H2BECCS Phase 1 Final Report

By

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1 Introduction

It is now known beyond reasonable doubt that rising temperatures caused by global warming threaten ecosystem stability. The extensive modeling of the Intergovernmental Panel on Climate Change (IPCC) has been used to set a warming target of 1.5 - 2°C, which, if met, will prevent the worst consequences of climate change. To achieve this, "global net human-caused emissions of CO_2 would need to fall by about 45% from 2010 levels by 2030, reaching net zero in 2050". Despite affluent nations announcing pledges to abate CO_2 emissions, actions have been insufficient to prevent emissions from rising. As such, we are accelerating towards warming of 3 - 4°C by 2100.

In 2019 the UK became the first major economy to commit to ending its contribution to global warming by setting a legally binding target of net zero CO_2 emissions by 2050. This means decarbonizing our energy supply by replacing fossil fuels with renewable energy and hydrogen where possible, and abating CO_2 via carbon capture, utilization, and storage (CCUS) where not. With 40% of the UK's energy being renewable, virtually no low carbon hydrogen produced or used, and no commercial CCUS plants, rapid scale-up is needed. Therefore, the 2020s will be vital in terms of investing in innovative new technologies and low-carbon projects if we are to reach net zero by 2050.

A favored technology in many net zero roadmaps is hydrogen production from biomass gasification. In this method heat, steam, and oxygen react to convert biomass to hydrogen and other products. As plants consume CO_2 from the atmosphere to grow, creating hydrogen from biomass, the net carbon emissions of this method can be low, and even carbon negative. As such, this collective project between the Cool Corporation, Kew Technologies, and Petrofac aims to convert syngas derived from refuse-derived fuel (RDF) to low-carbon hydrogen and a high-value form of solid carbon - carbon nanotubes (CNTs).

This technology has multiple benefits. Firstly, we create negative carbon emissions, as the carbon from the biomass is permanently locked into the form of a CNT. Secondly, we create clean hydrogen which can be used to displace fossil fuels in energy production and transportation. Thirdly, CNTs are an extremely high-value material with a large and expanding market, generating a large revenue stream for the process. The only waste product is water, which can either be disposed of or electrolyzed to produce more hydrogen.

By the end of this project, this technology will be demonstrated and validated on an industrial scale. We have seen promising results from our laboratory scale experiments and are thus scaling up to a demonstration plant. As a stepping stone to net zero 2050, the UK is aiming for 5GW of low carbon hydrogen production capacity by 2030, as set out in the Ten Point Plan for a Green Industrial Revolution, and this technology will not only contribute towards hydrogen goals but also pioneer a novel process that will further the UK's lead in climate technology.

2 Life Cycle Analysis

The carbon life cycle assessment (cLCA) was performed for Cool's technology, which had a system definition of the embodied emissions in the plant (steel structure), equipment, and input materials and the operational emissions arising from equipment energy use.

The process for calculating the emissions intensity of Cool's CNT's was to obtain the: mass of steel required for the structure of the plant, the mass of equipment, and the equipment's power consumption, the mass of the syngas. Petrofac provided detailed plans on the plant design, which included an estimate for some of the plant and equipment masses along with the expected power consumption. Some plant elements, such as hand-railing, ladders etc., did not have masses disclosed, but instead lengths or areas, so mass values were estimated using densities. Similarly, some of the equipment was missing mass estimates, so masses from comparable equipment were used as an approximation.

The operational energy consumption of the equipment was estimated using the power consumption values supplied by Petrofac. However, some of the equipment runs continuously while some run intermittently. Therefore, it was assumed in a 24-hour operation the intermittent equipment would run for 12 hours out of the 24.

To estimate the embodied energy of the input materials it was assumed that the iron catalyst is not appreciably consumed during a day's operation. Furthermore, the carrier gasses are assumed to be recovered to levels of 99% so are not included in the emission calculation. Therefore, the only reaction input is the syngas provided by Kew Technologies.

3 Engineering Design

The FEED (preliminary Front-End Engineering Design) was done in collaboration with Petrofac, and that detailed engineering will begin at the onset of Phase 2 of the project. The primary objective of here is to demonstrate the commercial viability of the novel Cool Corporation technology route to separate hydrogen and carbon from a feed gas consisting primarily of hydrogen and carbon dioxide, such as that derived from Syngas.

3.1 Basis of Design

The Basis of Design (BOD) document sets the scope of the project and records the rationale, criteria, principles, assumptions, and constraints behind major design decisions. This plant will process around 174 kg/hr of syngas and generate around 0.23 MW of hydrogen, in line with H2BECCS project guidelines. It is intended to be used for up to 5 years at the Kew facility however the design life will be $>$ 10 years for testing at other facilities. The overall turndown capability of the process units shall be targeted for 50% of the design capacity. The operating basis of the facility is 24 hours per day with a targeted annual availability of 85%.

The key constraints in terms of defining the scale of the pilot plant are the £5 million budget and 2-year project timeline. The plant will be located at the Kew Technology Sustainable Energy Centre in Wednesbury, UK, where the syngas will be supplied by Kew Technologies. The plant was also designed to fit on compact skids that can be easily transported on the road by HGVs.

The flow diagrams are accompanied by detailed heat and mass balance at each stage of the process as computed via ASPEN (or similar) simulations. The simulation results were used to obtain the parameter range that will most likely produce best outputs (detailed in the testing section later) and to most efficiently utlize the input gas feedstock.

3.2 Detailed Engineering Package

Subsequently, detailed P&IDs were generated which help outline the components and secondary processes that are required to enable the key technologies. From there, equipment lists were produced for all principal items of process and utility equipment with supporting process data for all numbered items of process equipment. This help define the process performance requirements and design conditions for all equipment items during the detailed design, as well as formulate the cost estimations. The equipment list is complemented by a balance of design reports which includes information such as mechanical, civil, and electrical criteria and the selection process.

For example, the mechanical work includes preparing equipment data sheets for main equipment and preparing functional specifications for equipment, packages, and materials handling.

- Equipment data sheets
- Functional specifications for equipment, packages, and materials handling
- Participation in design reviews such as HAZOP, HAZID and layout.

Separately, the electrical diagrams include detailed schematics of all of the electrical systems in the facility. They are used to provide control and safety systems and field instrumentation to ensure safe and reliable operations. Moreover, civil and structural packages help inform contractors where structural elements such as concrete, beams, or foundations should reside and the specifications for those elements. These detailed drawings and designs are primarily used during the construction phase. Finally, materials reports confirm the materials selected for piping, vessels and equipment in order to select the most cost-effective materials to meet the process design basis, environmental conditions, heat and material balance and blowdown scenarios developed during the project. These were summarised in the following documents:

- Materials selection report
- Control and Safety System Architectural Diagram
- Control and Instrumentation Package Requirement Specification
- Overall Key Single Line diagram
- Electrical Load List
- Civil / Structural Architectural Design Basis
- Civil and Structural MTO
- Structural MTO

3.3 Plot Plan & 3D Model

With the information on plant design and sizing, the layout and arrangement of the plant were created. This is important as the arrangement of equipment leads to the first estimates of piping materials. The plot plan is an aerial view is also used to show the layout of all buildings, equipment, surrounding land, roads, etc. This plan is essential for ensuring there is enough space for workers to move about, and ensuring enough space in the surrounding area to meet safety requirements. 3D models visualise the plot plan in a rendered image, which are useful for presentation purposes with clients, investors or in competitions.

3.4 Health, Safety, and the Environment

Importantly, the health, safety and environmental impact of the proposed pilot plant were reviewed and studied comprehensively. This is to ensure the safe, efficient, and continuous operation of the process.

4 Testing Regime

4.1 Overview of Testing Approach

The technology employed in our pilot plant design was carefully developed and tested on a laboratory scale (carried out prior to the Phase 1 project funded by BEIS). However, the thermal catalytic reactions involved in the syngas to CNT process have a relatively large number of input and output variables (denoted 'factors' and 'responses' respectively). Crucially, the functionality and performance of the plant here are defined by multiple responses of interest (such as hydrogen output, carbon efficiency, and energy efficiency), and different sets of factors are likely required depending on the relative priority of these responses. Moreover, the relationship between these variables is often dependent on the process scale and sometimes interdependent. For these reasons, a traditional one-at-a-time or trial-and-error approach will likely be ineffective here because i) the optimized factors can be easily missed from the experiments; and ii) the testing process will be inefficient (a large number of experiments are required). Therefore, a Design of Experiment (DOE) approach will be used whereby the parameter space is scanned based on statistically designed tests - all factors are tested at the same time even if they are interdependent. Consequently, the individual and combined impact of the factors can be more accurately and systematically analyzed.

Here, the parameter space for factors is defined from a combination of experimental data, literature, and information from comparable processes at a similar scale. This parameter space was then used as a reference for the operational limits of the pilot plant. In the first instance, the purpose of the testing is in fact to understand the relationships between the factors and responses of interest.

4.2 Functional Testing

The main purpose of the functional tests is to better understand the capability of the pilot plant when operating under different conditions. The main factors of interest include operating temperature, pressure, gas flow rate, and catalyst feed rate. The feedstock gas components are fixed initially based on our design (with consideration of Kew's current setup and capability). The main responses of interest are overall carbon efficiency, CNT quality, impurity content, and energy efficiency.

4.3 Performance Testing

Based on the results from functional testing, performance testing will be carried out to evaluate the long-term capability, reliability, and maintainability of the pilot plant. Specifically, this includes three main studies. Firstly, the impact of the variations of factors over time will be examined. For example, despite the high robustness of the syngas stream from Kew technology, there could be small variations depending on Kew's other project requirements. These are in the first instance neutralized by the Water Gas Shift process from Kew which guarantees a very consistent stream. However, should the need present itself when the input gas feedstock varies (such as more CO content), Cool's process can be tailored to neutralize the changes. This mainly involves altering the reaction parameters for methanation which can help efficiently consume all the CO and CO_2 contents. Sensitivity tests will be conducted to find out if such changes are required and the time/cost required. This is an extension to the sensitivity tests carried out during Phase 1. Secondly, the long-term operation will provide us with important information with regard to the reliability and repeatability of the various components and processes, as well as the best maintenance/repair strategy to maximize operation continuity. Finally, we aim to gather data regarding the unit economics via long-term testing - thus formulating the best strategies for commercial operations.

Notably, the plant is designed specifically to allow these tests to occur. For example, we have several parallel reactors (for example 3 for methanation), enabling various operation capacities to be tested. Moreover, the operating conditions of the equipment had been designed to fulfill all range of parameters of interest.

These tests will also be run according to an iterative approach whereby the various factors are examined constantly and reviewed periodically – so that the tests can be continuously tailored based on the subject of interest.

5 Project Plan

5.1 Project Timeline

The overall duration for the schedule is 23 months, including 1 month for approval of the final report by BEIS. In summary, the duration of the detailed design, procurement, delivery, and construction phase is 17 months in total, which involve the collaboration between the Cool Corporation and Petrofac. During this period, the critical path mainly follows the tender, award, delivery and installation of the CVD reactors. This is followed by a 6-month demonstration stage where detailed performance testing (as described above) will be carried out (1000+ hours).

5.2 Cost

The above engineering design is also supported by a detailed cost estimate. The primary tools employed were from Petrofac's Estimating department. For example. Block Estimating Tool (BE$T) is a proprietary Microsoft Excel based estimating program which was created in-house for preparation of cost estimates of various phases of projects from study, concept, feasibility to FEED. The base date of the estimate is Quarter 4 of 2022 (22 Q4).

Total project costs are GBP £4.45 million. This can be broken down into the following categories; materials and equipment £930k, fabrication £120k, site construction £170k, civils and earthworks £170k. This brings direct cost to £1.45 million. Indirect cost include; labour at £1.87 million, and misc cost are £170k. This brings total indirect cost to £2.05 million. Therefore, the total project cost is £3.42 million, which with a 30% contingency comes to £4.45 million.

6 Route to Support H2BECCS Commercialization

Cool's proposed technology has a distinct advantage over other H2BECCS technologies: we produce an ultra-high-value by-product, CNTs, along with hydrogen. As a result, we have a unique business model whereby we tap into two separate markets - syngas/CCUS and CNTs. In particular, the revenue we generate from the CNT application market will hugely reduce the effective cost of our green hydrogen, making them a lot more attractive. A short introduction to the two markets is presented here. Note that the CCUS market is included here as CO_2 is one of the main components of syngas, thus the CCUS and syngas markets have evident synergies. The application of Cool's unique technology may also help attract some of the players in the CCUS market (currently larger in size) to the syngas market, thus further helping the commercialization of H2BECCS.

6.1 Syngas and CCUS Market

The target market for Cool's technology is both point sources of CO_2, syngas from RDF, and CNT users. Firstly, the syngas market is unique in that it can simultaneously be a product, or a byproduct / form of energy storage for subsequent applications such as turbine, engine, or energy generation. The syngas used in the Cool/Kew process is produced by RDF. Due to the unique positions of syngas / RDF, direct data gathering is difficult as they are often not the final product. Nevertheless, we know that the syngas market is dominated by the chemical industry. Demand for fertilizer production takes up most of the produced syngas (53%), and the remainder is split between other chemicals such as hydrogen, methanol and power ('gas to liquid' fuels and electricity). Furthermore, whereas electricity production takes up a small portion of syngas today (4%), it is increasingly gaining traction as a source of carbon neutral electricity. Importantly, the waste to energy market can be used as a best reference as RDF and syngas are produced in the largest quantities here. The global waste to energy market is projected to grow from $33.28 billion in 2022 to $44.62 billion by 2029, at a CAGR of 4.3% in forecast period, 2022-2029. This market is also expected to continue growing thanks to both economic incentives and increasingly strict government policies on landfill waste (more waste needs to be recycled). For example, in Nov 2020, India inaugurated the municipal solid waste processing facility of Jawahar Nagar, Hyderabad, with 19.8 MW. The plant comprised two RDF-fired boilers and is equipped with a world- class multi- stage flue gas cleaning system and online continuous emission monitoring systems.

Separately, CCUS is being utilized in end use industries such as oil and gas industries, power plants, cement industry, chemical industry, and others. The CCUS market is expected to grow dramatically at a CAGR of 52.7% between 2021 and 2030. It is expected to reach $36.35 billion by 2030, driven by the need for rapid decarbonization of industries and also to meet the Paris Agreement. The cumulative capacity is expected to reach 1616.2 MT per annum by the end of 2030. In comparison, the global syngas market size was valued at $43.6 billion in 2019 (by Allied Market Research's account), and is projected to reach $66.5 billion by 2027, growing at a CAGR of 6.1% from 2020 to 2027. At present, North America is the prominent region utilizing CCUS, with about 55.03% of the total revenue, followed by Europe. Europe is expected to witness the fastest CAGR of 13.35% between 2022 and 2027. The growing government initiative for the development and deployment of CCUS coupled with increasing adoption of net-zero emission targets is propelling the market growth.

The Cool Corporation's technology offers an unique value proposition whereby an extremely high value product is produced. In the short term, our route to market involves the continuous collaboration with our existing partner, Kew technology, which already have the capacity to produce syngas / RDF that can supply our pilot plant and potentially first commercial plant. This simultaneously provides us with a realistic, tangible, and clear route to success, and offers our partner fantastic value and environmental proposition due to our unique technology.

In the medium to long term, our technology is compatible with most RDF/syngas providers. This is thanks to our two-stage process whereby the first stage can be tailored to process most $CO/CO_2/H_2$ combinations. As mentioned earlier, Europe is the largest WtE market, and easiest for us to work with thanks to the preferable policies and geographical proximity. As further described in deliverable 1.3 'Site Report', we will focus on emitters above a minimum volume of emissions per annum, the location's proximity to other infrastructure, the suitability of a plant for CCUS integration. A list of key players is identified in Europe, constituting over 10s of billions USD in these markets. Meanwhile, the Asia-pacific region is also a key area for the Cool Corporation to explore in long term. In general the waste recycling percentage is much lower, representing a huge potential market. Key players include Hitachi Zosen Corporation, Mitsubishi Heavy Industries Ltd, China Jinjiang Environment Holding Co. Ltd, China Everbright International Limited, and Babcock & Wilcox Vølund. By providing a high value proposition of syngas/RDF application, we could potentially help further expand this market.

Additionally, a detailed site location survey was conducted. The result of this survey was that within the UK 42 industrial CO_2 sites and 1 CO site were identified as suitable for Cool's technology at scale. The single CO site is the Wytch Farm L1 oil & gas exploration and production plant operated by Perenco UK and is located in Dorset, as part of the Southampton industrial cluster. The 42 CO_2 sites are located within different industrial clusters within the UK, and span industries from cement to power generation.

6.2 CNT Market

Moreover, the global market for CNTs (including single, double, and multi-wall ones) are around 7 billion USD in 2021, and expected to grow at over 10% a year until at least 2028. In 2021, this roughly consists of $1.6 billion dollars in north America, $4.0 billion dollars in the Asia-Pacific region, and $1.3 billion dollars in Europe. Specifically, the CNT market in the UK is expected to be over $125 million USD in 2022, based on the estimation by Barnes Report, at around 10%of the European market. This is expected to grow to around $175 million dollars by 2028 with the current trend.

Specifically, multi-wall nanotubes (MWCNTs) are easier to produce and can be made with higher energy and carbon efficiencies as compared to single wall nanotubes, although the additional defects may lead to the slightly lower properties. Nevertheless, MWCNTs found applications in conductive polymer composites, structural additives (such as cement), Li ion batteries, displays, solar cells, and nanoelectronics, which represent the biggest current and potential industries of CNTs by volume and quantity. MWCNTs have distinct advantages over previously used materials or additives in these applications such as carbon black, with electrical conductivity, mechanical strength, or thermal conductivities over an order of magnitude higher. Moreover, to the UK, MWCNT represent by far the largest contributor at over 65% of the overall market share. Currently, the key end users for CNTs (potential customers) are in the electrical and electronics industry, aerospace & defense, energy, sporting goods, automotive and industrial. The electronics and automotive industry are the two biggest current consumers globally. However, a promising segment for CNT application is identified as the industrial construction materials such as metal and concrete, as strength, durability, corrosion resistance, thermal or electrically enhancing additives. For example, the addition of CNTs in cement has shown an improvement in the cement compressive and tensile strength, as well as thermal conductivity.

The Cool Corporation's technology provides a unique value proposition as we manufacture CNTs from a low-cost source via a carbon negative process. We specifically target MWCNTs due to the lower cost, higher carbon efficiency, and wider current and potential markets. In the short term, composite additives in the electronics and automotive industry are obvious targets. However – signing distributing agreements have shown to be effective for other stakeholders, and could be beneficial to the Cool Corporation in early stages as it lower the marketing, sales, and other overhead costs. Examples are Sigma Aldrich, Alibaba, RS components etc. We will also cooperate with UK-based SMEs who are potential CNT users due to their lower adoption cost (smaller facilities and higher flexibility), such as the electronics and electrical firms (over 18000 as mentioned above), automotive companies (such as JLR, Aston Martin, JCB) where the co-founders have a relationship with from both private and working environment.

In medium to long term, however, we identify industrial materials, in particular the cement industry, as a large potential user. Based on IEA's analysis, up to 4.3 Gt of cement was produced globally in 2020. This represents a potential market of over 4 Mt of MWCNTs which is nearly unmatched by other industries. As mentioned above, the addition of CNTs has shown clear improvements on the strength, durability, corrosion resistance, and thermal properties of cement.