WASTE-TO-HYDROGEN: CHALLENGES AND OPPORTUNITIES IN THE UK SCENARIO

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ABSTRACT

Hydrogen is widely recognised to play a key role to decarbonise various industries, as well as transportation, heating and power sectors, for it does not generate greenhouse gas emissions at the point of use. Understanding the technologies that can generate low carbon hydrogen is essential in planning the development of future gas networks and more sustainable manufacturing processes. One promising approach is hydrogen production by gasification of waste or biomass. This paper summarises work undertaken to design a commercial Waste-to-Hydrogen (WtH$_2$) plant, which includes an assessment of current development stage of technologies, the identification of an appropriate scale for the plants, and development of specifications for process design and output streams. The overall production levels of hydrogen product is observed to be limited by the availability of sustainable feedstocks; however, the results of negative CO$_2$ emissions achieved via biohydrogen production shows that its overall potential to reduce GHG emissions is significantly better, as compared to other form or low carbon hydrogen. In particular, biohydrogen application is capable of generating negative emissions that are required to offset GHGs from other sectors in the future. In combination, low carbon hydrogen production pathways can make a very important contribution to achieving net zero commitment in UK.

1. INTRODUCTION

In recent years hydrogen has received increasing attention as a potential fuel that could be produced from non-fossil fossil sources, can be generated with low greenhouse-gas (GHG) emissions, and generates no emissions at the point of use. As such, hydrogen is believed to play a key role in achieving Net Zero ambitions, across Europe, and UK in particular (Gov.uk, 2019).

The UK has set a target to reach Net Zero GHG emissions by 2050. This requires the current 522 Mt CO$_2$-eq emissions per year to reduce to zero over the next three decades. Carbon emission reductions can partly be achieved through increased renewable electricity generation and electrification; however, the adoption of low or zero carbon fuels, such as hydrogen, are expected to play a significant role. Hydrogen is currently used as an industrial feedstock, mainly for ammonia production and in oil refineries (Chapman et al., 2019). It is mostly produced from fossil fuels reformation, namely steam methane reformation (SMR) and autothermal reforming (ATR) of natural gas, also known as 'grey hydrogen'. There are three main technologies that can produce hydrogen with low carbon impact:

- Electrolysis using renewable electricity to produce 'green hydrogen'
- ATR and SMR with carbon capture and storage (CCS) to produce 'blue hydrogen'
- Reformation of biogas or gasification of biomass with CCS to produce 'biohydrogen'.

Green hydrogen offers a small-scale solution that can be cost effective for some applications such as filling stations for hydrogen vehicles. However, currently the cost of hydrogen produced by electrolysis is far more expensive than SMR grey hydrogen (£6.20/kg versus £1.90/kg for transport-grade) and it does not offer significant greenhouse gas (GHG) benefits unless renewable electricity is used (Al-Qahtani et al., 2021). Power-to-gas (PtG) technologies rely on this principle. This development is particularly attractive due to the availability of renewable power generation in excess of immediate electricity demand and an expectation that this availability will increase with the share of intermittent renewable power generation (Götz et al., 2016).

Steam and autothermal methane reforming involves reacting natural gas with steam or limited amount of oxygen, at high temperatures over a catalyst to produce syngas (a

mixture of H_2 and CO). This is then further processed to maximise H_2 generation (via water gas shift reaction, WGS) and separate H_2 product from a CO_2-rich stream. Production capacities of hydrogen from a typical steam methane reforming plant range between 150 and 440 MW with an energy efficiency of typically 70% (Al-Qahtani et al., 2021). If SMR is to become a major low-carbon source of hydrogen, carbon capture and storage is essential. It is estimated that between 71% and 92% of the CO_2 in steam methane reforming can be captured; however higher capture rates will be needed if the process is to be used in the long term (Materazzi et al., 2019). Furthermore, CCS barriers are no exclusively technical, with CCS cost being the most significant hurdle in the short to medium term. Auto-thermal reformation (ATR) is a similar process to steam methane reformation (SMR), which is a proven technology used to produce the majority of 'grey' hydrogen in the world today. Rather than combusting natural gas to raise steam, and produce carbon dioxide, as with the SMR process, the ATR process utilises natural gas within the reactors, with carbon dioxide produced from the feedstock at high pressures and relatively high purity. This provides a single stream for carbon dioxide separation and removal rather than multiple carbon dioxide streams at variable pressures and purities from the SMR process, allowing for a higher carbon dioxide capture rate (>95%) than SMR. As well as providing a low-cost way to capture carbon dioxide, ATR also shares the same benefits of SMR, namely that the technology is based on well-proven chemical engineering technology, which can be easily scaled-up and produces hydrogen at a relatively low cost (dependent on the natural gas price). The carbon dioxide stream captured from the ATR plant can be injected into offshore carbon storage facilities, as is being planned around several industrial clusters in the UK, including the HyNet cluster in the North West of England and the Acorn project in North East of Scotland (Edwards et al., 2021).

Biohydrogen is the newest addition to the low-carbon hydrogen choices. Several techniques have been proposed by many researchers for the thermal conversion of solid organic materials to biohydrogen, via gasification or pyrolysis (Barisano et al., 2017). Biohydrogen offers the prospect of low carbon hydrogen production from low-grade – in large fraction renewable – fuels, at parity with the cost of natural gas, and with the potential of negative carbon emissions if the separated CO_2 is sequestered. A number of studies have been reported in the literature for biohydrogen production from first-generation biomasses, especially from starchy and sugar-rich biomasses due to easy fermentability attribute of these feedstocks by anaerobic organisms which increases H_2 yield compared to other organic substrates (Chong et al., 2009). Waste and second-generation biomass materials, although readily available and abundant, have limited uses in terms of chemical feedstocks, due to the need for pre-treatment and presence of many contaminants which add complexity and costs. Thermochemical treatment of waste fuels for hydrogen or chemical production, therefore, presents a number of unique issues demanding specific design and feedstock choices and technical solutions. Generally speaking, the conversion schemes use heat and various combinations of steam, oxygen and CO_2, to convert the feedstock to various amounts of char, hydrocarbon gases, hydrogen, and carbon oxides, with ash being a by-product of most waste feedstocks. Ash residues are usually classified as a hazardous waste on account of their high alkalinity and other pollutant species (e.g. heavy metals and soluble chloride and sulphate salts); as such, they require specific treatment before disposal. Therefore, before hydrogen from waste can be deployed commercially several barriers must be overcome. Firstly, the technical feasibility of hydrogen production from waste derived feedstock must be demonstrated to show that the concept is credible and sufficiently robust. Secondly, the process must be optimised for commercial deployment, with designs produced, environmental impact understood and costs modelled. Finally, the chosen designs must be deployed at larger scale, with hydrogen supplied to end users. Extensive work is needed to push forward commercial deployment of hydrogen production from waste by systematically working to address each barrier. Most of the work present in the literature focuses on single aspects, and in most cases on biohydrogen processes utilizing pure biomass as a feedstock (Antonini et al. 2021; Barisano et al. 2017) This work aims at addressing at least some of these barriers in a more systematic and unified form. First, main technical challenges and latest developemnts of biohydrogen plants are appraised. Different low carbon hydrogen production routes are then compared from a Life Cycle assessment (LCA) perspective, to understand deployment and integration opportunities in UK over the next 30 years.

The hydrogen production methods selected were electrolysis (on-site, large scale off-site and off-shore), methane reformation (ATR and SMR) with carbon capture and storage (CCS) and waste (MSW and waste wood) gasification with CCS. Fossil fuel, renewable feedstocks and energy sources, were flexed in the analysis, an example being replacing waste with pure biomass or plastics for the biohydrogen with CCS pathway. Upstream GHG emissions associated with electricity, natural gas and biomass production, plus transportation were also included in the study to give the most complete picture.

2. TECHNOLOGICAL ASPECTS

2.1 Feedstock quality

Thermochemical treatment of biomass feedstock, and gasification in particular, are gaining strong traction in Europe giving the numerous opportunities associated to product flexibility and low environmental impact. Recent studies have proven that Bio-H_2 offers the largest potential in terms of GHG removal (Rosa et al 2022; Valente et al., 2019), thanks to the biogenic origin of the carbon in the feedstock. However, Bio-H_2 production should ideally rely on the use of second or third generation biomass as primary feedstock to avoid land use competition with food crops and intensification of deforestation, habitat loss and loss of soil fertility. Municipal Solid Waste (MSW) and waste in general, represent an ideal source because of their large availability and low cost. From a climate change perspective, the use of waste as feedstock not only ensures large and economical availability for consistent hydrogen supply,

but also avoids use of current disposal technologies, which are known to contribute enormously to GHG emissions and water and land pollution (Materazzi & Foscolo, 2019).

Biomass to H_2 plant performances and environmental attributes are obviously strictly dependent on feedstock composition. Generally, the quantity of organic (biomass) content in the feedstock can vary from 40-60% in weight in household waste (see Table 1) to above 90% in waste wood. As such, hydrogen from household or commercial waste is only partially renewable due to the presence of plastics based carbon, and only the energy contribution from the biogenic portion is typically counted towards renewable energy targets (and only this element is eligible for renewable financial incentives). However, to simplify the discussion, we leave the prefix -bio in the hydrogen product from thermochemical plants regardless the percentage of biomass in the feedstock, to distinguish it from other low-carbon hydrogen routes. If the waste is pre-treated to separate out the biogenic fraction, and only this used for hydrogen production, then this can be considered wholly renewable. In fact, waste cannot be thermochemically treated in its original form when collected. The untreated municipal or commercial waste is first mechanically pro-cessed in a material recycling facility (MRF). This is done to homogenise the material and remove part of the moisture, recyclables (e.g., metals and dense plastics) and reject materials (e.g, oversize and inert). Waste treated to give greater than 90% biogenic content is considered to be on a par with biomass for many of the incentive schemes in UK, although as it is still a waste derived fuel, it remains subject to all the environmental controls relating to waste.

The material is then shredded using tearing motion to achieve a rough shred of waste residues, with a homogenous, predetermined particle size between 1 and 50 mm, depending on the gasification reactor requirements. The final feedstock is in the form of floc of refuse derived fuel (RDF), which is then further dried on-site using waste heat from the process. Typically, a 100,000 tonnes MSW feed produces an output of ca. 60,000 to 80,000 tonnes of RDF with a moisture content of 10-17%, 10-20% ash content and 15-25 MJ/kg calorific value (CV) (Materazzi et al., 2019).

A good potential reference WtH$_2$ plant size could treat around 100,000 tonnes per annum of RDF, this being supplied from a reasonably sized town, accounting for residual domestic, commercial and industrial waste arisings. This is also similar in scale to small conventional energy from waste facilities. Bus fleets have been identified as the earliest likely adopters of hydrogen for transport. A typical bus will consume around 5 tonnes per annum of hydrogen. A large depot will operate around 100 buses, i.e. 500 tonnes per annum or 20 GWh. This equates to around 5% of the WtH$_2$ plant scale identified. This suggests that transport applications in the medium term are likely to be serviced by slip streams from larger plants designed to service grid or industrial customer applications.

2.2 Waste gasification development stage

Compared to pure biomass, waste feedstock introduces a greater concentration and diversity of contaminants, due to the high number and variability of sourcing points. This presents a major challenge, compounded by the fact that more sophisticated applications (including catalytic processes for Bio-H$_2$ production and fuel cells for transportations) have very low tolerances.

The state of technology development for biomass or waste gasification for fuels and hydrogen production is generally seen to be in the TRL (Technology Readiness Level) range 7 to 8, however, it is not a clear-cut issue. This has recently reviewed by the Department for Business, Energy & Industrial Strategy (BEIS) in UK (BEIS, 2021). Firstly, most biomass and waste-fuelled gasifiers are fundamentally unsuited to the production of syngas as an intermediate to hydrogen or gas fuel production, principally because they are air-aspirated rather than oxygen blown. Air-aspirated gasifiers entrain large volumes of nitrogen in the syngas – the removal of nitrogen from the product (hydrogen, biomethane etc.) being expensive and difficult to accomplish. It is important to note that much of industrial fatigue with biomass or waste gasification has been with gasifiers of this type. Gasifiers suited to the production of bio-hydrogen will not be air blown – they must be indirectly heated or oxygen/steam blown, and ideally they would operate significantly above ambient pressure. At least one gasification

TABLE 1: Waste feedstock composition analysis.

Waste fractions [wt% as received]	MSW	Waste wood
Paper and cardboard	22.7	0.8
Wood	3.7	93.4
Metals	4.3	1.7
Glass	6.6	-
Textile	2.8	-
WEEE	2.2	-
Plastics	10	0.5
Inert/aggregates/solid	5.3	2.5
Organic fines	35.5	1.1
Miscellaneous	7.1	-
Proximate analysis [wt%, as received]	**RDF**	
Fixed Carbon	8.90	10.75
Volatile matter	64.70	64.24
Ash	11.80	0.41
Moisture	14.60	24.6
Ultimate analysis [wt%, dry ash free (DAF)]	**RDF**	
Fossil Carbon	20.51	0.80
Biogenic Carbon	36.23	50.13
Hydrogen	6.86	5.76
Oxygen	31.78	43.01
Nitrogen	4.1	0.28
Sulphur	0.18	0.01
Chlorine	0.34	0.01
Energy content [MJ/kg DAF]	**RDF**	
Gross calorific value (HHV)	28.99	24.08
Net calorific value (LHV)	27.02	22.73

technology, the HT Winkler, having been deployed successfully in East Germany before unification, would appear to be at or near a TRL of 9. The HT Winkler is in a class of its own in this respect, but the owners of the technology, Gidara Energy, do not offer their technology for third party developers; it is reserved for their own projects. Other steam-oxygen technologies, such as the Thermoselect process, are deemed suitable for hydrogen production from waste, due to the high temperatures involved in the process which are effective towards removing tars and inertifying ashes. The process, now licensed by JFE group, has been demonstrated at sufficiently large scale for power production in gas turbines and for ancillary fuel gas for steel treatment plants (Yamada et al., 2004). However, there is no extant and diversified technology base at TRL 9 that could support the immediate and widespread implementation of thermochemical biohydrogen facilities at this time. At the current time investors in bio-hydrogen projects are faced therefore with procurement of gasification technologies that are at around TRL 7 or 8 for bio-syngas production; from which bio-hydrogen would be manufactured (Hofbauer & Materazzi, 2019). Technologies for production of hydrogen from syngas are well proven and at TRL 9, so the primary technological risk rests with the gasification technology.

Another class of suitable technologies is that of multi-stage conversion processes, which combine bulk gasification in conventional fluidized bed reactors with high temperature reforming steps to deal with tars. This has also the advantages that ashes, naturally abundant in waste feedstock, are collected in a vitrified form, which is classified as inert material.

Examples of these technologies, adopted in semi-commercial plants, are available in Canada and US, where gasification units, such as those licensed by TRI and Enerkem, are being tested at scale for production of clean syngas suitable for catalytic applications, specifically for jet fuel and methanol production. Some of these multi-stage technologies have been tested and demonstrated at pilot or demonstration scale in Europe and UK, but major challenges arise during scale-up (Materazzi & Taylor, 2019). To address this problem, the UK company ABSL embarked some years ago on a programme of developments at Swindon, beginning with a pilot-scale gasifier and plasma reforming technology, and 50kWth Bio synthetic natural gag (SNG) demonstration project. The pilot plant experience has enabled ABSL to continue development of the RDF to BioSNG/BioH$_2$ concept with a semi-commercial (1/10th scale) demonstration plant currently under commissioning in Swindon (Materazzi & Taylor, 2019). Up-scaling to a full commercial capacity (by a factor of 10) would be a reasonable stretch in capacity, subject to learning-by-doing and satisfactory performance with the semi-commercial demonstrator. Similar endeavours have been undertaken by other UK companies, such as Kew Energy, who are testing their pressurised fluidised bed gasifier (7MWt), coupled with a thermal cracker to break down the tars. However, such plants would be a first-of-a-kind facility and as such be seen by potential investors as presenting an enhanced technology risk, in comparison with technologies that had already accrued an operational track record and a TRL of

9. Hence, the demonstration of a semi-commercial facility that can be scaled-up by a reasonable scaling factor (e.g. a multiple of <10x), coupled with demonstration of satisfactory operation, will be a key step in addressing technology risk for waste to hydrogen plants, and several attempts can be observed already in UK and Europe landscapes (BEIS, 2021). Nevertheless the technology risk is enhanced compared to a "proven" technology, and pump-priming measures in the sector need to be such that investors see the enhanced risk as being acceptable; otherwise, it is likely that investment in the sector will not be forthcoming.

2.3 Pre-combustion CO$_2$ capture

Whilst post combustion capture from the flue gas of a biomass power station is not yet a common practice, the technologies used for both power generation and for post combustion capture are mature and each at a state of development where they could be classed as commercially proven. Hence, the technology risks associated with applying BECCS to biomass power generation are low.

Pre-combustion capture refers to removing CO$_2$ from syngas, typically post water gas shift stage in a gasification or pyrolysis plant. The same concept would apply to blue-hydrogen production plant, where syngas is generated grom natural gas, so the technology risks are shared between the two low carbon hydrogen pathways. Compared to post-combustion technology, which removes dilute CO$_2$ (~5-15% CO$_2$ concentration) from flue gas streams and is at low pressure, the shifted synthesis gas stream is rich in CO$_2$ and at ideally higher pressure, which allows for easier removal. Due to the more concentrated CO$_2$ (also due to the lack on N2 in syngas from steam-oxygen gasification), pre-combustion capture typically is more efficient, but the capital costs of the base waste gasification process and gas cleaning sections are often more expensive than traditional fossil-based power plants. Today's commercially available pre-combustion carbon capture technologies generally use physical or chemical adsorption processes, and will cost around $60/tonne to capture CO$_2$ generated by an integrated gasification combined cycle (IGCC) power plant (Balcombe et al., 2018). The goal of biohydrogen's research efforts is to reduce this cost to $30/tonne of CO$_2$. The commercial technologies for pre-combustion CO$_2$ capture available today share a similar process layout consisting of two successive phases of absorption and desorption of CO$_2$. The absorption phase uses a solvent to remove CO$_2$ from the shifted syngas, producing a H$_2$-rich stream. The following phase desorbs CO$_2$ regenerating the solvent that is recirculated to the absorption phase. These technologies differentiate according to the solvent used and the specific operating conditions that it requires. They are characterised as physical (e.g Selexol, Rectisol, etc.) or chemical (e.g. amine, Benfield, etc.) depending on whether the CO$_2$ is simply physically dissolved or is chemically bound to the solvent. A key difference is that chemical absorption requires increasing temperature for desorbing CO$_2$, whilst in physical absorption this can be achieved by solely reducing the pressure (L'Orange Seigo et al., 2014).

The H$_2$-rich stream is often purified via pressure-swing adsorption (PSA) to obtain a H$_2$ stream suitable for gas

grid injection (>98% v/v) or transportation (>99.999% v/v), which is then compressed for storage. The tail gas from the PSA contains primarily CO_2 and H_2, as well as traces of other combustible (e.g. CH_4) and non-combustible (e.g. N_2) substances from syngas and of the solvent. The gas is burnt in a gas engine for generation of electricity and thermal energy. The former can be sold to the electric grid operator, whilst the latter is recovered in the WGS phase. On the other hand, the CO_2-rich stream from the desorption phase is compressed to 60 bar and transported via lorry, sea tankers and finally through pipelines prior to being injected in saline aquifer at 110 bar.

2.4 Alternative low-carbon hydrogen production routes in UK

Low carbon hydrogen in the UK is currently produced by electrolysers on-site at hydrogen refuelling stations; the emissions of which are dominated by the use of grid electricity for the electrolyser. However, by 2030, other production pathways will emerge. In addition to onsite electrolysis, low carbon hydrogen will be produced from natural gas, using either newbuild ATRs fitted with CCS, or by retrofitting old SMRs with CCS. Around 2030 or shortly after, large centralised or offshore electrolysers may emerge, with electrolysers directly connected to offshore wind turbines, and hydrogen transported to the shore by pipeline. At this time, it is likely that several biohydrogen plants with CCS will be operational in UK, and therefore, a comparison of impact of different producing technologies is critical. Figure 1 shows the comparison of different production routes,

defined within specifed boundary conditions, under examination in this work.

3. METHODOLOGY

With the application of LCA according to ISO 14040 and ISO 14044 guidelines, a comparison of different low-carbon hydrogen production routes was undertaken (ISO, 2006a, 2006b). For the construction of this LCA model, primary inventory data for a 50 MW Bio-H_2 plant have been collected from the UK waste gasification company, ABSL. The production of Bio-H_2 from waste is considered a multifunctional process, defined as an activity that fulfils more than one function; in this case, the thermochemical process dealing with waste and energy generation. Following the relevant ISO standards, the environmental benefits from recovered resources should be accounted for by expanding the system boundaries to include the avoided burdens of conventional production (Clift et al., 2000). The environmental burdens of Bio-H_2 production include: the direct burdens allocated to all the operational units and elementary flows considered in the system boundaries; the indirect burdens allocated to the external supply of material and energy processes; and the avoided burdens allocated to the recovery of materials from waste during the RDF preparation stage (e.g. ferrous metals and non-ferrous metals), as well as the production of electricity and hydrogen. A conservative uncertainty analysis on the impact of Bio-H_2 has been carried out to account for application of different technologies and corresponding energy requirements, as well as the variation due to the waste composition which causes a large
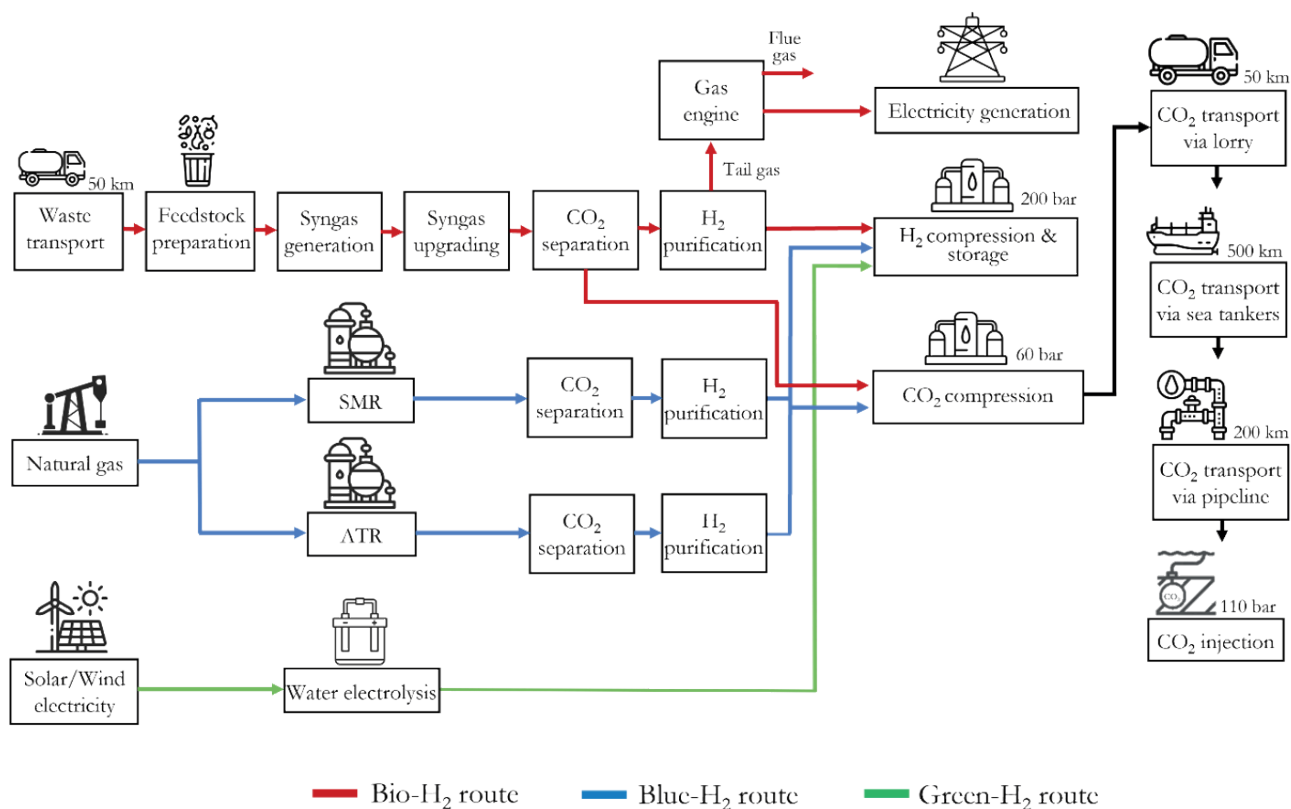

FIGURE 1: Schematic of low-carbon hydrogen production modelled steps.

part of the overall uncertainty (Amaya-Santos et al., 2021). A monoethanolamine (MEA) carbon capture technology was modelled with a 90% carbon capture rate for the Bio-H_2 models. Although MEA is not deemed the best industrial solvent for CCS, due to its low stability and high corrosivity, its choice was dictated by presence of detailed data in the literature and LCA database.

Table 2 reports the key inventory data of the three hydrogen production technologies, summarising the total input and output flows per functional unit (1 MWHHV of transport-grade H_2). The data from Antonini et al., (2020) for steam methane reforming and autothermal reforming coupled with 90% carbon capture using methyl diethanolamine as a solvent was used for comparative analysis. Description of the Green-H_2 inventory dat is presented in (Amaya-Santos et al., 2021).

The provision of external materials and energy to the process and the treatment of end-of-life wastes (Clift et al., 2000) are activities in the background system and are modelled using the cut-off system model, ecoinvent database (version 3.8) (Wernet et al., 2016). Such process include: the chemicals production and supply required as fluidising agents (e.g. oxygen), gas cleaning chemicals and CCS solvent (MEA); the net thermal energy and electricity requirements/generated; the treatment of wastewater effluents. Ecoinvent datasets were also used for CO_2 transportation via lorry and sea tankers. Life cycle impacts were assessed across the categories that represent the highest environmental priorities according to normalisation using the EF 3.0 global reference normalisation and weighting factors (Sala et al., 2019).

## 4. RESULTS AND DISCUSSION

4.1 Climate Change Impact

Different scenarios of the Bio-H_2 production process are presented with regards to climate change impact (CCI). These scenarios showcase the consequences of capturing point carbon emissions via carbon capture and storage (CCS) and of considering (thereby crediting) the biogenic carbon fraction of feedstock. A carbon capture rate of 90% is employed in all cases with CCS. The baseline biogenic fraction of RDF used is ~60% as per Table 1. When accounting for the difference between biogenic and fossil carbon, biogenic carbon emissions to air is considered carbon neutral and thus impacts from CO_2 process emissions of fossil origin are only considered. Corresponding scenarios produce a carbon negative impact when CCS is applied to the system, as carbon is effectively being removed from natural carbon cycle. This translates to the total climate change impact of the Bio-H_2 of -118 CO_2 eq./FU for scenario using RDF (from MSW) as a feedstock, and -293 kg CO_2 eq./FU for scenario using waste wood (WW). Bio-H_2 from WW outperforms MSW due to sequestration of its ~100% biogenic carbon content. The results for wood gasifcation are well corroborated with Antonini et al. (2021) with impacts ranging between -252 to -515 kg CO_2 eq. / MW H_2 albeit for different gasifier technologies modelled herein. The system boundaries of this analysis also include CO_2 transport and storage. Waste wood processing requires more initial feed throughput to generate the equivalent amount of hydrogen compared to MSW. Thus, resulting indirect process emissions are more positive for WW. Counterintuitively, the higher CO_2 production rate for waste wood also results in greater environmental impact savings.

In Figure 2, an additional analysis is presented, in which the avoided emissions associated to the MSW counterfactual are included. If not treated in advanced thermochemical facilities, current waste management practises call for disposal either through incineration or landfill. Incineration with energy recovery (WtE) represents the most common practice around the world and thus is considered as a realistic counterfactual. Similarly, to previous cases, only emissions associated to the fossil carbon fraction of feedstock have been accounted for. Although electricity and materials are recovered from the process, and thus credited on the final GHG output, the incineration option still shows a

TABLE 2: Key inventory data of the three hydrogen production processes. Flow quantity is referred to functional unit (1 MWHHV transport-grade H_2) and 1h as unit of time. *adapted from (Antonini et al., 2020).

Key flows	Units	Biohydrogen (MSW)	Biohydrogen (Waste wood)	Blue Hydrogen *SMR	Blue Hydrogen *ATR	Green Hydrogen
Input						
Feedstock type		MSW/RDF	Waste wood	Natural gas		Water
Feedstock	kg	442.2/283.6	372.2			226.8
	m³			116.4	117.6	
Oxygen	kg	89.4	101			n.a.
Electricity	MJ	514	617	27.7	115.7	4974
Thermal energy	MJ	1550	1657	-	-	n.a.
Output						
Hydrogen [MJ]	MJ	3600	3600	3600		3600
Materials recovered [kg]	Kg	17.1	-	-	-	-
CO_2 released [kg]	kg	46.5	53.5	120.63	38.1	0
Sequestered CO_2 [kg]	kg	414.4	484.1			n.a.
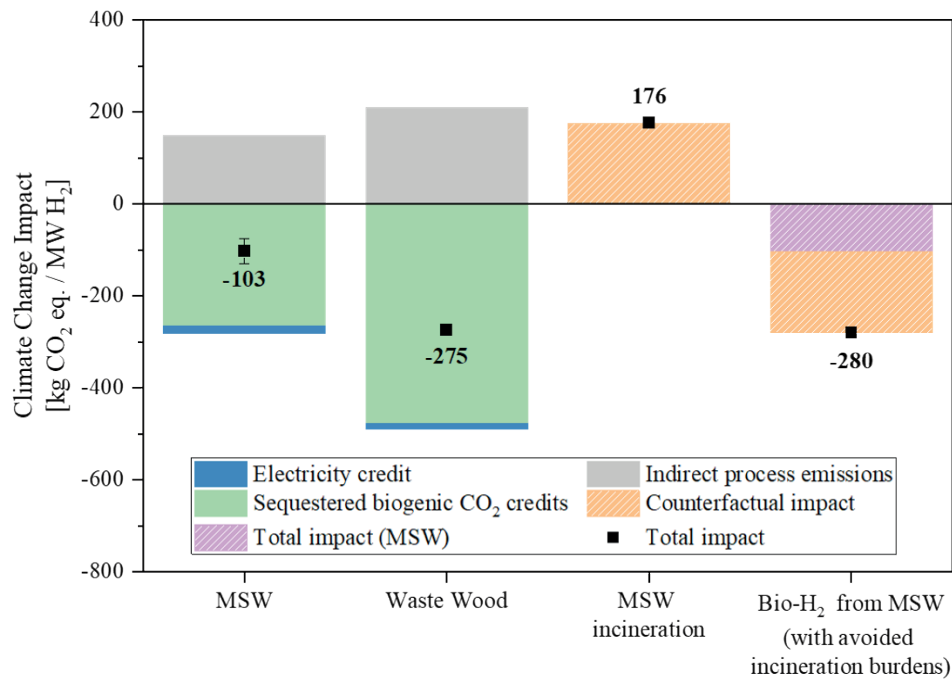
FIGURE 2: Climate change impact (CO_2 eq. per FU) regarding carbon capture and storage and considering the biogenic fraction of the CO_2 stream. Uncertainties calculated based on technical variations in energy usage and feedstock composition.

substantial climate change contribution of 176 kg CO_2 eq. for the equivalent amount of MSW to produce 1 MWHHV H_2. Therefore, by diverting waste from being incinerated, the benefit of Bio-H_2 on climate change can be further pronounced, with a negative contribution to climate change of -280 kg CO_2 eq. per MWHHV of H_2 produced. Even higher benefits could be observed if considering other waste management practises, such as landfill or incineration with no energy recovery, as a counterfactual.

4.2 Comparative analysis between Bio-H_2, Blue-H_2 and Green-H_2

4.2.1 Climate change impact

In the present analysis, the environmental performance of the Bio-H_2 technology is compared to other two competitive low-carbon technologies, Blue- and Green-H_2, considering the Climate Change (kg CO_2 eq.) impact only. The results are expressed per functional unit, 1 MWHHV of transport grade hydrogen produced from all examined processes. The comparison of the environmental performance of the three routes has been performed taking into account the environmental burdens allocated solely to the production of hydrogen i.e. excluding system expansion methodology. In this analysis, CO_2 transportation and storage have not been included across technologies for consistency. The contributions to climate change of the technologies are depicted in Figure 3. Bio-H_2 production shows the lowest contribution to climate change, equating to -293 kg CO_2 eq for waste wood and -118 kg CO_2 eq/FU for MSW. These results show that the production of hydrogen from MSW or waste wood together with the sequestration of carbon, is not only an effective solution to waste disposal, but it is also appropriate to achieve the objectives proposed by the Net Zero

2050; its implementation involves the removal of a fifth to a third ton of CO_2 per MWHHV of H_2 produced every hour.

Blue-H_2 produced via steam methane reforming process (SMR) with CCS process (carbon capture rate of 90%, with MDEA CO_2 adsorption) produces 143 kg CO_2 eq. per MWHHV H_2 as modelled by Antonini et al. (2020). The use of alkanolamines, MEA and MDEA, are widely used solvents in amine-based capture technologies. This study assumes a similar impact from MEA and MDEA for comparison, although it has been shown that for certain applications MDEA may fare better energetically. Approximately 32% of the impact derives from the embodied carbon of natural gas feedstock, rendering the process sensitive to changes in natural gas source (Antonini et al., 2020). According to the authors, 66% percent of impact derives from direct CO_2 emissions. The upstream emissions are associated to its processing and, for imported NG, to its liquefaction and shipping. The remaining climate change impact is ascribed to the electricity required during the steam reforming and carbon capture process, CO_2 liquefaction and H_2 compression. The difference between SMR and ATR in favour of ATR is related to the higher CO_2 fraction in the syngas generated by the latter, and therefore, more efficient carbon capture. A competitive Green-H_2 route of production is limited by the high electricity demand of the electrolyser. Amaya-Santos et al. (2021) reports a large environmental burden when electrolysis is conducted using the current electricity grid mix. By using low-carbon intensity grid supplied by renewable sources, this limitation can be overcome. In a similar vein, any processes with a high electricity input will benefit from future decarbonisation of the grid. As shown in Figure 3, the electricity demand of the electrolyser and H_2 compression unit met by electricity produced 100% from solar and 100% from offshore wind contribute 99 kg CO_2 eq. per
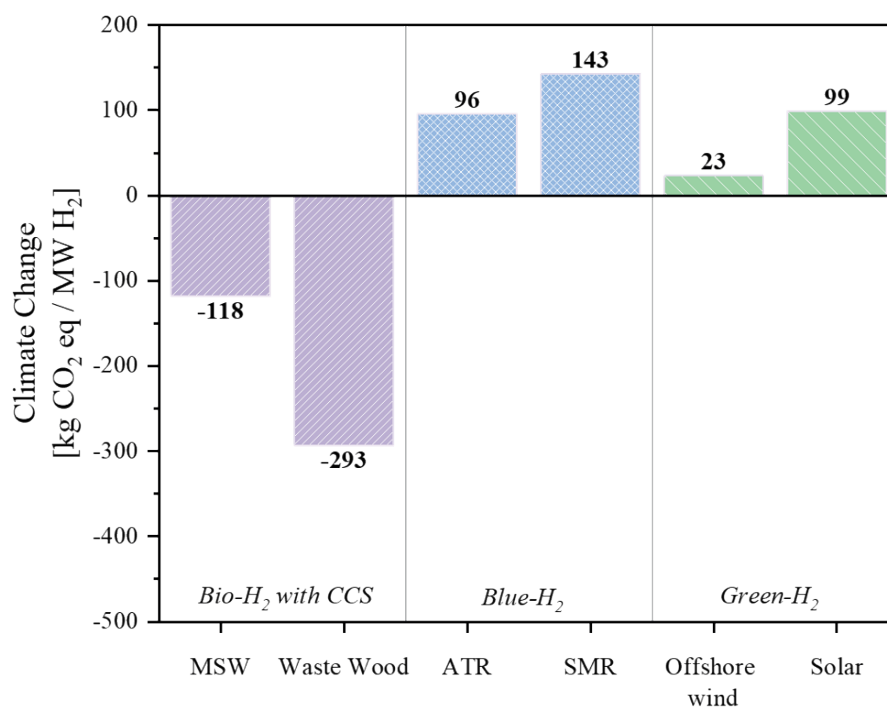
FIGURE 3: Climate Change contribution comparison of Bio-H_2, Blue-H_2 and Green-H_2 production technologies.

MWHHV H_2, and 23 kg CO_2 eq. per MWHHV H_2, respectively. The greater impact from solar compared to offshore wind is attributed to the manufacturing of silicon solar cells.

4.2.2 Environmental impact of other categories

The impacts for all other categories are normalized to the absolute maximum value in each category thereby depicting a ranking of environmental performances between technologies, shown in Figure 4. For assessing carbon neutral or negative technologies, it becomes imperative to understand the trade-offs that come with, in the case of Blue- and Bio-H_2, the implementation of CCS.

Between the gasification of MSW and waste wood, waste wood tends to perform worse on all impacts categories owing primarily to differences in feedstock throughputs. MSW produces more hydrogen per input of waste feedstock than biomass owing to its higher hydrogen content and lower oxygen content than biomass (see proximate analysis, Table 1). Therefore, with overall improved energy efficiency and feedstock conversion efficiency, MSW may serve as a preferential technology that is carbon-negative while also reducing the trade-off across other categories. The higher net electricity consumption of Bio-H_2 (143 kWh/MW H_2 for MSW and 171 kWh/MW H_2 for WW) compared to Blue-H_2 reported by Antonini et al. (2020) (18 and 53 kWh/MW H_2 for SMR and ATR respectively) plays a part in Bio-H_2 faring worse in Acidification, Ecotoxicity, Eutrophication (marine & terrestrial), Ionizing radiation and Photochemical Ozone Formation. While, Resource – Use (fossil) and Ozone Depletion are led by Blue – H_2. Eutrophication (freshwater) is led by Green-H_2 from offshore wind and Human Toxicity, Land Use and Particulate Matter are led by Green-H_2 from solar.

4.3 Interaction between low carbon hydrogen production pathways

It will be extremely challenging for any one of the low carbon hydrogen technologies to meet alone the expected level of hydrogen demand set out by Net Zero ambition. It seems likely that all options will play a role in the transition to hydrogen. Green hydrogen has the potential to be produced sustainably in large volumes. However, it will take time for low carbon electricity generation to grow to the scale that meets current electricity demand, plus the additional demand required to decarbonise heat and transport with hydrogen. In addition, electrolyser technology requires several years to develop to the point that it can produce hydrogen at costs that compete with blue hydrogen. Blue hydrogen can be produced at large scale in a few years' time at relatively low cost. However, it is a less sustainable solution in the long term and cannot match the carbon savings achieved by green hydrogen and biohydrogen. Biohydrogen has the potential to generate negative carbon emissions if combined with carbon capture and storage. However, overall production of biohydrogen is limited by the availability of sustainable feedstock. It cannot be produced in sufficient volumes to meet the overall expected demand.

There are important synergies between different low carbon hydrogen production pathways. For example, blue hydrogen might establish the hydrogen market that green hydrogen will meet in future or build the carbon sequestration network required for biohydrogen to deliver negative emissions. These negative emissions can offset the residual emissions from blue and green hydrogen production. Green hydrogen might supply hydrogen to consumers that are remote from the blue hydrogen production centres. The different hydrogen production options all have different
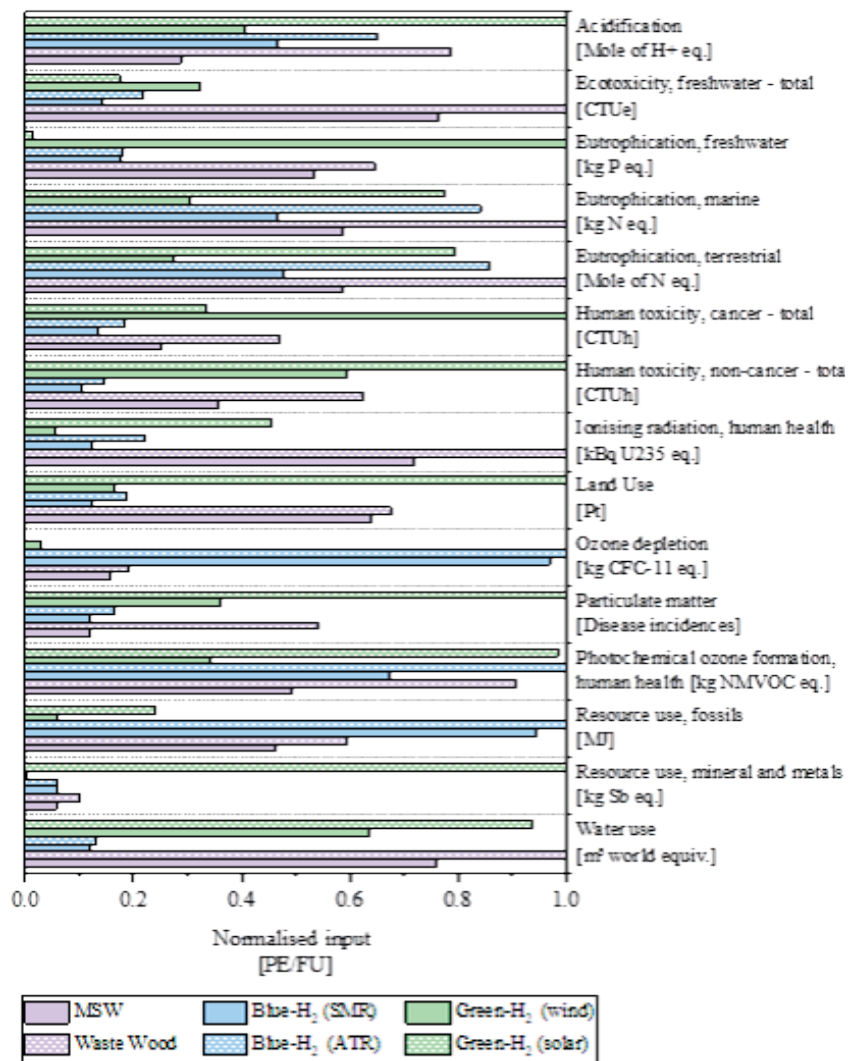
FIGURE 4: Life cycle performance of all other impact categories normalized. Absolute impact numbers are normalised to 1 to the technology with the highest impact in each category.

infrastructure requirements, with blue and bio hydrogen reliant on CCS infrastructure. The large-scale ATR plants required for blue hydrogen production also suits the large industrial clusters, where infrastructure, such as a supply of natural gas and potentially by-product oxygen are available. The industrial clusters across the UK would therefore suit blue hydrogen production, with the locations along the East coast and North West England developing plans for carbon dioxide pipelines for offshore carbon dioxide storage (see Figure 5). The industrial clusters in South Wales and Southampton would require shipping carbon dioxide to offshore storage sites. Green hydrogen production can be developed at smaller scale than blue hydrogen and although green hydrogen does not require CCS infrastructure, there are benefits to installing electrolysers alongside renewables or close to hydrogen demands / hydrogen infrastructure. The map of industrial clusters in Figure 3 also highlights regions where there are large energy demands from industrial processes, which could become early adopters of hydrogen. At a smaller scale, where hydrogen can be transported via road tankers to serve transport demands,

green hydrogen production plants could be located where renewables are best-sited (to access lowest cost power). In the medium term, larger green hydrogen production plants will be developed either in locations close to very large renewable assets (e.g. in coastal locations where offshore wind farm electricity is landed) or in locations closer to large-scale users, such as industrial clusters, to avoid long range hydrogen transport before wider conversion of the gas network becomes available to transport 100% hydrogen. A 100% hydrogen gas network would open up more options for green hydrogen production sites, including the production of hydrogen offshore, connected to offshore wind farms. At a certain scale, the cost of transporting energy in a gaseous form (as hydrogen) can be lower than the costs of transporting energy via electricity. There would be further cost benefits for hydrogen transport if oil and gas pipelines could be repurposed for hydrogen transport. However, an environmental consideration to H_2 transportation means and distances in the ongoing research on the impact of fugitive hydrogen emissions on the greenhouse gas effect (BEIS, 2022). Biohydrogen would require CCS
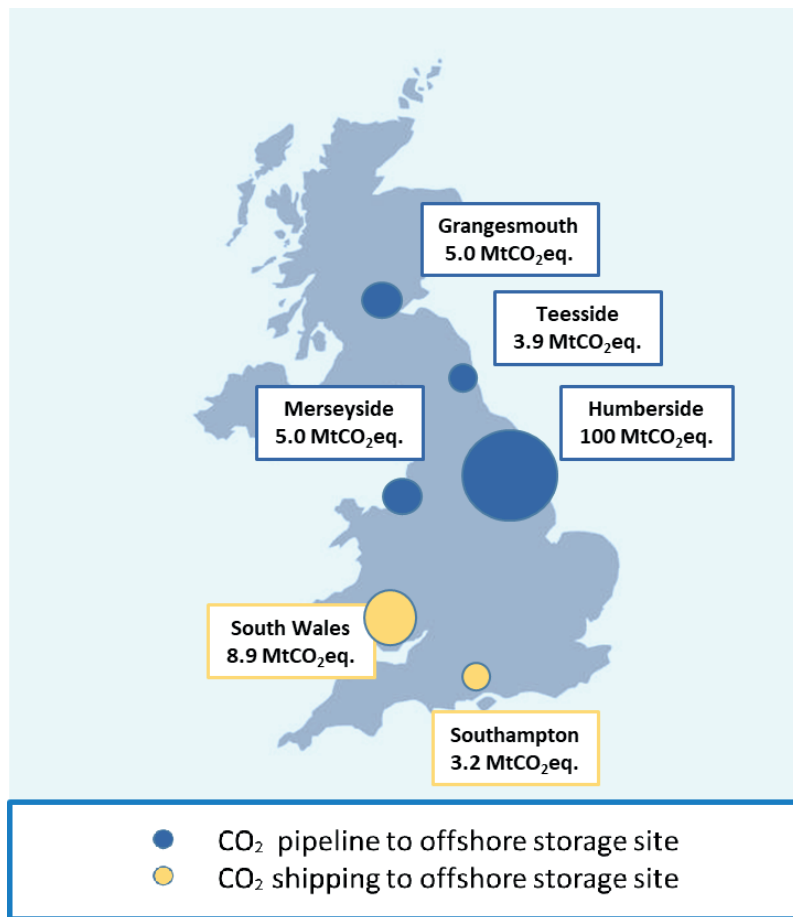
FIGURE 5: Location of industrial clusters in the UK and annual GHG emissions from each (Adapted from BEIS, 2021).

infrastructure to deliver very high GHG savings and therefore is suited to the industrial clusters shown in Figure 4. The use of biohydrogen without CCS can still provide GHG emission savings relative to incumbent fuels and converts waste streams into a valuable product, with hydrogen a higher value output than electricity from energy from waste plants. There could therefore be a degree of flexibility with regard to siting some of the plants at locations without CCS infrastructure across the UK, although the full benefits of the technology would require siting around the industrial clusters, or locations with carbon dioxide demand. Biohydrogen technology can also be deployed at far smaller scales than blue hydrogen, allowing it to offer a more distributed approach to hydrogen production.

5. CONCLUSIONS

There is a significant scale-up challenge for low-carbon hydrogen production if the UK is to meet its Net Zero target by 2050. Given the significant demands for low carbon hydrogen it is clear that all of the three low-carbon production routes are needed and that these need to be developed at pace. The build out rates for all the options presented above will be challenging to meet, and support to develop low carbon hydrogen markets will be needed to encourage investment in delivering the scale-up of the hydrogen production capacity. This work showed that Bio-H$_2$ can be a competi-

tive technology to aid the near- and medium-term transition to hydrogen economy, as well as a long-term complement to other low carbon hydrogen alternatives. Not only it is an effective solution to waste disposal, but it is also appropriate to achieve the objectives proposed by the Net-Zero 2050 for it being a viable carbon-negative technology.

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