KEW TECHNOLOGY

CCH$_2$ I Carbon Capture and Hydrogen

An innovative BECCS-H$_2$ Greenhouse Gas Removal solution

BEIS Direct Air Capture (DAC) and Greenhouse Gas Removal (GGR) Innovation Programme | Phase I Report

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Executive Summary

DAC and GGR programme overview and background

Engineered greenhouse gas removals (GGRs) are recognised by all stakeholders as an essential component to reach net zero. Removal of atmospheric CO_2 would allow the UK to reduce its legacy emissions as well as significantly reduce emissions from sectors which have proven challenging to decarbonise due to a lack of suitable 'proven' technologies. GGRs encompass a wide range of technologies at different stages of development including Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS). BECCS projects involve the conversion of waste or biomass into useful alternatives in power, heat, hydrogen or other low-carbon and zero-carbon advanced fuels. As the biomass/waste feedstock has a biogenic carbon content stored from the atmosphere via photosynthesis, the BECCS process results in negative CO_2 emissions if those emissions are captured and sequestered/utilised.

Hydrogen produced via BECCS (BECCS-H_2) represents a valuable zero-carbon energy vector, with potential of reducing emissions from sectors such as heavy industry, aviation, and transport. In recognition of this potential, the UK Government has stated its ambition to reach 5GW of hydrogen production by 2030. In contrast to BECCS, DACCS does not produce other usable energy vectors.

The Department of Business, Energy and Industrial Strategy (BEIS) DAC and GGR Programme officially began in 2021 and aims to provide £70 million to identify and demonstrate GGR solutions that have the potential to be deployed at significant scale in order to reach the UK Government GGR target of 5 MtCO_2/year by 2030.

KEW's GGR solution: CCH_2

KEW, one of the Phase I winners of the GGR competition, has proposed a modular BECCS-H_2 GGR solution, called the Carbon Capture and Hydrogen Purification (CCH_2) product; a modular BECCS-H_2 technology for achieving cross-sectoral deep decarbonisation and delivering GGR through negative emissions. The CCH_2 product is capable of producing high purity CO_2 as well as industry-grade and fuel cell vehicle (FCV) H_2 using KEW's advanced gasification process. When using a biomass/waste feedstock, the process is a prominent and compelling example of both BECCS-H_2 and GGR. The KEW CCH_2 product solution includes the following key features:

- **A pressurised advanced gasification unit, a form of Advanced Conversion Technology (ACT)**, which can utilise a wide variety of non-recyclable waste and low-grade biomass feedstocks processes by unique application of pressure, a fluidised bed gasification system and a proprietary downstream synthesis gas (syngas) reformation process. This provides increasing feedstock security but also uniquely supporting the land and community regeneration as well as other Government development programs seeking to widen and deepen the UK biomass resources supply chain.
- **Carbon capture ready syngas with consistent composition and quality**, KEW's proprietary process, the Equilibrium Approach Reformer (EAR), produces a clean, H_2-rich syngas as the key output product from the KEW advanced gasification process. KEW's ACT process can therefore provide a consistent, clean, composition of syngas, free of any hydrocarbons (tar) and contaminants to enable stable performance parameters, low-cost operations and reliable syngas offtake ready for pre-combustion carbon capture and for further upgrading into H_2-rich advanced fuels. The lack of syngas consistency and quality has been the traditional 'achilles heel' of other precursor ACT technologies.

- **CCH_2: the carbon capture with H_2 production GGR solution**, the reformed H_2-rich syngas is then further upgraded through water-gas shift (WGS) conversion to H_2 for industrial use (as a replacement for fossil derived H_2 or natural gas) with the CO_2 selectively removed from the syngas stream via pre-combustion capture. The removed CO_2 will then be liquefied and purified before being transported to the nearest pipeline or utilised in the production of concrete or building materials; where it will be sequestered (remain locked away) in an environmentally friendly way for maximum GGR impact. The H_2 can be further purified (e.g. using Pressure Swing Adsorption: PSA) to meet the specification required for fuel-cell / transport applications.
- **A unique modular approach for the ACT sector**, enabling early adopters to overcome the current "gasification graveyard" of large-scale, bespoke project solutions by offering repeat proven units while allowing for the subsequent installation of additional modules in a flexible, rapid deployment approach. KEW's modular solution, aided through the application of pressure provide 8x the capacity of equivalent-sized atmospheric units thus enabling commercially viable projects in compact footprints for the decentralised industrial market that is not well served by a large scale centralised production and supply model. The modularity also enables installations across the whole of the UK local to feedstock supply; in dispersed sites or near CCS pipelines.
- **Existing, operational advanced gasification plant at commercial scale**, with unique support from the Energy Technologies Institute (ETI), KEW has constructed, commissioned and is now operating the Sustainable Energy Centre (SEC) – a commercial scale, advanced gasification plant to underpin the BECCS-H_2 GGR solution and will demonstrate the First-Of-A-Kind (FOAK) CCH_2 product. As the SEC proves the ACT part of the BECCS-H_2 process, this limits the technology development risk incurred with developing the GGR solution to only the incremental risk in the CCH_2 module development, not the whole end-to-end process.

Developing the CCH_2 product; focus of the Phase I feasibility

KEW's core focus in Phase I of the DAC and GGR Programme was to assess the technical and commercial feasibility of the proposed GGR solution, the CCH_2 modular product, to provide a strong foundation for the subsequent detailed engineering, development and demonstration of it in Phase II.

Overall, in Phase I KEW conducted key work on defining and refining the design, specifications, safety, and business model of the CCH_2 modular product by:

- **Designing CCH_2's scope, configuration and detailing the key system specifications**, including evaluating the most appropriate CO_2-H_2 separation technique, carbon capture and energy performance, gas storage requirements, and safety hazards/mitigation techniques.
- **Analysing the business case for commercial deployment** of the modular product and comparison of the estimated solution costs to the BEIS estimated 2030 and 2050 GGR costs based on £/tCO_2 removed.
- **Forming a strong foundation for Phase II Demonstration Phase** to retrofit the existing KEW commercial-scale demonstration plant, the Sustainable Energy Centre (SEC), to accommodate the development and demonstration of the CCH_2 product to prove successful and continuous operation of the fully integrated BECCS-H_2 technology in commercial-scale context. The successful demonstration would increase the TRL of the technology to TRL8 such that the design should be ready for commercial exploitation from the end of Phase II in 2024.

Overview of the CCH_2 product

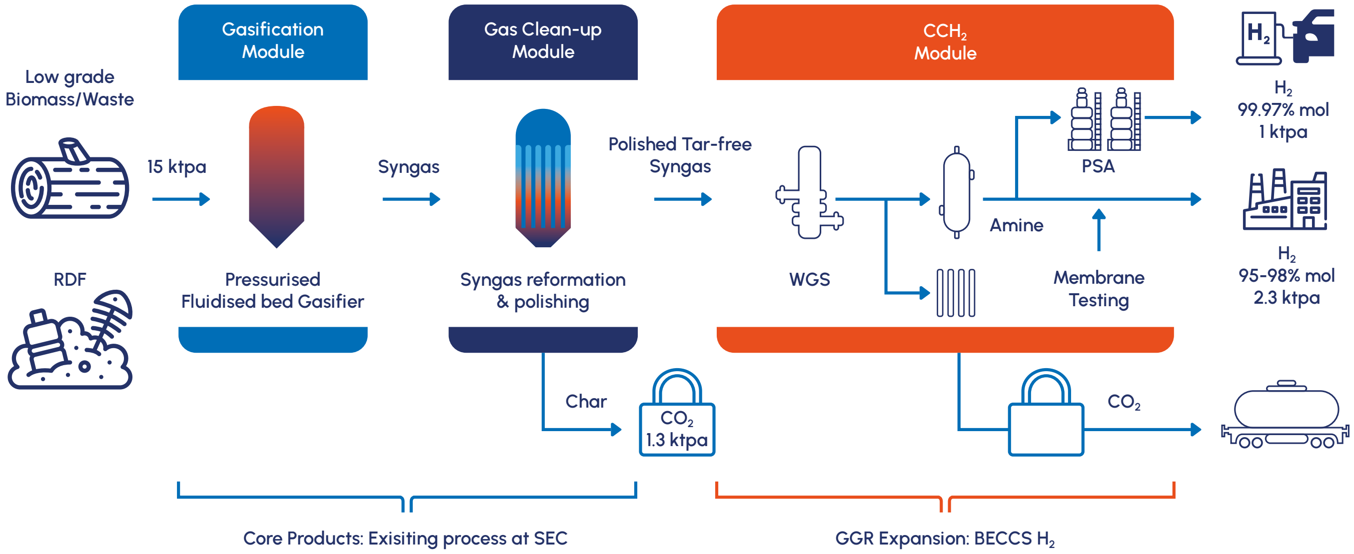

Figure 1: The innovative BECCS-H_2 GGR solution: CCH_2

The core scope of the Phase I feasibility, to be demonstrated at commercial scale in Phase II, is designated by the blue bracket above, with additional supporting activities working on the complete value chain.

The proposed CCH_2 product is designed to fit within a c.225m^2 space, with the storage vessels positioned apart in the required storage area, meaning not only can it be accommodated at the SEC, but also confirms its land requirement at industrial end user sites is also small unlike large, risky, “mega-projects”. The CCH_2 module will further process the syngas that has been produced by the existing and operational upstream Advanced Conversion Technology (ACT) which comprises of advanced gasification, subsequent syngas reformation and clean up steps. The add-on CCH_2 module will separate the CO_2 and H_2 contained in the syngas for utilisation and sequestration of the CO_2 and downstream application of the H_2 in industry and transport (see Section 2.4. for a more detailed description).

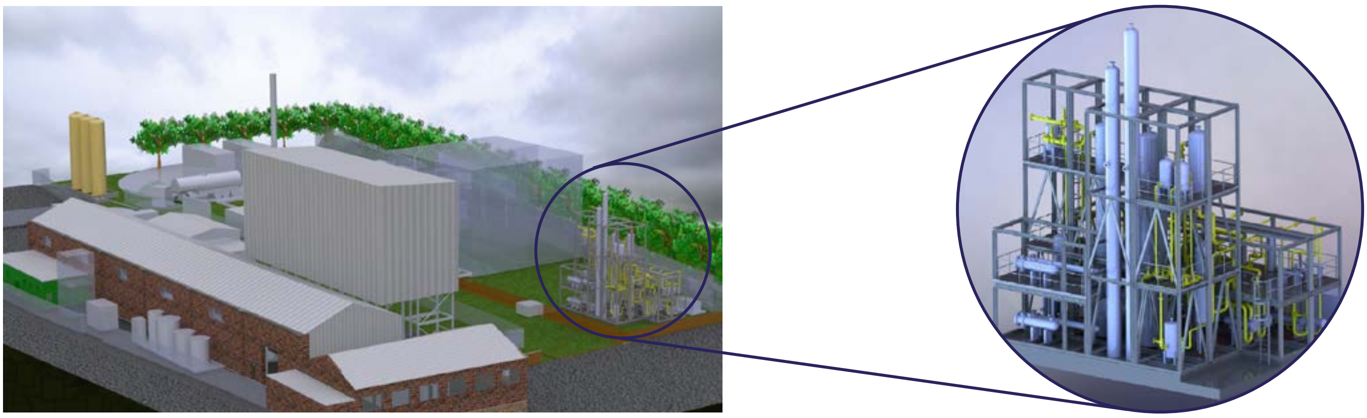

Figure 2: Spatial visualisation of the CCH_2 model at KEW’s commercial plant at the Sustainable Energy Centre in the UK (proposed Phase II location).

Core conclusions of the Phase I feasibility

A low-cost GGR solution

Fundamental to ensuring that GGR technology can be effectively rolled out across the UK economy is demonstrating that it is not only technically viable, but also economically viable across a range of deployment scales (as not all installations will or can be the same size). KEW's Phase I commercial and financial assessment concluded:

- KEW's GGR solution can be deployed at a lower overall cost to the taxpayer/ consumer, comparing favourably to published forecast costs. KEW's analysis indicates that by 2030, it is forecasted the value of the H2 will be largely paying for the overall system (see Figure 3).
- Further economic advantages are forecast after 2030 to enable the BECCS-H_2 route to be a cost neutral methodology to remove CO_2 from the atmosphere.
- Indicative existing and projected future costs are shown below comparing some of the possible technical solutions clearly indicating significant value for money benefits arising from the proposed BECCS-H_2 solution.

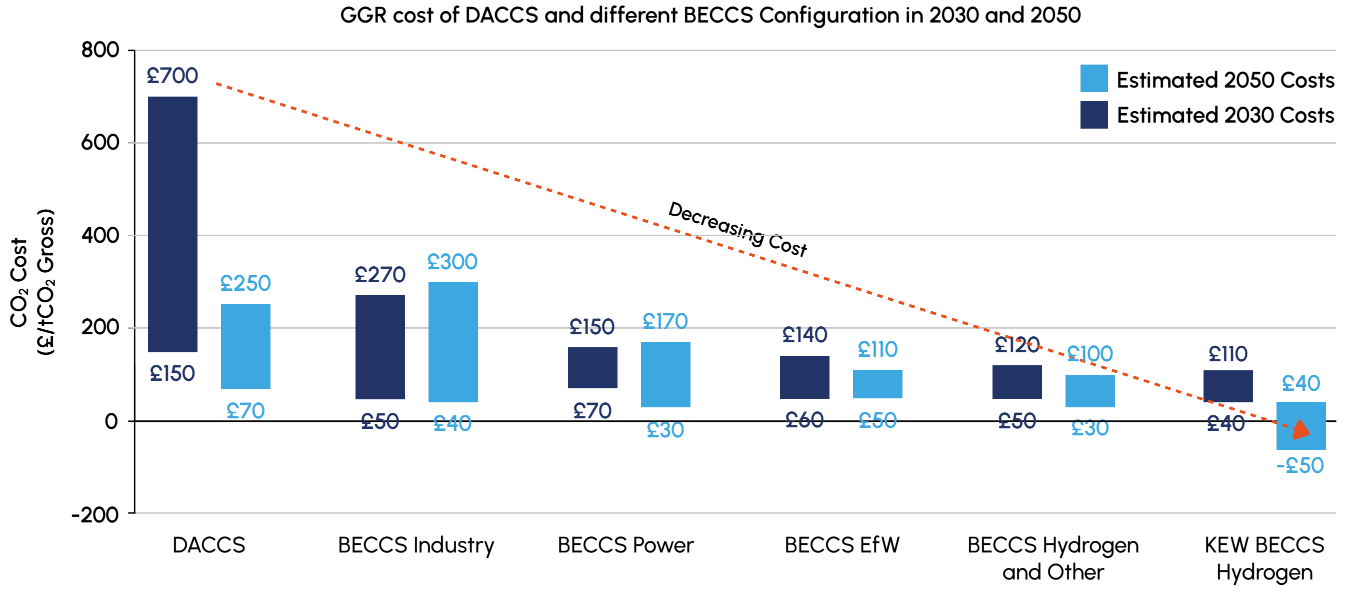

Figure 3: Comparison of KEW's estimated solution costs to the estimated 2030 and 2050 GGR costs based on £/tCO_2 removed, with BECCS Hydrogen highlighted as the cheapest potential GGR option[1].

[1] Data derived from BEIS report (2021) "Greenhouse gas removal methods and their potential UK deployment", https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment data/file/1026988/ggr-methods-potential-deployment.pdf

Wider drivers supporting CCH_2's pathway to becoming a low-cost GGR solution in the longer term

- **Waste to value:** effective utilisation of the valuable waste and biomass resource through BECCS for H_2-rich fuels. Incineration of waste to produce electricity is an increasingly poor route from a GHG viewpoint given recent significant grid decarbonisation from wind and solar deployment; and addition of post-combustion carbon-capture costly (due to low CO_2 concentration and atmospheric pressure). Advanced gasification of the waste enables provision of energy vectors that tackle the harder to decarbonise sectors including industrial processes and transport. This further emphasises the need to prioritise feedstock resources for BECCS intended for H_2 and H_2-rich fuels rather than the conventional, inefficient model of generation for grid electricity.
- **End-product driver:** H_2, as the energy vector produced through the advanced gasification of waste is of higher value than electricity, the sale of H_2 -rich products provides consistent revenue for the purchase of the biomass feedstocks which can be then sourced in the most environmentally beneficial way (e.g. local, considering biodiversity and rural economies). Overall, BECCS-H_2 can play a significant role in parallel to multiple other H_2-rich fuels production routes whilst also contributing significantly to GGR with significant potential for provision of negative-carbon energy products.
- **De-risked scale up through the modularisation of the BECCS-H_2 solution:** at the core of KEW's strategy is standardised factory-build modular construction which enables strong ongoing cost-reductions enabling wide-spread deployment. The modules can be installed and commissioned at host industrial sites in short timescales with minimal disruption and risk, making use of locally available feedstock. KEW's CCH_2 product is based on the same approach.

An innovative technically viable GGR solution

A detailed FEED study was undertaken in Phase I which evaluated potential technologies to be incorporated in the CCH_2 module, and following selection delivered a costed design ready for commencement of the Demonstration Phase. A summary of the core technical feasibility conclusions is described below.

- The process design to produce Hydrogen to industrial grade (90-98% purity), which was shown to be cost-effective, or Fuel Cell Vehicles (FCV) grade (99.97%).
- The CCH_2 module can thus service multiple markets, thus providing operational flexibility and economies of scale through serial deployment. Depending on the Hydrogen purity, the overall process efficiency differs:
    - For distributed industrial H_2 production for use in fuel switching at smaller industrial sites, the conversion efficiency of the feedstock to industrial H_2 is c.56 60% (LHV basis),
    - This reduces to c.46% (LHV basis) for FCV-grade H_2 due to the reduced yield and additional compression energy
    - Nevertheless, both routes exhibit roughly double the conversion efficiency of BECCS for electricity (c.25%), which, if coupled with electrolysis to produce H_2 would result in an overall conversion efficiency of c.16-18%.
- In addition to the advantage of pre-combustion CO_2 capture over post-combustion due to the higher CO_2 concentration, the cost and energetic savings due to pressurised operation were characterised. These will offset the otherwise higher costs of smaller-scale facilities.
- However, it is noted that as economies of scale for larger facilities are stronger for carbon capture and H_2 purification processes than for gasification, that future commercial scale plants would be most likely to marry multiplexed ACT modules with single larger CCH_2 units.
- The proposed CCH_2 design utilises commercially proven technologies in order to enable swift commercial deployment. Technologies such as Membranes (For separation of H_2 and CO_2) and Sorption Enhanced Water Gas Shift (SEWGS) could offer benefits in improved efficiency and lower costs (even for smaller-scale units) and will thus be tested at small-scale during the proposed demonstration project.

Achieving wider impact; environmental and social benefits

Ultimately, the deployment of CCH_2 product will stimulate the domestic supply of and demand for biomass, developing new regional biomass crops and growing the national capacity of local, biodiverse supply chains financed by the H_2 revenue. As a result, UK's biomass value chain will be strengthened to support future-proof energy generation.

KEW's business plans forecast that 3,500 jobs would be supported in rural regions, particularly important during a period of adjustment to a post-CAP economy.

KEW's proposed geographically distributed deployment model provides value to all areas of deployment and more so to rural society while bolstering the UK's reputation as a pioneer in green technologies.

Summary of the GGR Phase I feasibility justifying progression to demonstration

- **A complementary technology solution:** given the forecast demand for H_2, KEW's development of the BECCS-H_2 technology would not be in competition with other GGR technologies but would complement these projects by providing unique benefits to industrial users and, through modularisation, a more welcoming space for GGR investors. This broadens the horizon of negative emissions contributors and creates a more comprehensive and diverse portfolio of the UK GGR potential for 2030 and beyond.
- **Demonstration ready:** the existence of the SEC, the proposed Phase II location, as a proven commercial scale demonstrator of the advanced gasification technology significantly reduces the commercial and financial risks of installing and developing the GGR solution as the development of the CCH_2 product is incremental.
- **Overall, BECCS-H_2 GGR route proposed here is founded on the principle of converting the maximum possible energy** contained in a wide-range of biomass and waste sources into a carbon-free energy vector: H_2. Alongside sequestration of the CO_2, this offers a strong opportunity for net removal of greenhouse gases from the atmosphere.

Demonstration Phase definitive outcome; further CCH_2 development and commercial-scale demonstration

The Demonstration Phase will deliver a commercial-scale GGR facility from biomass/waste to H_2 production. Based at the SEC, KEW's flagship commercial-scale facility in the Midlands UK.

It will build on the existing commercial scale equipment, to demonstrate the "**innovation in the integration**" of the full end-to-end process of the BECCS-H_2 GGR solution via fully integrating the advanced gasification, H_2 production, and CCS components within the CCH_2 modular product.

Building on the key insights from Phase I, the Demonstration Phase currently has the following initial objectives:

1. Technical: manufacturing of the CCH_2 module, followed by installation of the add-on module and a series of tests followed by continuous operation of the end-to-end CCH_2 system.
2. Value Chain: to evaluate potential and viable opportunities for low-grade biomass feedstock supply that provide the longer-term strongest GGR capability; through testing and demonstration at commercial scale. Phase II will also evaluate the technical, commercial, and operational feasibility of CO_2 and H_2 offtake, considering the logistics of CO_2 and H_2 transport.

These objectives are intended to integrate based on the indicative timeline shown in Figure 4 and summarised in more detail in Section 3.

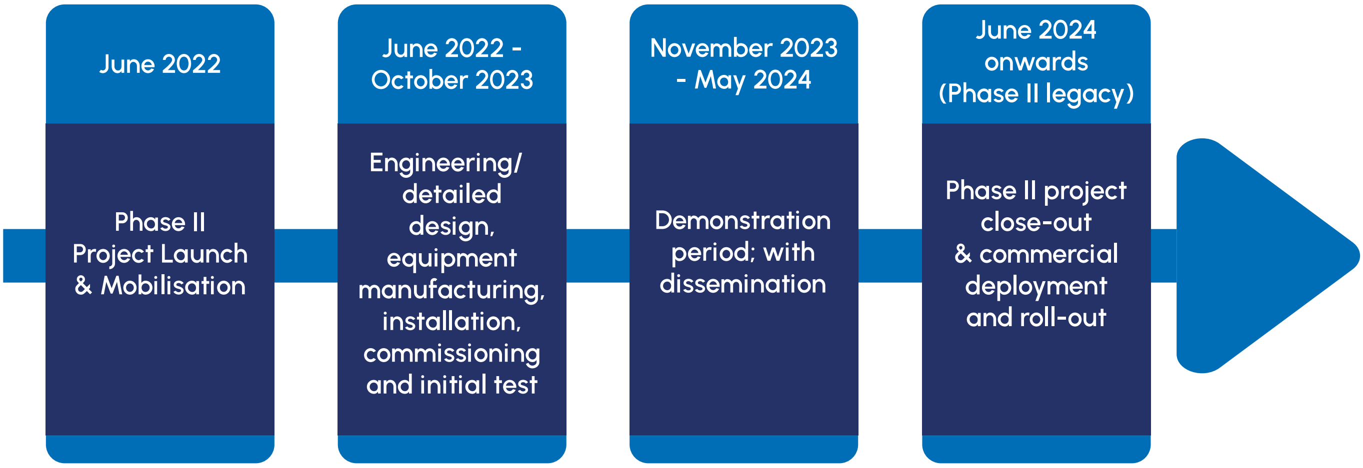

Figure 4: Timeline of CCH$_2$ development pathway

As the Demonstration Phase will use the existing, operational SEC facility for syngas production, which is the most technically challenging aspect of BECCS for H_2 . The use of this existing ACT plant also substantially reduces the Demonstration Phase development period, costs and risks, as KEW has already developed the syngas production knowledge, engineering facilities, and risk mitigation strategies. Therefore, early design and implementation of a Phase II demonstration project is expected to be significantly less complex, and KEW could accelerate the CCH$_2$ product development to commercial deployment. Overall, KEW's Demonstration Phase Development Plan will provide a low-risk development and deployment of GGR technology as it builds on existing, proven gasification technology.

CCH_2’s commercial deployment pathway

It is critical to ensure that the development of the H_2 economy is supported by a robust carbon capture plan. The UK Government has stated its ambitions for achieving net zero carbon and the role that CCUS needs to play and is willing to support the rapid development of the sector via infrastructure incentive support in a similar way to renewable electricity.

If this support framework is structured appropriately, it will allow of a basket of technologies to come to the fore, which can address both large-scale generation and supply (i.e. electrolysers linked to CCS pipelines) and smaller scale decentralised production from ACT syngas linked to off-grid /remote industrial locations.

KEW believes that a modular approach to decentralised H_2 generation with CCUS should be a key part of the technology solution basket, working alongside larger scale projects. The modular approach offers the following advantages compared to larger scale electrolysers:

1. Decentralised solution to serve off grid industries or those industries that are not near a planned CCS pipeline or centralised sources of H_2 generation.
2. Providing a more rapid roll out that in turn would drive a rapid deduction in supply chain costs. This would enable the sector to become less reliant on government subsidy support, as already evidenced in the renewable electricity sector.
3. Smaller scale projects are easier to deploy and finance, as they overcome key barriers such as EPC engagement and deliverable feedstock solutions. A more rapid rollout would establish technology performance, enabling investor return requirements to fall alongside supply chain costs.

Achieving the right support framework will provide additional benefits of supporting the Government in its strategy of creating a viable UK biomass feedstock supply chain at a local level, creation of UK green technology leadership / green collar job creation, as well as supporting the broader ‘Levelling Up’ agenda, given the distribution of off-grid industry across the UK. Equally, smaller scale decentralised projects offer a compelling taxpayer ‘value for money’ story as roll-out drives supply chain cost and investor return requirement reductions.

1

CCH$_2$: an ACT route to a BECCS-GGR solution

1.1 The Advanced Conversion Technology (ACT) opportunity

1.1.1 The problem; big is not always beautiful

One of the key challenges impacting the UK/Europe's ability to achieve energy and climate targets has been that global waste and energy systems were heavily reliant upon less efficient, very large mass-burn Incineration, to convert waste into energy. A technology gap has and still exists for small scale decentralised technology solutions (in the <10MW scale) to provide a more flexible and local solution to waste treatment into valuable end energy vectors, applicable for hard to decarbonise energy end user sectors. This technology gap was identified by the Energy Technologies Institute around 2012, and resulted in a development programme which provided strong support to KEW's technology development.

The benefits of supporting small scale ACT was the ability to efficiently convert a wide range of both residual waste and/or biomass directly into a range of high-value energy vectors, rather than just electricity and occasionally low-temperature heat, which are the only outputs from the incumbent waste incineration. The UK and global market had seen many failed medium and large-scale ACT projects, where either (i) waste types, (ii) residue outputs, (iii) and more typically the failure to deal with the resultant long-chain hydrocarbons (tar) within the syngas stream, had seen many projects fall and significant investment and confidence in the technology lost. Ultimately, these failed ACT technologies had sought to accelerate from lab-scale demonstration to full scale commercial operations, without sufficient investment being made in the RandD cycle that is critical to bridge the technology scale up element of the technology readiness curve.

1.1.2 Addressing the problem; start small to build big

KEW's mission is to simultaneously tackle two of the most significant global environmental issues – providing low or negative carbon/sustainable energy supply through the effective conversion of waste in a true circular economy framework. De-fossilisation is the biggest challenge of the current century, with circular economy becoming the dominant issue from a resource preservation and allocation perspective. KEW's process enables the high efficiency use of non-recyclable waste and biomass feedstocks through high pressure conversion into high-value energy products such as advanced fuels (hydrogen, aviation fuel, diesel), heat as well as power through compact, modular efficient plants. The syngas produced comprises significant but stable proportions of H_2 and CO, enabling efficient pathways to these advanced fuel vectors. KEW's modular plants are carbon capture ready to achieve greater than 100% GHG saving vs. fossil fuels, in line with governments' net-zero aspirations.

KEW's key technology USP is operating the ACT system under pressure, with a patented syngas reformation step, which enables the cracking of the longer hydrocarbons and removal of impurities which otherwise create challenges with solids and tar build up – one of the biggest challenges in the gasification space. Additionally, the use of pressure is a strategic design characteristic which gives rise to the significant benefits of economised scale and costs enabling KEW's unique strategy: to apply its technology into embedded energy projects and deploy its technology immediately while allowing a gradual commercial ramp-up of larger advanced sustainable fuels production facilities with leading strategic partners

KEW's modular, high-pressure system is capable of processing a wider basket of waste and biomass feedstocks. Uniquely the system can effectively process low-grade biomass such as sewage sludge, AD digestate and waste 'fines' with minimal front-end pre-treatment. This effective solution for low grade waste feedstocks diverts commercial and industrial waste material from landfill, generating an economic saving as well as providing an environmental benefit.

The modular high-pressure design combined with the processing of low-grade feedstocks drives a compelling economic proposition compared to other decentralised technologies, meaning projects with KEW's technology require significantly less government incentives to achieve required levels of financial return required by the funder community. Equally our modular technology and high levels of syngas composition provides a unique stepping stone towards high value energy vectors such as hydrogen, distillates and LPG alternatives.

From an emissions perspective, the solution is fundamentally low carbon, significantly reducing the emissions associated with the applications which they fuel. Moreover, the KEW solution is inherently carbon capture ready; enabled for pre-combustion capture. This is much more cost effective than attempting post combustion capture and KEW's plants produce pressurised CO_2 reducing cost for capture and sequestration.

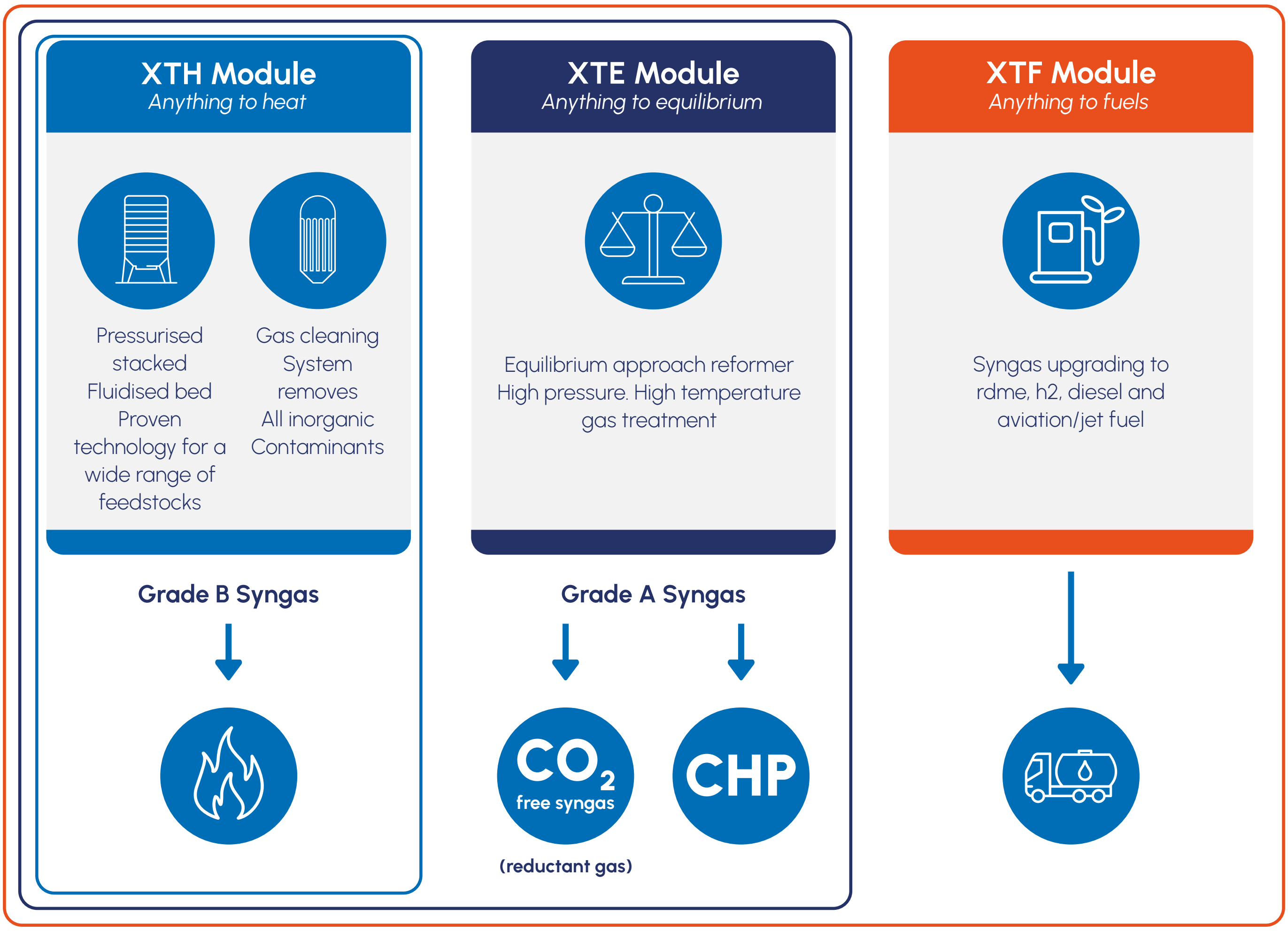

Figure 5: KEW's solution overview

- A robust, proprietary stacked fluidised bed **giving excellent feedstock flexibility and cost effectivness.**
- **The first UK technology to achieve “End of Waste”** status.
- Unique pressurised operation makes system **compact and cost effective – fully factory built.**
- Pressurised syngas supply gives unprecedented **advantages for industrial integration and synthesis applications.**
- Patented Equilibrium Approach Reformer completely **normalises gas composition independent of input feedstock.**

1.2 The carbon capture via H_2 production opportunity

KEW’s proposed Greenhouse Gas Removal (GGR) solution involves capturing CO_2 released from biogenic wastes (or biogenic portions of wastes) and low-grade biomass feedstocks when those solid feedstocks are gasified and processed into H_2-rich vectors via the Carbon Capture and Hydrogen (CCH_2) product.

Step 1

During the growth of the biogenic matter, whether it is food or energy crops, photosynthesis sequesters CO2 from the atmosphere to form carbohydrates in the crop

Step 2

The biogenic matter is then utilised as the feedstock for the ACT process and are then pre-treated ready to for gasification

Step 3

Where the carbon and energy content are gasified into syngas

Step 4

That is upgraded and reformed to H2-rich syngas

Step 5

The reformed H2-rich syngas (free of any hydrocarbons (tar), contaminants and is of a consistent composition) is then further upgraded through water-gas shift (WGS) conversion (and PSA for transport applications) to pure H2 for downstream industrial use (as a replacement for fossil derived H2 or natural gas) or for transport use with the CO2 selectively removed from the syngas stream via pre-combustion capture

Step 6

The removed CO2 will then be liquefied and purified before being transported to the nearest pipeline or utilised in the production of concrete or building materials; where it will be sequestered (remain locked away) in an environmentally friendly way for maximum GGR impact

Step 7

Effectively reducing the quantity of greenhouse gas emissions in the atmosphere. In addition, the ACT process also produces char, which is a process by-product rich in carbon. This by-product presents an additional option for carbon sequestration by locking carbon long term either in soil or materials via multiple identified routes

One of the options of interest is the production of sustainable fertilisers. These products not only deliver carbon sequestration benefits, but also improve soil quality by enriching the carbon content and retaining nutrients longer term. These soil improvement materials could be used to assist in the development of a commercially viable sustainable energy crop grown on marginal land through improving the quality of that soil.

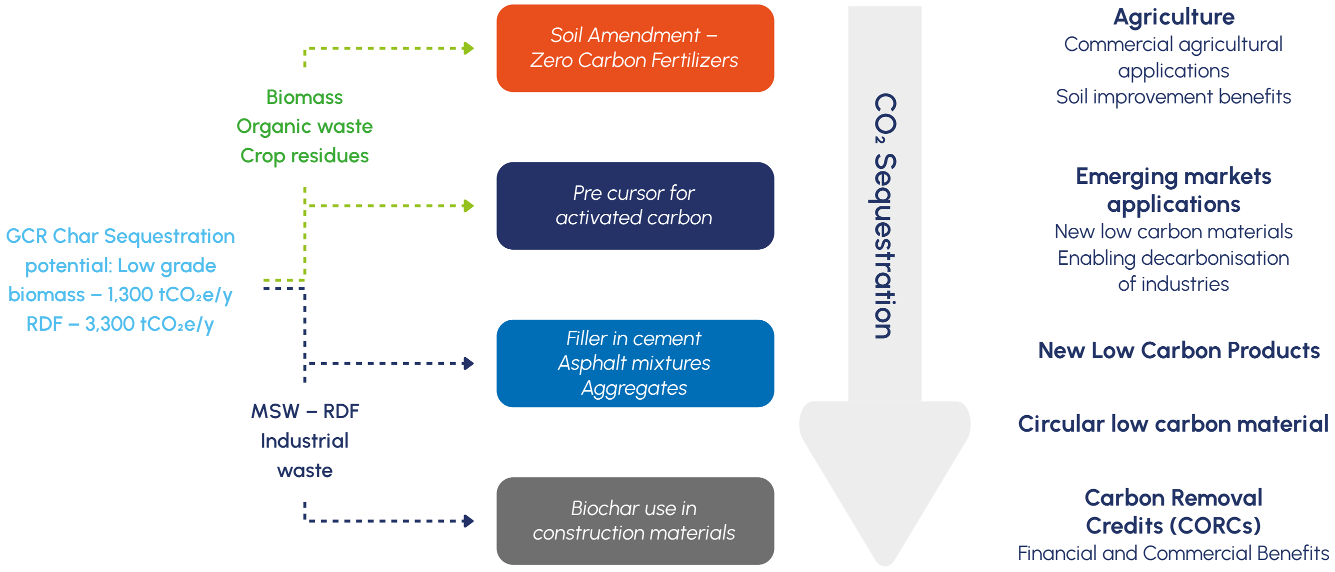

Figure 6: Char utilisation and sequestration; a form of CCUS

1.3 A BECCS-H$_2$ Greenhouse Gas Removal (GGR) solution; KEW's CCH$_2$ product proposition

KEW's commercial and technical GGR Phase I feasibility study on the BECCS-GGR technology route, in the form of the proposed CCH$_2$ product solution, is focused on being the end-to-end innovative integration of the conversion of syngas from KEW's advanced gasification technology into H$_2$ and clean CO$_2$.

Each modular CCH$_2$ product:

- Consumes around c.15,000 tonnes of feedstocks per year.
- Produces c.4MW energy output as Hydrogen product (c.120 kg/hr).
- Provides net c.20,000 t.p.a. of CO$_2$e removal.

KEW is proposing an end-to-end fully costed and risk mitigated solution which brings together existing proven technologies, in an innovative BECCS-GGR solution (see Section 1.2 above).

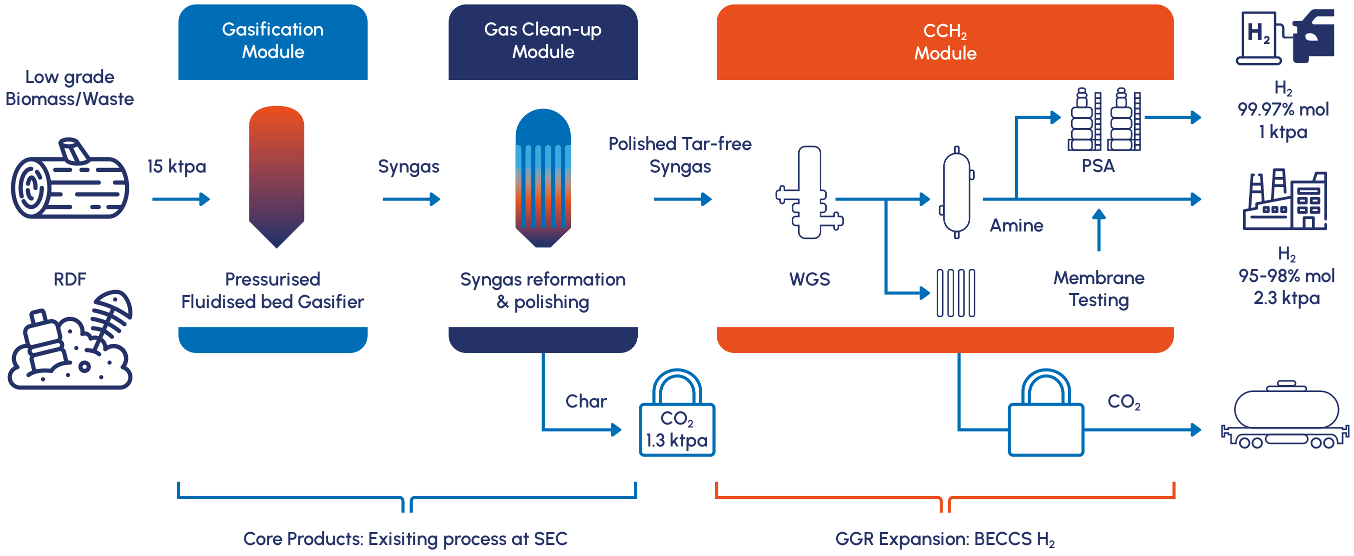

Figure 7: Integrated core components of KEW's GGR solution

The ACT gasification technology is already commissioned and in operation at the Sustainable Energy Centre (SEC) in Wednesbury near Birmingham, UK. It is at this site that KEW is proposing to demonstrate the First-Of-A-Kind (FOAK) CCH2 product and deliver the GGR Phase II Project by designing, integrating and installing the additional downstream CCH2 modular add-on unit that will capture and remove the CO_2 from the syngas and prepare it for offtake, whilst producing a commercially viable H_2 product.

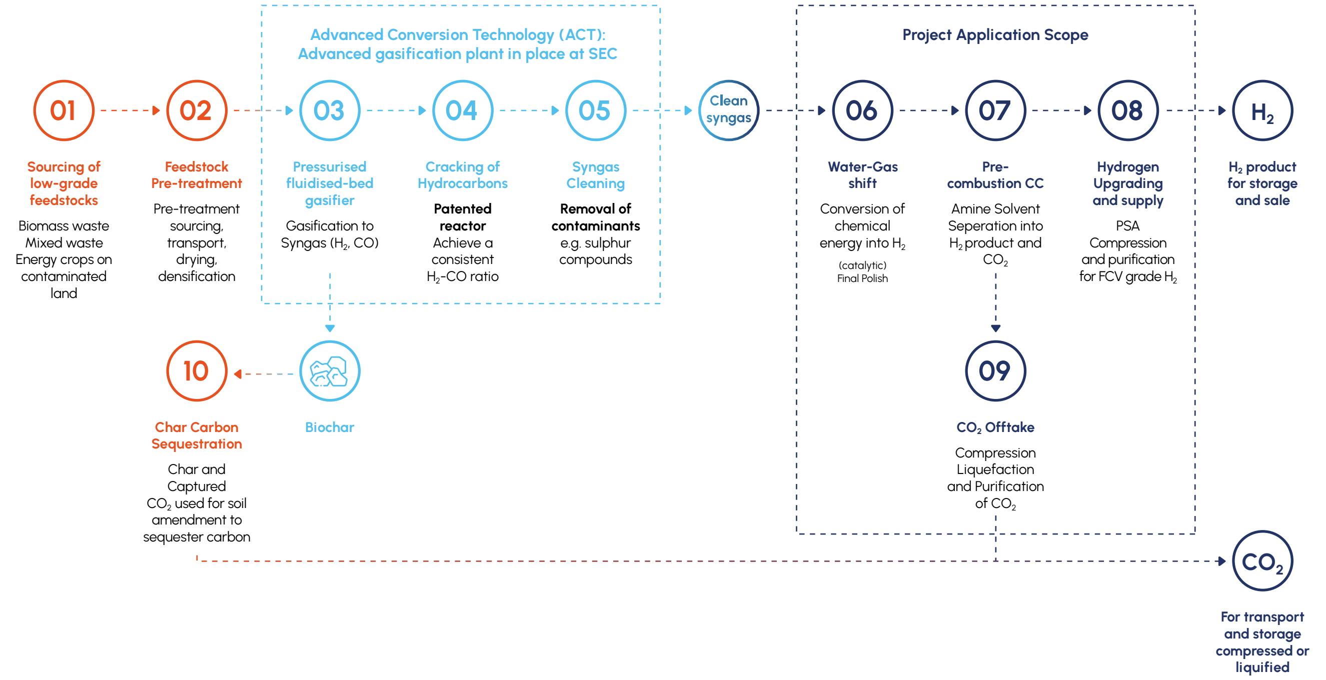

Figure 8: Summary of the process steps that make up KEW's proposed GGR solution

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Benefits of the CCH$_2$ product; a compelling BECCS-GGR solution

2.1 Context; alignment with emerging policy and macro drivers

The conversion of waste (RDF) and biomass into H_2 with the capture of CO_2 for utilisation or sequestration is a promising GGR approach with the revenue from the H_2 providing critical support to the overall economics of the envisaged project. This is in line with the UK Government policy trajectory on biomass, as outlined in the recently published Biomass Policy Statement which highlights:

- Gasification is a key area of innovation due to its feedstock flexibility and useful product production.
- BECCS-H_2 could contribute a total of 30 MtCO_2/year in negative emissions by 2050.
- BEIS and CCC analysis recognises a potentially increasing role for biomass gasification with CCS as a hydrogen production route as early as 2030.
- Biomass gasification with CCS could provide up to 20% of total H_2 production by 2050.

2.2 Achieving negative GGR cost; commercial benefits

2.2.1 A low-cost GGR solution; CCH2

There are currently a range of GGR technologies being developed utilising different technology solutions. Cost estimates for some of these technologies have been developed and published by BEIS as summarised in the chart below.

For comparison, KEW evaluated net costs for its intended configurations for this period using the same sequestration cost assumptions and the following configurations:

2030: Compact facilities of 3x modular units, which can be deployed close to feedstock sources, and energy users. In order to deliver multiple facilities in this period it is assumed that the CO_2 would be transported in liquefied form via train (or worst case HGV) to pipelines. A cost assumption of £38/t CO_2 was used as being the average of the 'truly-dispersed' sites category analysed in BEIS dispersed sites report. The resultant cost range is very similar to the BEIS estimate for BECCS H_2 and is based on achievable deployment plans meeting the requirements for commercial finance.

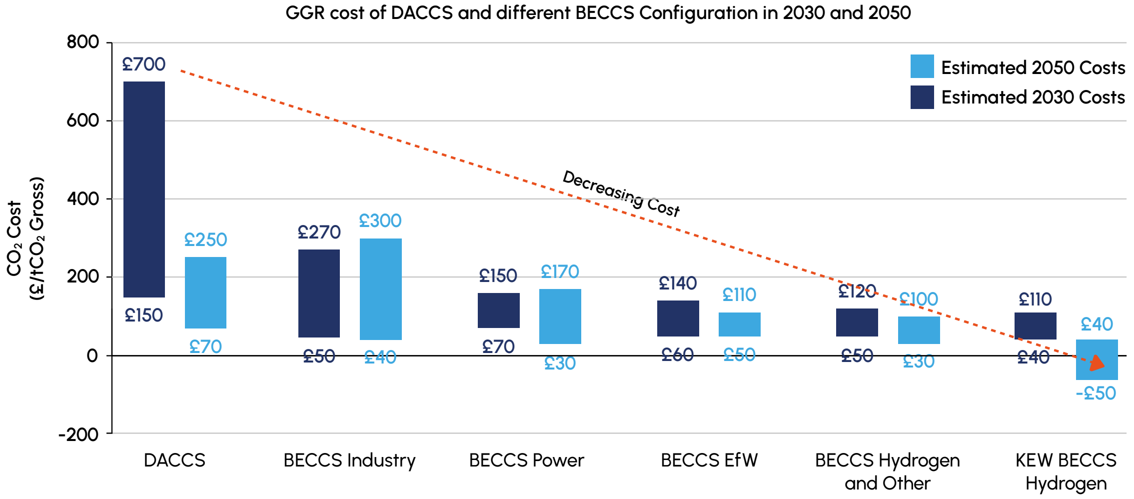


Figure 9: Comparison of KEW's estimated solution costs to the estimated 2030 and 2050 GGR costs based on £/tCO_2 removed, with BECCS Hydrogen highlighted as the cheapest potential GGR option[1].

KEW has added its own GGR cost estimate ranges for 2030 and 2050 for the proposed CCH_2 project configuration at a commercial scale to those of those produced by BEIS (see right hand columns in Figure 9).

2.2.1.1 Pathway to achieving a low-cost GGR solution

KEW's financial assessment (see Figure 10), is based on a multiplexed technology solution consisting of 3 CCH_2 modules. KEW expects the x3 CCH_2 multiplexed configuration will provide robust economic benefits versus the proposed Phase II x1 unit demonstrator due to economies of scale in the CCH_2 section (see Section 2.3 for modularity benefits of the CCH_2 product that lead to better economies of scale).

In order to drive its financial assessment, KEW has made a number of assumptions (see Figure 10 below) (using the commercial x3 CCH_2 product as the base case), which includes projections for how the costs of CO_2 sequestration are anticipated to reduce significantly over time as H_2 markets and technology continued to develop. The results of these scenarios are shown below:

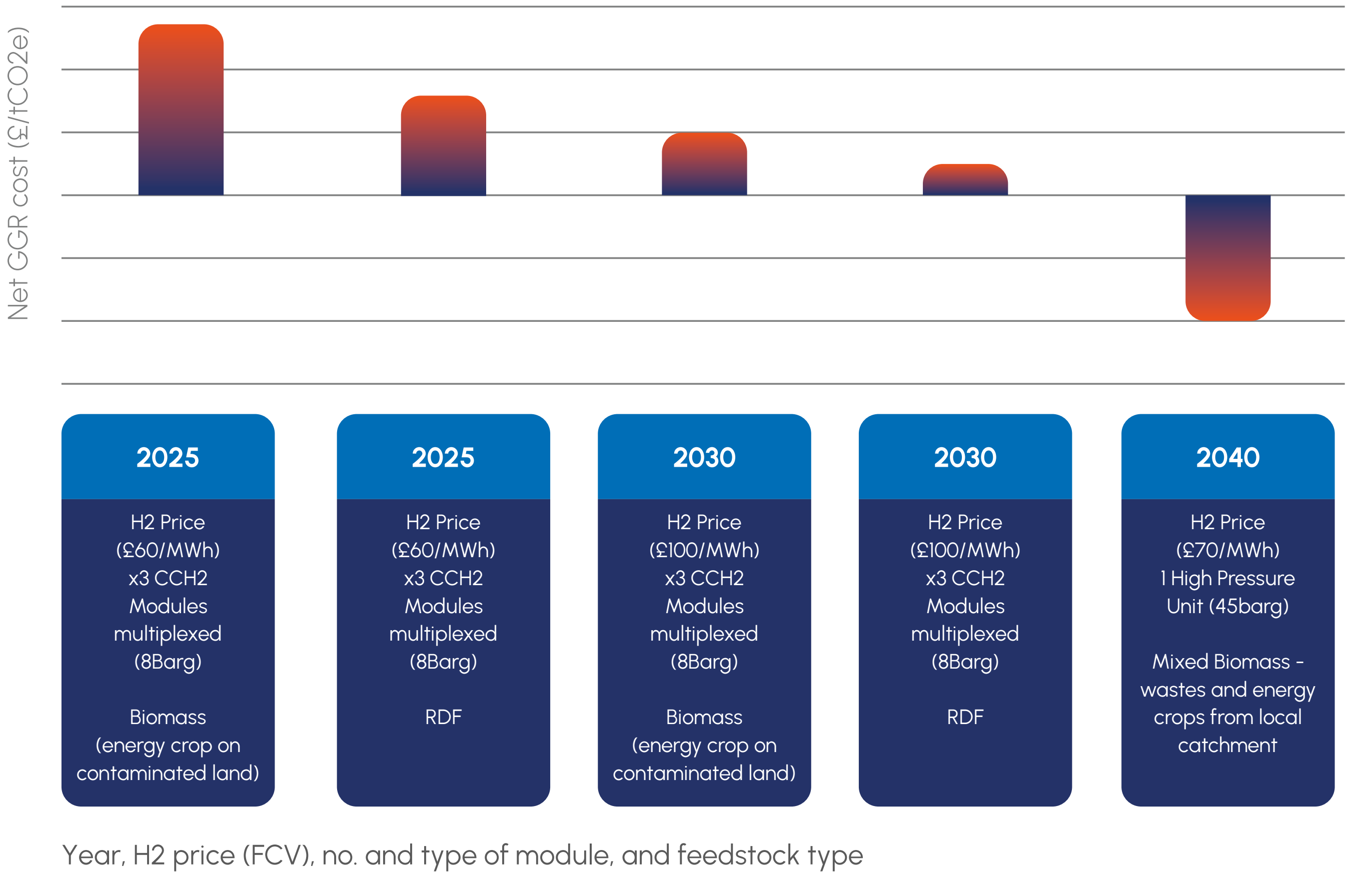


Figure 10: Illustration of initial assessment of the potential commercial development of the CCH_2 net GGR cost reduction pathway

Table 1: Explanation of the assumptions

Assumption	**Explanation**
Year	2025 selected as the first full year in which a commercial unit could be installed and enter operation during which it would building its commercial reputation. 2030 selected as being representative of a commercial unit with significant commercial track record. 2040 provides a longer-term vision into the future where KEW has had the opportunity to develop, demonstrate and commercially exploit a larger throughput, more efficient advanced higher-pressure (upto 50bar) advanced gasification unit producing >50MW of H_2 per unit.
Hydrogen price	For year 2025, £60/MWh represents KEW's estimate of the price which can be obtained in an early commercial deployment in the transport sector where customers still require comfort in terms of the quality and consistency of the hydrogen product as product liability insurance is unlikely to be available. For year 2030, £100/MWh represents a full commercial price for exploitation in the transport sector and should be achievable once a track record of delivery of acceptable quality and quantity of product has been demonstrated. For year 2040, £70/MWh represents a 50-50 blend of industrial sales (£40/MWh) and transport sector sales (£100/MWh). A 50-50 sales mix has been assumed as the volume of H_2 produced in this larger configuration may exceed the immediate transport H_2 needs. Should all the H_2 be deployed in the transport sector, the net GGR cost would fall significantly.
Configuration	For years 2025 and 2030, the 3x CCH_2 modules multiplexed represents KEW's expectation of the initial commercial plant configuration balancing economies of scale and ability to deploy the H_2 produced. For year 2040, the higher-pressure, higher-throughput unit deployed will provide significant CAPEX and OPEX savings and will follow product development and the further development of both the hydrogen markets and CCUS availability.
Feedstock	In Phase 1, KEW compared the economics of energy crops and of RDF. The darker shaded bars are those which use energy crops as feedstock. These show the significant improvement in financial performance and lowering of the CO_2 sequestration price achieved with greater market development / technology proving and then further improvements with technology development. Comparing the first-second bars and third-fourth bars shows the difference in financial performance when using RDF as a feedstock with using energy crops. There is a significant economic benefit as a gate fee is earned with RDF but as this is not 100% biogenic/renewable, the GGR wider impacts potential is not maximised. However, the GGR tCO_2e impact is comparable and great nonetheless as well as is able to provide negative emissions.

2.2.2 Wider drivers supporting CCH_2 ’s pathway to becoming a low-cost GGR solution

2.2.2.1 End-product market drivers

KEW’s proposed BECCS-GGR route is founded on the principle of converting the maximum possible energy contained in a wide-range of biomass and waste sources into a CO_2-free energy vector: H_2. Alongside sequestration of the CO_2, this offers a strong opportunity for net removal of greenhouse gases from the atmosphere.

The revenue from the H_2 enables new supply chains to be developed, for example, for the collection of forestry waste, the diversion from land-spreading of digestate, sewage sludge and other low-grade waste streams, and energy crops grown on contaminated or marginal land.

Further economic advantages are forecast after 2030 to bring down the cost further.

The initial facilities are likely to be built on existing industrial sites to provide H_2 direct for industrial purposes; with CO_2 liquefied for use in existing applications or for transport to hubs for CCS pipelines.

Large scale BECCS-H_2 plants tied in directly to CCS pipelines are a compelling future aspiration, and KEW’s plans for higher-pressure (up to 50bar) larger scale CCH_2 units producing >50MW of H_2 align with this vision.

That said, the lessons from gasification projects around the world are that a pragmatic staged approach based on processes already proven at scale is vital to success. KEW’s vision is one of ‘start small to build big’ (see Section 4 for more detail on this approach suitable for commercial deployment of innovative and emerging technologies).

2.2.2.2 Drivers enabled through KEW’s feedstock flexibility

The biomass energy crop and RDF scenario comparison in the analysis above is necessary as they present comparable GGR impact. The feedstock flexibility of KEW’s fluidised bed gasifier is fundamental to this as homogenous ‘wood’ input is not required and waste (e.g., refuse derived fuel) can also be consumed with gate-fees providing the critical commercial stepping stone to enable facilities to be financed whilst equipment costs are decreased, and carbon taxes or other mechanisms are established to reward the greenhouse gas removal (see Section 4).

Below is an outline of KEW’s key observations on the feedstock supply chain development and how KEW envisions adapting to this with its future-proofed technology feedstock flexibility:

- Additional sources of biomass are going to be needed to supply the energy required. This can best be achieved through a combination of the growth of low-grade biomass energy crops on un-used land and utilising waste biomass streams.
- Utilising this range of biogenic feedstock enables many current environmental issues to be addressed and provide an economically valuable disposal route for biogenic-rich waste materials and a gradual expansion from today’s feedstock position of only RDF.

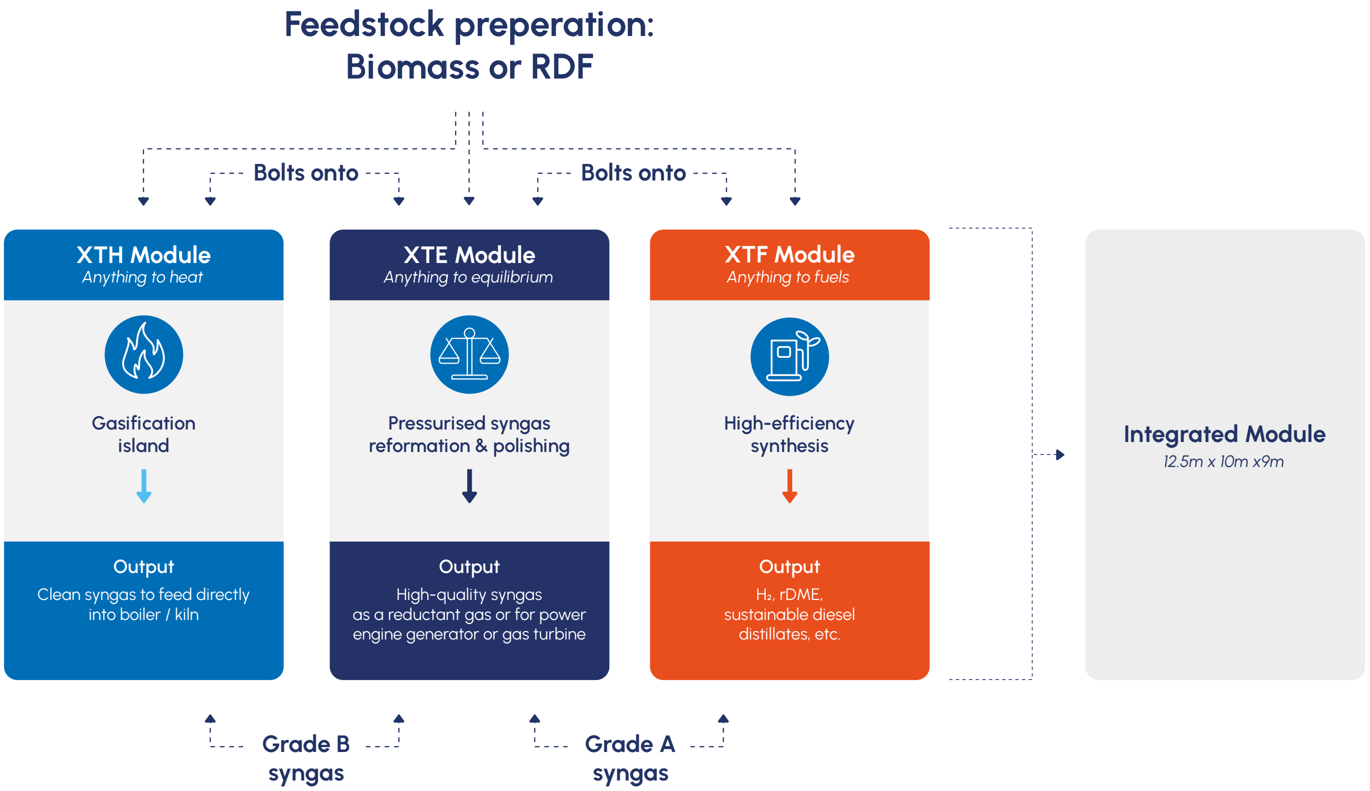
- It is clear that the growth of low-grade biomass crops for GGR projects and for H_2 supply cannot divert land away from food production so it must be grown on land which is currently fallow or otherwise considered to be marginal for crops or animal rearing.
- The only way to promote the growth of these energy crops is for there to be a ready outlet for the biomass which means that there must be process plants in existence at the time of planting, so the growers know they have a viable, economic route to market.
- Similarly, with sewage sludge and much of AD digestate, there is no reliable supply chain for the economically beneficial use of them as decarbonised energy feedstocks. KEW's flexible technology will allow the gradual development of the supply chain for these waste products as the portfolio of operational KEW plants expands.
- Typically, investors will not fund the construction of biomass processing plants without the supply of biomass being readily identifiable and available through a fixed price investment grade long term contract. KEW's modular technology can unblock this situation as it is capable of processing RDF, sludge, digestate and energy biomass crops to create the H_2-rich fuels for deep decarbonisation. Therefore, RDF would act as a commercial stepping stone for the BECCS-GGR solution with the potential to switch from RDF to sludge/digestate/low grade biomass energy crops, which can potentially be made without additional investment or expensive retrofitting as those supply chains develop to commercial scale.
- To meet the UK's target for decarbonising the economy, all available biomass and biomass-rich feedstocks will need to be utilised and KEW's flexible, modular gasification technology allows that transition to occur over time.
- Overall, it is not a matter of one vs the other but how to build on existing supply and build more sustainable energy plants/energy generation.

2.3 Achieving rapid scale-up; modularity benefits

At the core of KEW's strategy is a standardised factory-build modular construction approach. This provides a scaled supply chain of compact modules, capable of being assembled at end user industrial sites via transportable frames in shorter construction periods than incinerators. This enables ongoing cost reductions as experienced with wind turbines, low construction risk, and projects viable at smaller scale so they can consume feedstock from a local catchment area and provide energy where required.

KEW's CCH_2 product is based on the same modular platform approach whereby the three main process systems are divided up and each provide either syngas for heat, or reformed syngas for reductant gas or electricity application, or further upgrade to 2nd generation advanced fuels. They are referred to as the XTH, XTE and XTF modules.

The modules can be arranged according to the energy needs of the client. This allows for a standardised but versatile product offering and helps businesses adapt to a rapidly evolving energy market with bolt-on modules for future capital investment. This modular approach allows for standardisation of the technology; avoiding the need for re-engineering and can be easily replicated with minimal cost, time and risk.



- Assembled offsite
- Ease of installation
- Standard low cost build

- Robust and established supply chain to enable scale of supply
- Simple EPC contract structure
- Limited balance of plant/civils
- Future proofs technology towards 'Net-Zero'

Figure 11: Breakdown of KEW's modular sustainable energy solutions. This CCH_2 project is based on the XTF module development and product portfolio.

All KEW modular solutions start with its basic XTH module which gasifies RDF or other biogenic feedstock to produce a hydrogen-rich syngas. This syngas can be combusted to provide industrial heat or, with the addition of KEW's second module cleaned and upgraded so it is capable if use in a gas engine to produce electricity or for use in more sensitive industrial heat settings or for reductant gas purposes. The third step would be the additional of KEW's XTF module to refine further the syngas, separate it into its constituent elements of CO and H_2 or prepare it for further processing into sustainable fuels.

As part of the development of this flexible, modular solution, KEW has already demonstrated its XTH and XTE modular processes at the SEC and is now developing the XTF module product portfolio to include CO_2 removal and H_2 production: the CCH_2 modular product. Hence, the BEIS Direct Air Capture and Greenhouse Gas removal (DAC and GGR) competition is a key enabler for the development of the XTF product portfolio through the CCH_2 modular product.

2.4 CCH_2 optimised design and configuration; technical benefits

Outlined below, is the core technical benefits that determined the most optimised technical design and configuration for CCH_2‘s initial deployment:

Analysis of the CCH_2 system specifications revealed that:

- The contaminant limits for Industrial grade H_2 was relatively straightforwardly achieved (90-98% purity), however a further process step will be needed to further reduce impurities to be suitable for FCVs (99.97%).. End-user requirements and overall economic considerations will determine the extent of any additional technical process steps.
- When producing industrial and fuel cell grade Hydrogen, the complete removal of carbon from the process stream is required. KEW have designed the CCH_2 unit to produce Hydrogen to industrial grade or Fuel Cell Vehicles (FCV) grade This flexibility between Hydrogen purities allows the CCH_2 module to service multiple markets, thus providing operational flexibility and in-built redundancy.
- For distributed industrial H_2 production for use in fuel switching at smaller industrial sites, the conversion efficiency of the process from feedstock to H_2 product is c.56–60% (LHV basis), reducing to c.46% (LHV basis) for FCV-grade hydrogen given the additional compression energy and reduced hydrogen production results in FCV cases being around 10% less efficient than the industrial hydrogen cases. Nevertheless, both routes exhibit roughly double the conversion efficiency of BECCS for electricity (c.25%), which, if coupled with electrolysis to produce H_2 would result in an overall conversion efficiency of c.16-18%.
- CO_2 destined for sequestration can contain some contaminants, however, the current liquified CO_2 transport network requires food-grade standards to be met (99.999% purity) in order to avoid contamination of tankers. As very few plants will have direct access to a sequestration pipeline, the CCH_2 module is designed to produce a food grade liquid CO_2 specification suited for transportation to sequestration pipelines.

The evaluation of a variety of CO_2 and H_2 separation technologies revealed that:

- Solvents had lower CAPEX/OPEX cost than membranes while still maintaining acceptable performance for CO_2-H_2 separation.
- As a result, KEW will pursue solvents as the primary separation method for CO_2-H_2 and evaluate membrane and SEWGS.
- This technology choice will also lead to a reduced CO_2-H_2 compression energy and H_2 processing costs.

KEW reviewed the performance of the CO_2 removal solvents provided for both industrial and FCV-grade H_2 production. The assessment found:

- That an average 93% capture rate could be achieved with upto 99.98% achievable from the data analysed.

2.5 Achieving wider impact; environmental and social benefits

2.5.1 Environmental benefits

There are multiple direct and indirect environmental benefits identified during Phase I that would result from the deployment of the CCH_2 product solution and span across the up, mid and down-stream supply chain.

2.5.1.1 Up-stream environmental benefits

Under the BECCS vision utilising biomass, KEW's proposal is to use low grade biomass grown on marginal, grassland and contaminated land. This would have multiple added direct GGR benefits, such as:

- Contaminated and marginal land both present an interesting opportunity for low grade biomass production that does not compete with arable land. For example, SR-C willow has the ability not only to grow in nutrient poor soils but also displays a high metal uptake from the soil like Ni, Cd and Zn reducing the contamination levels and restoring the land and local ecology in a cost-effective way.
- There are indirect impacts resulting from developing the biomass supply chain to target supply of low-grade biomass crops on marginal land, linked to direct land use change emissions (dLUC). The impact from changing traditional land use (contaminated land, marginal or poor soil quality) to growing low grade biomass crops would have a benefit relating to reduced emissions in the range of -42 – 144 tCO_2/ha removal capacity depending on the crop. This carbon reduction potential is achieved through photosynthesis during crop growth and also by means of fixing of carbon in soils.
- Severely contaminated or degraded land with poor quality soil presents another interesting potential opportunity to establish low-grade biomass supply chains in decentralised locations.
- The significant expected increase in low grade biomass crops by 2050, highlighted in the recent biomass policy statement[2] is projecting that up to 1.4 Mha of land could be used for energy crop production enabling the UK to meet 10% of its energy demands . Similar estimates are supported from ETI's energy models, which estimate that 130 TWh of energy could be supplied from bioenergy crops[3]. Although KEW's internal assessment is lower than these values, such a significant increase will lead to an increase in the number of people employed in the bioenergy sector from current levels, as well as an associated increase in the supply chain (i.e., market for end products, machinery for planting/harvesting). Developing low-grade biomass crops on marginal land for future use in BECCS will allow farmers to increase productivity and create more all-year-round jobs in rural areas, thereby fully valorising underutilised land while producing feedstocks that can reduce GHG emissions. As demand and productivity grows, farmers' profitability would increase, acting as an incentive to expand production further.

[2] BEIS (2021) Biomass Policy Statement https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1031057/biomass-policy-statement.pdf

[3] Climate Change Committee (2020) - Sixth Carbon Budget https://www.theccc.org.uk/publication/sixth-carbon-budget/

2.5.2 Mid and down-stream environmental benefits

Moreover, by extracting the maximum value from low-grade biomass, through efficient processing and the production of higher value energy vectors in H_2 and H_2 -rich sustainable fuels, BECCS-GGR plants will be able to pay an economic price for the low-grade biomass that is produced sustainably, thus incentivising farmers to plant this marginal land. This would support the advancement of the low-grade biomass supply chain that is currently not developed, generating fair paid jobs and better utilising (or even remediating) marginal and contaminated land.

In addition, specific added environmental benefits result from the use of char and sustainable fertilizers in soil applications. This added route can improve soil quality and even reverse soil degradation[4], while helping retain nutrients such as ammonia, phosphorous and carbon in the soil. The soils maintain these nutrients longer term, which avoids nutrient leaching into water resources and mitigates significant environmental damage[5].

[4] Food and Agriculture Organisation of the United Nations (2015) ‘Status of the World’s Soil Resources’ https://www.fao.org/3/i5199e/i5199e.pdf

[5] CCm Technologies website (2021) https://ccmtechnologies.co.uk/technology-benefits

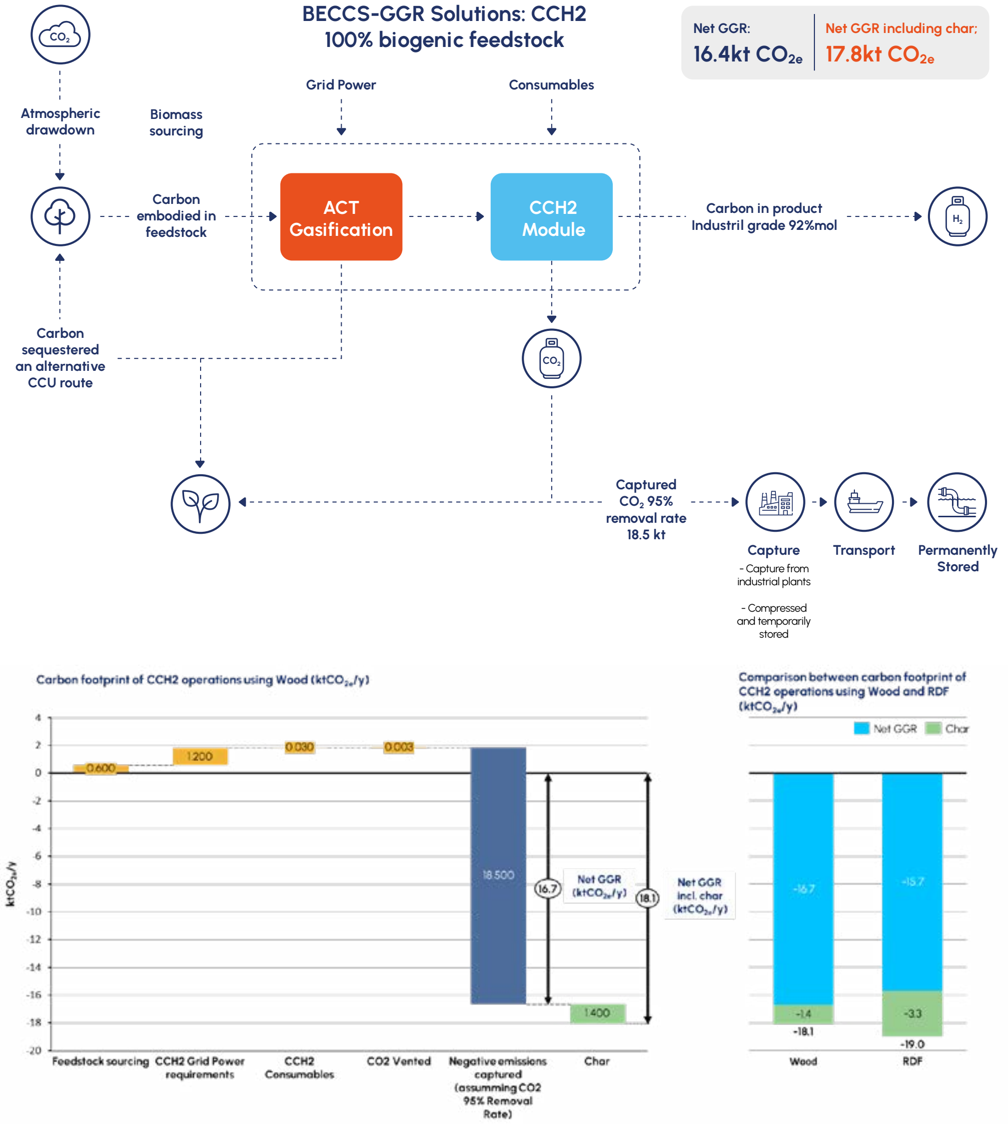


Figure 12: Carbon lifecycle diagram of the CCH_2 integrated solution. This example uses biogenic energy crop as feedstock. Units are ktpa CO_2e.

Overall, integration of the generated waste products enabled by KEW's feedstock flexible solution allows the development of an "end-to-end" environmentally-friendly solution which:

- Enables significant cost competitive GHG emissions reductions through impactful GGR;
- Demonstrates applied circular economy concepts across many areas and;
- Overcomes disadvantages linked to distance from major centralised zero carbon hubs or CO_2 storage facilities.

2.5.3 Social value benefits

Significant progress has been achieved during Phase I of the project to understand the impactful social value benefits deploying the CCH_2 product could have. This social impact can be seen across several sectors and across the supply chains.

As the CCH_2 product is location flexible due to its modular nature, its social value can be described as a fivefold benefit solution:

1. Use existing local residual non-recyclable waste and low-grade biomass wastes.
2. Creating year round job opportunities in the area of deployment (and more so in rural areas where biomass supply chains would be developed).
3. Adding value to unutilised marginal or contaminated land whilst improving biodiversity.
4. Allowing businesses to tap into cost-effective lower carbon solutions with a defined pathway to negative carbon enabling them to stay globally competitive.
5. Generate H_2 revenues which can be used to cross-subsidise CO_2 sequestration.

The level of impact of these varies according to location. To put this into context with an example, KEW is currently taking part in a sustainable fertiliser production trial which is utilising the char produced in KEW's gasification process. CCm Technologies is combining KEW's char with digestate to produce a carbon negative product that can be used in rural inland agricultural areas like Shropshire and Wales. This project is a clear example of three different sectors integrating to create new opportunities while adding value to existing waste streams and utilising existing marginal lands.

3

Definitive outcome of CCH_2 Demonstration Phase

3.1 Summary of Phase I findings leading into Demonstration Phase

The Phase I findings of the techno-commercial feasibility and design study of the BEIS greenhouse gas removal (GGR) program demonstrates KEW's CCH_2 solution proposal could:

- Convert a wide variety of non-recyclable waste and low-grade biomass feedstock into a valuable H_2 energy vector product.
- Reduce industrial reliance on fossil-derived H_2 and natural gas as well as provide zero-carbon fuel for transport.
- Capture CO_2 for long term underground storage or for incorporation into sustainable building materials.
- Provide a revenue stream for the collection of biomass waste streams and remediation of contaminated land with multiple parallel social and environmental benefits.

3.2 Phase II objectives

The aim of the Phase II project will be to retrofit the existing SEC plant to accommodate the development of a full-integrated CCH_2 unit, commission and prove successful and continuous operation of the technology in full-scale commercial context, thus, increasing the TRL of the technology to TRL8 such that the products are ready for onward commercial exploitation.

The Phase II project technical and operational objectives include:

- Build and demonstrate the integrated end-to-end CCH_2 process: The CCH_2 module coupled to KEW's existing ACT plant will convert waste/biomass into H_2 and CO_2, and resolve the current uncertainties surrounding:
    - CAPEX
    - OPEX
    - Performance
    - Feedstock flexibility
    - Product quality (H_2 and CO_2)
    - Greenhouse Gas Removal achieved
- The design and build will then be followed by a series of tests followed by operation over an extended period.

The Phase II project will also assess the overall value chain covering:

- Feedstock selection and testing to determine the best economic mix residual waste and biomass as it becomes increasingly available and commercially viable;
- The production and commercial sale of H_2;
- The assessment of commercial CO_2 CCUS routes;
- An assessment of the char to determine the most beneficial application from a commercial and GGR view point;
- Preparation for financing and commercial exploitation and deployment including feedback from infrastructure funding and EPC partners to understand their level of appetite and what risks they perceive and;

- Dissemination of KEW’s findings across industry, academia and the wider business community.

The targeted key outcomes of the Phase II Project are:

Proven integrated system for low-grade feedstocks conversion to H2 and char products with CO2 captured ready for utilisation and sequestration; at a commercially viable scale.

Dissemination of key findings to wider stakeholder groups in order to further develop BECCS H2 route to substantial contribution to net zero targets

Successful demonstration of strong Greenhouse Gas Removal capability and growth potential.

Defined economic proposition

Provide a platform for commercially led projects, through removal of key roadblocks and risks around feedstock supply, financing, offtake, insurance and project delivery. This technology development first being demonstrated at the SEC also proves the ability to KEW’s customers to upgrade installations later as energy requirements, Government regulations or project economics change. This ability to upgrade performance over time reduces technical risks thus providing better value for money for taxpayers as incremental risks are better managed.

3.3 Demonstration Phase II facility; the Sustainable Energy Centre

KEW’s ACT is already being demonstrated at the Sustainability Energy Centre (SEC) in Birmingham, UK. The full-scale commercial flagship facility, co-funded by the Energy Technologies Institute (ETI), converts 15,000tpa of mixed biomass and waste based feedstocks into a high-quality syngas vector. The existing production of consistent quality syngas provides a sound, risk mitigated technical basis on which to base the Phase II development. The pictures below illustrate some of the equipment and testing activities at the SEC plant.

The SEC has been built on brownfield land that is located in a semi-urban/industrial area in Wednesbury in the Black Country; an area at the centre of the first industrial revolution. The establishment of the SEC along with KEW’s involvement in the Repowering the Black Country Industrial Cluster is now helping to regenerate the local economy by creating new, permanent skilled jobs, creating a local engineering supply chain, and all the while providing a local distributed energy solution. KEW is working with local universities and higher education bodies to provide industrial placement, training and graduate opportunities and will be able to expand these opportunities in Phase II.

Figure 13: KEW's advanced gasification plant at the SEC

3.4 Phase II timeline

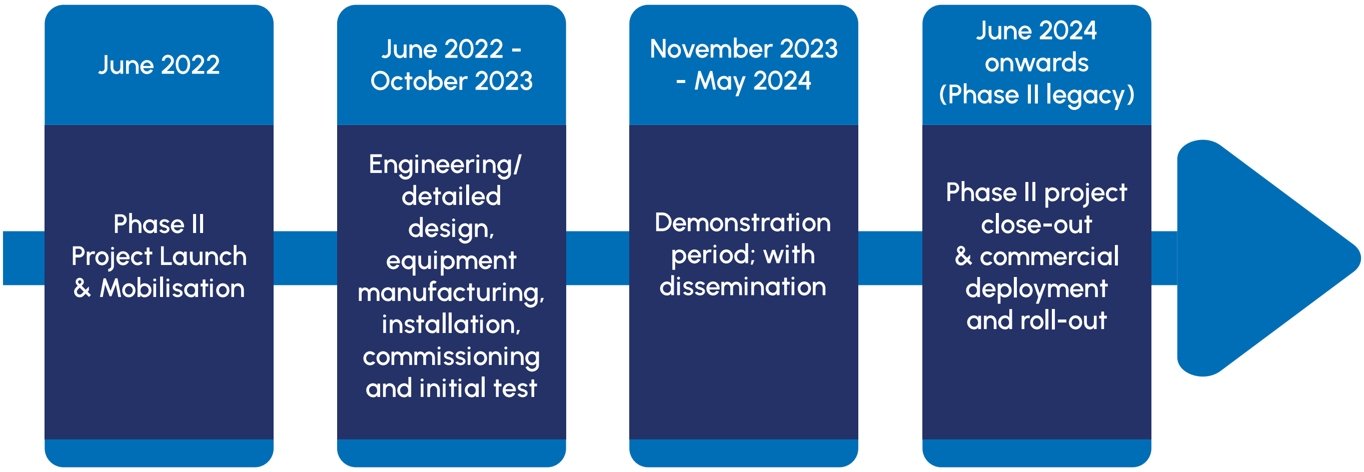


Figure 14: Timeline of CCH_2 development pathway

4

CCH$_2$ commercial deployment pathway

4.1 Overcoming the challenges to GGR deployment

In order to meet the Paris Agreement goals, all major governments must take wide ranging action across the following major energy and carbon-intensive sectors to achieve their Net Zero ambitions: industry, energy, transport and buildings. Although each sector has very different requirements, the common consensus is that low-carbon H_2 energy vectors and CCUS technologies can play a very significant role in achieving meaningful and sustainable decarbonisation to help achieve a world beyond fossil fuels.

Industry is widely spread throughout the UK with only a very limited number of areas having ready access to both low-carbon H_2 supply and the proposed major undersea CCUS infrastructure. These H_2 and CO_2 hubs will develop slowly over time but there will still be many areas where decarbonisation can only occur through on-site low-carbon H_2 production coupled with carbon capture in volumes which can be economically transported to the major CCUS locations from dispersed sites.

The main challenges required to be addressed to enable deep decarbonisation of industry to occur are:

- Developing and proving CCUS technologies and storage facilities at reasonable economic cost which permit a geographically diverse roll-out.
- Stimulating the development and deployment of sustainable energy production technologies via targeted government support that offers value for money for taxpayers
- Stimulating the biomass energy crop growth and other low grade biomass feedstocks (sludge, AD digestate) to form a well-structured biomass supply chain to provide the feedstock for these BECCS-GGR processes.

4.2 The need for a balanced solution portfolio; applying the lessons of renewable electricity

- Recent experience of decarbonising the UK electricity sector highlights the importance of not relying on the very large-scale projects as the sole/prime tool to achieve strategic outcomes. This is particularly true in the context of H_2 and CO_2 given the lack of existing infrastructure in place to supply end users in a similar way to pipeline natural gas. Reliance solely on large scale solutions will create significant long-term economic and financial issues in transporting large volumes of H_2 around the UK.
- Short to medium term solutions must therefore include dispersed/decentralised H_2 production co-located on industrial user sites. This must commence as quickly as practical on a technological and commercial pathway to decarbonisation across many fronts. Clearly there is a role for large scale H_2 generation and CO_2 capture, but as part of a portfolio of solutions including smaller scale decentralised projects.
- KEW believes that without equal access to affordable, small scale, modularised low carbon H_2 and CCUS technology, the UK economy risks becoming “two-speed” with those areas connected to CCUS pipelines advancing faster at the expense of other, mainly inland areas. This would be counter to Government’s Levelling Up agenda.

4.3 Modularity overcoming market barriers

- One of the obvious challenges with smaller modular projects is the ability to achieve the required level of scale that is needed to support the Government's decarbonisation agenda in the UK. All projects have a degree of complexity whether large or small, potentially creating an argument to support a focus on large scale projects. However, KEW's modular approach to decentralised projects can quickly achieve large scale deployment by circumventing many of the problems traditionally associated with larger scale 'First Of A Kind' gasification projects.

4.3.1 Achieving supply chain scale through modularisation

- Factory assembled equipment on skids or in containers has become increasingly the preferred approach in many areas of industry where there is a sufficient volume demand for a specific item to justify the upfront investment in the manufacturing, tooling and production line.
- KEW modular plants will avoid re-engineering existing processes with standardised modules which can be easily replicated with minimal cost, time and risk. This will be achieved by breaking out the core processes into their respective areas and optimising their design.

This enables production at scale as the modular units can be manufactured using lean techniques with supply chain bottlenecks mitigated. This would in parallel create a significant prospect for UK green technology leadership and the resultant green collar employment opportunity. Standardisation of manufacturing will also facilitate greater levels of contractual performance which will facilitate the rapid progression to full scope EPC (see section 4.3.2.3 below) and the increasing availability of performance-based insurance products that are also key in enabling infrastructure funding availability.

4.3.2 Reducing levelised cost of production through modularisation

There is historical evidence indicating that there are significant reductions per unit production when there are new technologies deployed commercially through repeatable modular delivery. This is a result of the "virtuous circle" where increased deployment leads to manufacturing gains, reducing prices, opening up new markets which drives sales, as shown graphically below. These unit cost reductions have been clearly seen in the renewable electricity sector where solar and wind power CAPEX costs have tumbled with widespread installation of repeatable modular solutions. In parallel with the reduced CAPEX, there has been a reduced need for taxpayer or energy user subsidies to the point where both solar and wind can now be delivered subsidy free.

KEW anticipates that the same experience will be seen with the deployment of its modular BECCS-GGR system. Initially, this will be deployed across industrial heat and sustainable liquid fuel situations. This initial deployment will drive unit uptake and, therefore, cost reductions. As CCUS technology becomes available, the cost reductions derived from heat and fuels deployments will benefit and enhance the economics of BECCS deployment of the same underlying advanced gasification technology.

KEW has made projections for the potential cost savings and would also point to historic precedent from other renewable sectors to support these projections. As detailed below, the cost reductions which will be achieved depend on the rate of deployment of KEW's technology. Historic comparators are shown in the chart below.

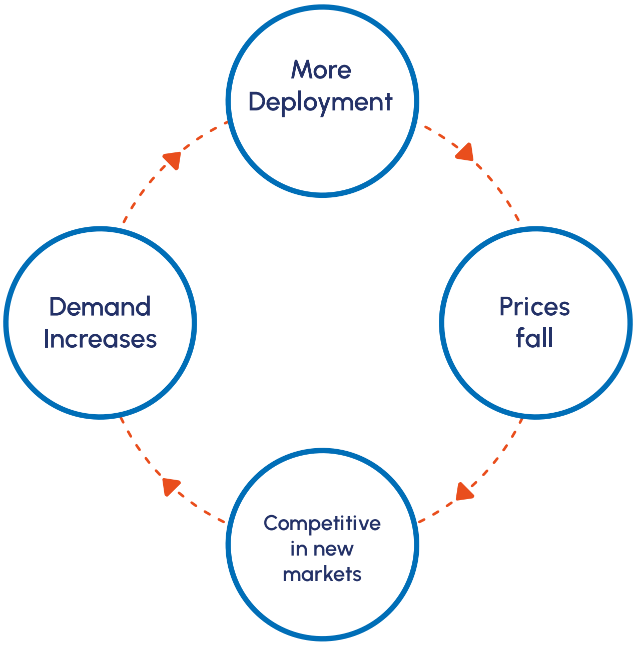


Figure 15: Virtuous circle

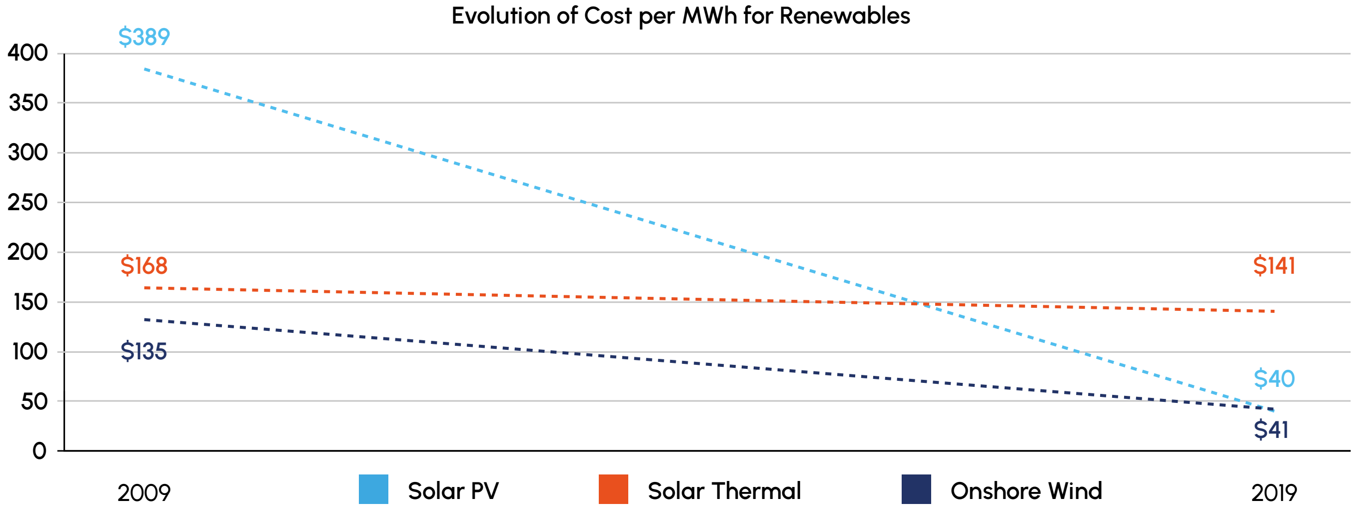


Figure 16: Comparison of the cost reduction of renewables over the last decade, correlated with the quantity of unit systems produced[6]

The reduction in costs over 10 years are most striking for Solar PV with a reduction of 89%. Substantial reductions were also seen for Onshore wind, reducing 70% with Solar thermal experiencing only a 16% reduction.

The cost reductions experienced are correlated not with time but with the deployment of identical or quasi-identical units with a consistent % reduction in costs for each doubling of the number of units in service. This constant cost reduction relationship was first identified in 1936 by Theodore Paul Wright and has been called "Wright's Law". Initially it was identified in the aerospace sector, but empirical data has held it to be accurate across a wide range of sectors not just aerospace but also automotive parts, aluminium, DNA sequencing and, most importantly, renewables.

[6] Our World in Data (2021) - Why do renewables become so cheap so fast? https://ourworldindata.org/cheap-renewables-growth

The implications of Wright's Law, the empirical data and the constant cost reductions means that the best way to achieve value for money for the taxpayer in industrial heat decarbonisation and BECCS-GGR, is to encourage the deployment of as many of KEW's ACT modules as possible to maximise the per unit cost savings. By the time CCUS is ready for commercial exploitation, if there have been many KEW modular solutions deployed across the UK (and other markets), this will significantly benefit the cost attractiveness of BECCS-GGR integrated solution underpinned by the ACT solution and reduce the need for subsidies. Wright's Law also implies that greater cost savings can be achieved through the deployment of many, smaller units than a few, very large projects.

Very large projects are harder and take longer to develop, more limited in where they can locate, place greater pressure on local feedstock resources and require significant investment that means their rate of deployment will be much slower and taxpayer subsidies would be higher and required to be offered for much longer. This would be, for example, the characteristics of a large BECCS project. With a small, flexible, modular system such as KEW's, the rate of deployment can be significant as they can be located in a wide range of industrial, rural and other settings, can process a range of feedstocks, produce a range of low-carbon energy products and the required investment quantum means that investment and funding decisions can be made quickly. All deployments of KEW's modules, whether in a specific GGR setting or more general industrial heat decarbonisation setting, will assist in achieving CAPEX cost savings.

This comparison in cost reduction performance between small, flexible projects and large inflexible projects can be seen from the graph above. Solar thermal installations, the equivalent of very large scale, bespoke BECCS installations, require significant investment, can only be deployed at a large scale to be viable and require particular sun characteristics to be economic, thus, limiting location choice. Onshore wind and solar PV, the equivalent of KEW's modular solution, can be located virtually anywhere at much lower investment cost as neither has these limitations. Consequently, they have been deployed in far greater numbers and have experienced far greater per unit output cost savings.

KEW's modular solution, exhibiting more closely the characteristics of solar PV and wind, will therefore experience greater cost reductions than for larger, bespoke BECCS/CCUS "mega"-projects and provide better value for money for taxpayers by requiring smaller subsidies and the existence of subsidy regimes for a shorter period of time.

4.3.2.1 Enabling access to finance through modularisation

The economically viable route to achieving practical low-risk commercialisation of the CO_2 capture technology lies in a step-by-step approach in which techno-commercial barriers are tackled incrementally to lower the risks for financial investors (and minimise costs that are required to be supported/funded by government). Commoditising an infrastructure asset class enables progressively more and cheaper funding into projects, achieving scale and driving down reliance on government support/subsidies.

Ultimately, KEW believes that starting small and building to scale through repeatable modular deployment not scaling individual unit size is the sensible, proven and low risk approach to commercialisation of innovative and emerging technologies. This approach overcomes the most critical challenges that always block commercialisation through a strategy of rapid scaling; especially the challenge of funding large scale First-Of-A-Kind (FOAK) projects.

Following a phased modular approach provides a viable way of achieving commercialisation and deployment of innovative and emerging technologies much sooner. It is inevitable that large-scale deployment can only be achieved economically when funders are comfortable with the real risk vs. return of the asset class. This can only be done gradually through the initial phased infrastructure roll-out of smaller, less capital intensive and less technically complex projects. Focusing on large-scale projects with unproven technologies and market commercials will necessitate an over-reliance on larger and longer-term government incentives, which will not benefit from the commoditisation of the asset class as demonstrated above for smaller modular based technologies such as KEW's.

KEW's modular solution provides the answer in that it can be deployed initially in a larger number of smaller projects with limited subsidy requirements to create investor confidence, operating track record and stimulate supply chain savings which will then benefit the future larger deployments involving larger numbers of KEW modules to address the larger scale requirements

4.3.2.2 Overcoming challenges to funding BECCS projects

The recent examples of this sector (gasification) trying to achieve immediate large-scale of operations provide very painful evidence that jumping to large scale is not the correct path. The financial investor community are well aware of these high-profile (and expensive) failures as are the relevant supply chain (specifically EPC), who will be very unwilling to offer the level of full EPC wraps required to achieve the underlying value for money debt/equity funding for large scale projects.

KEW's phased modular approach can overcome these traditional investor barriers to enable true scale of infrastructure to be realised.

4.3.2.3 EPC Buy-in

Outsourcing technology risk from projects via an investment grade full scope EPC wrap is a key 'non-negotiable' funder requirement for any project. In terms of ACT and BECCS, given the above mentioned high-profile large scale-gasification project failures and challenges, the EPC community will be very apprehensive of wrapping large scale infrastructure, given the likely requirement from the funding community for a Right to Reject (RTR). The risk of the RTR clause for large scale gasification projects is material and will dissuade most/all from participating in any EPC tenders, regardless of the potential EPC margin they could achieve given the downside risk.

Clearly, in the beginning, a smaller modularised project approach is the only way of securing a bankable EPC wrap in the short term as the RTR clause is less material (given the smaller CAPEX size) relative to the enhanced margin that could be earned from initial project deployment. It is also easier for an EPC to due diligence and get comfortable with the risks surrounding the delivery of an existing full commercial scale gasification process than one which has yet to be developed, designed or built.

Larger projects are likely to remain stuck in the ‘chicken and egg’ scenario of funders requiring full scope EPC, but EPC unwilling to commit to the required contractual terms that funders would expect (i.e., RTR) until technology performance is demonstrable.

4.3.2.4 Obtaining feedstock contracts

Feedstock is the other critical funder issue alongside EPC. Clearly, the larger the project, the more feedstock it needs and the fewer companies that are large enough to supply such volumes under contractual arrangements which are acceptable to investors. If a large project wishes to use RDF as feedstock, the recent rapid deployment of non-PFI merchant incinerators (<250ktpa of feedstock) means the available regional fuel catchments will not be able to support the project’s requirements.

It is unlikely in the short term that any new-build large projects will be awarded any long term local authority waste processing contracts given the level of technology and funding risk. Given this issue, there will be limited or zero investment grade feedstock suppliers who can contract with the required contractual damages/remedies clauses for the non-supply of material and therefore funders are unlikely to get comfortable with the resultant feedstock risk.

One possible mitigation to the above is to secure RDF waste volume from a number of separate feedstock suppliers. However, this approach is equally unlikely to be seen as bankable, as the analysis will still show the regional catchment cannot support a large-scale waste requirement, meaning separate suppliers will fight each other for the same scarce volume of material, forcing the weaker suppliers to further extend their catchment area to service their specific contract position. Ultimately, this leaves the project in a weaker position from a feedstock perspective and reduces feedstock gate fees thus increasing taxpayer funded subsidy requirements. Equally, multi-feedstock strategies cause major issues with the interface risk to OandM and how liability for operational outages is allocated i.e., how do you allocate liquidated damages related to the supply of out-of-specification feedstock when you have multiple feedstock counterparties? Investors are nervous of financing new projects which rely on multiple feedstock suppliers.

If a large-scale project wishes to use biomass feedstocks, this will not be immediately supplied by a UK supply chain, rather imported from regions such as North America.
Such large-scale importation of biomass will continually be questioned in terms of its true end-to-end sustainability and GHG intensity profile as well as macro issues around delivering real UK energy security. Equally, the infrastructure funder community will continue to have real challenges in getting comfortable with key risks such as forex exposure and the underlying indexation factors that influence the price of virgin fibre in overseas markets, which do not correlate to the revenue/remaining cost base of a UK based generation project as well as political risk from any future Government decision to tax, limit or prohibit the import of biomass.

A smaller project initially supplied by RDF, but capable of switching to sewage sludge, digestate or low-grade biomass waste feedstock is viable in the short-term as it can provide the infill between catchment areas of larger incineration projects. This will mean such smaller projects will be able to secure one bankable feedstock contract with clear interface risk management between feedstock and OandM that funders require. Moreover, with KEW's ACT specifically, the ability to accept variable feedstocks also mitigates the resulting sourcing risks as various forms of waste can be fed into the system. The unavailability in one feedstock can be offset with an abundance of another. Furthermore, as the biomass supply chain develops in the UK, a flexible process would allow seamless adaptation to an evolving feedstock landscape, thus we believe that KEW's BECCS-GGR technology solution is very well placed to manage the feedstock risk and feedstock evolution over time.

4.4 Achieving taxpayer value for money

Including smaller scale project solutions as part of a basket of project solutions could offer greater taxpayer value for money in the long term compared to a strategy of solely supporting a smaller number of large-scale projects. Smaller projects should be able to deploy quickly, enabling performance to be established, which in turn will drive down supply chain costs and reduce investor return requirements. Again, mirroring the recent learnings of the renewable electricity sector, rapid commoditisation of the asset class enables the rapid reduction in the level of government subsidy support required to achieve a reasonable economic return. All of this can be achieved without compromising the pace and the scale of infrastructure deployment.

Focusing solely on large scale solutions may provide impact and scale, but not necessarily value for money for taxpayers given the need to provide large scale projects with a fixed long term incentive level of support upfront, before (i) the asset class benefits from the positive impacts of commoditisation as highlighted above and (ii) investors and contractors can reasonably price the level of risk within each asset. Essentially focusing on large scale solutions locks the tax-payer into a long-term government incentive support that is likely to be expensive and not applying the successful lessons learned from the significant reductions in support needed for renewable electricity.

Acronym	Name	Acronym	Name	Acronym	Name
ACT	Advanced Conversion Technology	**EPC**	Engineer Procurement and Construction (Company)	**RDF**	Refuse Derived Fuel
AD	Anaerobic Digestion	**FCV**	Fuel Cell Vehicle	**ROC**	Renewable Obligation Certificate
BECCS	Bioenergy with Carbon Capture and Storage	**FEED**	Front-End Engineering Design	**RTR**	Right to Reject
BEIS	Department for Business, Energy and Industrial Strategy	**GGR**	Greenhouse Gas Removal	**SEC**	Sustainable Energy Centre
CAPEX	Capital Expenditure	**GHG**	Greenhouse Gas	**SEWGS**	Separation Enhanced Water Gas Shift
CCC	Climate Change Committee	**IP**	Intellectual Property	**SRC**	Short Rotation Coppice
CCH_2	Carbon Capture and Hydrogen Purification	**LHV**	Lower Heating Value	**WGS**	Water Gas Shift
CCS	Carbon Capture and Storage	**LPG**	Liquified Petroleum Gas	**XtH**	Anything to Heat
CCUS	Carbon Capture Utilisation and Storage	**OPEX**	Operating Expenditure	**XtE**	Anything to Equilibrium
DACCS	Direct Air Carbon Capture and Storage	**OandM**	Operations and Maintenance	**XtF**	Anything to Fuels
dLUC	direct Land Use Change	**PFI**	Private Finance Initiative		
ETI	Energy Technologies Institute	**PSA**	Pressure Swing Adsorption		