Department for Business, Energy & Industrial Strategy

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Hydrogen Supply Programme – Novel Steam Methane / Gas Heated Reformer

Phase 1 Final Study Report

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Novel Steam Methane / Gas Heated Reformer

Phase 1 Final Study Report

522018-8820-RP-002, Rev. No. 1A

Report for

Department for Business, Energy & Industrial Strategy
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1 Executive Summary

In order to support the UK Government's commitment to achieve net zero carbon dioxide emissions by 2050, new forms of bulk-supply, low-carbon hydrogen will be required to minimise emissions from domestic heating, transportation and industrial supplies. The Hydrogen Supply Programme has dedicated £20m in the period 2018-2021 to support development of UK-led hydrogen technologies that will contribute towards the energy transition within the UK and provide opportunities for the export of goods and services.

Wood is a global expert in hydrogen production by catalytic reaction and has been a world-renowned Hydrogen Technology licensor and supplier of Steam Methane Reformers since 1960. We have designed over 120 hydrogen plants for international clients with a capacity range from 8,000 Nm^3/h to 180,000 Nm^3/h in a single train. The total worldwide installed capacity of hydrogen plants designed by Wood exceeds 3.35 million Nm^3/h of product hydrogen.

Before the Hydrogen Supply Programme commenced, Wood had developed a flow sheet and process simulation for a hydrogen plant integrated with carbon dioxide capture such that over 90% of the CO_2 could be captured for long-term storage. Wood's Blue Hydrogen concept includes a novel Gas Heated Reformer (GHR) for which we had developed a full process and mechanical design. As part of Phase 1 of the Hydrogen Supply Programme, Wood was awarded Lot 1 funds to develop its existing Blue Hydrogen Concept further to feasibility level, developing an equipment list, plot plan, AACE Class IV capital cost estimate and economic model. This report summarises the results of the feasibility analysis.

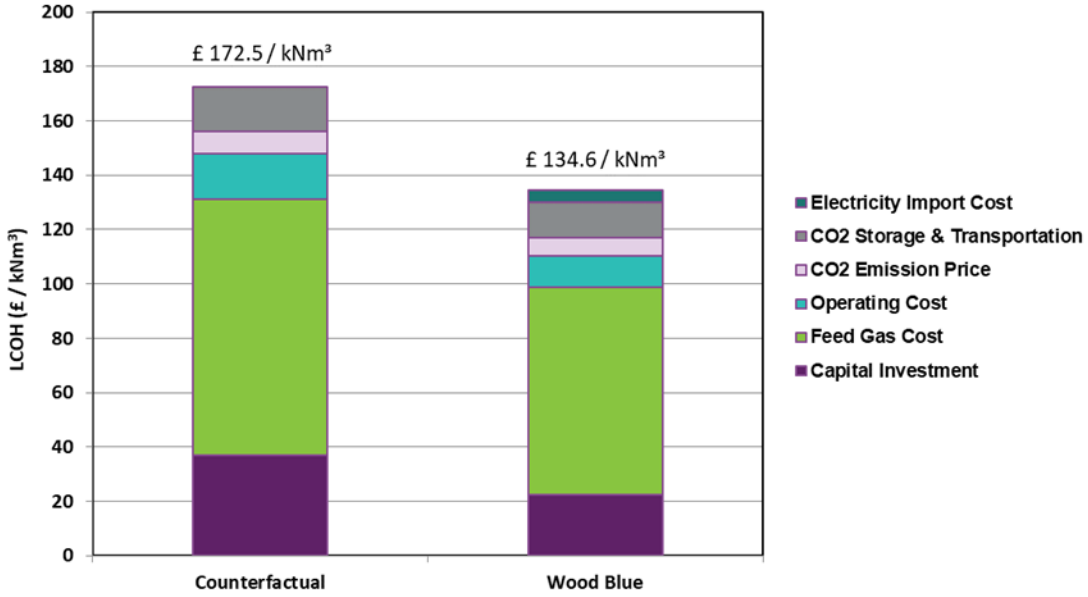
Since Wood's Blue Hydrogen design is an enhancement of our existing licensed technology, with a single novel equipment design and the addition of conventional solvent-based CO_2 capture unit, the Technology Readiness Level (TRL) of overall design can be rapidly brought up to TRL 7 (sub-scale demonstration, fully-functional prototype) through limited pilot-testing of the GHR. Furthermore, the design can be readily retro-fitted to an existing Steam Methane Reformer to dramatically reduce CO_2 emissions from existing refineries and petrochemical facilities.

As part of the feasibility assessment, the Wood Blue Hydrogen concept has been compared against the counterfactual case provided by BEIS. This is conventional Steam Methane Reformer (SMR) designed for a capacity of 100,000 Nm^3/h, with post-combustion carbon capture on the reformer flue gas using a proprietary amine solvent. BEIS provided some data on the technical and economic performance of the counterfactual, and Wood obtained other elements from the Wood-authored report "Assessing the Cost-reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology", from which it was developed.

Wood's Blue Hydrogen concept performs well by comparison to the benchmark case, as demonstrated by the table below:

Key Performance Indicator	Counterfactual	Wood Blue SMR
Net Power Efficiency (LHV basis)	67.2 %	78.3 %
Hydrogen Yield	66.6 %	84.3 %
EPC Contract Cost	£ 207 m	£ 122 m
Total OPEX (excl. FEED & Carbon Price)	£ 25.0 m pa	£ 22.4 m pa
Levelised Cost of Hydrogen	£ 172.5 / kNm^3	£ 134.6 / kNm^3
Cost of CO_2 Avoided	- £ 44.6 / te CO_2	- £ 88.9 / te CO_2

The costs for construction and operation of the facility over a 25-year project life can be attributed as shown in the following chart:



Wood has performed a market assessment for the use of hydrogen in the UK and globally. There is a wide range of possible outcomes for levels of hydrogen demand. The IEA and CCC both characterise outcomes in terms of strategic choices at national level. By 2030, there are minimal increases in hydrogen consumption under all CCC scenarios, however the strategic choices taken before then condition the outcome in 2050 with much greater differences. A conservative assumption can be made that an underlying market for hydrogen will experience organic growth, with the demand from the refining sector being amongst the most predictable and stable of the future potential markets. There is a substantial global market for SMR upgrade due to the appreciable size of the existing fleet.

If current UK Government policy is delivered, then there will be a substantial market for new build Blue Hydrogen from 2030 onwards. Before this there is a revamp opportunity that utilises the GHR for capacity and / or efficiency improvements to existing facilities.

In order to prove the Blue Hydrogen concept and demonstrate our Gas Heated Reformer, Wood intends to push ahead with development of a pilot plant facility and we have submitted an application to BEIS for funds to support the detailed design of a facility under Phase 2 of the Hydrogen Supply Programme. Once proven at pilot level, Wood intends to develop a standard Blue Hydrogen offering in a range of capacities that fits the market. This may, for example, include designs at capacities of 50, 100 and 150 kNm^3/h. In parallel, we will be seeking to offer the Gas Heated Reformer as a retrofit to existing facilities to increase capacity, increase efficiency and reduce excess steam production. Depending on the market, these revamp opportunities could include a carbon capture element, but this is less clear and is much more dependent upon government support.

Wood is confident that with funding support from the Hydrogen Supply Programme, coupled with its own internal resources, we can deliver a robust, cost-effective solution for low carbon hydrogen, ready to address the market as it develops.

2 Abbreviations and Acronyms

AACE	American Association of Cost Estimators
ACCE	Aspen Capital Cost Estimator
BEIS	Department for Business, Energy and Industrial Strategy
BFD	Block Flow Diagram
BFW	Boiler Feed Water
BL	Battery Limit
C2's / C3's	Hydrocarbons with two / three carbon atoms in the molecule
CAPEX	Capital Expenditure
CCC	Committee on Climate Change
CCS	Carbon Capture & Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CuO	Copper Oxide
DECC	Department of the Environment and Climate Change
E&I	Electrical & Instrumentation
EIA	Environmental Impact Assessment
EPC	Engineering, Procurement & Construction
EUR	Euro (€)
FEED	Front End Engineering Design
FID	Final Investment Decision
FOAK	First-of-a-kind
FOB	Free-on-Board
GBP	Great British Pound (Pounds Sterling)
GHR	Gas Heated Reformer
H_2S	Hydrogen Sulphide
HHV	Higher Heating Value
HO	Home Office
HT	High Temperature
IEA	International Energy Agency
IHS	IHS Markit Ltd
ITT	Invitation to Tender
LCOH	Levelised Cost of Hydrogen
LHV	Lower Heating Value
LP	Low Pressure
LT	Low Temperature
LTS	Low Temperature Shift
MCP	Multi-Cylinder Pack

MT	Medium Temperature
MTS	Medium Temperature Shift
MWe	Megawatts Electrical
MW_{th}	Megawatts Thermal
NiO	Nickel Oxide
NOAK	nth-of-a-kind
NPSH	Net Positive Suction Head
NPV	Net Present Value
OPEX	Operating Expenditure
P&ID	Piping & Instrumentation Diagram
PFD	Process Flow Diagram
PMT	Project Management Team
PSA	Pressure Swing Absorption
R&D	Research & Development
RPI	Retail Price Index
S&T	Shell & Tube
SMR	Steam Methane Reformer
TEA	Techno-Economic Assessment
TIC	Total Installed Cost
TRL	Technology Readiness Level
TWR^{TM}	Terrace Wall Reformer (Trade Mark)
UK	United Kingdom
USD	United States Dollar
ZnO	Zinc Oxide

3 Introduction

3.1 Hydrogen Supply Programme

In 2018, The UK Department for Business, Energy and Industrial Strategy (BEIS) launched the Hydrogen Supply Programme. This aims to identify and test novel approaches to supplying bulk low carbon hydrogen to the gas grid, industry, power, transport and / or import terminals, as part of the UK Government's drive towards achieving net zero carbon emissions by 2050. BEIS established a £20m fund for the Hydrogen Supply Programme in the period 2018-2021, to be spent in two phases.

Wood applied for and was awarded Phase 1 funding in each of the first two categories, developing low carbon versions of its successful hydrogen production technology, using our FW Terrace Wall™ Reformer. A full list of the successful applicants for Phase 1 funding may be found at https://www.contractsfinder.service.gov.uk/Notice/e07c3de7-a6a9-4ee8-bb3f-b76a9528fbd4 .

3.2 Wood History in the Supply of Hydrogen Technology

Wood is a global expert in hydrogen production by catalytic reaction as a worldwide recognised Hydrogen Technology licensor and Steam Reformer Heater supplier since 1960.

Our deep company experience in Fired Heaters resulted in the development of a specific design for Steam Reformer Heaters, named the Terrace Wall™ and branded using the historic 'Foster Wheeler' name. Due to its unique characteristics, the Terrace Wall™ design provides a number of advantages to hydrogen production in terms of performance, flexibility and reliability, bringing Wood technology to be very much appreciated all around the world. The Terrace Wall™ reformer accounts for 300 of the 2000 fired heaters that Wood has installed over the last 70 years.

Wood designed over 120 hydrogen plants for international Clients with a wide production capacity range (from 8,000 Nm^3/h to 180,000 Nm^3/h single train). The total worldwide installed capacity of hydrogen plants designed by Wood exceeds 3.35 million Nm^3/hr (~ 3 billion SCFD) of hydrogen.

These figures do not complete the long-established track record of Wood in supplying hydrogen technology. Wood has experienced recent success in the supply of very large modular designs. In this study, Wood presents the more recent and novel concept of advanced steam reforming that allows us to address a broader portion of the market, reaching more specific Clients' needs concerning revamp opportunities and minimisation of steam production for energy efficiency purposes.

3.3 The Novel Steam Methane / Gas Heated Reformer Concept

Hydrogen is a highly efficient, storable, and transportable energy carrier that can be utilised in the heat market and for transportation purposes. During the ongoing transition to a low carbon economy, the market for hydrogen technology providers is becoming more and more demanding in terms of energy optimisation. Providers are facing the challenges of decreasing the CO_2 emissions and reducing the mass of carbon released to the atmosphere from Hydrogen Production Units.

The proposed hydrogen supply demonstration presents improvements on the standard Steam Methane Reforming (SMR) with post-combustion CO_2 capture. The 90% recovery of CO_2 has already been achieved by means of post-combustion capture scheme, but this is very demanding in terms of installation investment as well as energy consumption. The proposed configuration allows the facility to reach the same performance in terms of recovered carbon, using a more efficient scheme, i.e. capture from the high pressure, high concentration syngas instead of from the atmospheric flue gas, while improving the efficiency in terms of generated CO_2.

The proposed concept is the Gas Heated Reformer (GHR), in which the duty for the steam reforming reactions is provided by the heat transfer between the fresh feed gas (i.e. natural gas or vaporised naphtha/LPG with a small amount of recycle hydrogen) and the reformer outlet effluent at high temperature (identical to the ones achievable in a traditional SMR). In this process scheme, all the reformer feed gas passes through the GHR, where it is heated and partly converted. The Gas Heated Reformer equipment is a vertical vessel containing vertically-supported tubes filled with catalyst. Heat exchange with a product syngas from an upstream reformer provides the heat for the endothermic reforming reaction.

The gas is then fed to the main reformer where final conversion takes place. The hot effluent from the reformer is cooled in the GHR and the sensible heat is used for reforming.

The process configuration and operating conditions of the traditional hydrogen production process have been tailored in order to improve the process efficiency in terms of feed and fuel consumption and, hence, in terms of the carbon content inside the process. For this reason, the proposed configuration deals with a gas heated reformer combined with the steam reformer furnace based on the Terrace Wall™ design. This combination will be referred as advanced SMR.

The Terrace Wall™ Reformer offers a number of unique advantages including:

- Uniform, controlled symmetrical heat;
- Compact plot design;
- High level of shop prefabrication, providing better quality control and lower installed cost.

The GHR benefits from enhanced integration with Terrace Wall™ Reformer for all of the above-mentioned reasons. Moreover, on the process side the favourable outlet temperature of the traditional SMR based on Terrace Wall™ design, which can exceed 920°C, improves the efficiency in reducing the generated CO_2 and improving the carbon capture performance of the overall system. The improved energy optimisation reduces the overall fuel demand, and thus results in a decrease in CO_2 emissions from the new integrated scheme.

The technology is based on well-proven equipment, such as fixed bed reactors and shell & tube heat exchangers, except for the GHR itself. The cores of the hydrogen production and purification are the SMR technology and the Pressure Swing Adsorption (PSA) Unit.

The development of a proprietary Advanced Steam Methane / Gas Heated Reformer concept by Wood arises from the need to address the low carbon hydrogen production. The market for hydrogen technology providers is becoming more demanding due to some specific requests from Clients concerning revamp opportunities and minimisation of steam production for energy efficiency purposes.

Some of the achievable targets for the novel concept are:

- Increasing the energy efficiency by minimising fuel gas consumption and steam production;
- Decreasing the CO_2 emissions and increasing the avoided carbon release to the atmosphere.

In other terms, the proposed scheme represents an outstanding improvement in the reduction of the carbon footprint with respect to the counterfactual. Together with the efficiency improvements that result in operating cost advantages, another advantage of the proposed scheme is the reduction of the capital investments. This implementation allows a reduction in operating costs and plot space requirements of hydrogen plants over the whole range of capacities, for both green and brown field projects: these are important features driving the hydrogen supply market. The wide plant capacity, virtually identical to that of the traditional steam reforming process, fits well with the bulk hydrogen market: suitable for a future range of applications, including the gas grid, industry, power, and transport.

3.4 Study Basis

The main requirement from BEIS is that the hydrogen production process operates at a bulk capacity of 100,000 Nm^3/h product hydrogen, to meet the needs of future low-carbon domestic heating, industrial processes and large-scale transportation. Thus, the focus is for industrial scale-production, rather than small-scale generation using electrolysis. The hydrogen is required to meet an industrial specification of 99.9 mol% purity at 20 barg and ambient temperature. The overall CO_2 capture rate needs to exceed 90% across the plant.

The carbon dioxide product stream must be dehydrated, compressed to 30 barg and cooled to ambient temperature ready for export to a CO_2 collection system. Transportation and storage of the carbon dioxide is assumed to be conducted by others under a tariff arrangement.

4 Concept Definition

4.1 Process Engineering

4.1.1 Description of the Process

Refer to Block Flow Diagram 522018-8110-25-0001 (Attachment 1) for diagrammatic flow scheme of the Blue Hydrogen Production Unit.

Natural gas initially mixes with the hydrogen recycle from the downstream process and passes through a feed preheater. The heater is indirectly heated through a shell and tube heat exchanger from the downstream Terrace Wall Reformer™ (TWR™) product stream. The Hydrogen recycle provides the feedstock for the downstream hydrogenation of sulphur containing compounds in the feed stream.

The preheated feed gas enters the sulphur adsorber column, where the gas passes through a single deep bed of catalyst-based adsorbent material. The catalyst bed removes trace amounts of sulphur-based compounds in the gas stream. The removal of sulphurous compounds is necessary to prevent the TWR™ catalyst from being poisoned and, consequently, deactivating the reforming catalyst. Deactivating the catalyst would reduce the process efficiency and interfere with the temperature distribution across the reformer tubes.

The desulphurised gas then mixes with steam and is passed through the pre-reformer. In the pre-reformer, higher chain hydrocarbons are converted into methane, carbon dioxide, carbon monoxide and hydrogen. Additional steam is injected into the gas leaving the pre-reformer, under flow control to maintain the correct steam/carbon ratio for the reforming process.

The process gas then enters the gas heated reformer (GHR). In the GHR, methane is partially converted to hydrogen and carbon monoxide in an endothermic reaction. The process gas is heated in the GHR by the heat from the syngas exiting the TWR™. This results in the gas leaving the GHR achieving the desired inlet temperature for the TWR™, as well as the reaction in the GHR achieving the desired methane concentration at the GHR outlet. The reforming in the GHR means that the advanced TWR™ does not require supplemental fuel gas firing compared to traditional steam methane reforming (SMR).

As the process gas exits the GHR and passes through the TWR™ reaction tubes, the final conversion of methane to hydrogen and carbon monoxide takes place. The reforming reaction is strongly endothermic and requires high process temperatures to favour greater equilibrium concentrations of carbon monoxide and hydrogen.

The TWR™ is a proprietary Wood technology, which features a high efficiency radiant section providing a uniform heat flux along the length of the single row catalyst tubes. The process gas exits the TWR™ and enters the shell side of the GHR, exchanging heat to the TWR™ feed stream.

The gas stream is then fed through a syngas cooling train, which consists of a series of heat exchangers.

The syngas then passes through the shift reactors, where the CO present in the syngas is 'shifted' to CO_2 through the water-gas shift reaction.

After the shift reactors the syngas is cooled further before the it is sent to the Amine Unit where the CO_2 is removed. The syngas product leaving the Amine Unit is then divided into two streams; one stream is sent to the TWR™ furnace as a fuel gas for heating the catalyst tubes, the second stream is sent to the pressure swing adsorption (PSA) unit. The Hydrogen is separated from the syngas in the PSA's absorbent, and the residual tail gas is then sent to the TWR^{TM} as a fuel providing supplemental firing of the reformer furnace. From the PSA unit, the Hydrogen product stream is sent to the B.L. Some of the Hydrogen is separated from this stream to be recycled to the front of the process under flow control to be mixed with the incoming the feed gas.

Key Features of the Wood Hydrogen Process are: The advanced SMR process achieves a minimal/zero net export of steam, with the condensate/steam recovery system integrated across the process. The GHR uses the hot effluent from the TWR^{TM} as the heating medium for preheating the feed to TWR^{TM} catalyst tubes simultaneously reducing steam generation and increasing the energy efficiency of the process. The injected steam for the reforming process is generated by recovering the heat from reformer flue gas and the hot process gas. Condensate is utilised across the plant in recovering heat from the process and converting the BFW to steam for the reforming process. The deaerator and condensate stripper are integrated into the steam system for maintaining the specification for the steam and condensate that circulates around the process.

4.1.2 Equipment Sizing

Wood's feasibility study includes the engineering design for the proposed Advanced SMR process. Each of the individual items of equipment have undergone a robust process design to meet the requirements of generating 100,000 Nm^3/hr of hydrogen product. The process design covers all aspects of the process defined in section 4.1.1, including, but not limited to, the following sections:

- Feed preparation
- Pre-reforming
- Advanced SMR
- Shift reaction
- Syngas cooling/heat recovery
- CO_2 capture and compression
- Hydrogen purification
- Utilities and offsites

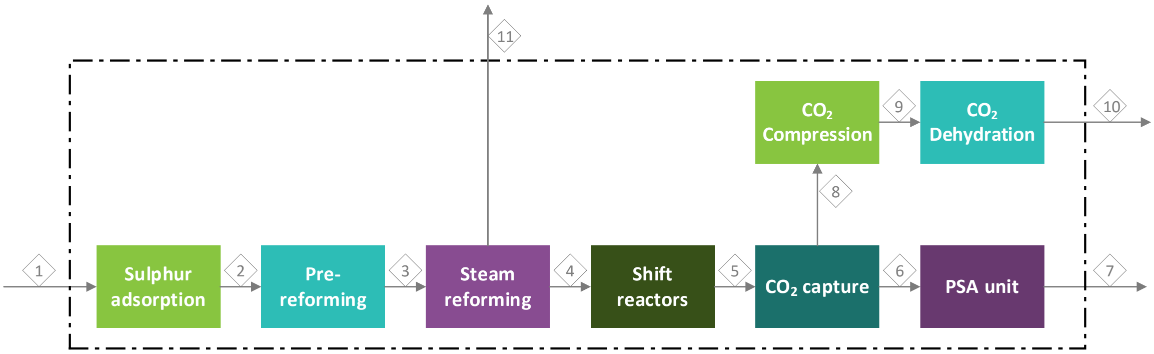
The equipment sizing enables the hydrogen product specification to be achieved whilst achieving a CO_2 recovery of 90%. The equipment employed in Wood's proposed advanced SMR technology is sized and optimised to maximise the hydrogen yield whilst eradicating fuel gas consumption and minimising steam production.

Wood's proposed technology utilises conventional hydrogen generation equipment combined in a novel way to further optimise the efficiency of the process. The combination of conventional equipment and the innovative approach employed by Wood reduces the technical risk associated with the scheme and delivers an innovative design for large scale low carbon hydrogen supply.

Heat and material balances have been developed using industry proven simulation software, the output from which has been used for sizing process equipment. The equipment sizing methodologies are those applied in the design of Wood's 100+ hydrogen and synthesis gas plants installed world-wide, which have a total installed capacity of more than 3.5 MNm^3/hr of hydrogen. The equipment designs have been benchmarked against Wood's own project database to validate the design.

4.1.3 System Material Balance

A material balance has been developed using industry proven simulation software. The material balance is based on the definition of the system boundary (battery limit) of Wood's 'Blue'



hydrogen generation plant. Wood's proposed scheme is a multifunctional product system due to the hydrogen product stream and the carbon dioxide by-product stream. The battery limits and material stream numbers are shown in Figure 4-1.

Figure 4-1: Summary block flow diagram, battery limit definition, and labelled material streams

The summary material balance is provided in Table 4-2, giving details on the process operating conditions and compositions of the process streams given in Figure 4-1.

Note that for the sake of clarity, some Battery Limit streams, such as demineralised water and combustion air have been excluded.

The boundaries defined in Figure 4-1 illustrates the main process flows entering and exiting the battery limits. The description for the main import and export process flows are given in Table 4-1.

Table 4-1: Battery limit streams

Line number	Line description
1	Natural gas feed to process
7	Hydrogen product export
10	CO_2 product export
11	Terrace Wall Reformer^{TM} flue gas

Table 4-2: Blue Hydrogen Summary Material Balance

Parameter	1	7	10	11
Temperature (°C)	37.8	47	43	128
Pressure (bara)	36.5	21.0	30.0	1.0
Molar flow (kmol/hr)	1,675	4,460	1,570	7,295
Volumetric flow (Nm^3/hr)	35,810	100,000	30,235	163,285
Hydrogen (mol%)	0.0	> 99.9	1.5	0.0
Methane (mol%)	94.3	< 0.1	0.0	0.0
Carbon monoxide (mol%)	0.0	0.0	0.0	0.0
Carbon dioxide (mol%)	0.8	0.0	98.5	2.1
Nitrogen (mol%)	0.5	0.0	0.0	67.0
Water (mol %)	0.0	0.0	0.0	29.5
Sulphur compounds (mol%)	0.1	0.0	0.0	0.0
C_2 + hydrocarbons (mol%)	4.3	0.0	0.0	0.0
Oxygen (mol%)	0.0	0.0	0.0	1.4

4.2 Plant Layout

Wood has developed a high-level plant layout as part of the concept design conducted in this feasibility study. The arrangement of process units is important in ensuing the hydrogen plant is safe, economical and easy to access for operations and maintenance. Refer to plot plan (522018-8230-01-0001) for details on the layout of the proposed hydrogen plant. For the purpose of this study, the steam reformer furnace is assumed to be upwind of the unit.

The most important considerations in designing the plant layout are those that concern the process. Initially the equipment is arranged in the general order of the process flow. The layout is then modified to accommodate specific process requirements: for example, elevating equipment to take advantage of gravity flow in the case of condensing service / two phase lines or to meet pump requirements (NPSH, suction lines etc.). The first example is particularly applicable to the heat recovery stage of the process, where water starts to condense out of the vapour stream as it cools to the amine unit operating temperature. Knockout drums are implemented into the process to ensure unnecessary/excessive equipment elevations are avoided and to maintain sufficient access for operation and maintenance. The BFW circulation pumps have deliberately been located adjacent to the reformer's furnace and generally pump suction line lengths have been minimised across the plant. Other factors are included such as minimising the overall length of pipework which directly impacts the installation cost. The pipework is minimised by adhering to the main process flow and the careful positioning of the equipment.

Unit layout is a linear arrangement about a single interconnecting rack containing interconnecting piping and distribution headers, with spur racks serving the Steam Reformer Furnace and CO_2 compression. This structure also provides support for the elevated air coolers, which are grouped to reduce hot air recirculation.

The operation and maintenance of the plant is a key factor when designing the plant layout. Having good access for operators allows the plant to be run in a safe and reliable manner. This reduces the chance of accidents and makes detection of malfunctions more likely. Equipment that requires frequent attendance is located such that it is easy to get to via short and direct routes. Furthermore, the plant layout is configured such that there is adequate access around the site for construction and maintenance (e.g. cranes for lifting units, catalyst loading, packing changes etc.). The access for the units of equipment is from a perimeter road with dedicated areas for maintenance. The chemical dosing packages are located to provide easy access from the perimeter road for unloading. The CO_2 compressor is shown in a compressor shelter with maintenance access from the perimeter road. The dehydration molecular sieves are also located to provide easy access from perimeter road for desiccant replacement.

Where possible, heat exchangers are positioned in groups to save capital on service pipework, structural work and maintenance provisions. Ideally, as in the case of this plant, the syngas cooling train heat exchangers are positioned in close proximity with each other due to the natural progression of the process flow through the heat recovery section of the process. Generally, the plant layout develops parallel to the sequence of the main process flow i.e. the process units of operation in the later downstream processes are positioned progressively further away from the battery limit. This is a natural result of the philosophy employed to minimise the length of pipework. However, some units, such as the PSA unit, require large footprint areas, and can, therefore, go against the general trend. The PSA unit has three product streams; the hydrogen product generated from the system, the furnace firing PSA tail gas, and the hydrogen recycle to the front end of the process. The three product streams from the PSA unit all require piping to the front end of the process and, therefore, justify the location of the PSA unit to minimise the length of the multiple product streams.

5 Techno-Economic Assessment

5.1 Capital Cost Estimating

The aim is to produce an instantaneous 2Q2019 capital cost estimate at Concept Level for Wood's Blue Hydrogen concept, reflecting Engineering, Procurement & Construction (EPC) costs.

The Estimate has been developed utilising the ACCE (Aspen Capital Cost Estimator) estimating software to generate the equipment costs and the application of Total Installed Cost (TIC) factors to generate the bulks and direct construction costs. The Wood version of ACCE is calibrated with real equipment cost data obtained from live FEED and EPC projects within the company.

5.2 Techno-Economic Assessment Conclusion

The purpose of the techno-economic assessment is to evaluate whether Wood's Advanced SMR process is technically and economically feasible. The techno-economic analysis concluded that Wood's advanced SMR process is technically viable in producing bulk low carbon hydrogen at the specifications set by BEIS. Wood's Advanced SMR process delivers the same hydrogen output as the counterfactual case, with the following benefits:

- ≈15% better net efficiency;
- ≈25% better hydrogen yield;
- ≈40% less capital investment (CAPEX);
- ≈10% less operational expenditure (OPEX);
- ≈15% less carbon footprint;
- ≈20% reduction on the LCOH.

Overall, the TEA has concluded that Wood's scheme is technically and economically superior to the counterfactual.

Wood's scheme is a novel technology, with only one processing step to be proven at a pilot level. Wood is extremely confident that the process will deliver the technical improvements and performance described in the preceding sections and, therefore, believes it fully warrants funding for a pilot plant trial and subsequent commercialisation.

6 Business Development Plan

6.1 Short Term

The Phase 1 work has confirmed that the proposed solution is technically and commercially advantaged compared to the counterfactual.

The short term plan for the proposed solution is to build on the work in Phase 1 and carry out the following activities:

- Find a site for the demonstration plant
- Detailed design for the demonstration plant

Completion of the above will give confidence in the cost, schedule and deliverability of a demonstration plant.

6.2 Longer Term

Wood has a long track record of delivery process technology and complex projects. Wood is confident in being able to address the market as it develops.

Wood will develop a standard blue hydrogen offering in a range of capacities that fits the market. This would typically be in 50 kNm^3/h increments say 50, 100 and 150 kNm^3/h. This approach will minimise the engineering design that is required for each installation. Wood has access to a supply chain that accesses capacity, high value and high-quality fabrication locations such as South Korea. It is expected that there will also be a retrofit and custom plant demand. Aspects of the hydrogen supply solution can be applied to existing facilities. A GHR could be added to an existing hydrogen plant to increase capacity, increase efficiency and reduce steam production. It is likely that these applications will be the first commercial utilisation of Wood's GHR. Depending on the market these revamp opportunities could include carbon capture as well but this is less clear and is much more dependent on government support whereas the addition of a GHR could be a cost effective revamp solution.

The Terrace-Wall Reformer technology has a modular building block design. The reformer can be prefabricated off site with minimal hook up required on site, for smaller capacities a total modular solution is possible. Maximising modularisation and minimising onsite work is key to the accelerated role of out of our blue hydrogen solution as construction skills availability is likely to be a constraint.

With 15,000 people in the UK and 60,000 people globally Wood has the flexibility to execute many complex projects in numerous locations and therefore we are confident in being able to progress many parallel projects.

The development of a demonstration plant is key and will achieve the following:

- Operating data, this data will validate the models that have been used to date in developing the hydrogen supply solution.
- Successful operation will give Wood the confidence to provide the required performance guarantees.
- Reference plant, the demonstration plant will be the first operating reference for the GHR element of the solution.
- Optimisation, knowledge gained from demonstration plant will be incorporated into the design of the first commercial facility.

- Minimise scale up risk, the greatest uncertainly in the Blue Hydrogen solution is the GHR, the demonstration plant will use a small number full size reactor tubes. This almost eliminates scale up risk and the increase in capacity is achieved by scale out (a greater number of tubes will be sued rather than large or longer tubes).

Wood estimates that the cost technology development program from the completion of Phase 2 of the Hydrogen Supply Completion to commercialisation is approximately £15m.

Wood does not expect the market for bulk blue hydrogen to be significant until the 2030's (this is based on our own research and others' view on the market). With this in mind, Wood is confident that with funding support such as the Hydrogen Supply Programme, when coupled with its own internal resources, that Wood will have a cost-effective viable solution for low carbon hydrogen ready to address the market when it arrives.

Attachment 1 Block Flow Diagram

- 522018-8110-25-0001 – Blue Hydrogen Block Flow Diagram Rev 1

Attachment 2 Plot Layout

- 522018-8230-01-0001 – Blue Hydrogen Plot Plan Rev 0 wood.