Where there's muck

Energy from Waste and Biomass

Industry Background From Longspur Research

25 November 2022
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Industry background research available to all professional investors under MiFID II as a minor non-monetary benefit

Selected Companies

Bioenergy and CCS

Drax Group (DRX LN)*

Velocys (VLS LN)*

EQTEC (EQT LN)*

Powerhouse Energy (PHE LN)*

Verbio

Enviva Inc

Montauk Renewables

Green Plains

Cropenergies

Gevo

2G Energy

China Everbright Greentech

Futurefuel

Aemetis

Quantafuel

Xebec Adsorption

**Longspur Research client*

ENERGY FROM WASTE AND BIOMASS

Energy from biomass or waste can be genuinely low carbon and sustainable, representing a major tool in the decarbonisation toolbox. The ability to add carbon capture technology creates an immediately available negative emissions solution and adding liquid fuels allows the decarbonisation of sectors previously seen as challenging. Demand for all these solutions is likely to grow as decarbonisation and energy security become essential requirements in the energy mix.

Biomass and waste can be low carbon

Bioenergy including biomass and waste feedstocks can be genuinely low carbon and sustainable. Recent research shows that calculated properly on a forest basis, biomass can payback the emissions given out when the biomass is burnt in a reasonable timeframe. Waste to energy also reduces emissions and if non-recyclable waste left to decompose naturally or in landfill, the methane released has a greenhouse gas emission potential of 22 times that of CO_2. Combined with carbon capture, bioenergy technologies represent the most developed and immediate negative emissions technology (NET), now essential to hit the Paris Agreement target of 1.5°C by 2050.

There is plenty of sustainably sourced feedstock

There are a range of technologies, all of which can provide commercial solutions using a variety of feedstocks. The ability to create liquid fuels adds to the attraction of this growing component of the low carbon solution toolbox. Bioenergy technology falls into three main categories, being thermal, thermo-chemical and biochemical technologies, each with different characteristics and suitable for different feedstocks. There is sufficient feedstock for bioenergy to play a major part in decarbonisation. Bioenergy availability studies with a high level of agreement in the scientific literature point to a figure of about 100 EJ of sustainable biomass available annually. This compares with the c.40 EJ of bioenergy required to meet a 1.5°C outcome in our analysis of the IPCC's mean mitigation pathways.

Where to find exposure

We estimate that bioenergy will be required for c.7% of all global energy needs in our mean mitigation pathway analysis. This is a substantial opportunity for investors yet there are limited companies with exposure to this. Technologies and leading companies include BECCS (**Drax Group** – DRX LN), gasification to create renewable fuels (**EQTEC** – EQT LN), gasification to create hydrogen (**Powerhouse Energy** – PHE LN) and gasification and Fisher Tropsch to create sustainable aviation fuel (**Velocys** – VLS LN).

Industry background from Longspur Research

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Biomass and waste can be low carbon

Biomass is almost 100% pure fuel and waste can contain up to 60% of the same biogenic material. Both can be low emission energy solutions with biomass removing CO2 from the atmosphere when it grows and waste use preventing high emission methane being released into the atmosphere from landfill sites. While there is active debate on the level of emission benefit our analysis of academic work in these areas suggests both are strong solutions for preventing climate change.

Despite some vocal opposition, we see strong academic support for the low carbon credentials of well managed biomass. For waste, non-recyclable waste left to decompose naturally or in landfill has to potential to emit greenhouse gas emission in excess of 22 times that of CO2 in the form of methane. As such, it is of great importance that this waste is distributed in a way so that the methane does not find its way into the atmosphere. With less than 20% of all waste being recycled globally, waste-to-energy technologies are starting to be utilised as an efficient waste management technology to curb emissions, as well as proving an alternative source of low carbon energy in the process.

Biomass and waste offer negative emission solutions

Combined with the right technologies both feedstocks can create negative emission solutions. These are now recognised by the IPCC and others as essential to a net zero outcome. Bioenergy Carbon Capture and Storage (BECCS) is the most immediately available and scalable negative emission technology. Companies like **Drax** (DRX LN) are offering BECCS at a significant scale with an initial two units having the potential to deliver 40% of the UK's negative emission requirement. **Velocys** (VLS LN) is now targeting a negative emission potential of -375gCO2e/GJ which is the equivalent of removing 4 tanks of fossil fuel for every one filled with Velocys fuel.

There is plenty of sustainably sourced feedstock

There is sufficient feedstock for bioenergy to play a major part in decarbonisation. Bioenergy availability studies with a high level of agreement in the scientific literature point to a figure of about 100 EJ of sustainable biomass available annually. This compares with the c.40 EJ of bioenergy required to meet a 1.5oC outcome in our analysis of the IPCC's mean mitigation pathways.

Advanced fuel options can decarbonise hard to abate sectors

The ability of advanced biomass and waste to energy technology solutions to synthesis low carbon fuels creates opportunities to decarbonise areas such as shipping and aviation. While basic biofuels such as ethanol and biodiesel are not really low carbon, biofuel derived methane, hydrogen, ammonia and methanol can show very low carbon "well to wake" emissions and provide useful fuelling options. **EQTEC** (EQT LN) is targeting projects to created hydrogen and renewable natural gas and more advanced biofuels and **Powerhouse Energy** (PHE LN) is targeting a distributed hydrogen solution.

Limited opportunities to play this investment theme

While a number of listed companies are active in the key conversion technologies, opportunities for investors to play these opportunities are limited.

Listed bioenergy companies

Company	Market Cap (£m)	EV (£m)	Ticker	Description
Verbio	4,275	4,083	VBK GY	Biodiesel and bioethanol
Enviva Inc	3,287	4,602	EVA UN	Wood pellets for biomass
Drax Group*	2,448	3,706	DRX LN	BECCS
Montauk Renewables	1,485	1,467	MNTK UR	Landfill gas
Green Plains	1,664	2,056	GPRE US	Bioethanol
Cropenergies	1,118	1,085	CE2 GY	Bioethanol
Gevo	411	135	GEVO UR	Biobutanol fuels
2G Energy	385	382	2GB GY	CHP running on biogas
China Everbright Greentech	329	2,354	1257 HK	Biomass
Futurefuel	304	131	FF UN	Biodiesel
Aemetis	153	348	AMTX UQ	Advanced biofuels
Quantafuel	81	77	QFUEL NO	Thermo-chemical
Velocys*	64	56	VLS LN	Sustainable aviation fuel
Powerhouse Energy*	59	52	PHE LN	Waste to hydrogen
Xebec Adsorption	49	77	XBC CT	Biogas and gas processing
Eqtec*	36	43	EQT LN	Advanced gasification

Source: Bloomberg, Longspur Research, *Longspur Research client

Using data from the Active Net Zero Global Clean Energy Universe from Longspur Radnor Indices, we can plot the performance of the key bioenergy companies in the market. These companies took longer than other clean energy sectors to benefit from the rotation into positive ESG stocks that began in 2020 but have held their values well in recent months as relative pricing of bioenergy has compared well against natural gas and energy security concerns have created a heightened degree of interest.

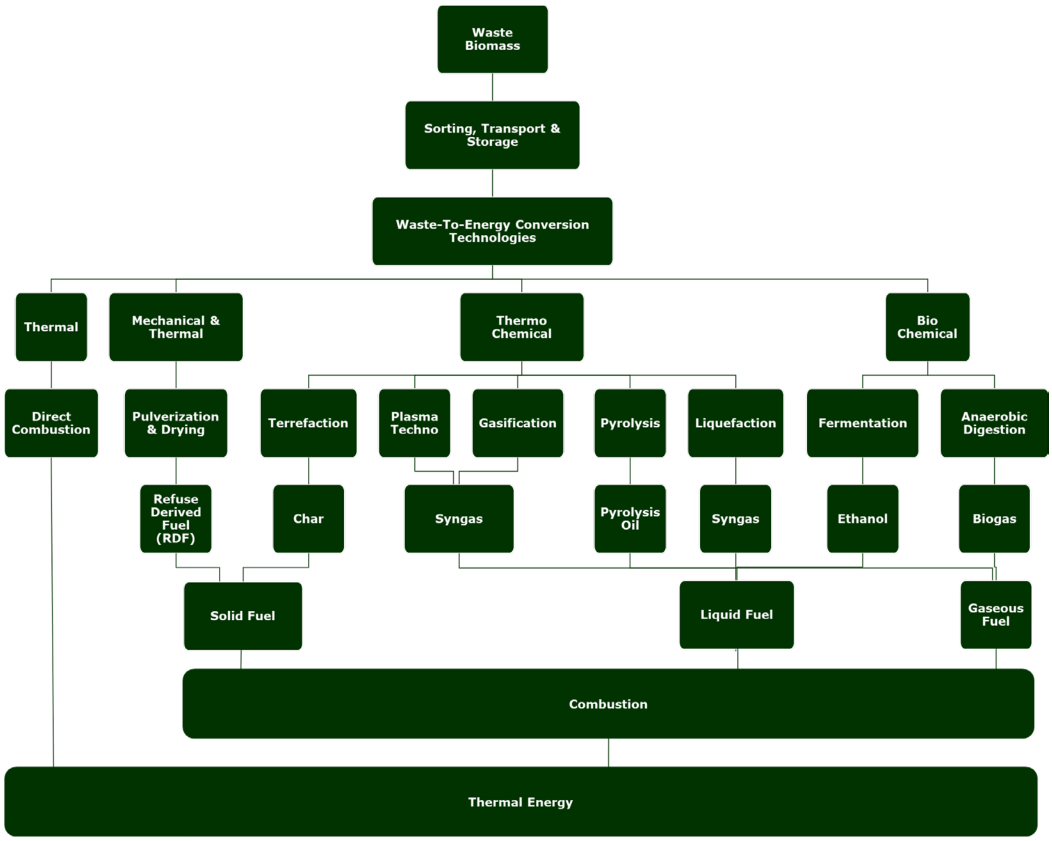
Active Net Zero Global Clean Energy Universe - Bioenergy

Source: Longspur Radnor Indices

BIOENERGY TECHNOLOGIES

Biomass and waste to energy (WTE) technologies encompass a range of solutions and most can be used for either biomass or waste. The technology falls into three main categories, being thermal, thermo-chemical and biochemical technologies, each with different characteristics and suitable for different feedstocks.

Bioenergy technology summary



Source: Longspur Research, Gumisiriza et al. Biotechnol Biofuels (2017) 10:11 DOI 10.1186/s13068-016-0689-5

THERMAL CONVERSION TECHNOLOGIES

Thermal conversion technologies involve a full oxidative combustion of waste biomass in order to generate heat. Direct combustion as the name suggests is the burning of biomass directly to convert chemical energy stored in plants into heat and electricity. Industrially, the process is such that biomass is burnt in a furnace to produce thermal energy that is subsequently used to heat boilers and produce steam. The pressure of the steam is then used to drive a turbine attached to an electrical generator which in turn generates electricity.

Waste incineration techniques involve a full oxidative of the waste in an incinerator enabling the production of thermal energy and simultaneously removing the waste material in a controlled emissions environment. This process involves converting the biomass either directly into CO_2 and water vapour or indirectly into CO, H_2 and Char. The concentration of oxygen available is the determinant in selecting the suitable process. The direct conversion process is favourable at a higher oxygen concentration environment whilst the indirect conversion technique is suited where there is limited oxygen supply.

Straight incineration of waste creates CO_2 emissions which, while better than the methane emissions created by landfill, results in a relative high carbon intensity. For that reason, policy may move to prevent its further development and already the EU has ruled this out from the Sustainable Finance Taxonomy Regulation other than for the disposal of non-recyclable hazardous waste.

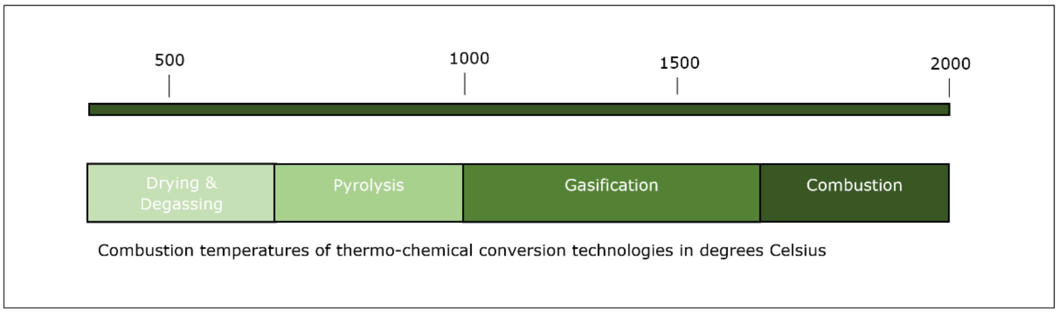
Biomass incineration can be low carbon and we examine the science behind this later in the note. It also provides a source of large-scale dispatchable generation providing much needed inertia or spinning reserve to power grids which is essential to maintain the frequency stability of these systems. In both cases the biggest potential comes with the addition of post combustion carbon capture. This creates a negative emission solution and we see this as the most immediately viable of the negative emission technologies (NETs). Oxycombustion, where the biomass is burnt in pure oxygen creating pure CO_2 is also an option for a NET but is less proven and currently higher cost.

THERMO-CHEMICAL CONVERSION TECHNOLOGIES

Sometimes referred to as Advanced Thermal Treatment (ATT) technologies, thermo-chemical conversion techniques utilise a series of chemical conversion techniques at different temperatures including gasification requiring oxidation or pyrolysis in the absence of oxygen. These technologies use changing temperatures through overlapping spatial and temporal stages of drying and degassing, pyrolysis and gasification and finally full oxidation combustion that turns the biomass into ash. These processes require controls to be put in place to enable temperature separation and subsequent thermo-chemical reaction that will otherwise not occur.

A key difference between thermo-chemical technologies and incineration is that the former is used to recover the chemical value of the feedstock whilst the latter is used to recover its energy value. The bi-products of pyrolysis and gasification can be used as fuel to generate heat and in turn electricity or can be used as a secondary feedstock for subsequent fuel generation. Incineration bi-products generally cannot be used as a fuel source, consisting of ash and flue gas made up of carbon dioxide and water, mixed with nitrogen from the air. While thermo-chemical conversion can also produce carbon dioxide this can be in a reasonably pure form allowing direct capture and sequestration.

Combustion temperatures of thermo-chemical technologies



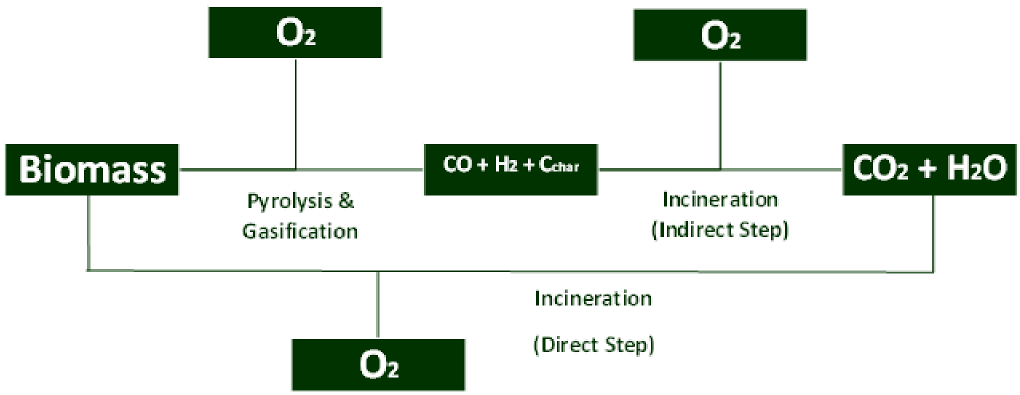
Source: Longspur Research, Gumisiriza et al. Biotechnol Biofuels (2017) 10:11 DOI 10.1186/s13068-016-0689-5

PYROLYSIS

Pyrolysis is the thermal decomposition of organic matter in the absence of oxygen. The process occurs at relatively low temperatures, generally between (400-900 °C), with biomass processing optimal at a temperature of 700°C. This occurs in the absence of oxygen resulting in the of pyrolysis (bio-oil), char and synthesis gas (syngas) which comprises hydrogen and carbon monoxide. Syngas also contains higher hydrocarbons such as ethane and propane as well as small char particles and such properties are favourable for use as a secondary fuel to produce electricity.

The typical process for pyrolysis starts by milling the biomass in order to increase the surface area and therefore provide more favourable conditions for the transfer and reaction of heat. The biomass is then dried in order to increase gas efficiency within the reactor before going through the process of anoxic thermal degradation to generate the pyrolysis products, being, syngas, bio-oil and char. This step involved the condensation of the gases for the extraction of the bio-oil as well as the secondary treatment of the syngas and char. The main gases produced through the pyrolysis process are methane, carbon monoxide and hydrogen, with properties of each enabling the fuel to be easily transported and stored prior to use in the production of heat, power and chemicals. Synthesis gas can be used to power gas engines and turbines to generate electricity more efficiently that conventional steam boilers. Whilst the pyrolysis of biomass will emit greenhouse gases in the form of flue gases, these are much smaller when compared to the direct combustion and incineration thermal techniques described above.

Product generation during pyrolysis and gasification

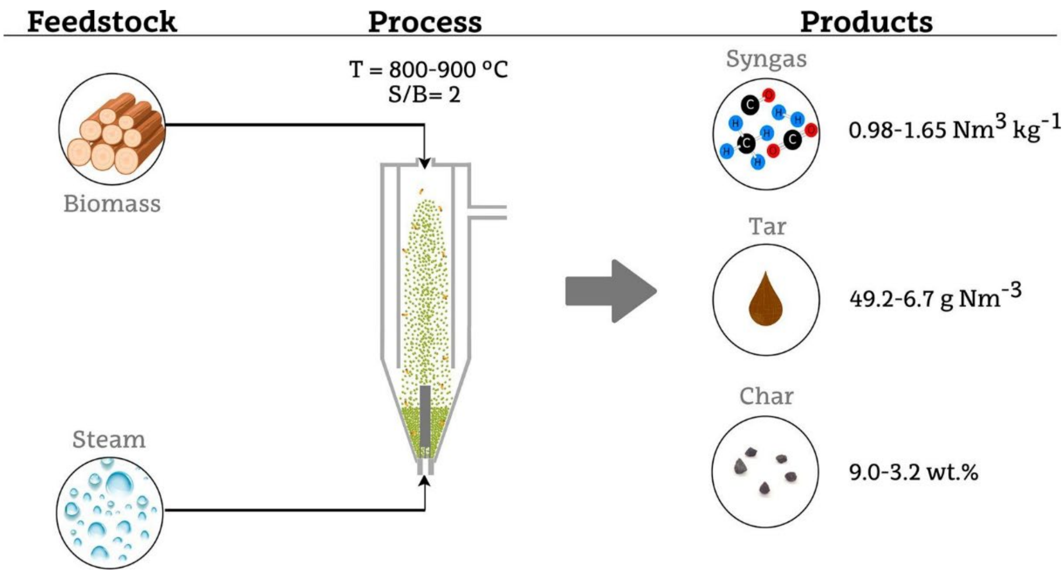


Source: Longspur Research, Gumisiriza et al. Biotechnol Biofuels (2017) 10:11 DOI 10.1186/s13068-016-0689-5

GASIFICATION

Gasification involves the partial oxidation and conversion of waste or biomass into usable synthesis gas at elevated temperatures of between (500-1800°C). Biomass gasification occurs as the char reacts with carbon dioxide and water vapour (steam) to produce carbon monoxide and hydrogen. This syngas can be used as a fuel for heat and electricity. Due to a higher combustion temperature this can be more efficient than incineration. The feedstock materials used in the gasification process are transformed entirely into a gas using a highly controlled supply of oxygen to produce a purified syngas, differing from the incineration process where materials are processed in the open presence of air.

Simple gasification process outline



Source: TRI Technology Update & IDL R&D Needs. D. Burciaga Biomass Indirect Liquefaction Strategy Workshop. DOE, March 20, 2014

During the gasification process there are many chemical reactions, although the final result is a gas mainly composed of hydrogen (H2) and carbon monoxide (CO) but also including CO2, CH4, C2Hn, H2O, N2, a minority of tars and suspended solid particles. The raw syngas then goes through a hot gas conditioning stage which removes tars followed by cold gas conditioning which results in a very pure syngas. This can then be further processed according to the final application.

Applications are heat and the generation of electricity with the latter combusting the syngas in a gas engine connected to a generator. Syngas can also be processed into a range of biofuels including hydrogen and hydrogen carriers such as methanol and ammonia. Biomethane can also be produced.

Advanced gasification is a thermochemical process characterised by the purity of the syngas it produces, the operational plant availability it supports and the commercial opportunities this creates, without applying combustion and with a very clean CO2 and emissions profile.

Biomass with a high moisture content i.e., wet biomass is not seen as promising feedstock for conventional thermo-chemical gasification processes. However, recently developed technology known as supercritical water gasification (SCWG) uses water in the reaction process, removing the requirement to dry the feedstock and subsequently avoiding the high processing costs associated with the drying process. The SCWG process differs from the standard gasification process in that it produces increased amount of hydrogen and lower amounts of carbon monoxide with reduced formation of tar as a biproduct and inorganic ingredients such as such as salts remain in the solution, avoiding any corrosion problems experienced during the gas treatment process.

BIOCHEMICAL CONVERSION WASTE-TO-ENERGY TECHNOLOGIES

Biochemical conversion technologies are generally more eco-friendly than its thermo and thermo-chemical counterparts given the process is using organic matter to derive enzymes to utilise energy stored in the biomass rather than using waste matter. Biochemical conversion technologies include composting to generate heat, bioethanol fermentation and anaerobic digestion for biogas production.

Bioethanol is generally produced from the fermentation of various feedstocks that contain fermented sugars and carbohydrates. These feedstocks are categorised from 1st to 4th generation feedstocks ranging from 1st generation food waste, namely kernels and starch crops; non-edible second generation feedstocks including forest residue, woody and herbaceous biomass and animal fats; 3rd generation feedstock produced from algal biomass and fourth-generation bioethanol produced from captured carbon dioxide considered carbon negative as carbon produced from this technology is less compared to the carbon captured.

Whilst the carbon reduction elements of bioethanol processing are evident, the application of bioethanol fermentation as a wate-to-energy approach are in early stages of development and have limitations. The conversion of biomass into bioethanol produces other highly polluting wastes such as distillery slope that cannot be used biofertiliser and can be problematic when used as an engine fuel by increasing the degradation of the fuel pumps as well as undesirable spark generation.

ANAEROBIC DIGESTION

Anaerobic digestion is the natural process in which microorganisms' breakdown organic materials. Biogas can be generated during the anaerobic digestion process when organic material is broken down in the absence of oxygen. Anaerobic digestion for biogas production takes place in a sealed reactor vessel which is designed and constructed in various shapes and sizes specific to the site and feedstock conditions. The biogas is made up of methane (CH_4) and carbon dioxide (CO_2), with very small amounts of water vapor and other gases and when this gas is cleaned, removing the CO_2 and other gases, the biogas becomes a renewable energy source to generate renewable natural gas (RNG) that can be used to power engines and turbines to generate heat and electricity, power alternative fuel vehicles and as an addition the natural gas pipeline. The biproduct of the anaerobic digestion process is a material called digestate, a wet nutrient dense mixture that can be utilised as a fertiliser for crops.

LANDFILL GAS GENERATION

Methane can be extracted from waste in situ in landfill sites where it is produced as a result of biological decomposition. It can be extracted by a system of wells and burnt in flares, or more productively in suitably modified internal combustion engines to produce electricity. Power generation from landfill gas takes about 65% of the methane generated from the decomposition of waste and burns it in a reciprocating engine, which itself powers a generator. Although the generation of methane rises over the first few years to a peak and then declines, sites are designed to retain the methane so that a smooth production output can be achieved. There is an initial lead time before full output is achieved. Following this, a site can run for up to 40 years before output begins to decline rapidly.

FEEDSTOCK SUSTAINABILITY - WASTE

When it comes to waste the argument is complicated by the fact the biogenic content of any waste may be as low as 50%. However while gasification technology releases CO2, it represents a potentially considerable reduction in CO2 compared to other options for waste treatment – typically 25-30% less. As such it is a key contributor through avoided emissions. The biogenic content of waste that goes to landfill will decompose and release methane with a greenhouse gas potential worth 28 times that of CO2 when assessed over a hundred year period. Simple incineration of this waste is the most common alternative to landfill and by converting the waste into heat and CO2 the GHG impact is reduced. However the gasification process goes further by also avoiding emissions from electricity and heat generation. If a downstream e-fuel process such as hydrogen production is added, the offset from vehicle emissions makes the CO2 saving significant.

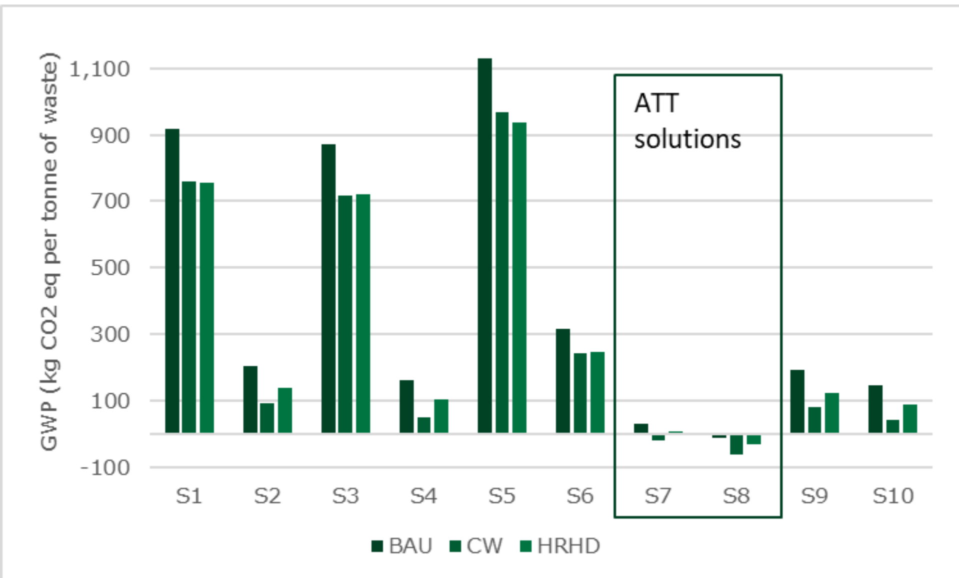
Avoided greenhouse gas emissions in the gasification of waste

tCO2e per day	Power maximised	eFuel maximised
Emissions from gasification system	70.67	70.67
Emissions offset by electricity production	-33.75	-24.64
Emissions offset by heat production	-22.79	-22.79
Landfill offset	-15.8	-15.8
HGV offset	0	-36.08
Net daily emissions	-1.67	-28.64

Source: Engsolve for Powerhouse Energy

Research by University College London looked at a number of integrated waste management options for treating municipal solid waste arising from the 2012 London Olympics. The results showed that processes that used advanced thermal treatment (ATT) as a significant part of the process had the lowest greenhouse gas emissions in every case they considered. Gasification and pyrolysis are the leading ATT technologies.

Global warming potential of different integrated waste solutions



Source: UCL

To quote the UCL research:

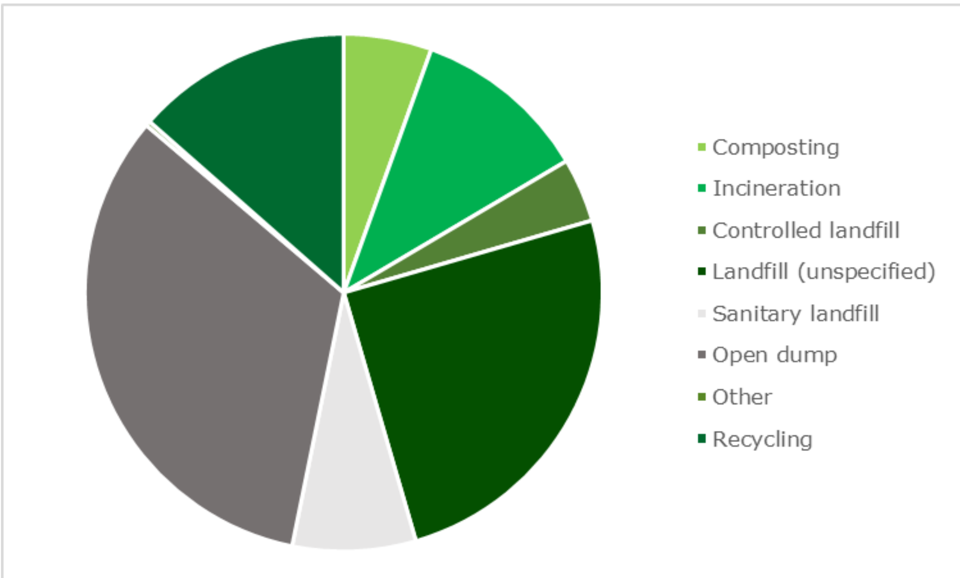
"it can be seen that [integrated waste management strategies] with landfill as the primary waste treatment technology have the highest direct and indirect burdens and the lowest avoided burdens. [Strategies] with Advanced Thermal Treatment as the primary technology have the lowest impacts regarding GWP. These results can be explained by the fact that the amount of electricity generated from landfill gas (0.369 MJ/tonne MSW) is significantly less than the amount of energy generated from the EfW or ATT plants (1.03 and 2.95 MJ/tonne MSW respectively). At the same time, the GHG emissions associated with landfill process are higher than those resulting from other waste treatment facilities."

Notably ATT was a better option than landfill or incineration.

WHY WE NEED A WASTE SOLUTION

There is a major need to deal with non-recylable waste including single use plastic. Left in landfill, this can decay to emit methane with a greenhouse gas potential of 22 times that of CO2. The world is still landfilling over a third of all waste, open dumping a further third and incinerating over 10%. Less than 20% is recycled or composted.

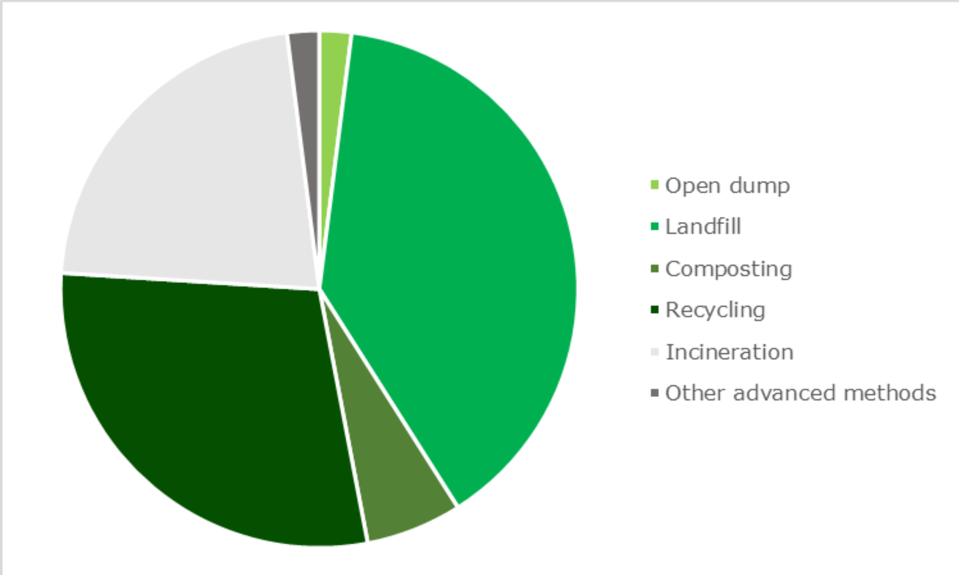
Waste Destinations



Source: World Bank

Even high income countries who can more easily afford to invest in advanced waste solutions still show high levels of landfill, with recycling at just around a third of waste destinations.

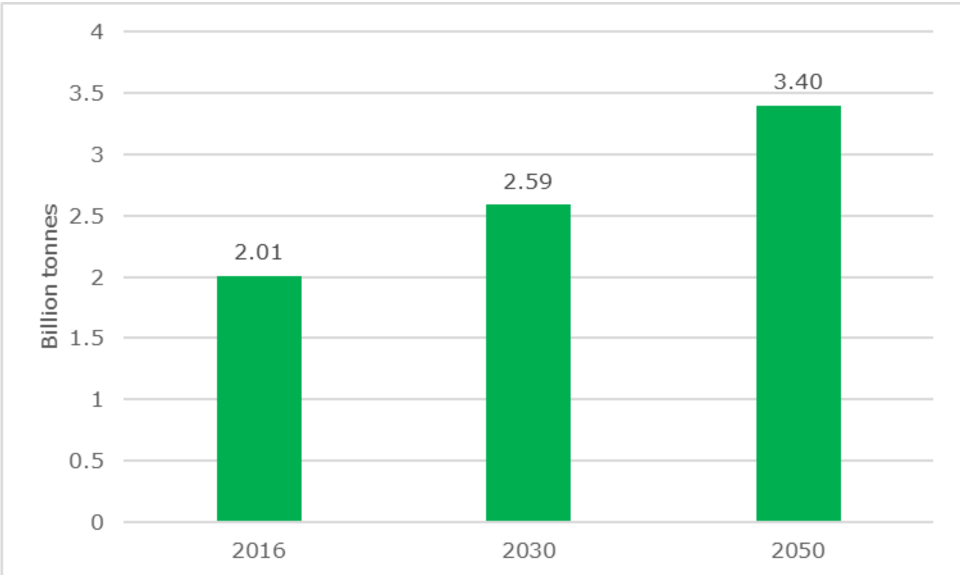
High income country waste destinations



Source: World Bank

Waste generation is also forecast to grow strongly into the foreseeable future.

Projected global waste generation



Source: World Bank

With this expected high growth in waste generation and much of that going to landfill where it decomposes to emit methane, waste to energy solutions can be a major solution resulting in lower emissions and a reduction in landfill.

BIOMASS – SEEING THE WOOD FOR THE TREES

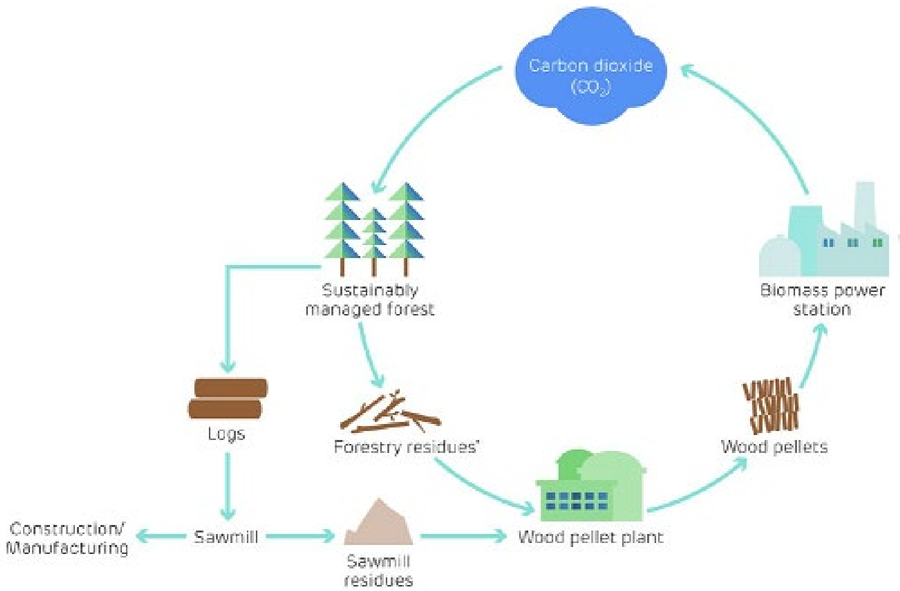
Most people understand that if you grow a tree that removes one tonne of CO2 from the atmosphere and then burn it to release that tonne the net carbon impact is zero. Most people also understand that there will always be potentially significant issues of timing and emission losses in this system so that it can at best only ever be low carbon as opposed to zero carbon. This is also true of most decarbonisation solutions to a greater or lesser degree.

But if the tonne of CO2 can be captured when the tree is burnt and permanently sequestered away then the solution can become carbon negative provided the losses and timing impacts are less than the carbon captured. If fact the timing issue becomes largely irrelevant if all or most of the CO2 is captured. This is how BECCS can provide a negative emissions solution. The real arguments are around whether the losses and timing differences outweigh the benefits.

BIOMASS IS LOW CARBON

As a tree grows, photosynthesis removes CO2 from the atmosphere and converts it to carbon in the wood. Burn a tree and that CO2 goes back into the atmosphere. Biomass combustion at the in biomass units therefore releases CO2 but by using wood from forests that are continually growing, and replacing the biomass burnt with new biomass, results in a theoretically carbon neutral outcome as the CO2 released on burning is taken out again by the new biomass growth.

CO2 Cycle for a Normal Biofuel



Source: Drax Group

Of course this only makes sense if you manage the forests in a sustainable way. There are also losses along the way, notably in pelletisation and transport that mean it is not a carbon neutral process, although done properly it can be a very low carbon process in practice.

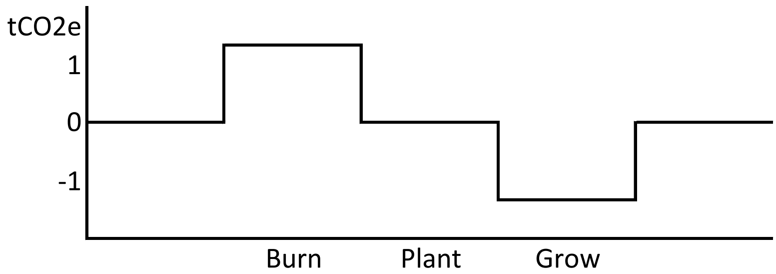
There is a concern that it takes time to recapture the emissions from burning the tree in new forest growth and there is a lot of opposition to biomass based on this concern. However, the most recent studies all show that biomass is a genuine source of low carbon generation. Despite its many advantages, biomass has attracted many critics over the years with the two major criticisms being 'carbon debt' and 'supply response'.

Carbon debt

Carbon debt arises from the logic that the combustion of forest feedstocks releases emissions into the atmosphere, which cannot immediately be removed as it takes a number of years for the replacement trees to sequester the amount of carbon released, thus resulting in net negative carbon emissions in the short-term. Although there is sense in this logic, its basis is in arbitrary carbon accounting assumptions, which are increasingly seen as flawed.

If we take a very simplified model of a biomass cycle, many commentators start with burning of the biomass in the power station. Let us assume this releases 1t of CO_2. Then a new tree must be planted and at first it will not capture much carbon. It does this during its growth phase when, if it is the same size as the tree that supplied the original fuel it will remove 1t of CO_2 from the atmosphere.

Emissions from a simplified biomass cycle



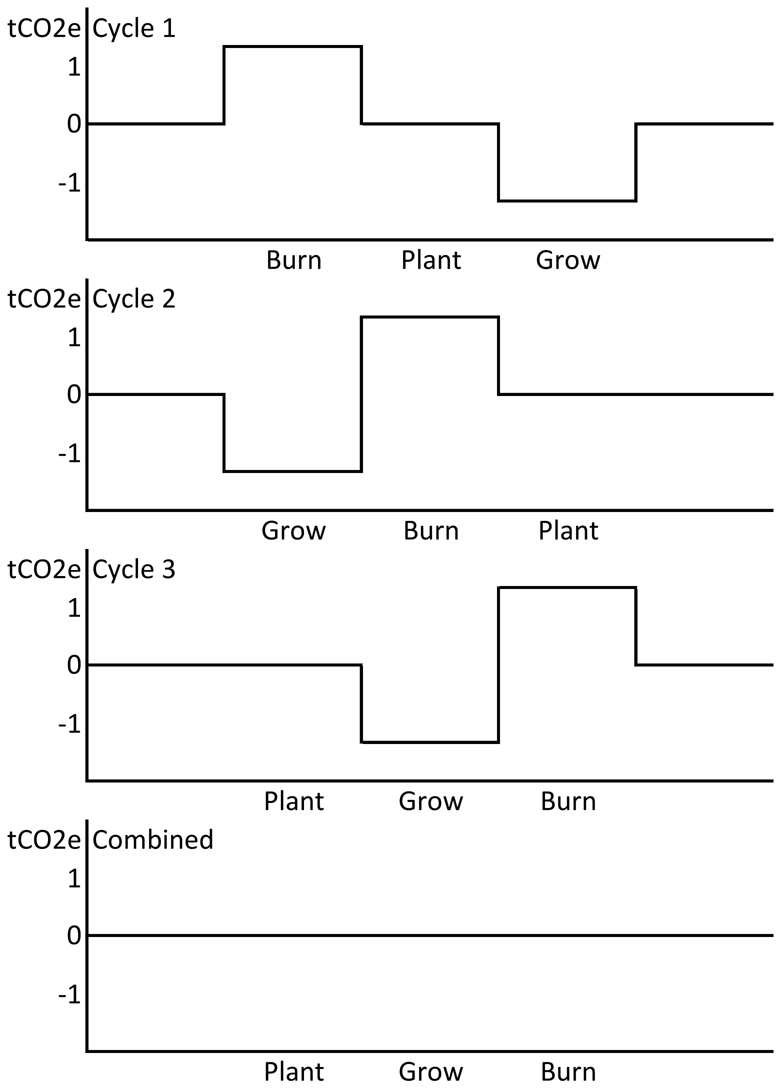
Source: Longspur Research

The gap between the release of CO_2 and its subsequent capture is the problem. If we worsen the climate by initially releasing CO_2, knock on secondary effects on the climate may be difficult to recover from even if we subsequently remove the CO_2. The problem here is that this simple model is too simple. Essentially it looks at a single stand of tress rather than considering the whole forest.

After the 1t of biomass is burnt in our model power station it will want to burn some more so a second cycle is started. To allow continuous operation this cycle take trees that have already been grown and therefore must start with the growth phase. After this cycle is complete a third is required. A tree must have already been planted and grown in order to supply the power station. After three cycles a picture of emissions is built up that results in no temporal difference between phases and no overall emissions. Because burning goes on continuously , planting and growing need to go on continuously.

Of course, this only works if there are enough cycles which implies a big enough forest with various stages of growth and harvesting. In our simple model the forest is harvesting 33% of its trees at any one time. Taking the Southeast of the US as the example, only 2% of the forest is harvested in one year while the remaining 98% is kept in various stages of regrowth, resulting in a net increase in the amount of carbon stored in the forest every year as more carbon is sequestered from growing trees than mature trees. Of this 2% the vast majority is being used for construction timber which keeps the carbon sequestered over a long period of time. The fibre for biomass is principally sawmill residues, low grade roundwood, thinnings, branches, tops and bark.

Emissions from a continuously operating biomass project



Source: Longspur Research

Supply response

The supply response criticism assumes that biomass simply depletes existing resources. However in an environment where demand for biomass is growing, as is likely if BECCS is pursued as a solution to climate change, more land will be afforested with the carbon negative growth phase leading the cycles.

In both cases above we have simplified the arguments for clarity. Obviously forests are complex systems and detailed research is needed. Recent research published this year includes a review of the literature (A. Favero, A. Daigneault, B. Sohngen, Forests: Carbon sequestration, biomass energy, or both? Science Advances, 2020; 6). The authors conclude the expanded use of wood for bioenergy will result in net carbon benefits. They also stress the need for an efficient policy to regulate forest management and poor management assumptions is one of the reasons that some earlier studies have come out against biomass.

"Studies that assume there is little to no management response, or consider only use of the extensive margin, predict that bioenergy demand will increase carbon emissions (16, 17). Studies that allow efficient investments in forestry management find that bioenergy policies lead to a net increase in forest sequestration (18–22)."

A lot of the negative research is based on a number of assumptions that do not reflect actual and future practice in an environment where biomass is growing.

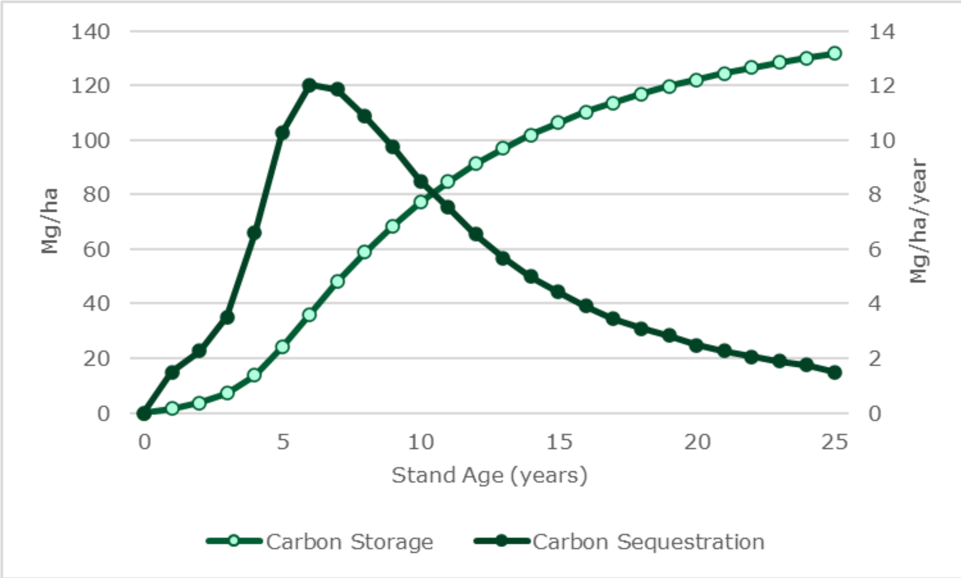
Forests need to be seen as dynamic systems and analysed accordingly. Carbon capture is maximised when these systems are properly managed and in this regard it is worth stressing that the forests of key biomass sources such as Northern Europe or the US Southeast have been continuously managed for centuries and is currently growing its carbon stocks. Most carbon is captured as the tree grows not when it is mature. This can be simply seen by looking at the carbon material in trees at different stages of their lives.

CO2 capture potential from trees at different stages

Source: Longspur Research

For one of the species most used for biomass combusiton, loblolly pine, the maximum amount of carbon capture takes place around six years after planting and falls dramatically thereafter.

Carbon sequestration and storage for managed loblolly pine



Source: Carlos Gonzalez, University Of Florida

Carbon payback periods

Calculated properly on a forest basis, biomass can payback the emissions given out when the biomass is burnt in a reasonable timeframe. Carbon payback is a concept used to compare the emissions released in creating a renewable energy technology against the low or zero carbon benefit of its operation.

Again, using recent research (P. Dwivedi, M. Khanna, M. Fuller, Is wood pellet-based electricity less carbon-intensive than coal-based electricity?, Environmental Research Letters, 2019; 14), for a forest using loblolly pine, the carbon payback ranges from 2 to 32 depending on management approach, with the research concluding that convergent management pespectives with wood pellets relative to a no-harvest baseline show a break-even period of about three years.

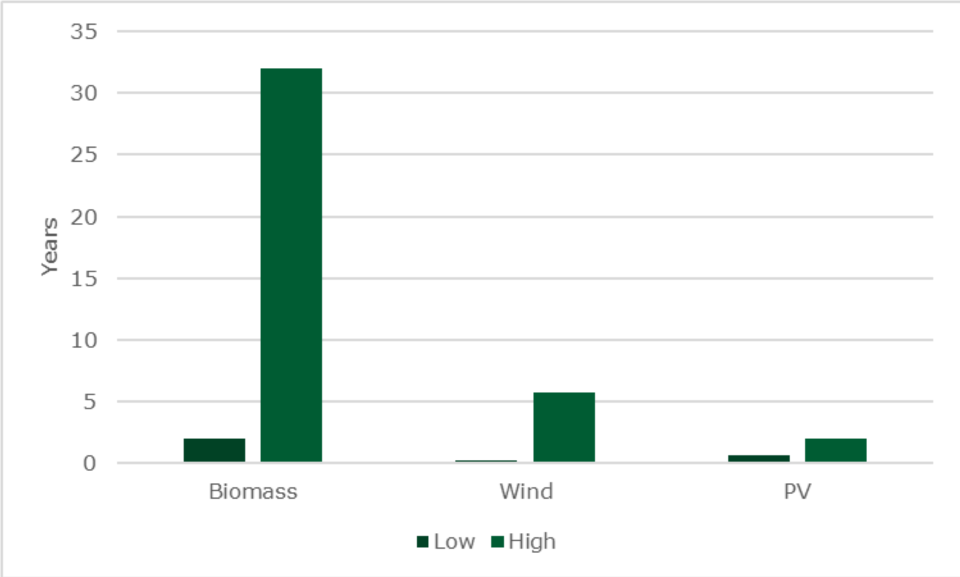
Older research concurs:

“We consider the landscape-level carbon debt approach more appropriate for the situation in the Southeastern United States, where softwood plantation is already in existence, and under this precondition, we conclude that the issue of carbon payback is basically nonexistent.”

J. G. G. Jonker, M. Junginger and A. Faaij, Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States, GCB Bioenergy (2014) 6, 371–389

When we look at the range of payback periods for other low carbon technologies, biomass can be shown to be as beneficial to a low carbon environment as any. Obviously payback periods will vary from project to project. The values below are believed to be typical and are from a range of academic sources. While badly managed biomass has a long payback period, well managed biomass lies between the range of paybacks for other renewables.

Carbon payback periods



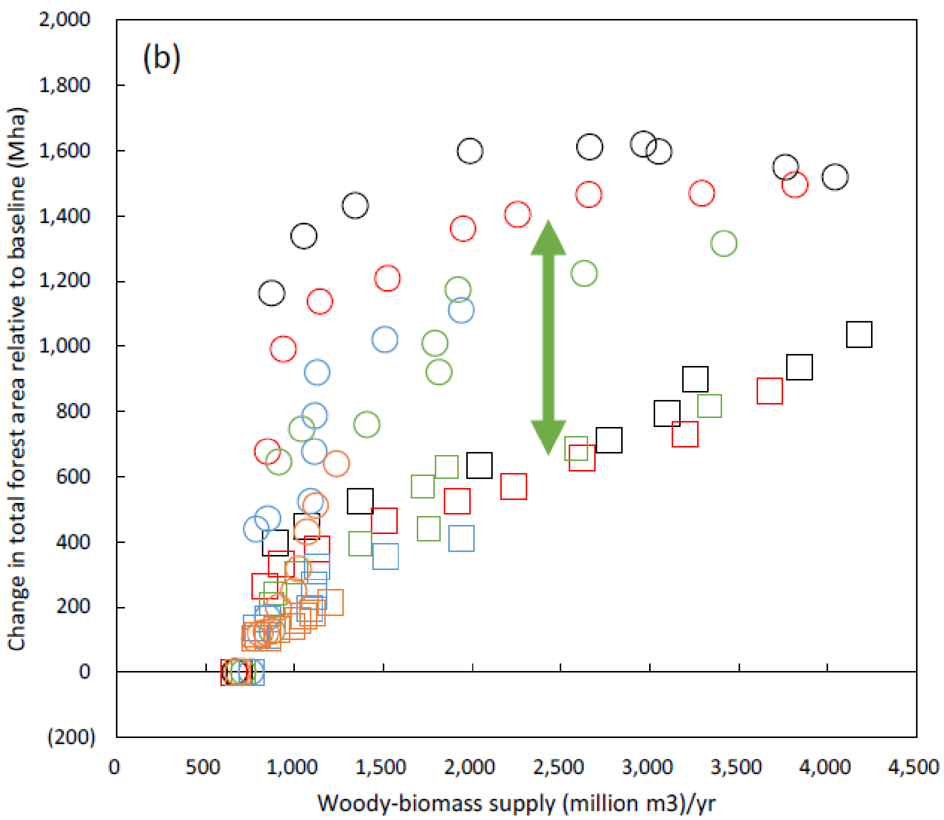
Source: P. Dwivedi, M. Khanna, M. Fuller, Is wood pellet-based electricity less carbon-intensive than coal-based electricity?, Environmental Research Letters, 2019; 14; C. Thomson, G. Harrison, Life Cycle Costs and Carbon Emissions of Onshore Wind Power. ClimateXChange, 2015; M. de Wild-Scholten, Energy payback time and carbon footprint of commercial photovoltaic systems, Solar Energy Materials and Solar Cells, 2013

Put simply, well managed biomass project can have a lower carbon payback than a badly designed windfarm sited on an upland peat bog.

MORE BIOMASS MEANS MORE CARBON STOCKS

Recent work has shown that increasing woody biomass supply can lead to an increase in forestland area globally with the amount of increase depending on policy support. (A. Favero, A. Daigneault, B. Sohngen, Forests: Carbon sequestration, biomass energy, or both? Science Advances, 2020; 6). The range of outcomes is from a slight decrease of carbon stocks of 33TgCO2/yr to a large increase of 2,300TgCO2/yr with some policy outcomes resulting in a 75% increase in land in forests.

Carbon sequestration and storage for managed loblolly pine



Source: A Favero, A Daigneault, B, Sohngen, 2020

IS THERE ENOUGH FEEDSTOCK?

IMMEDIATE POTENTIAL - WASTE

Currently waste can be landfilled, incinerated, recycled or sent for composting and digestion. In an ideal world no waste would be incinerated or landfilled and it is the amount of waste which is going to these destinations that represents the size of the feedstock pool available for waste to energy.

We have detailed data for the top 25 recycling regions in Europe and the US. This shows that Germany has the highest recycling rate at 66.1% of total waste generated. As these countries already support recycling it is likely that they will also support envirionmentally sound treatments for waste that is not recycled. Totalling this figure gives us 283 Mt of waste per annum.

Recyling Rates and Residual Waste

	Total waste	Recycling Rate	Recycled	Landfill	Incineration	Market	Market
Germany	51.0	66.1%	33.7	4.8	16.0	20.8	20.8
Singapore	7.8	61.0%	4.8	3.0	0.0	3.0	2.7
South Korea	18.2	59.0%	10.8	3.1	4.6	7.7	6.2
Taiwan	7.5	58.0%	4.4	0.1	3.0	3.1	2.5
Netherlands	9.5	56.6%	5.4	0.2	3.6	3.8	3.2
Austria	4.8	55.9%	2.8	0.1	1.8	2.0	1.6
Slovenia	0.9	53.9%	0.5	0.2	0.2	0.4	0.3
Belgium	4.7	53.5%	2.5	0.9	2.0	2.9	1.6
Switzerland	6.0	52.7%	3.2	6.0	2.9	8.9	2.0
Italy	30.1	52.6%	15.8	7.4	5.9	13.3	10.2
Luxembourg	0.4	48.3%	0.2	0.1	0.1	0.2	0.1
Sweden	4.4	48.1%	2.1	0.0	2.2	2.3	1.5
Denmark	4.5	46.3%	2.1	0.1	2.4	2.4	1.5
UnitedKingdom	31.6	43.5%	13.7	7.4	9.9	17.3	10.7
Norway	2.2	42.8%	1.0	0.1	1.1	1.2	0.7
Poland	10.9	42.3%	4.6	4.9	1.4	6.4	3.7
Australia	13.3	41.6%	5.5	6.2	1.6	7.8	4.5
Finland	2.7	40.6%	1.1	0.3	1.3	1.6	0.9
France	33.4	39.6%	13.2	9.0	11.6	20.6	11.3
Hong Kong	5.6	36.5%	2.1	3.6	0.0	3.6	1.9
United States	234.5	34.6%	81.1	123.3	30.1	153.4	79.5
Total	484.0		210.5	180.9	101.6	282.5	167.6

Source: Eunomia for the European Environmental Bureau, Longspur Research

Of course these countries are likely to want to attempt to improve their recycling rates which would reduce the waste available for treatment. Germany's high recycling rate may represent a reasonably acheiveable maximum globally. We can apply this rate to the other countires to estimate the amount of waste that cannot be recycled and is therefore available as waste-to-energy feedstock. This comes to 168Mt per annum.

IMMEDIATE POTENTIAL - BIOMASS

US forestry biomass

The USA has over 750m acres of forest land representing 35% of its total landmass. It currently supplies more than 25% of global industrial wood production. The forest resource has been growing annually since the 1950's and is protected by statutes, regulation and certification with best practice in forest management and sustainability.

USA Forestry Overview

Type of land	United States	Conterminous United States
Total land	2.3 billion acres	1.9 billion acres
Forestland	751 million acres	623 million acres
Timberland	514 million acres	475 million acres

Source: USDA US Forest Service

The southeast is a key fibre basket with vast resources of sustainable forestry. Inventories have increased by at least 50% since 1950 and the commercial forestry industry is well established.

The US Department of Agriculture Forest Service estimates that at a price of US$60/dry ton, there will be 61.6m available dry tons on non-federal land in the USA in 2030.

Forecast Wood Biomass Availabilty at $60/t

	2017	2022	2030	2040
All land				
Logging residues	17.9	19.4	21.4	20.7
Whole-tree biomass	69.9	73.7	59.8	60.7
Federal land excluded				
Logging residues	15.7	17.1	18.8	18.4
Whole-tree biomass	52.3	55.4	42.7	46.1
Total: Baseline (all land)	87.8	93.1	81.1	81.5
Total: Baseline (no federal)	68.1	72.5	61.6	64.5

Source: USDA US Forest Service, Forest biomass and wood waste resources 2016

WIDER POTENTIAL

Waste

The wider global potential for waste is more signficant. If we take the World Bank forecasts for waste generated out to 2050 and again assume the German recycling rate as a maximum then we currently could have a market of 680Mt, rising to 880Mt in 2030 and to over 1bn Mt in 2050.

Global waste available for treatment

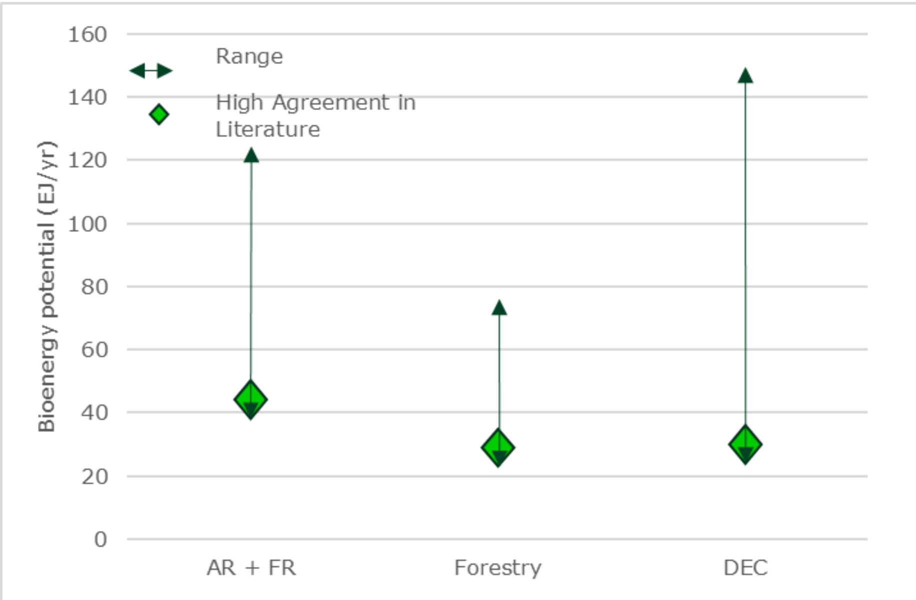
Billion tonnes	Waste generation	Waste available for treatment
2016	2.01	0.68
2030	2.59	0.88
2050	3.40	1.15

Source: World Bank, Longspur Research

Biomass

One of the main criticisms of biomass is based on concerns that there may be insufficient biomass that can be harvested in a sustainable fashion to make the process genuinely low carbon. A great many assessments of sustainable global bioenergy potential have been published with a large range of outcomes. However, the availability figures with a high level of agreement in scientific literature point to a figure of about 100 EJ of sustainable biomass available annually.

Ranges/high literature agreement on sustainable bioenergy potential



Source: Grantham Institute

Just using the figure for agricultural and forestry arisings of 50EJ, if we assume a utilisation of 90% this would need gasification capacity of 1,762GW.

Further comfort is given in the recent (October 2021) study by Imperial College London Consultants on European biomass which concludes that "the potential availability of sustainable biomass, with no harm to biodiversity, could support an advanced and waste-based biofuel production of up to 175 Mtoe in 2050."

The study itself appears conservative as the following quotation shows.

"It is important to highlight that the biomass potential availability estimated in this study are based on very conservative assumptions. [ ] Therefore, it can be concluded that the biomass potentials in 2030 and 2050 would most probably be higher than those estimated by this study."

WASTE-TO-ENERGY POLICY IN KEY MARKETS

European Union

The EU has introduced five facilities that could benefit biomass and waste to energy even if only indirectly. Across these the key message is that basic waste to energy incineration has no place in the sustainability agenda with major EU institutions, excluding it from financial support.

- **The Recovery and Resilience Facility (RRF)**

  Coming into effect in February 2021, the facility provides €723.8 billion in loans and grants that will support EU member states to build more resilient and sustainable economies, as well as help them to achieve a green and digital transition.

- **European Regional Development Fund and the Cohesion Fund**

  Two funds that provide €234 billion for allocation to strengthen the EU's economic, social, and territorial cohesion as well as promote sustainable development. The funds support investment activities in (1) additional capacity for waste recycling, (2) separated waste collection, and (3) waste reuse. However, treatment of residual waste is excluded from financial support.

- **Just Transition Fund**

  A fund of €40 billion is one of the pillars of the Just Transition Mechanism, which sets the roadmap towards climate neutrality for 2050 in an effective and fair manner.

- **EU Taxonomy Regulation**

  Published in 2020, the Taxonomy regulation is a classification system with six environmental objectives that include climate change mitigation, the transition to a circular economy, and pollution prevention and control.

- **European Investment Bank (EIB)**

  The EIB created the Climate Bank Roadmap that provides the guidelines for climate and sustainable development finance while supporting the EU Green Deal.

ESG – EU TAXONOMY

Biomass for climate mitigation has been recognised as sustainable in the underlying agreement on the EU Taxonomy on Sustainable Investment. Under the Renewable Energy Directive II (RED II) biomass needs to show an 80% reduction emissions against a fossil fuel benchmark. This is assumed to be 100gCO_2e/kWh. Many biomass combustion facilities run above this level with the energy inputs to pelleting and transportation resulting in typical values of around 125gCO_2e/kWh. However, powering pelletisation with renewable energy can easily bring the figure below the threshold and we expect this route to be followed by many.

USA

Currently, the US processes 14% of its waste in waste-to-energy (WTE) plants but is behind the European nations and the Asia Pacific region. In the waste to energy sector The United States Congress approved the Consolidated Appropriations Act, 2021. The recently adopted act includes a 26% investment tax credit (ITC) for "Waste Energy Recovery Property."

Since the introduction of renewable energy technologies such as solar and wind, investment tax credits have been successfully used to speed up development by lowering costs. With the recently passed Consolidated Appropriations Act, operators looking to implement waste heat recovery technologies will be able to do so with the help of an attractive investment tax credit.

UK

1) Resources and Waste Strategy

The Resources and Waste Strategy for England was introduced in December 2018 and is the first major policy shake-up in this space in more than a decade. It outlines a national deposit return scheme, changes to extended producer responsibility requirements and measures to increase food waste collections.

Consultations on several key measures began in 2021. The consultation process was originally set to begin in early 2020 but was delayed by the best part of a year amid Covid-19. As such, the Department for Food, the Environment and Rural Affairs (Defra) confirmed that a UK deposit return scheme will be implemented in 2024 at the earliest, while a UK-wide weekly food waste collection service will only be launched in 2023. We can expect further consultations and decisions in the near future.

2) Environment Bill

The Environment Bill is used to support the delivery of the UK's 25-Year Plan for the environment and to clarify how environmental protection frameworks will operate post-Brexit. The Bill is used to make provision about targets, plans and policies for improving natural environmental protection.

WHY BECCS IS ESSENTIAL

The most recent report from the UN Intergovernmental Panel on Climate Change (IPCC); the Working Group III (WG3) part of its sixth assessment report (AR6) was published in April. This is a major analysis of emission pathways to mitigate climate change and is based on over 3,000 different pathways. The 2,913 page report screens these down to 1,202 scenarios divided into eight climate categories and seven illustrative pathways. These include pathways based on current government policies and show that these put us in line for global warming of 3ºC which has bad outcomes as outlined in earlier IPCC reports. Even just going over 1.5ºC is bad enough.

"Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans."

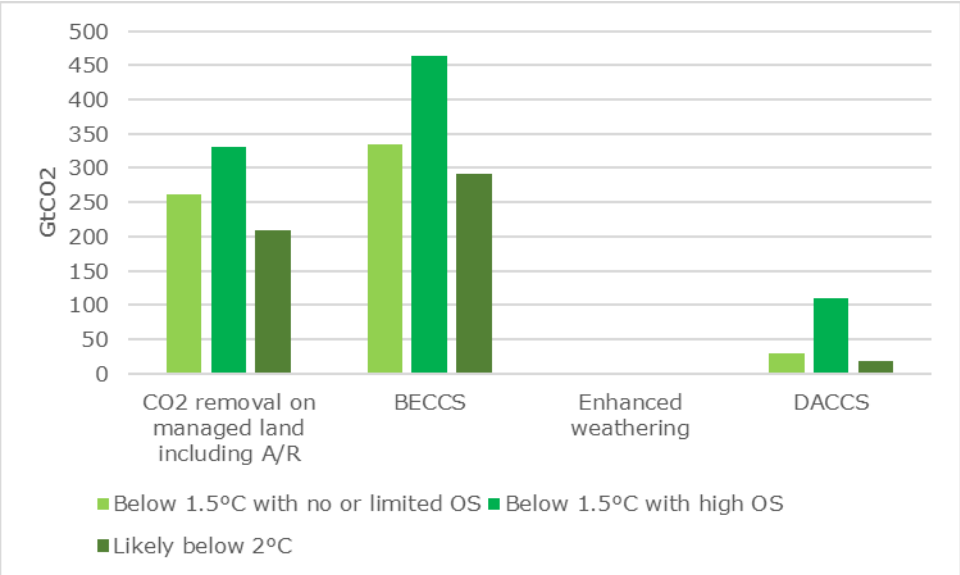
Nearly all scenarios that limit warming to below 2ºC (C1-C4) show some form of carbon dioxide removal (CDR) or to use the UK term GGR. This ranges from 30 $GtCO_2$ of CO_2 removal to 360 $GtCO_2$.

"The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved."

Note that CDR *"cannot serve as a substitute for deep emissions reductions"* so is not a mere antidote to the continued burning of fossil fuels.

It remains clear that the most likely CDR solution is Bioenergy with Carbon Capture and Storage (BECCS).

Breakdown of contributions to global net CO2 emissions



Source: IPCC, Longspur Research

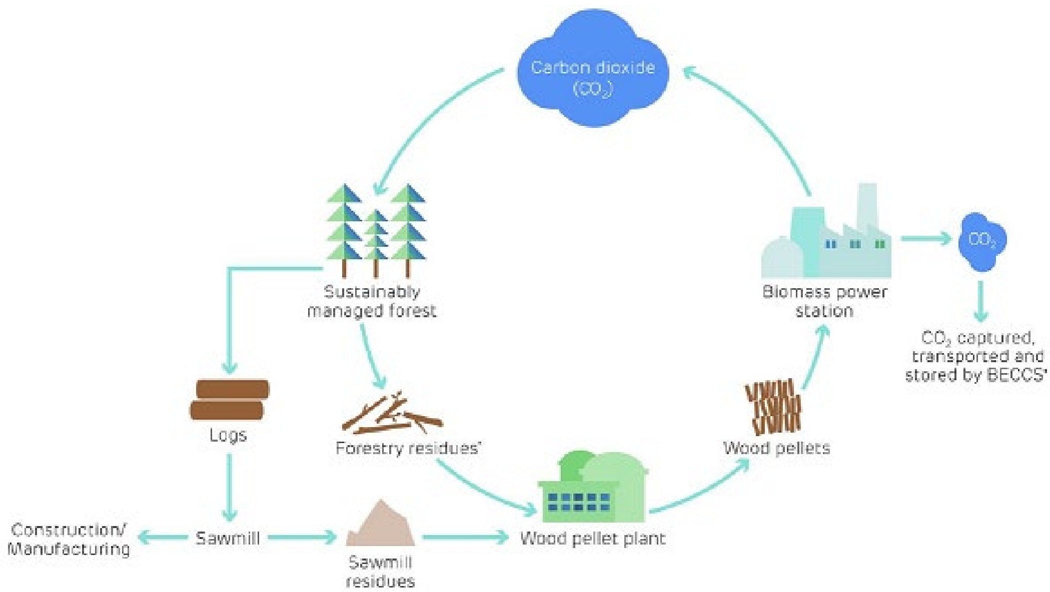
While reforestation and other nature-based solutions are helpful in the short term, nature-based solutions "do not continue to sequester carbon indefinitely", and a warming world is expected to put increased stress on ecosystems through things such as wildfires and expanded habitat for pests, putting "accumulated carbon…at risk of future loss due to disturbances". It is helpful then that many of the companies we see involved in CDR are focusing on forestry waste including the removal of brash and other combustibles from the forest floor.

DELIVERING BECCS

Bioenergy with carbon capture and storage results in carbon dioxide being removed from the atmosphere. It thus goes beyond zero emissions. Given that some greenhouse gas emissions are extremely difficult to avoid, the only way to get to zero is to have sufficient negative emissions to offset the unavoidable ones. Hence the "net" in net zero. BECCS is the leading technology solution likely to achieve this.

There are several stages to BECCS; biomass production and generation, carbon capture, and finally carbon storage. Taking the CO2 from the biomass generation process and storing it underground means that in principle, every tonne of CO2 captured by the growth of the tree is permanently removed from the atmosphere.

CO2 Cycle with CCS



Source: Drax Group

CARBON CAPTURE TECHNOLOGIES

A number of bioenergy solutions can be augmented with carbon catpure technology to deliver a BECCS solution. The key technologies are outlined below.

Technical readyness level of BECCS technologies

Technology	BECCS Product	TRL with CCS	BECCU/S Products	TRL with CCS/U
Combustion	Heat, Electricity	Commercial	-	-
Gasification	Syngas, heat, electricity	Commercial	Ethanol, bio-diesel	Demonstrated
			EOR	Commercial
Pyrolysis	Biochar, bio-oil, syngas	Commercial	Biochar, coordinator	Commercial
Liquefaction	Bio-oil	Lab-Pilots scale	-	-

Source: Global CCS Institute, The LCFS and CCS Protocol 2019

There are three principal methods of achieving carbon capture.

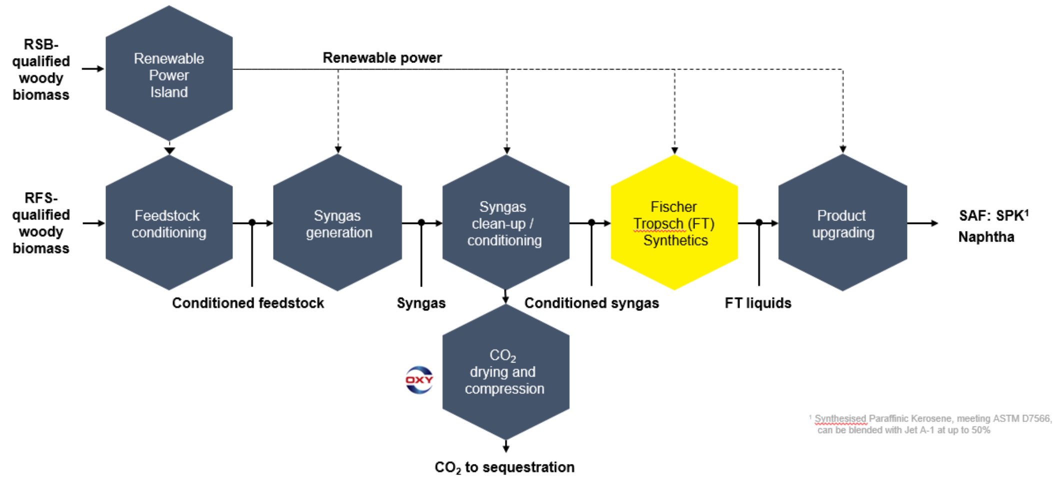
1. Pre-combustion capture

2. Oxy-fuel combustion

3. Post-combustion capture

Pre-combustion uses gasification or steam methane reformation of fossil fuel to create hydrogen and pure CO2. Essentially this is the technology available for appropriately configured gasification projects such as that used by UK biomass-to-fuel company Velocys. Velocys will combine this with power for the project from a biomass power island with post-combustion capture to deliver a negative emission fuel with a carbon intensity of -375gCO2e/GJ. This is a major negative emission score. With the company's target market of aviation fuel having a carbon intensity of 87gCO2e/GJ this means that a tank of Velocys fuel would save the carbon of four tanks of the fossil fuel equivalent.

Pre-combustion capture in gasifcation

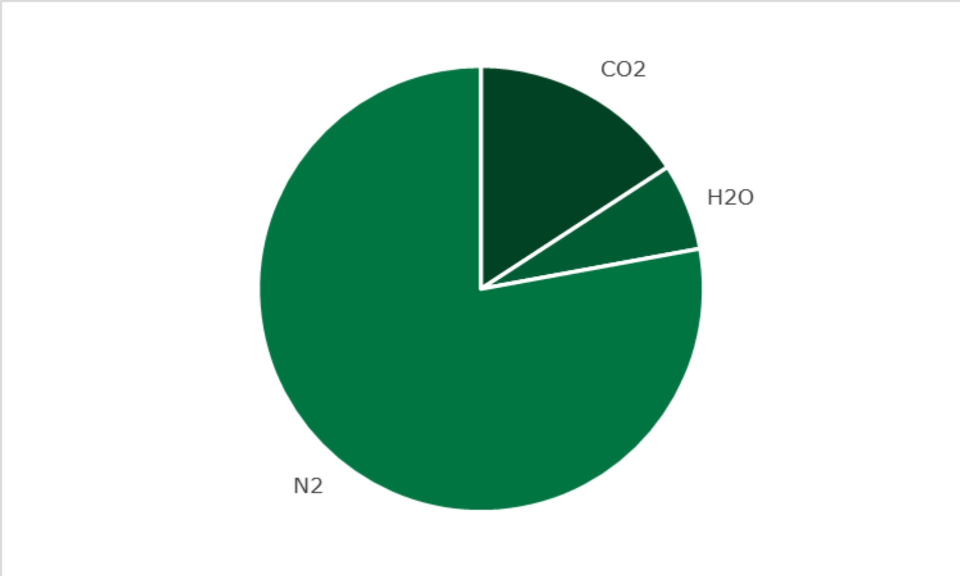


Source:Velocys

Oxy-fuel combustion undertakes fuel combustion in pure oxygen rather than in air. This results in a relatively pure CO2 flue gas. Effectively the other flue gases are removed at the oxygen separation stage necessary to produce the oxygen. However, production of pure oxygen can be expensive reducing the efficiency of the solution.

Post combustion capture removes the CO2 from the wates gases in a combustion process and has the potential to be a large scale negative emissions technology. The problem with post combustion capture of CO2 from waste gases is that the waste gases are not comprised of pure CO2. Less than a quarter of the flue gas will be CO2 with water and nitrogen comprising much of the rest. The capture process essentially deals with splitting out the CO2 from this gas stream.

Flue gas emissions



Source: Syed Muzaffar Ali, University of Boras

Post combustion capture involves removing the CO2 from the flue gases. The use of amines (most commonly monoethanolamine, MEA) to take out the CO2 is well proven technology, being used in the oil refining industry. This could be used today for CCS from biomass power stations. The barrier is simply cost. The main costs are threefold.

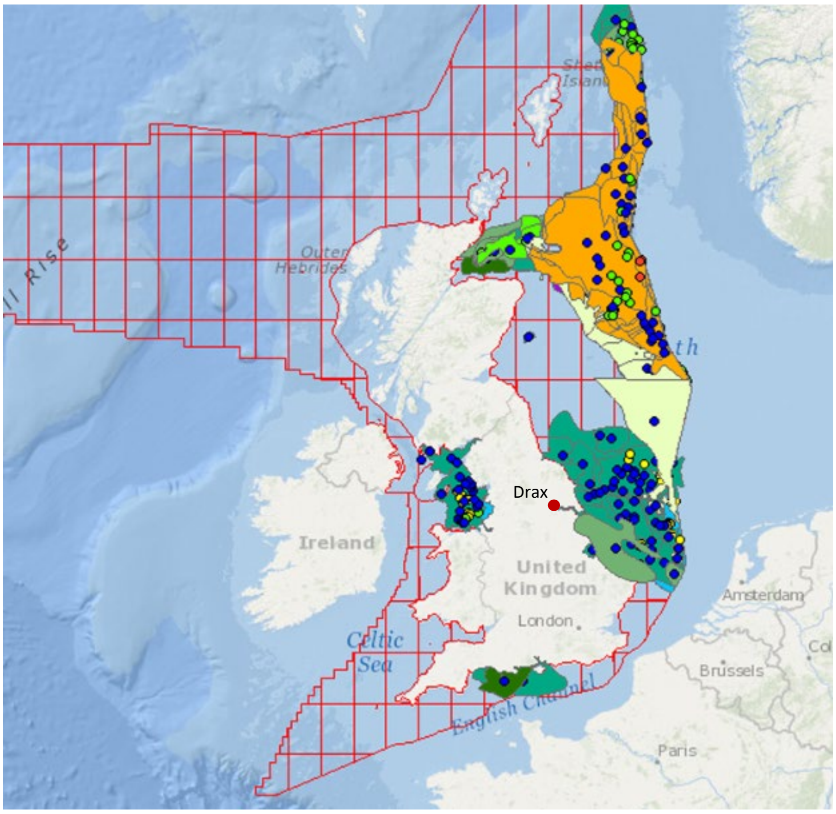
- Capital costs
- Parasitic load and low pressure steam from the host power station (represented by a loss of overall plant efficiency)
- Cost of the amines

The parasitic load energy penalty required for the extraction of low pressure steam can be significant. Data from available studies (Smelster et al., 1991; Mimura et al., 1997; Bolland and Undrum, 1999; Marion et al., 2001; Hendriks, 1994) give a range of 22% to 30% for a retrofit plant. A new plant designed for CCS can reduce this range through design optimisation to between 9% and 22%.

Additionally there is a cost in removing the CO2 and storing it. The CO2 itself has uses in a number of industries including (and perhaps ironically) the oil and gas industry where it is used for enhanced oil recovery. Given that there will still be a need for oil in the chemicals industry even in a net zero scenario, this is not all bad.

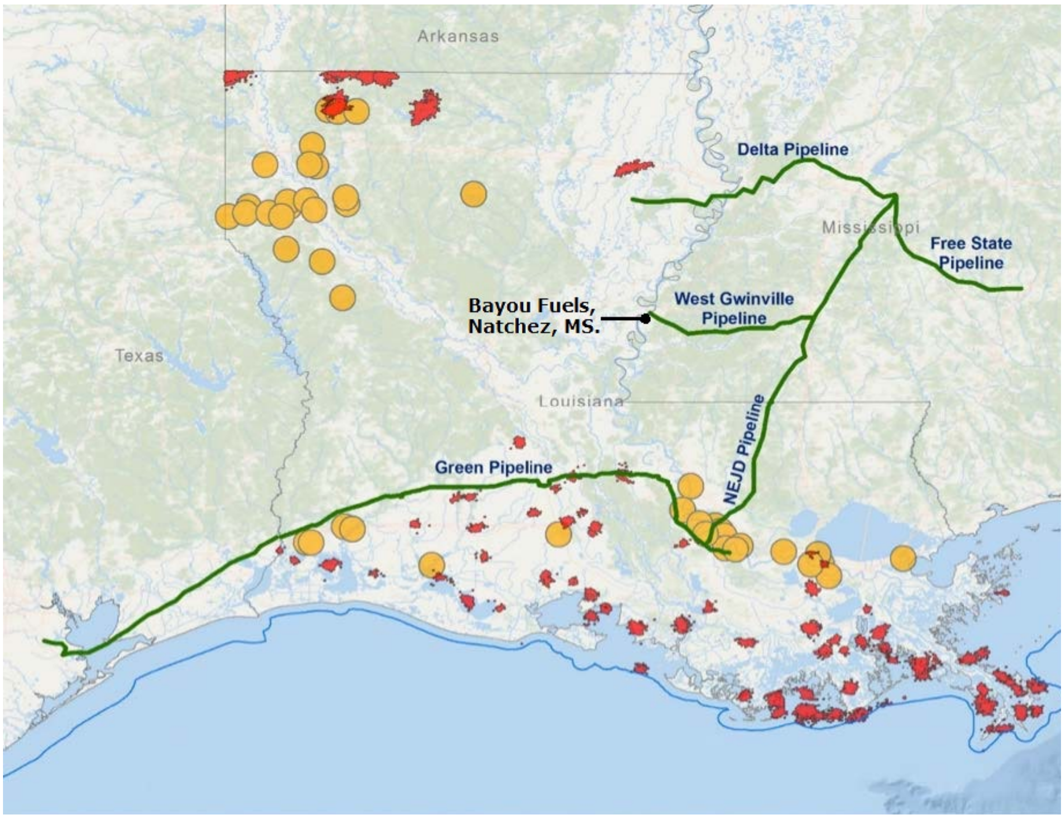
For now we assume that there will be willing offtakers of the CO2 at zero cost or who will offest any costs through their own subsidies. However this is not guaranteed and transmission and storage costs may need to be reflected in the level of support given at the capture level.

Potential CO2 Storage UKCS



Source: CO2 Stored

Gulf Coast CO2 Pipelines and Connected Assets



Source: South Eastern States Energy Board

COST OF CCS

We can estimate the cost of normal amine post combustion capture. The Petra Nova CCS project in Texas was constructed for US$1.0bn and operates on a similar size unit to those currently planned at Drax in the UK although only processes 37% of the emissions. This is a reasonably recent project and gives us a start point for estimating capital costs with an equivalent cost for processing the 100% of emissions at US$2.7bn or £2.0bn. The market cost of monoethanolamine is currently around €1300/tonne and despite recycling the amine, 1.5kg is required to be made up for every tonne of CO2 captured. The typical efficiency give up for CCS is 26 percentage points. We can use these factors to estimate a levelised cost of CO2 capture.

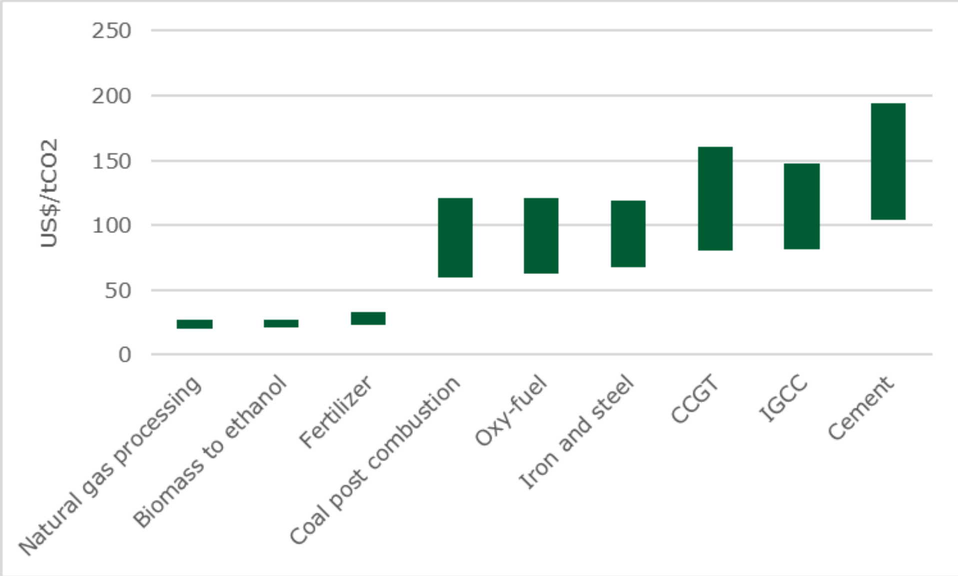
Amine post capture CCS cost estimates

	FOAK
Life (years)	25
Availability	90.0%
Effective tax rate	19.0%
WACC	10.0%
Capital Recovery Factor	0.1102
Capacity (MW)	645.0
CO2 captured (mt)	4
Capital cost (£m)	2,000
Efficiency give up	33%
Electricity cost (£/MWh)	58
MEA make up (kg/tCO2)	1.5
MEA cost (€/t)	1,500
Costs per tonne of CO2	
Capital cost	55.1
Electricity cost	25.6
MEA cost	2.0
Levelised cost of CO2 per tonne	**82.7**
LCoCO2 US$/t	**103.3**

Source: Longspur Research

This is consistent with findings from the global CCS Institute for coal post combustion which will be similar for these biomass units, having been converted from coal units.

CCS costs of CO2 capture



Source: UK Parliament, adapted from Global CCS Institute

Improving the costings

The use of the cheaper solvent solutions can allow potential cost savings using technology available today. Further solvent development has the potential to reduce operating costs significantly in future. These new solvents are cheaper but also the low pressure steam requirement is reduced. We also assume this similar system could be delivered at a lower capital cost as the solvent is less corrosive allowing cheaper steel to be used.

Revised post capture CCS cost estimates

	FOAK	NOAK
Life (years)	25	25
Availability	90.0%	90.0%
Effective tax rate	19.0%	19.0%
WACC	10.0%	10.0%
Capital Recovery Factor	0.1102	0.1102
Capacity (MW)	645.0	645.0
CO2 captured (mt)	4	4
Capital cost (£m)	2,000	1,250
Efficiency give up	33%	10%
Efficiency give up	33%	10%
Electricity cost (£/MWh)	58	58
MEA make up (kg/tCO2)	1.5	1.5
MEA cost (€/t)	1,500	1,500
Costs per tonne of CO2		
Capital cost	55.1	34.4
Electricity cost	25.6	7.8
MEA cost	2.0	2.0
Levelised cost of CO2 per tonne	**82.7**	**44.2**
LCoCO2 US$/t	**103.3**	**55.2**

Source: Longspur Research

FUNDING CARBON CAPTURE

The US model

The USA is a leader in support for CCS through its 45Q tax credit programme. The Energy Improvement and Extension Act 2008 amended by the Bipartisan Budget Act 2018 allows tax credits for every tonne of CO2 stored or used, including for EOR. These tax credits can be used against a carbon storage operators tax liability or sold in the tax equity market. Under the original rules the value of the credits for EOR projects rise from US$19/tCO2 in 2019 to US$35/tCO2 in 2026. The values are higher where the CO2 is sequestered without any further utilisation with credits rising from US$31/tCO2 in 2019 to US$50/tCO2 in 2026.

45Q Tax Credit Values (US$/tCO2)

	2019	2020	2021	2022	2023	2024	2025	2026	2026 onwards
Dedicated geological storage	31	34	36	39	42	45	47	50	Indexed
CO2-EOR	19	22	24	26	28	31	33	35	to
Other CO2 utilization processes	19	22	24	26	28	31	33	35	inflation

Source: Global CCS Institute, The LCFS and CCS Protocol 2019

The International Energy Agency (IEA) estimated that the credit could spur $1bn of investment in 10m-30m tonnes of CO2 storage capacity. However, the Inflation Reduction Act of 2022 has now increased the value of credits with up to US$85/tCO2 for permanently stored CO2 and to US$60/tCO2 for EOR and industrial uses. Additionally the capacity requirements for eligible projects have been reduces to 18,750 tonnes per annum for power projects and to 12,000 tonnes per annum for other facilities. There is also a seven-year extension to qualify for the tax credit which gives new projects until January 2033 to begin construction.

Carbon credits

It should be possible to trade the negative emissions created by CCS to offset obligations under carbon taxes. The UK government has signalled that it will replicate the European Emissions Trading Scheme (EU-ETS) in the UK post Brexit. The ETS itself has seen prices remain resilient to the COVID 19 pandemic. While emissions have clearly fallen, the Market Stability Reserve (MSR) mechanism has kept prices high and the outlook remains strong.

Both schemes work on the basis that qualified carbon avoidance can generate a carbon credit. CCS goes further than mere avoidance. The underlying logic is that any CCS project should generation two carbon credits per tonne of CO2.

This principle was effectively recognisesd under the NER300 mechanism set up under the ETS. This was aimed at encouraging CCS and set aside 300 mt of EUAs. Take up has been poor thanks in part to an extremely bureaucratic process and also the decline in the value of EUAs prior to the introduction of the MSR.

If a similar principle was followed in the UK, CCS could benefit to the tune of £66/t of CO2.

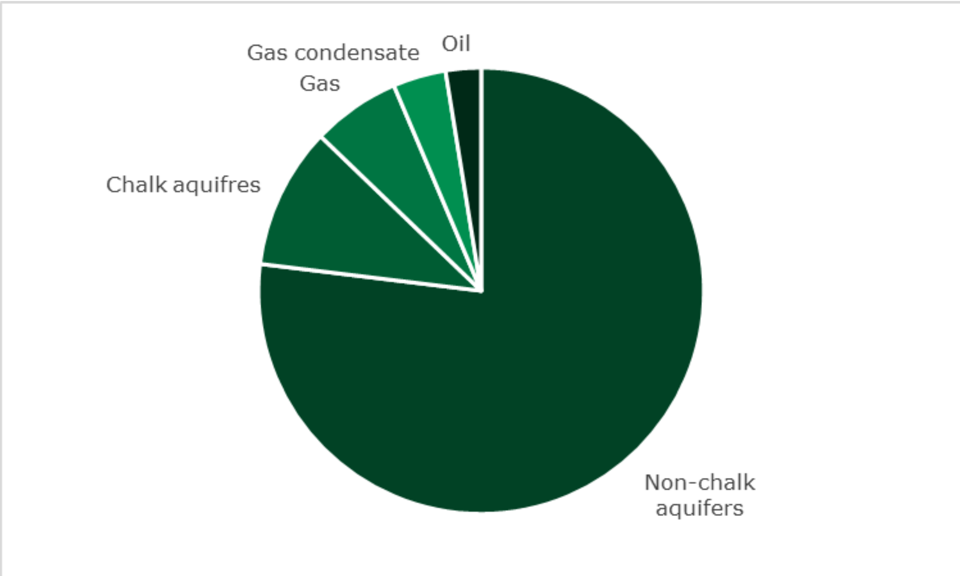
CfDs in the UK?

The UK is currently consulting on fudning for CCS including BECCS. Leading power industry consultants, Cornwall Insight, together with international consultants, WSP, conducted a study of market based frameworks for CCS funding for the Department of Business, Energy and Industrial Strategy (BEIS) in 2019. This particularly focused on contract for difference (CfD) type support in line with current support for large scale renewables in the UK. Three options were examined, a baseload CfD, a hybrid CfD and a flexible CfD with a capacity payment. The third option was seen as the most viable. While the detail would be critical for success, our observation is that the CfD programme has been very successful in incentivising new offshore wind in the UK and this could be a valid approach for CCS.

IS THERE ENOUGH CO2 STORAGE?

Taking the UK as an example the country expects it will need to capture up to 130MtCO2pa to reach net zero by 2050. The UK has a P50 estimate of 78GT of storage capacity, primarily in saline acquifers. A simple division shows that the UK has 600 years of CO2 storage capacity which feels adequate.

CO2 storage capacity in the UK



Source: Energy Technologies Institute

LIQUID FUELS FROM BIOENERGY

The ability to transform bioenergy and waste into liquid fuels brings options to industries previously seen as hard to decarbonise. These include shipping, aviation and heavy-duty road transport. While batteries are very suitable for short range transport, the key long-haul solutions are liquid fuels of one form or another. Bioethanol and biodiesel have residual lifecycle emissions that can be on the high side, and we see the main low carbon contenders as hydrogen, ammonia, methanol and biomethane. Their key characteristics are shown below against those of the major fossil fuel alternatives.

Main liquid fuel options for long haul transport

Fuel type	LHV	Volumetric energy density	Storage pressure	Storage temperature	Tank volume*
	[MJ/kg]	[MJ/l]	[bar]	[°C]	
Liquefied Ammonia	19	12.7	1 or 10	-34 or 20	4.1
Liquefied Hydrogen	120	8.5	1	-253	7.6
Methanol	20	15.8	1	Ambient	2.14
Methane	50	23.4	1	-162	2.3
LPG	46	25.5	1	-42	2
MGO	43	36.6	1	Ambient	1
HFO	40	35	1	Ambient	1

Source: KR (2020), Vries (2019), MAN (2019)

Engines for liquid fuels

All these fuels can be used in reciprocating engines with greater or lesser degrees of modification, normally to the fuel delivery systems. Major engine manufacturers are working on methanol and ammonia ready engines with methanol units already in service. Ammonia engines remain in development and are only expected in 2025.

MAN's established two-stroke engine is used with a Liquid Gas Injection (LGI) methanol component as an added feature. The engine modification provides an additional benefit of not requiring selective catalytic reduction (SCR) technology to remove NOx from the exhaust by a process in which water is mixed into the methanol during the combustion process. This enables methanol to meet the NOx IMO Tier III regulation without the additional treatment required for fossil fuels.

MAN has also developed an additional dual fuel engine that can run on any type of methanol as well as mixing methanol with HFO. This gives ship owners the ability to transition to green methanol as prices for renewables become more competitive and gives potential investors the added security knowing there is fuel flexibility in case of a fuel shortage.

Wartsila has retrofitted four-stroke methanol engines using common rail fuel injection technology. These have been operating successfully since 2015 on the Stena Germanica operating between Kiel and Gothenburg. Rolls Royce is also developing a four-stroke methanol engine under its MTU brand.

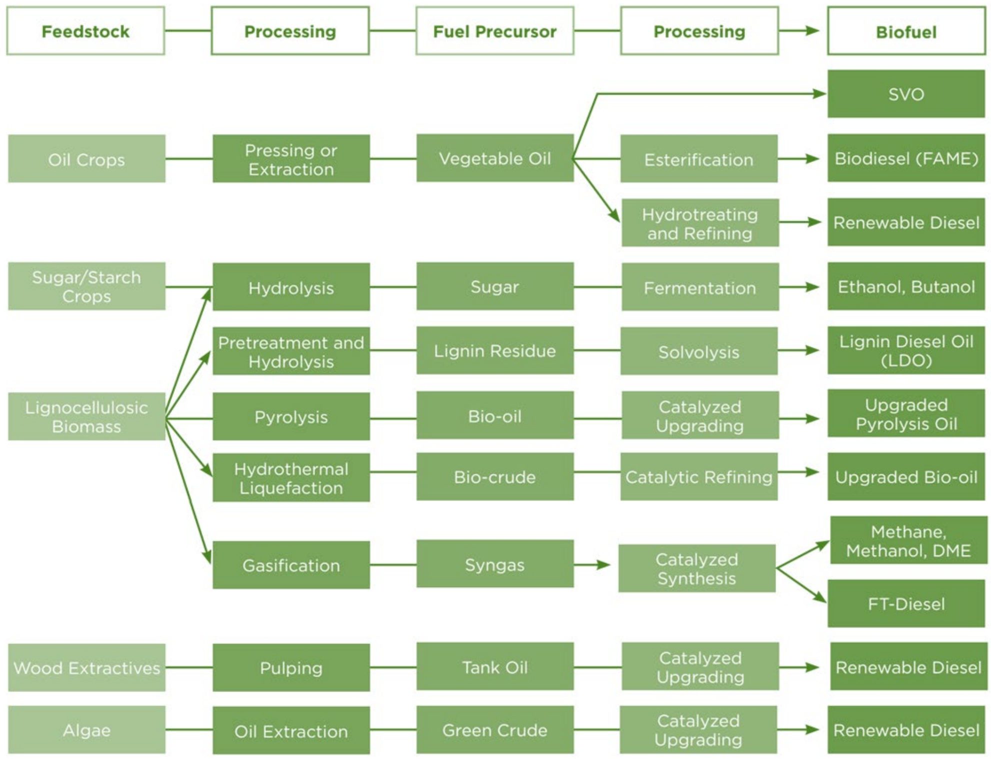
Fuel cell solutions

These fuels can also be used in hydrogen fuel cells to create electricity for use in electric motor propulsion systems. These take pure hydrogen and convert it to electricity electrochemically without combustion. Some fuel cells have the ability to reform methane, ammonia or methanol to hydrogen so that these fuels can be used as well. The ability of a fuel cell to do this varies, with high temperature PEM and solid oxide fuel cells most able, although the latter lack the flexibility that HT PEM cells can offer. This is really an option for new build only but may become a solution in time. Advent Technologies has already demonstrated its Serene marine fuel cell as part of the RiverCell demonstration project funded by Germany's Federal Ministry for Digital and Transport.

BIOFUELS AND BIO-LNG

Biofuels are primarily derived from biomass that is converted into liquid or gaseous fuels. A number of processes and technologies are used to produce biofuels, whether it be first generation biofuels derived from vegetable oil and animal fats, second generation biofuels derived from animals' waste and plant matter or third generation biofuels, derived from algae. The most suited form of biofuels for transport are hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME) otherwise known as biodiesel and bio-LNG. It is important to considered that each feedstock differs in its GHG emission reduction capabilities with lifecycle GHG reductions in the range 20-90% are typically reported for different biofuels, making many of these poor low carbon solutions.

Biofuel process streams



Source: Longspur Research, ABS

HVO is considered a 'drop in' fuel meaning it is a direct substitute for current fossil fuels in existing reciprocating engines. Untreated vegetable oils are not practical as a drop in fuel based because they reduce the engine lifespan due to a build-up of carbon deposits and damage to engine lubricant. HVO is a much higher quality fuel having undergone the process of removing the oxygen using hydrogen. FAME or biodiesel is not considered a drop in fuel but instead can be blended with conventional fuel making it an ideal transitional fuel, but long-term usability is unlikely.

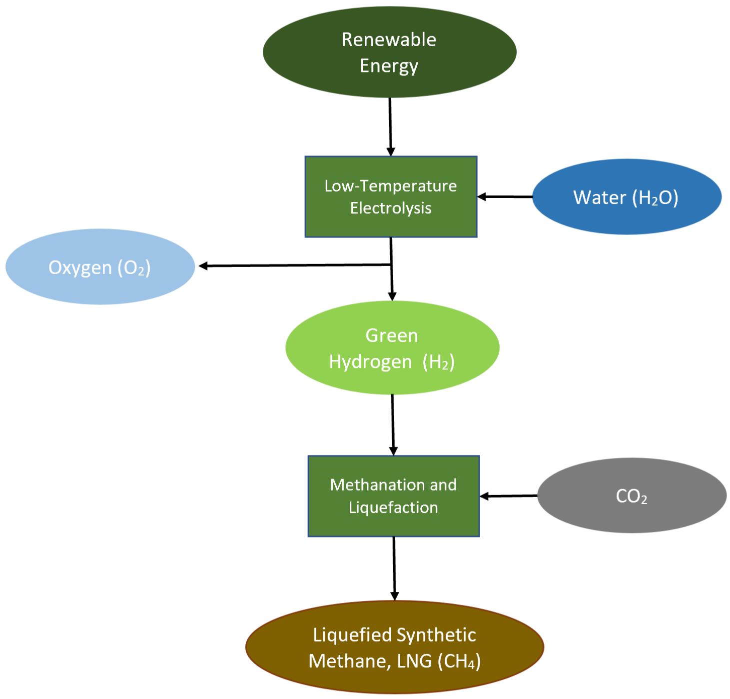
Bio-LNG is liquefied methane (CH4) from biogas, which is produced by the anaerobic digestion of organic waste. Alternatively, hydrogen can be methanised using captured CO2 to create eLNG. Provided methane slip can be avoided, burning LNG releases only carbon dioxide (CO2) and water (H2O) into the air. Since the bio-LNG is produced from biodegradable materials, the carbon dioxide is from sources that would anyway release CO2 in a natural combustion process. Therefore bio-LNG is a sustainable and renewable product that does not add any new CO2 into the atmosphere. Well-to-wake, the GHG emissions balance of bio-LNG can be even negative.

In addition to being carbon neutral, bio-LNG is also a high-energy biofuel that can be blended at any ratio with fossil LNG. Bio-LNG for ships can also be transported, stored and bunkered in ports utilising existing LNG infrastructure. The use of LNG emits close to zero NOx and SOx emissions and no particulate matter.

In November 2020, Total completed the world's largest LNG bunkering operation to date in Rotterdam, supplying 17,300 cubic meters of LNG to the CMA CGM Jacques Saade, 13% of which was bio-LNG. A month later, UECC bunkered the Auto Energy with drop-in bio-LNG, and in Finland, Gasum has bunkered ESL Shipping's dry bulk carrier Viikki with 100 percent renewable bio-LNG. The IEA estimates that biomethane (bio-LNG in gaseous form) production from sustainable feedstocks in Europe has the potential to grow from 18 bcm today to 125 bcm by 2050 – representing more than 25 percent of today's total EU gas consumption. Between March and June 2019 Maersk and the Dutch Sustainable Growth Coalition (DSGC) ran a successful pilot project where a large Triple-E vessel sailed 25,000 nautical miles from Rotterdam to Shanghai and back on biofuel blends alone, using up to 20% sustainable second–generation biofuels.

BIO-LIQUIFIED NATURAL GAS (LNG)

Bio-LNG (eLNG) process map



Source: Longspur Research

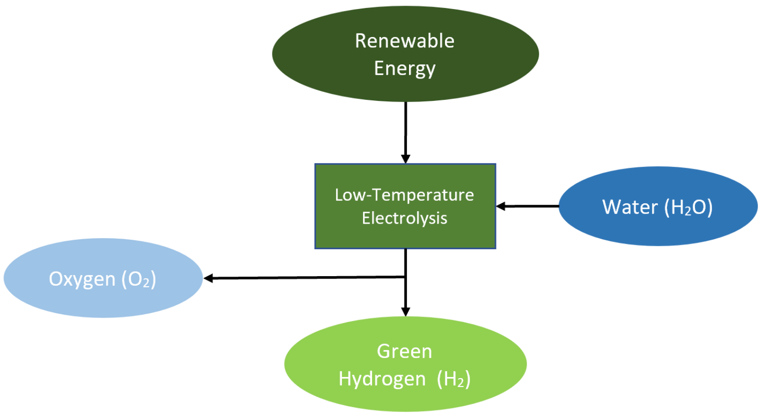
Liquified Natural Gas (LNG) is considered by many in the shipping industry as the ideal transitioning fuel for shipping decarbonisation. Whilst natural gas is a fossil fuel, it offers a lot of environmental benefits when compared to traditional shipping fuels and can be deployed today at a fraction of the cost of alternative low carbon green shipping fuels. Its growing popularity amongst shippers is largely due to its ability to minimise the long-term impact of GHG emissions and meet short term regulatory requirements implemented by the IMO. With the initial 40% GHG reduction target set by the IMO for 2030, a move to LNG gives the shipping industry an immediate carbon reduction of 23% on a well-to-wake basis according to an independent study commissioned by industry coalition, SEA-LNG, with minimal changes to infrastructure and engine technology needed to meet the 2030 IMO target. Additionally, moving to LNG reduces SOx emissions and particulate matter by 90% and NOx emissions by 80% when compared to HFO and will enable vessels to reduce their EEDI rating and Carbon Intensity Indicator by c.20%.

However, while LNG fuel has the effect of appearing to reduce CO2, engines using LNG can cause methane slip, where unburned fuel is expelled in the exhaust. This has a global warming potential of 21x that of CO2. In fact, in April 2021, the world bank released a report dismissing the long term role of LNG based on methane slip. Whilst engine manufacturers are making progress to reduce the release of methane through after treatment with methane oxidation catalysts, results are yet to be verified, high temperatures are required, and catalyst materials are expensive. On board, LNG must be pressurised, and temperature controlled, and this is also required during bunkering.

The real reason LNG is seen as a transition fuel is the potential to move from natural gas to biofuel and synthetic LNG showing a pathway to net zero outcomes by 2050.

HYDROGEN

Green hydrogen process map



Source: Longspur Research

Hydrogen is currently produced by steam reformation of methane in natural gas. Steam methane reformation (SMR) is energy intense and a major emitter of CO2. While carbon capture and storage (CCS) is an option to reduce the CO2 emissions, creating 'blue' hydrogen, it is expensive and does not completely eliminate emissions. Green hydrogen is produced by a process called electrolysis where water is split into hydrogen and oxygen using renewable electricity. Most importantly given the focus of this note, low carbon hydrogen can also be produced from the gasification of biomass or waste with the resulting syngas then passed through pressure swing adsorption to yield purified hydrogen.

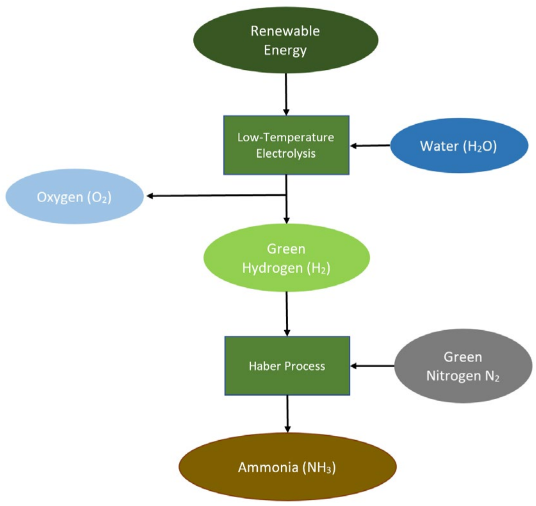
Some heavy duty transport propulsion including shipping and rail is already diesel electric, so the electric motor component already exists potentially creating a retrofitting opportunity. Advanced fuel cells, such as Advent Technologies high temperature PEM cell, can reform methanol, LNG or ammonia instead of relying on pure hydrogen.

Alternatively, hydrogen can be burnt in an internal combustion engine but the downside of anything in air, consisting of mainly nitrogen is that NOx are produced. There is potential for an after-treatment device to be fitted to the engine to remove the NOx but this is still an unproven technology. The world's first hydrogen powered vessel is currently being tested in Belgium in the Hydroville project using a small sixteen passenger ferry operating between Kruibeke and Antwerp in Northern Belgium. The project has been going for three years using a hybrid engine and has been successful to date.

The biggest challenge for using hydrogen for long distance transport is how difficult it is to store in comparison to not only the HFO but other potential fossil free fuels being considered. Hydrogen cannot simply replace current bunker fuel in the current system as in order to store it as a liquid, it will need to be cooled to temperatures of around minus 253°C requiring heavy cryogenic tanks that take up precious space.

AMMONIA

Green ammonia process map



Source: Longspur Research

Ammonia is liquid fuel that can be either combusted or used in a fuel cell and can still be produced using green hydrogen, alleviating some of the problems of hydrogen storage.

Ammonia is basically a hydrogen carrier but is arguable more suitable as a fuel source as it has a higher energy density. Ammonia (NH3) is produced by combining hydrogen and nitrogen. The nitrogen required is extracted from the air after liquefaction and the hydrogen produced through the process of water electrolysis, using either renewable or fossil fuel sources in the process. These hydrogen feedstocks are generally gasified to form synthesis gas (CO and H2), which can then be reacted with water and nitrogen to produce ammonia. The Haber Bosch process enables the nitrogen and hydrogen to be reacted to create ammonia.

One of the advantages ammonia has is it is already a traded commodity, used to produce fertilizer. This means that the infrastructure and procedures associated with transporting ammonia are already in place as ammonia is frequently loaded and unloaded from gas terminals onto ships and vice versa. Additionally, ammonia can be stored as a liquid at minus 33 degrees Celsius at ambient pressure on board the vessel and at port site facilities without the need for cryogenic tanks. Ammonia was therefore first considered a transport fuel for hydrogen or hydrogen carrier as once transported, the ammonia can be cracked back to hydrogen. However, ammonia has never been bunkered.

According to an Ammonia 2020 white paper by catalysis company Haldor Topsoe, if 30% of marine fuel consumption was replaced by green ammonia, 150m million tonnes of ammonia would need to be produced given its energy density. Using the process of electrolysis or synthesis technology, 1500TWh of renewable energy would be needed to produce this amount of green ammonia. To put this in perspective, the final power production could be achieved by installing 200 GW of wind power and 200 GW of solar photovoltaics (PV) in sites with good wind and solar resources.

Whilst ammonia is carbon free tank-to-wake and has the potential to be carbon free well-to-tank as well through the production of green ammonia, there is still uncertainty around

N_2O emissions and ammonia slip post combustion. N_2O or nitrous oxide is a major greenhouse gas and is emitted when ammonia is combusted.

As with methanol, MAN's ME-LGIM engines combustion principle based on diesel cycle can be retrofitted to run on ammonia with slight modifications to the fuel delivery system. The high-pressure direct-injection systems used in DF engines, such as the MAN ME-LGIM and ME-LGIP, can inject fuel at optimum levels and timing to avoid ammonia slip. As with methanol, MAN's dual-fuel engines will not require selective catalytic reduction (SCR) technology to remove NOx from the exhaust. Ammonia engines are only expected to be available after 2025.

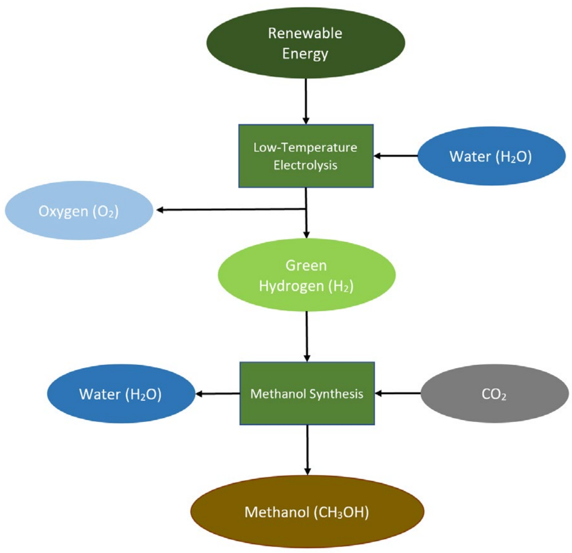
METHANOL

Methanol has been identified by the IMO as a fuel that delivers climate benefits today. Methanol is four parts hydrogen, one part carbon and one part oxygen and is typically produced from natural gas through reformation of the gas with steam to produce syngas and then converting and distilling the syngas to produce methanol. This is known as 'grey' methanol and today accounts for 95 per cent of total methanol used in the shipping industry. In saying this, grey methanol produces 80 per cent less NOx, 99 per cent less SOx, 95 per cent Particulate Matter (PM) and approximately 20 per cent less CO_2 than HFO on a tank-to-wake basis according to MAN Energy Solutions, enabling compliance to the IMO's 2020 SOx emission regulations as well as the Tier III NOx emission regulations when combined with modern engine technology.

Whilst 'grey' methanol is considered a low carbon pathway fuel, the benefit of methanol is greatly enhanced through its ability to evolve into 'blue' and then 'green' methanol as these processes become more commonplace. 'Blue' methanol is produced through the utilisation of Carbon Capture and Storage (CCS) and natural gas. CCS is the process of capturing CO_2 before it enters the earth's atmosphere and storing it underground or reusing it. Additionally, 'green' methanol or renewable methanol in the form of bio-methanol derived from biomass or e-methanol derived from renewable energy has potential to produce a zero-carbon fuel.

RENEWABLE METHANOL

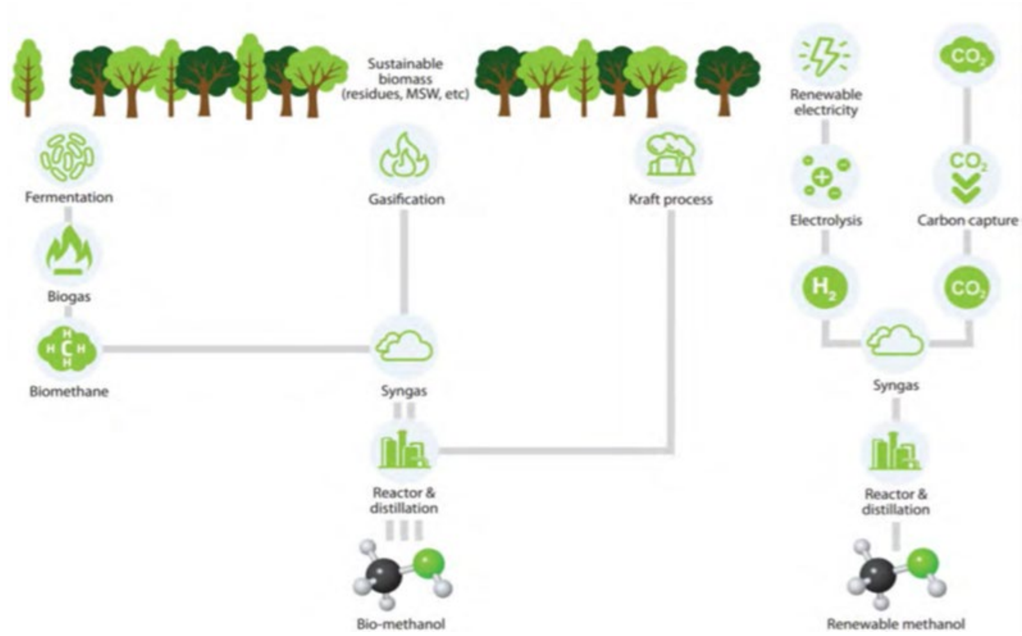
Renewable methanol process map



Source: Longspur Research

Renewable methanol can be produced using renewable feedstocks and renewable energy in the form of either bio-methanol or e-methanol. Bio-methanol is produced from biomass from sustainable biomass feedstocks such as forestry and agricultural waste, biogas from landfill, sewage, municipal solid waste (MSW) and black liquor from the pulp and paper industry (IRENA 2020). Green e-methanol is produced by combining green hydrogen from renewable energy through electrolysis and CO2 from carbon capture.

Bio-methanol and renewable methanol compared



Source: Proman - Sea Commerce presentation 2021

Methanol is available in over 120 ports and is already being used by over 20 ships making it the fourth most used marine fuel globally. One of the reasons for this is the ability of methanol to be stored and transported using current infrastructure as it remains in liquid form at normal air temperature and pressure. Bunkering is already available on a vessel to vessel or shore to vessel basis.

Additionally, methanol is considered the safest alternative fuel with a long history of handling in both shipping and a number of other energy applications. In addition to being easily handled and transported, methanol is a clear and biodegradable liquid and when spilled in water quickly dilutes to non-toxic levels with no environmental effects or damage to marine ecosystems. The safety of methanol was confirmed in November 2020 with the IMO's approval of guidelines for methanol to be used as a safe ship fuel.

Considerable progress has been made in recent times to enable methanol to be used as a drop-in fuel or dual fuel using current engine technologies. Both Wartsila and MAN have developed methanol dual fuel engines built using the same technology as diesel fuel engines with nominal changes needed at little cost. One operator already has c.12,000 hours of safe operation of methanol dual fuel engines.

BIOENERGY FUEL SOLUTIONS COMPARED

We see four key issues when comparing renewable fuels.

- Density
- Emissions
- Cost
- Useability

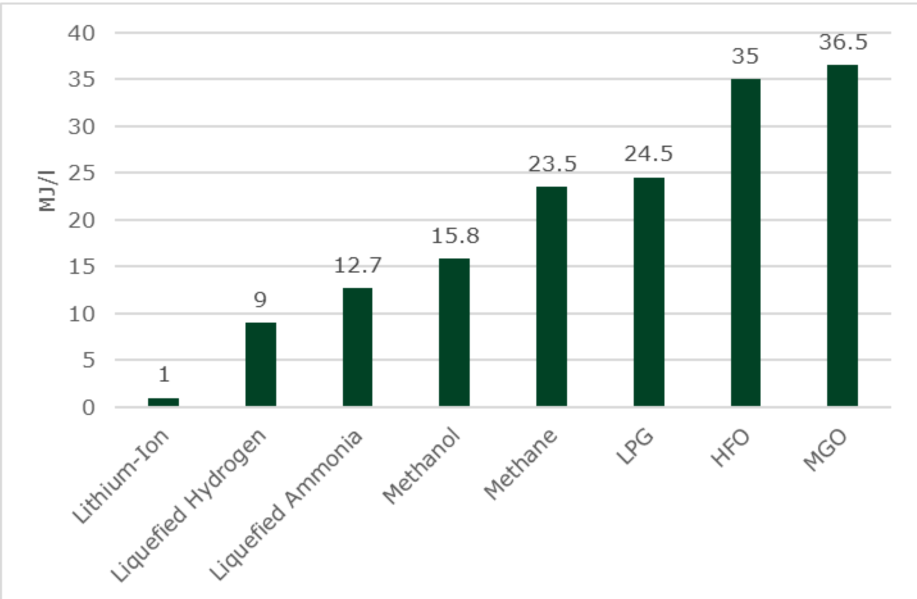
ENERGY DENSITY

The energy density of transport fuels is important when assessing the storage solutions required for these fuels. The higher the energy density of the fuel, the more energy may be stored or transported for the same amount of volume. Very Low Sulphur Fuel Oil (VLSFO) is the fuel being used by most shippers in the Emission Control Areas as it complies with the latest IMO regulations without use of a scrubber.

The volumetric energy density is high at 39.4 (MJ/I). LPG and LNG have a lower volumetric energy density at 24.5 (MJ/I) and 21.6 (MJ/I) with LNG providing the benefit of a 12% reduction in CO_2 emissions when compared to VLSFO, and LPG only providing a 2.7% CO_2 reduction. Of the potential low carbon fuels available biofuels have the highest energy density depending on the source at 20 MJ/I. Methanol whether produced from fossil fuels, recaptured CO_2, or renewable electricity has an volumetric energy density of 15.8 MJ/I. Ammonia has a higher energy density than hydrogen making it potentially more suitable than hydrogen as a fuel source but its low flammability characteristics as well as its low heating value require a pilot fuel injection to initiate the combustion process. Liquid ammonia has an energy density 11.5 MJ/I compared to 8.5 MJ/I for liquid hydrogen.

Battery technology has by far the lowest energy density amongst the alternative solutions, and this combined with range limitations makes employing battery technology for long-distance transport unfeasible.

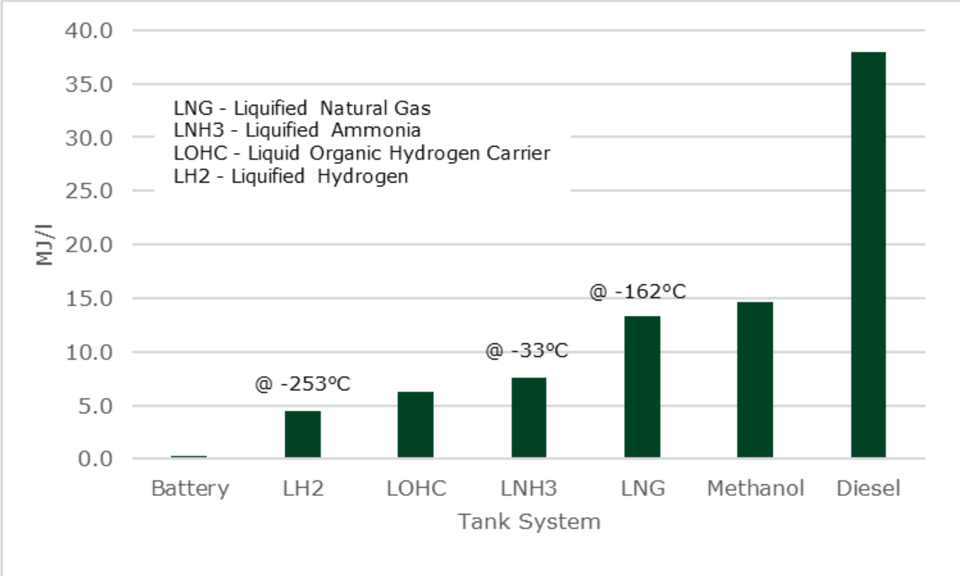
Volumetric energy density



Source: Longspur Research

Simple energy density is only part of the story. Where a fuel requires refrigeration or pressurisation, the space taken up by associated refrigeration equipment eats into the net carrying capacity of the vessel beyond that required to store the fuel. If we compare energy per volume of tank system, the positions of both LNG and ammonia worsen although methanol, as a liquid, remains unchanged.

Energy per volume of tank system

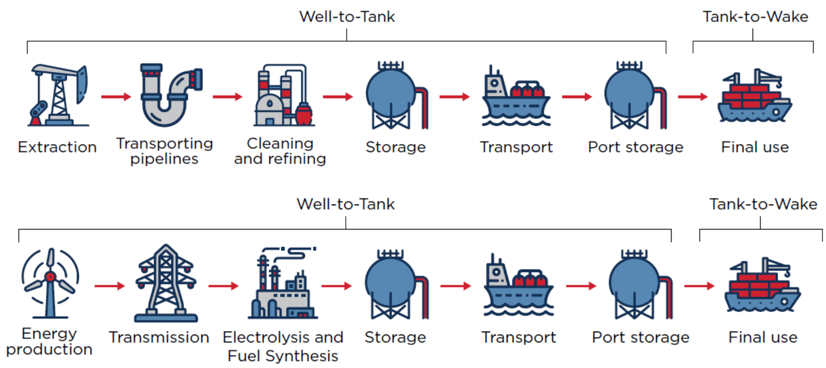


Source: Methanol Institute

LIFE CYCLE EMISSIONS OF TRANSPORT FUELS

When analysing the emissions of transport fuels, we use a well-to-wake analysis, including emissions from the whole life cycle from extraction and energy production to final use of the fuel in the vehicle. This is broken down into well-to-tank emissions and tank-to-wake emissions for fuels derived from fossil fuels and renewable sources as detailed below.

Well-to-wake



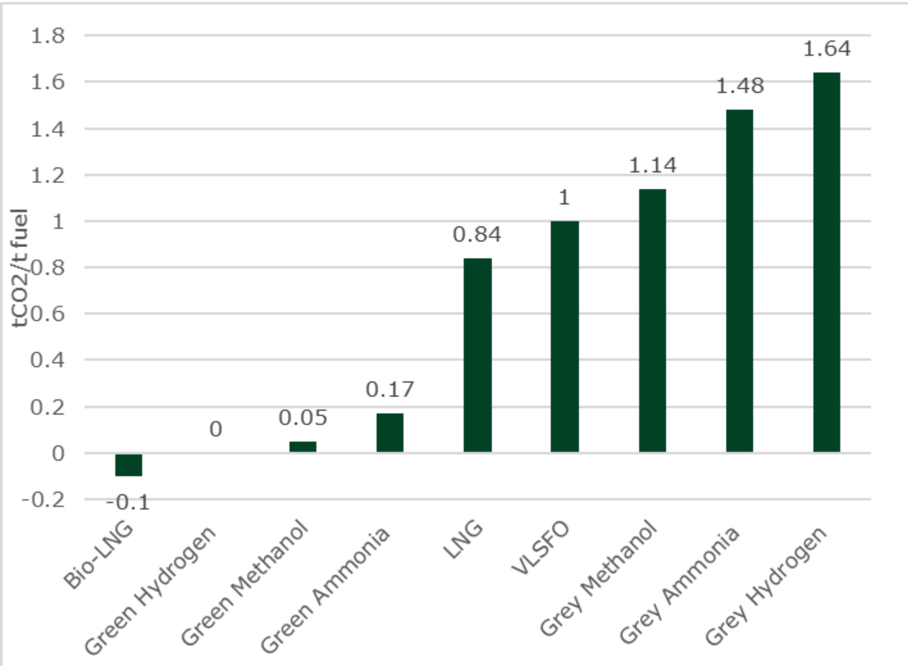
Source: Longspur Research

Using very low sulphur fuel oil (VLSFO) as a reference point, the International Convention for the Prevention of Pollution from Ships (MARPOL) calculates 3.114 tonnes of CO_2 per tonne of fuel (tCO_2/t fuel) tank-to-wake. Alternative fuels ammonia and hydrogen have similarly high emissions when produced using fossil fuels given the high amount of energy required in the production process. In fact, hydrogen and ammonia produces 64% and 48% more well-to-wake emissions when compared to VLSFO when using fossil fuels in the well-to-tank process. Hydrogen is emission free tank-to-wake given that water is the only biproduct of the process and burning ammonia will require pilot fuel for combustion given its low flammability as well as potential NOx emissions. Based on the need for a pilot light, CO2 emissions are calculated at 0.098tCO2/t fuel tank-to-wake assuming the ammonia is produced from green hydrogen which has zero co2 emissions.

LNG from fossil fuels reduced emissions by 12% at 2.750tCO2/t fuel when compared to VLSFO tank-to-wake according to MARPOL with the potential to reduce CO2 emissions by 100% well-to-wake when using bio-LNG and even result in negative emissions when CO2 is captured in the process. This is based on burning LNG in a dual fuelled diesel engine. However, a high level of energy is required for green Bio-LNG and CCS and will only be feasible when the price of renewable electricity becomes more competitive and CCS technology further develops.

Grey methanol actually has slightly higher CO2 emissions than VLSFO on a well-to-wake basis) and grey hydrogen and grey ammonia are even higher. Grey methanol does have reduced SOx, particulate matter and NOx emissions, something which VLSFO cannot provide. Green methanol using hydrogen produced from electrolysis of water and CCS capturing CO2 can enable nearly 100% reduction in CO2 well-to-wake if all the CO2 is captured with only small emissions from the combustion of pilot light fuel.

Well-to-wake emissions



Source: Longspur Research, ABS

LEVELISED COSTS

Fuel pricing is likely to be based on its levelized cost of energy which is the marginal cost per unit of energy output plus the amortised value of the capital costs again in terms of cost per unit of energy output.

$$LCOE = \frac{Sum\ of\ costs\ over\ lifetime}{Sum\ of\ electrical\ energy\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{It + Mt + Ft}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}}$$

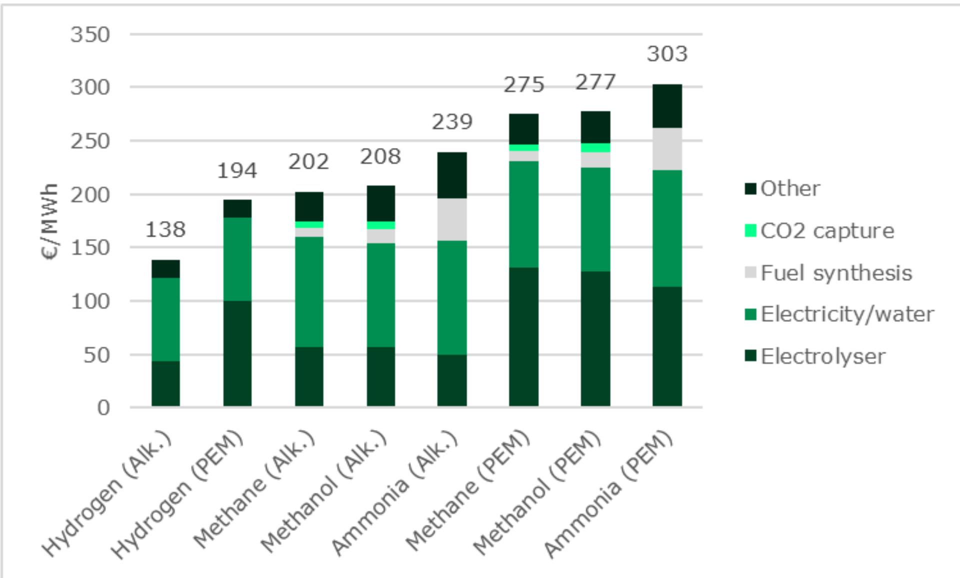
Clearly the method of production is key to determining the LCoE. These are discussed below.

LEVELISED COSTS COMPARED

We have used levelized cost calculations from Dias et al (Dias V, Pochet M, Contino F and Jeanmart H (2020) Energy and Economic Costs of Chemical Storage. Front. Mech. Eng. 6:21) which in turn are based on multiple references and in our view are well constructed.

The outcomes for the main transport fuel alternatives are dependent on the exact method of production. Most use hydrogen as an input and this can be created using SMR plus CCS ("blue" hydrogen) or from electrolysis using either alkaline or PEM electrolysers. We show the cheapest options below.

Production costs for marine fuels suggest hydrogen lowest cost



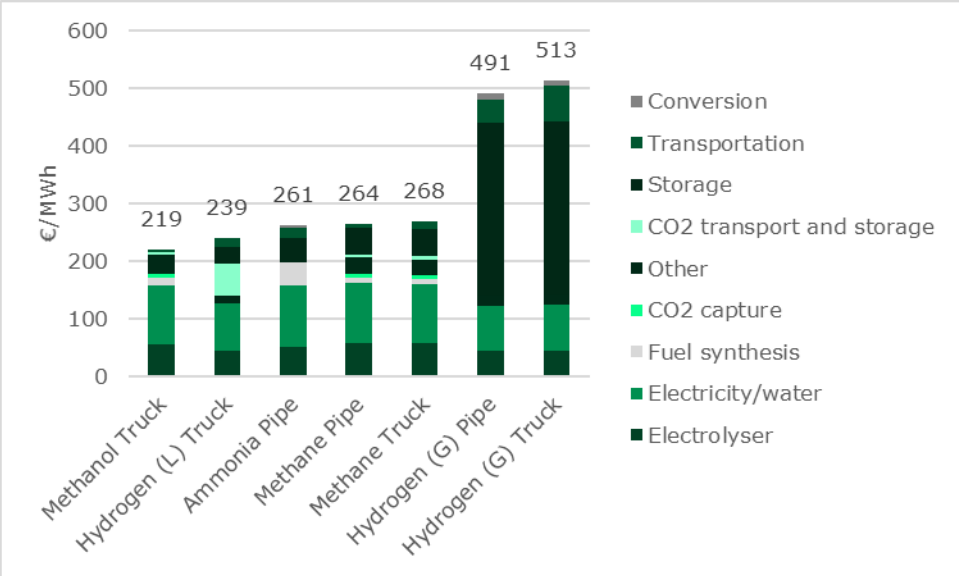
Source: Longspur Research, Dias et al

This suggests that hydrogen is the cheapest fuel to produce at the point of production. However, these calculations are only for the cost of fuel at the point of production and do not include delivery and storage costs.

Hydrogen can be stored in any state, as a compressed gas, or liquified or even as a solid using hydrides or sorbents. All these forms of storage consume energy reducing the final efficiency of the fuel and adding to its levelized cost. By comparison, methanol is a liquid and easily stored and transported at ambient temperatures. Ammonia requires some cooling to -33°C to liquify it.

Dias et al have also provided levelized costs at the point of use including assumptions on storage and transport.

Full delivered costs show methanol as lowest cost option



Source: Longspur Research, Dias et al

This shows the somewhat dramatic impact of cost and storage on the final levelized cost of hydrogen in a gaseous state. Liquid hydrogen is more reasonable and beats ammonia and methane but methanol, even trucked in, has the cheapest levelized cost at the point of delivery.

OTHER FACTORS

Flammability and explosion risks

The transport industry takes safety extremely seriously given the seriousness of situations that in static use cases might be more easily contained. Fire is one of the key risks that concerns those regulating the industry.

According to the Royal Institution of Naval Architects, "fire remains one of the top three causes of loss for marine vessels in the World Fleet, and is a major risk for Ro-Ro ferries, due to their open decks, and Passenger Ships due to ever increasing passenger numbers. The risk of fire may never be eliminated, but its effects can be mitigated" (Fire at Sea, Royal Institution of Naval Architects 2014). In Europe, a study by the Marine Incident Response Group found that ship fires posed the greatest risk to maritime safety compared to other types of maritime incidents.

Lithium-ion batteries have had some well-publicised issues with thermal runaway which can in certain circumstances lead to fire. There have been a number of well-publicised incidents involving lithium-ion batteries catching fire including the Samsung Galaxy Note 7, the Boeing 787 Dreamliner and the Tesla Model S.

Lithium-ion flammability – potentially catastrophic at sea

Source: AJ Gill

Of course, fuels, being energy carriers, tend to be flammable. Generally, for all the options considered here, this is an issue that can be managed by good fuel handling procedures and vessel design. Lower flashpoints on liquid fuel alternatives to diesel require management although this is true of gasoline where handling procedures are already well established.

Toxicity

The potential impact of fuels on the environment or on mankind is a key concern.

Lithium-ion is a potential environmental hazard on disposal although we feel that the marine industry is sufficiently regulated to minimise irresponsible disposal.

Methane is relatively non-toxic but is explosive in concentrations between 5% and 15%.

Ammonia is toxic and corrosive. It has a strong odour and is very irritating to the eyes, throat and respiratory tract - even in small concentrations in the air. It also has toxicity issues for fish and other marine life.

Data from the European Chemicals Agency shows that methanol is barely toxic for aquatic organisms (fish, invertebrates and algae). For humans it is toxic if swallowed.

As an extremely light gas, hydrogen tends to escape into the atmosphere if spilled, where it has minimal impact. It can explode although again the blast and heat tend to rise upwards rather than outwards making hydrogen fires more survivable and explaining why the majority of those on the Hindenburg airship survived its conflagration.

In terms of human toxicity, the following table shows the hazard statements required for marine fuels according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS).

GHS hazard statements required for main fuels

Hazard statements	Ammonia	H2	MeOH	LNG	LSHFO
H220 Extremely flammable gas		X		X	
H221 Flammable gas	X				
H225 Highly Flammable liquid			X		
H226 Flammable liquid and vapour					
H227 Combustible liquid					X
H280 Contains gas under pressure; may explode if heated	X	X			
H281 Contains refrigerated gas; may cause cryogenic burn or injury	X				
H304 Toxic if swallowed	X		X	X	X
H304 May be fatal if swallowed and enters airways					
H311 Toxic in contact with skin	X		X		
H314 Causes severe skin burns and eye damage	X		X		
H315 Causes skin irritation					X
H331 Toxic if inhaled	X		X		X
H332 Harmful if inhaled					X
H350 May cause cancer					X
H351 Suspected of causing cancer					
H361 Suspected of damaging fertility or the unborn child					X
H370 Causes damage to organs, optic nerve, central nervous system					
H373 May cause damage to organs through prolonged or repeated exposure					X
H410 Very toxic to aquatic life with long lasting effects	X				X
H411 Toxic to aquatic life with long lasting effects					
Number of statements	8	2	5	2	9

Source: Oko Institut eV, Proman AG

Infrastructure

We have already touched on this in terms of the additional requirements of liquifying hydrogen, LNG and ammonia as well as the costs impact of these. But these requirements also require investment and deployment of liquefaction and other infrastructure which is not yet in place. Fuel handling within the vehicle is also an important consideration. With a typical vessel operating life of between 20 and 30 years, owners need to make decisions now about expected operating conditions in 2050. This gives methanol an advantage as it is already in use, can be retrofitted with minor engine modifications, and does not require the pressurised and cryogenic storage that ammonia and hydrogen require.

LIQUID FUELS SUMMARY

Batteries are severely limited by density as far as long-haul transport is concerned. Hydrogen in gas form is also limited unless it can be produced at a point close to the demand, but liquid hydrogen is acceptable as is ammonia. Biomethane and methanol are much closer to the high density seen in fossil fuel solutions.

Emission reductions are greatest for biomethane, green ammonia, green methanol and hydrogen. However, ammonia has a question mark over nitrous oxide emissions which can potentially increase its global warming potential as a fuel.

Ammonia also has useability concerns given its toxicity and associated handling requirements. Hydrogen scores well on these areas with the possible exception of flammability although we think concerns here tend to be overstated. Methanol also does well given its relative lack of ecotoxicity and although some care is required to avoid human consumption this is easily managed.

Finally, while hydrogen has a low levelized cost at the point of production it is the point of delivery that matters and here methanol is the lowest cost.

Sustainable fuel options summarised

Criterium	Hydrogen	Ammonia	Methanol	LNG	Li-ion	HFO
GHG reduction potential	5	4	5	5	5	1
Density	2	3	4	4	1	5
Cost	2	1	3	1	2	5
Useability	4	3	4	3	4	3
Average	3	3	4	3	3	4

Source: Longspur Research based on Oko Institut eV

Taking all these factors into account suggests methanol is the best solution available today. Firstly, it is available today and is technology proven so can be selected for new build or it can be retrofitted to existing fleets. It is dense enough to be useable without significantly displacing load capacity and it is useable without too many hazards. It can be bunkered vessel to vessel or shore to vessel. Finally, it is the lowest cost option at the point of delivery.

Other options should not be ruled out as individual use cases will work better with some solutions than others. Notably lithium-ion batteries will find markets in short haul transport.

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