Renewable gas and CCU

Contribution to WP1 of the IEA Bioenergy Intertask project
"Renewable gas - deployment, markets and sustainable trade"

April 2021

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Published by IEA Bioenergy

1. Towards a new carbon economy

Similar to how the global energy system is dominated by fossil fuels, production of chemicals and plastics are almost exclusively based on fossil sources of carbon, in the form of crude oil, natural gas or coal. Finding a new way to manage carbon as a resource and literal building block for society in a world where fossil fuel extraction and use is largely phased out will be a challenge that accompanies the reduction of global GHG emissions. There is basically a need to develop a "new carbon economy" based on carbon sources other than fossil fuels. Some of the demand will be met by using biogenic carbon directly from biomass, but there is a potential to basically reverse the current system: Making CO_2 the starting point of the carbon economy, rather than it being the largest waste product.

The essential elemental building blocks of the petrochemicals sector – hydrogen (H), carbon (C), and oxygen (O) – are found in abundance in the world in the form of CO_2 and water, H_2O, so there is in one sense no shortage of feedstocks. However, the reason why these are available in abundance in the natural world is that they are very stable chemical combinations of the individual elements.

Essentially, CO_2 and H_2O are produced in large volumes from combustion processes. Correspondingly, to reverse the process and use CO_2 and H_2 from H_2O as building blocks will require additional energy. However, with ongoing and continued cost reductions in solar & wind, a reverse carbon economy becomes increasingly viable, especially if combined with policy that supports the transition.

This paper reviews the current status of technologies, markets and policies aimed at synthesizing organic chemicals from CO_2 and H_2, with a more deep-dive focus on the simplest hydrocarbon, methane, CH_4.

2. Biomass-based gases: digestion & gasification

Building renewable fuels, chemicals and materials based on CO_2 and H_2 is a rapidly expanding field. Norhasyima & Mahlia (2018) reviewed the number of patents published on different CO_2 capture and utilization (CCU) technologies over the time period 1980-2017 and found in total 3000 patents, half of which were published after 2010. It is important to note that CCU includes things such as enhanced oil recovery (EOR) and mineral carbonation. However, the applications focus on herein – chemicals and fuels – made up more than half of the total. Chauvy & Weireld (2020) note that more than 150 different products have been identified as possible to manufacture via CCU. While most of these are high-value/low-volume chemicals, one of the more basic CCU products is also one with the largest current market, namely methane (CH_4) which is the main component in natural gas and a widely used feedstock in the chemical industry.

There are some volumes of renewable methane being produced already today, although not primarily via the CCU route but as a key component of different renewable gases produced from biomass. Biomass-based gases can be produced through several different process, with the one currently most widely deployed being anaerobic digestion (AD).

Biogas produced through anaerobic digestion is typically made up of 40-70% CH_4 with CO_2 making up most of the remainder. Biogas also includes different trace elements (H_2S, N, CO…) that make up only up to a few percent of the total volume, but that are key determinants of biogas quality (Rodin et al. 2020; Vasco-Correa et al. 2018).

Another way of producing gaseous energy carriers from biomass is through gasification, whereby biomass is heated to high temperatures but without combustion, resulting in the production of so-called syngas, composed primarily of H_2 and CO with only marginal shares of CH_4. However, through further synthesis of the syngas, it is possible to produce very pure methane via a process called methanation. While there have been large-scale pilot & demonstration facilities focused on biomass-to-methane via gasification, full commercialization appears to remain elusive (Ahlström 2020).

In the light of the disparity in terms of commercial maturity between production of CH_4 via AD on the one hand and via gasification on the other, we will focus the remainder of our analysis on biogas produced from AD. Therefore, it is worthwhile to take a closer look at the characteristics of the process and corresponding supply chain and how these affect the prospects of using CO_2 from biogas for CCU applications.

A central starting point to be aware of when discussing AD is the heterogeneity of systems and value chains in which the process can be applied and integrated. To begin with feedstocks, this covers a broad range though with the common theme of being some form of waste product or process residue. Crop residues, food waste, manure and sewage sludge are some of the most common types of feedstock used (WBA 2020).

Similarly, there is wide heterogeneity among the settings and scales in which AD processes are used, including everything from very small household-level digesters (of which there are more than 40 million in China alone) via farm-level digesters to large centralized installations at e.g., wastewater treatment plants (Vasco-Correa et al. 2018).

"Large" in this context needs though to be taken as a relative indicator, because AD facilities on the whole are small compared to many other forms of energy facilities, e.g., other bioenergy facilities. This holds true both for the production and consumption, as can be indicated from how the average capacity of units producing electricity from combustion of biogas is only around 0.6 MW in Europe (European Biogas Association 2019).

On a global level, direct combustion of biogas for generation of heat and/or electricity is the most common means of utilization (Vasco-Correa et al. 2018), but here as well there is substantial heterogeneity. Especially important for our current purpose is the practice of upgrading biogas to biomethane. This is done by separating out the CO_2 component and most of the trace elements in order to obtain a CH_4 stream that is of sufficient quality that it can be blended with, and/or used in applications originally designed for, CH_4 of fossil origin (natural gas). This allows for injection into existing gas grids or for use in gas-powered transportation (cars, buses, trains or ships).

3. Biogas as a CCU carbon source - capture

Continuing with the narrative of heterogeneity being a key characteristic of anaerobic digestion systems, there are also several different ways in which biogas can act as a source of carbon for CCU systems. Rodin et al (2020) distinguish between two main pathways, the first being utilization of CO_2 captured from the upgrading of biogas to biomethane and the second being capturing of CO_2 from combustion of biogas. However, the second route could arguably also be divided complemented by a third route, namely capturing of CO_2 from combustion of upgraded biomethane. In the following, we will review these three options in terms of potential and techno-economic properties.

Capture and utilization of CO_2 from biogas upgrading is along with CO_2 originating from fermentation processes - e.g., in bioethanol production plants - typically seen as one of the lowest hanging fruits when it comes to sources of biogenic CO_2. In both these cases, the CO_2 is separated out in a very pure form as part of existing processes and as such the additional cost of capture are very low.

A conceptually straightforward way to implement CCU technology as part of this process is to introduce a methanation stage to the upgrading process, so that the separated CO_2 stream is combined with H_2 and synthesized into CH_4, which supplement the CH_4 obtained in the separation stage. If the H_2 is produced via electrolysis powered by clean electricity, this system can have very low life cycle emissions (Zhang et al. 2020).

It is however also quite possible to utilize the separated CO_2 stream for other purposes as well, although some applications may require further upgrading of the CO_2. The reason is that since the main objective of the separation process hitherto has been to obtain a clean CH_4 stream, with the CO_2 being more of a residue, the CO_2 stream can contain trace elements that can act as contaminants (Rodin et al. 2020).

The second route, direct combustion of biogas with air, will be less advantageous in terms of capture efficiencies as the CO_2 concentration will be substantially lower, on the order of 8-15%. This is higher than concentrations in flue gases from pure CH_4 - for the obvious reason that the biogas already is made up of a large share of CO_2 - but will still mean that further processing steps will need to be added in order to obtain a concentrated CO_2 stream (Rodin et al. 2020).

The characteristics and potential of the third route, capture of CO_2 from combustion of upgraded biomethane, will to a large extent be determined by the setting in which the combustion takes place. As was noted earlier, there are great variations here.

To start with the clearest case: if the combustion takes place in a transportation vehicle, then CO_2 capture is for all intents and purposes out of the question[1]. Secondly, if the biomethane has been injected into the natural gas grid, then most likely any CO_2 capture will be implemented at large combustion or processing facilities.

Regardless, the biomethane portions will just be mixed in as a small portion of the total methane combusted or processed and while it may as such improve the total life cycle emissions scorecard, it requires no further discussion here.

Finally, if the biomethane is combusted in pure form, there is potential to extract a strictly biogenic CO_2 stream, but the CO_2 concentrations will be low, around 3-10%, meaning that further upgrading will be needed for utilization.

[1] Although it should be mentioned that there are projects investigating the possibilities of capturing CO2 from ship engines for onboard storage (Roussanaly 2021).

4. System aspects of biogas as a CCU source

Costs and feasibility of CO_2 capture is to a large extent reliant on a few key parameters. CO_2 concentration in the source gas is arguably the central parameter to take into account, but the extent of economies of scale and availability of on-site process heat can also be highly important (Olsson et al. 2020). It was noted earlier that AD systems typically are quite small and distributed, which means that from a CO_2 capture cost perspective, they are at a major disadvantage compared to e.g., power stations or pulp & paper mills that may be two orders of magnitude larger in terms of point source CO_2 volumes.

However, AD has a major advantage in the very high CO_2 concentrations that become available from the separation of CO_2 and CH_4 in the biogas upgrading stage. Given that this CO_2 also becomes available "for free" as a by-product, this makes for very low capture costs which compensate for the scale disadvantage. Yet, the capture step is only the first step of CCU or CCS value chains, and techno-economic characteristics of the full chain need to be considered. There are substantial economies of scale in the transportation phase of the CCS supply chain, indicating that carbon capture and storage may not be a suitable option for biogas facilities. Instead, utilization options that make use of the CO_2 at, or close to, the production site may be preferable.

One factor that speaks in favor of this is that electrolyzers tend not to be associated with economies of unit scale which means that they could lend themselves well for distributed deployment. Furthermore, the modular and "granular" properties of electrolyzers is an indication that they could have steep experience curves as the industry scales up (Wilson et al. 2020), further improving the competitiveness of processes such as CCU that are based on green H_2.

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