Phase 1 SBRI Hydrogen Supply Competition

Bulk Hydrogen Production by Sorbent Enhanced Steam Reforming **(HyPER) Project**

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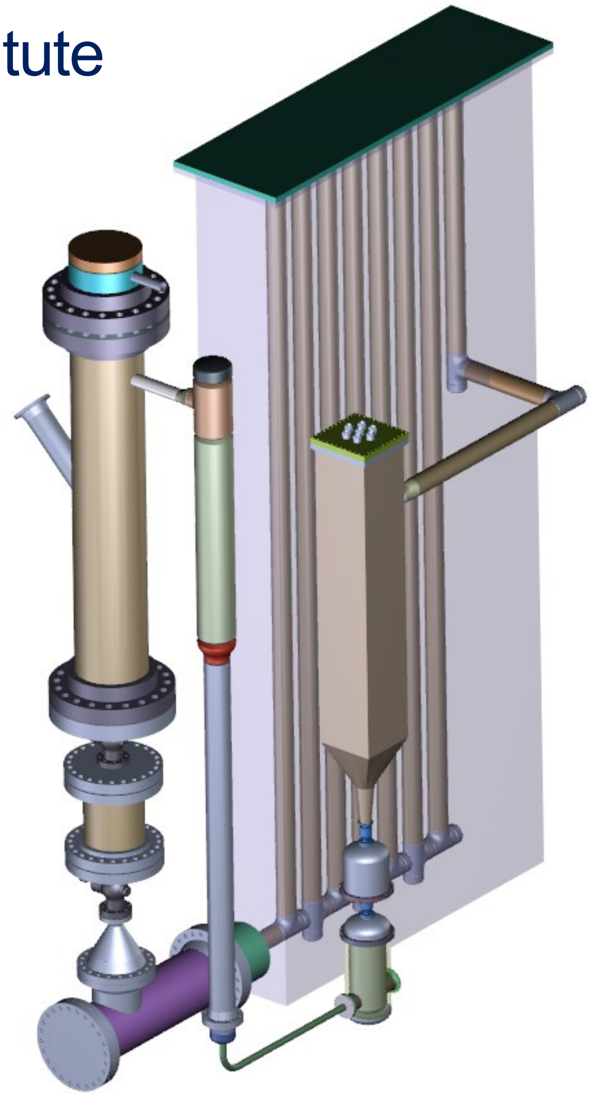

Executive Summary

Low carbon hydrogen (H_2) will play an important role for decarbonising industry, power, heat and transport. The Royal Society concluded that steam methane reforming with some form of carbon capture and utilisation/storage (CCUS) was one of the most likely technologies to be deployed at scale in the near to mid-term. We propose to answer the call for technology development leading to a low carbon bulk H_2 supply through pilot scale demonstration of the sorption enhanced steam reforming process, based on an existing GTI technology.

The Phase 1 feasibility study confirmed the opportunity for the GTI sorption enhanced steam reforming process to offer bulk low carbon H_2 production with over 50% CAPEX reduction and up to 98% carbon capture through integrated CO_2 separation. With the potential to develop zero carbon H_2 reforming as part of scale up, this technology could significantly accelerate affordable decarbonisation of heat, power and transport. For Phase 2, we propose a pilot scale demonstration using our existing expertise to take this technology from TRL 4 to 6, demonstrating the process as a full-chain integrated system for commercial industrial deployment.

Application of the H_2 production technology demonstrated in the HyPER project, and deployed in industrial clusters, offers accelerated and affordable decarbonisation to meet the UK net zero 2050 target.

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1. Introduction to H_2 and Phase 1 of the HyPER Project

Hydrogen (H_2) is already globally utilised at a scale of approx. 55M Tonnes every year, where it is used to make ammonia, methanol, and other chemicals in addition to being widely used in oil refineries. With the global ambition of decarbonising every aspect of society we must revolutionise the technologies and processes that we currently use, for which H_2 can play an important role, for example in decarbonising heating systems, vehicles, energy storage, power production, and energy-intensive industries. However, it is imperative that the use of H_2 in these sources is ‘clean’ – i.e. zero or minimal CO_2 emissions produced during the H_2 production step.

Steam Methane Reforming (SMR) technology is the predominate technology used in the production of bulk H_2, but it emits 8-12 kg of CO_2 for every kg of H_2 produced. Although conventional SMR has been extensively studied for H_2 production. Decarbonising it entails installing a separate carbon capture unit downstream of the facility to comply with the next-generation carbon emission targets.

This Phase 1 project explored the feasibility of producing bulk quantities of H_2 from the sorption enhanced steam methane reforming process integrated with an indirectly heated calciner to facilitate the separation and removal of CO_2 from the system in a solid phase. This has been extensively developed in the US by the Gas Technology Institute (GTI). The Compact H_2 Generator (CHG) Technology patented by GTI can reduce the LCOH up to 20% and CAPEX over 50% compared with SMR technology with 98% carbon capture.

2. Summary of Phase 1 activities and outcomes

2.1 H_2 market assessment

The market study considered the potential geographical market opportunities and different conflicting parameters for the adoption of the proposed CHG technology. Countries with high natural gas consumption/export were addressed initially since the CHG technology requires natural gas use. Countries with carbon capture and storage programmes or those affiliated with CO_2 pipeline networks were also promising candidates for rapid take-up and commercialisation. Furthermore, the suitability of several smaller "off-the-grid" industry applications were also investigated because of the suitability of the CHG technology for such installations.

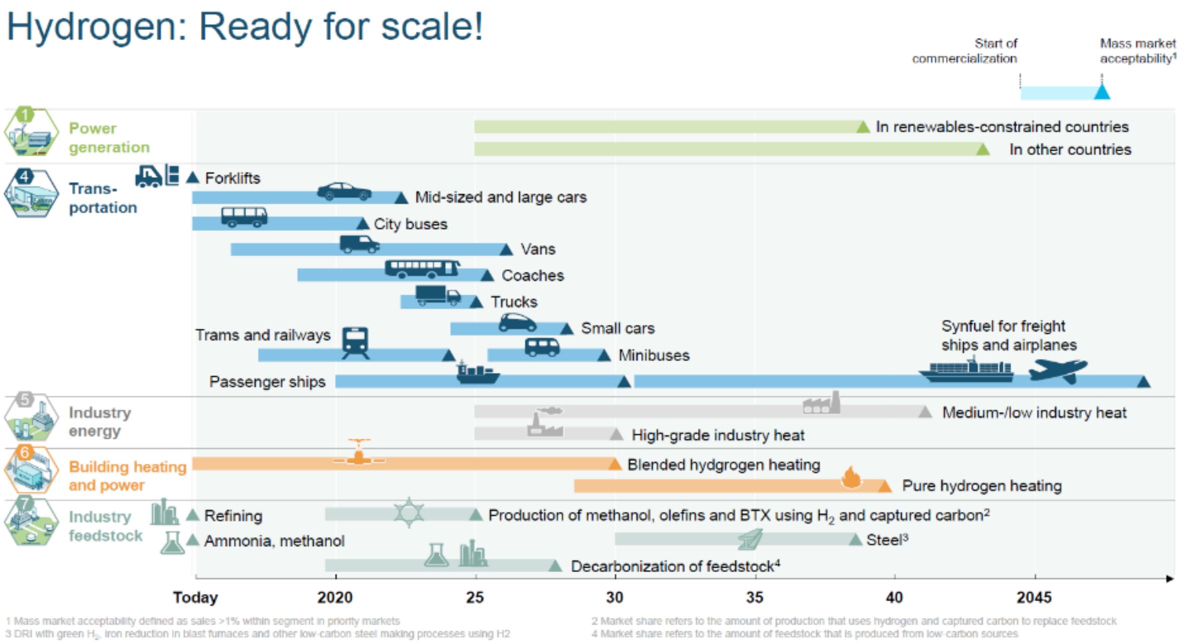


Figure 1. Hydrogen deployment and scale up pathway.[1]

H_2 itself is a carbon-free fuel and will play a key role in the energy mix for countries with established CO_2 reduction schemes. For instance, western European countries have already forecast an increase in H_2 demand from vehicles of all sizes, rail networks, heating, fuel and chemical production and power generation (see Figure 1 for an example of the H_2 deployment and scale up pathways suggested by the Hydrogen Council [1]). Many countries continue to rely heavily on natural gas to secure their energy supply and account for variations in electricity generation caused by weather, seasonality, and the intermittent generation profile of renewables. This continued use of natural gas is often seen as conflicting with greenhouse gas emission reduction goals and thus H_2 is being explored as a clean energy vector that can be stored, transported and used in similar manners to natural gas. Our study highlighted that countries with a high penetration of renewables would still opt for gas-to-power technologies, using natural gas to produce H_2, as it is able to balance supply and demand, and has minimal visual impact on the environment and is therefore more socially acceptable.

The adoption of the proposed CHG H_2 production technology does require functional and available CO_2 storage to be considered a low carbon option. Therefore, those countries investigating and implementing CO_2 capture with use, geo-storage or export are key target markets. Some countries have identified market opportunities for H_2 export and have put in place financial incentives towards this goal and H_2's overall use at different scales.

The growth of the CHG technology will be linked with the expanding H_2 market, greenhouse gas emissions legislation, and the development of key infrastructure (i.e. gas grid). Therefore, near-term applications of the proposed CHG technology will be focussed on industrial clusters where multiple potential uses of H_2 exist. The CHG technology has the capacity to scale up and expand into new markets as commitment to act on emissions legislation increases. At the current market maturity level, the CHG technology represents a prime candidate in the field of H_2 production.

2.2 Process modelling

The process modelling activities were focussed on chemical equilibrium calculations and optimisation of the system to maximise the CO_2 capture rate, H_2 yield, and overall thermal efficiency. The process modelling was performed using Aspen Plus software. The reformer equilibrium was modelled with data from HSC equilibrium software, which is based on Gibbs energy minimisation. The modelling was performed for two different plant sizes:

1) 300 MW_{th} counterfactual for benchmarking and demonstration of the potential of the CHG at full-scale, once commercialised
2) 1.5 MW_{th} pilot plant as the concept for Phase 2 of this competition

The counterfactual plant layout was simplified by excluding without thermal integration for comparison at the pilot scale. Modelling of the CHG concept was performed to demonstrate high pressure operation (4-30 bara) of the technology together with a closed sorbent loop. This approach also facilitated flexible system control during the demonstration of the critical components prior to whole plant testing.

A detailed description of the Pilot design is provided in section 2.4, but the overall CHG is based on the sorption enhanced steam reforming process. This process is a second generation hydrogen production process but offers a simpler process layout compared to the counterfactual. There are two main reactors in this process, 1. a reformer/carbonator which in the CHG is a fluidised bed reactor, 2. a calciner utilising an entrained flow reactor. Within the reformer/carbonator the methane in natural gas is steam reformed into an impure mixture of H_2 and CO, the CO is then converted into CO_2 by the water gas shift reaction and in doing so produces more H_2. The CO_2 is captured with a sorbent and removed from the gas stream thus leaving a relatively pure stream of H_2 that can be further purified by a Pressure Swing Adsorber. The captured CO_2 is released in the calciner thus the overall process generates two final gas streams, one of high purity H_2 and one of high purity CO_2, the CO_2 can then be transported, stored or used and is prevented from entering the atmosphere and causing more climate change.

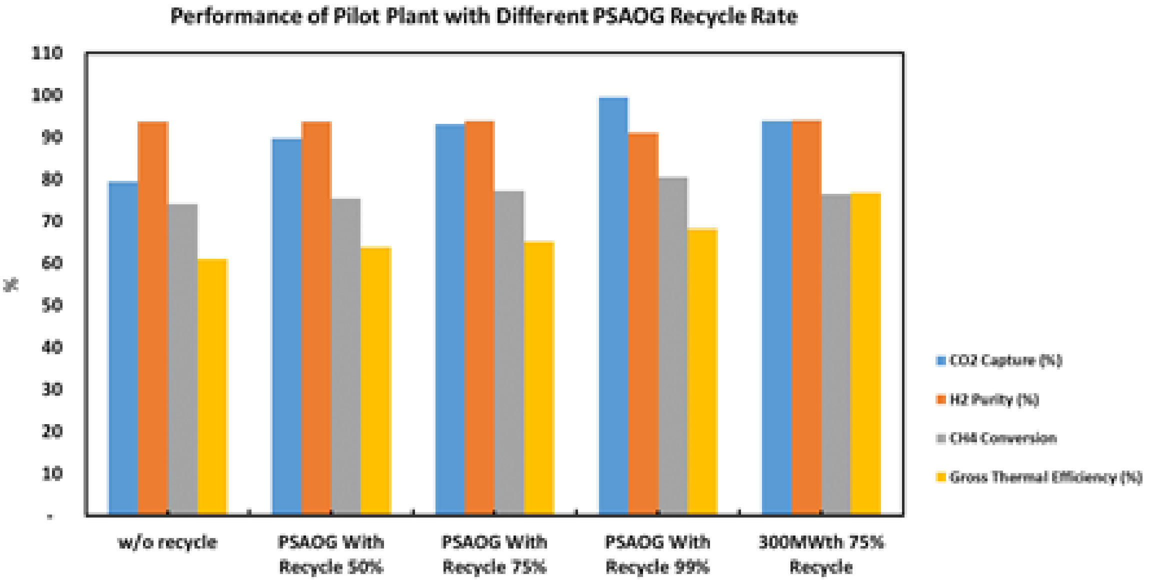


Figure 2. Performance of 1.5 MW_{th} pilot plant with different PSAOG recycle rate.

Optimised process modelling demonstrated that the CHG was able to achieve CO_2 capture of >93% by recycling the Pressure Swing Adsorption Off Gas (PSAOG) into the process. An overall layout of the modelling is available to view in Appendix 8.1. The methane conversion at equilibrium changed as a function of steam to carbon ratio, temperature, and reactor pressure. The amount of steam used as an input influenced the overall thermal efficiency of the system therefore different process models were developed for different PSAOG recycle fraction (see Figure 2). A recycle fraction of 75% was considered for the full-scale and pilot plant models but this could be further increased if higher CO_2 capture rates are required. The H_2 in the PSAOG recycle stream negatively affects the methane conversion by shifting the reactor equilibrium and therefore the equilibrium process models were developed with and without an additional membrane unit to scrub out the H_2 before it was recycled. The extent of carbon capture can be increased to nearly 98% through addition of this H_2 membrane.

In order to finalise the preliminary design of the pilot plant, the minimum turn-down of the process has been modelled considering the minimum superficial velocity requirement inside the fluidised bed reactors. The process turn-down potential was found to be around 60% which can be further extended by controlling the operating pressure or steam-to-methane ratio. A set of process scale-up models were also developed for 50 MW_{th} and 150 MW_{th} systems to estimate the impact on the Levelised Cost of Hydrogen (LCOH). Unlike the pilot scale model that excludes thermal integration, the scale-up models considered this to increase the overall thermal efficiency. The results indicate that the thermal performance of 50 MW_{th} and 150 MW_{th} systems are similar to that of the 300 MW_{th} system.

2.3 Techno-economics of the CHG process

The original CHG process was optimised for the lowest LCOH production, but as a result could not better the carbon capture rate of the Counterfactual at 90.1% [2]. During the feasibility study, the proposed process was reviewed, and a number of potential carbon capture optimisation options were identified by the project team and confirmed through extensive process modelling. As indicated in Section2.2, the recycling of the PSAOG represented the most cost-effective means of increasing carbon capture. A further improvement was made from the addition of a secondary H_2 separation step, utilising a commercially available H_2 membrane technology. In addition to these process improvements a transport calciner was proposed in place of an indirect-fired rotary kiln on account of concerns over the effectiveness of heat transfer to the fine sorbent particles.

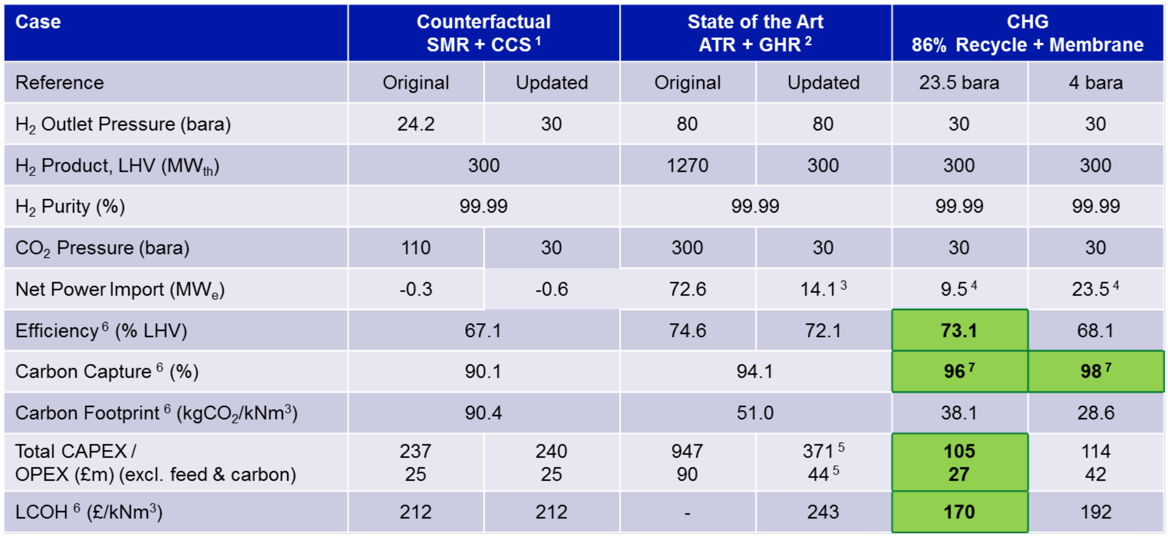
Despite the techno-economic benefits of operation at elevated pressure, the process has thus far not been proven at the nominal design operating pressure of 24 bara. Therefore, the lower-risk option of lower pressure operation was also considered.

The basis of the economic assessment of the CHG process was a bottom-up cost estimate carried out for a 60 MSCFD (approximately 200 MW_{th}) plant on the US Gulf Coast, delivering 99.99% H_2 product purity and with the major equipment including materials, labour and transport carried out in 2005.

A methodology was used to determine the Engineering, Procurement and Construction (EPC) contract cost based on the bottom-up cost estimate with cognisance taken of the construction, project contingency and EPC service costs utilised in the counterfactual EPC contract cost. To ensure the selected approach was robust a baseline SMR costing carried out in 2005 utilising the same methodology was treated similarly for comparison against several references. The difference in costs was found to be a maximum of ±10%, well within tolerances anticipated in an AACE Class IV estimate, and therefore determined to be fit for purpose.

All costs are presented on a Q1 2017 basis and for cost escalation from 2005 price indices from the Bureau of Labour Statistics for US industrial gas production [3] were utilised. For variable operating costs, an electrical import was costed as appropriate to reflect compressor duties, whilst the cost for storage of CO_2 was assumed constant.

The performance and cost metrics of the optimised CHG high- and low-pressure options versus the counterfactual Steam Methane Reforming plus post-combustion capture and State of the Art (SOTA) - deemed to be Auto Thermal Reforming (ATR) plus Gas Heated Reformer (GHR) [4] - are presented in Table 1. The counterfactual and SOTA were updated according to 20 years lifetime and a discount rate of 10%.



Case	**Counterfactual SMR + CCS[1]**		**State of the Art ATR + GHR[2]**		**CHG 86% Recycle + Membrane**	
Reference	Original	Updated	Original	Updated	23.5 bara	4 bara
H_2 Outlet Pressure (bara)	24.2	30	80	80	30	30
H_2 Product, LHV (MW_{th})	300		1270	300	300	300
H_2 Purity (%)	99.99		99.99		99.99	99.99
CO_2 Pressure (bara)	110	30	300	30	30	30
Net Power Import (MW_e)	-0.3	-0.6	72.6	14.1[3]	9.5[4]	23.5[4]
Efficiency[6] (% LHV)	67.1		74.6	72.1	**73.1**	68.1
Carbon Capture[6] (%)	90.1		94.1		**96[7]**	**98[7]**
Carbon Footprint[6] ($kgCO_2/kNm^3$)	90.4		51.0		38.1	28.6
Total CAPEX / OPEX (£m) (excl. feed & carbon)	237 25	240 25	947 90	371[5] 44[5]	**105** **27**	114 42
LCOH[6] ($£/kNm^3$)	212	212	-	243	**170**	192

[1] BEIS Benchmarking report 13333-8820-RP-001
[2] H21 North of England report
[3] Scaled by product output and lower pressures
[4] CO_2 compression power and costs from IEAGHG Report 2017-2
[5] Scaled using power, n = 0.65
[6] Calculated using BEIS LCOH Calculator Tool
[7] Projected carbon capture target based on analysis

Table 1. Techno-economic evaluation summary.

The CHG provides a clear advantage in carbon capture rate (up to 98%) and efficiency (up to 73%) over the Counterfactual SMR+CCS and compares well with ATR+GHR. On a single train basis, the economic analysis highlights that, for the high-pressure case, this advantage is underwritten by a reduced capital expenditure (£105m vs £240m; a 56% reduction) and a reduction in LCOH of 20% ($£212/kNm^3$ to $£170/kNm^3$). For the 4 bara scenario, the CAPEX reduction is 53% and LCOH ($£192/kNm^3$) is 10% lower than the Counterfactual.

The CAPEX and LCOH savings confirmed through Phase 1 activities highlight the dual advantage of the CHG technology in terms of improved economics coupled with performance. At 38.1 $kgCO_2/kNm^3$ the carbon footprint for the high pressure CHG case is just 42% that of the Counterfactual. Operation at low pressure further reduces carbon footprint to just 28.6 $kgCO_2/kNm^3$. The process also has the potential to reach near-zero carbon emissions with 100% recycle.

2.4 HyPER pilot plant design

The proposed HyPER pilot plant is a 1.5 MW_{th} pilot system of the CHG process, which includes both the reforming and sorbent regeneration systems. The proposed system, shown in Figure 3, enables detailed evaluation of the two key remaining risks of the system, which are elevated pressure sorbent enhanced reforming in a bubbling fluidised bed and reliable high-temperature solids handling. With the exception of process integration, the substitution of multi-cyclones for filters and simulation of the recycle stream, all of the main equipment expected of the full-scale plant is present on the pilot. The PSA, H_2 membrane separator and recycle gas compressors required for recycle at full scale represent commercially available equipment having minimal technical or cost risk and, on that basis, have not been considered for demonstration on the proposed pilot.

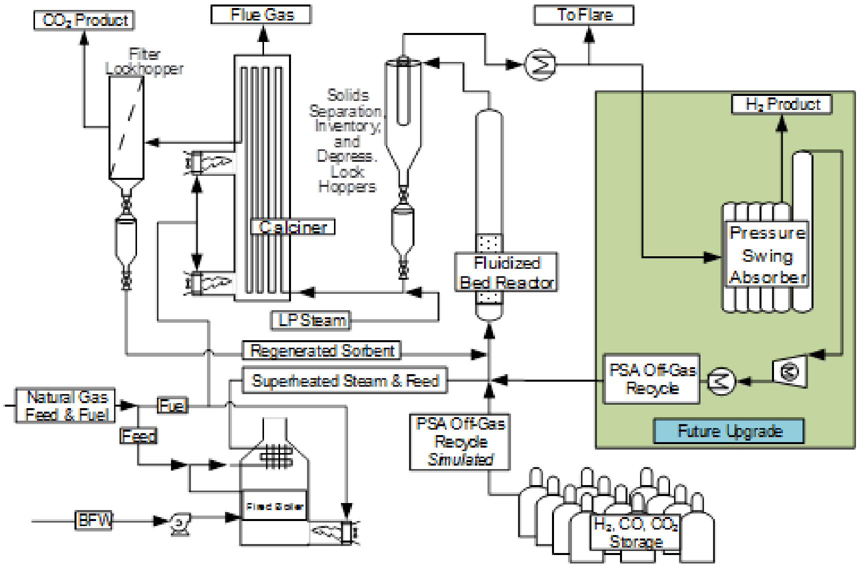


Figure 3. Proposed 1.5 MW_{th} pilot system.

The proposed maximum output of 1.5 MW_{th} represents an approximately 20x scale-up on the existing 71 kW_{th} facility in the US, achieved through a combination of increased physical size and operating pressure. The 1.5 MW_{th} pilot has been sized and a preliminary design of the test article is shown in Figure 4.

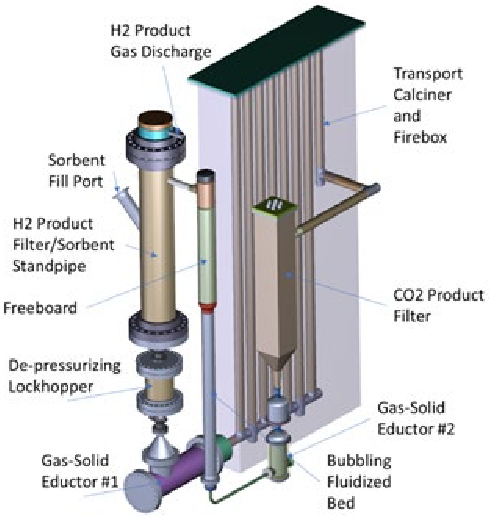


Figure 4. Proposed 1.5 MW_{th} pilot test article configuration.

The intent of the proposed pilot facility is to demonstrate the continuous operation of the CHG process at high pressure, producing a high yield of H_2 product and high capture rate of CO_2. However, it is recognised that there are a number of risks attendant to accomplishing this objective. Operation at lower pressure has been shown to be both technically (for optimal H_2 yield) and economically feasible, and therefore the achievement of this operating point would also be considered a success, should any issues with operation at elevated pressure arise. In addition, the lack of process integration specified (e.g. thermal integration) on the pilot is intentional in order for the facility to remain flexible for the controlled proving of components prior to whole system testing.

The preliminary engineering design carried out in the feasibility study included preliminary engineering including Process Design and Safety, Piping, Mechanical, Electrical, Control and Instrumentation, Layout, Civils and Construction activities with several preliminary deliverables as follows:

- PFD (Appendix 8.2)
- Heat and mass balance
- Preliminary P&ID
- Equipment list and specifications
- Valve and line list
- Operating philosophy
- Plot plan
- HAZID/ENVID

These deliverables allowed for a clearer understanding of the technical barriers to scale-up and plant reliability. All the engineering activities will be carried out in more detail in the next Phase giving further understanding of any residual technical barriers and potential mitigations following pilot demonstration.

3. Overall achievements of Phase 1 and short-term development plan

The Phase 1 feasibility study confirmed that GTI's CHG Technology with Integrated CO_2 Capture can offer:

- The lowest cost H_2 compared to the Counterfactual SMR + CCS by up to 20%
- Substantially lower CAPEX than Counterfactual by up to 56% with similar OPEX
- Equivalent H_2 purity to Counterfactual while achieving up to 98% CO_2 capture
- A significantly lower carbon footprint (<40% of the Counterfactual)

Full development of GTI's CHG technology uses the ongoing small pilot-scale (0.071 MW_{th}) efforts at GTI in Chicago, US, in the Phase 2 demonstration (1.5 MW_{th}) under the BEIS Phase 2 Competition. The current work at GTI is funded with US-\$6.5m (~£5.2m) by the U.S. Department of Energy (DOE) with a further DOE feasibility study underway for a ~30 MW_{th} H_2-to-Power project. Figure 5 below shows the short-term development plan. The long-term operation of the existing GTI small-scale pilot combined with the larger scale/ high-pressure Phase 2 pilot operation will ensure that all major process risks will have been reduced sufficiently to advance the technology to commercialisation.

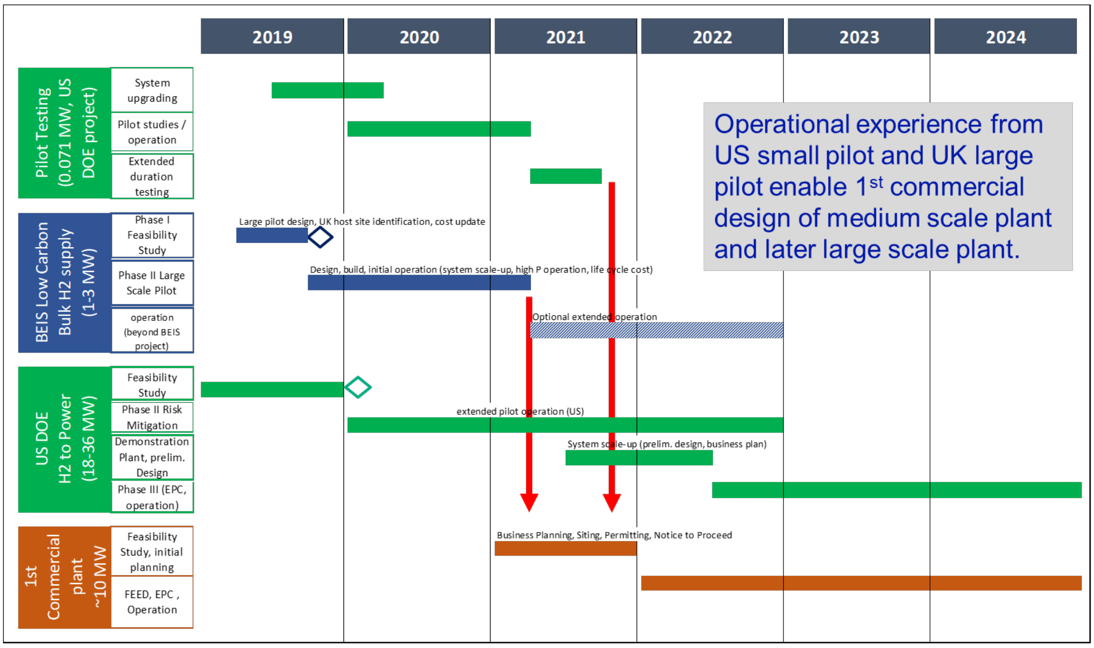


Figure 5: Short-term development plan.

It is anticipated that the substantially lower CAPEX compared to conventional SMR technology will be the key driver for a first commercial adopter, even without the requirement for high CO_2 capture rates. Initial business planning for such a project can start as early as

2021 with commercial operation before end of 2023 at an estimated cost of ~£12m for a 10 MW_{th} design. The optimised 10 MW_{th} design will then become the basis for larger 50 MW_{th} modules, benefitting from the compactness and low CAPEX of the CHG process, and ultimately leading to 300 MW_{th} and 1500 MW_{th} systems.

In Phase 1, GTI, Doosan Babcock, and Cranfield University went through a structured process to identify technical, environmental, economic, commercial, financial and project management risks that need to be addressed. This provided a complementary assessment to risks already identified and addressed under ongoing GTI activities. The primary technical challenges relate to the operation of a steam methane reforming reaction in a fluidised bed that includes a catalyst and a sorbent. The proposed pilot system will be able to operate at higher pressure compared to the existing pilot at GTI.

For the short-term development, the key remaining commercial risks relate to 1. the total equipment costs of the pilot, 2. the business arrangement between the parties and key suppliers, 3. and identification of an early commercial opportunity.

1. Substantial efforts have been made to keep the cost of the pilot low while achieving technical goals. e.g. rather than including a PSA for off gas recycle, that recycle stream can be simulated through increased feed flow rate and dosing of impurities. Lower cost construction materials will be used to account for the limited expected operating life of the pilot and to accelerate the manufacture of the pilot.
2. The project partners have developed a teaming agreement that lays out their business relationship.
3. For early market entry, small industrial applications (10 MW_{th}) have been identified with a number of possible first commercial projects at UK sites expected as part of the BEIS grand challenge for Industrial Clusters.

4. Description of Phase 2

The purpose of Phase 2 is to validate the performance, operability and chemistry of the HyPER system at a relevant scale and drive the HyPER technology towards commercialisation. To achieve this purpose, a 1.5 MW_{th} pilot will be designed, constructed and commissioned at Cranfield University.

The detailed design will rely on the work completed in Phase 1 and results from the cold flow validation testing of the transport calciner and the fluidised bed/freeboard tests. The transport calciner cold flow testing will validate the particle velocity relative to the gas velocity and verify the operability of the configuration currently envisioned. The fluidised bed/freeboard cold flow testing will ensure the freeboard height is greater than the terminal disengagement height of the spouting bed of catalyst particles. A HAZOP will be convened upon completion of the updated Phase 2 Process Flow Diagram (PFD), definition of operating conditions, and the Piping & Instrumentation Diagram (P&ID). The results from the HAZOP will allow the design to be finalised and released for fabrication.

The site preparation will utilise the requirements from the PFD and the results of the HAZOP to begin upgrading the facility to meet the testing requirements and to operate in a safe and reliable manner. Details from the design will also be used to ensure adequacy of the existing structure for supporting the test equipment. Instrumentation and control equipment will be procured in line with the P&ID and equipment specifications that are compatible with the data acquisition and control system. The existing control logic from GTI's US pilot will be used as the basis for the control programming.

Construction will occur in parallel with the site preparation. Equipment will be inspected and cleared for installation in line with an assembly planning. Operating procedures will again rely on GTI's existing procedures for their basis. A Facility Requirements Review will be held to ensure the Pilot is ready for commissioning for the first test campaign. Upon commissioning, the first test campaign will commence.

The 1.5 MW_{th} Pilot testing is divided into four campaigns which incrementally gather data and complete the integrated Pilot. Test campaign 1, shown in Figure 6 and bordered by the smallest dashed line, will validate the operation of the transport calciner, with the key objectives of determining the heat balance of the calciner firebox and operational limits of the calciner. The specific operating limit parameters are calcining temperature, calcination rate and effect of steam concentration.

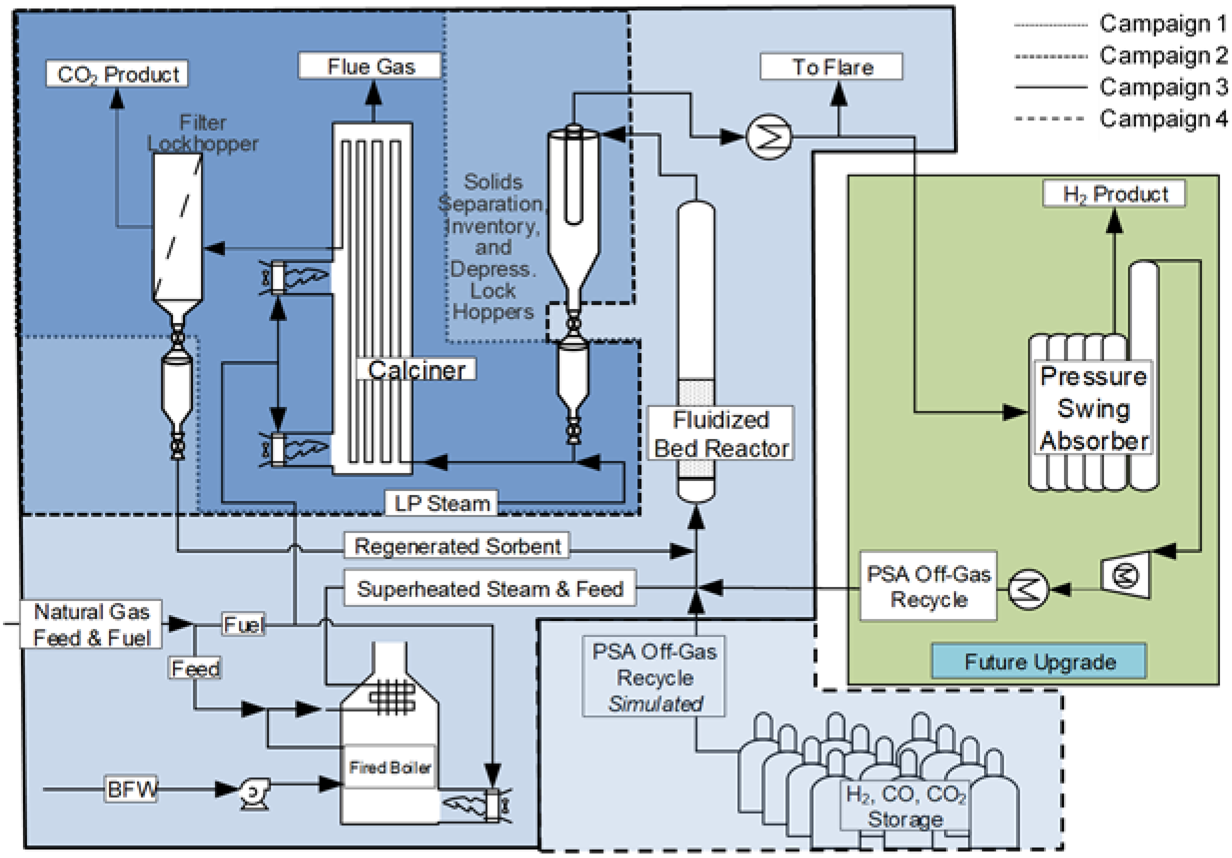


Figure 6: HyPER 1.5 MW_{th} Pilot test campaigns 1, 2, 3 and 4, layout and description.

Testing Campaign 2, shown in Figure 6 bordered by the medium dashed line, will incorporate the pressurising lock hopper and H_2 filter vessel into the system, with the key purpose of validating operability of the pressurising lock hopper. The specific operability data are the fill/drain cycle time, aeration rates, and stoppage resolution.

Testing campaign 3 (Figure 6, bordered by the solid line) will incorporate the bubbling fluidised bed reactor and be the first campaign which generates H_2. Figure 6 shows the complete configuration, less the recycle simulant. This test series will incrementally grow the output by starting at low pressure (4 bara) to demonstrate the functionality of the system. The testing will incrementally increase the operating pressure once the performance data and system reliability are achieved. The operating pressure will be increased to the following pressures; 4 bara, 8 bara, 16 bara, and 24 bara. Other than overall proof of operation, this campaign will enable refinement of the equilibrium models and fluidised bed reaction kinetics- both of which are extremely valuable for future process modelling and system optimisation.

Recycling the PSAOG is one of the novel features conceived during testing campaign 1 of the overall project. To simulate the impact of the recycle the feed will be increased, and the required contaminants will be injected from bottled storage. This test campaign (testing campaign 4, shown on Figure 6 and boarded by the largest dashed line) will adequately simulate the HyPER system concept and is where true validation of whole system performance can be achieved. The results of the testing will be evaluated during the pilot testing and will be used to refine the comparison against the counterfactual plant. The key pieces of information are the validation of the system's methane conversion, sorbent reactivity, and calciner firebox efficiency. These three parameters drive the overall process performance.

In conjunction with the HyPER 1.5 MW_{th} Pilot testing, the commercialisation effort will identify pathways for commercialisation and develop relationships with organisations relevant to those pathways.

5. Economic benefit to HM Government of Phase 1 and 2

GTI's CHG technology with integrated CO_2 capture offers substantial advantages over a conventional approach of H_2 production with CO_2 capture. Our Development Plan also shows that with the CHG approach, large scale deployment of a low carbon H_2 solution, i.e. at a 1500 MW_{th} scale, is feasible as early as 2030 and at lower cost than the Counterfactual or any alternative solution that we are aware of. Acceleration of large scale, close to net-zero H_2 production through CHG could transform decarbonisation of heat and industry by more than halving the capital cost compared with the Counterfactual.

Based on the LCOH analysis, the cost of H_2 production at a 10 TWh/yr scale has been calculated and is 20% lower than the counterfactual. The results demonstrate the excellent value for money that the CHG technology offers. If the CHG technology was deployed at a scale of 10 TWh/yr by 2035, in line with UK Government intentions, then the HM Government could expect to see a £140m Return on Investment (RoI) in the 24 bara scenario or £67m RoI in the 4 bara scenario, relative to the Counterfactual (SMR + CCS). These calculations assume 8000 operational hours per year and are based on the lower heating value of H_2. These projections display the significant economic benefits that could be realised in the UK economy each year over the lifetime of operation, thus providing jobs, clean growth, and cheap and sustainable bulk H_2 supply.

The ambitious development timeline is enabled by leveraging the substantial investment by the U.S. Department of Energy (DOE), specifically the ongoing small-scale pilot work at GTI which is funded by the DOE with US-$6.5m (~£5.2m). This funding is in addition to prior cumulative investment by GTI (and predecessor Aerojet Rocketdyne) and DOE in excess of $20m (~£16m). The DOE is also funding a Phase I feasibility study for a ~30 MW_{th} H2-to-Power project in the US. We anticipate that this study will result in a follow-on Phase 2 de-risking effort at an estimated $3-4m (~£2.4-3.2m) investment focused on CHG-based H_2-to-Power. The design and engineering expertise, including proprietary design aspects, as well as the operational experience gained in the US projects, will be directly utilised in the proposed BEIS project. The projects have been designed such that there is no duplication of technical or de-risking efforts and work cooperatively towards a common goal ensuring maximum effectiveness in the use of funding.

6. Beyond Phase 2

Doosan Babcock with GTI and Cranfield University defined the long-term development plan by building on the short-term development plan to not only achieve the proposed 'stretching' target for H_2 supply above, but also define a product line scale up strategy to deliver state of art scale, cost and performance significantly better than that achieved by the counterfactual. Doosan Babcock has used its plant and process systems product design approach to define the optimal path to large utility scale H_2 production, considering the challenges associated with reliability and performance that may emerge from the Phase 2 demonstration plant.

The extent of deployment required to support a H_2 pathway to net zero in the UK by 2050 even by a progressive blending strategy, would need similar scale and investment in the counterfactual technology to the build rate of utility scale H_2 production plant in the UK's H21 Max Scenario [4]. We have used this UK market demand to define the route to market and drive the timeline for scale up. The £130Bn H_2 production plant CAPEX costs (2023-2050) for H21 Max UK Rollout are extrapolated for current state-of-the-art (ATR) from the H21 North of England 12.15 GW_{th} bulk H_2 production facility cost of £8.5Bn. With this scale of ambition in mind for alternative lower cost H_2 production technologies like the CHG, the 10 TWh/yr by 2035 (equivalent to deployment of up to four counterfactual scale plants) would require earlier achievement of 300 MW_{th} scale for the CHG technology.

The long-term development plan not only achieves this but also considers how to deliver a net zero carbon H_2 solution. At an anticipated CO_2 capture performance post Phase 2 optimisation approaching 98%, the consortium is confident that a viable net zero carbon H_2 production CHG solution is achievable in the long-term development plan (by 2023). This would turn state of art reforming/carbon capture from a transition technology into one that unlocks affordable zero carbon H_2 from methane to complement green H_2 from electrolysis.

Our technology development roadmap and product roadmaps are targeting notice to proceed (NTP) on the 300 MW_{th} unit scale by 2025, deployable in modules for a 1500 MW_{th} CHG plant. This would not only achieve 10 TWh/yr scale production before 2030 but also provide a viable alternative for possible selection in a UK net zero carbon H_2 build programme. The proposed development programme would look to consolidate the techno-economic advantages over the counterfactual through learning by doing at each product scale up stage, to realise the significant CAPEX and LCOH benefits (56% and 20% respectively). To achieve the route to market, the technology development roadmap focuses on delivering three principal low carbon H_2 product lines; a 10 MW_{th} small Industrial scale CHG; a 50 MW_{th} small Utility scale CHG; and a 300 MW_{th} large utility scale CHG with an initial twin train concept for the first 300 MW_{th} plant (150 MW_{th} each).

7. References

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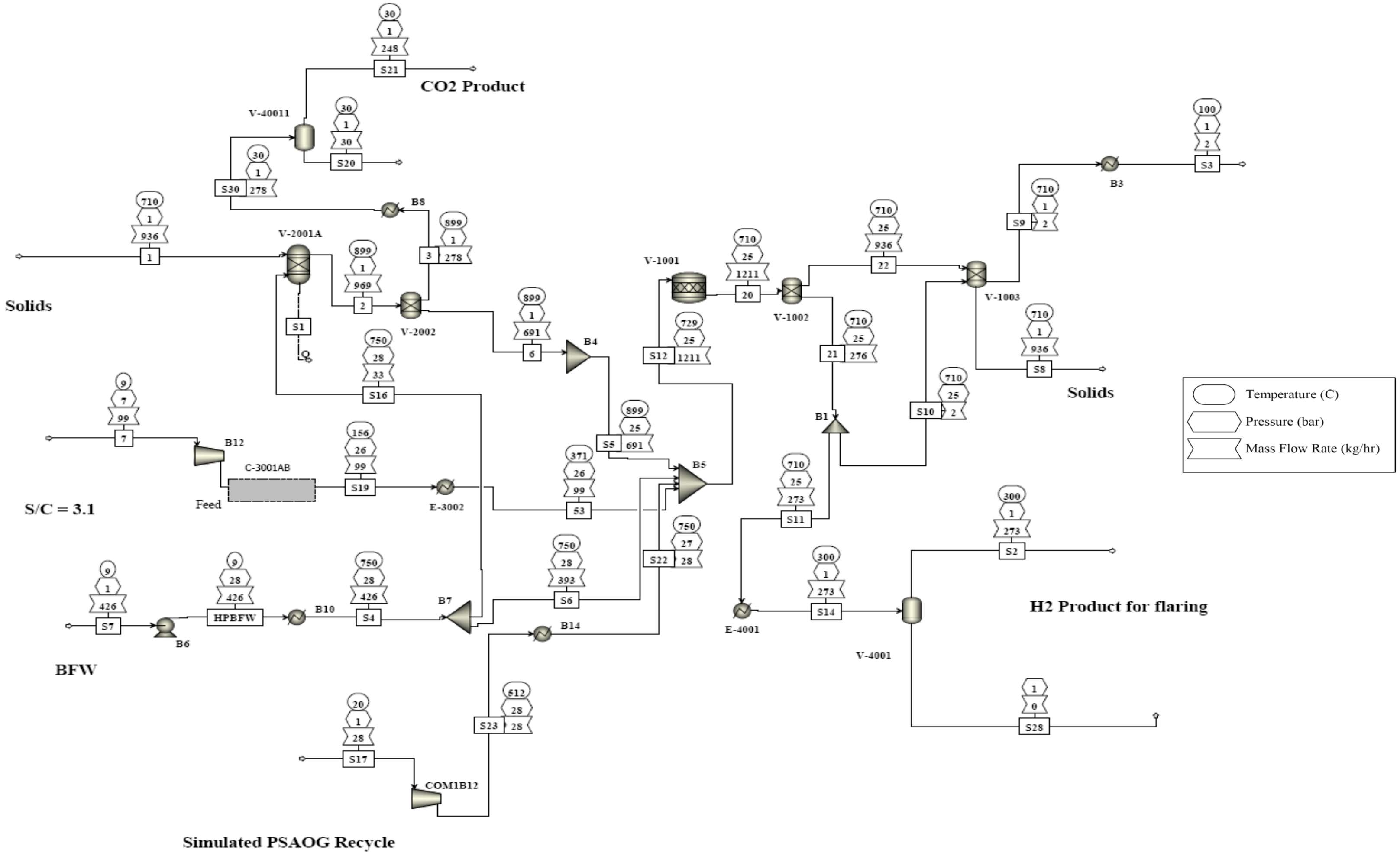
8. Appendices

8.1 Aspen process flow sheeting model



8.2 Process flow diagram (PFD)