Biomass, BECCS and electrolysis for climate-neutral liquid fuels

Synthetic e-fuels, biofuels, and BECCS can be 'carbon-negative' and therefore have a valuable role to play in a 'net-zero' energy system

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The energy transition has many geopolitical, economic, and environmental drivers. Principle drivers include diversification of energy supply, avoidance of dependence on fragile fossil fuel supply chains, avoiding price spikes in traded commodities, and mitigating climate change. Synthetic e-fuels and carbon dioxide (CO_2) utilisation from bioenergy with carbon capture and storage (BECCS) related to biofuels can be part of the solution. The recycling of atmospheric CO_2 into synthetic fuels using renewable energy offers a solution with no net CO_2 emissions. Renewable synthetic liquid fuels will therefore play a key role in the energy transition alongside green hydrogen, as traditional refined products are challenged by fossil-free energy vectors.

Carbon accounting and credible climate-neutral claims

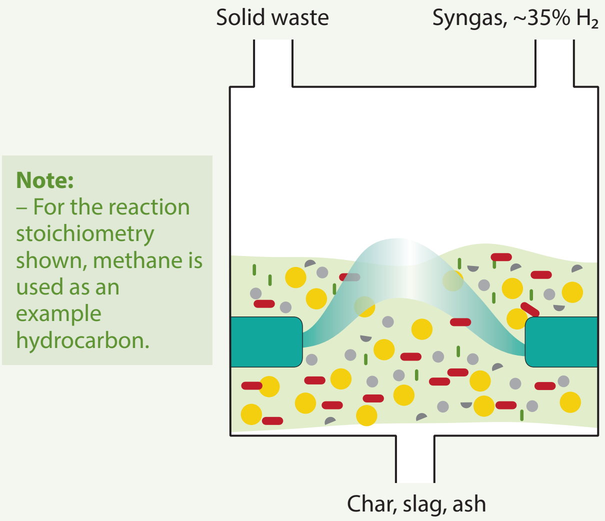
The production of liquid fuels from biomass can be carbon neutral or carbon negative. Greenhouse gas (GHG) emissions that emanate directly from production are referred to as Scope 1 emissions. However, in a full lifecycle analysis of the environmental impact, it is important to go beyond production of the fuel and consider GHG emissions from the use of the fuel: referred to as Scope 3 emissions. For example, ammonia and hydrogen yield no CO_2 emissions when used. On the other hand, synthetic e-fuels or synthetic methanol do emit CO_2 when burned to release its energy value. So-called Scope 2 emissions, which are generated by inputs to the process such as power generation, must also be accounted for, and all three must be considered for a valid 'carbon negative' declaration.

Furthermore, we must think beyond carbon neutrality to 'climate neutrality', meaning the CO_2 equivalence of methane emissions must be considered. For example, biogas, biomethane, and renewable LNG are all low-carbon energy vectors, but if there are methane leaks that result from their production or distribution, they can have a very negative environmental impact. Per tonne of emissions to the atmosphere, methane is a much more potent GHG than CO_2.

The mechanics and principles of 'carbon accounting' and 'life cycle analysis' are well documented in ISO standards, and these can be followed to justify the use of labels such as 'climate neutral' or 'carbon negative' for certain fuels. For example, these standards give guidance on how the substitution of fossil fuel usage or the avoidance of alternative biomass decomposition pathways can have a positive effect on carbon accounting calculations.

Some biomass-related pathways to produce energy vectors have the potential to be carbon negative or GHG emissions negative. According to the EU Renewable Energy Directive, certain modes of biomethane production from biogas are regarded as carbon negative. Annex VI declares numerical values for the climate impact of biomethane production from various digester technologies and feedstocks for heat and power or mobility applications. In certain scenarios, there are significant carbon-negative impacts of producing and using renewable biomethane.

Another example would be the gasification of biomass to make syngas and the conversion of that syngas to gasoline, either via methanol and methanol-to-gasoline process (MTG) or via Fischer-Tropsch (FT). This pathway could be



	Plasma gasification of solid hydrocarbons, eg waste
Carbon feedstock	Municipal solid waste, dried waste water treatment sludge, biomass, waste paper, tyres, etc
Target chemical reactions	Hydrocarbon + 0_2 → 2CO + $4H_2$ Hydrocarbon + H^2O → CO+ $3H_2$
Additional side reactions	Hydrocarbon + 20_2 → CO_2 + $2H_20$
Carbon produced as	CO, CO_2, char, slag and ash
Product gas pressure	Close to atmospheric pressure
Product gas temp	~1,000°C

Figure 1 Plasma-based gasification of waste or biomass

carbon negative if the CO_2 from the biomass gasification process is captured and permanently sequestered, referred to as BECCS. However, the overall life cycle of that pathway must consider the CO_2 emissions from the use of methanol or liquid fuel. Furthermore, if the gasification is optimised for hydrogen production using reforming within the gasification process, and subsequent water gas shift reactions and BECCS are involved in sequestering the CO_2 emissions from the process, we can produce a fuel that has zero emissions when used.

In the case of other lower temperature biomass thermolysis processes, such as pyrolysis, we often yield solid carbon as char in addition to producing liquid fuels similar to heavy fuel oil. Locking carbon into biochar is also regarded as carbon negative, and in the EU, the regulations allow for carbon credits through this pathway.

Limitations to scaling up biofuels and the use of MSW as an alternative feedstock

Biomass gasification to yield syngas is a viable techno-economic pathway to methanol and other liquid fuels. However, the difficulty of securing mass-scale biomass feedstock has limited scale-up and has acted as a bottleneck for biofuels. The planting of energy crops to displace food production and deforestation to make way for energy crops must be avoided if biofuels are to be a sustainable part of our future.

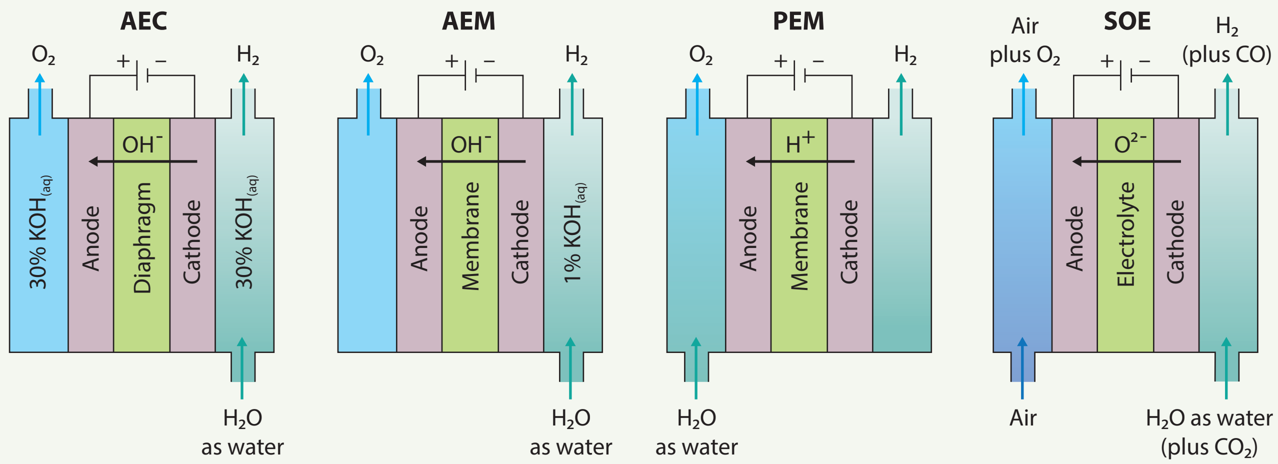
Biomass collection and use are therefore limited to regions with significant agricultural waste, such as the central Californian valley, where almond shells or pruning clippings from orange groves are abundant. Other notable examples include managed forests, such as in Canada or northern Europe, where saw-mill wastes can be used as pelletised woodchips.

The use of municipal solid waste (MSW) as an alternative feedstock to biomass is technically possible. Both have similar moisture content and handling properties. MSW is generally around 50% biomass, even after sorting out the green and paper fractions. The residual content is often plastics from packaging that are also hydrocarbons, like biomass.

Gasification technologies have been used to process biomass and MSW. See **Figure 1** for a generic plasma gasifier representation. Some have even made the bridge from MSW to biomass. For example, the InEnTec plasma gasifier has been used on more than 13 MSW gasification projects since 1995. Aetemis is also planning to deploy the InEnTec plasma gasifier for a biomass-to-hydrogen gasification process in the US using feedstock signed for walnut, almond, and pistachio nut waste from Californian farms with 20-year supply contracts now signed. A life cycle analysis study has concluded that this is a carbon-negative process due to avoidance of CO_2 emissions from crop waste burning on the farms. The Plagazi system, which is designed to process landfill waste, or MSW, also uses a plasma gasification reactor at the heart of its process.

Captured CO_2 & synthetic e-fuels as a solution

An effective solution to the biomass feedstock issues is the use of captured CO_2 and synthetic e-fuels. An alternative pathway to synthetic



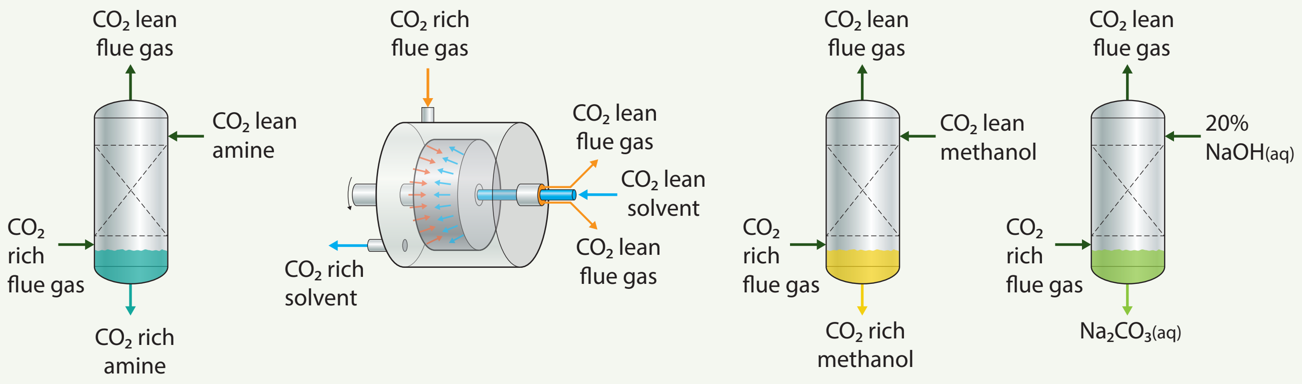
	Alkaline electrolysis cell (AEC)	Anion exchange membrane/alkaline electrolyte membrane (AEM)	Polymer electrolyte membrane/proton exchange membrane (PEM/PEMEC)	Solid oxide electrolysis cell (SOE/SOEC)
Electrode material	Cathode: Ni, Co or Fe Anode: Ni	Cathode: Ni / Ni al loys Anode: Fe, Ni, Co oxides	Cathode: Pt/Pd Anode: IrO_2i RuO_2	Cathode: Ni Anode: La/Sr/MnO (LSM) or La/Sr/Co/FeO (LSCF)
Electrolyte	Lye: 25-30% potassium hydroxide solution in water	Anion exchange ionomer (e.g. AS-4)	Fluoropolymer ionomer (e.g. Nation, a DuPont brand)	Zirconium oxide with ~8% yttrium oxide
Energy source	100% electrical power	100% electrical power	100% electrical power	~25% heat from steam, ~75% electrical power
Current density	Up to 0.5 A/cm^2	0.2-1 A/cm^2	Up to 3 A/cm^2	Up to 0.5 A/cm^2
Hydrogen or syngas product	Hydrogen	Hydrogen	Hydrogen	Hydrogen (or syngas if fed with steam and CO_2)
Gas outlet pressure	Up to 40 bar	Up to 35 bar H_2, 1 bar 0_2	Up to 40 bar	Close to atmospheric
Cell temperature	~80°C	~60°C	~60°C	~750 to 850°C

Figure 2 Electrolysis technologies for hydrogen or syngas production

liquid hydrocarbons is through electrolysis. This can be using a solid oxide electrolyser cell (SOEC) system with CO_2 feed to yield syngas, a conventional polymer electrolyte membrane (PEM), or an alkaline electrolyser to make hydrogen and then convert it to hydrocarbons with the addition of CO_2 and further processing. For example, hydrogen and CO_2 can be converted to methanol using a hydrogenation process over copper and zinc-oxide catalysts. Alternatively, the CO_2 can be reduced to carbon monoxide (CO) to form syngas in combination with hydrogen.

In the case of electrolysis, significant amounts of electrical power must be consumed. For the process to be carbon neutral, this must be renewable power from solar, wind, or hydro schemes. Nuclear power is low-carbon, but the debate is open as to whether it is a 'sustainable' mode of power generation or not. These are effectively the Scope 1 emissions.

For the CO_2 feed to the e-fuels process, implementation of BECCS on major biomass power generation facilities can provide abundant raw material. For example, the Drax power plant, which opened in 1974 in North Yorkshire, is the largest thermal power plant in the UK. It was previously coal-fired and has switched to burning imported wood pellets in recent years. It is still the UK's largest single CO_2 emitter but is regarded as carbon-neutral because it burns biomass.



	Amine-wash with tower contactor	Amine-wash rotating disk contactor	Methanol wash	Mineralisation
Separation principle	Absorption	Absorption	Absorption	Absorption
Specific energy demand	3 $GJft_{CO2}$	Predominantly electrical power, with heat	1.4 $GJft_{CO2}$	8.3 $GJft_{CO2}$
Typical temperature	40-60°C	40-60°C	-40°C	<35°C
Typical pressure	Ambient	Ambient	25-70 bar_g	Ambient
Typical CO_2 removal	90%	90% (target)	Up to 100%	90%
Typical CO_2 purity	>99%	95% (target)	>98.5%	CO_2 mineralisation to Na_2CO_3
Typical plant size (tonnes per year CO_2 removal)	40,000-400,000	1,000-500,000	> 100,000,000	1,000-75,000
Technology maturity level	Commercial from many suppliers	Laboratory, eg ROTA-CAP from GTI &CCSL	Commercial, eg Linde Rectisol	Demonstration, eg SkyMine

Figure 3 Absorption-based process for CO_2 capture from flue gases

On the other hand, those CO_2 emissions could be sequestered or utilised for e-fuel production. Until major emitters such as the Drax plant implement BECCS, there will be an ongoing debate about how 'climate friendly' large-scale biomass to energy really is. The good news is that Drax is planning to implement BECCS as part of the ambitious and visionary Zero Carbon Humber project. According to Drax, it aims to become a carbon-negative company by 2030. In its climate change proposal, it claims that BECCS at Drax could remove up to 8 million tonnes of CO_2 per year. This is around 40% of the BECCS with power needed to meet the UK Climate Change Committee's Balanced Net Zero Pathway.

Capturing CO_2 from the post-combustion flue gases is at the heart of BECCS. Carbon capture has been executed at scale using amine solvents, chilled ammonia, methanol, or potassium carbonate for decades. See **Figure 3** for some process examples.

CO_2 removal from sour gas is an essential unit operation in upstream natural gas processing. Biomethane to biogas upgrades also rely on CO_2 removal using such technologies. CO_2 is also recovered from beer fermentation to provide gas to dispense the beer in pubs and restaurants, or to carbonate the beer when packaged into bottles or cans.

The CO_2 captured by such processes can be of a very high purity after drying, liquefaction, and distillation. Achieving food-grade purity for use in beverage carbonation is possible. The capture of biogenic CO_2 using BECCS can yield a suitable high-quality feedstock for combination with hydrogen in synthetic e-fuels production.

In the refining sector, carbon capture has been executed on the CO_2-rich process gas stream of steam methane reformers (SMR) at several refineries. The gases leaving the water-gas shift reactor and prior to the PSA hydrogen purification unit have a high CO_2 concentration and are at high pressure, yielding a high partial pressure of CO_2 that is ideal for cost-effective CO_2 capture (see **Figure 4**).

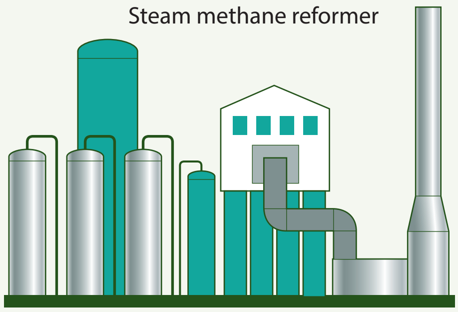
An amine wash system is used at the Air Products SMR at the Repsol refinery at Tarragona in Spain. A vacuum pressure swing adsorption (VPSA) system has been used to capture CO_2 from the Air Products SMRs that operate at the Valero refinery in Port Arthur, USA. **Figure 5** shows the basics of a VPSA process for CO_2 capture.

It is evident there is a way to produce these synthetic fuels in a carbon-neutral or carbon-negative way if the CO_2 used in the process has been captured from BECCS. Also, the refining sector has a depth of experience capturing CO_2 from fossil fuel processing, and this expertise will be largely transferrable to biogenic CO_2 capture.

Bioethanol as an alternative to synthetic e-fuels

Bioethanol is an exceptional energy vector. A lot can be done with it, the CO_2 emissions from the process are very concentrated, and capture costs are low in comparison to carbon capture and storage (CCS) from a power plant, to name an example. The ideal locations for bioethanol production include those where there is suitable agricultural land to support it, where there is no deforestation to create that agricultural land, and where competing food uses are considered.

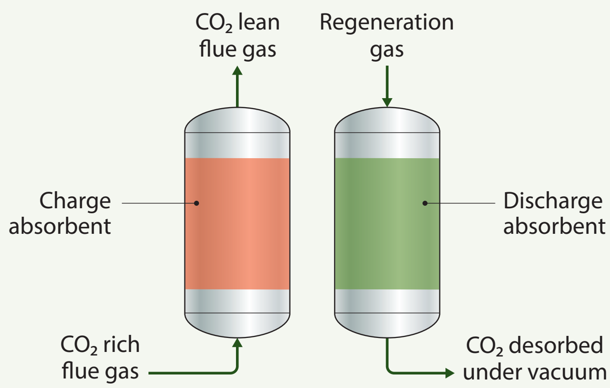
Bioethanol is used today to blend with gasoline and reduce the climate impact of liquid fuels. In the US, blending is up to 15%, and in Europe, it is limited to 10%. In some countries, such as North



Notes:
– CO_2 emissions are also associated with the energy and power requirements for this industry sector.
–These can potentially be decarbonised with renewable power and electrical heating or microwaves.
–CCS to capture CO_2 from the process and/or the associated energy production is possible

Oil refining	
Application that releases CO_2	Hydrogen production from methane reforming for fuels desulphurisation
Chemical reaction producing CO_2	CH, + H_2O → CO+ $3H_2$ CO+ H_2O → CO_2 + H_2
Decarbonisation approach for CO_2 generated by the process	Use turquoise hydrogen or green hydrogen to avoid the reforming reaction; or feed the reformer with biomethane instead of natural gas
Reactions for the decarbonised process	As above using renewable methane
Other industries with similar applications	Ammonia, urea, methanol, gas-to-liquids

Figure 4 Process CO_2 emissions from steam methane reforming



VSA- vacuum swing adsorption and desorption	
Separation principle	Adsorption
Specific energy demand	1.7 GJ/t_{CO2} (mostly power)
Typical temperature	<40°C
Typical pressure	Cycling between moderate pressure and vacuum
Typical CO_2 removal	<90%
Typical CO_2 purity	<95%
Typically combined with	Cryogenic liquefaction
Typical plant size (tonnes per year CO_2 removal)	1,000-500,000
Technology maturity level	Demonstration / Commercial, eg Air Products Port Arthur SMRs, USA

Figure 5 VPSA adsorption technology for CO_2 capture

America and China, the use of 85% ethanol as an alternative to gasoline is an established practice.

If in the future we are faced with a scenario where liquid fuels demand falls as electric mobility becomes dominant, there will still be many valuable outlets for bioethanol. These will include reforming to hydrogen to support hydrogen fuel cell mobility or hydrogen-fired internal combustion engines, which would also be zero CO_2 emissions vehicles.

Ethanol to aviation fuel or jet fuel using ethanol to jet (ETJ) technology is also a viable option. According to a report from the US Department of Energy, a life cycle analysis was conducted using the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model of corn to jet fuel using the ETJ process, and it confirmed that the life cycle could indeed be carbon negative.

Gevo, a leading American renewable chemicals and advanced biofuels company, and Axens, a well-established French company in the energy and petrochemical sector, have recently announced a partnership in the US to commercialise this ETJ pathway. Gevo will be the operator, and Axens will bring proprietary technology to the table. The technology pathway is achieved through dehydration, oligomerisation, and hydrogenation. The core technologies for these process steps can be leveraged from decades of experience in the refining and petrochemical sectors.

Penetration of e-fuels and biofuels vs green hydrogen

Currently, green ammonia or green hydrogen from renewable power or blue and turquoise hydrogen with carbon capture in various forms are in the spotlight and regarded as scalable solutions for clean energy vectors. Utilisation equipment such as fuel cells and hydrogen or ammonia-fired gas turbines are rapidly emerging to use hydrogen and ammonia directly. Even aviation is considering the use of hydrogen or ammonia as a fuel.

Synthetic e-fuels and bio-based liquid fuels will need to compete for attention, funding, and project capital. There are some key points for synthetic e-fuels that utilise captured CO_2 and biofuels to focus on to compete with hydrogen and ammonia. These include:

- Use of renewable or low-climate impact electrical power to provide energy for e-fuels production
- Continued development and capital cost reduction of solid oxide electrolysis, which is an ideal-fit technology for CO_2 utilisation to make syngas in the e-fuels value chain
- Use of agricultural waste as a feedstock, including rice husks, coconut husks, nut shells, and pruning clippings
- Avoidance of deforestation to make space for energy crops
- Consideration of urea fertilizer use and the CO_2, methane, and nitrous oxide emissions from crop cultivation. There are agricultural practices that can reduce these emissions significantly
- The use of managed woodlands with certified wood if wood is the biomass in question
- Use of fast-growing seasonal crops that rapidly remove CO_2 from the atmosphere whilst yielding energy vectors at low cost. Grasses and food crop wastes are good examples
- Careful consideration of land use or land re-use with respect to local food requirements or the regional impact on food pricing. As an example, Germany was criticised for converting many acres of food-crop land to biogas production. Whilst the German public could tolerate the small consequent increase in food prices, other regional countries with lower per-capita incomes said their people were being hit with unaffordable higher food prices due to regional supply issues
- Finally, a responsible approach to communication with consideration of full life cycle analysis. In any claims of 'climate neutrality' or 'carbon negative' processes, it is essential to build trust and avoid the accusation of 'green washing'.

Conclusion

Synthetic e-fuels, biofuels, and BECCS can play a significant role in the energy transition towards net zero. They might not be in the spotlight to the same extent as hydrogen, but that is by no means a reflection of their potential as part of the solution to our current dependence on fossil fuel supply chains. In some cases, they can be 'carbon-negative' and therefore play a valuable role in a 'net-zero' energy system to balance out difficult-to-decarbonise processes in other sectors.

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