Biomass-to-hydrogen *Policy Briefing*

Key messages

- Hydrogen (H_2) is a versatile energy vector that will play a key role in our future energy system. One of the key strengths of H_2 is that it doesn't produce any emissions at the point of use. There are, however, upstream emissions related to H_2 production, so it is important to know how it is made.
- H_2 production at industrial scale is primarily *via* reforming of fossil feedstocks, which results in significant CO_2 emissions. Therefore, alternative routes which can produce low carbon H_2 must be deployed at scale. While water electrolysis is a well-known example for achieving this, H_2 production from biomass can also contribute towards low carbon H_2 targets.
- H_2 can be produced from biomass feedstocks including crops, forestry biomass, and wastes and residues, using a number of different biomass-to-H_2 conversion technologies.
- As biomass is composed of carbon, oxygen, and hydrogen, both H_2 and CO_2 can be generated during the conversion process. This biogenic CO_2 can be released but if the system is operated alongside carbon capture and storage technology, it can also be sequestered underground. As a result, Hy-BECCS (Hydrogen Bioenergy with Carbon Capture and Storage) systems are unique in providing the potential for negative emissions.
- The lifecycle emissions associated with biomass-to-H_2 depend on the technology used, the feedstock, and other details of how the system is operated. Providing the appropriate feedstock and system configuration is used, biomass-to-H_2 systems can produce H_2 that meets the UK Low Carbon Hydrogen Standard, even without the application of CCS.
- To fully evaluate biomass-to-H_2 systems the efficiency of the biomass-to-H_2 conversion must be considered as well as the life cycle carbon intensity.

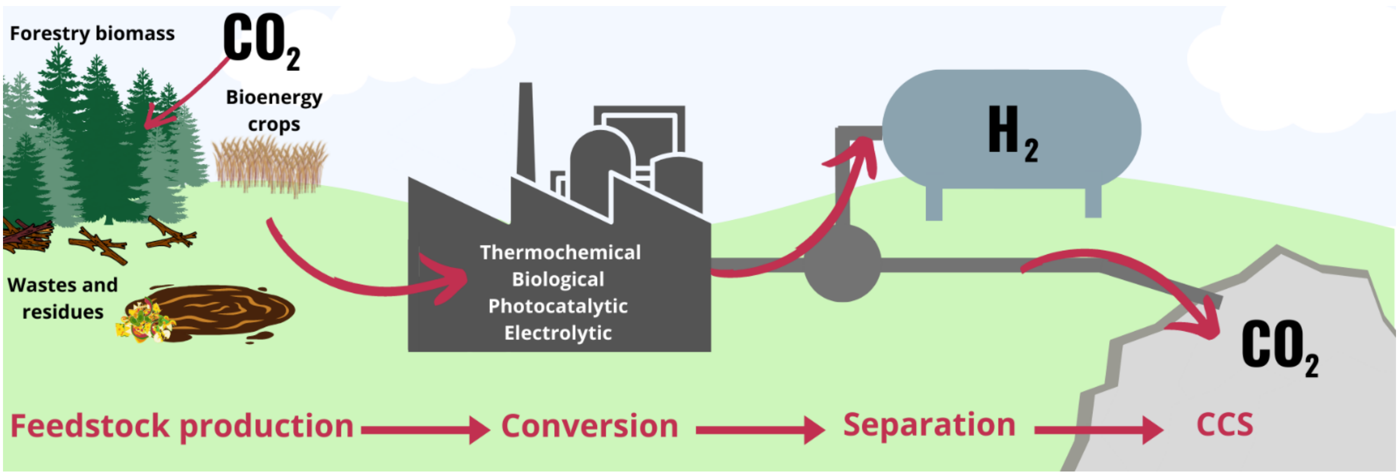

Figure 1. Schematic depicting the routes for producing H_2 from biomass feedstocks, and how this can be linked to CCS.

Introduction

Anthropogenic greenhouse gas (GHG) emissions are leading to a rapid increase in global temperatures and changes to the climate. Many nations have now signed up to legally binding targets such as the Paris Agreement and set their own net zero emission targets. Achieving these ambitious climate targets demands a reduction in emissions across all sectors of society and industry, and this must include sectors which are considered hard-to-abate (for example where a deployable fuel is needed, or high temperatures are required). There is no one size fits all solution, and different vectors, technologies and approaches must be developed and deployed in coming years.

In many decarbonisation scenarios, hydrogen (H_2) has been highlighted as having an essential role to play [1]. It is extremely versatile: it is used as a feedstock for manufacturing, but can also replace high carbon fuels as energy vectors for many applications (through the direct use of H_2 as a fuel and via the use of low carbon fuels which have been derived from H_2) [2, 3]. As a result, low carbon H_2 could support the decarbonisation of numerous sectors [4]. H_2 combustion does not contribute to anthropogenic CO_2 emissions.

H_2 is already produced at industrial scale but this is mostly *via* reforming of fossil feedstocks like natural gas [5], which causes significant CO_2 emissions [4]. In order for H_2 to support decarbonisation targets, alternative routes that lead to low carbon H_2 must be deployed at scale [1, 4]. Increased production of low carbon H_2 will require a combination of different approaches, which could include water electrolysis using renewable electricity, fossil-based production with carbon capture and storage (CCS), and production from biomass feedstocks [3]. There are already several plants in operation that combine steam methane reforming and CCS but in 2019 the IEA reported that less than 0.7% H_2 produced globally came from renewable sources or fossil plants fitted with CCS, and less than 0.1% H_2 production came from electrolysis [4]. Scaling up low carbon H_2 production will require barriers to be overcome, and costs to be reduced. Emissions from H_2 production must be kept as low as possible if its potential to support decarbonisation is to be realised, and so policies such as the UK Low carbon hydrogen standard will be important [6].

The UK Hydrogen Strategy demonstrated that the UK is committed to using H_2 as an energy vector and that it will be essential to the UK's transition to Net Zero. Although at the moment there is virtually no low carbon H_2 production in the UK, the UK government has set targets for 10 GW production capacity by 2030 [2, 7]. In the near term this will be from CCS enabled natural gas reforming and electrolysis of water, but the strategy indicates biomass-to-H_2 systems playing a role from 2030 onwards. Biomass-to-H_2 technologies combine the merits of H_2 with the carbon sequestration potential of biomass. Although the integration of these technologies awaits demonstration at commercial scale, and they face unique barriers that need to be overcome, they can potentially lead to negative GHG emissions. Biomass-to-H_2 technologies are unique in providing the potential for net GHG removals (i.e. negative emissions) and can also have some benefits compared to other BECCS routes.

Often H_2 produced by different technologies is referred to by colours. For example, when produced *via* water electrolysis it is referred to as green H_2. In this briefing we have not used this colour system. The colour classification for biomass-to-H_2 seems to vary according to where you look. In reality what is important when considering potential H_2 production routes for the future is the carbon footprint and wider sustainability impacts associated with production and so these will be the focus of this briefing.

Substantial work has gone into researching and developing technologies for H_2 production from biomass, but if deployment in the 2030s is to be achieved appropriate policies need to be put in place to enable refining and development at scale and incentivise systems that are sustainable. The aim of this briefing is to give an overview of H_2 production from biomass for both researchers, industry, and policy makers working in this area as we transition to net zero.

Biomass-to-H_2

The different routes for generating H_2 from biomass feedstocks [5, 8] (Figure 1) follow these steps:

1. **Feedstock production/ sourcing**:
Biomass feedstocks that could be used for H_2 production include wastes and residues (including food and municipal waste, agricultural residues, forestry residues, sewage sludge etc), purpose grown crops (both first generation crops such as maize, and second-generation perennial crops such as miscanthus), forestry biomass, and novel biomass sources such as algae. Lignocellulosic feedstocks (woody crops and forestry biomass) along with wastes and residues are of particular interest for the bioenergy sector as they would improve sustainability performance, while decreasing competition with food production.

2. **Conversion**:
H_2 is produced from biomass feedstocks using thermocatalytic (conversion of biomass by heat, sometimes aided by the presence of a catalyst), biological (conversion by microorganisms), electrochemical (conversion due to application of electric current), or photocatalytic (conversion by a catalyst which is activated by the absorption of light) technologies [5, 8, 9]. These processes usually produce CO_2 (and other by-products) alongside the H_2. In many cases conversion is preceded by pre-treatment processes such as drying or hydrolysis.

3. **Separation and purification**:
H_2 is separated from CO_2 and other by-products and purified for use.

4. **CCS**:
The CO_2 produced during biomass conversion can be captured and stored in CCS, or alternatively it may be released or utilised.

Biomass-to-H_2 technologies

Table 1 provides more details the technologies for H_2 production from biomass. Different conversion technologies for H_2 production can convert different feedstocks, and each technology comes with different advantages and limitations. For example, biological processes tend to be less energy intensive than thermochemical routes, but they also often have lower yields and production rates [5, 9]. Biomass-to-H_2 conversion technologies also differ in their technological maturity, with some are currently at very low technology readiness level (TRL), while others are already close to deployment. Two of the most mature technologies for bioderived H_2 production are biomass gasification and biomethane reforming, and these are discussed in more detail below.

Biomass Gasification

Gasification involves the thermal breakdown of biomass, and the key product is syngas (a mixture of H_2, H_2O, CO, and CO_2). Following syngas clean-up, water-gas shift reactions can be used to alter the ratio of the syngas components [10]. Different approaches to gasification (such as steam gasification or supercritical water gasification) have different strengths and weaknesses [11]. There are already commercially operating gasification plants and there are some biomass-to-H_2 gasification plants in the pipeline. Although there are no examples of fully developed process chains (combining the individual components) for the production of H_2 *via* gasification it is expected that it could be achieved at commercial scale in the near future because many of the individual components are technologically proven [12]. Technical barriers such as tar formation and use of inconsistent or unreliable feedstocks such as waste still pose some barriers for gasification. Efforts to overcome these, improve efficiency and reduce costs, will be key to the wider deployment and success of gasification (whether or not the desired end product is H_2).

Biomethane reforming

Anaerobic digestion (AD) is a widely deployed biomass technology for converting wastes and residues (or sometimes crops) into biogas, which can be upgraded into biomethane. Natural gas reforming is a mature technology for producing fossil-derived H_2 (via the production of syngas) and replacing the natural gas in this reforming process with biomethane would allow biomass-derived H_2 production. Both biomethane and H_2 can be low carbon fuels, although they have different properties and H_2 is being produced via additional processing steps with inevitable energy and economic costs. Decisions on the most appropriate energy vector need to consider available infrastructure, overall efficiency and energy balance, life cycle emissions, and economic cost. In some cases, it makes more sense to use biomethane directly, but in others it makes sense to convert to H_2.

H_2 separation

As biomass is composed of carbon, oxygen, and hydrogen, most technologies for H_2 production from biomass result in mixtures of gases that contain H_2 and CO_2. To produce a supply of H_2, it must be separated from these mixtures [12]. Technologies such as pressure swing adsorption, physical and chemical absorption, and membrane permeation are already used at commercial scale, but there is ongoing research and innovation to produce new and improved separation systems [12]. It is important to consider the availability and application of suitable separation technologies when developing and deploying biomass-to-H_2 systems.

Separation steps increase energy consumption and cost, and there will often be a trade-off between amount of H_2 recovered and the purity [12]. It is therefore essential for separation steps to be included in any analysis looking at environmental impacts or economic feasibility of biomass-to-H_2 systems. Given the potential trade-offs it is also important to understand the purity of H_2 that is actually required. This depends on the application: fuel cells require very high purity levels, whereas industrial high temperature heat and power generation do not [1]. As the production and use of H_2 becomes more widespread, general specifications for purity might be further developed. Future research should include efforts better understand purity requirements and how biomass-to-H_2 systems can meet them [9].

Integration with CCS

Most biomass-to-H_2 technologies produce gas mixtures containing CO_2 from which H_2 must be separated, meaning that they are well suited to integration with CCS technology (Figure 1). Operating biomass-to- H_2 systems alongside CCS means that biogenic CO_2 is sequestered underground, giving negative GHG emissions. This is in contrast to systems operating CCS alongside fossil derived H_2 production, which can only ever decrease the extent of positive emissions as the carbon being sequestered is originally derived from fossil feedstocks. Biomass-to-H_2 combined with CCS (Hy-BECCS) is an example of a wider group of negative emission technologies known as BECCS (Bioenergy with Carbon Capture and Storage) [8, 13]. Other forms of BECCS include post-combustion systems where CO_2 is captured from the flu gas after biomass combustion. This is the typical arrangement envisaged for electricity generation (power-BECCS). BECCS technologies have the potential to enable negative emissions [1, 14], but life cycle analysis of the entire supply chain is important to determine the true potential for negative emissions [8, 14]. The deployment of BECCS at scale (including Hy-BECCS) requires further development of technologies and of necessary infrastructure, and faces a number of specific challenges that are explored in more detail in a previous briefing from the Energy and Bioproducts Research Institute [14]. To support the transition to net zero and make the best of the feedstocks available and provide the products required, a combination of different BECCS approaches will be needed [13].

As well as CCS, there is also growing interest in technologies for utilising captured CO_2 in food and drinks or to produce products such as chemicals, materials, or fuels [15, 16]. Unless the CO_2 is used to produce long lifetime products these systems would not result in negative emissions [8] and so, at large scales biomass-to-H_2 may be best used with CCS. However, CO_2 utilisation can support reduced emissions where generating products from captured CO_2 reduces the need for virgin fossil feedstock that are otherwise be needed to make those products. CO_2 utilisation systems coupled with biomass-to-H_2 would therefore reduce emissions whilst also improving resource efficiency and providing an extra revenue stream for biomass-to-H_2 projects. Whilst CCS will rely on geological storage and is therefore likely be localised in particular regions or clusters, systems designed to utilise the CO_2 from biomass-to-H_2 technologies could be applied to small scale deployments or in regions not connected to CCS infrastructure [13]. It should be noted that some CO_2 utilisation technologies require H_2 and therefore a better consideration of the interplay between these systems and H_2 production systems is required.

Some biomass-to-H_2 technologies also produce solid carbon by-products (i.e. production of biochar in gasification or pyrolysis). This can be another route to carbon storage and potentially negative emissions if the solid carbon is incorporated in long lifetime applications such as soil amendments, cement, or other products for the construction industry.

Table 1. Key routes to H_2 from biomass

Technology	Details	TRL *	Advantages	Limitations
Thermochemical				
Gasification [3, 5, 10, 11, 17]	Thermal biomass breakdown at high temperatures (>700°C) in the presence of oxidising agents such as oxygen or water. Products include syngas (producer gas), tar, and solid carbon products (ash and char). Water gas shift reactions can be carried out after gasification to increase H_2 yields. The H_2 production varies according to specific setup, including oxidising agent, feedstock, reactor design and catalyst used.	Development/ deployment	● Can use a wide variety of feedstocks, including lignocellulosic biomass, wastes and residues, and when supercritical water gasification allows use of wet feedstocks like algae ● Higher yield and efficiency than some other routes ● Scale-up feasible due to individual components within supply chain already being technologically mature	● Variable yields of H_2 ● Issues with char and tar formation ● High operating temperature ● Expensive reactor
Pyrolysis [5]	Thermal breakdown of biomass to bio-oil, biochar and non-condensable gas. It can be performed at lower temperatures than gasification (400-600°C). The bio-oil or biochar products can be put through reforming processes to produce H_2. Or bio-oil can be used as a gasification feedstock.	Research/ development	● Can use a wide variety of feedstocks, including lignocellulosic biomass, wastes and residues ● Relies on existing industrial processes	● Further processing steps are required for H_2 production, variable yields of H_2 ● Expensive reactor ● High operating temperature ● Potential for catalyst deactivation
Biomethane reforming [1, 5]	Biomethane produced via anaerobic digestion (AD) can be converted to syngas via reforming processes that are usually used for natural gas.	Development/ deployment	● Relies on existing technologies ● AD allows waste utilisation	● AD is limited in the feedstocks that it can use ● In some cases, it makes more sense to use biomethane directly rather than convert to H_2
Other thermochemical [5]	Other thermochemical routes include technologies for reforming biomass or bio-derived species, such as aqueous phase reforming and partial oxidation, and more information on these technologies can be found in the literature.			
Biological				
Dark Fermentation [5, 18-21]	Breakdown of biomass feedstocks by microbes, producing H_2, CO_2 and organic acids. Product distribution varies dependent upon the process conditions (including the microbe and feedstock used).	Development	● Utilisation of variety of feedstocks including wastes streams, residues, and wastewater ● Less energy-intensive than thermochemical routes ● Pre-established technical know-how due to similarity with AD ● Simple reactor technology ● Potentially useful/ valuable co-products ● Integration with photo fermentation in two step process can increase yield and efficiency	● Low yield of H_2 ● Large amount of by-products ● Pre-treatment required for some feedstocks
Photo fermentation [5, 18-21]	A light dependant process where photosynthetic bacteria use captured solar energy to produce H_2 and CO_2 from organic acids or biomass	Research	● Utilisation waste streams ● Potential for using algae (high growth rate) ● Less energy-intensive processes than thermochemical route ● Integration with dark fermentation in two step process can increase yield and efficiency	● Low yield of H_2 and rates of production ● Low solar conversion efficiency and issues with light distribution ● Less financially competitive than dark fermentation ● Pre-treatment required for some feedstocks ● Expensive bioreactor ● Cannot convert raw biomass
Microbial electro hydrogenesis cells (MECs) [5, 18, 21, 22]	Microbial fuel cells in which electrochemically active microbes oxidise bioderived molecules such as glycerol and ethanol (often fermentation products) at one of the electrodes.	Research/ development	● Lower electricity demand than water electrolysis ● No purification of H_2 required ● Less energy-intensive processes than thermochemical routes ● Able to make use of aqueous solutions of bio-based molecules such as wastewater and outputs of fermentation	● Cannot directly convert most biomass streams ● Expensive ● Low rates of H_2 production
Electrochemical				
Proton Exchange Membrane Electrolysis Cell (PEMEC) [5]	Electricity provides the energy needed for oxidation of bioderived molecules such as glycerol and ethanol (often fermentation products) [5].	Research	● Lower electricity demand than water electrolysis ● No purification of H_2 required ● Able to make use of aqueous solutions of bio-based molecules	● Cannot directly convert biomass or bioderived polymers ● Expensive catalyst ● Low rates of H_2 production
Photocatalytic				
Heterogenous photocatalysis [23]	Photocatalysis is a light driven chemical reaction that can be used for the (photo)reforming of biomass substrates into H_2 via redox reactions. The photocatalyst material is activated via the absorption of light and then facilitates the oxidation of biomass which can result in H_2 production.	Research	● Can operate under ambient conditions (e.g., room temperature and atmospheric pressure) ● Can utilise solar irradiation to perform photo-reforming to produce H_2 ● Can potentially use a range of biomass resources	● Low yields of H_2 generation ● Low solar to H_2 efficiencies ● Large scale production of suitable and cost-effective catalysts needed ● No pilot scale studies to date and lack of reactor focussed research in the literature

** Technology Readiness Level (TRL) 1 – 3 research, 4 -6 development, 7 -9 deployment (note that this is without CCS and that the TRL with CCS where relevant would often be lower than that given for the technology). It should be noted that TRLs vary from one variation on a technology to another and can change rapidly, and therefore the TRLs listed here are intended to be a comparative guide only.*

Lifecycle GHG emissions of biomass-to-H_2 systems

The potential for low or even negative lifecycle GHG emissions associated with biomass-to-H_2 systems are a key factor in their desirability. Figure 2 shows lifecycle GHG emissions for two biomass-to-H_2 technologies, and clearly demonstrates that biomass can be used to produce H_2 with lower emission values than traditional natural gas reforming [3, 12, 13, 24-35]. It should be noted that this does not include emissions relating to feedstock production (fertilisers etc), and so reflects scenarios where low emission biomass feedstocks such as wastes, or residues are used. Data from the literature shows biomass gasification or biomethane reforming of low emission feedstocks, without the application of CCS, resulting in H_2 with a GHG intensity of 1 to 19 gCO2e/MJ-$H_{2(LHV)}$. Therefore, biomass-to-H_2 systems can meet the UK Low Carbon Hydrogen Standard (i.e. they produce H_2 with associated emissions of less than 20 gCO2e/MJ-$H_{2(LHV)}$ at point of production [6]) even without the application of CCS, provided the appropriate feedstock, technology, and system configuration are used. Additionally, biomass-to-H_2 technologies are unique in providing the potential for negative emissions.

Figure 2 includes several different studies/ data points for each H_2 production route. Variations in net lifecycle emissions can be seen between technologies, but also between different examples of the same technology, due to differences in the system configuration (particularly differences in conversion efficiency, carbon capture rate, and processing requirements). The impact of the system configuration and the metrics used to understand these systems are discussed in more detail below.

To understand the emissions associated with biomass-to-H_2 it is useful to consider the GHG flows that are involved (Figure 3):

- Feedstock production: Growing plants sequester CO_2 from the atmosphere and lock it up as biomass. There are some emissions associated with the use of fertilisers, or fuels for transport.
- Conversion and separation: Generating H_2 from biomass releases the carbon from the biomass, often in the form of CO_2. The energy use and ancillary inputs associated with conversion also lead to emissions.
- CCS: If CCS is applied during the conversion the biogenic CO_2 is stored rather than released to the atmosphere.

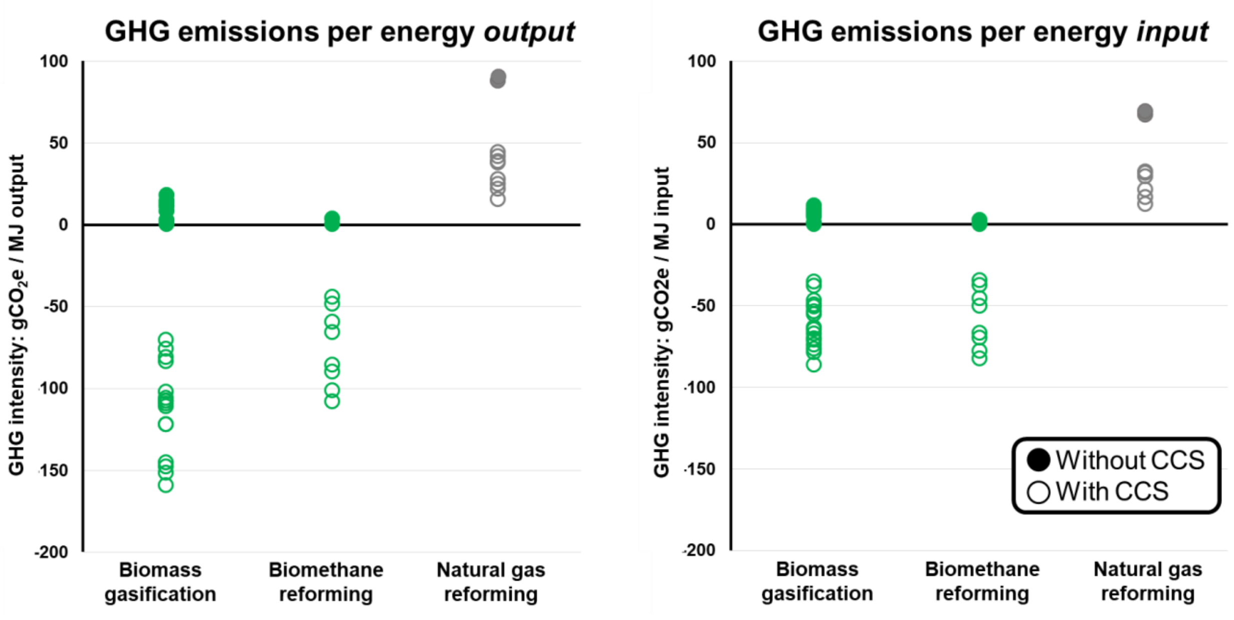

Figure 2. GHG intensity of different biomassto-H_2 routes, with GHG intensity of natural gas reforming included for comparison. All systems are shown with and without CCS. This data was obtained by reviewing the published literature and a spreadsheet providing more information is available upon request [3, 12, 13, 24-35]. Lower TRL biomass-to-H_2 routes are not included in this comparison. (Left) shows GHG intensities in gCO_2eq per MJ output (i.e. gCO2e/MJ-$H_{2(LHV)}$) and (right) shows GHG intensities in gCO_2eq per MJ input (biomass or natural gas). The range of GHG intensities for each type of system is due to differences between the selected system configurations. These ranges do not include uncertainties and emissions relating to feedstock production (fertilisers etc) are not included in the lifecycle emission figures for the bioenergy systems. As the points represent separate discrete systems, the "average" should not be interpreted as necessarily more "representative", "realistic" or "typical".

The net lifecycle emissions of the system result from the balance between the amount of CO_2 emitted (upwards arrows in Figure 3) and the amount sequestered (downwards arrows in Figure 3). If no CCS is applied the net emissions from the system are likely to be slightly positive because, although the biogenic carbon emissions cancel out, there are residual emissions from the chemical and energy use. If CCS is applied, the overall process could be net negative. The possibility for or extent of net negative emissions relies on the residual emissions and how much of the CO_2 is captured.

Processing Requirements

In Figure 2Figure 2, the emissions forming the 1 to 19 gCO2e/MJ-$H_{2(LHV)}$ lifecycle emissions of the biomass-to-H_2 systems without CCS are emissions related to processing and ancillary inputs. Variation seen between the different systems is due to differences in how they are configured and operated. These process related emissions are notable and worth minimising. Decarbonisation of other parts of the supply chain, for example grid electricity production or transport fuels, will also reduce these emissions.

Efficiency of biomass-to-H_2 systems

The conversion efficiency of a system describes how efficiently the feedstock (in this case biomass) is converted to the product. A lower efficiency system will require more biomass to produce the same amount of H_2 (Figure 4). Although biomass-to-H_2 production can be achieved with a relatively high efficiency, some system configurations do result in lower conversion efficiencies. For example, use of ancillary energy systems to support very high CO_2 capture can lead to lower efficiency systems (see section below).

Energy systems are often assessed by considering the lifecycle emissions per unit of energy output (as shown in the left-hand graph in Figure 2) but this does not provide any information on the efficiency of the system. A complete understanding of the system can be achieved through the use of two different metrics, describing the emissions per energy output *and* the emissions per energy input (i.e. per unit biomass used) [13]. The right-hand graph in Figure 2 shows GHG emissions expressed per unit of biomass feedstock used. When the data is expressed in this way there is less variability in the GHG emissions performance between biomass systems.

Understanding the system efficiency is particularly important when considering Hy-BECCS systems. Low efficiency Hy-BECCS systems report greater negative emissions per unit of energy produced than equivalent high efficiency systems. However, low efficiency systems also produce less H_2 and they do not always lead to greater negative emissions overall (see Figure 4). Where two systems

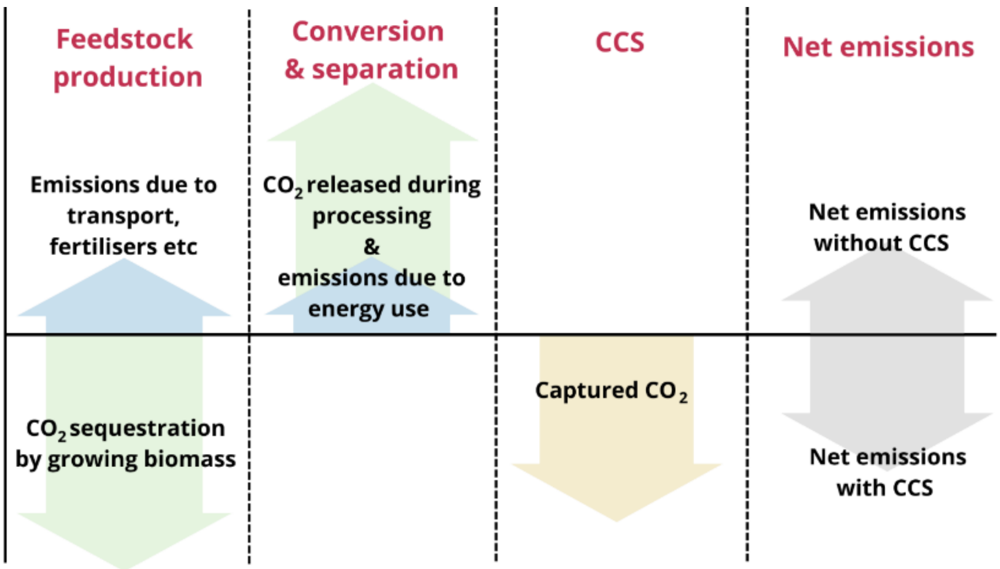

Figure 3. Lifecycle greenhouse gas emissions associated with biomass-to-H_2 systems. Note the magnitude of the CO_2 changes are illustrative but not to scale.The size of the arrows do not directly reflect measured values but reflect what the overal system might look like. The net emissions depend on the relative sizes of the different positive and negative emissions across the system.

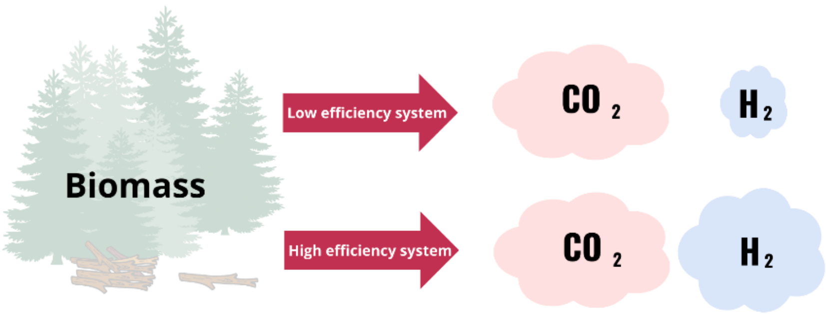

Figure 4. Schematic explaining the difference between high and low efficiency systems. Low efficiency systems produce less hydrogen per unit of biomass used than high efficiency systems, but the CO_2 to H_2 ratio is increased due to the low H_2 production.

achieve similar negative emissions per unit of biomass used, the one with the highest H_2 productivity would be the most desirable.

Carbon capture rate

Differences in carbon capture rates (i.e. how much of the CO_2 is captured) is one reason for the differences in the negative emissions achieved by Hy-BECCS systems such as those shown in Figure 2 [3]. Carbon capture rates vary according to the effectiveness of the carbon capture technology used or how the plant is designed (for example, what proportion of the CO_2 streams that carbon capture is applied to).

High capture rates appear to be beneficial for systems designed to remove CO_2, but in Hy-BECCS systems trade-offs between H_2 production efficiency and CO_2 removal rate have been observed [13]. In a scenario where sustainable biomass resources were unlimited; the highest negative emissions would be the ideal process operation. However, in reality sustainable biomass is limited, and it needs to be used efficiently.

Accounting for biogenic emissions

Some GHG accounting approaches do not consider the biogenic carbon flows within a bioenergy system because the biogenic carbon released during processing matches that absorbed by the feedstock during growth (see Figure 3) and in effect the emissions and absorptions cancel each other out. However, explicitly accounting for the biogenic carbon flows enables consideration of measures to maximise absorption or minimise emissions of biogenic carbon and is essential when evaluating the benefits from BECCS processes.

Counterfactual

As well as having low or negative associated GHG emissions, biomass derived H_2 can displace other highly GHG emitting processes or fuels and this increases the overall emissions benefit that is achieved [8]. The process or fuel that is displaced is referred to as the counterfactual. A greater GHG saving is achieved where a higher emission counterfactual is being displaced or where a greater biomass-to- H_2 conversion efficiency results in more of the emission counterfactual being displaced. Both of these effects are likely to result in greater GHG benefits for H_2 production over biomass used for electricity generation (for both processes using CCS and equivalent feedstocks) if grid electricity continues to decarbonise faster than alternative H_2 production.

Feedstock

Emissions relating to feedstock production are excluded from the lifecycle emission figures in Figure 2. Therefore, the lifecycle emissions quoted for the biomass-to-H_2 systems here represent those that would be achieved for systems using low emission feedstocks. Emissions relating to biogenic waste feedstocks (e.g. from MSW, agricultural or forestry residues) are typically allocated to the demands that drive the waste streams, and so they are usually be considered low-emissions feedstocks. Where high carbon intensity feedstocks (such as corn) are used, the results will be different, and care must be taken to ensure lifecycle emissions remain low.

Drivers and opportunities

Negative emissions

The key driver for developing and implementing biomass-to-H_2 technologies is the potential for negative emissions. The Intergovernmental Panel on Climate Change (IPCC) and the UK's Climate Change Committee (CCC) have suggested that negative emission technologies, including BECCS, will play an essential role in tackling climate change [36, 37]. Biomass-to-H_2 systems are unique in providing low carbon H_2 with the potential for negative emissions. On top of this, Hy-BECCS can have benefits over other BECCS technologies:

- In general biomass-to-H_2 is well suited to utilisation with carbon capture as the H_2 and CO_2 streams need to be separated anyway in order to supply the H_2. Hy-BECCS can therefore be achieved with very little additional energy relative to biomass-to-H_2 without CCS. This is in contrast to post combustion power-BECCS where the carbon-capture is a separate additional stage [8].
- Hy-BECCS produces a flexible, deployable fuel (which doesn't release CO_2 when burned unlike other biofuels) [8, 24].

Smaller scale or decentralised deployment

Biomass-to-H_2 technologies could be deployed in large scale centralised plants, but they also provide opportunities for decentralised smaller scale deployment. Although small scale facilities might face some barriers in terms of economies of scale and H_2 transport logistics, they could also have a number of benefits: opportunities to prove and further develop technologies before deploying at larger scales ("learning by doing") and thus de-risking investment; scaling-up via deploying many instances of a technology that can be largely manufactured off-site; more sites where H_2 can be produced and used in one location, which would be beneficial for countries without a gas grid or in remote locations that are not connected to the gas grid; utilisation of local resources, such as agricultural residues, thus providing benefits in terms of available biomass resource; opportunities for CO_2 utilisation technologies linked to H_2 production (as not all parts of the country will be connected to CCS, particularly in small scale sites). Recent studies have highlighted these possibilities for decentralised Hy-BECCS deployment [13, 24].

Wider sustainability benefits

Sustainability is much more than GHG emissions. As well as enabling GHG reductions these systems can have wider sustainability benefits for society (such as equality, jobs, and skills), economy, and the environment (providing ecosystem services, such as improvements to water availability and quality, and soil carbon) [38].

Barriers and challenges

All routes to low carbon H_2 face barriers around costs, technology scale up, policy and regulatory uncertainty, infrastructure, storage and transport, and safety [1, 2]. There are a number of challenges that are of particular importance for biomass-to-H_2 systems that are discussed here.

Cost

Currently, the cost of fossil derived H_2 (with or without CCS) is lower than that of biomass-derived H_2 [5, 17]. Novel biomass technologies for H_2 production are likely to have high capital (plant construction etc) and operational (feedstocks, auxiliary inputs, energy, labour etc) costs. However, additional value provided by the sale of coproducts can improve the system economics, and as deployment of biomass technologies increases, there is potential for improvements and optimisations to bring costs down.

Sustainable feedstock availability

Bioenergy and other non-energy uses of biomass are increasingly recognised as an important tool for reducing reliance on fossil feedstocks and tackling GHG emissions, and as a result the demand for biomass resources is set to increase. Biomass is a limited resource and there are likely to be many competing uses. As well as the potential benefits discussed above, all bioenergy projects (including biomass-to-H_2) will come with sustainability risks. To meet growing demand for biomass production, mobilisation of biomass feedstocks will have to be scaled up, and this may lead to increased sustainability risks. It is important to understand the trade-offs, so that wider benefits can be identified and risks addressed [38]. There are Government Regulations and voluntary certification schemes aimed at reducing negative impacts from biomass systems, but these tend to focus on a small number of sustainability issues and require minimum thresholds to be met rather than incentivising best practice [38].

CCS

As with all CCS applications, there are additional barriers that must be overcome for the deployment of biomass-to-H_2 with CCS [1, 4, 14, 39]. For example, the economics of BECCS systems are often unfavourable without incentives being put in place because the CCS aspect itself does not generate valuable products [8, 9]. Policy will therefore have a particular role to play in determining the economic viability of Hy-BECCS systems.

Other barriers

Discussion with stakeholders during the development of this briefing indicated a number of additional barriers for biomass-to-H_2 systems. This included challenges associated with scaling up new technologies, previous failures [40], social acceptance (which is key factor in the implementation of all bioenergy systems due to concerns around fairness or sustainability [8, 41]) and consistency of policy and regulation.

Conclusion

H_2 will be a key energy vector for a net zero future, and biomass-to-H_2 technologies combine the merits of H_2 with the potential benefits of biomass. Lifecycle analysis of biomass-to-H_2 systems demonstrates that biomass derived H_2 can be low carbon, provided the correct feedstock and system configuration are used. Additionally, implementing with CCS in Hy-BECCS systems can potentially provide negative emissions and this is the key driver for development and deployment of biomass-to-H_2 technologies.

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