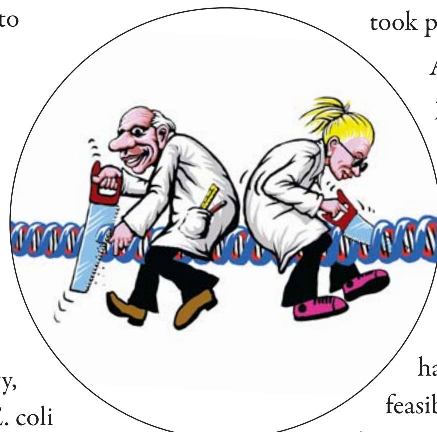
- Taxon Biosciences.

While not a Synthetic Biology company *per se*, because they are only combining natural communities in novel ways instead of engineering their genes, Taxon maintains an extensive library of genetic sequences that appear to be relevant to Microbial Enhanced Hydrocarbon Recovery. They boast that, "new microbes with enhanced properties to recover residual oil are currently in development. These discoveries offer the promise of converting non-economical oil fields into economical resources and extending the life of mature oil fields."[60]

60 see http://www.taxon.com/applications.php

Non-Commercial Research on Engineered Microbes for MEHR/MEOR

There appears to be on going non-commercial, academic or purely scientific research into bioengineering microbes for Microbial Enhanced Hydrocarbon Recovery, and this includes Synthetic Biology approaches.



Rhamnolipids

Between 2004 and 2007, researchers at the California Institute of Technology funded by the US Department of Energy, successfully engineered new strains of E. coli and Pseudomonas aeruginosa to produce a type of surfactant called a rhamnolipid.

The team demonstrated that injecting these engineered organisms into oil wells could increase the amount of oil recovered when the wells are flooded (a common step for recovering oil). They claim they could recover 42% of the remaining oil after water flooding. In their report to the US government, the CIT team concluded that, "implanting this surfactant-making ability in microbes adapted to oil makes feasible an in situ MEOR process that requires little operator maintenance."

The report specifically describes the engineering that took place as "synthetic biology."[61]

A further study by Chinese researchers published in 2014 also reported on bioengineering common oil microbes to produce rhamnolipids for MEOR, a piece of research funded by the Daqing Oilfield Company of Heliongjiang Province. The researchers concluded that the engineered organism had, "demonstrated the potential feasibility of Rhl as a promising strain to enhance oil recovery through anaeriobic production of rhamnolipids."[62]

A 2011 study, also by Chinese researchers, reported on the re-engineering of an Enterobacter bacteria and Geobacillus strain to inject into oil fields to produce a polymer substance called exopolysaccharide, The researchers concluded that, "this approach has a promising application potential in MEOR."[63]

61 Report on Project: "Bio-engineering High performance Microbial Strains for MEOR by Directed Protein-Evolution Technology," National Energy Technology Laboratory/US Department of Energy, December 2008.

62 F. Zhao *et al*. "Heterologous production of Pseudomonas aeruginosa rhamnolipid under anaerobic conditions for microbial enhanced oil recovery," *Journal of Applied Microbiology,* Vol 118, Issue 2, pages 379–389, February 2015.

63 Sun. S, "Exopolysaccharide production by a genetically engineered Enterobacter cloacae strain for microbial enhanced oil recovery." *Bioresour Technol,* May 2011;102(10):6153-8.

Oil Sands Leadership Initiative (OLSI) – Syn Bio for the Tar Sands

(OSLI) is a network of oil companies active in Canada's tar sands extraction region, who are collaborating to improve the area's public image and support industry activities. The network includes ConocoPhillips Canada, Nexen, Shell, Statoil, Suncor Energy, and Total E&P. Since 2010, OSLI has been sponsoring Synthetic Biology research that "addresses oil sands challenges," offering sponsorship to several teams of students who compete in IGEM (International Genetically Engineered Machine Competition – a sort of annual Olympiad for young synthetic biologists).

Arising out of its IGEM sponsorship programme, OSLI hosted a 2012 workshop on potential applications of Synthetic Biology to the tar sands at the ConocoPhillips Canada office in Calgary, Alberta. Participants reported that the goal of the workshop was to bring together industry representatives and researchers to discuss the current state of research in both petroleum microbiology and synthetic biology, and to identify areas of common interest for collaboration.
In particular the aim was, "to determine what barriers or threshold conditions that synthetic biology technologies must meet in order to be considered by oil sands companies for their operations." The consensus of the meeting was that, "the most important technology platforms to continue to look into and which may provide early benefits to the oil industry are microbial degradation/conversion systems (i.e. MEHR/MEOR) and biosensor systems."[64]

OSLI's IGEM sponsorship programme reflects these priorities, and focuses on use of engineered microbes to transform heavy bitumen oil into lighter, more transportable crude, as well as on using microbes for sensing the condition of oil reserves and for helping in environmental clean-up.

64 Calgary IGEM, "The Oil sands Leadership Initiative." http://2012.igem.org/Team:Calgary/Project/HumanPractices/Collaborations

65 OSLI, "Biological Solutions For the oil Sands," archived online at http://2010.igem.org/User:Meagan/Oil_Sands

Synthetic Biomining and Bio-leaching

Beyond the fossil fuel majors, other mining and extractive industries are keeping an eye on Synthetic Biology, particularly in the area of metals extraction. Biomining (or bioleaching) describes the application of microbes to mined metal ores, in order to increase the extraction of metals. An acidic solution containing rock-eating microorganisms is added to a heap of mined material. The microbes then make their way through the heap, leaching out the metals for easier recovery. Using natural microbes for this purpose is already a well established technique, and bioleaching currently accounts for an estimated 20 per cent of the world's mined copper, in use at around 20 mines around the world. A related biomining technique, biooxidation, is also commercially employed for recovering about 5% of the world's gold. Biomining approaches are presented as more environmentally sustainable than traditional heat and pressure techniques for processing metal ores, because of their lower energy requirements. They are also viewed as a means to make smaller mines economically viable and easier to start, as well as to extend the value of existing mines. Lower grade ores that may previously have been discarded or ignored can be recovered with these techniques. This means areas previously free of mining may become attractive to this ecologically damaging industry. Teams of Synthetic Biologists are now also exploring options for improving the effectiveness of biomining techniques using synthetically engineered organisms.[66] Bioleaching with engineered microbes could pose significant ecological risks since it involves environmental release.

66 MIT – Mission 2015, Biodiversity, "Bioleaching: Making Mining Sustainable." http://web.mit.edu/12.000/www/m2015/2015/bioleaching.html

Universal BioMining

Universal BioMining (UBM) is a synthetic biology start-up in San Francisco USA who describe themselves as "focused on applying Synthetic Biology and bioprocess engineering to the mining industry." UBM has developed synthetic microbes that they claim will improve bioleaching and bioxidation processes for both copper and gold.

UBM's lead product is a method of recovering gold from the tailings (waste streams) of goldmines, and the company claims they can recover billions of dollars of additional gold with their technology. For their Syn Bio copper project, UBM is targeting the 70% of low grade copper ore that cannot be processed by existing bioleaching method. They claim their technology could eventually produce up to 2 billion dollars worth of additional copper annually, from low grade ores previously regarded as uneconomical waste. UBM freely admits that a constraint on the development of their technology is that it will involve the environmental release of engineered synthetic organisms; but they express confidence that the US Government will grant them release permits, despite the lack of regulation protocols or governance capable of assessing and overseeing the environmental release of such microbes. In 2014, Universal Biomining's bioleaching process was evaluated as part of an exercise carried out by Woodrow Wilson Center for Scholars exploring the ecological issues in Synthetic Biology.[67] In 2012, UBM also partnered with SETI institute (that uses computer data from volunteers to search for extra-terrestrial life) to receive a $125,000 research grant from NASA (the US Space agency), exploring use of Synthetic Biology for biomining of regolith (dust, soil and rock from other planets, including the moon).[68]

IGEM (International Genetically Engineered Machine Competition)

As mentioned above, IGEM is an annual competition or Olympiad for synthetic biologists competing to design novel applications for Synthetic Biology. There have been a few IGEM teams developing biomining applications:

- 2012 Stanford Brown Team - attempted to engineer bacteria to recover metal ions from electronics or soils, with a view to use in space missions.[69]
- 2014 University of British Columbia IGEM Team - engineered a Caulobacter bacteria to perform biomining processes to separate chalcopyrite, which is the main ore of copper.[70]
- 2014 HNU China IGEM team – engineered yeast strains to act as biomining agents.[71]

67 "Creating a Research Agenda for The Ecological Implications of Synthetic Biology," Woodrow Wilson Center, 2015. www.wilsoncenter.org/sites/default/files/SYNBIO_create%20an%20agenda_v4.pdf

Conclusions and Next Steps

As this report makes clear, the self-projected image of the emerging Synthetic Biology industry, as a clean, green business sector that will help usher in a post-fossil fuel era, is increasingly unsupportable – and probably always has been. Like any powerful technology, entrenched interests are shaping the new field and leveraging the technology to protect and boost their own profits and keep the fossils and minerals flowing from the ground.

From injecting engineered organisms into oil wells to developing the means to turn fracked and flared gas and coalbed methane into higher value compounds, the extractive industries are experimenting with Syn Bio in their R&D strategies as a means of bringing additional reserves and resources into economic exploitation. The Syn Bio companies, for their part, are tying their futures ever closer to the fate of the extractive economy, apparently happy to retool themselves to serve the carbon majors. While some approaches, such as Microbially Enhanced Hydrocarbon Recovery, are still far from commercial application, others, such as bioconversion of natural gas to other fuels, is moving apace. We may very soon find ourselves buying methanotroph-derived plastics, fuels, foods and even pharmaceuticals, novel products whose health and ecological effects have still been barely imagined, much less explored. Industry will try to tell us such products are "green" because their production captures and use methane that otherwise would have been flared or vented.

The new, unholy merger of Synthetic Biology with the big extractive industries warrants very close attention from anyone who is concerned by fossil industry expansion on climate grounds, or worried about biotech industry expansion on biosafety and justice grounds. A dialogue between the Climate Justice and anti-biotech movements would be very fruitful and at this stage, rather urgent.

68 "Biomining of regolith simulants for biological in situ resource utilization." http://sbir.gsfc.nasa.gov/content/biomining-regolith-simulants-biological-situ-resource-utilization

69 http://2012.igem.org/Team:Stanford-Brown/Biomining/Introduction

70 http://2014.igem.org/Team:British_Columbia/ProjectBiomining

71 http://2014.igem.org/Team:HNU_China

Climate Action

For those resisting fossil fuel expansion by fracking, who oppose pipelines or new exploration in sensitive areas, there is a vital need for meetings and discussions about how "gaseous fermentation," MEHR and biomining are changing the game. By potentially increasing the value of fracked gas and shale oil, increasing the carbon intensity of methane-derived products, as well as unlocking 40-60% more fuels from known reserves, this new industrial strategy truly is potentially enormous in its implications for the climate. Society also needs to consider the economic, health, environmental and planetary effects of how MEHR approaches could extend the lifetime and boost the fossil fuel production of all the oil, shale and coalfields that remain on earth, adding billions of tons to the soil, water and atmospheric deposition of CO_2. Such conversations should be getting underway to help develop appropriate civil society and governance response strategies that can address these new threats and expose them as false solutions. If, at some point in the future, synthetically engineered microbes are to be deployed at local oil or gas fields, or are going to be used in fermentation facilities close to production sites, then this may introduce an entirely new class of local risks that workers, communities and ecologists will want to better understand. Certainly, even at this relatively early phase, it would be in line with the Precautionary Principle to demand a moratorium, that fossil companies do not incorporate synthetic biology approaches into any commercial or outdoor operations at this time, pending more complete assesment that takes all players into account and is independent of immediate economic bias.

We may very soon find ourselves buying methanotroph-derived plastics, fuels, foods and even pharmaceuticals, novel products whose health and ecological effects have still been barely imagined, much less explored.

As COP21 of the Climate negotiations in Paris approaches, those following the negotiations need to be on guard that the oil and gas industry might attempt to secure political support for 'gaseous fermentation', and bioconversion of gas to liquids fuels and other products.

The industry is already focusing on action to mitigate flaring and venting as a key part of its proposed action plan to address climate change. They will attempt to misrepresent these techniques as a "low carbon, green option" because they allow the industry to avoid flaring and venting of methane. It will be argued that capturing stranded gas from extraction operations and turning it into saleable products through synthetic biology is "carbon capture use and storage" (CCUS). Civil Society groups have warned against allowing Carbon capture and storage (including Carbon Capture and Use) to become part of a deal at Paris whereby countries side step real emission reduction commitment by pursuing instead set "net zero" targets allowing unproven and possibly damaging sequestration technologies. Additionally some parties to the UNFCCC are showing increasing political support for Enhanced Oil Recovery, under the guise of Carbon Capture and Storage. This growing enthusiasm for EOR and CCS must not mistakenly translate into political or social support for Microbial Enhanced Oil Recovery and the risky release of engineered synthetic organisms.

Biodiversity Protection

Meanwhile, the on going processes to evaluate and address the topic of Synthetic Biology at the UN Convention on Biological Diversity (CBD) should also address the climate and biosafety risks that may follow from Syn Bio's switch to pursuing fossil resources and its experimentation with biomining. The CBD's SBSTTA could in particular recommend precautionary measures be taken, to ensure that engineered synthetic organisms, including methanotrophs, are not released into the environment, and that engineered organisms for Microbially Enhanced Hydrocarbon Recovery are not permitted to be released at this time.

The CBD's SBSTTA could in particular recommend precautionary measures be taken, to ensure that engineered synthetic organisms, including methanotrophs, are not released into the environment,

The extreme genetic engineering industry of Synthetic Biology (Syn Bio) is shrugging off earlier pretensions that it would usher in a clean, green 'post-petroleum' economy. Now they are partnering with big oil, coal, gas and mining interests.

As the extreme biotech industry and the extreme extraction industry move towards deeper collaboration, the safety risks and climate threats emanating from both will start to become ever more entangled. This report details this emerging fossil-biotech alliance.

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