Department for Energy Security & Net Zero

KEW TECHNOLOGY

CCH_2 | 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

Content

Glossary

AACE	Association for the Advancement of Cost Engineering.	**IRR**	Internal Rate of Return
ACT	Advanced Conversion Technology	**JV**	Joint Venture
BECCS	Bioenergy with Carbon Capture & Storage	**KPI**	Key Performance Indicator
BEIS	Business, Energy & Industrial Strategy (Former UK Govt Dept)	**LCA**	Lifecycle Assessment
CAPEX	Capital Expenditure	**LCHS**	Low Carbon Hydrogen Standard
CC	Carbon Capture	**LCOH**	Levelised Cost of Hydrogen
CCH2	Carbon Capture and Hydrogen Production	**LPG**	Liquified Petroleum Gas
CCS	Carbon Capture and Storage	**MOU**	Memorandum of Understanding
CE	Conformité Européenne	**MRV**	Monitoring, Reporting and Verification
COMAH	Control of Major Accident Hazards	**NOBO**	Notified Body
DAC	Direct Air Capture	**NZIP**	Net Zero Innovation Portfolio
DESNZ	Department for Energy Security & Net Zero (UK govt)	**OPEX**	Operating Expenditure
DME	Dimethyl Ether	**PFD**	Process Flow Diagram
EMB	Energy and Mass Balance	**PID**	Piping & Instrumentation Diagram
EPC	Engineering, Procurement & Construction	**PPFT**	Project Plan & Finance Tables
ETI	Energy Technologies Institute	**PSA**	Pressure Swing Adsorption
ETS	Emissions Trading Scheme	**PWA**	Pressurised Water Absorption
EU	European Union	**RDF**	Refuse Derived Fuel
FCV	Fuel Cell Vehicles	**ROC**	Renewable Obligation Certificate
FEED	Front End Engineering Design	**SAF**	Sustainable Aviation Fuel
FEL	Front End Loading	**SBRI**	Small Business Research Initiative
FOAK	First of a Kind	**SEC**	Sustainable Energy Centre
GGR	Greenhouse Gas Removal	**SMBC**	Sandwell Metropolitan Borough Council
GHG	Greenhouse Gas	**SME**	Small-to-Medium Enterprise
H000	System Integration	**SMR**	Steam Methane Reforming
H0100	System Guard Bed & Water Gas Shift	**SPK**	Synthetic Paraffinic Kerosene
H0200	System Compressor	**SRF**	Solid Recovered Fuel
H0300	System Cryogenic Separation	**SWIP**	Small Waste Incineration Permit
H0400	System CO2 Storage	**TRL**	Technology Readiness Level
H2BECCS	Hydrogen Bioenergy with Carbon Capture & Storage	**UKCA**	United Kingdom Conformity Assessment
HAZOP	Hazard Operability	**WGS**	Water Gas Shift
HMB	Heat and Mass Balance		
HSE	Health, Safety and Environment or Health & Safety Executive (UK regulator)		

Executive summary

DAC and GGR Programme overview and background

Engineered greenhouse gas removals (GGRs) are recognised by all stakeholders as an essential component in achieving net-zero emissions. The removal of atmospheric CO_2 not only allows the UK to address its legacy emissions but also significantly mitigates emissions from sectors that have proven challenging to decarbonise due to a lack of suitable 'proven' technologies. GGRs encompass a diverse range of technologies at various stages of development, including Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS). BECCS projects convert waste or biomass into useful alternatives in power, heat, hydrogen, or other low-carbon and zero-carbon advanced fuels. As biomass and waste feedstocks contain biogenic carbon stored through photosynthesis, the BECCS process results in negative CO_2 emissions if those emissions are captured and sequestered or utilised.

Hydrogen produced via BECCS (H_2-BECCS) represents a valuable zero-carbon energy vector with the potential to reduce emissions from sectors such as heavy industry, chemicals, and transport. Recognising this potential, the UK Government has set an ambitious target of achieving 5GW of hydrogen production by 2030. In contrast, DACCS does not produce other usable energy vectors.

CCH_2: An ACT route to a BECCS-GGR solution

A technology gap remains for scalable, decentralised solutions that provide a flexible, local approach to waste treatment and the generation of valuable energy vectors. Identified by the Energy Technologies Institute in 2012, this gap is particularly significant for hard-to-decarbonise sectors that need low-carbon energy solutions. KEW's Advanced Conversion Technology (ACT) addresses this need by enabling the conversion of waste and low-grade biomass into high-value energy vectors, such as hydrogen, methanol, methane, SAF and other advanced molecules, offering a more flexible, decentralised alternative to traditional waste incineration. KEW's ACT system processes a broad range of feedstocks and employs a unique high-pressure advanced gasification approach to convert waste into syngas, ensuring a low-carbon, cost-effective solution for energy production.

The key challenge in scaling ACT systems has been overcoming the complexities of tar and long-chain hydrocarbons in the syngas stream. Previous large-scale projects failed due to these challenges and the insufficient investment in bridging the technology readiness gap from lab-scale to commercial-scale operations. KEW's solution bypasses these issues with a modular product based on the existing and operated high-pressure system capable of processing low-grade feedstocks, offering a proven path toward the decarbonisation of sectors such as industrial heat, transport, and chemicals.

Addressing the problem: start small to build big

KEW's technology offers an efficient, modular solution to the global environmental challenges of waste management and carbon reduction. By enabling the conversion of non-recyclable waste and biomass into advanced molecules like hydrogen, KEW not only addresses decarbonisation but also contributes to the circular economy. The system's modular design allows for scalable, decentralised projects with significantly reduced costs compared to traditional large-scale systems. KEW's patented approach also ensures that its technology is carbon capture ready, allowing for the pre-combustion capture of CO_2, thus offering greater than 100% greenhouse gas savings relative to fossil fuels.

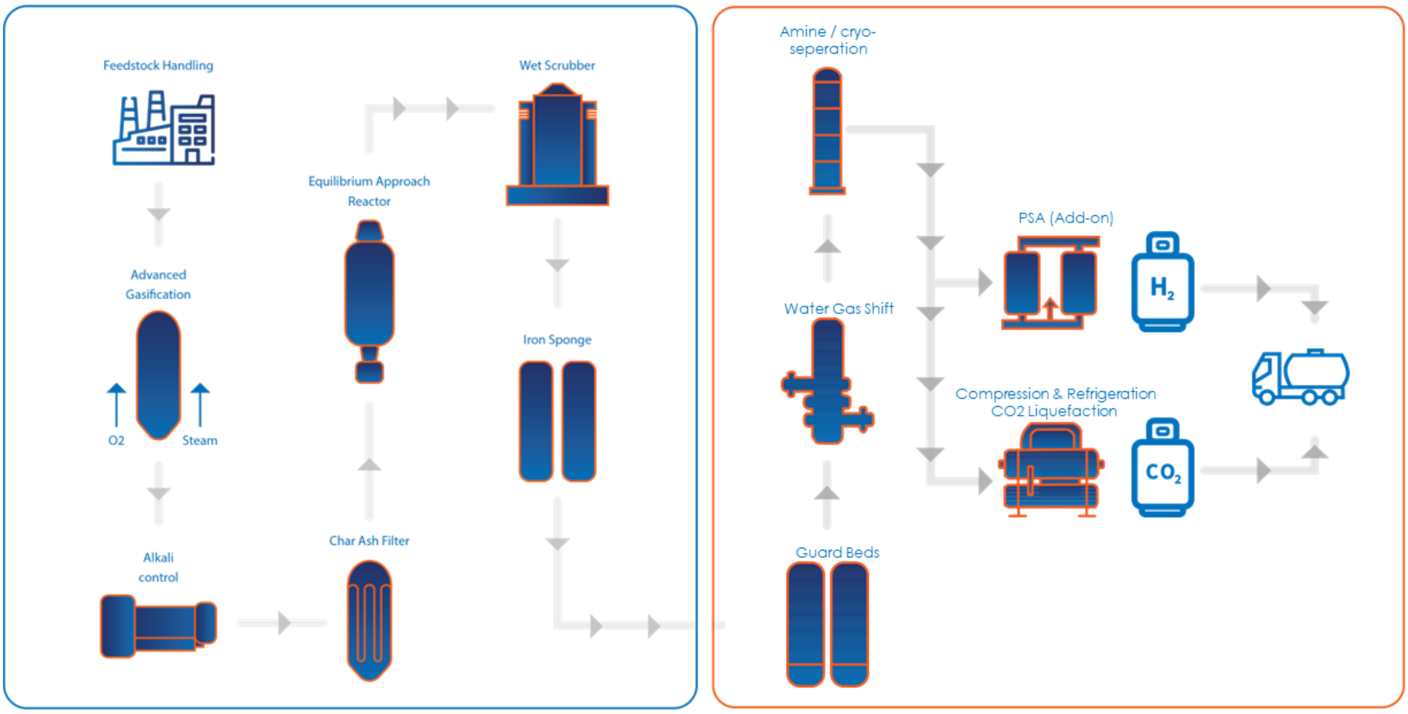
The modular design of KEW's system ensures that it can efficiently handle a diverse array of feedstocks, including various non-recyclable wastes and low-grade biomass such as sewage sludge, AD digestate, and waste 'fines,' providing an economic and environmental solution for underutilised land. The modular system enables cost-effective scalability, allowing for incremental expansion of advanced sustainable molecules production facilities, which can be rapidly deployed in various industrial and rural settings across the UK.

CCH_2 project: the carbon capture via H_2 production overview

KEW's Phase II GGR driven solution proposition is capturing CO_2 released from biogenic wastes and low-grade biomass feedstocks during advanced gasification and processing them into hydrogen-rich energy vectors. The CCH_2 product integrates KEW's advanced ACT with carbon capture and hydrogen production to produce high-purity hydrogen and liquefied CO_2, offering both negative emissions and valuable energy products. The CCH_2 modular product is designed to handle approximately 15,000 tonnes of feedstock per year, producing 5MW of hydrogen output and capturing >20,000 tonnes of CO_2 annually.

Key features of the KEW CCH_2 solution include:

- Advanced Gasification unit: A pressurised advanced gasification unit that utilises a wide variety of non-recyclable waste and low-grade biomass feedstocks through a unique combination of pressure application, a fluidised bed gasification system, and a proprietary downstream synthesis gas (syngas) reformation process. This not only enhances feedstock security but also supports land and community regeneration while aligning with Government programs to broaden the UK biomass resource supply chain.
- Carbon-capture ready syngas: KEW's proprietary Equilibrium Approach Reformer (EAR) produces a clean, H_2-rich syngas as the main output from the advanced gasification process. This approach ensures a consistent, high-quality syngas that is free of contaminants, enabling low-cost operations and reliable syngas off-take suitable for pre-combustion carbon capture and upgrading into hydrogen-rich advanced fuels.
- H_2 Production and CO_2 Capture: The reformed H_2-rich syngas undergoes water-gas shift (WGS) conversion to produce hydrogen for industrial use, replacing fossil-derived hydrogen or natural gas. CO_2 is selectively removed from the syngas stream through pre-combustion capture, then liquefied and purified for transportation or use in concrete production, where it can be sequestered effectively for maximum GGR impact. The hydrogen can be further purified to meet fuel-cell and transport application specifications.
- Modular approach: The modular design allows early adopters to bypass the typical "gasification graveyard" associated with large-scale bespoke projects. KEW offers repeatable, proven units with the flexibility for additional modules to be installed rapidly. This modularity supports the deployment of compact projects in decentralised markets, enhancing access to feedstock supplies across the UK.
- Operational advanced gasification plant: KEW has constructed and is now operating the Sustainable Energy Centre (SEC), a commercial-scale advanced gasification plant that underpins the GGR-BECCS solution and will demonstrate the FOAK CCH_2 product. This operational facility mitigates the technology development risk by limiting it to incremental risks associated with the CCH_2 module development.



CCH$_2$ high-level process schematic

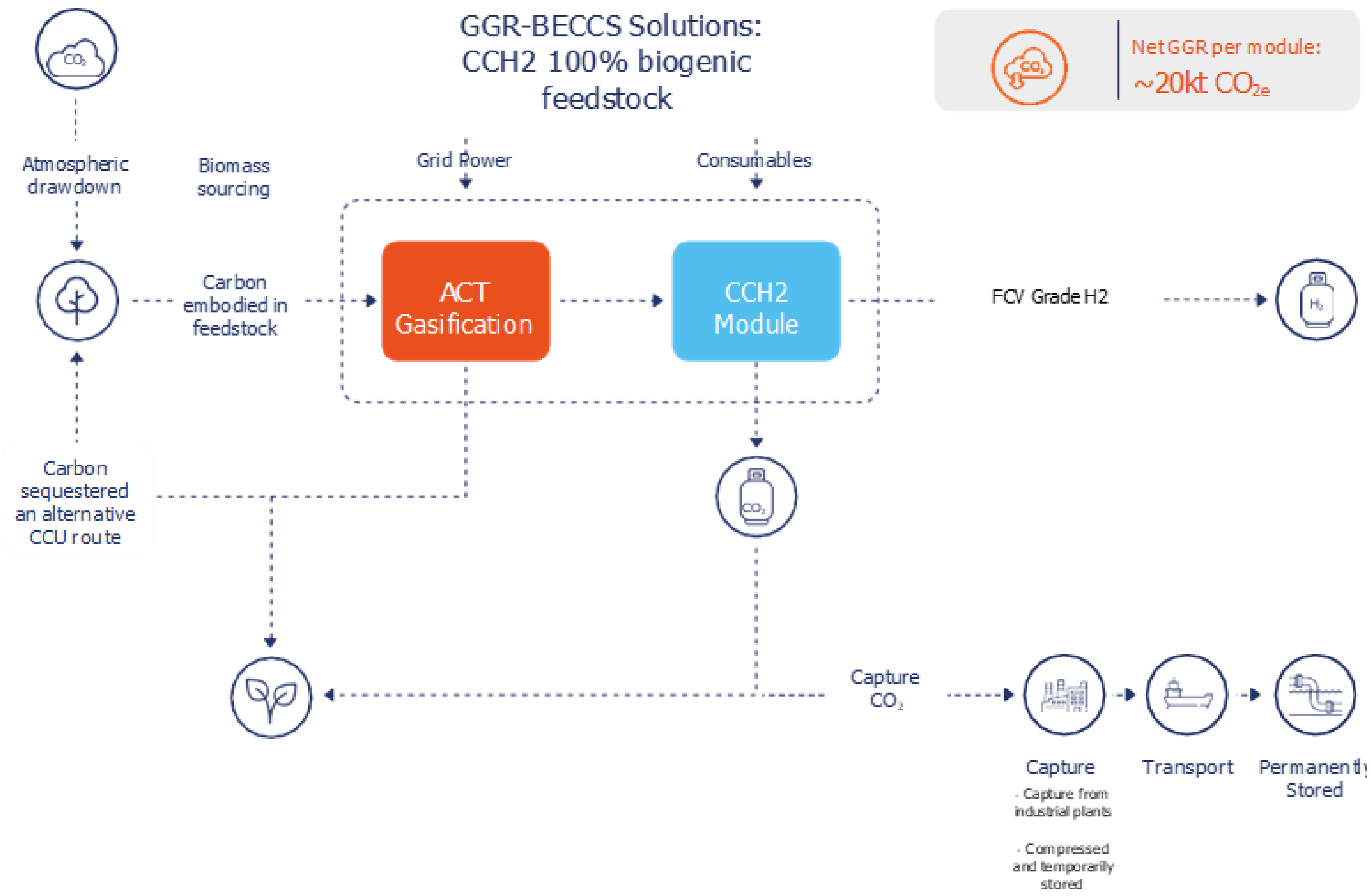
Project £/tCO_2 economic benefits

The cost of CO_2 capture for KEW's solution ranges between £20-120 per tonne of CO_2 (tCO_2) for First-Of-A-Kind (FOAK) projects. The lower end of this cost spectrum is achieved when using waste as a gate fee, while the higher end corresponds to using biomass as the cost of goods. This pricing is extremely competitive when compared to the cost of Direct Air Capture (DAC) as based on the World Resources Institute the cost of DAC technology varies widely, typically ranging from approximately $250 to $600 per tonne of CO_2 captured. This translates to roughly £200 to £480 per tonne, based on current exchange rates. Additionally, a 2022 report by the International Energy Agency (IEA) projected that, with further deployment and innovation, DAC capture costs could decrease to under $100 per tonne of CO_2.

Therefore, KEW's solution remains significantly more cost-effective in the near term and is targeting additional cost reductions with mass deployment. The affordability of KEW's CO_2 capture is driven by the sale of hydrogen, making the process more economically viable and enabling it to compete with other carbon capture technologies like DAC, which still face much higher operating costs.

Environmental and social benefits

During the project KEW worked with NNFCC to produce iterations of the LCA analysis and model.



The results demonstrate that **KEW Technology's proposed GGR-BECCS CCH2 technology product will successfully meet the emissions threshold criteria for the LCHS while producing negative carbon hydrogen. Additionally, we conducted a scenario assuming the venting of CO2, in case CCS infrastructure is unavailable, and confirmed that the CCH2 technology product would still surpass the LCHS requirements, providing over 50% headroom.** This headroom is important as it ensures the technology remains compliant with emissions standards even under less optimal conditions or unforeseen operational challenges, offering a buffer for future policy/regulatory changes and uncertainties in system performance.

Furthermore, KEW's GGR-BECCS system offers a range of environmental and social benefits, including significant GHG emissions reductions, job creation, and local economic development. By utilising low-grade biomass and waste materials, KEW's technology contributes to land regeneration, while its modular design enables deployment in a variety of locations, overcoming the limitations of large, centralised infrastructure projects.

In addition to carbon capture, KEW's technology has shown promise in improving soil quality and reducing nutrient leaching through the use of sustainable fertilisers derived from by-products. The overall system demonstrates a viable, scalable solution to decarbonising the industrial, transport, and energy sectors while contributing to the circular economy.

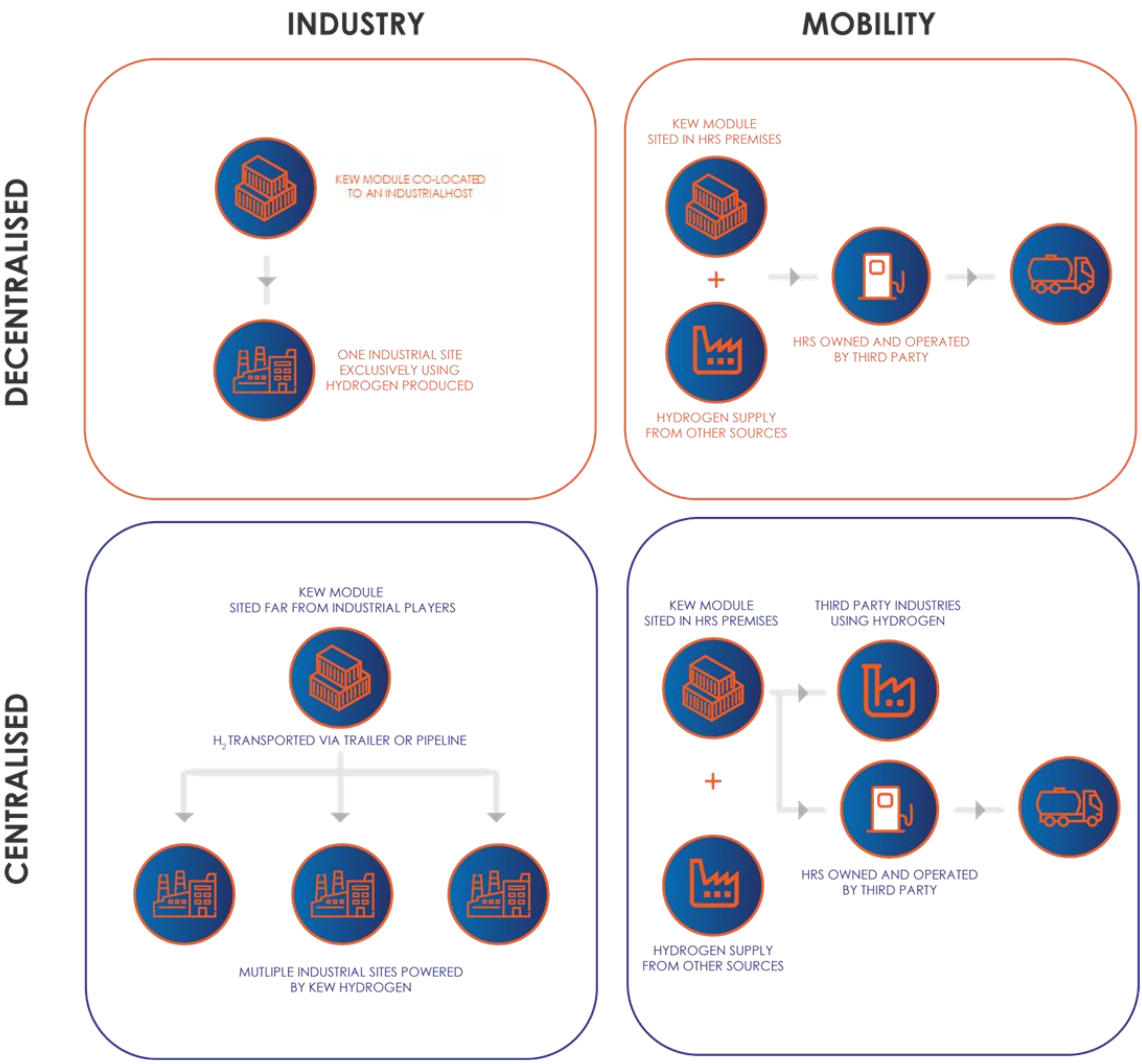
Overcoming challenges to GGR deployment

Achieving the UK's Net Zero goals will require diverse, decentralised solutions. KEW's modular approach addresses key challenges such as feedstock availability, scalability, and the need for rapid deployment. KEW believes that the use of small-scale, modular systems will play a critical role in decarbonising hard-to-reach sectors and contributing to the government's Levelling Up agenda. The modular approach not only reduces the cost of deployment but also accelerates the adoption of sustainable energy technologies, creating opportunities for investors and providing value for taxpayers.

Route to market and achieving wider impact

KEW's technology offers a clear route to market, with modular deployment enabling scalability and reducing financial risk. By overcoming barriers to financing and feedstock supply, KEW's approach supports rapid commercial adoption and provides a pathway to the large-scale deployment of GGR-BECCS systems. As the market for low-carbon hydrogen and carbon capture technologies matures, KEW is well-positioned to lead the way in delivering scalable, low-cost, and flexible solutions for decarbonisation.

In conclusion, KEW's CCH_2 solution represents a significant step forward in the development of advanced conversion technologies, offering both environmental and economic benefits. Through continued innovation, modular deployment, and strategic partnerships, KEW is committed to advancing the commercialisation of sustainable energy technologies and driving the UK's progress toward a decarbonised future.



Potential CCH2 commercial applications matrix

Phase II update

KEW was awarded funding for the Phase II GGR & DAC competition in April 2022 after successfully delivering several high-profile UK government-supported programs that demonstrated its unique technology. In Phase II, KEW focused on testing and demonstrating the integration of these technologies at the Sustainable Energy Centre (SEC), to progress toward Technology Readiness Level TRL 8. While the installation and testing of some components were not completed due to project constraints, significant progress was made in the development of the core ACT system, which consistently produced high-quality syngas. This laid the foundation for future work to achieve full-scale deployment.

Ancillary studies informed the project's direction, including the preceding GGR and DAC Phase I study and a parallel H_2 BECCS Phase I study. Together, these projects engineered an integrated demonstration plant to showcase the advantages of ACT in achieving low-cost carbon capture by leveraging revenues from hydrogen production.

During the Phase II project, KEW advanced to an almost complete detailed design, including procurement and site infrastructure readiness. Despite being unable to complete the installation of the CCH_2, KEW conducted an extensive demonstration and testing campaign of the upstream ACT plant, achieving the significant milestone of producing a clean syngas with a consistent H_2 composition. Advanced gasification tests have been carried out in stages since 2022, accumulating thousands of hours of testing duration. The progress made during Phase II, including studies on CO_2 and hydrogen markets and the completion of key technical milestones, positions KEW's technology for future commercialisation.

The achievements of the ACT demonstration and the engineering of the CCH_2 have recently culminated in a new partnership to build a full-scale hydrogen plant with carbon capture. Development for this project is already underway, with a view to begin detailed design and construction in Q2 2025. KEW is also focused on establishing additional commercial partnerships for H_2 and CO_2 offtake, which will leverage the insights gained from the studies completed during this GGR Phase II.

Looking ahead, KEW remains committed to engaging with key stakeholders and investors to build on this momentum, with the ultimate goal of developing the project into a fully operational CCH_2 facility. The team's dedication to innovation and collaboration continues to drive progress toward a sustainable and decarbonised energy future.

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 R&D 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.

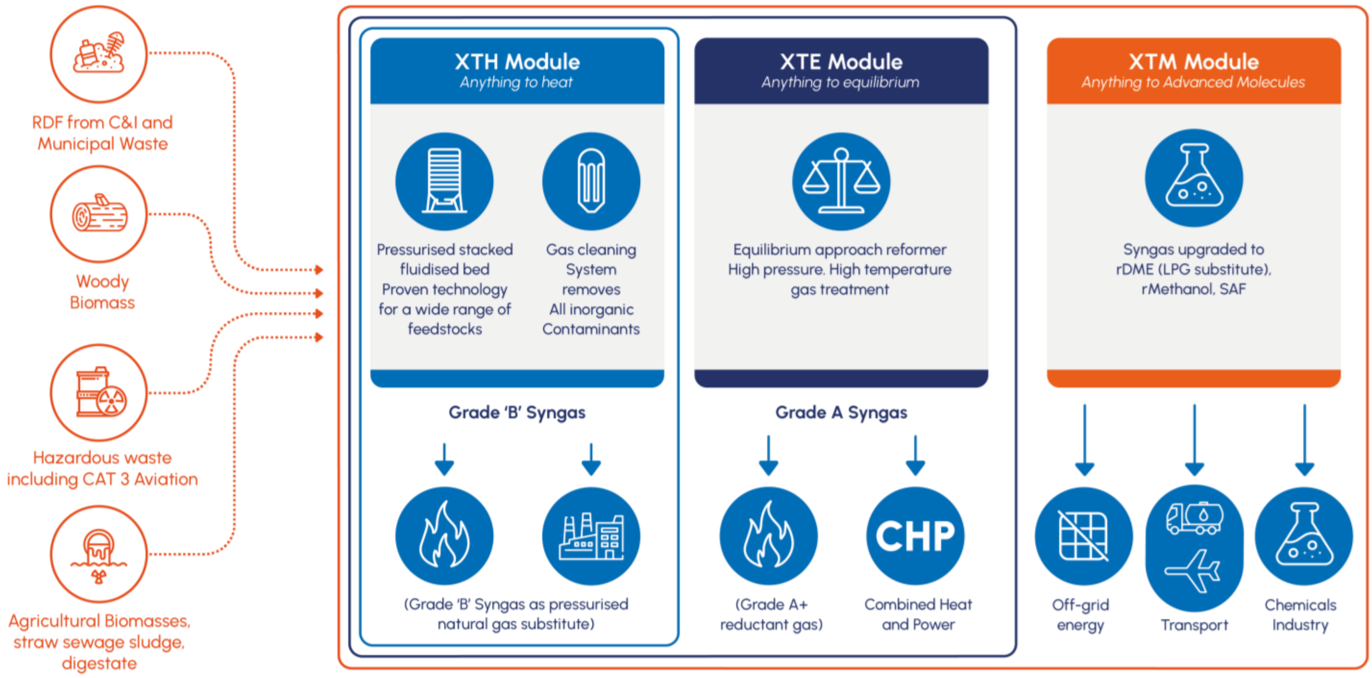
KEW's key technology USP is operating the ACT system under pressure, with a patented syngas reformation step, which enables the cracking of the longer hydrocarbons and removal of impurities which otherwise create challenges with solids and tar build up – one of the biggest challenges

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 partner.

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.



- A robust, proprietary stacked fluidised bed giving excellent feedstock flexibility and cost effectiveness.
- 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 CCH_2 project: the carbon capture via H_2 production Phase II overview

KEW's proposed 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.

At the beginning of the Phase II GGR project, KEW had designed a H_2 BECCS system capable of capturing CO_2 from syngas derived from waste biomass. It used an innovate CCS arrangement; the ACT coupled with water gas shift (WGS) and separation of H_2:CO_2 by cryogenic liquefaction. This process produced a food grade CO_2 product that could be sold to the market or also sent to geological storage. By default, this process also produced a low carbon industrial hydrogen product of 61%vol purity. Building on incumbent CCS technologies such as amine solvent, KEW's aim was demonstrate a different approach. It would improve the overall efficiency of the amine CCS process by avoiding high heat consumption in the CO_2 desorption step and instead utilise the compression/cooling energy of the CO_2 liquefaction stage to separate the H_2 and CO_2 molecules. Thus, hitting two birds with one stone.

The GGR funded scope is actually a sub-set of KEW's wider carbon capture and hydrogen production system (CCH_2), that completes KEW's BECCS system. Sitting parallel to GGR, are additional units; a pressurised water absorption (PWA) and pressure swing adsorption (PSA) which provide a complimentary route to hydrogen purification utilising the syngas coming from the GGR WGS. PWA and PSA are currently inside the scope of DESNZ's H_2 BECCS programme.

The PWA exhibits the following key benefits compared with amine: lower energy requirements, lower LCOH profile, increased hydrogen production capacity, and lower greenhouse gas (GHG) intensity. Critically, the refined H_2 product meets the standards of many industrial applications without need for further purification. A pressure swing adsorption (PSA) unit was to be placed downstream to purify the H_2 to 99.97mol% suitable for fuel cell vehicles (FCV) and other transport applications. The GGR cryogenic liquefaction system was then available to purify and liquify the CO_2 coming from the PWA (instead of the shifted gas coming from the WGS). This combined arrangement between the GGR and H_2 BECCs scopes created an elegant solution that KEW called CCH_2 module.

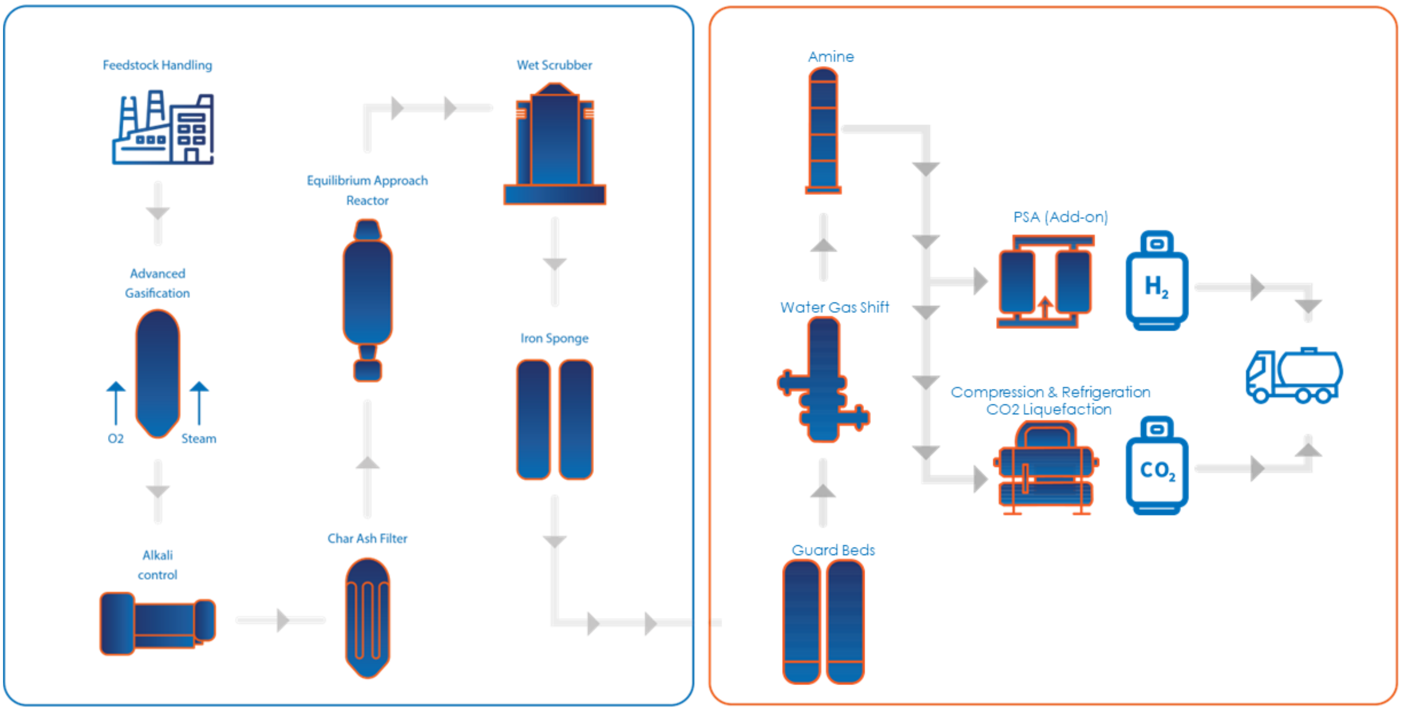


Figure 1: Summary of the KEW GGR solution

This worked well since the two DESNZ programmes had matching deadlines (March 2025) so were running on parallel schedules, and as a result their demonstration periods would have shared the same operating hours to deliver shared results.

1.3 CCH$_2$ project: the carbon capture via H$_2$ production product proposition for commercialisation

KEW's commercial BECCS-GGR technology process, 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 ~5MW energy output as H_2 product (c. 200kg/hr) at FCV grade purity.
- Provides net >20,000 t.p.a. of CO_2e removal.

KEW product offering provides an end-to-end fully costed and risk-mitigated solution which brings together existing proven technologies, in an innovative GGR-BECCS solution.

2 CCH_2: project overview

2.1 Phase II project aims

The GGR programme aims to identify effective methods for achieving greenhouse gas removals at the scale of mega tonnes of CO_2 equivalent ($MtCO_2e$) or greater, with a target cost of less than £200 per tonne of CO_2e removed, while fostering innovation to support this outcome.

In alignment with this goal, KEW's complementary Phase II aim was to 'build and test' the CCH_2 modular plant at the Sustainable Energy Centre (SEC). Following installation and commissioning, the test programme was designed to demonstrate the successful and continuous operation of the technology in a full-scale commercial setting. This would increase the Technology Readiness Level (TRL) of the integrated system to TRL 8, preparing it for commercial exploitation.

Specifically, this involved demonstrating the conversion of approximately 15,000 tonnes per year of waste/biomass into a hydrogen-rich gas, and further upgrading it to capture and liquefy around 20,000 tonnes per year of CO_2.

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 H2 BECCS route to substantial contribution to net zero targets.
- Successful demonstration of strong Greenhouse Gas Removal capability and growth potential.
- 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.
- Defined economic proposition.

2.2 Phase II progress summary of project aims

2.2.1 Techno-commercial progress of overarching competition objectives

Table 1: Techno-commercial progress of overarching competition objectives outlined in the GGR guidance document

Summary	Description	Achieved?	Status
Advances deployment of GGRs in the UK	**Competition objective #1:** In Phase I, the goal was to evaluate, optimise, and produce high-quality designs for GGR solutions that, if implemented, would significantly advance the development of GGR technologies in the UK.	✓ Yes	Evidence of progress was demonstrated through the completion of Phase I work and the subsequent award of the Phase II contract. In Phase II, further detailed design work was carried out, preparing the project for the fabrication and supply of materials.
Successfully construct, operate, test, refine and evaluate to remove GHG from atmosphere at scale	**Competition Objective #2:** In Phase II, the best of these designs will be applied to successfully construct, operate, test, refine, and evaluate processes and technologies capable of removing GHGs from the atmosphere at scale.	× No	Project terminated prior to construction and testing.
Identify commercial and technical steps to deploy GGR in UK/overseas to remove GHG in millions tonnes per annum	**Competition Objective #3:** In Phase I, and in greater detail in Phase II, identify the commercial and technical steps that could be taken forward (in partnership with others, where appropriate) to deploy the GGR technology commercially in the UK and abroad, with the aim of removing GHGs from the atmosphere at a scale of millions of tonnes per annum, at the lowest possible cost.	⇨ Partial	KEW completed several studies that contributed to the overall commercial scaling and deployment of the technology, including analyses of the CO_2 and H_2 markets. This work led to commercial agreements with multiple customers, as well as agreements for feedstock supply through on-going HoTs discissions. KEW also began collaborating with new partners, including manufacturing design firms, as part of other projects, to roll out multiple modular plants following the project. The full and final commercial deployment report was not completed due to the early termination of the project.

2.2.2 Technical progress of project objectives

Table 2: Technical requirements stipulated by DESNZ in GGR guidance document

Description	Achieved?	Comments
Projects in Lot 2 must have a minimum capacity of 1,000 tCO_2e per annum. For clarity, projects are required to install and operate at these minimum capacities during Phase 2. This means that for solutions consisting of multiple identical small units (modules), a sufficient number of modules must	✓ Yes	At the end of Phase I, a full-scale plant was proposed for the demonstration. While the already built ACT island was at commercial scale, the downstream syngas to H_2-CO_2 section was scaled down during Phase II to better manage the budget. The revised plant was sized to capture approximately 3,000tCO_2

be installed during Phase 2 to demonstrate the minimum capacity (100 or 1,000 tCO_2e per annum).		per annum, which still exceeds the minimum requirement of 1,000tCO_2e per annum.
Innovation & TRL: Lot 2 projects must demonstrate at the application stage that they are at TRL Level 6 and, by the end of Phase 2, must show that they have achieved TRL Level 7 or higher.	⇨ Partial	While the individual technical components of the ACT and CCH_2 are known and proven at TRL 8-9, the integration of these subsystems is at TRL 6. This would have been raised to TRL 8 by the end of the demonstration project, had the testing been completed.
Eligibility scope: Direct air capture of CO_2 (through mechanical capture from well-mixed air), biochar (using biomass to generate a solid primarily composed of carbon), bioenergy with CCS (BECCS, where biomass combustion generates a CO_2 stream of appropriate concentration and purity for permanent sequestration), advanced weathering (using minerals applied to soil to capture and permanently sequester carbon), and removal of CO_2 from seawater via chemical or electrochemical means. Technologies that remove non-CO_2 greenhouse gases, including methane, nitrous oxide, and F-gases, are also in scope.	✓ Yes	The KEW CCH_2 system design was within the scope described as Bioenergy with CCS (BECCS).
Project boundary: The start point of the process is either: (a) the input of sustainable biomass into a process that captures carbon dioxide, (b) dilute CO_2 (from the atmosphere or seawater), or (c) another dilute GHG from the natural environment.	✓ Yes	As per (a) – KEW's ACT system utilises sustainable biomass as the feedstock and captures CO_2 in the CCH_2 module.
Project boundary end point: The project boundary end point is one of the following: (a) a stream of concentrated CO_2 that meets the specifications set out in Annex 4 (based on the Shell Cansolve process at Peterhead), (b) a product in which carbon is chemically fixed permanently, with a proposal for storing or using that product, or (c) for greenhouse gases other than CO_2, reaction products with a lower Global Warming Potential (GWP). Acceptable end products include building materials, biochar, carbonated minerals, or forms of carbon permanently stored in seawater.	✓ Yes	As per (a) KEW's CCH_2 system produces CO_2 with purity 99.99%vol to comply with food-grade specifications.
Environmental acceptability: Applicants must assess the potential environmental impacts of the GGR technology they propose to develop, considering the eventuality of its deployment at scale in the UK.	✓ Yes	Commercial scale x1 module unit would remove ~20ktCO_2/yr from the atmosphere. Viable commercial scale 3x modules would capture ~60ktCO_2/yr.

3 System design, development & demonstration

Under the GGR scope, a system was designed and engineered for demonstration at KEW's Sustainable Energy Centre (SEC) in the West Midlands, UK. The following provides details of the system design and development status.

3.1 Unit operations summary

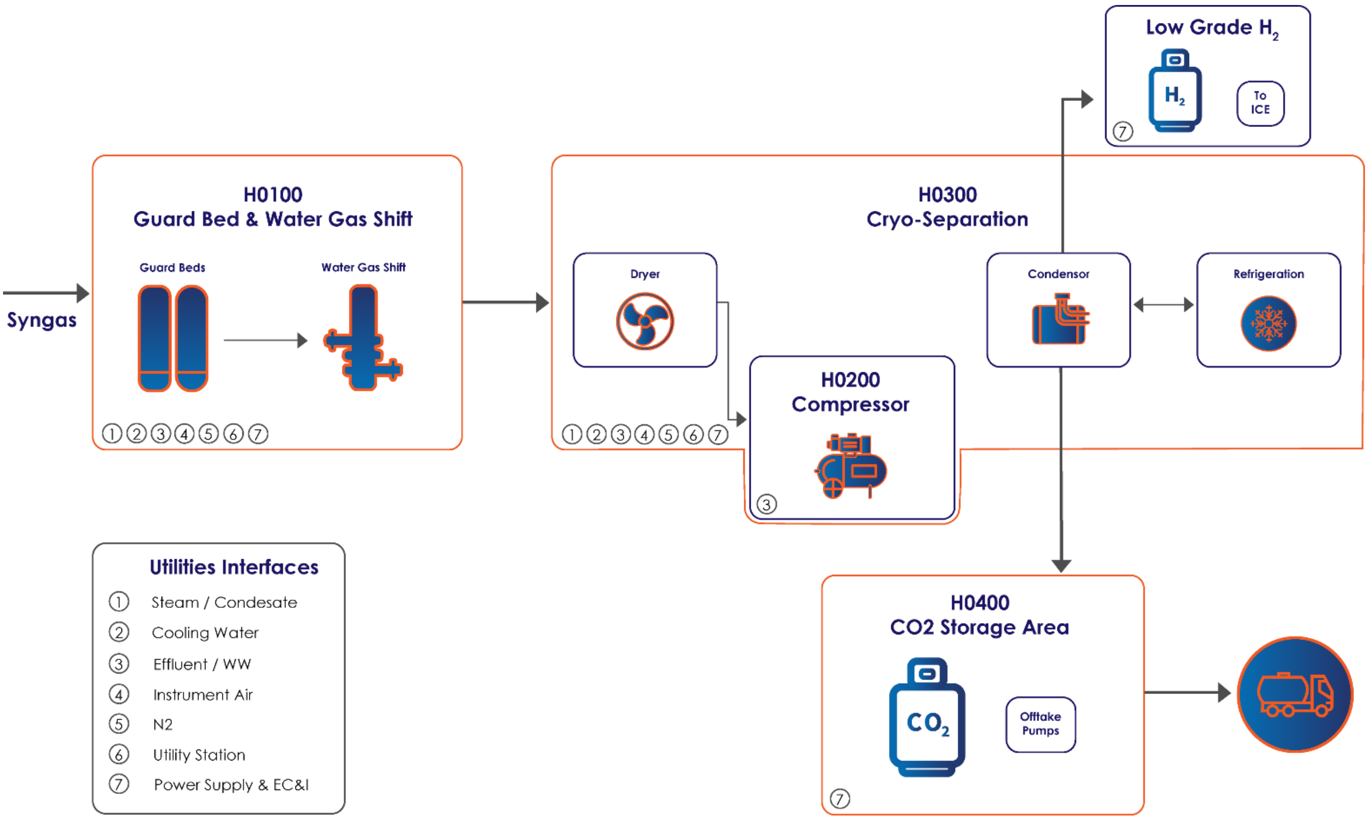


Figure 2: In scope GGR process systems, part of KEW's CCH$_2$ Phase II demo scope

As shown in Figure 2 above, the GGR is split into the following key unit operations:

3.1.1 Unit H0100: Guard Bed and Water Gas Shift unit

Guard Beds units

Water Gas Shift (WGS) reactors (LT and HT)

Three guard beds to remove majority impurities from syngas to avoid contamination and premature degradation of the catalysts in the WGS reactors. After passing through series of Guard beds syngas is further processed in LT and HT Shift Gas Reactors.

3.1.2 Unit H0200: 30 barg Compressor

This unit majorly contains two sets of reciprocating compressors in parallel which shall compress shifted gas to 30 barg in order to reach the operating pressure required by the cryogenic separation process.

3.1.3 Unit H0300: Cryogenic Separation and Liquefication

This unit is fed by the upstream shifted gas, and it contains:

Dehydration condenser (at low pressure)
Cryogenic separation
CO2 upgrading (stripping column)

3.1.4 Unit H0400 CO_2 Storage and offtake

This unit is separated out due to the nature of the equipment and special layout requirements needed for safe storage and vehicle filling.

This unit has liquid CO_2 storage tanks and their transfer pumps.

3.2 System description

3.2.1 Unit H0100: Guard Bed and Water Gas Shift unit

3.2.1.1 Syngas polishing guard beds

The syngas (5 barg pressure) is fed to the activated carbon and alumina beds for the removal of trace acid gas components and particulate metals. Metals removal is necessary to avoid the risk of poisoning the downstream reactor catalysts. The unit acts as a polishing unit since bulk metals removal has already been undertaken in the ACT.

The gas is then sent to an expendable carbon-based chemical sorbent to remove Carbonyl Sulphide (COS) and Carbon disulphide (CS_2) and is then finally fed into a bed for polishing of any remaining Hydrogen sulphide (H_2S).

3.2.1.2 Water Gas Shift (WGS) reactors

After the guard bed polishing, the syngas is sent to the WGS to be converted into a shifted gas where CO has been removed leaving only a high concentration of H_2 and CO_2. The gas is mixed with steam and then run over a catalyst to cause the shift reaction as follows:

$$CO + H_2O \xrightarrow{\text{yields}} H_2 + CO_2 \quad \Delta H_r = -41 \text{ MJ / kmol}$$

The conversion takes place with 2 adiabatic reactors:

- High temperature water gas shift (HTWGS)
- Low temperature water gas shift (LTWGS)

3.2.2 Unit H0200 and H0300: 30 barg Compressor and Cryogenic Separation and Liquefication

3.2.2.1 Before the compressor

The feed gas initially enters a low pressure (LP) dehumidifier to ensure proper compression operational range, which is essentially a gas cooling exchanger to condense the majority water vapour in the shifted gas. The condensate is removed through a liquid separator to reach about 200ppm residual humidity in the syngas.

3.2.2.2 Gas compressor unit

The H_2-CO_2 mixture is then compressed up to 30barg and then cooled using the site cooling water on the cold side of a heat exchanger at evaporative tower water temperature and a second after-cooler fed with chilled water.

3.2.2.3 After the compressor

Since the downstream low-temperature heat exchanger (within the H0300 Cryo skid) can only accept minimal traces of water to prevent freezing, a final dehydration using an adsorbent material is necessary. So, the high pressure dehumidified gas passes through a series of molecular sieves in order to remove traces of water in the shifted gas. Prior to the molecular sieves, the gas stream is further cooled down with a refrigerant (ethylene glycol) and some more water is separated.

3.2.2.4 CO_2 Separation and Cryogenic Liquefaction

The H_2-CO_2 mixture which is now dried and compressed enters the CO2 liquefaction heat exchanger to reduce the temperature down to the design temperature, which was selected at around -50°C. At this temperature, the thermodynamic equilibrium shows a final gas composition of >70% of hydrogen, with a CO_2 recovery efficiency of around 2/3.

The cold side of the heat exchanger will receive a coolant vector such as ethylene glycol and ammonia (as refrigerant material) from the electrical chiller.

3.2.2.5 CO_2 upgrading (reboiler)

As the liquid CO_2 produced in the condensation unit will also have smaller number of volatile compounds in this liquid phase (mainly hydrogen), driving to a CO_2 quality that is about 99% and not suitable to be categorized as food-grade. So, a further rectification unit to upgrade the CO_2 quality is needed able to strip out the undesired gas CO_2 loss.

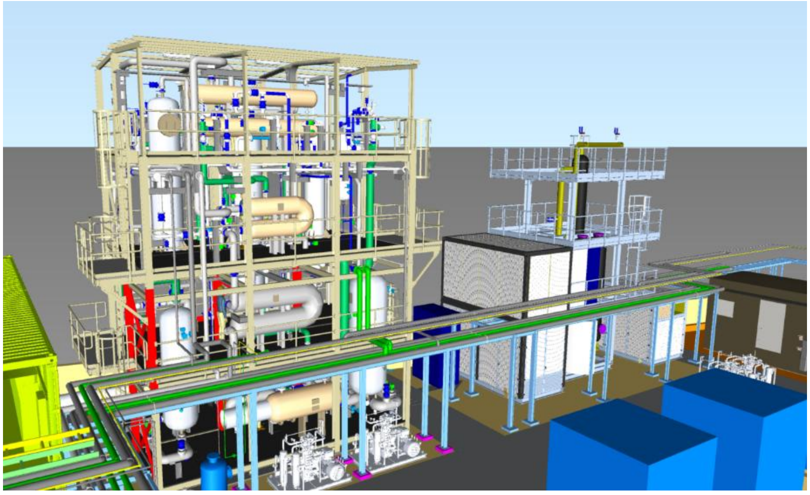


Figure 3: Screen shot of the 3D model showing H100 module, H200 compressors, H300 cryo skid and H000 integration piping.

3.2.3 Unit H0400: Liquid CO_2 storage

Liquified CO_2 will be stored at 20barg below -15°C to ensure a proper storage and transportation condition. The storage vessel will be sized to stock at least 5 days of production and will be designed to allow the required accessibility for transporting vehicles.

Liquid CO_2 storage will be arranged to facilitate food grade CO_2 export from the plant, from one single vessel whilst considering safety issues for truck filling operations.

A single duty liquid CO_2 pump are envisaged feeding a single road tanker filling point. The pump will be sized to fill a single road tanker in 30 minutes (nominal capacity 25 m3). Plant design capacity will be based to schedule one road tanker per day to remove the liquid CO_2 produced.

3.3 Operational summary

During the project period, KEW's SEC has been operated in campaigns around a progressive build programme during the project period through 2022-2024, generating valuable operational data to guide its ongoing development. The system has been tested on a wide range of feedstocks including pulp and paper industrial waste and waste wood, but most of the operations have been on refuse derived fuel (RDF) based materials.

Figure 4: KEW's advanced gasification/ACT plant in operation

The campaign runs produced a clean syngas with a 1:1 H_2 composition, which serves as the feed gas for the CCH_2 GGR system. The smooth operation of the ACT island is a critical component of the overall BECCS process, and without it, the GGR-funded project scope would be redundant.

In fact, the GGR-funded scope consists of sub-systems that are already proven and well-established commercial technologies, such as the water-gas shift and CO_2 liquefaction. Therefore, although KEW's GGR project was terminated before the demonstration of its CO_2 capture systems, the loss of these test results does not diminish the significant progress and performance achievements of the upstream core advanced gasification/ACT island. The recent results from the ACT gasifier are discussed below.

3.4 Feedstock performance

The plant has operated on a variety of feedstocks, demonstrating consistent and reliable performance across a wide range of materials.

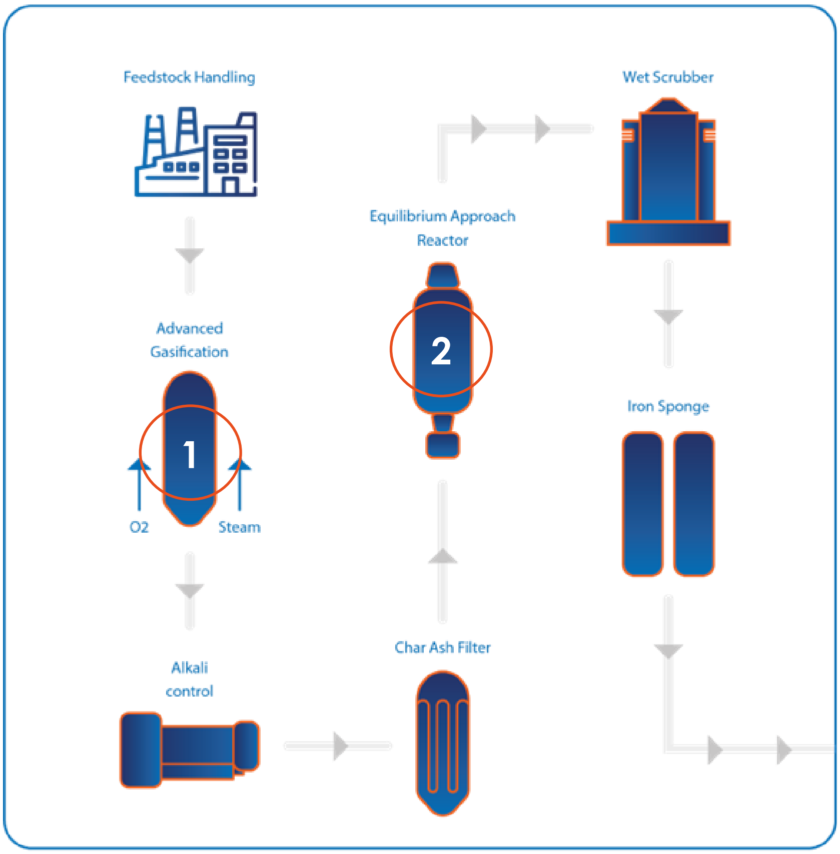


Figure 5: ACT process flow

The syngas produced from the gasifier ('1' in the process flow above) varies as expected based on the incoming material, with higher plastic content leading to lower hydrogen levels. However, the syngas produced from the proprietary equilibrium approach reformer ('2' in the process flow above) consistently maintains the expected H_2-CO ratio.

KEW's approach to gasification is non-catalytic, which avoids the issues of catalyst fouling that occur with RDF and biomass contaminants. It enables advanced gasification producing hydrogen and CO through the total reformation of hydrocarbons, operating at higher temperatures than simple cracking for greater efficiency, aided by a recuperation step. This approach offers significant advantages over plasma-based systems in terms of efficiency, residence time and cost. The high pressure in KEW's system allows for a longer residence time, reduced soot production, and more complete conversion with lower operating costs.

4 Benefits & challenges

The assessment of benefits and challenges takes a step away from the Phase II demonstration project to look at the full-scale application of the technology. The numbers provided in the following section are based on KEW's commercial modular ACT product (10MWt) GGR-BECCS plant.

4.1 CapEx, OpEx & £/tCO_2

4.1.1 Cost of CO_2 capture

The cost of CO_2 capture for KEW's solution ranges between £20-120 per tonne of CO_2 (tCO_2) for First-Of-A-Kind (FOAK) projects. The lower end of this cost spectrum is achieved when using waste as a gate fee, while the higher end corresponds to using biomass as the cost of goods. This pricing is extremely competitive when compared to the cost of Direct Air Capture (DAC) as based on the World Resources Institute the cost of DAC technology varies widely, typically ranging from approximately $250 to $600 per tonne of CO_2 captured. This translates to roughly £200 to £480 per tonne, based on current exchange rates. Additionally, a 2022 report by the International Energy Agency (IEA) projected that, with further deployment and innovation, DAC capture costs could decrease to under $100 per tonne of CO_2.

Therefore, KEW's solution remains significantly more cost-effective in the near term and is targeting additional cost reductions with mass deployment. The affordability of KEW's CO_2 capture is driven by the sale of hydrogen, making the process more economically viable and enabling it to compete with other carbon capture technologies like DAC, which still face much higher operating costs.

4.2 Lifecycle Analysis (LCA)

4.2.1 Summary

The GGR-BECCS system is built upon the fundamental arrangement of utilising end of life waste or low-grade biomass as the feedstock to produce syngas and subsequently hydrogen. The hydrogen product is key in determining the choice of LCA model; here the Low Carbon Hydrogen Standard (LCHS) – developed by DESNZ – was selected.

During the project KEW worked with NNFCC to produce iterations of the LCA analysis and model.

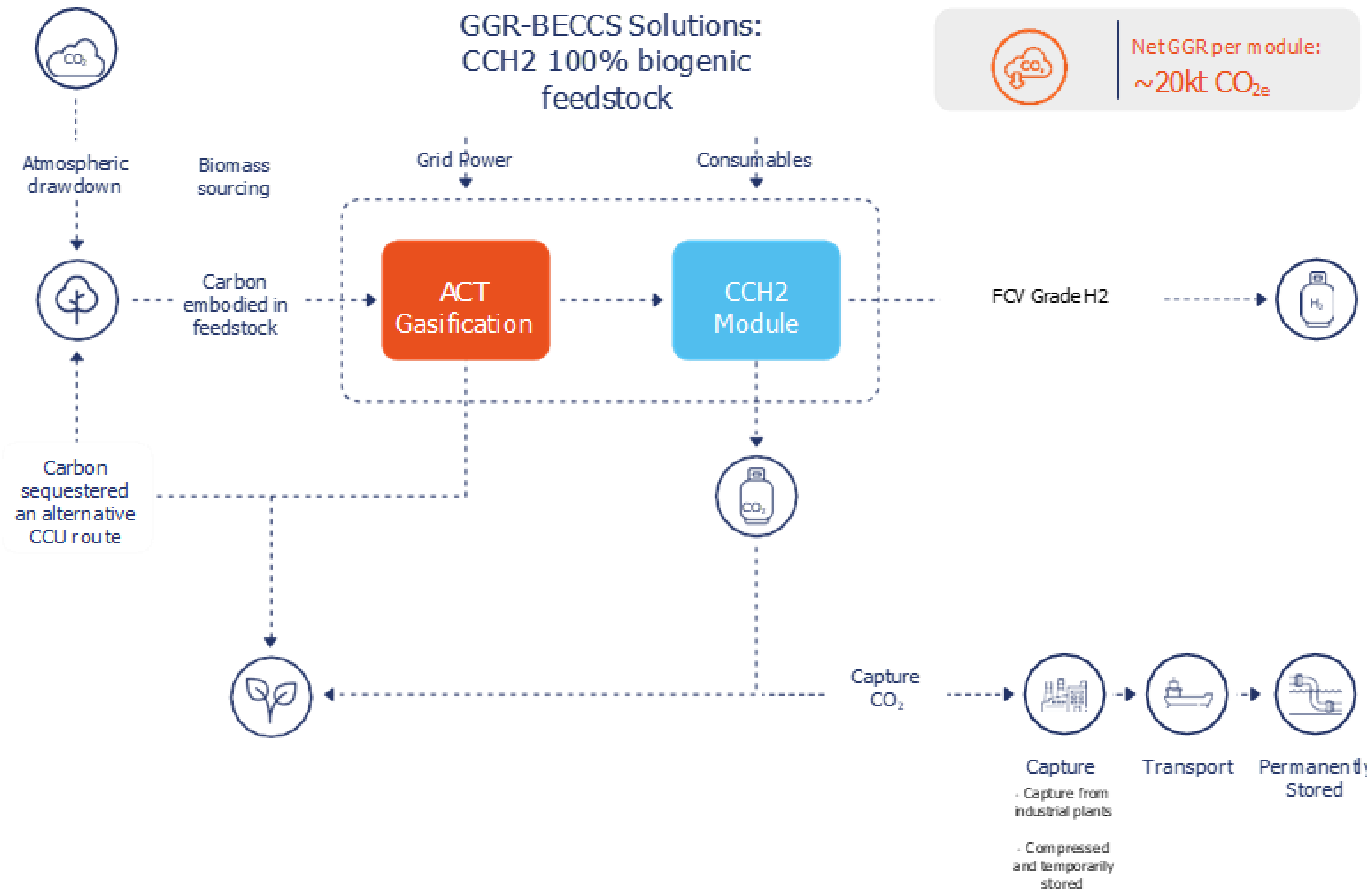


Figure 6: LCA results using LCHS methodology

The results demonstrate that **KEW Technology's proposed GGR-BECCS CCH2 technology product will successfully meet the emissions threshold criteria for the LCHS while producing negative carbon hydrogen. Additionally, we conducted a scenario assuming the venting of CO2, in case CCS infrastructure is unavailable, and confirmed that the CCH2 technology product would still surpass the LCHS requirements, providing over 50% headroom.** This headroom is important as it ensures the technology remains compliant with emissions standards even under less optimal conditions or unforeseen operational challenges, offering a buffer for future policy/regulatory changes and uncertainties in system performance.

Currently, under the LCHS, carbon sequestration through material products such as storage in char and carbon black used in construction materials is not recognised. However, if such methods of sequestration were to be accepted, it would further enhance the negative carbon impact of the technology.

The negative-carbon hydrogen produced by the technology can then be deployed across a range of market segments, including fuel switching in industry, transport (either as hydrogen or converted into methane, methanol, DME, or SAF), or as a chemical feedstock. In all of these applications, the hydrogen would serve to displace fossil fuels, facilitating decarbonisation in some of the most challenging sectors to abate.

4.2.2 Methodology

The lifecycle assessment was calculated in accordance with the LCHS. This methodology is designed for hydrogen production pathways such as by electrolysis of water using renewable energy, steam reforming of natural gas with carbon capture and storage (CCS) and thermos-chemical conversion of waste/biomass with CCS. The methodology considers the value chain of the production pathway and allocates emissions to the relevant products of the process. This includes emissions associated with the feedstocks, energy & material inputs, and process CO2 emissions, which are common to most LCA methodologies. In addition to these parameters, other parameters considered include emissions from fugitive non-CO2 emissions such as CH4, N2O, SF6, HFC and PFC and a waste counterfactual for the diversion of waste from its current application, in this case energy from waste (EfW). Additionally, the LCHS requires that the hydrogen output be standardised to 3MPa and 99.9% purity. The calculator has been built to comply with all these conditions as set out in the LCHS.

4.3 Measurement Reporting & Verification (MRV) Methodology

A standardised MRV framework is essential for ensuring that we are comparing like for like in the rapidly evolving race to net-zero, where different technologies can produce a variety of low, zero, or negative carbon molecules for a broad range of end energy applications. Such clarity and comparability are not only crucial for accurate GHG emissions reporting but also facilitate participation in essential Environmental, Social, and Governance (ESG) reporting for infrastructure projects of this nature, product certification schemes, and potential monetary policy incentive mechanisms.

Essentially, a universally recognised MRV policy suite is key to ensuring that sustainability metrics are judged fairly and transparently, fostering an environment where investments are made with confidence, and sustainability goals are pursued with a clear understanding of their impact.

During the project period, with support from ERM, KEW carried out an extensive study of the ACT-GGR/BECCCS systems and their role within waste, biomass, renewable energy (electricity), carbon capture/credits/taxes and hydrogen markets, in order to propose a suitable MRV methodology.

In doing so, KEW has been able to highlight the nuanced variations of GHG emissions reporting calculations and demonstrate that their current uses are exclusive to other market's business models. KEW also did a thorough examination and comparison of compliance standards which are initially underpinned by:

International Sustainability and Carbon Certification (ISCC) scheme; whilst considering
Renewable Energy directive(RED)
Low Carbon Hydrogen Standard (LCHS); and;
Renewable Transport Fuel Obligation
The conclusions of the work were that for ACT-GGR/BECCS technologies like KEW's .:

- There are too many schemes in the UK and Europe to try to conform to varying by the end molecules produced and/or the end-sector application.
- There is a clear need for a standardised MRV directive for the respective technology pathways irrespective of end-sector application.

KEW recommends:

- ✓ The harmonisation of carbon accounting and MRV requirements with existing frameworks (listed above) to ensure a level playing field for various molecules produced by the same technology and minimise fragmentation of the policy for energy markets.
- ✓ Further collaborative project work involving a broad spectrum of stakeholders including industry players, technology developers, policy makers and certification bodies to focus on the harmonisation and alignment with existing international best practices. This will be crucial to ensure a MRV framework that is robust, transparent and adaptable for our road to net-zero.

4.4 Achieving wider impact; environmental and social benefits

The GGR-BECCS CCH2 technology product are key building blocks in bridging the circular economy. As previously mentioned, the process uses end of life waste or low-grade biomass as the feedstock to recover energy; producing syngas and subsequently hydrogen.

More broadly, the integration of the generated waste products with the GGR-BECCS CCH2 solution allows the development of an "end-to-end" customised solution which:

- Enables significant cost competitive GHG emissions reductions
- Demonstrates applied circular economy concepts across many areas; and
- Overcomes disadvantages linked to distance from major centralised zero carbon hubs or CO2 storage facilities.

4.4.1 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.

4.4.1.1 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[1] 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[2]. 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.

4.5 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, GGR-BECCS 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.

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

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

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[3], 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[4].

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.

4.6 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.

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

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

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.

5 Route to market

5.1 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.

5.2 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.

5.3 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.

5.3.1 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.

5.3.2 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

Figure 7: Virtuous cycle

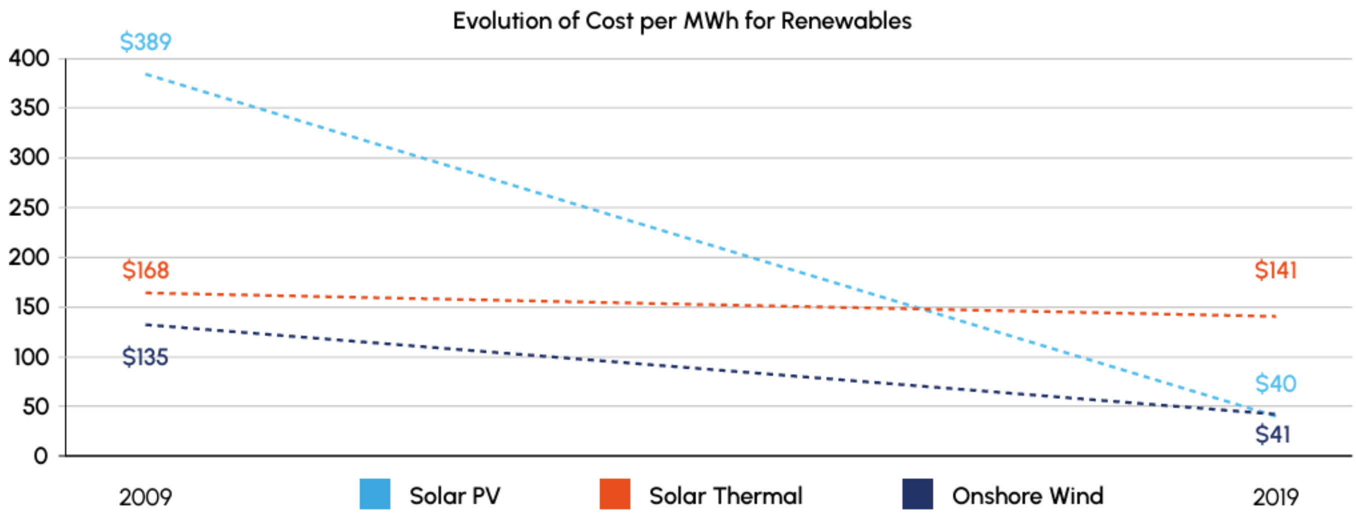

Figure 8: Figure 16: Comparison of the cost reduction of renewables over the last decade, correlated with the quantity of unit systems produced[5]

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

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.

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.

5.3.3 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

5.4 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.

5.5 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.

5.6 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.

5.7 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.