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...a world beyond fossil fuels

KEW H_2: ZERO-CARBON BULK SUPPLY

Part of:

BEIS Hydrogen Supply Competition

Phase One Report: Feasibility Study

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IN COLLABORATION WITH:

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Executive Summary

Hydrogen Markets & Supply Pathways

Hydrogen can be used as a flexible, storable energy vector which emits no CO_2 at the point of use and thus offers a key tool in the challenge of rapid global decarbonisation. Demand for hydrogen in the European Union (EU) is projected to increase sevenfold from 325 TWh in 2015 to 2250 TWh by 2050[1], through substantially increased demand for hydrogen in the energy, transportation and industry sectors. Existing demand is predominately from industrial applications (mainly ammonia and fuel refining)[2] with potential for growth in line with de-carbonisation through use of hydrogen for heating applications and as a reductant in steel production. The upper demand forecasts account a substantial application of hydrogen as an energy vector where it is injected into gas grids and used in fuel cells for transportation and energy storage. The pace and reach of this latter demand growth is uncertain as it is influenced by many factors.

Hydrogen, unlike electricity, cannot be considered as one uniform standardised commodity. Purity requirements vary significantly from as low as c. 60%-80% for some industrial applications, to at least 99.7%[3] and higher for some fuel cells, with 99.999% as the high-purity standard. The presence of contaminants, such as sulphur which shortens the effective life of many catalysts, is often more critical than the presence of inert compounds like H_2O, CO_2 which reduce the energetic content. Thus, the term 'purity' hides a multitude of issues. Hydrogen specification is important in that for many processes (excepting electrolysis) for producing hydrogen, the purity significantly affects the cost. The real requirements of the application should be considered in order to derive the specification that optimises all aspects of the supply and consumption chain.

The majority of current hydrogen supply is produced through the reforming of natural gas using steam methane reformers (SMR) and this is forecast to grow with ambitious projects such as Hynet. The use of electricity to electrolyse water is also proposed as a future bulk supply route. Both approaches can be 'low-carbon' through the application of carbon capture with SMRs, and the use of unique renewable sources for electrolysis.

This document discusses an alternative and complimentary opportunity: the production of hydrogen through gasification and purification by making use of energy contained in residual waste and biomass. Residual waste, as well as having considerable detrimental impacts in its disposal, contains valuable energy much of which is not recovered (through incumbent approaches of landfill or incineration). The use of biomass (including biomass waste) enables the opportunity for very low-carbon energy supply; it is critical though that the maximum useful energy is recovered from this valuable source, such as through the conversion to hydrogen.

KEW Hydrogen Production Technology

KEW has developed advanced gasification technology which converts a wide-range of feedstocks into a clean hydrogen-rich syngas which can be further purified to supply bulk hydrogen. This technology is incorporated in KEW's first of a kind demonstration plant at the Sustainable Energy Centre (SEC) in Wednesbury, which initially will consume the syngas in a high-efficiency engine to produce electricity. KEW's technology is particularly suitable for future supply of Hydrogen due to the following factors:

- KEW's system has been shown in tests to produce a fully-cracked syngas with virtually no hydro-carbons and a consistent hydrogen composition. This facilitates the downstream purification to produce the hydrogen product as tars which could precipitate causing fouling, and methane whose energy content would be wasted, are not present.

- KEW's testing has demonstrated that a wide-range of feedstock's can be used, including residual waste from municipal, commercial & industrial sources, and biomass including dry agricultural wastes, thanks to the system's proprietary reformer, known as the Equilibrium Approach Reactor (EAR)
- The plant uniquely operates at elevated pressure (7barg); and thus is more compact than other atmospheric systems,
- The compact design means that future projects will utilise factory-built modules; which significantly reduces project costs and risks.
- Plants can be constructed adjacent to prime Hydrogen consumers many of whom will also require heat. Waste heat from the plant can thus be usefully used increasing the overall system efficiency.

During the BEIS Phase 1 'Hydrogen Supply' project, KEW developed preliminary design and costings for a Hydrogen Production Module (HPM) which can be located alongside a KEW Advanced Thermal Conversion (ATC) gasification plant to provide 81 MWh of hydrogen per day (3 tonne / 28Nm^3) with a purity of 98%. The system will be electrically self-sufficient as c. 25% of the Syngas is consumed in an engine to power the whole facility. Accounting for this, KEW's models forecast the overall efficiency (energetic content of Hydrogen product divided by energy in feedstock) of first-generation systems consuming residual waste at 49.7%. The provision of waste heat to on-site users would increase the overall energy recovery.

KEW Modular Plants

KEW's vision is to deliver decentralised low-carbon energy solutions in modular units that can be rapidly deployed in embedded applications. This approach mitigates process risk – as each new project is a deployment of a proven modular unit and construction risk and cost as minimal site works are required. Economies of scale are derived from lean manufacture of multiple units as opposed to construction of very large plants. Modules can be integrated into industrial and other sites providing waste heat as well as hydrogen, and growth can be accommodated with the addition of more modules. The module capacity fits well with many on-site industrial applications where typically one to three ('triple module') modules could be deployed.

The core ATC gasification and HPM modules remain the same whatever the application, producing hydrogen at 95-98% purity which meets the requirement of initial industrial clients which KEW has consulted. However, the addition of a further purification step can be easily added to increase purity to 99.7% or higher if required.

In the future, KEW will also develop 'big-brother' plants operating at higher pressure with 10 times the throughput (c. 1,300 Kg per hour) for applications such as ammonia production where the existing facilities are of that scale. These units would still come with the benefits of a factory-build approach and production volume would also derive from other markets such as sustainable fuels supply.

Lifecycle Cost

Table 1 below shows that the costs of production of hydrogen compare favourably to the reference large-scale SMR; even without accounting for the added benefits of embedded supply, and facilitated project financing due to lower overall CAPEX.

Table 1: Comparison of LCOF of KEW's hydrogen supply (98% purity) vs traditional large scale SMR

		SMR ref (446MWt) Proposed 99.99% purity target [4]		**KEW Triple Module Plant (21MWt) 98% Purity**		**KEW High-Pressure Plant (70MWt) 98% Purity**	
Carbon Capture (CC)		**No CC**	**CC 90%**	**CC 80%**			
Energy source		**Natural Gas**		**Biomass**	**RDF**	**Biomass**	**RDF**
CAPEX	£K	144,000	237,000	29,385	29,385	73,463	73,463
H_2 production	Kg/hr	9,000	9,000	133	126	133	126
LCOH - with carbon tax	p/kWh	**6.5**	**5.5**	**6.3**	**4.4**	**4.9**	**3.0**
LCOH - no carbon tax	p/kWh	4.0	5.3	8.5	3.6	7.1	2.2

In the United Kingdom (UK) and most developed countries, there is currently a high 'gate-fee' payment to consumers of residual waste (or residual derived fuel (RDF)), and thus KEW's initial projects will consume RDF. In the future, as the supply chain for biomass (and notably waste biomass) develops, KEW would envisage commercially viable projects consuming a mixture of feedstock's and later only biomass. Carbon taxes would provide strong commercial driver for shifting to biomass and increasing carbon capture.

Zero-Carbon Supply

The efficient conversion of residual waste and biomass into clean energy products provides a valuable contribution to decarbonisation, especially when combined with carbon capture. Modelling conducted during Phase 1 shows that hydrogen produced from residual waste, taking into account the diversion of that waste from incineration, has a lower carbon intensity than hydrogen produced from natural gas in an SMR.

For RDF, zero-carbon hydrogen supply can be achieved by the capturing approximately 38% of the CO_2 emitted from the plant (achieving a similar carbon intensity to large scale SMRs with 90% capture). For biomass, zero carbon can be achieved with approximately 16% CO_2 capture. For both feedstocks, negative-carbon hydrogen can be produced when these respective CO_2 capture rates are increased. This is shown in Figure 1 below. KEW has noted that 80% carbon capture (CC) is realistically the top-end rate of capture when considering a best plant performance scenario when all financial drivers and incentives are in place.

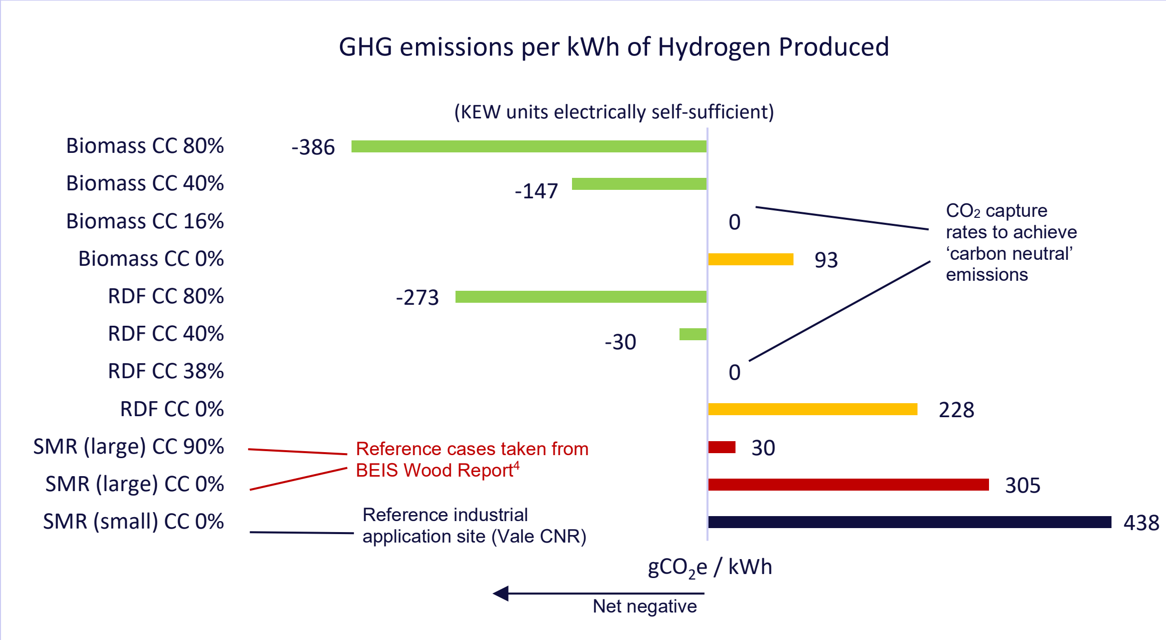

Figure 1. Carbon footprint (CO_2 intensity) of KEW plants for hydrogen production. Biomass and RDF have been compared against large and small SMRs, with CC rates 0%, 40% and 80%. CCS rates needed for achieving neutral emissions have been included also; 16% for biomass and 38% for RDF.

This 'BECCS' vision (Bioenergy with Carbon Capture and Storage) has been noted as forming an invaluable part of a future 'net-zero' energy mix, by offsetting carbon emissions from other sectors which cannot commercially or technically achieve zero emissions.

Carbon capture and utilisation (CCU) technologies are more appropriate for KEW's initial markets than carbon capture and storage (CCS) being distributed at industrial sites. These technologies were explored during phase 1 and will be further evaluated and tested during the proposed Phase 2 project.

Phase 2 Project – Launch pad for Exploitation

KEW's proposed Phase 2 Project is to design and build a Hydrogen Production Module (HPM) which will be initially tested at SEC, thus taking advantage of the facility already in operation and providing excellent value for the funding. The hydrogen module will be designed to be a high-fidelity containerised package that can be rolled out as standardised units.

Following the demonstration at SEC, the intention is to ship the unit to an industrial client. KEW have been working with Clydach Nickel Refinery (Vale Europe Ltd) (Vale CNR) in South Wales, for over a year and developed advanced stage plans for the integration of KEW modules onto the site with the eventual aim of decarbonising the energy and hydrogen supply by replacing fossil fuel consumption with residual waste and biomass. The benefits of utilising waste heat and providing a range of energy vectors (in this case carbon monoxide too) are compelling for embedded applications.

The long-term demonstration of the hydrogen supply solution at an industrial client will provide an invaluable reference and sound launch pad for deployment to further industrial clients, in the South Wales industrial cluster and beyond. This is thus in step with the Industrial Cluster Mission for a low-carbon cluster by 2030 and net-zero by 2040[5].

Contents

1 Hydrogen Markets

KEW conducted a market analysis of the hydrogen production and use with the support of its project partner, the University of Birmingham (UoB). KEW have also benefited from contributions from CR+ who, as sub-contractor on the Phase 1 Project, provided insights from industry in the South Wales industrial cluster and other regions, with support from professor Jon Maddy of the University of South Wales.

1.1 Current Hydrogen Market

Industrial use of hydrogen is currently one of the largest established commercially active market. Of the established industrial uses, over 50 % of hydrogen is consumed during ammonia formation for agriculture. A further 10 % is used in the production of methanol and the additional 10 % for other applications[2]. This is shown in Figure 2. Ammonia demand for hydrogen is 31 MtH_2/yr. and methanol at 12 MtH_2/yr[6]. Currently 65% of the hydrogen demand for ammonia and methanol production is met by natural gas, followed by 30% by coal-based production. A conventional ammonia production plant has the capacity to consume between 57,500 and 115,000 tonnes of H_2 a year[7]. Around 25% is used in fossil fuel refining processes. In the refining process, high purity hydrogen is used to crack heavier hydrocarbons from crude oil as well as increase the hydrogen ratio of the fuel. It is important to note that more than 60% of the hydrogen used in refineries is produced using natural gas, according to recent a International Energy Agency (IEA) report[8]. The same report suggests, about 38 MtH_2/yr., or 33% of the total global demand for hydrogen is used by refineries as feedstock, reagent and energy source. Around two-thirds of this hydrogen is produced in dedicated facilities at refineries or acquired from suppliers (together called "on-purpose" supply). Hydrogen production is responsible for around 20% of total refinery CO_2 emissions, and produces around 230 $MtCO_2$/yr. In terms of capacity outlook, current global refining capacity is high enough to meet rising refinery demand, which implies that the majority of future hydrogen demand is likely to arise from existing facilities already equipped with hydrogen production units.

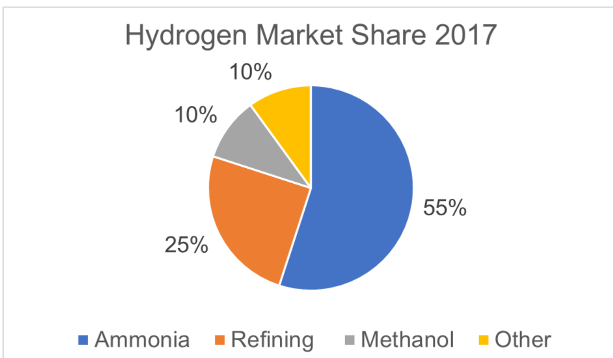

Figure 2: Uses for hydrogen by market share, in 2017[2].

Currently, the use of hydrogen for mobility is negligible with only 6500 Fuel Cell Electric Vehicles (FCEVs) on the roads globally[8] while only 10 % of the world's FCEVs are based in Europe[9]. Despite the low number of FCEV, a noticeable growth in deployment is observed in recent years propelled by more countries entering the list of FCEV users, see Figure 3 below[6][8].

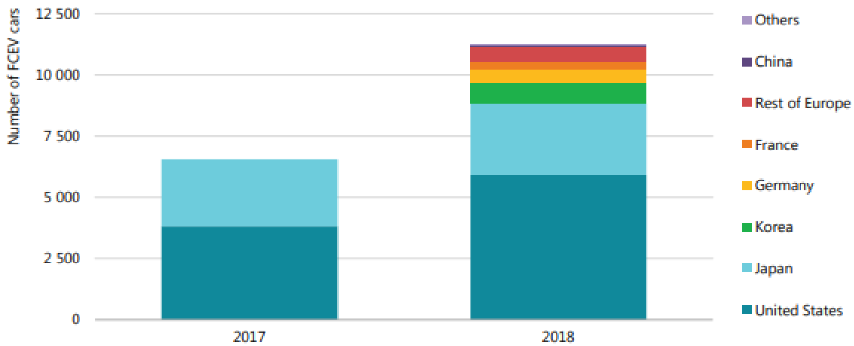

Figure 3: Fuel cell electric cars in operation. There is some growth in recent years, however the impact is practically negligible. Further advancement in technology and infrastructure is needed to progress this market[6][8].

1.2 Future Hydrogen Markets

Since hydrogen is an energy carrier it has applications in the future for both energy and non-energy-based applications. Aside from industrial markets, there are two other main markets for the future of hydrogen; hydrogen for mobility (transport) and hydrogen gas grids (energy storage and distribution for both power and heating). A summary of the future hydrogen market structure is given in Figure 4.

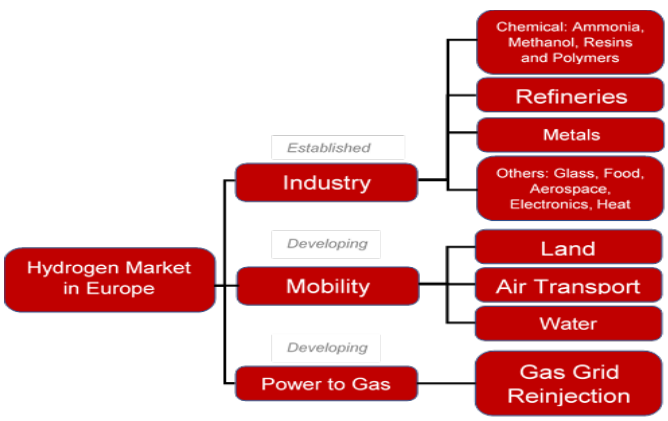

Figure 4: Developing hydrogen markets in the EU include power-to-gas and mobility (transport), whilst industry use is clearly well established

1.2.1 Industrial Markets

In total, the demand for hydrogen is forecasted to increase sevenfold within the EU from 325 TWh in 2015 up to 2250 TWh in 2050[1]. This increased demand for hydrogen will stem mainly from energy and transportation with further growth from industrial uses. Even with the “business as usual” strategy for hydrogen demand it still more than doubles to 780 TWh in 2050[7]. According to the analyses and predictions described in the IEA report, hydrogen demand in oil refineries will increase by 7% under existing policies[6]. However, in a scenario realised by the Paris Agreement, the hydrogen demand is expected to decline slightly by 2030, mainly due to the general reduction in oil demand projected by tightened product quality standards, efficiency boosts and electrification. As a summary, the report depicts the future hydrogen demand in this sector in both scenarios in Figure 5.

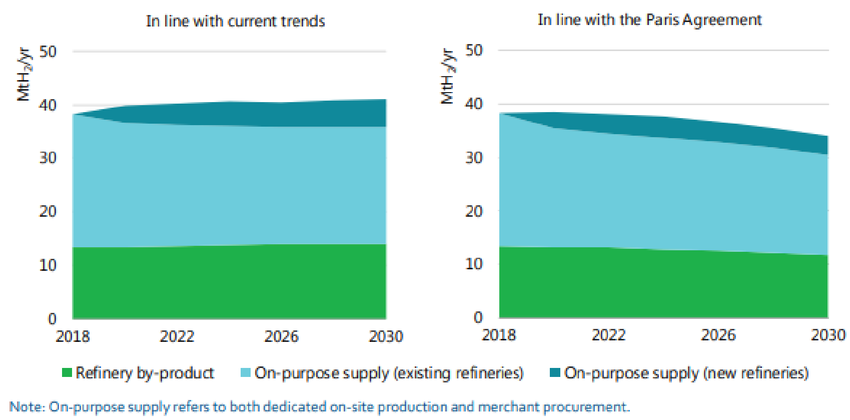

Figure 5: Future hydrogen market in oil refining; comparing two different scenarios[6]. The reduction in demand in the latter scenario (Paris Agreement) is due to reductions in oil demand as plats to curb carbon emissions are executed.

According to IEA analysis, hydrogen demand for primary chemical production will increase from 44 Mt/yr. today to 57 Mt/yr. by 2030, in correlation with the growing demand for ammonia and methanol[6][10][11]. Use of ammonia is expected to increase both as fertiliser and for other applications (plastics and explosives). In the case of methanol, two growing applications are predicted alongside the current industrial uses (fuel additive and thermoset plastics): methanol-to-olefins and methanol-to-aromatics. The predictions are illustrated in Figure 6:

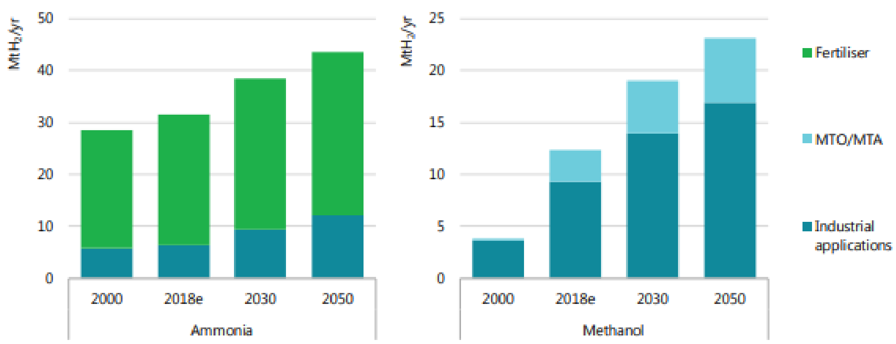

Figure 6: Hydrogen demand for primary chemical production for existing applications under current trends[6] 10 11

1.2.2 Hydrogen Grid Networks

There is a growing demand within Europe for the injection of gas into the gas grid. The final consumption of gas from the grid in Europe was 4454 TWh in 2016[12]. In addition to the large consumption of natural gas within Europe the natural gas grids offer large storage capacities. This allows for decoupling of gas production and gas consumption. These gas grids are in most cases composed of a transmission grid which is connected to storage facilities, supply points, distribution grids and some large gas consumers[13]. A power to gas plant can connect to either the distribution or transmission grid to inject hydrogen into the gas network. It would be preferable to inject the hydrogen into the distribution grid since the necessary pressure for injection is only 5 to 10 bar compared to the 40 to 60 bar for the transmission grid. There is also a limit to the amount of hydrogen that can be injected into the gas network. In Europe, this is up to 10% by volume but there is ongoing work to further develop this[14]. In the UK, the Gas Safety (Management) Regulations currently only permit 0.1% hydrogen in the grid network[15], despite this however, the UK Health and Safety Executive (HSE) granted exemption to the HyDeploy project in 2018 to blend up to 20% hydrogen with normal gas supply at Keele University[16].

Further work is however required regarding the end usage of hydrogen added to natural gas since compressed natural gas (CNG) vehicles and gas turbines are currently designed for feed gases featuring no more than 2% to 3% hydrogen[17]. Due to these reasons, the development hydrogen grids requires further work on current natural gas grids in order to manage the amount of hydrogen in the pipeline. Correct locating of plants that account for the limits in terms of flow rate while also accounting for types of consumer must be considered. Additionally, the injected volumes of hydrogen must be carefully monitored for safety reasons and compliance with any specifications of hydrogen content. Hydrogen can also be used to form methane (natural gas) through methanation. Natural gas and biomethane is already injected into European gas grids. The price of natural gas varies while biomethane benefits from tariffs or premiums. If no support mechanisms are implemented for power to gas processes, then wholesale gas prices will dictate the price of hydrogen or syngas produced by said power to gas plants[13].

1.2.3 Hydrogen for Transport

An additional future market for hydrogen usage is for transport and mobility. As discussed above, the number of FCEVs powered by hydrogen has been very low. However, hydrogen fuelled transport is still seen as part of the future in a hydrogen economy. At present, hydrogen mobility cannot rely on existing pipelines or infrastructure. It is likely though that in the future refuelling stations featuring hydrogen production through electrolysis, hydrogen compression and storage and refuelling infrastructure will be developed[13]. This represents a market for power to gas production of hydrogen. Although FCEVs and hydrogen refuelling stations are proven technically, their commercial adoption requires further investment. IEA report highlights the large potential of hydrogen deployment in future road transport. This estimation is based on the use of hydrogen both in FCEV and as energy carrier “fuel” in internal combustion engines. As a quantitative indication of the potential, if all the 1 billion cars, 190 million trucks and 25 million buses currently on the road globally were replaced by hydrogen powered vehicles, hydrogen demand would be as high as 300 Mt hydrogen per year, more than four times the current global demand for pure hydrogen[6].

Parallel to road transport, rail and maritime sectors have substantial potential for hydrogen utilisation. The Porterbrook and the University of Birmingham’s Centre for Railway Research and Education have developed UK’s first hydrogen train “HydroFLEX” following a successful proof-of-concept. Fuel Cell trains offer the potential for conversion from Diesel power to emissions-free transport (particularly important in inner-cities) without the often-insurmountable barrier of electrifying railway lines. A small number of Hydrogen fuelling stations would be needed to replace current diesel fuelling depots.

Although, ships do not use ammonia as fuel today, the current energy value of global ammonia trade is equivalent 3.5 Mt hydrogen per year. Several research and demonstration projects are looking at the firing of ammonia as fuel for ships. Aviation is also considered as potential hydrogen markets in future applications[6].

1.3 Hydrogen Purity Requirements

For industrial uses such as hydrocarbon refining, ammonia production or methanol, hydrogen purities of approximately 95% are the needed. Depending on the application, the sulphur content should be limited to avoid catalyst degradation in downstream conversion processes. This to preserve the catalyst and limit degradation of performance[18].

Hydrogen used for the application of combustion in gas turbines does not require a very high purity as long as the energy density limits are maintained (Wobbe Index). The hydrogen for this application will be diluted in nitrogen or steam such that the combustion temperature is limited to reduce NO_x emissions.

Wide scale hydrogen grid networks are yet to be developed, and there is a wide range of suggested purities that would be required to satisfy market demands. The H21[19] report identifies various purities for the proposed hydrogen grid networks in Leeds, with a minimum of 99.5% hydrogen. However, IGEM and DNV GL are reviewing standards for hydrogen purity as part of the current UK Government Hy4Heat project. Final report and recommendations are pending, but they propose a draft standard hydrogen purity of 98%, indicating *"This value is a good compromise between hydrogen cost and effects on boiler"[20].*

Hydrogen for fuel cells require very pure hydrogen compositions of no less than 99.7 %. This is in line with ISO 14687-2:2012 standard, and it is necessary to preserve the catalyst and limit degradation of performance of the fuel cell[3].

1.4 Hydrogen Supply Pathways Comparison

SMR is at present the most economically viable process for producing hydrogen. This is followed by coal gasification (CG) and other hydrogen production methods based on the use of fossil fuels. The main reasons these appear to be the most economical is since these are already well-established techniques that are mature and infrastructure for these processes already exist. However, the problems associated with the use of fossil fuels as both a feedstock and an energy source are key limitations in terms of both depletions of non-renewable resources and CO_2 emissions. In addition to this, the use of both fossil fuels for energy and feedstock makes these processes heavily dependent upon their prices. Because of this, research has been leading towards alternate renewable methods[21].

Biomass gasification is an attractive method to produce hydrogen since it is an abundant feedstock that is readily available and renewable. Methods using biomass produce low net CO_2 emissions and in cases where carbon capture is employed can even have a negative total CO_2 contribution. Biomass thermochemical pyrolysis and gasification can offer efficiencies in the range of 35 % to 50 % offering an effective means of hydrogen production. Thermochemical processes of biomass do however suffer from problems with feedstock impurities and seasonal variability. This has a subsequent effect on the hydrogen content[22]. Biological processes such as fermentation and bio-photolysis also provide the advantages of hydrogen production and recycling whilst emitting low CO_2 emissions. Where photolysis is concerned there is also the argument of CO_2 usage due to its consumption in the photosynthesis. However, biological processes provide low hydrogen yields and low reaction rates. Yet, there could be future uses for biological production of hydrogen in small scale processes for local production of hydrogen or for centralised waste recycling and treatment[21].

Electrolysis offers clean and sustainable pathways to produce hydrogen (using renewable electricity). However, the efficiency and cost of electrolysis does vary depending on how the electricity is generated. For electrolysis the efficiencies range from 40 % to 60 % but it is expected that as these processes become more mature the efficiencies may increase.

Table 2: Summary of the costs for different hydrogen production processes[23].

Process	Energy Source	Feedstock	H_2 Energy Capacity *	CAPEX (mil. £)*	Hydrogen Cost (£/kg)*
SMR w/ CCS	Fossil Fuels	Natural Gas	-	170	1.71
SMR	Fossil Fuels	Natural Gas	-	136	1.57
CG w/ CCS	Fossil Fuels	Coal	-	411	1.23
CG	Fossil Fuels	Coal	-	329	1.01
Autothermal Reforming ATR of CH4 w/ CCS	Fossil Fuels	Natural Gas	600MW	139	1.12
CH4 Pyrolysis	Internally Generated Steam	Natural Gas	-	-	1.20-1.28
Biomass Pyrolysis	Internally Generated Steam	Woody Biomass	2-45 MW	2-40	0.94-1.66
Biomass Gasification	Internally Generated Steam	Woody Biomass	1-90 MW	5-112	1.33-1.54
Direct Bio-Photolysis	Solar	Water + Algae	-	38 (£/m2)	1.60
Indirect Bio-Photolysis	Solar	Water + Algae	-	102 (£/m2)	1.07
Dark Fermentation	-	Organic Biomass	-	-	1.94
Photo-Fermentation	Solar	Organic Biomass	-	-	2.13
Solar PV Electrolysis	Solar	Water	-	9-41	4.36-17.53
Solar Thermal Electrolysis	Solar	Water	2-50MW	17-318	3.84-7.90
Wind Electrolysis	Wind	Water	-	377-381	4.44-4.54
Nuclear Electrolysis	Nuclear	Water	-	-	3.13-5.27
Nuclear Thermolysis	Nuclear	Water	10-800MW	30-1589	1.64-1.98
Solar Thermolysis	Solar	Water	1-9MW	4-12	6.01-6.33
Photo-Electrolysis	Solar	Water	-	-	7.81

** Note: These figures are approximations adapted from the Cyprus University report[23]. Hyphen means no data available or N/A*

1.5 Conclusion

The hydrogen market is on the precipice of a major leap in growth and development. It is clear there will be significant increases in demand for high purity hydrogen for the transport and gas grid network markets in the near future (10-20 years) as the necessary infrastructure develops. KEW currently sees hydrogen fuel cells as a less important opportunity (at least in the short term) since they will likely only be adopted by large scale freight and public transport systems (whilst non-freight transport will comprise electric vehicle (EV) technology only), or energy storage systems for intermittent renewables such as wind and solar. This is shown in Table 3.

The demand for industrial grade purity hydrogen (95-98%) will also continue to increase in line with global increases in demand for ammonia and ethanol. Indeed, industrial grade hydrogen is already an established market that is now looking to reduce its carbon footprint, which therefore provides significant opportunity for renewable hydrogen technologies such as KEW’s gasification technology.

There is also potential opportunity for lower grade hydrogen (80-95%) for cooking, heating and power generation for countries lacking good energy infrastructure. Many developing countries fall into this category and would benefit from embedded hydrogen generation local to the point of use.

Table 3: Summary of market opportunities for hydrogen consumption, comparing three levels of hydrogen purity.

H_2 purity	**Low**	**Medium**	**High**
	80-95%	95-98%	99.5% or higher
Acceptable applications	Heating / cooking & power generation	Industrial Use (e.g. Ethanol, Ammonia production or as a reductant in metal refining)	Fuel cells (energy storage, freight transportation) & H_2 grid Networks
Opportunities for KEW	UK not a primary market due to large supply of cheap natural gas dominates; this may change in future as UK moves toward net zero by 2050. On the other hand, countries lacking good energy infrastructure could benefit from embedded gasification plants now, for local H_2 supply.	Industrial sites could accept the purity of KEW's embedded hydrogen technology. KEW's multi-modular approach allows for competitive LCOH. The initial obvious market for this is the UK, but EU and beyond can be considered for future.	Further processing of gas could be utilised (using PSA) to achieve high purities, KEW will maintain a watching brief on this market as it matures.
	Note: All remaining non H_2 impurities comprise of inert gases (CO_2, N_2 or H_2O). Other reactive or corrosive compounds (CO and H_2S) are not present in KEW's H_2 gas. This is		

2 Hydrogen Production Technology

2.1 The KEW Advanced Thermal Conversion (ATC) Plant

The ATC process converts low grade waste and biomass into a clean syngas ready to be sent to the engine and the subsequent HPM. The key benefits of KEW ATC technology are associated with commercial flexibility and risk-mitigation during the project delivery phase; notably:

- Any feedstock with a carbon content can be utilised, including biomass, commercial/industrial waste, municipal waste and hazardous/clinical waste.
- A consistent syngas quality is achieved irrespective of feedstock input from the reforming process within the EAR.
- The EAR also produces syngas that is virtually free from hydrocarbons. This is a major advantage for onward supply of hydrogen.
- The compact nature of the technology (due to the high operating pressure) means that it can be factory-built in modules. This is a major risk mitigating factor for project delivery, noting that current projects in the field of ATC in the UK have poor delivery track records even when the technology is TRL9 due to their largely field-erected nature. KEW's approach drives down cost and risk.
- Smaller vessel size and overall plant footprint compared to traditional small capacity (50tpd) gasifiers such as atmospheric bubbling fluidised bed (BFB), fixed bed and plasma technologies, brings commercial advantages such as deployment in tight urban spaces or at existing industrial sites.

The system is therefore highly suited for small to medium scale facilities that can produce hydrogen local to its point of use, as well as larger facilities (which would operate at higher pressure c. 50 bar).

2.2 ATC Process description

The process steps of the ATC are shown in Figure 7 and are detailed as follows:

- <u>Feedstock processing</u>; The reception area is designed for preparing the incoming feedstock (refuse derived fuel (RDF) or shredded demolition wood (biomass). Here, RDF may be blended with biomass to increase biogenic content (up to 100%). The blended feedstock is then shredded and densified into a medium density 'cube' fuel.
- <u>Gasification</u>; The cubed fuel is then fed into a pressurised bubbling fluidised bed (BFB) gasifier (7MWt). The gasification process thermally converts the feedstock into raw syngas by subjecting the feedstock to high temperatures but restricting the flow of oxygen to prevent complete combustion occurring. These conditions allow for a complete degradation of the fuel and convert it into a gas comprising a dense mixture of hydrocarbons (syngas).
- <u>Filter</u>: The syngas then enters a high efficiency filter that removes 99.999% of the entrained solids by mass in the gas stream. This step reduces the likelihood of problems due to ash fouling in downstream equipment significantly.

- Cracker: The syngas then enters the EAR at high temperatures to break down the tars (heavy hydrocarbons) and methane into their simpler molecules, primarily H_2, with CO and CO_2 as by-products. The cracker is critical for ensuring syngas gas quality and consistency irrespective of feedstock type and is a critical unique selling point (USP) of the KEW technology solution.
- Cooling & heat distribution: The cracked gas, is then cooled to recover a significant amount of high-grade heat for use elsewhere in the process (steam production) and to generate additional electricity using an Organic Rankine Cycle (ORC) generator.
- Quench: The cooled syngas is then quenched in a high mass transfer scrubbing system that has very high efficiency for the removal of fine particulate matter, HCl and H_2S. Part of this polished syngas (about 20%) is then fed into a power generation system that generates power for the plant duties.
- CO_2 removal (post combustion): small quantities of CO_2 are captured using the exhaust flue gas from the syngas engine and the char combustor using amine absorption. The quantities of carbon capture are comparatively smaller compared to the HPM pre-combustion capture due to the relatively smaller flows being diverted to these processes.

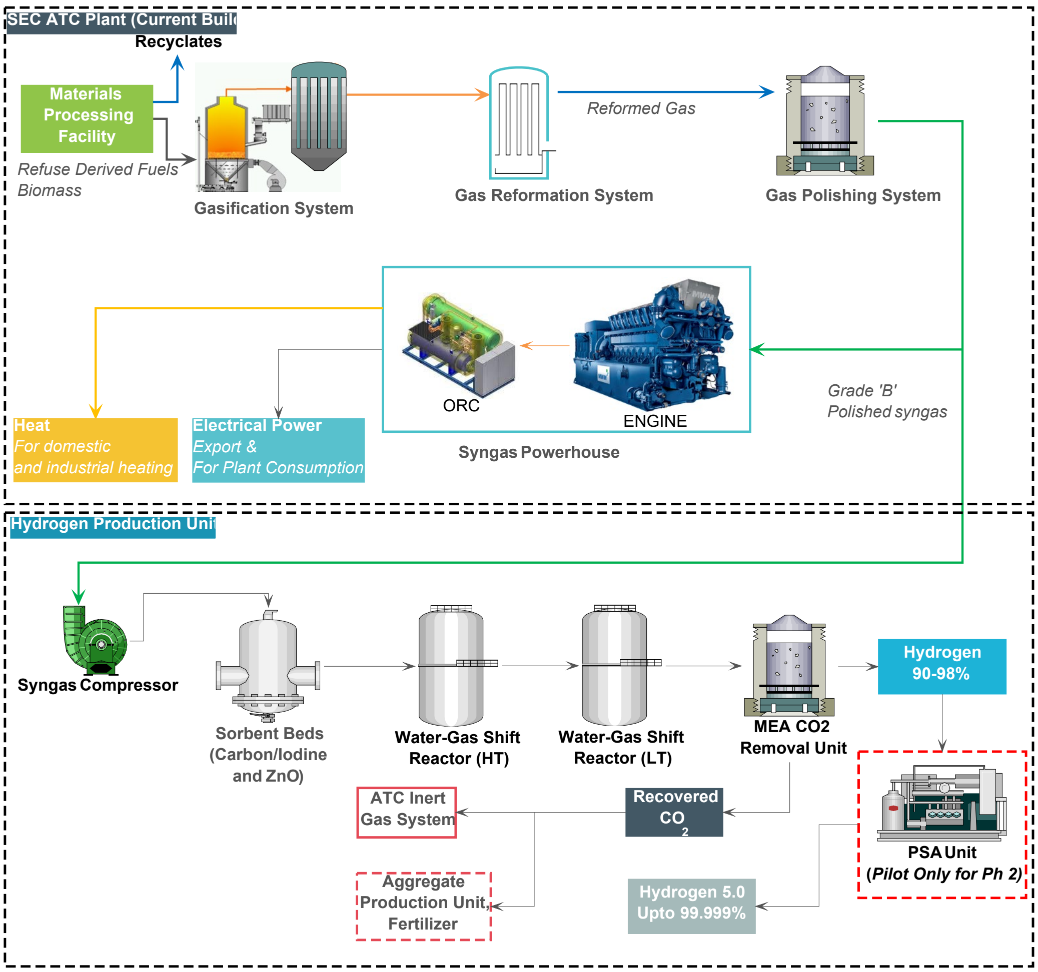

Figure 7: KEW ATC and HPM process overview

2.3 The Hydrogen Production Module (HPM)

The HPM has been designed to produce hydrogen at 98% purity levels in bulk quantities using the syngas feedstock producing in the ATC modular plant. It is also designed to recover a stream of CO_2 that has a purity level of >98% also. The final design choices (including scale) to get these two outputs have been influenced by a number of factors including process considerations, risk, budget, vendor capabilities and KEW's overall commercial strategy.

2.4 HPM Process Options Analysis

A range of configurations have been evaluated by combining equipment manufacturer data into KEW's global process model (GPM) which allows for a full-cycle analysis. Additionally, KEW has evaluated the effects of macro components within the waste such as plastic and biomass, with hydrogen purity. The effects of these complex inter-related factors have been tested in KEW's GPM in 20 configurations as part of the front-end engineering design (FEED) study; conclusions of which are detailed in the following section 2.5 'HPM Process Description'. Summary of the process options analysis work is shown in Table 4 below.

Table 4: Pre-considerations and hypothesis of system arrangement options.

Function	Key Considerations and Analysis of Options
Water Gas Shift (WGS) – Sour or Sweet	• Sweet WGS technology is well understood and cheap but sorbent costs can be high as ppb level purity is needed • Sour shift catalysts exist from vendors such as Topsoe (e.g. SSK-10) but very expensive and lifecycle cost is unknown • Operation of sour shift catalysts can be complex as desulfurization steps are challenging – generally considered to be unsuitable for smaller applications • If sour shift is used, then acid gas must be removed from CO_2 also – potentially limits its end-use
CO_2 Removal	• MEA, carbonate systems evaluated • Work packages including work by WRK Design & Service Ltd (WRK) looking at specific options for both solvent type and method (packed column, fluidized bed) to reach optimal • Stripping energy and exergy (temperature of strip) evaluated in detail in context of ATC plant heat streams
Operating Pressure	• Evaluated on the basis of equipment cost, WGS performance • Another consideration is potential need to polish final product with PSA (partial) to bring purity up. The market research in earlier sections of this report shows that most industrial users can tolerate a range around 98%
Hydrogen Purity	• Key challenge is to remove inert gases – N_2 from the syngas stream • Fuel bound N_2 impossible to remove and hence final purity is dependent on biogenic content of feedstock • Evaluation of production cost vs. desired purity (cost benefit). Lifecycle costs are shown in subsequent sections.
CO_2 Capture	• Capture/reuse of CO_2 in plant as inert gas • Capture of CO_2 within ash/aggregate • Use of CO_2 for fertilizer production • Other local options

2.5 HPM Process Description

- Syngas compression: The syngas is pressurised to 16bar. Evaluations have shown that the added energy cost penalty (~30kW) of compressing before the WGS as opposed after the CO_2 removal, is offset by better WGS conversion efficiency and overall lower capital cost due to small vessels and piping.

- Desulphurisation: The syngas passes through a carbonyl sulphide (COS) hydrolysis unit to convert COS to hydrogen sulphide (H_2S). A subsequent iodine impregnated carbon bed is used to achieve sulphur levels of <10ppmv. This is followed by a zinc oxide (ZnO) bed with an alumina layer to polish all of the sulphur from the gas down to 5-20ppbv.

- Water Gas Shift (WGS): A 2-stage high and low temperature WGS system converts of all the CO into H_2 and CO_2 using steam, in the following chemical reaction: $CO + H_2O \rightarrow H_2 + CO_2$, $\Delta Hr = -41$ MJ/kmole. It uses commonly available WGS catalysts; FeCr for high temperature shift and Cu based for low temperature. This process ultimately converts the syngas into a hydrogen gas of 51% purity.

- CO_2 Removal (pre-combustion): Firstly, a quench stage is needed to remove water and all other condensable components from the gas stream a subsequent monoethanolamine (MEA) solvent is used to absorb and strip the CO_2 from the syngas. The captured CO_2 gas is 98% pure and is utilised in downstream carbon utilisation and sequestration (CCUS) activities including aggregates and fertiliser production. The hydrogen gas is 98% purity. The remaining molecules in the gas are the CO_2, and N_2 inert gases.

- Pressure swing absorption (PSA): An optional 'add-on' unit enable further stripping of the inert gases to produce hydrogen of '5 nines purity' (99.999%). This option may be introduced when commercially viable consumer markets are later identified (primarily H_2 gas grids or fuel cells).

2.6 Plant Performance Summary

The plant mass flows, energy and overall efficiencies are summarised in Table 5 below. It should be noted that the PSA technology is currently considered an optional add-on that will initially be trialled in preparation for the development of the high purity consumption market. An energy balance of the KEW ATC and HPM plant is shown in Figure 8.

Table 5: KEW single module (7MWt) performance summary. Calorific values are given as lower heating value (LHV). Conversion efficiencies includes the use of approximately 20% syngas to power the plant parasitic loads.

Process	**-**	**ATC & HPM**	**PSA (Add-On)**
Product	**Feedstock Input (RDF)**	**H_2 Product**	**H_2 Product**
H_2 Purity Level	-	98.0%	99.999%
Chemical Energy (kWt)	6950	3457	3104
Mass Flow (kg/h)	1635	129	93
Calorific Value (LHV) (kJ/kg)	15300	96334	119888
Conversion Efficiency	-	48-50%	44-45%

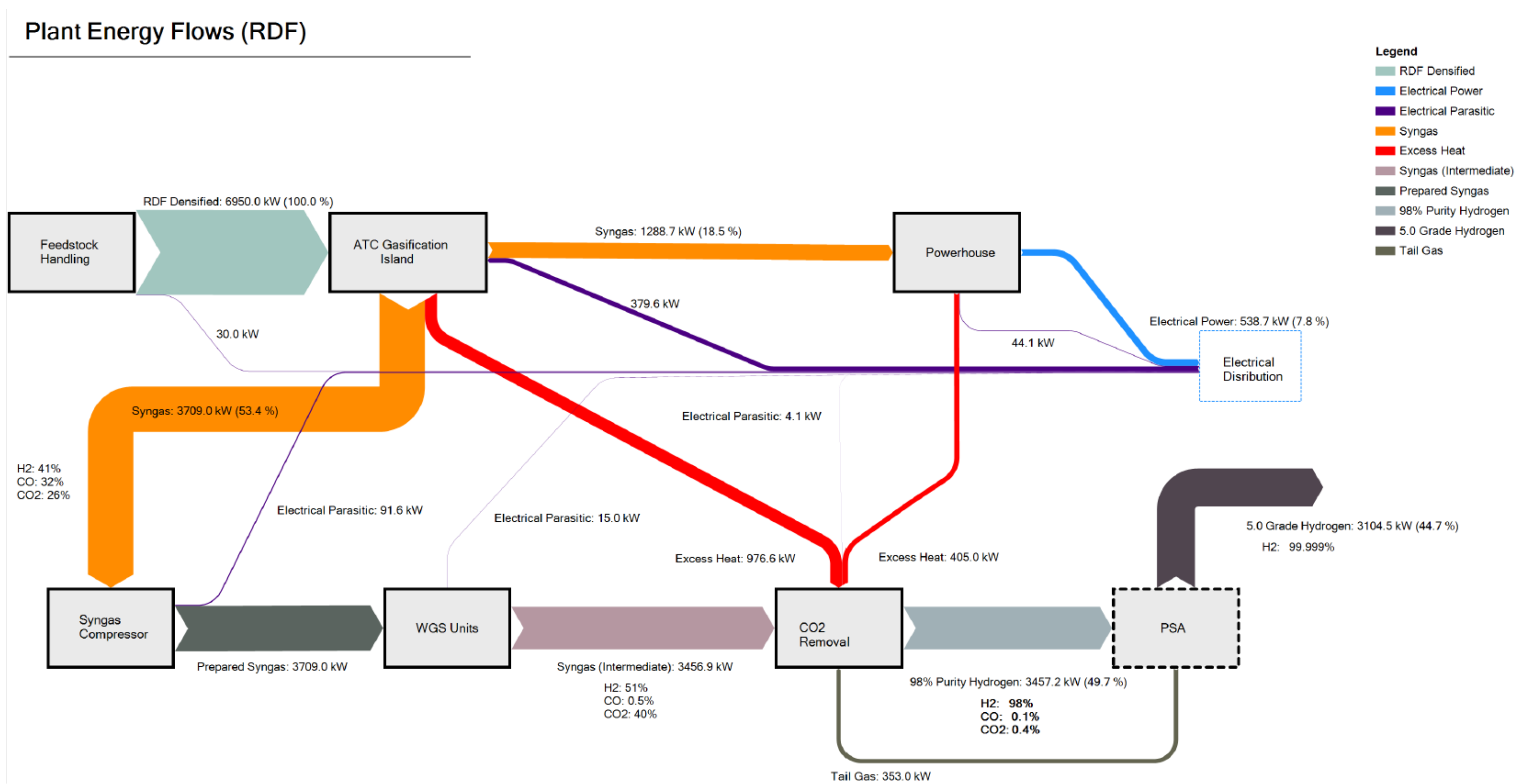

Figure 8: Energy balance of the KEW ATC and HPM plant technology. With PSA, the plant produces 3.1MW of hydrogen of 99.999% purity, from 7MW of feedstock. Since the plant is self-sustaining, no electricity or natural gas is imported for subsequent processes; it can be seen that the plant electrical loads are powered by the syngas engine, also the ATC gasification island, the power house and tail gas provide c. 1.8MW thermal energy for the CO_2 stripping process.

3 Carbon Capture Technology

One of the merits of KEW's approach to sustainable hydrogen production is the potential to deliver negative carbon emissions which are an essential element of our future energy system. These negative emissions are needed to offset those emissions which cannot be prevented in time for the UK's net zero target in 2050. This is particularly pertinent now since the government actions to date have fallen short of what is needed for the previous targets and well short of those required for the net-zero target[24].

In this feasibly study, KEW worked with its project partners WRK and Energy Technologies Institute (ETI) to investigate the technologies available for CO_2 removal. the outcome of which has been implemented into the HPM design. Similarly, KEW conducted a commercial assessment of carbon capture, utilisation and storage (CCUS) opportunities in the market, as well as a preliminary FEED to understand their integration with the ATC and HPM plant.

3.1 CO_2 Removal Processes

The selection of specific carbon dioxide capture process technologies heavily depends on the type of carbon dioxide generating plant and fuel used. KEW's ATC and HPM system provides an ideal platform for pre-combustion carbon capture by absorption since the high carbon dioxide concentrations in the shifted syngas steam enhance absorption efficiencies. In addition, the syngas engine and char combustors can utilise post-combustion capture; although it is less efficient than pre-combustion, the removal of CO2 from exhaust gases will contribute to improving the plant's overall CO_2 intensity (carbon footprint). Absorption is the most mature and commonly adopted technology due to its higher efficiency and lower cost.

In the FEED study, KEW focused on pre-combustion capture and looked at a variety of mechanical arrangements, temperature conditions and solvents for absorption processes to determine the optimum process that can strip CO_2 effectively at a reasonable cost. A novel idea called the downflow gas contactor (DGC) reactor was proposed by WRK, which sees increased absorption efficiencies due to increase surface contact area between the gas and solvent. However, this method was unfeasible for KEW's application due to the large flows of syngas being too much for a single DGC bubbling column. It would require multiples of those columns to achieve the required rates of CO_2 removal, which would not be economic for KEW.

KEW has opted for a traditional absorption and regeneration column which comprises of an amine absorber, amine desorber with top partial condenser and bottom reboiler, a heat exchanger, a lean amine cooler, and an acid gas cooler and knockout drum. Removal efficiencies of 90-99% of the CO_2 in the gas stream, have been calculated from KEW's GPM, with CO_2 purity of around 95-98%. Depending on the downstream CCU process, the solution will be either ammonia or monoethanolamine (MEA) solution will be used.

The post-combustion sections of the plant (syngas engine and char oxidiser) will utilise an MEA based solution in a separate absorption and regeneration process. However, these processes have not yet been simulated in the KEW GPM.

3.2 Storage and Utilisation

Although technologies for underground storage exist and their potential to store high volumes of CO_2 is widely recognised, the overall costs (capital and operating) of using current methods are still high and must be substantially reduced before being widely deployed. For example, KEW's CO_2 could be sent into a saline aquifer such as the Bunter field in the North Sea or depleted gas fields like Hamilton in Liverpool Bay. However, since the SEC is situated in the Midlands, this option is presently unviable as substantial investments would be required to build the pipework and compression facilities to transport dried carbon dioxide to the North of the UK. In general, economical large scale CCS deployment is not expected until the late 2020s which may be too late for reversal of the impacts and effects of climate change. It is clear that comparative large-scale CCS projects which propose to fill undersea caverns with CO_2 in the North and Irish seas are very long in the planning, require huge capital investment, and require significant support from government resources if they're to be realised. Other issues with underground storage are that there is always a risk of CO_2 leakage which could potentially cause more damage than if dilute emissions were to continue unabated.

KEW has chosen two mature processes that have more compelling economic benefits and are achievable in the immediate short term future. These processes will utilise the CO_2 as follows:

- Fertilizer production using ammonia solution to extract the CO_2 and react it with nitrogen rich organic fibres to make fertiliser for agricultural use.

- Building materials (concrete aggregates) formed by mineralization of CO_2 (carbonation) using calcium rich fly ash.

These two options will have been determined as the current optimal solutions for the 2-10MWe size of plant that KEW has market interest in because their operating capacities match the CO_2 flows delivered by the ATC and HPM. Also, they only require comparatively small CAPEX compared with underground storage options, making private and local investments much more viable, and where those operations can develop independently from government incentives. In addition, these technologies would operate as supply-based production systems which satisfy a market demand, which makes the economics much more attractive.

CCm Technologies Ltd (CCm)'s fertiliser unit has been proposed. It requires an ammonia solution to be circulated through the scrubbing system to capture the CO_2. Further investigation will be required to understand the mechanical and chemical arrangement for this integration. Trials will be run at the SEC to test CCm's technology during to Phase 2 of this BEIS 'Hydrogen Supply' project to get a better understanding of the techno-economics, efficiencies and overall greenhouse gas (GHG) emissions impact of the system in the wider context of the environment.

KEW will also pursue post-combustion capture options since the ATC plant could also be deployed to simply produce heat and power, without hydrogen production. KEW has engaged with Carbon8 systems; a UK based company that produces an aggregate product for the construction industry from lime rich ash sources (such as cement dust), mixed with CO_2. The approach has other synergistic benefits for KEW as the fly ash product from the ATC plant would also be upgraded to this higher value aggregate while capturing the CO_2 produced.

Table 6 below shows a list of other alternative companies for CCUS. These companies are similar in that they use CO_2 to produce saleable products; mostly building materials but also some agricultural fertilisers[25].

Table 6: Summary of key players in the CCUS arena, for small to medium scale carbon capture operations[25].

Company name	Process Type/IP	Inputs	Product
CCm Research	CO_2 combined ammonia coated waste fibres	Waste fibres and CO_2 from exhaust gas	Fertiliser and soil conditioner
Carbon8	Accelerated Carbonation Technology (Modules)	Ash, cement kiln residues, CO_2	Aggregates and fill e.g. for blocks and screed
Carbicrete	Carbonation of Steel Slag		Cement-free concrete
Calera	Carbonate precipitates from CO_2 in water/brine		Cement
Co2 Upcycling		Fly ash + CO_2	Graphitic nanoplatelets (GNPs) Graphene oxide (GO) Graphene quantum dots (GQDs) Enhanced fly ash (EFA)
Blue Planet	CO_2 sequestered coating over a substrate		Lightweight aggregate
Mineral Carbonation International	MCI Carbonation Reactor	Serpentine magnesium silicate rock	Magnesium carbonate and silica sand
Carbicrete	Carbonation of Steel Slag		Cement-free concrete
New Sky Energy	CarbonCycle™	NaCl, KCl, Na2SO$_4$, $NaNO_3$ + CO_2	Carbonates, bases and acids
Carbstone Innovation		Powdered steel slags, water, CO2	Tiles, roof tiles, paving bricks, kerb stones, building blocks
Carbon Cure Technologies	Direct injection of CO_2 gas into green concrete/mortar	Concrete/mortar + CO_2	accelerated cured concrete
Orbix / Recoval Belgium	Carbonation of steel slag using CO_2 from flue gas		Construction materials including blocks and tiles
Solidia Technologies	CO_2 curing for cement manufacturing	Sand, aggregate, CO_2	Carbonate cement/concrete
Caboclave	Precipitation of nano-$CaCO_3$ crystals	Cement, aggregates + CO_2	Concrete blocks
Alcoa	Red Mud treatment with flue gas CO_2 with enzymes		Construction fill material, soil amendment/fertiliser
The C2B Project		Flue gas	Sodium bicarbonate BICAR®
Green Minerals	Carbonation of olivine	Olivine rock + CO_2 additives	Building materials

4 Waste & Biomass Feedstocks

KEW's integrated ATC and HPM plants have the capacity to operate on a variety of waste & biomass feedstock's, whilst being able to produce a consistent syngas. This gives added flexibility to respond to price variations, government incentives or supply chain issues, by simply moving to an alternative feedstock supplier. These waste feedstock's range from residual wastes (including RDF) from household, commercial and industrial sources, to agricultural wastes and wood / biomass.

The key themes to be taken away from this section are that there is an abundance of waste in the UK which requires an ever-increasing capacity for effective treatment. Consequently, there are favourable economic opportunities when compared to fossil fuel based hydrogen production. In addition, current biomass consumption in the UK is not an efficient use of energy resources (biomass incinerators net electrical efficiency of no more than 20%). Using biomass for hydrogen production offers better conversion efficiency along with net negative carbon emissions when pre-combustion CCU is employed.

4.1 Waste

4.1.1 Waste Feedstocks

Waste feedstock's come in many forms and are derived from several major sectors of the economy. For KEWs gasification technology, residual wastes are suitable and include household municipal solid wastes (MSW), commercial or industrial waste. Normally, these residues are processed into pellets or briquettes and referred to as refuse derived fuel (RDF) or solid recovered fuel (SRF).

Other wastes include agricultural or forestry wastes. Forestry wood wastes in particular should not be confused with biomass crops since, although they have similar biogenic and calorific qualities, wood waste has different counterfactual GHG emissions, as well as different market pricing and availability.

Table 7: Types of waste feedstock's available for KEWs ATC and HPM plant technology

Agricultural	Forestry products	Municipal wastes
Harvesting residues Straws Corn stalks	Harvesting & forestry residues Bark Woodchip	Commercial/Industrial waste MSW/RDF Wood waste Sewage sludges
Processing residues Rice husks Sugarcane bagasse Olive/palm oil residues Fruit residues	Primary process residues Bark Sawdust's Offcuts	Urban green wastes Leaves Grass and hedge cuttings
Animal wastes Poultry litter Meat/bone meal	Secondary process wastes Sawdust's Offcuts	

4.1.2 Demand for Treatment of Residual Waste

In recent times, the UK has been an exporter of a proportion of its residual waste. With annual increases in landfill tax, landfill disposal costs have increased which since 2008 has seen the UK develop a RDF export business in to Europe, in order to divert waste, from landfill, the overall cost of this export has tended to mirror the costs of landfill disposal plus landfill tax. Export has steadily grown, as shown in the Table 8. It is forecast that the tonnage will remain fairly constant, at around 3.2m tonnes per year, as uncertainty surrounding Brexit, associated exchange currency issues, transport costs and the cost of Trans Frontier Shipment, puts pressure on the UK producers to consider alternative options[26].

Table 8: RDF/SRF export from England and Wales between 2010 and 2016

RDF/SRF Exports	2010	2011	2012	2016
Tonnes per annum	34,733	680,631	739,535	3,200,000

The UK currently supplies 25% of all energy from waste (EfW) feedstock which has a gate fee to the Netherlands. However, the Dutch Government are currently considering the introduction of a €30/tonne levy on all RDF imports. Sweden is also considering the introduction of an incineration tax on imported material. If these policies are imposed, it is likely to make some UK RDF exports uneconomical. This would result in them being retained in the UK and landfilled if replacement UK based treatment infrastructure is not available, or exported further afield which would also be more expensive. A number of local authorities, heavily reliant upon this RDF export market are already looking at contingency planning. It would therefore make more sense for this waste feedstock to be channelled into generating and producing zero carbon hydrogen.

The UK is now dealing with a significant capacity issue with regards treatment of its waste. As recently as September 2019, the UK Government forecasted a 20M tonne residual waste gap by 2035, meaning the UK will need 7.5Mt of additional treatment capacity. Energy-from-waste (EfW) technologies including incineration and gasification are proposed as important turnkeys in the provision of new waste treatment capacity[27]. Here, KEW is poised to capitalise on this opportunity with its ATC and HPM technologies.

It is worth pointing out that RDF is more energy dense than most wood and biogenic based feedstock's due to the higher calorific value. When a waste-based RDF feedstock is coupled with cost effective carbon capture technology the opportunities to generate and produce zero carbon hydrogen are significant.

4.1.3 Waste Wood

The amount of processed waste wood in the UK being used in the biomass sector jumped by 24% to 2.1 million tonnes in 2018. But less waste wood is arising overall with total volumes falling by 0.5 million tonnes to 4.5 million tonnes last year. With the export market taking 8% of production primarily for biomass, the overall amount of waste wood going for burning in biomass plants now represents nearly two thirds of all waste wood processed. According to the Wood Recycling Association, this was due to the fact that "the UK was processing for planned biomass plants that faced delays in commissioning, so the fuel continued to be exported"[28].

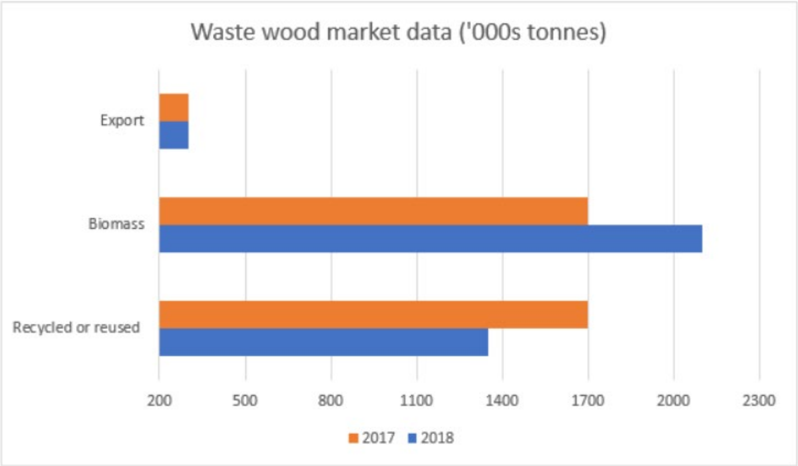

Figure 9: Allocation of waste wood from the UK. More than half is sent for energy production as a biomass feedstock. Waste wood can be used to generate hydrogen in KEW's ATC and HPM plants

4.2 Biomass

Biomass crops (non-waste) needs to be given serious consideration by investors and policy makers for energy production, since the biomass crops provide an important carbon sink for the earth during growth, making it a very low carbon solution. When coupled with KEW's carbon capture system, net-negative carbon emissions can be achieved. These negative emissions are needed to offset those emissions which cannot be prevented in time for the UK's net zero target in 2050. This is particularly pertinent now since the government are reported to be late on their programme to achieve the net-zero target[24]

Analysis from the ETI Bioenergy report[29] consistently highlights the continued importance of developing the bioenergy sector to deliver cost-effective emissions reductions. Until recently bioenergy production has been dominated by waste feedstock's, but demand for more sustainable UK-grown and imported biomass to support emissions reduction targets has risen and, to further increase supplies of UK-grown biomass, more energy crops and forestry need to be planted.

Bioenergy must play a significant and valuable role in the future UK energy system, especially when combined with CCS. Together they can deliver net negative emissions of c.-55 million tonnes per year and meet around 10% of UK energy demand in the 2050s, ultimately reducing the cost of meeting the UK's 2050 GHG emission reduction targets by more than 1% of GDP (~130 TWh/ yr in 2050)[29].

4.2.1 Biomass for Hydrogen Production

KEW has conducted a process simulation and run a GHG study to understand the lifecycle costs as well as the net-negative carbon footprint that can be achieved using KEW plants which accounts for the full supply chain; from the growth of biomass crops, through to the final consumption pf hydrogen as an energy vector. Results of the lifecycle costs are shown in the following chapter (5 'Lifecycle Costs').

The study from ETI reaffirms these points; that net-negative carbon emissions can be achieved if using biomass to produce hydrogen. This is shown in Figure 10 where hydrogen from biomass feedstocks are compared to a baseline fossil fuel (natural gas) without CCS. Bio-hydrogen chains without CCS offer an average of 130% GHG emission savings compared with this baseline. With CCS, H_2 chains deliver 320% GHG emission savings from the fossil baseline. The actual negative emissions of the CCS component in bio-hydrogen chains are smaller than the CCS component of the bio-electricity chains, since the latter are generally less feedstock efficient, and hence they capture more CO_2 per MJ of final product[29].

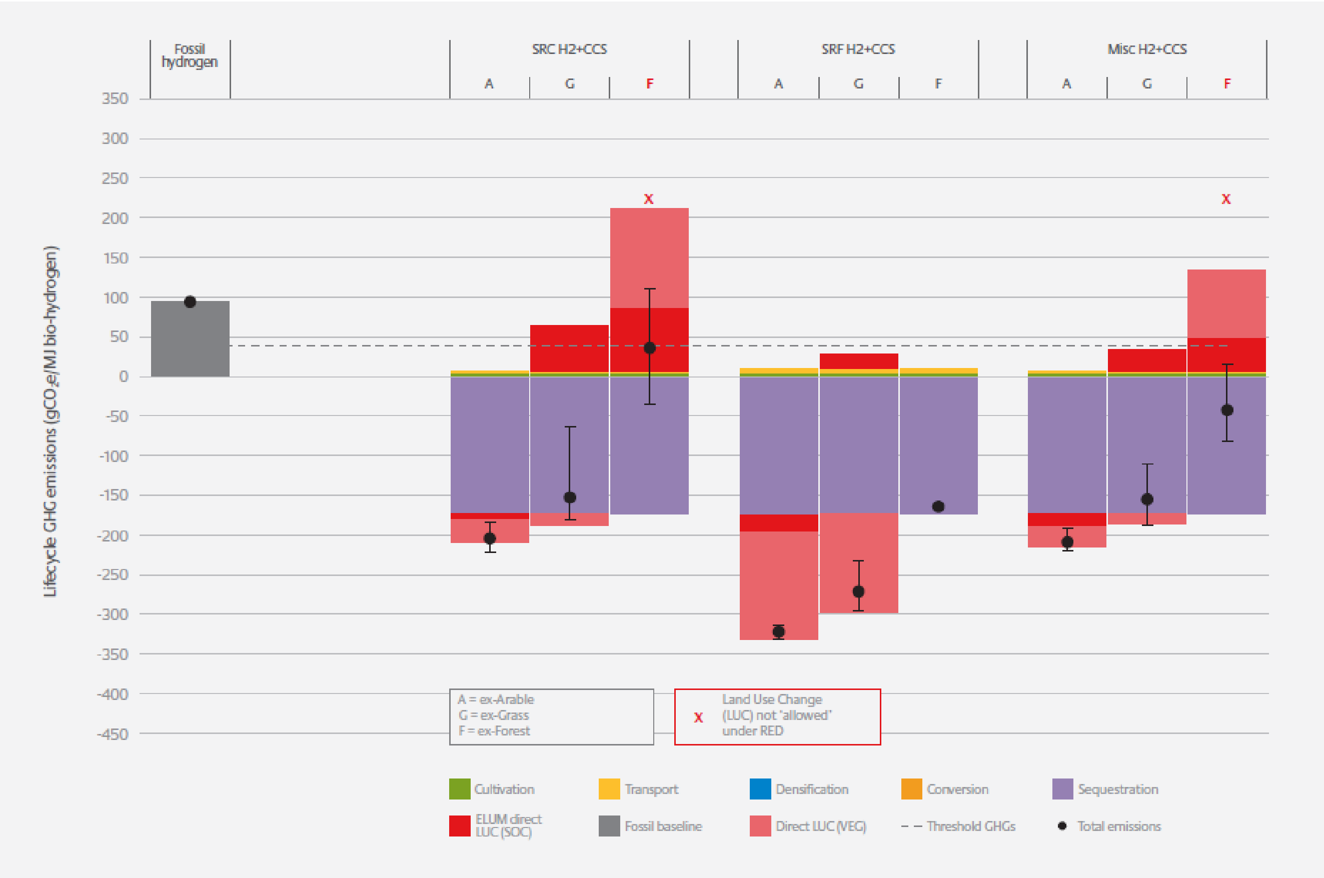

Figure 10: CO_2 intensities of hydrogen production comparing different biomass feedstock's (short rotation coppice (SRC), short rotation forestry (SRF) and Miscanthus) alongside natural gas as the baseline fossil fuel. Note the black dot indicating total emissions for each scenario; practically all biomass options give net-negative emissions[29]

4.2.2 Biomass Supply

The UK biomass supply market is immature due to its complexity of multiple value chains and the political and scientific uncertainties around land use change and the sustainability of using biomass for energy. In 2016/17 energy crops represented only less than 2% of the overall biomass fuel market and this is evident by the fact that the UK currently imports almost all of its biomass[28]. In 2014 figures showed UK importing 4.6 million tonnes, from countries including the United States of America, Canada and Latvia. Most of this was consumed by Drax power station (approximately 4 million tonnes), making it the fourth single largest pellet importer in the world after UK, Denmark and Italy. This figure is expected to rise significantly to around 13 million tonnes by the end of 2020 once Drax converts its fourth combustion unit and when Lynemouth and Teesside biomass plants come online. Beyond this, demand for the country will continue to grow as the UK moves towards the 2050 net-zero emissions target[30].

The theoretical maximum available land for SRC and miscanthus in the UK, not impinging on food production, has been modelled to be between 0.93 and 3.63 Mha in England and Wales. Research suggests that SRC uptake could be between 0.62-2.43 Mha representing between 3-13% of the 18.26 Mha of agricultural land in the UK. If this land were used for miscanthus uptake could be up to 2.80 Mha correspond to total potential electricity generation of 59.3TWh equivalent[31].

Although this figure only refers to electrical generation (59.3TWh), it should be noted that this is based on a net conversion efficiency of 20%, as is the current best in class for biomass incineration power stations[32]. KEW's hydrogen production technology on the other hand would allow for a much improved conversion rate for producing a useful energy vector (hydrogen) as net conversion efficiencies of 48-50% can be achieved using the ATC gasifier and HPM. This provides a compelling case for the reallocation of biomass resources to hydrogen production.

5 Lifecycle Costs

5.1 Levelised Cost of Hydrogen (LCOH)

KEW's larger installations can be competitive on a direct price comparison with steam methane reformers (SMR) plants referenced in the Wood report[4]. To achieve the same supply as the SMR reference, 100 KEW gasifier modules (7MWt each) or 10 higher-pressure KEW plants would be required. This would be achievable in a region or cluster with the advantage of stage by stage build. Table 9 below shows the comparison of levelized cost of hydrogen (LCOH) with traditional large scale SMR.

Table 9: Comparison of LCOF of KEW's hydrogen supply (98% purity) vs traditional large scale SMR

		SMR ref (446MWt) Proposed 99.99% purity target [4].		**KEW Triple Module Plant (21MWt) 98% Purity**		**KEW High-Pressure Plant (70MWt) 98% Purity**	
Carbon Capture (CC)		No CC	CC 90%	CC 80%			
Energy Source		Natural Gas		Biomass	RDF	Biomass	RDF
CAPEX	£K	144,000	237,000	29,385	29,385	73,463	73,463
H_2 production	Kg/hr	9,000	9,000	133	126	133	126
Carbon tax	p/kWh			-2.2	0.8	-2.2	0.8
Feedstock (cost or gate fee)	p/kWh			1.3	-3.5	1.3	-3.5
Heat Network Revenue offset	p/kWh			-1.6	-1.6	-0.5	-0.5
Production Cost	p/kWh			8.9	8.6	6.4	6.2
LCOH - with carbon tax	p/kWh	**6.5**	**5.5**	**6.3**	**4.4**	**4.9**	**3.0**
LCOH - no carbon tax	p/kWh	4.0	5.3	8.5	3.6	7.1	2.2

The key assumptions in the model are:

- These KEW plants are electrically self-sufficient as some syngas (initially ~25%) is sent to the gas engine to power the rest of the plant equipment, derived from KEW's GPM results. Thus, the LCOH is independent of electricity price. Where a low-cost, low-carbon electricity supply is available, hydrogen production can be boosted by c. 25%. This is based on substituting the plant O_2 concentrator system (that consumes syngas engine power) with an alternative renewable power supply. These performance benefits were determined using KEW's GPM, however further cost benefit analysis is needed to understand the impact of grid electricity price on LCOH for this optional scenario.

- Feedstock prices are set to £20/tonne for Biomass and -£50/tonne (i.e. gate fee) for RDF.

- The CCU system removes 80% of the CO_2 from the clean gas stream at a purity of 95-98%. Although higher removal rates are often quoted, a more conservative figure has been taken, recognising the challenges in small-scale CCU.

- A Cost of capital / discount Rate of 10% has been used.

- CAPEX costs have been calculated from the current data available on the equipment and as such have varying degrees of certainty. In particular, the costs of the major package CCU modules (carbonation and fertiliser production) depend on the final installation arrangement and requires a detailed design. On the other hand, well-known equipment that is commonly used by KEW such as vessels, pipework, valves, compressors and pumps have a greater degree of certainty associated with them.

The most significant uncertainties in relation to operating costs relate to the HPM and CCU. Operating costs for the HPM have been estimated from industry knowledge, however catalyst life are a significant factor and uncertainty exists until long-term trials have been completed. Technical performance, as noted previously, including conversion rates, electrical power consumption and reliability clearly have substantial impact on the overall viability of the technical approach. Hence the need for the extended testing and demonstration period.

In commercial operation, feedstock availability and cost along with the rate carbon taxes are the most significant variables affecting Hydrogen cost. Figure 11 illustrates the range of costs for KEW's initial target market. If the carbon taxes are as have been forecast in the Wood report, then waste fuelled plants will be highly competitive and biomass fuelled plant (in locations with high availability of low-cost biomass (<£30/t)) will have LCOH 7p/kWh and will be highly attractive for many industries.

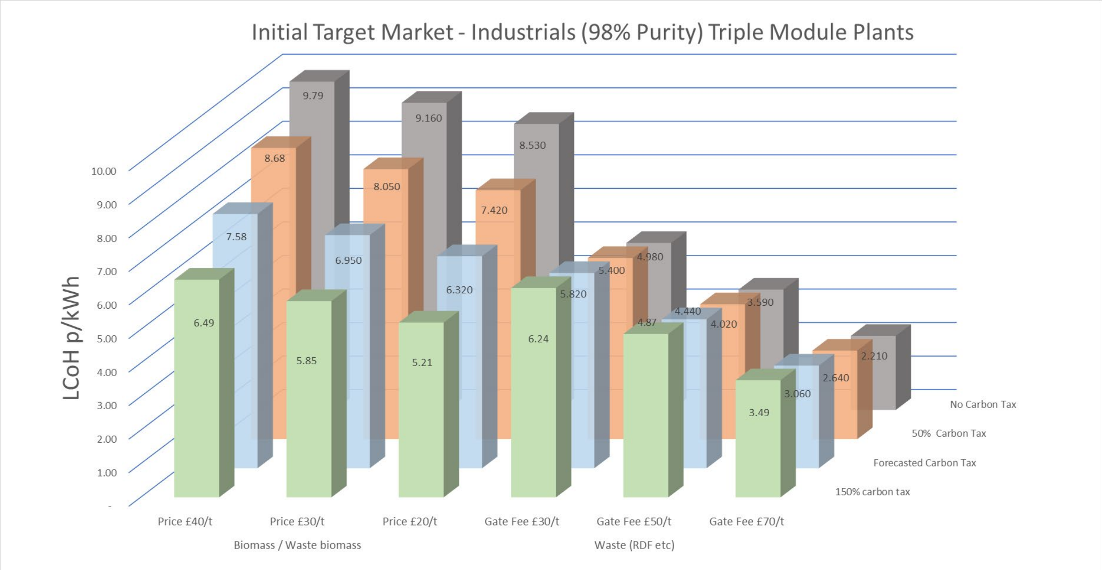

Figure 11: Comparison of LCOF and carbon footprint of KEWs plants vs traditional large scale SMR

The flexibility in feedstock consumption will offer a protection as differing blends of waste, biomass and other waste types can be taken according to commercial advantage. The forecasted acceleration in carbon taxes increases from 2030 onwards could herald plants switching from waste to biomass, especially if gate fees reduce, and spurn new investment in plants focussed on biomass.

Another critical factor in commercial viability is the rate of CAPEX reduction - the factory-build approach will bring many advantages in accelerating and sustaining this reduction; with the assistance of lean and design-for-excellence (DFX) manufacturing approaches.

5.2 Greenhouse Gas (GHG) Emissions Model

A greenhouse gas (GHG) emissions model has been developed to analyse the change in GHG emissions related to the supply of energy from KEW plants. This life cycle analysis (focussed only on carbon emitted – i.e. CO_2e) has been conducted using a consequential approach. Thus, the current destination for residual waste (likely landfill) is considered as the default and emissions avoided by diverting to KEW plants is considered as a benefit. The reference data for the model is sourced from DEFRA[32] and UK Govt energy statistics[33]. The scenarios modelled are listed in Table 10.

Table 10: Various carbon capture (CC) scenarios modelled in the GHG model

Scenario	Detail
RDF CC 0%	Residual waste (no carbon capture)
RDF CC 40%	Residual Waste (40% of CO_2 captured)
RDF CC 80%	Residual Waste (80% of CO_2 captured)
Biomass CC 0%	Biomass (no carbon capture)
Biomass CC 40%	Biomass (40% of CO_2 captured)
Biomass CC 80%	Biomass (40% of CO_2 captured)

The carbon capture proportion refers to the proportion of emitted CO_2 which is captured at the plant and either sequestered or beneficially used. The report on carbon capture considers the potential alternative mechanism for capture and applications. The designations of 40% or 80% are broad brush assumptions for the purposes of indicating the potential carbon saving impact. KEW are planning detailed investigations and trials (partially under the BEIS ‘Hydrogen Supply’ project) to evaluate several different routes. Some technologies would capture CO_2 from the product gas stream (where hydrogen is being prepared for example and additional CO_2 is produced via water gas shift of the CO) and these are likely to achieve a higher capture rate than those capturing CO_2 from exhaust gases. Thus, also depending on the application of the syngas (e.g. hydrogen or combustion in an engine for power); achievable capture rates may vary.

At this stage though 0, 40% and 80% provide reasonable estimates of levels of capture achievable during KEW’s route to commercialisation as follows:

- 0% immediately;
- 40% within 2 years, after further testing of the technologies for this application
- 80% in the longer term after not only further development, but also financial drivers such as carbon taxes provide required commercial justification.

It should also be noted that these figures understate the benefit as the waste heat from the ATC plants has not been factored in. If this heat is usefully used and displaces other fossil-fuel sources, then the carbon saving is significantly improved.

The supply of 98% pure hydrogen has been considered, as this purity is suitable for many current industrial applications and for fuel switching from natural gas. (Clearly achieving higher purity – e.g. 99.999% hydrogen purity requires further processing and is more energy intensive thus increasing related carbon emissions).

Figure 12 compares carbon intensity of hydrogen provided by ATC units, assuming these units are electrically self-sufficient (use c. 25% of Syngas for electrical generation for parasitics load).

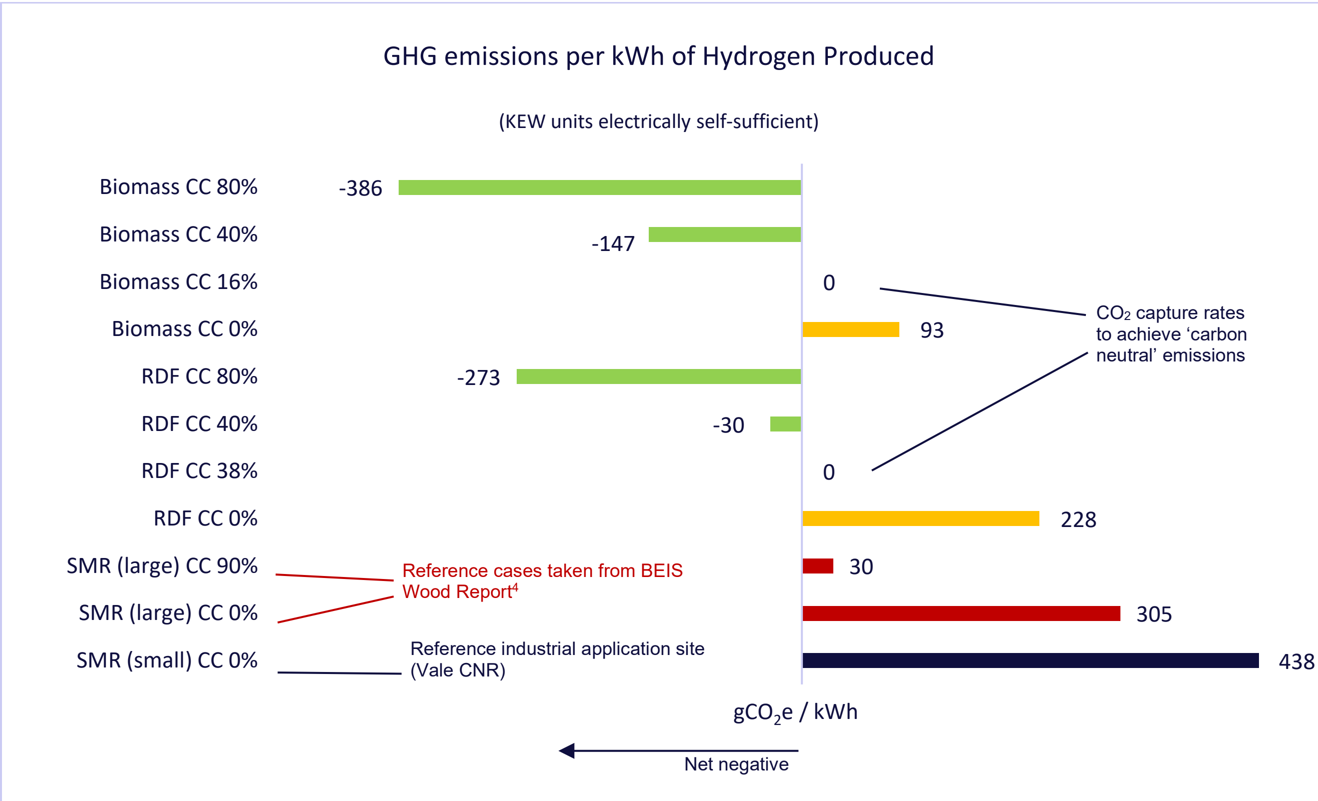

Figure 12: Carbon footprint (CO_2 intensity) of KEW plants for hydrogen production. Biomass and RDF have been compared against large and small SMRs, with CC rates 0%, 40% and 80%. CC rates needed for achieving neutral emissions have been included also; 16% for biomass and 38% for RDF.

These figures actually understate the benefit as the waste heat from the KEW plants has not been accounted for. The heat should essentially be treated as free 'zero-carbon' heat. When this heat is used to displace other fossil-fuel sources, as will be the case at Vale CNR (see section 6.3), then the carbon saving is significantly improved. In short, efficient ATC plants (such as KEWs) can provide lower carbon energy sources now to industrial consumers and a pathway to zero and in the future negative carbon energy.

The diagram shown in Figure 13 gives an overview of the logic and assumptions behind KEW's GHG model, and hence, illustrated how the results presented in Figure 12 have been derived. It shows a visual representation of the transfer of CO_2 between materials and the atmosphere through various industrial and commercial activities. It can be seen that the biomass acts as a major sink for atmospheric

CO_2, whilst the RDF counterfactual emissions are negated as the feedstock is diverted to KEW's ATC & HPM plant.

However, the model lacks detail of the comparative downstream CO_2 emissions of the fertiliser compared with construction aggregates, as well as the alternative CO_2 sequestration options of underground geological storage. Similarly, the model is lacking detail on the capital carbon costs of the construction of its plants (materials, equipment and transport for contractors), even through this is shown in Figure 13. Indeed, KEW expects that its small sized plants and rapid deployment would results in highly favourable capital carbon costs, especially when compared to the other massive energy projects in the UK such as nuclear, which employ many thousands of contractors and take 10 years to build. Nevertheless, both these GHG areas are more complex and require further investigation to fully understand the impacts. KEW intends to develop the GHG model for downstream use, geological storage and capital carbon costs.

It should also be noted that the post-combustion CO_2 removal processes (exhaust gas of the syngas engine and char oxidiser) shown in diagram in Figure 13 have not been simulated in the KEW GPM or studied on a cost basis thus far, but merely aim to illustrate the additional opportunities to increase CO_2 capture beyond 80%. Again, this is an area KEW will investigate further.

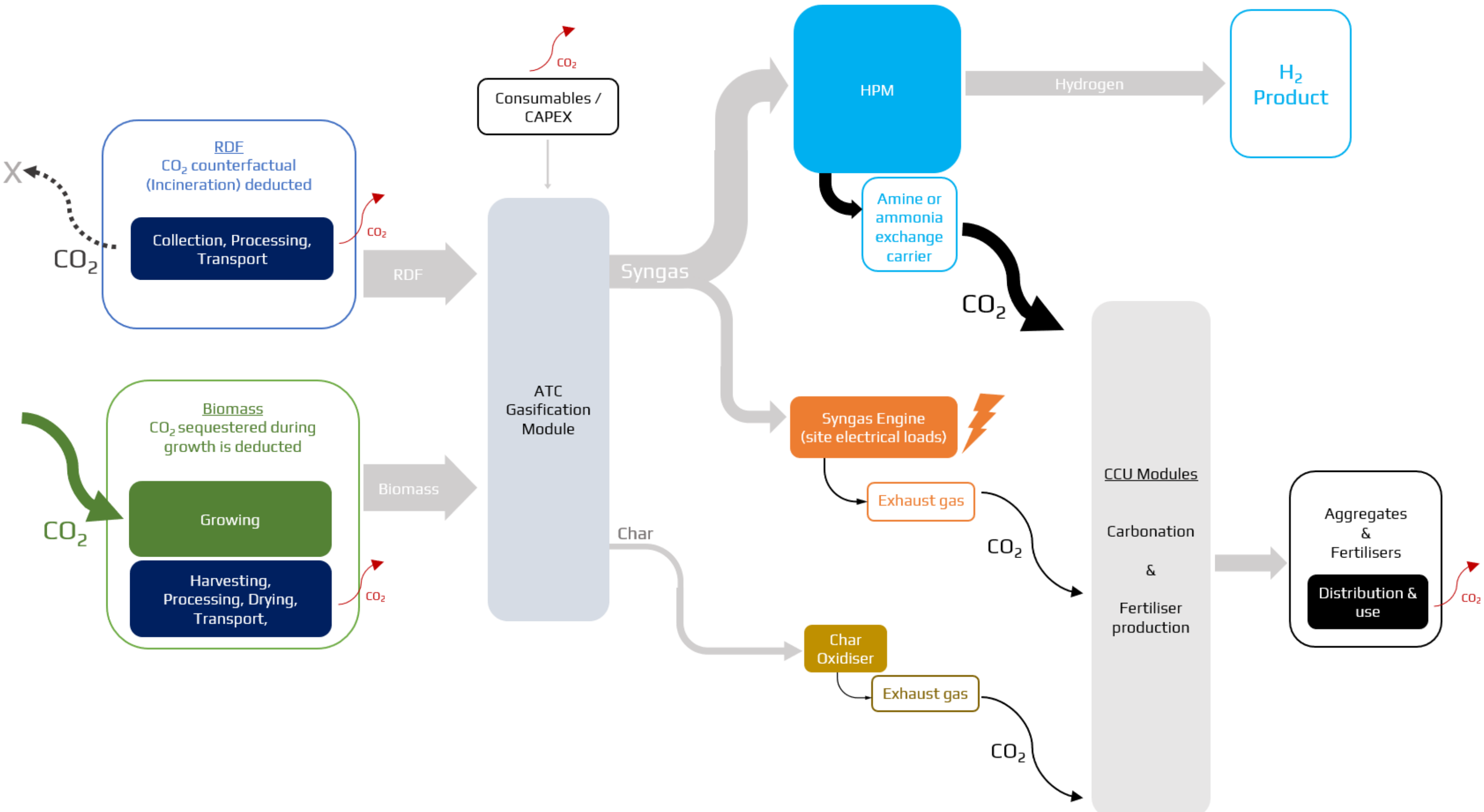

Figure 13: Illustration of KEW's GHG emissions model for the conversion of RDF and biomass into hydrogen. It demonstrates the flows of CO_2 (both emissions and sinks) along the hydrogen supply chain and production system.

Note: that the exhaust gas post-combustion CO_2 removal process is included to illustrate the additional opportunity to increase CO_2 removal beyond 80%, however it has not been simulated in the GPM or studied on a cost basis thus far and is the subject of further investigation.

6 KEW's Route to Commercialisation

6.1 Industrial Supply

Hydrogen in the purity range of 95% to 98% are required for industrial applications, including reductant applications as evidence in section 1 of this report. For this reason, KEW's ATC and HPM have been designed to target these purity levels so they can be deployed primarily within or nearby to industrial sites. This will be the main commercial pathway KEW will follow in the immediate to short term future.

6.2 Sustainable Energy Centre (SEC)

Phase 2 of this project will see the HPM undergo a detailed design, fabrication and installation during 2020. The ATC and HPM will then be tested at the SEC in Wednesbury around the end of 2020 and into 2021, thus taking advantage of the SEC facility already in operation. At the core of KEW's approach to commercialisation, planning is needed to take realistic and measured steps. The capability to build cost-effective and energy efficient small-scale plants is a critical enabler in being able to plan these achievable steps. The HPM demonstration facility planned at the SEC is expected to produce approximately 3480 kWh per day of hydrogen at 98% purity consistently.

6.3 Clydach Nickel Refinery (Vale Europe Ltd)

Often, the hardest step is to move from demonstrator to initial commercial plants. Therefore, KEW have sought out a real industry site for an initial plant with a compelling financial incentive for the host. This forms the short-term development element of our exploitation plan. After testing at SEC, the HPM will be deconstructed and shipped to Vale CNR to demonstrate the modular build in an industrial setting. The HPM will be integrated alongside a new KEW ATC gasifier module to allow the unit to accrue operational hours and "demonstrate" consistent quality and quantity.

Vale CNR in particular has been identified as an ideal industrial hydrogen user because they are already openly engaging in decarbonisation activities. As part of a separate programme; the BEIS Industrial Fuel Switch (IFS) project, Vale CNR is working to decarbonise its plant operations, and in particular, reducing the carbon footprint of its heat, power and hydrogen consumption. Specifically, they are looking to switch away from natural gas which is currently used for heating processes across the activating kiln, and pellet and powder production plants, as well as the natural gas that is used for generating hydrogen in the plant's steam methane reformer (SMR) that reduces the nickel ore. The IFS conveniently ties in with this BEIS 'Hydrogen Supply' project (lead by KEW) and will complement both companies wider commercial objectives.

The hydrogen generated by the SMR is currently 98% pure and the demand is between 1300-2800 Nm^3/hr. This is shown in Table 11 below:

Table 11: Vale CNR Hydrogen Requirements

Product	Purity	Volume Flow Demand	KEW Supply Per Module
Hydrogen	98%	1300-2800 Nm^3 /hr	1000-1400 Nm^3/hr

The hydrogen consumption data shows significant variation so further work needs to be conducted at Vale CNR to record accurate and reliable operational data. This research, along with planning and permitting with the local authorities and environment agencies on behalf of Vale CNR, will form a significant work package for the Phase 2 of the BEIS 'Hydrogen Supply' project.

The carbon reduction opportunities are compelling. Displacing this hydrogen with a medium purity supply from the KEW plant could be extremely attractive, following a grant funding phase. It is envisaged that the hydrogen supply at Vale CNR could be part of a larger programme and scheduled in at the time when risks are sufficiently mitigated. In the long term, around 3 module sets supplying hydrogen could be sited at Vale CNR. The siting of the first hydrogen module at Vale CNR will immediately contribute to carbon reductions.

Subsequent commercial roll-outs will see the same modules repeated and deployed. By repeating the existing plant design engineering costs will be reduced for subsequent projects.

Our study into Industrial Hydrogen has aligned us closely with a Primary Industry, located in South Wales. Our Hydrogen Module is versatile and could be located, in association with a KEW ATC Plant in a wide range of Industrial processes & locations, to deliver Industrial grade renewable hydrogen. As a consequence, it is sensible to consider Feedstock (waste & biomass) availability & suitability across the UK in general but also provide a focus and consider arisings within the South Wales area, to address the requirements of the project, when it is located at Vale CNR.

6.4 Industrial Clusters

KEW are seeking other alternative or additional 'first plant' opportunities to make that critical jump from demonstrator into commercial sales. Large scale foundation industries such as the metals (ferrous & non-ferrous), ceramic, glass, chemical, and mineral could be a natural home for KEW's plants due to its multi-energy vector production. This benefit is reinforced by the fact that foundation industries are particularly exposed to volatility from the energy supply industries. Initial investigations by KEW's project partners CR+ have revealed that the energy consumption corresponds to between 5 & 35% of those sites' operational costs, and this exposure, in the light of the UK's decarbonisation goals, represents significant commercial risk. KEW's renewable, multi-vector energy offering (heart, power and hydrogen) will help to mitigate these risks.

CR+ identified at least 12 sites across three major UK industrial clusters (South Wales, West Midlands and North West), that could utilise approximately 5 KEW modules each. This equates to approximately 100 KEW modules overall that would demand 1.5m tonnes RDF feedstock per year (approximately 50% of the current UK export[34]). All sites have a need for self-sufficient heating and power for their processes and plat utilities. Initial figures suggest 4-6 KEW ATC modules would be needed to satisfy these needs.

KEW will look to secure a market share of the vast Industrial market for bulk hydrogen at 95% to 98%, with a particular focus on the industrial clusters in South Wales, the North West of England and the West Midlands Energy Innovation Zones.

There is also other exploration regarding the "most cost-effective hydrogen purity level that can be delivered through the grid", with purity expected to be at the 98% level,[35] but further research is required and investigations are ongoing. Further into the future, KEW will monitor the fuel cell market as it develops. There will be an opportunity to introduce a Pressure Swing Adsorption (PSA) unit to KEW's modular system to provide high purities of up to 99.999% ("5 nines purity"). It should be remembered though, that the ability to gain consistent outputs rather than high levels of Hydrogen purity is key to the application of the KEW Technology within the industrial sector.

Table 12: Summary of energy vectors available from KEW's technology

Gas Product	Syngas	Hydrogen (98%vol)	Hydrogen (99.999%vol)
Useful Energy Vector	Heating & Power	Heating & Hydrogen	Heating & Hydrogen
Conversion Technology	ATC	HPM	PSA

6.5 Hydrogen Economies

A recent report by WSP about feasibility of zero-carbon hydrogen presents a brief outlook on potential hydrogen economy compatible with the 2050 "net-zero" objective of the UK Government. The overall technologies and pathways forward are assessed and introduced which includes electrolysis, SMR and gasification with carbon capture along with utilisation and storage of carbon (CCUS)[36]. This vision is shown in Figure 14.

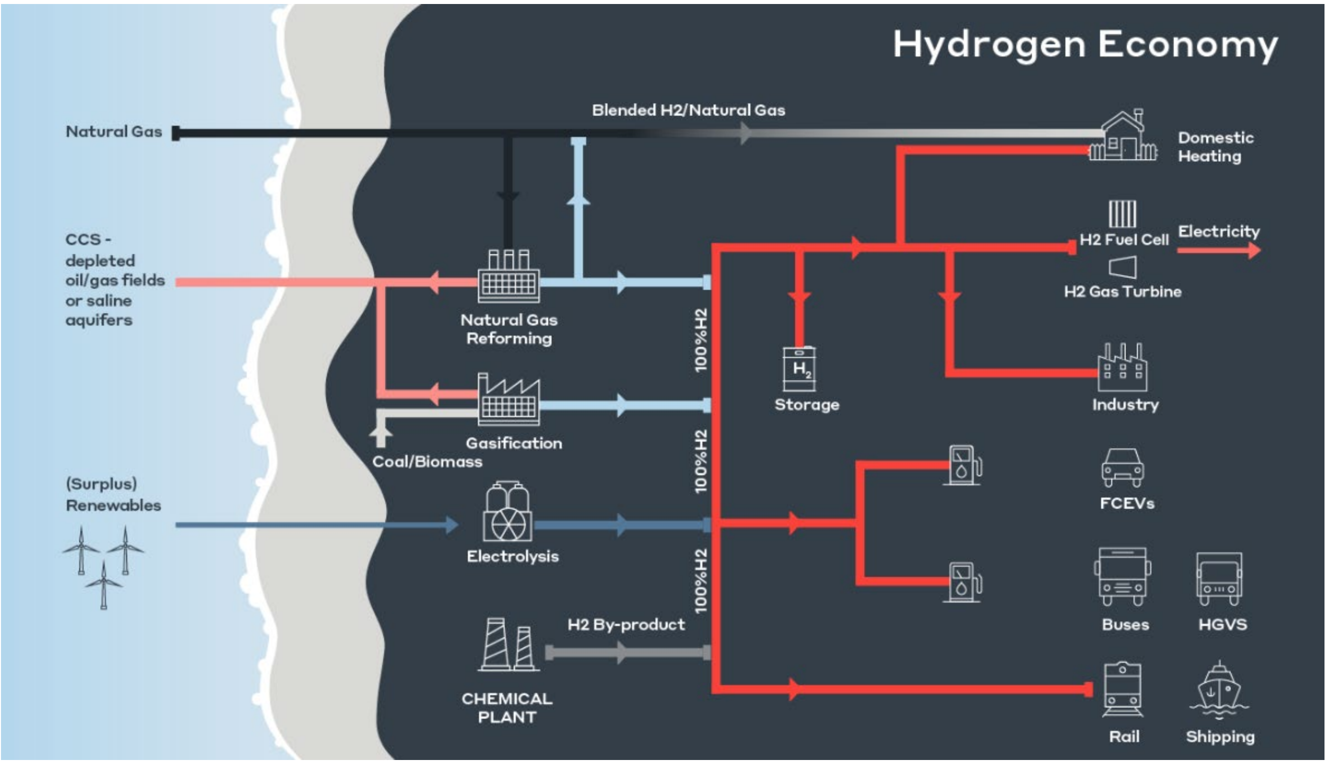

Figure 14: Hydrogen economy vision compatible with the 2050 net-zero emission target. Biomass gasification with CO_2 capture would provide net-negative carbon emissions that would balance the overall economy to net-zero[36].

While the hydrogen production process itself cannot be made zero carbon, there is a way to make it 'net zero'. Applying carbon capture to CO_2 emitted from the combustion of biomass has been proposed as a viable approach to remove CO_2 from the environment – referred to as Bio-Energy with Carbon Capture and Storage (BECCS). CO_2 is absorbed from the atmosphere during the growth of the tree (or other biomass source) and is then permanently stored following capture of the CO_2 from the combustion products of the biomass; therefore, hydrogen produced from gasification will be carbon negative[36].

The opportunity for negative carbon emissions energy sources through BECCS (Bioenergy with Carbon Capture and Storage) has been noted as forming an invaluable part of a future 'net-zero' energy mix, by offsetting carbon emissions from other sectors which cannot commercially or technically achieve zero emissions. However, the commercial drivers for traditional BECCS plants are currently not strong enough (high biomass costs and weak carbon tax regimes), so intermediate steps along the pathway are required. KEW's ATC and HPM plants that consume a wide range of feedstock's, including waste, are a critical enabler for progressing along the BECCS pathway.

Therefore, KEW plants will initially consume RDF to capitalise on the surplus residual waste supply in the UK, and will target a low carbon hydrogen product of 95-98% purity. Subsequent deployment will drive engineering costs down and open up the opportunity for wider industrial applications. Beyond this, when the appropriate government incentive programmes and biomass agriculture schemes are realised, KEW plants will take on biomass feedstocks to produce the same hydrogen product with negative carbon emissions.

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