Department for
Energy Security
& Net Zero

KEW TECHNOLOGY

Pressurised Water Absorption H_2-CO_2 Separation

KEW Technology's Innovative H_2 BECCS Solution

DESNZ Hydrogen with Bio-Energy and Carbon Capture (H_2 BECCS) Innovation Programme

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Executive Summary

H_2 BECCS Phase I approach

The objective of this Department for Energy Security & Net Zero (DESNZ) funded research programme, Hydrogen Bioenergy with Carbon Capture and Storage (H_2 BECCS) Phase I, is to investigate a range of innovative but less technically proven hydrogen and carbon dioxide (H_2-CO_2) separation solutions to assess and compare:

- Their key process performance, including greenhouse gas (GHG) balance
- Relative Levelised Cost of Hydrogen (LCOH)
- The ability to test the preferred technology(s) utilising our existing proprietary advanced gasification solution, a form of Advanced Conversion Technology (ACT), at our commercial scale demonstrator

Leveraging public funded work

KEW has won and successfully delivered several high profile UK government supported programmes, and the legacy of several of these has provided a strong foundation for this project. Of most relevance is the recent work KEW is developing under the DESNZ Greenhouse Gas Removal (GGR) Programme (read more about this here: KEW's CCH_2 | Carbon Capture and Hydrogen GGR report). This aims to demonstrate a fully integrated GGR system, by developing a hydrogen production system with final cryogenic separation for direct Liquid CO_2 capture, to be tested alongside KEW's existing advanced gasification plant, at our Sustainable Energy Centre (SEC); an operational facility producing tar-free syngas in the West Midlands, UK.

Leveraging our unique commercial scale demonstrator

Over the past 10 years, we have developed, and tested at commercial-scale, our proprietary high-pressure advanced gasification process at the SEC. This flagship facility converts biomass and biomass-rich waste streams (e.g. RDF) into clean, tar-free, hydrogen-rich synthesis gas (syngas).

Uniquely this enables KEW to test net-zero technology innovation in a 'real-world' engineering environment, adding robustness to our analysis and conclusions for Phase I of this programme

Evaluation of technology options

KEW, together with Aston University, assessed five technology options for CO_2 separation across a number of key criteria. The outcome of this assessment is shown in the following table.

Table 1

	Amine	**Carbonate**	**Pressurised Water**	**Cryo with PSA**	**Cryo with Membrane Package**
Market Features					
Greenhouse Gas Balance	🟩	🟨	🟩	🟨	🟨
Levelized Cost of Hydrogen	🟥	🟥	🟩	🟨	🟨
Thermal energy requirments	🟥	🟥	🟩	🟩	🟩
Electrical energy requirments	🟩	🟩	🟨	🟥	🟥
Environmental risk (chemicals utilization)	🟥	🟨	🟩	🟩	🟩
CO_2 storage capability	🟨	🟨	🟨	🟩	🟩
Hydrogen purity	🟩	🟩	🟨	🟨	🟥
Hydrogen efficency	🟥	🟥	🟩	🟨	🟩
KEW Needs					
Independency from key IP of a third -party	🟥	🟥	🟩	🟨	🟨
KEW technical internal knowledge development	🟥	🟥	🟩	🟩	🟩
Analysis of the prospected market positioning	🟥	🟥	🟩	🟨	🟨
Utilization in other processes of KEW interest	🟩	🟩	🟩	🟥	🟥

Our preferred technology solution for H_2-CO_2 separation would be a Pressurised Water Absorption (PWA) solution.

We selected this particular process mainly for its greater energy efficiency compared to the other available technologies currently on the market, such as amine solvent solutions already widely used in industry for removing CO_2 from gas. These more technically proven solutions need a significative amount of thermal energy that would require combustion of a substantial proportion of the energy product unless a waste heat source is locally available.

Overview of the PWA solution

At its simplest, PWA is very similar to a SodaStream. Under pressure, CO_2 is absorbed into the liquid, but the H_2 is not and separation is achieved. As soon as the pressure of the CO_2-rich liquid is reduced, the CO_2 is released and can be captured.

Further work is required to validate the technology in a CO_2 separation from H_2 context, given there are no existing reference hours for this specific application. This is the focus of our H_2 BECCS Phase II proposal.

Design philosophy for Phase II H_2 BECCS

As part of the Phase I deliverable, we have assessed the optimal design for integrating the proposed PWA based technology solution with our operational advanced gasification commercial-scale demonstration plant at SEC. This design was based on DESNZ and KEW specific criteria.

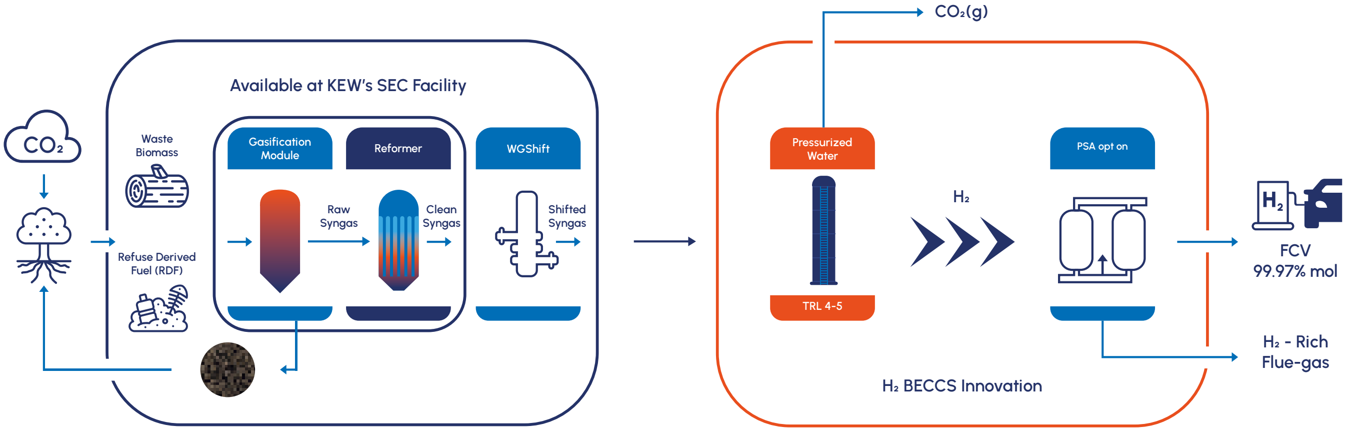


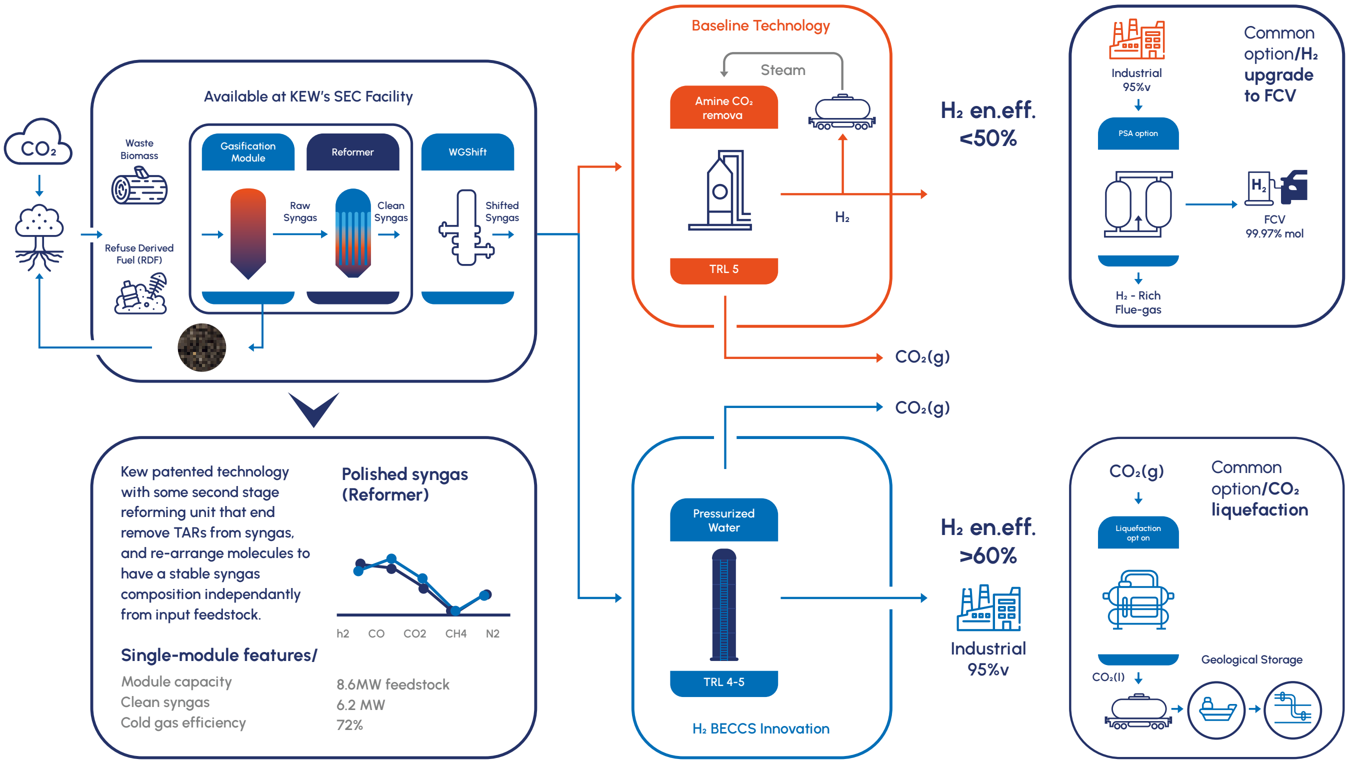
Figure 1. Proposed process scheme for Phase II H_2 BECCS add-on demonstration plant

This basis of design is core to our proposal for Phase II of the H_2 BECCS programme (see section 8 in the main report).

Amine versus PWA

Process models were built (in Aspen) for both separation systems to incorporate with KEW's process model for its advanced gasification (waste-to-syngas) proprietary process and the hydrogen production steps. These models produced energy mass balances (EMBs) for multiple sets of conditions for comparison in different scenarios.

Figure 2. Scope and key performance criteria of the H_2-BECCS Innovation Phase II project with respect to the existing H_2-BECCS components



Kew patented technology with some second stage reforming unit that end remove TARs from syngas, and re-arrange molecules to have a stable syngas composition independantly from input feedstock.

Single-module features/

Module capacity	8.6MW feedstock
Clean syngas	6.2 MW
Cold gas efficiency	72%

***Steam can also be produced by using "clean syngas" with an advantage in terms of CAPEX, but this will result into a minor quantity of recovered CO_2**

Table 2: A comparison of key data for the seperation step

Waste Biomass			
H_2/CO_2 seperation step One Module Facility		**Industrial Customer H_2**	
		Amine System	**Pressurised Water Absorption**
Shifted syngas (post WGS) to separation stage	kWt	4108	4108
Thermal duty (steam)	kWt	1245	-
Power consumption	kWe	204	391
Hydrogen product energy out	kWt	3923	3781
H_2 purity	%v	93.4%	91.7%

- Amine systems require substantial thermal energy to regenerate the solvent. Whilst R&D is ongoing for new formulations to reduce this, the burden is considerable. Thus, apart from scenarios where very low-cost, low-carbon heat is available (e.g. waste heat) the cost and/or GHG impact is substantial.

- PWA systems have a marginally higher power consumption (pumps, etc.), and higher capital expenditure (CAPEX) costs, which together could contribute around 1p/kWh to the hydrogen cost. However, this cost is substantially lower than the value of the heat required for the amine systems.
- PWA systems utilising only water (retained/recycled, not continuous consumption) offer lower environmental impact and risk than the use of chemical solvents.

In conclusion, if the PWA systems achieve the performance that has been modelled, then this innovation will provide a significant step forward on the pathway to cost effective hydrogen supply from H_2 BECCS systems.

Environmental and social benefits

KEW's H_2 BECCS solution 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.
If using low-grade biomass or energy crops, the plant is utilising a feedstock that is 100% biogenic. An independent assessment of our GHG analysis for this scenario has an overall capture and savings of over 25,000 tonnes a year of CO_2 per module producing over 1,000 tonnes a year of transport-grade hydrogen at fuel cell vehicle (FCV) purity of 99.97% (per the ISO 14687-2 standard).

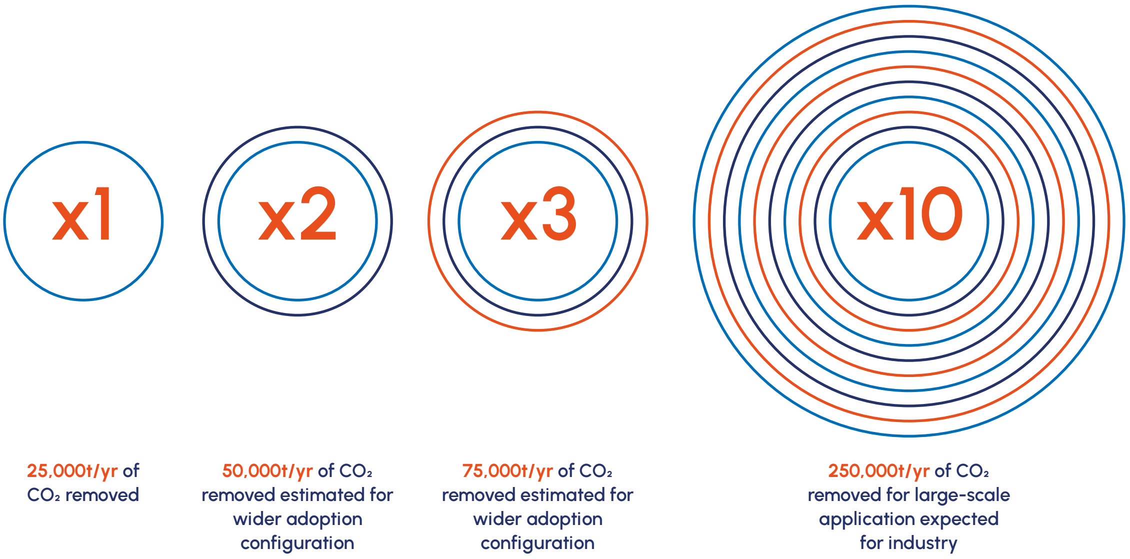


Figure 3. CO_2 saving per module roll-out

KEW has already completed significant work to understand the environmental and social benefits of its BECCS solution under the Greenhouse Gas Removal funded project and has validated the same benefits are applicable for this H_2 BECCS solution. For complete details, read more here: KEW's published CCH2 | Carbon Capture and Hydrogen GGR report, in Section 2.5; "Achieving wider impact; environmental and social benefits".

Figure 4. Fivefold social and environmental benefits

Proposed next steps for H_2 BECCS Phase II

The aim of the Phase II H_2 BECCS project will be to retrofit our operational advanced gasification plant, currently producing tar-free syngas from waste, to accommodate the development and demonstration of the PWA system. The demonstration will prove successful and continuous operation of the technology within the context of this innovative H_2 BECCS end-to-end system. This will increase the Technology Readiness Level (TRL) of the technology to TRL 8, such that the design will be ready for commercialisation thereafter, through a de-risked engineering development for the specific scale required by the projects.

This following table summarises the main technical key performance indicators (KPIs) which will be measured during the Phase II test and demonstration programmes, and used to formulate the commercial proposition to end users.

Table 3

System Area	KPIs and Objectives
H_2 product (industrial)	> 95% H_2 purity %mol > 36kg/hr in moral operation
H_2 Product (FCV)	99.97% H_2 purity %mol
CO_2 removal	Target conversion is 98% by mass
CO_2 liquefaction	Within specification for F&B offtake 99.99%mol
Energy performance	Yield/throughput of hydrogen .95% of total output by energy Conversion efficiency (pressurised water) = 82%
Overall integrated performance	Performance monitoring using a multi-parameter analysis system Conversion efficiency waste to H_2 (Industrial) 49% CAPEX and OPEX validation LCOH (hydrogen) £/kWh LCO CC (carbon capture) £/tCO_2e

Context Setting

1.1 DESNZ and H2 BECCS context

There are two complimentary factors underpinning the research and development into H_2 BECCS:

- The need to produce renewable hydrogen to support the growing hydrogen economy
- The need to generate net negative carbon emissions to enable the UK to meet its 2050 net zero legally binding target

Therefore, research is needed to identify those technology solutions which provide the best combination of process efficiency and value for money. The aim would be to identify an innovative technology to improve the currently available processes (typically amine-based), targeting the reduction of the LCOH production.

The objective of this DESNZ funded H_2 BECCS Phase I research programme is to investigate a range of innovative but less technically proven H_2-CO_2 separation solutions to assess and compare:

- ► Their key process performance
- ► LCOH
- ► The ability to test the technology(s) with our existing waste-to-syngas technology solution, at our commercial-scale advanced gasification demonstration plant

1.2 KEW's existing funded innovation in CO_2 separation

KEW is currently developing a range of high-profile, government backed projects at our flagship demonstration facility, where the proposed technology solutions include a CO_2 removal unit. Examples of relevant programme work include:

1. **The DfT F4C grant: increasing the H_2-CO ratio and removing CO_2 to provide the feed-gas composition required by the Fischer-Tropsch reaction for renewable and recycled carbon diesel (rDiesel) production**
2. **The DESNZ GGR project: demonstrating the end-to-end process with a double-stage water gas shift process to maximize CO shift into CO_2, maximizing hydrogen production. This includes a cryogenic separation system, as the project focus is on cost-effective CO_2 capture and sequestration solutions, and not hydrogen purity.**

From the above government supported programmes, our analysis of these existing 'proven' processes highlights that they are very energy-intensive (electrically or thermally), with flow through implications for the relevant levelised cost of production of the final energy molecule.

KEW’s technology is the key building block for our H_2 BECCS Phase I work

2.1 Our advanced gasification technology, a form of Advanced Conversion Technology

Our technology is unique in its compact nature and ultra-low emissions, making it ideal for integration into industrial and commercial premises, converting a wide-range of biomass or non-recyclable wastes into tar-free, hydrogen-rich, clean syngas. This can then be used to produce sustainable energy-vectors for use in hard-to-abate sectors. Some of those vectors include natural gas and coal substitutes for industrial fuel switching, LPG substitutes for off-grid energy as well as other advanced fuels and chemicals, including hydrogen, methanol, and sustainable aviation fuel (SAF). Overall, our proprietary and proven waste-to-syngas innovative technology has the following key differentiated advantages, summarised. **Please see figure 5**

2.1.1 Our H_2 BECCS demonstration platform: at KEW’s Centre of Excellence for emerging and innovative technologies

The development of a commercial-scale operational waste-to-syngas (syngas that is tar-free and of consistent composition) represents the most challenging part of the H_2 BECCS process and has been typically one of the main reasons of failures of other gasification projects. As we have developed, proven and now operate such a waste-to-syngas process at the SEC, we have de-risked a critical element of the waste-to-hydrogen end-to-end solution.

For Phase II of H_2 BECCS programme, we propose to retro-fit the proposed H_2 BECCS add-on technology module; to facilitate rapid TRL progression of our more cost-effective syngas-to-hydrogen proposed innovative solution at commercial-scale. Similar to other demonstrations at this facility, we will then adopt our standardised modular approach for the H_2 BECCS commercial product deployment, once core proof is achieved at our demonstration plant.

This ability to test technology innovation in a proven ‘real-world’ production facility is unique. It significantly reduces the costs required to run an actual trial (as our advanced gasification platform element is already a sunk cost) as well as reducing risks in the final deliverable.
Please see figure 6

H_2-CO_2 Separation

3.1 Step 1: Over-arching factors influencing technology shortlisting

Our initial step was to identify the key factors that were considered to be the most important when shortlisting available technologies. The finalised criteria are listed below:

- Achieves a competitive LCOH by reducing the Capital Expenditure (CAPEX) and/or Operating Expenditure (OPEX) per unit output

- Equally, reduces the cost of CO_2 capture
- Enables CO_2 to be prepared as liquid for distributed sites (road, rail) or as a gas if directly connected to CCS pipelines, respectively
- Improves the GHG emissions / carbon footprint of the hydrogen product, by utilising low carbon sources of energy
- Is scalable 3x to 15x to ensure rapid and effective commercial deployment
- On or near ready for commercialisation (TRL 5 or TRL 6) where it was likely that they would reach this stage in the next year or two with appropriate support
- Creates a unique market positioning and opportunity to patent new intellectual property (IP) to drive job creation in the UK and keep the UK at the forefront of developing environmental solutions

3.2 Step 2: Technology screening

Following definition of key criteria, the next step was to assess the currently available technologies to identify the most promising ones for further, more detailed research and engineering development. During this stage, we collaborated with Aston University as they have detailed specific experience in this area.

We were looking to identify how to improve the H_2-CO_2 separation step of the H_2 BECCS process, with a special interest in liquefied-CO_2 integrated processes, as it is considered the most likely solution for carbon capture and sequestration (CCS) in the mid-term future for the majority of the plants that will probably be located in dispersed sites (i.e. not co-located with a CCS pipeline). This market can be enabled due to our standardised modular solution, which enables the development of small and medium-size distributed plants. We believe this will be a critical part of the commercial road map, given that the planned CCS pipelines will only serve limited areas of the country and a country-wide CO_2 collection pipeline network is extremely unlikely (noting full nationwide grid coverage has not been achieved with the existing natural gas grid). As evidenced by BEIS' research[1] , CO_2 if liquefied, can be cost-effectively transported from dispersed sites via rail (preferred) or road to CCS pipelines. Thus, the proximity to CCS pipelines does not have to a major barrier to deploying H_2 BECCS.

An initial desktop study assessed the following broad technologies based on the criteria as outlined above:

- Absorption processes (chemical and physical)
- Pressure swing adsorption (PSA)
- Membrane technologies (CO_2 selective and H_2 Selective)
- Cryogenic separation

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[1] .CCS Deployment at dispersed industrial sites; Element Energy for BEIS; research paper number 2020/030'

3.2.1 Chemical absorption

- Works through a chemical reaction attaching the CO_2 to a basic reactant which can then be separated out from the remaining gas with the CO_2 and stripped from the reactant
- Most of technologies developed recently are aimed at post-combustion absorption (in anticipation of power generation facilities being brought within the UK or EU Emissions Trading Schemes, later in this decade) as more effective for low CO_2 concentrations and low pressure operations
- The TRL of these technologies tends to be either fully commercialised (TRL 9, and low independence by key third-party suppliers/partners) or at early stage of development for new molecules (R&D stage, TRL 2-4). Therefore, it did not meet our selection criteria of being close to commercialisation (TRL 5 or 6).

3.2.2 Physical absorption

- Works through the physical absorption of the CO_2 into solvents or liquids;
- Processes based on patented or proprietaries molecules are present on the market, but again the TRL level and the low-independency of KEW in developing the solution are not suitable for our criteria
- Pressurised water absorption was identified as having particular suitability for our pressurised process as it also works best at pressure; the process is already operational in the biogas sector, positioning our process idea at TRL 6, and giving development opportunities for its deployment in H_2 BECCS scenarios so it provides a good developmental technology.

3.2.3 Pressure swing adsorption

- Considered to be the best available technology (BAT) for higher hydrogen purities where accepted CO level is very low (needed for transport)
- Suffered in the economic assessment due to high CAPEX and OPEX
- It is usually used in combination with other methods (and can be also with proposed PWA) for final purification to fuel cell grade hydrogen

3.2.4 Membrane separation

- Well proven technology with plenty of applications in other fields, which can be used in conjunction with other methods (adsorption or cryogenic)
- Technology developments in this area relate more to development of membrane materials rather than process improvements.
- CAPEX and OPEX seems still quite high

3.2.5 Cryogenic separation

- Cryogenic separation of CO_2 and H_2 is based on the very different volatility of the molecules which reduces process stages and costs in the projects where liquid CO_2 is required
- Further potential benefits include removal of other components like nitrogen or methane within the same process, lowering the impact of special treatment for final upgrading of hydrogen to FCV grade
- Cryogenic process works at c.-55°C (CO_2 triple point where it can exist as a gas, liquid or solid), which limits the hydrogen purity, as the thermodynamic equilibrium is limited by this min temp achievable
- The already-pressurized process can ensure an effective combination with other pressurised processes such as PSA, membranes or pressurised water adsorption

3.3 Step 3: Summary of findings

Please see Table 1

Based on the conclusions of this initial analysis, we chose to focus on the PWA process as this had the most green and no red against the key assessment criteria.

Overall, the main drivers behind this decision were its lower energy requirement (low electrical and no thermal), a competitive LCOH (as it is not needed to raise steam for solvent regeneration, or significant electrical requirements for pressurization needed by other technologies), and potential for very a strong GHG savings profile (as electrical energy carbon footprint is expected to decrease quicker than the thermal energy scenarios).

Lastly, as the technology does not need to rely on third-party specialistic know-how or IP, it has also been considered a possibility for KEW to self-develop a relevant know-how, that will enable a commercial deployment in other fuels and chemicals production.

Overview of the PWA process

At its simplest, PWA is very similar to a SodaStream **See image 1.** Under pressure, CO_2 is absorbed into the liquid, but the H_2 is not and separation is achieved. As soon as the pressure of the CO_2-rich liquid is reduced, the CO_2 is released and can be captured.

Although the PWA solution described above is relatively simple, it should be noted that this technology has not been used to date specifically for CO_2 separation from H_2. Likely due to the past projects being mainly for chemical industry applications where CAPEX and footprint were more important than energy impact of the process.

However, more recently the technology has been applied to similar applications in biomethane upgrading. Therefore, we believe it can be considered as commercially and technically viable, and thus demonstrates a TRL 6 for the application in hydrogen purification, as it is already applied in a similar and comparable environment.

As the technology has been used mainly with the separation of other gases (biogas-methane), there will be a need to perform additional research and development to ensure its suitability for H_2-CO_2 separation. If this can be adequately demonstrated with KEW's existing gasification at SEC (our proposed approach for Phase II H_2 BECCS), the utilisation of this innovative technology solution with other advanced gasification technologies is also achievable. This would significantly enhance the market adoption potential relative to DESNZ's ultimate objectives around net-zero by 2050.

Interestingly, this solution can be applied even in other sectors relevant to the net-zero agenda. Some examples include:

- Blue-hydrogen production
- CO_2 separation from non-shifted syngas (which is relevant for other biofuels production where CO_2 removal is needed before final fuel synthesis (e.g. methane, methanol, Fischer-Tropsch processes (e.g. SAF) and dimethyl ether (DME), which is a LPG substitute).

Design plan for integration at KEW's flagship facility

5.1 Key design criteria

Key to the H_2 BECCS Phase II project will be ensuring a robust process for the design and integration of the PWA system with our operational advanced gasification plant, at our SEC facility. It is worth noting that although our prime focus will be to complete a preliminary design of the H_2 BECCS demonstration plant to be installed at the SEC, we will also go through a commercial-scale design. This will focus on a multiple-module solution that will enable a modular, standardised, and factory-built approach of this H_2-CO_2 separation stage, as per the modular approach of the waste-to-syngas stage.

As part of the Phase I deliverables, we have considered the basis of the H_2 BECCS demonstrator design that would be built out at our SEC facility under H_2 BECCS Phase II.

5.2 Design requirements

KEW has identified the following key general design criteria for detailed engineering activity:

- Minimize electrical consumption at lowest potential level
- CO_2 recovery ratio at min 97%
- Enhancement of H_2 to higher purity and efficiency
- Avoid CO_2 dilution, to enable CO_2-liquefaction for utilisation or sequestration
- Keep H_2 at pressure, and CO_2 if possible
- Optimised system design for integration with KEW's modular waste-to-syngas process and scale up to 3x and 15x modular units

For the Phase II demonstration project and its integration into the SEC 'live' production environment, KEW has added further site-specific, additional design criteria as follows:

- R&D Demonstrator is ¼ scale of SEC commercial scale (about 500kg/h of H_2-CO_2 incoming flow)
- Produce H_2 that can be utilised generating electricity or compressed for offtake trials
- Demonstrates CO_2 capture at both low 7 barg (interesting as this is the residual pressure of our process), and high pressure 30 barg (interesting for eventual final PSA upgrading to fuel cell grade)
- Demonstrate the process conditions suitable for a complete regeneration of the pressurised water, to minimise eventual needs of purging and re-filling **Please see figure 1**

A comparison of key data for the separation step: **Please see figure 2**

The key difference between the two solutions that impact the overall energy balance is that amine systems require substantial heat to regenerate the solvent (release the CO_2) and PWA requires more electricity for compressor/pumps load. The following summarised EMB is for a single KEW module facility, utilising waste biomass and producing hydrogen for a range of industrial applications (~93-95% purity). **Please see Table 4 and Table 2**

Comparison of PWA and amine systems

6.1 Thermal energy required for amine systems

The model assumed 1245 kWt of thermal energy required for solvent regeneration (based on performance of the proprietary solution of BASF). There are a substantial number of organisations developing improved solvents to reduce the thermal energy required for regeneration and also provide other improvements in relation to the environmental impact of the chemicals required. Thus, the figure quoted may be reduced in time.

The thermal energy required will remain a substantial burden, and if no alternative heat source is available, then heat would need to be derived by combustion of feedstocks or of the produced hydrogen. In order to maintain the net CO_2 capture, it would be necessary to combust hydrogen which would consume almost 25% of the produced hydrogen. This is clearly unlikely to be a commercially viable proposition. Alternatively, if natural gas was consumed, which would appear to be a retrograde step, then this would increase the carbon intensity of the hydrogen product by ~20g/ MJ and add considerably to operating cost and cost uncertainty.

The PWA system requires no thermal energy, but instead an additional 187 kWe of electrical power compared to the amine system. Based on the continuous production of 3.78 MW of H_2, if an electricity cost of £150/MWh is assumed, this would add only 0.74p/kWh to the LCOH. The ongoing decarbonisation of the grid leads to a reducing impact on the GHG model with the increased power requirement.

Thus, the PWA system is overall more financially compelling unless a very cheap source of heat is available (~2p/kWh). In order not to drastically affect the CO_2 intensity of the H_2 product, this would have to be a very low carbon source (not a fossil-fuel).

6.2 Hydrogen purity

The PWA system is predicted to produce a H_2 product with slightly higher CO_2 contamination level, but still suitable for most industrial applications. It is intended to conduct trials during H_2 BEECS Phase II to evaluate the purity achieved in different operating conditions including pressure of operation. Some commercial applications, including fuel cell vehicles, will require further purification using a PSA unit.

As the application of PWA in this field is innovative and unproven, there remains considerable uncertainty. The purpose of KEW's Phase II H_2 BECCS proposal (see Section 8 below) is to test the PWA for this application in a 'real-world' operating environment to address these and thus provide an evidenced set of performance data for deriving GHG impacts and LCOH.

6.3 Other factors

PWA systems have a marginally higher power consumption (pumps etc), 187kWe for the example scenario but assuming electricity cost of £150/MWh this adds only 0.74p/kWh to the LCOH.

The CAPEX and OPEX for both systems were compared at a range of scales. PWA systems do require higher initial investment of up to 50% of the separation step. However, being only a minor proportion of the cost of the full H_2 BECCS system, the impact of this on LCOH is minimal (~0.26p/kWh)

It should be noted that the example shown is for a small-scale system suitable for one advanced gasification module. As these processes benefit strongly from economies of scale, larger systems are likely to be deployed (such as to integrate with a 3-module system as shown in the GHG balance below). This will provide savings in CAPEX, and also parasitic loads.

PWA systems utilising only water (retained/recycled, not continuous consumption) offer lower environmental impact and risk than the use of chemical solvents with potential concerns in relation production of the chemical, risk of leakage, potential emissions to air and disposal.

All of these factors are provisional based on modelling. A key objective of the Phase II Project would be to provide the certainty and evidence required for commercial deployments.

6.4 Hydrogen cost

The cost of the Hydrogen product from the H_2 BECCS system is dependent on a very wide range of factors. Most prominent are feedstock cost (or gate fee in case of waste), electricity cost, CAPEX and OPEX.

Detailed modelling was completed and submitted to DESNZ including consideration of the CO_2 transport and storage cost and the benefit or revenue stream of the CO_2 sequestration.

KEW's initial H_2 BECCS modular plants, due to be deployed 2025-30, are forecast to achieve LCOH in a range of 5.8p/kWh to 7.4p/kWh for industrial applications (requiring ~90-95% purity). Production of high-purity H_2 for fuel cell vehicles (current specification 99.97%) requires an additional purification step (PSA) increasing costs due to CAPEX, power requirement and yield loss; initially pushing costs up to ~10p/kWh. Significant decreases in costs are expected during 2030-40 due to repeat serial manufacture of equipment, efficiency improvements and suitable increase in scale. Thus, costs trending downward below 4p/kWh will be achievable, opening up zero-carbon fuel to a very wide market.

Environmental & social benefits

7.1 GHG savings

KEW's H_2 BECCS solution is built upon the fundamental arrangement of utilising low-grade biomass or end-of-life waste as the feedstock to produce syngas and subsequently hydrogen. If using low-grade biomass or energy crops, the plant is utilising a feedstock that is 100% biogenic. An independent assessment of our GHG analysis for this scenario has an overall capture and savings of over 25,000 tonnes a year of CO_2 per module producing over 1,000 tonnes a year of transport-grade hydrogen at FCV purity of 99.97% (per the ISO 14687-2 standard).
Please see figure 3

We believe that further design will also find potential optimisation in the transport-grade process, eventually recycling the CO_2-rich gas upstream to enhance the pressurised water stage performance. This is another added value that can be derived from the pilot plant development.

Regarding end of life waste such as RDF, it typically comprises two parts: (i) the "renewable" carbon, which is in the biogenic fraction of the waste, and (ii) the recycled carbon fuel (RCF) element, comprised in the fossil fuel element of the waste. Under current government guidelines, these are treated differently when calculating the GHG emissions of a waste-to-fuel process. DfT recently consulted on a carbon accounting solution which would mean that the RCF element of the waste feedstock would be assessed based on an alternative use of the waste.

By doing this, DfT would be incentivising the use of the waste in a process which is significantly more efficient and lower carbon than the current default solution of waste incineration for electricity generation.

KEW strongly supports the adoption of the production of RCFs from mixed waste such as unavoidable and non-recyclable municipal waste with strong evidence to support it currently being one of the lowest cost ways of producing advanced sustainable fuels and chemicals. Furthermore, the cost of energy across Europe has increased dramatically in recent months, having particular impact in rural areas, where 24% of people were at risk of energy poverty or social exclusion already in 2019[2].

In addition to this, production of fuels from waste can also help communities to move away from landfill or incineration towards Advanced Conversion Technologies, such as advanced gasification, and supports improved waste collection and sorting infrastructure consistent with UK circular economy initiatives and Europe's Circular Economy Action Plan[3]. This enables simplified logistics and a more efficient use of feedstock, which can then in turn support local areas by creating jobs, contributing towards the economy, and supporting local residents with a sustainable fuel.

UK government have so far led the way on support for RCFs, especially in the transport sector, and we would like to see this expanded out of the limitations of transport so that renewable and recycled carbon industrial fuels, liquid gases (such as DME), and other advanced fuels and chemicals, can benefit and help lead their respective hard-to-decarbonise sectors to net zero and beyond.

7.2 Environmental and social benefits

KEW has already completed significant work to understand the environmental and social benefits of its BECCS solution under the GGR funded project and has validated the same benefits are applicable for this H_2 BECCS solution. For complete details, see KEW's published CCH_2 | Carbon Capture and Hydrogen GGR report, in Section 2.5; "Achieving wider impact; environmental and social benefits". **Please see figure 7 and figure 4**

Future development plan: Phase II H_2 BECCS proposal

8.1 Aims

The aim of the proposed Phase II H_2 BECCS project will be to retrofit our operational advanced gasification plant to accommodate the development and demonstration of the PWA system. The demonstration will prove successful and continuous operation of the technology within the context of the H_2 BECCS end-to-end system, benefiting from the already proven and operating proprietary waste-to-syngas plant.

Our existing plant, at our flagship SEC facility is at commercial scale, although, the PWA system demonstration will be ¼ scale of the commercial plant. Thus, it will increase the TRL of the technology to TRL 8, such that the design is ready for commercial scale engineering thereafter.

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[2] Rural Energy - Rural Energy (rural-energy.eu)

[3] A new Circular Economy Action Plan (europa.eu)

8.2 Objectives

The Phase II project proposal has been structured to achieve the key requirements identified by DESNZ, which are also aligned with our own vision for the development and commercialisation of the technology. Key objectives of the project include:

1. **Build and demonstrate the new technology in order to validate the engineering assumptions and resolve the current technical and cost uncertainties**
2. **Validate the lifecycle analysis and GHG savings model in accordance with Low Carbon Hydrogen Standard methodology, in order to highlight the environmental lifecycle benefits and growth potential in the context of net zero by 2050**
3. **Develop the commercial opportunities and model to optimise the value for money proposition and commercial partnerships necessary**
4. **Provide an investment platform for commercially led H_2 BECCS projects, via the removal of key roadblocks and risks around feedstock supply, financing, offtake, insurance and project delivery**
5. **Disseminate the key findings to stakeholder groups across industry, academia and the wider business community in order to further develop H_2 BECCS commercial and investment opportunities**

8.3 Test programme

The purpose of the demonstration phase is to operate the full H_2 BECCS system in a campaign of staged operations. During the operations, it is envisaged that with extensive evidence of the produced H_2 and CO_2 quality, and engagement with off-takers, adoption of the H_2 BECCS end-to-end solution across industry and transport applications will accelerate. The demonstration programme will include performance tests of the system using variable waste and biomass feedstocks and plant runs will be representative of long-run operational requirements.

This following table summarises the main technical KPIs which will be measured during the Phase II test and demonstration programmes, and used to formulate the commercial proposition to end users.

Commercialisation potential for H_2 BECCS

9.1 The Hydrogen opportunity

Please see table 2

Hydrogen has potential applications in many harder to decarbonise end user sectors:

- Industry: fuel switching to replace natural gas and other industrial fuels
- Transport: via fuel cells
- Space heating: industrial and residential

KEW believes there is a more immediate demand from industry for industrial fuel switching and anticipate this sector is most likely to be the early adopter of Hydrogen.

Hydrogen into transport (via fuel cells) represents an attractive and rapidly emerging market, but with significant challenges given the need to evolve the entire existing hydrocarbon orientated transport fuel infrastructure to hydrogen. This would also require a step-change in automotive manufacturers focusing on Hydrogen fuel cell cars alongside the preferred focus on electric vehicles. A more likely intermediate step could be to replace diesel trains or HGVs where a small number of fuelling depots can serve a substantial fleet. **Please see figure 8**

9.2 The CO_2 opportunity

As with hydrogen, existing CO_2 markets are already supplied with CO_2, although it is predominantly fossil CO_2 as there have been major issues with short term availability. As such, development of a 'new' stream of sustainable CO_2 from H_2 BECCS related processes can provide UK industry with a more robust, diversified and secure CO_2 supply chain, resilient from supply shocks arising from other issues impacting other sectors (i.e. the fertiliser market). Quality and purity of CO_2 will be key challenges that would need to be addressed and overcome to fully enable this market, and our H_2 BECCS demonstration aims to address that.

The other route for the CO_2 is in permanent sequestration. Two such projects are currently under development: HyNet and the North East Cluster but both are several years from being ready to accept CO_2 and the costs of sequestration remain uncertain (i.e. the taxpayer funded subsidies are currently uncertain).

9.3 Size matters – modularity enables small and large projects

Modularity provides a viable and cost-effective technology solution for smaller decentralised H_2 BECCS project requirements. Smaller projects will be required in the new hydrogen world, given the likely limitations of any hydrogen grid as well as the dispersed demand required for hydrogen refuelling stations for transport applications. Equally, using waste feedstocks within a local catchment area creates a genuine circular solution and would reduce end-to-end emissions through lower waste transport distances.

We believe that starting small and building to scale is the sensible, proven and low risk approach to the development and commercialisation of innovative and emerging technologies. This incremental approach overcomes each barrier in an individual, low risk step and gradually builds an integrated commercial solution. This approach is aligned with our business proposition based on a standardised modular solution, which inherently enables this scale-up vision.

Appendix 1 Tables

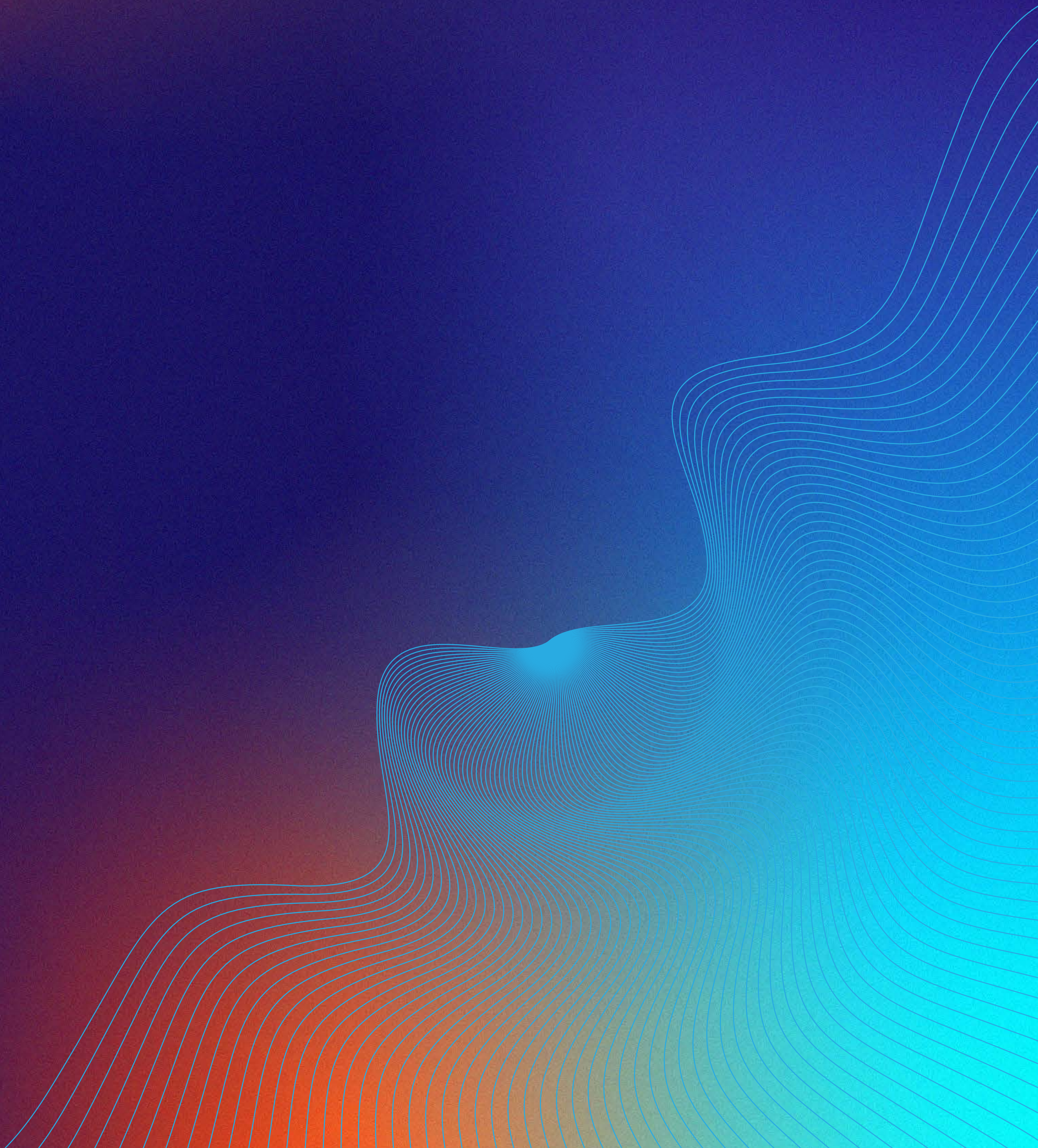


Table 1: Traffic light recap of the KPI considered during initial technological scouting and assessment

	Amine	Carbonate	Pressurised Water	Cryo with PSA	Cryo with Membrane Package
Market Features					
Greenhouse Gas Balance	🟩	🟨	🟩	🟨	🟨
Levelized Cost of Hydrogen	🟥	🟥	🟩	🟨	🟨
Thermal energy requirments	🟥	🟥	🟩	🟩	🟩
Electrical energy requirments	🟩	🟩	🟨	🟥	🟥
Environmental risk (chemicals utilization)	🟥	🟨	🟩	🟩	🟩
CO_2 storage capability	🟨	🟨	🟨	🟩	🟩
Hydrogen purity	🟩	🟩	🟨	🟨	🟥
Hydrogen efficency	🟥	🟥	🟩	🟨	🟩
KEW Needs					
Independency from key IP of a third -party	🟥	🟥	🟩	🟨	🟨
KEW technical internal knowledge development	🟥	🟥	🟩	🟩	🟩
Analysis of the prospected market positioning	🟥	🟥	🟩	🟨	🟨
Utilization in other processes of KEW interest	🟩	🟩	🟩	🟥	🟥

Table 2

The systems are essentially the same except for the H_2-CO_2 separation step. The comparison for this is shown below:

Waste Biomass			
H_2/CO_2 seperation step One Module Facility		**Industrial Customer H_2**	
		Amine System	**Pressurised Water Absorption**
Shifted syngas (post WGS) to separation stage	kWt	4108	4108
Thermal duty (steam)	kWt	1245	-
Power consumption	kWe	204	391
Hydrogen product energy out	kWt	3923	3781
H_2 purity	%v	93.4%	91.7%

Table 3

System Area	KPIs and Objectives
H_2 product (industrial)	> 95% H_2 purity %mol > 36kg/hr in moral operation
H_2 product (FCV)	99.97% H_2 purity %mol
CO_2 removal	Target conversion is 98% by mass
CO_2 liquefaction	Within specification for F&B offtake 99.99%mol
Energy performance	Yield/throughput of hydrogen .95% of total output by energy Conversion efficiency (pressurised water) = 82%
Overall integrated performance	Performance monitoring using a multi-parameter analysis system Conversion efficiency waste to H_2 (Industrial) 49% CAPEX and OPEX validation LCOH (hydrogen) £/kWh LCO CC (carbon capture) £/tCO_2e

Table 4

Waste Biomass			
One Module Scale Facility		**Industrial Customer H_2**	
		Amine System	**Pressurised Water Absorption**
Feedstock consumption	kg/hr	1584	1584
Wateer consumption	kg/hr	2600	2600
Char ash produced	kg/hr	91	91
Carbon black produced	kg/hr	43	43
CO_2 captured	kg/hr	2357	2357
H_2 yield (gross)	kg/hr	216	216
H_2 purity		93.4%	91.7%
Feedstock energy	kWt	6,735	6,735
Shifted syngas (post WGS)	kWt	4108	4108
Gross hydrogen product energy out	kWt	3923	3781
Power consumption	kWe	876	1,063
Thermal duty (steam)	kWt	1245	-
Total energy consumption (feedstock, power, heat)	kW	8856	7798

Appendix 2 Figures

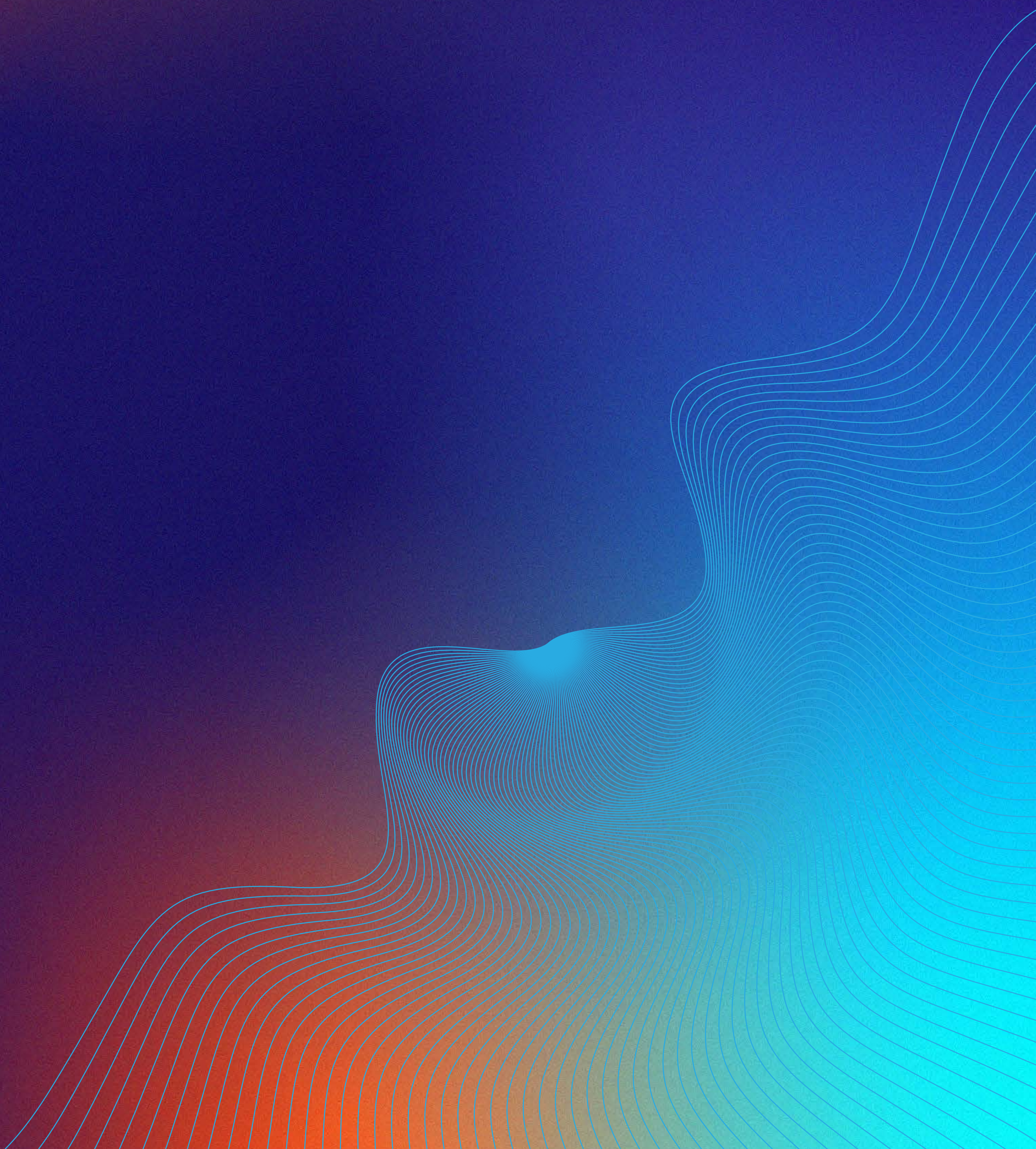


Figure 1. Proposed process scheme for Phase II pilot plant

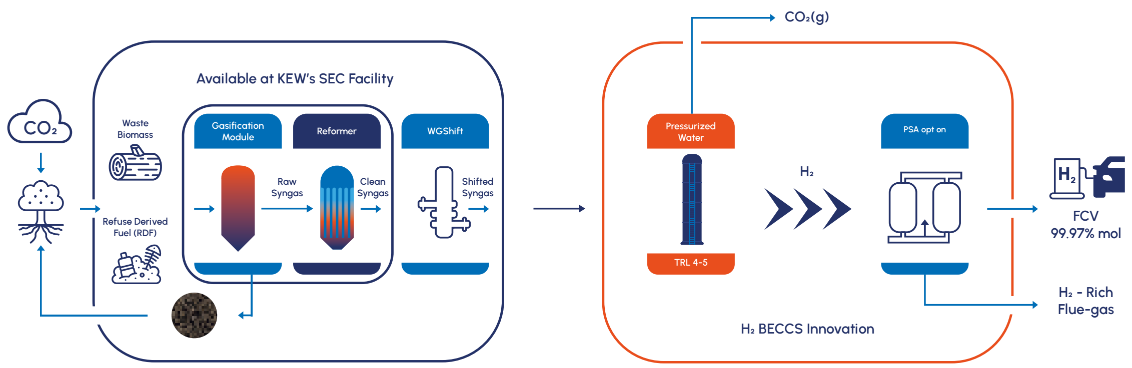
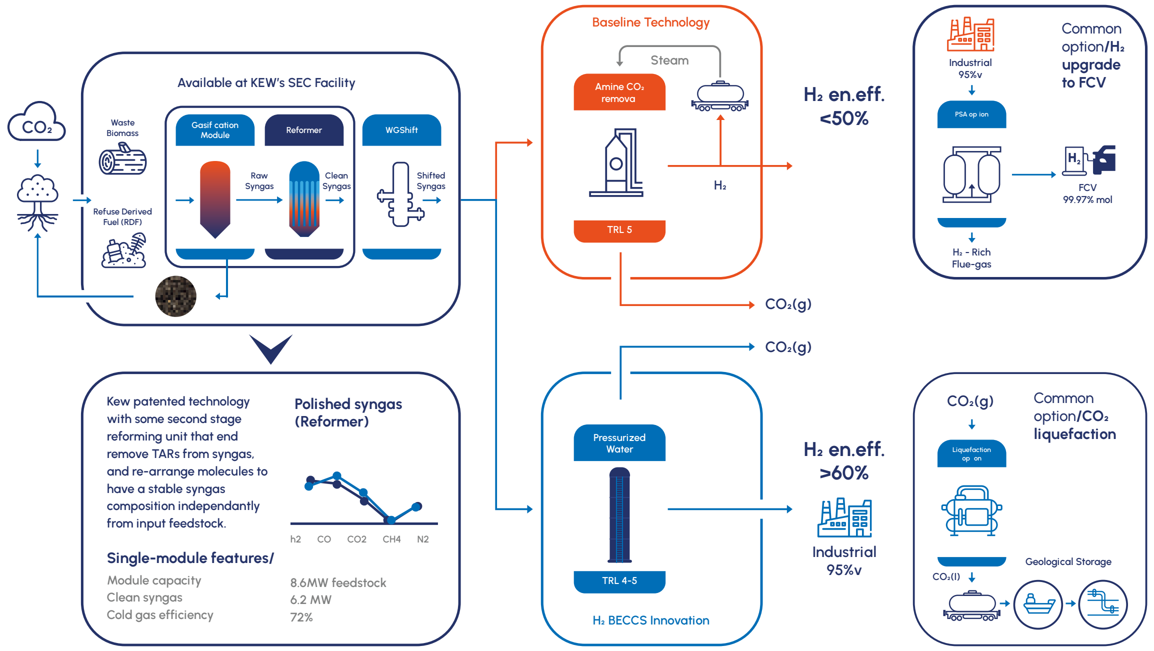


Figure 2. Scope and key performance criteria of the H_2-BECCS Innovation Phase II project with respect to the existing H_2-BECCS components



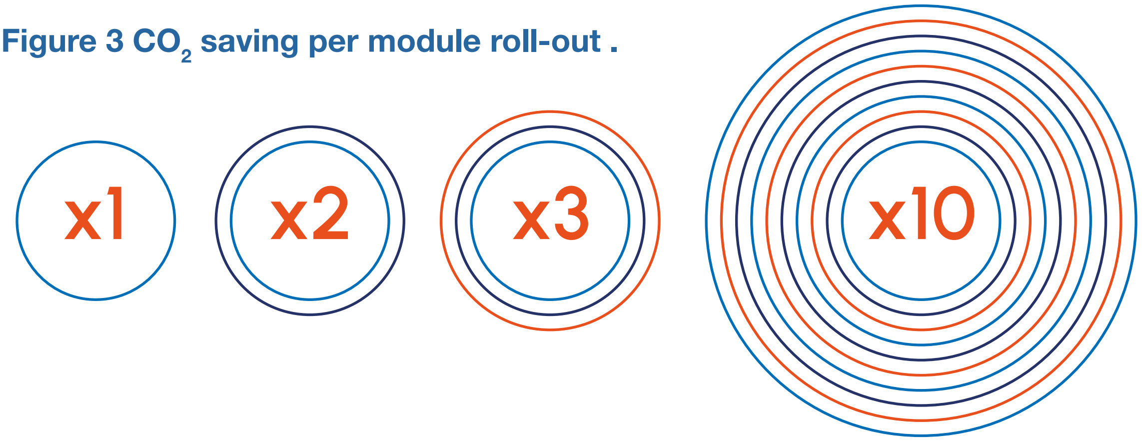
Kew patented technology with some second stage reforming unit that end remove TARs from syngas, and re-arrange molecules to have a stable syngas composition independantly from input feedstock.

Single-module features/

Module capacity	8.6MW feedstock
Clean syngas	6.2 MW
Cold gas efficiency	72%

*Steam can also be produced by using “clean syngas” with an advantage in terms of CAPEX, but this will result into a minor quantity of recovered CO_2

Figure 3 CO_2 saving per module roll-out .



25,000t/yr of CO₂ removed

50,000t/yr of CO₂ removed estimated for wider adoption configuration

75,000t/yr of CO₂ removed estimated for wider adoption configuration

250,000t/yr of CO₂ removed for large-scale application expected for industry

Figure 4. Fivefold social and environmental benefits

Generate H_2 revenues which can be used to cross-subsidise CO2 sequestration.

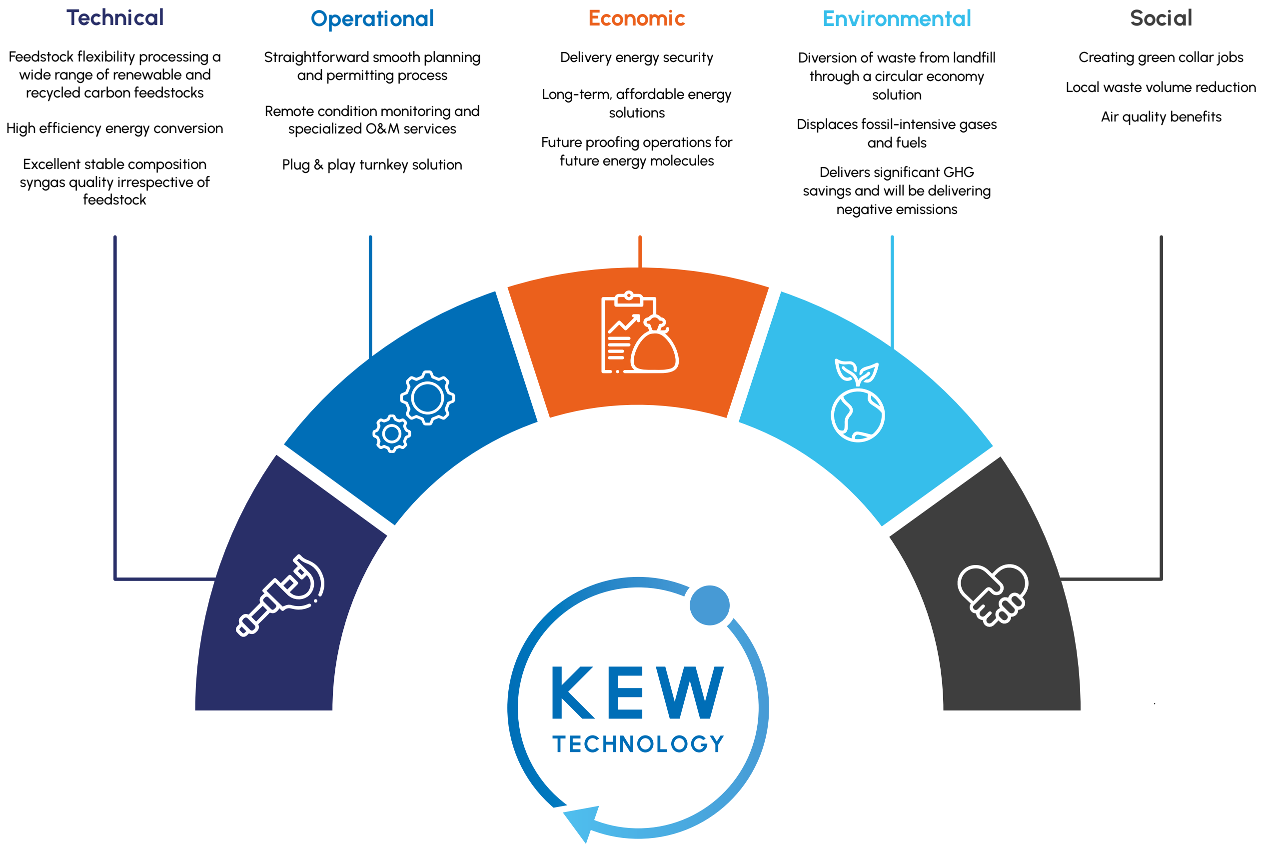
Use existing local residual non-recyclable waste and low-grade biomass wastes.

Allowing business to tap into cost-effective lower carbon solutions with a defined pathway to negative carbon enabling them to stay globally competitive.

Creating year round job opportunities in the area of deployment (and more so in rural areas where biomass supply chains would be developed).

Adding value to unutilised marginal or contaminated land whilst improving biodiversity

Figure 5.



Technical

Feedstock flexibility processing a wide range of renewable and recycled carbon feedstocks

High efficiency energy conversion

Excellent stable composition syngas quality irrespective of feedstock

Operational

Straightforward smooth planning and permitting process

Remote condition monitoring and specialized O&M services

Plug & play turnkey solution

Economic

Delivery energy security

Long-term, affordable energy solutions

Future proofing operations for future energy molecules

Environmental

Diversion of waste from landfill through a circular economy solution

Displaces fossil-intensive gases and fuels

Delivers significant GHG savings and will be delivering negative emissions

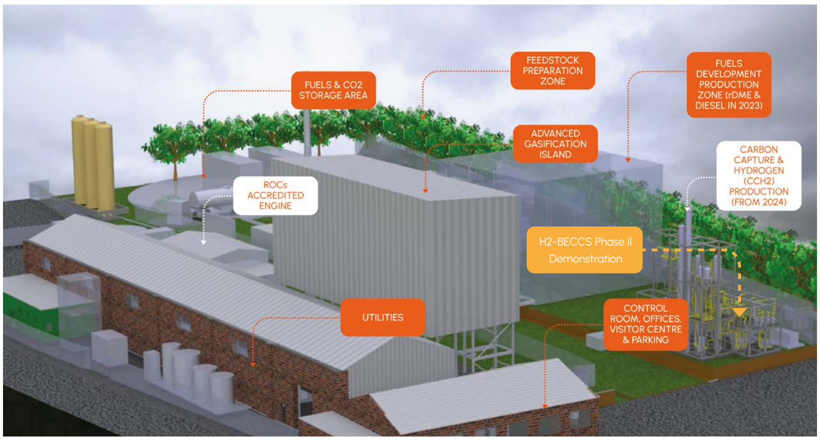
Social

Creating green collar jobs

Local waste volume reduction

Air quality benefits

Figure 6.



Cluster-Connected

Within the Black Country Industrial Cluster (BCIC)

Multiple local potential CO_2 offtakers (Prior to CCS

Prior Feedstock Success

Syngas production already proven for RDF and biomass

Both fuels are primary feedstocks for H_2-BECCS Phase II

Prime Location for Visitors

SEC is located in the heart of the Black Country

SEC is 25 mins from Birmingham and 2 hrs from London

EHS-Compliant

Currently in non-COMAH status (not a risk of hazards)

This will remain up to 5 tonnes hydrogen stored onsite

H_2-Consumption Options

SEC engine proven to be capable of consuming H_2

Acts as last resort mitigation against offtaker absence

Additionality from Exisiting Projects

Ongoing activities with multiple high energy users

These stakeholders (glass, metal refining, etc) are operationally invested in the H_2-BECCS system success

Feedstock

Kew's advanced conversion Technology (ACT) can untilise a wide variety of feedstocks, including those grown on contamindated land. This has a plethora of direct land use change (dLUC) benefits.

Scale

KEW's units are modular - they are factory built, containerised, and deployed onsite within shorter timeframes than a conventional bespoke build. They can be multiplexed for larger energy requirements.

Location

KEW's compact plants (with extensive internal emissions controls and syngas purification stages) can be located in both rural and urban environments - even in Air Quality Management Zones.

Figure 7. Overall summary of the environmental and social benefits potential derived from KEW's H_2

H_2-BECCS plant economics and beneficial impact on local economy

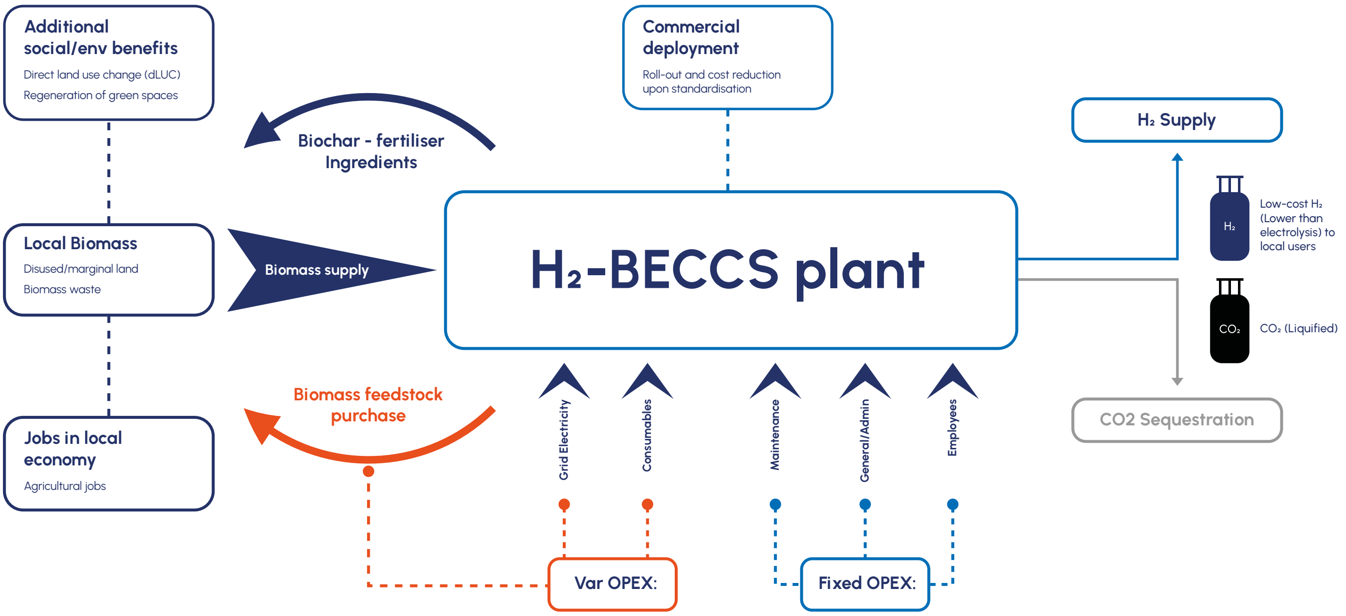
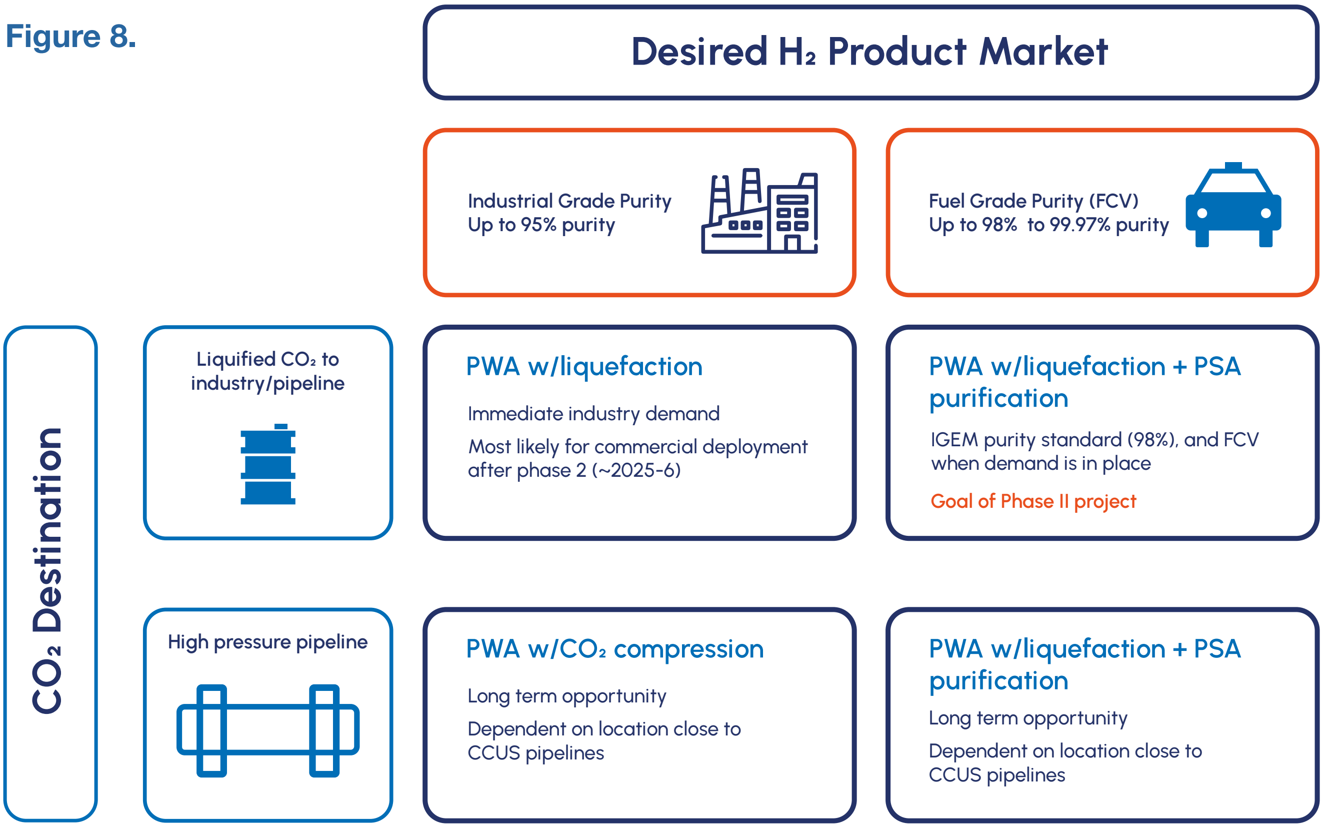


Figure 8.


Desired H_2 Product Market

Industrial Grade Purity
Up to 95% purity

Fuel Grade Purity (FCV)
Up to 98% to 99.97% purity

CO_2 Destination

Liquified CO_2 to industry/pipeline

PWA w/liquefaction

Immediate industry demand

Most likely for commercial deployment after phase 2 (~2025-6)

PWA w/liquefaction + PSA purification

IGEM purity standard (98%), and FCV when demand is in place

Goal of Phase II project

High pressure pipeline

PWA w/CO_2 compression

Long term opportunity

Dependent on location close to CCUS pipelines

PWA w/liquefaction + PSA purification

Long term opportunity

Dependent on location close to CCUS pipelines

Appendix 3 Images

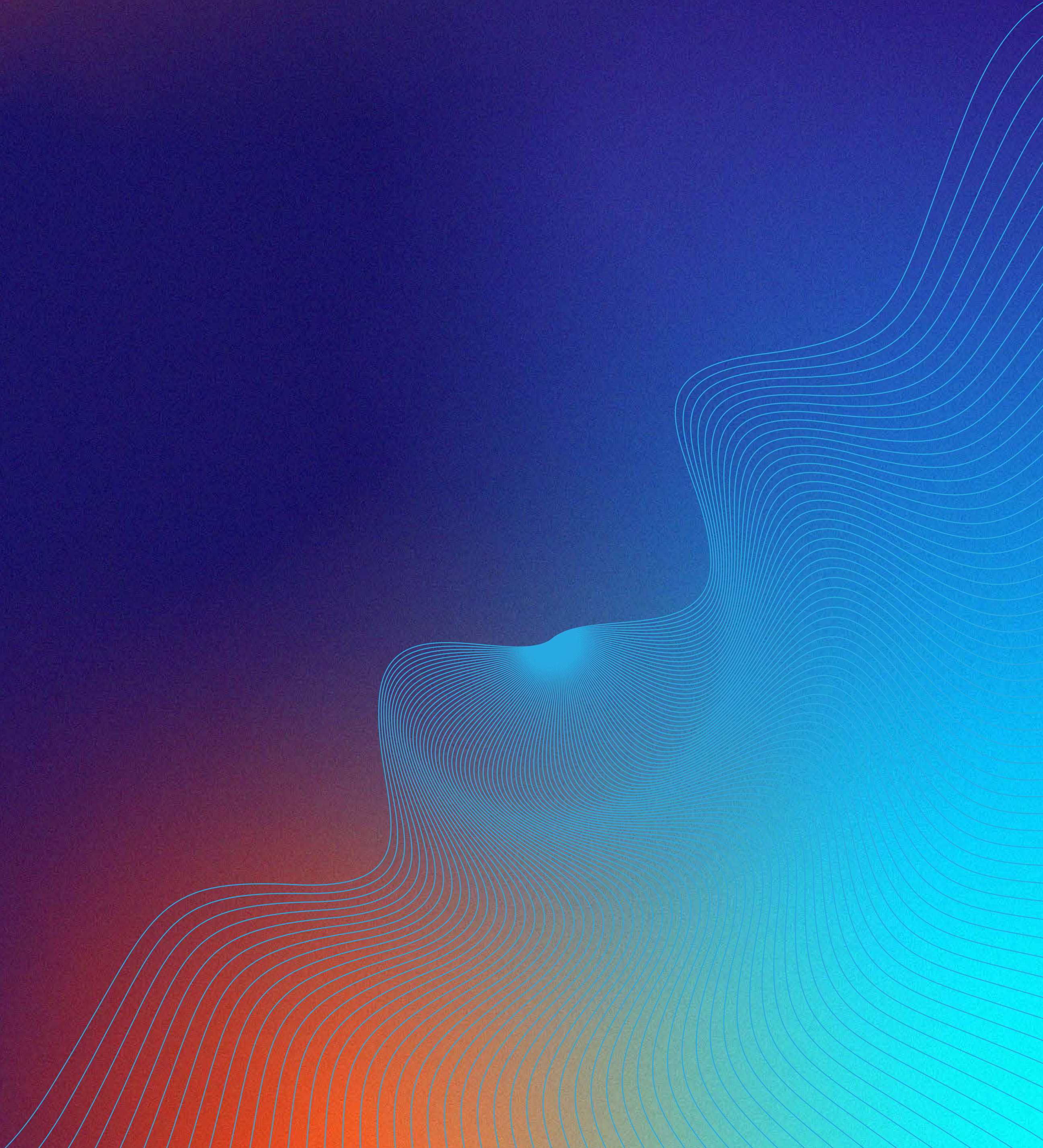


Image 1: SodaStream