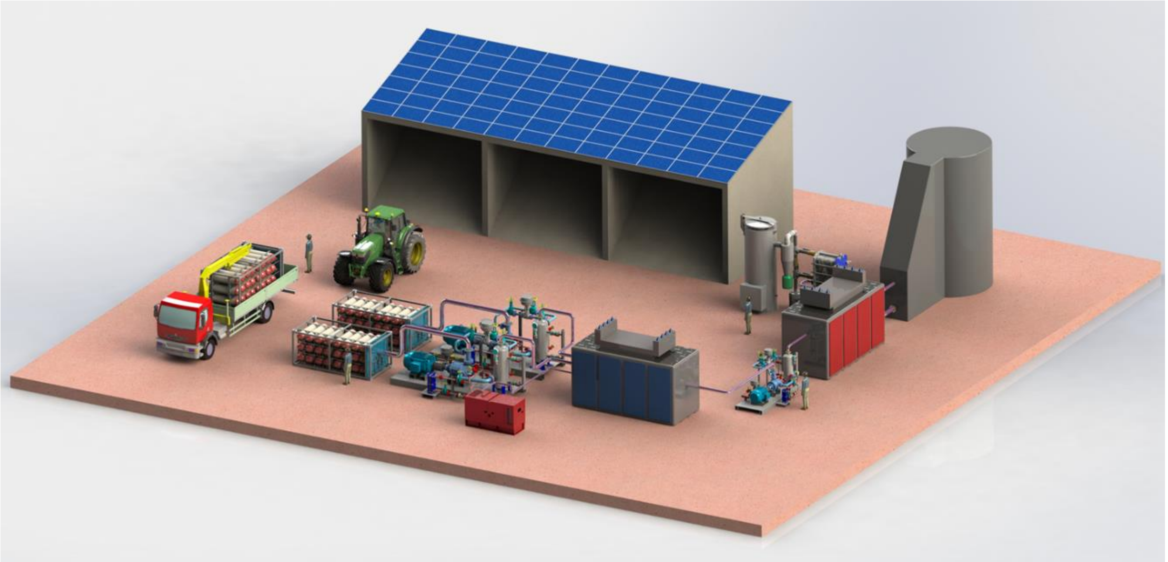
Northumbria University NEWCASTLE

Final Report



NEW$_2$H$_2$
North East Waste Wood Hydrogen Demonstrator

December 2022

North East Local Enterprise Partnership

South Tyneside Council

driver project services

BURO HAPPOLD

EXECUTIVE SUMMARY

The aim of the North East Waste Wood Hydrogen Demonstrator (NEW_2H_2) project was to complete a thorough feasibility analysis to determine the technoeconomic viability of a demonstration model of a scalable, modular and adaptable system that produces biohydrogen through the gasification of waste wood. Some 2,500 tonnes of waste wood would be available from sources within South Tyneside Council and Port of Tyne.

Different system configurations were considered and evaluated. Each system consisted of a common core design that consisted of the following key processes: waste wood preparation, gasification and enhancement of hydrogen content through the use of a gas swing reactor. The systems differed from one another in their further treatment of the gases produced, with either a formic acid plant or a methanol plant being considered. However, the favoured system configuration simply stored the hydrogen and carbon dioxide produced for sale or later use as commodities: the formic acid plant or the methanol plant could be added later if appropriate investment became available. The preferred system is designed to consume the 2,500 tonnes of waste wood available per year and will produce 138 tonnes of H_2 and 2,493 tonnes CO_2.

Common ancillary systems, such as a CHP for the conversion of residual tail gas into electricity, heat exchangers to extract waste heat from the gasifier system for either community use of storage in an energy sand store were also defined.

The cost of a system that would consume the available 2,500 tonnes of waste wood per year would be £13 – 15 million which is beyond the maximum budget for a Hydrogen BECCS Phase 2 project of £5 million.

The objective of the Hydrogen BECCS Phase 2 project is to build a demonstration system capable of producing hydrogen that can be extracted from the wood gasification process. A scaled-down demonstrator system that matches the preferred system design is proposed. This system will make use of a Spanner Re2 HKA-49 gasifier with a waste wood feed rate of 44.1 kg/h and an estimate hydrogen yield of 20 g per kg feedstock. The total CAPEX required to establish the scaled-down demonstrator system is expected to be £2,347,000 and fits within the BECCS Phase 2 budget. A full Phase 2 project proposal is being prepared.

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1 Introduction

1.1 Project Background

This project concerns an in-depth feasibility study to quantify the technoeconomic viability of a scalable, demonstration model of an adaptable, modular system that generates biohydrogen from gasification of waste wood. The system is designated the ‘North East Waste Wood Hydrogen Demonstrator’ – NEW$_2$H$_2$ (Figure 1).

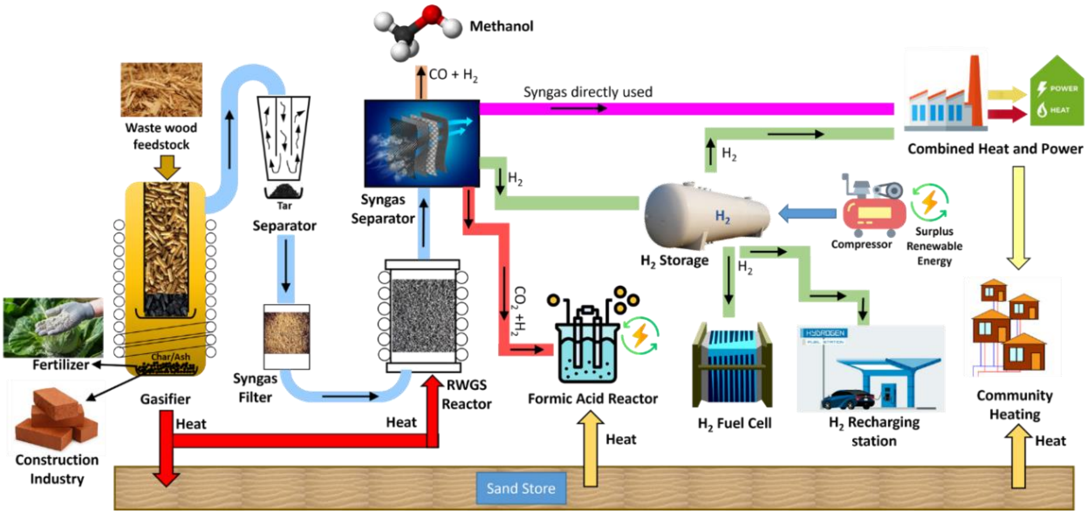

Figure 1: Pictorial Diagram of Original Concept as Presented in the Proposal

The NEW$_2$H$_2$ demonstrator will be located in South Tyneside near the Holborn site in South Shields. It will form part of the Holborn Renewable Energy Network (HREN) that aims to generate renewable energy by scavenging waste energy resources. The Holborn area has been largely derelict for many years. Developments in this location, such as NEW$_2$H$_2$, facilitate the regeneration of the area by supporting the vision of South Tyneside Council to establish a Renewable Energy Centre of Excellence. This project is a collaboration between local authorities (South Tyneside Council and the North East Local Enterprise Network), academia (Northumbria University) and industry (Driver Global Construction Consultancy and Buro Happold).

The primary objective of NEW$_2$H$_2$ is to generate hydrogen by upgrading syngas produced from the wood gasification process. A key part of the modular approach to the design means that the auxiliary systems can be implemented to maximise the return on investment after the core system has been established. This feasibility study determines the best system configuration, processes and components for optimising the hydrogen content of the produced syngas and which of the auxiliary systems are realisable within the financial scope of the project’s second phase.

NEW$_2$H$_2$, as presented in the project proposal, consists of core components of the system and optional auxiliary systems. The core system components are those necessary to produce and store biohydrogen. It consists of the wood processing and handling, gasifier, tar separator, syngas filter, reverse water gas shift reactor, syngas separator, hydrogen storage tank and compressor. The auxiliary systems are not required to produce biohydrogen, but use the stored hydrogen, other syngas components, waste products and waste heat to generate income streams that contribute to community heat and power. It consists of the fertiliser plant, wood ash brick manufacture plant, sand heat store, formic acid reactor, methanol production plant, combined heat and power plant, community heating distributed network, H$_2$ fuel cell refuelling station and hydrogen recharge station. The auxiliary systems are aimed at creating a circular economy where none of the by-products of the process are wasted, but instead are used as resources. Carbon capture and utilisation are achieved through the formic acid and methanol plants.

2 System Design and Digital Representation

2.1 Gasification Systems

The gasification technology is at the core of this systems design. Finding a solution that is both technically and economically viable is crucial to the success of the implementation phase. There are a number of companies who produce gasification systems that are either operating in the United Kingdom or have facilities under development. These include, but are not limited to, Nexterra, Meso Outotec, Spanner Re[2], Kew Technologies, Refgas, ABSL and EQTEC. In Table 1, a summation of the some of the hydrogen production systems that were considered as candidates is presented.

Refgas[1] have indicated that the information on the website is specifically for systems that are focused on power generation and does not apply to the available systems designed for hydrogen production. These produce syngas with a 30% hydrogen content which will be 97% pure after the pressure swing adsorber. The estimated cost for the turnkey solution to process 2,500 tonnes of waste wood per year is between £8 - 9 million and will have an area footprint of approximately 800 m^2. The hydrogen yield of the Refgas system is 30-35 kg/h for 1 tonne/h biomass. The system is currently rated at TRL 6, but will soon enter TRL 7.

Small scale solutions for wood gasification are available from Spanner Re[2] (Holtzkraft). The focus of their systems is producing syngas to burn in a CHP to generate electricity. The hydrogen content of the syngas is relatively low (13%-16%) which makes it a less ideal option if only hydrogen production is considered. However, the basic cost of the system, excluding works, is £162,000.00. This solution is not currently set up for hydrogen extraction, but if the components for extraction are added, the low cost of the gasifier makes it a potential solution for the demonstration model.

Kew Technologies is a British Company that is active in the field of gasification and hydrogen production. A document produced for BEIS in 2019 [1] indicated the Single Module Plant can produce 129 kg hydrogen per hour that has a purity of 98%. The mass flow of the RDF to this plant is 1,635 kg/h which translates to almost 80 g hydrogen produced per kg of feedstock. The hydrogen yield for biomass will produce similar results, however, the capacity that is required for the system in South Tyneside Council is almost six times smaller since only 290 kg feedstock is available per hour. KEW technologies appear to be focussed on industrial scale plants, which are much larger than what is needed in this context. The CAPEX cost of the KEW Triple Module Plant is in the order of £30 million.

The EQTEC system produces syngas with a hydrogen content of more than 50% after the water gas shift reactor. The estimated cost of the gasification system at the scale of 2,500 tonnes of waste wood per year is £6 - 7 million. The estimated area footprint of is 600 m^2 excluding the wood waste storage facility.

Table 1: Summation of Hydrogen Production Systems Operating or Planning Operation in the United Kingdom Considered in this Project

Company	Gasifier Technology	Syngas Composition	Biomass Specification
refgas	Downdraft Gasifier	<u>As reported on Website</u> **H_2 :10 - 17%** CO_2 :10 - 14% CO :17 - 21% N_2 :40 - 56%	Wood waste Grade A, B & C Spec G30 – G50

[1] Compact Syngas Solutions (CSS) trading as Refgas

Spanner Re²	Down Draft Gasifier	<u>Syngas composition</u> **H_2 : 13 - 16%** CO_2 : 7 - 12% CO : 17 - 20% N_2 : 47 - 62%	Wood waste Grade A, B & C
absl	Fluidised Bed Gasifier	<u>As reported on Website</u> **H_2 :32%** CO_2 :11% CO :33% H_2O :24%	Refuse-Derived Fuel (RDF)
EQTEC	Bubbling Fluidised Bed Gasifier	<u>Before WGS</u> **H_2 :40 - 44%** CO_2 :29 - 31% CO :21 - 25% H_2O :2.1 -2.5%	Wood waste Class A, B & C
KEW TECHNOLOGY	Fluidised Bed Gasifier	<u>Before WGS</u> **H_2 :41%** CO_2 :26% CO :32%	Commercial scale plant in the Midlands

Based on the information available the hydrogen production for the Refgas system and the EQTEC systems was estimated as shown in the table below:

Table 2: Hydrogen Production as Reported by Company

Company	Production [g H_2 / kg wood]	H_2 per annum [tonnes][2]	H_2 per day [kg]
refgas	30 - 35	75 – 87.5	205 - 240
EQTEC	50 - 55	125 - 137.5	342 - 377

The technology readiness for gasification systems that can produce hydrogen from wood waste is currently at TRL 6. There are at least five companies operating in the United Kingdom that can be partners in Phase 2 of this project to implement a pilot plant at the Holborn site. One of the companies, ABSL, have indicated that their current focus does not allow the resources to be involved in such a project. Communication could not be established with KEW Technologies, but they are a viable potential supplier for this system, as are Refgas and EQTEC. Due to the expense of the available systems, and the limitation of funding for the second phase of the Hydrogen BECCS programme, a partnership Spanner Re² system can be considered provided that the cost of the additional components and work, falls within the budgetary restrictions.

[2] Calculation based on 2,500 tonnes of waste wood per annum

2.2 Source of Waste Wood

Three sources of waste wood in the South Tyneside area have been identified: South Tyneside Garden Services, Middlefields Recycling Centre and Port of Tyne (Table 3).

Table 3: Sources and Quantities of Waste Wood in South Tyneside

Source of Waste Wood	Wood Classification	Estimate Quantity per Annum
South Tyneside Garden Services	Virgin Wood, Grade A	300 tonnes
Middlefields Recycling Centre	Mixed Wood, Grade A, B, C & D	2800 tonnes
Port of Tyne	Virgin Wood, Grade A	60 tonnes
	Tanalised Wood, Grade D	40 tonnes

Waste wood from South Tyneside Garden Services (Figure 2a) comes from trimmings and clippings of gardens and wooded areas maintained by the council. It can also contain large tree trunks from trees that have been felled or removed after being blown over during storms. This is virgin wood (Grade A) that can have moisture contents of more than 30% depending on the time of the year. The majority of the wood waste is found at the Middlefields Recycling Centre which contains household and business waste (Figure 2b). This wood can fall in any of the grade classifications and must therefore be sorted to remove the Grade D, plastic and metal content before it can be processed. A further source of waste wood is available from Port of Tyne where a clear distinction must be drawn between the Grade A and Grade D contribution. Any wood that has been treated with copper chrome arsenic (CCA) preservation treatments, creosote or tanalised must be disposed of as hazardous waste.

South Tyneside Garden Services, Middlefields Recycling Centre and Port of Tyne contribute a total of 3,200 tonnes per annum of Grade A, B, C and D waste wood to the sector. It is estimated that approximately 20% of the wood contribution consists of Grade D wood which cannot be used for gasification. This leaves an estimated 2,500 tonnes of waste wood per annum that can be used for the production of hydrogen. It translates to 6.85 tonnes per day or 0.29 tonnes per hour based on a 24-hour operation.

(a) (b)

Figure 2: Variety of waste wood available at the (a) South Tyneside Garden Services and from the (b) Middlefields Recycling Centre

There is a large variability in the types of waste wood that will be available. The wood obtained from the Garden Services will be seasonal both in type and moisture content, while the wood from the Recycling Centre will depend on what is brought in from the community. Port of Tyne will mostly contribute untreated wood pallets. A range of wood samples were tested in a calorimeter to determine the energy content of a variety of wood types and moisture contents. Six samples were taken from the waste wood of Garden Services (Figure 2a). The samples varied in moisture content from 9.8 % to 34.3 % and produced calorific energy values between 13.3726 MJ/kg (HHV) and 18.2782 MJ/kg (HHV). It is estimated that large quantities of future waste wood will consist of Ash wood due to the dieback cause by the fungus Hymenoscyphus Fraxineus. Therefore, Ash wood was tested and showed calorific values between 17.1802 MJ/kg (HHV) - and 18.1872 MJ/kg (HHV), which is comparable to the samples taken from the Garden Services. Pallets also provided comparative results of between 17.0912 MJ/kg (HHV) and 17.8105 MJ/kg (HHV). The calorific value is dependent on the moisture content of the wood and as such a lower moisture content will lead to higher calorific values. The waste wood should be dried to levels below 10 % moisture before gasification. This will strike a balance between optimising the gasification process and the energy input that is required to dry the wood chips sufficiently.

2.3 Concept Generation and Evaluation

2.3.1 Description of the Concepts for H_2 Production

Based on the requirements specification and the design in the context of South Tyneside Council, the initial concept as presented in the proposal was refined. This led to the definition of three concepts for hydrogen production. The three concepts make use of the same core components to produce hydrogen, but with slight variations of how the hydrogen is used and the method of carbon utilisation:

1. Concept 1 (Figure 3) will convert the carbon monoxide in the syngas to carbon dioxide using a water gas shift reactor. It will produce formic acid from the stored hydrogen and carbon dioxide.
2. Concept 2 (Figure 4) will convert the carbon dioxide in the syngas to carbon monoxide using a reverse water gas shift. It will produce methanol for the stored hydrogen and carbon monoxide.
3. Concept 3 (Figure 5) will make use of a water gas shift reactor and generate revenue by selling the hydrogen and carbon dioxide.

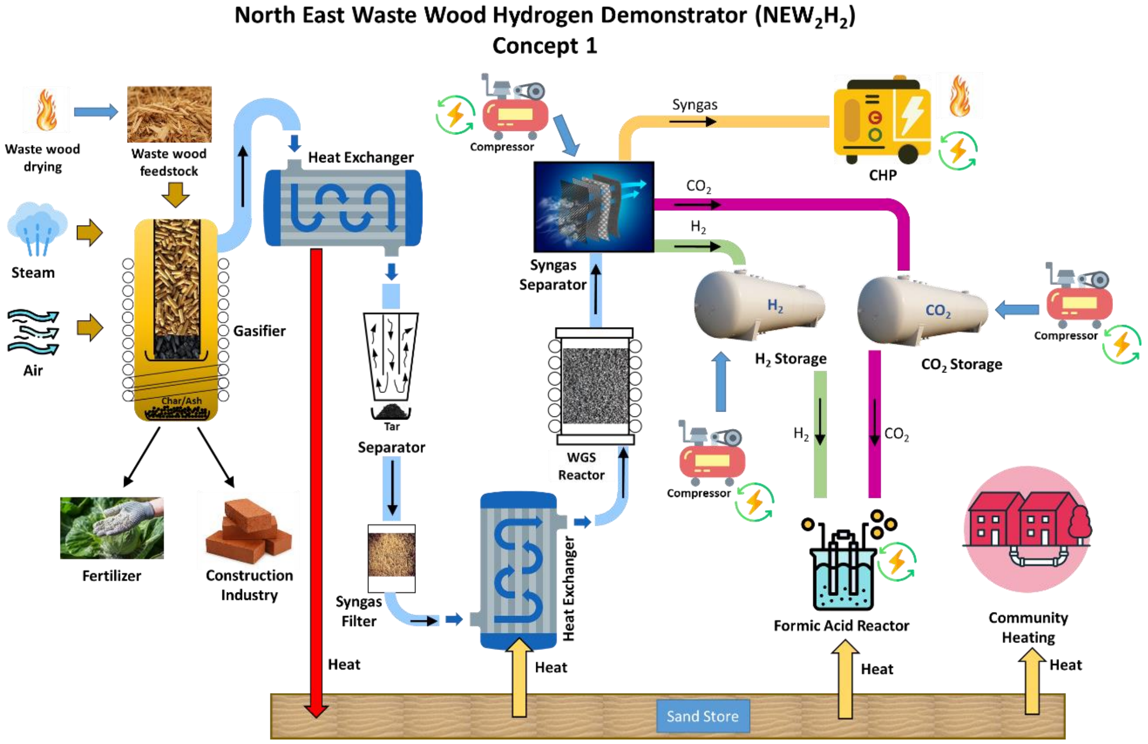

Figure 3: Concept 1 Pictorial Diagram

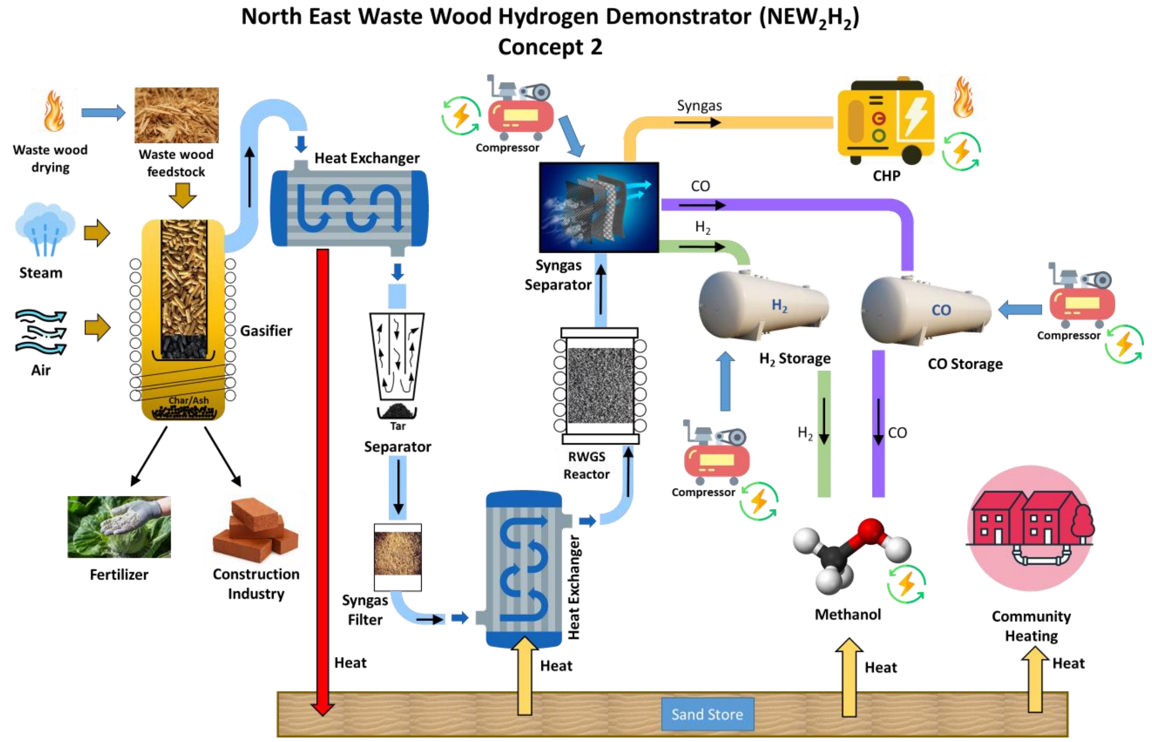

Figure 4: Concept 2 Pictorial Diagram

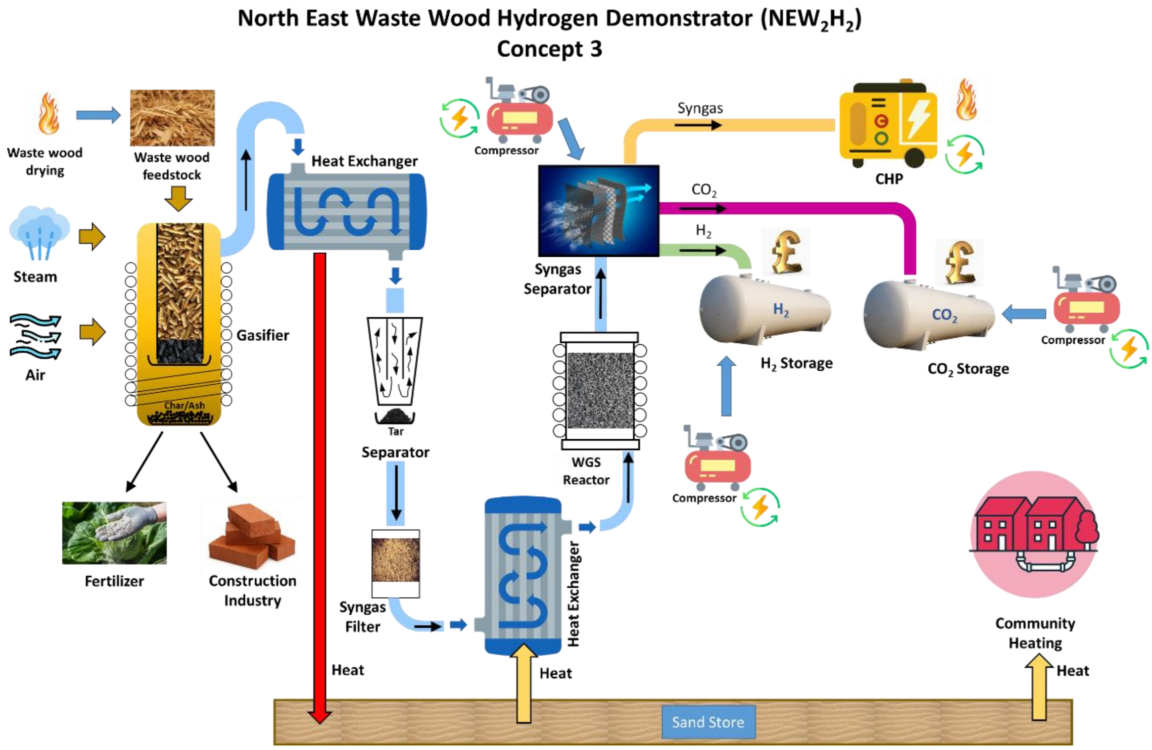

Figure 5: Concept 3 Pictorial Diagram

The options will be evaluated in terms of the potential return on investment in this document based on the selling prices of each of the products.

2.3.2 System Evaluation Based on Potential Income from Products

Concept 1 can theoretically produce 3,135 tonnes of formic acid per annum, Concept 2 can produce 1,815 tonnes of methanol and Concept 3 can produce 138 tonnes of hydrogen and 2,493 tonnes of carbon dioxide.

In Table 4 given the values calculated, the potential annual income, without taking the costs of production into consideration.

1. Concept 1 has the highest potential annual income of £3,034,680 assuming a price of 1,099 $/tonne (968 £/tonne) of Formic Acid.
2. Concept 2 can generate an income of £958,320 given the price of 599 $/tonne (528 £/tonne) of Methanol, which is the lowest of the three concepts.
3. Concept 3 is total of £1,658,384 consisting of the contributions of hydrogen at 7,060 $/tonne (6,218 £/tonne) and carbon dioxide at 365 $/tonne (321 £/tonne).

Concept 2 has the lowest potential income which is in the order of £700,000 lower than Concept 3. It has the same core components as Concept 3 (apart from the reverse water gas shift reactor), but it will require additional cost in comparison to acquire, install and operate the methanol plant as well as the electrolysers that are required to convert steam to hydrogen. The subsequent increased water utilisation of 1,225 tonnes per year, in comparison with the 418 tonnes per year required for Concepts 1 and 3, further challenges this concept as a viable solution for implementation.

Although Concept 1 has the highest potential income, there will be a significant cost and complexity of operation associated with implementation of the formic acid plant. Concept 1 has the same core components as Concept 3 apart from the formic acid plant. The modularity of the design allows for the full implementation of Concept 3 with the addition of the formic acid plant (Concept 1) at a later stage. This will manage the risk of plant failure since the plant can be commissioned and the efficiency of the hydrogen production processes ensured before additional complexity is added. It is also possible that the revenue of Concept 3 can be used in the long run to provide the funding necessary to implement the formic acid plant (Concept 1). From this evaluation Concept 3 will be selected as the preferred option as a phased implementation of Concept 1. This not only manages the risks associated with the project, but also limits the initial capital investment required while creating a clear path for funding future innovation of the plant.

Table 4: Concept Products Potential Annual Income before Costs

Concept	Product	Price [$/tonne]	Price [£/tonne]*	Quantity per annum [tonne]	Potential Annual Income before Costs [£]
1	Formic Acid	1,099[1]	968	3135	**3,034,680**
2	Methanol	599[2]	528	1,815	**958,320**
3	Hydrogen	7,060[3]	6,218	138	858,000
	Carbon Dioxide	365[4]	321	2,493	800,384
					1,658,384

[1] https://www.chemanalyst.com/Pricing-data/formic-acid-1242
[2] https://www.chemanalyst.com/Pricing-data/methanol-1
[3] https://www.chemanalyst.com/Pricing-data/hydrogen-1165
[4] https://www.chemanalyst.com/Pricing-data/liquid-carbon-dioxide-1090
* Calculated at £/$ exchange rate of 0.88

2.4 Site and System Safety Review

The recommended minimum safety distance for liquid hydrogen installations [2], as prepared by the Health and Safety Laboratory for the Health and Safety Executive, are shown in Table 5.

Table 5: Recommended Minimum Safety Distances for Liquid Hydrogen Storage [2]

Items	Distance [m]
Public establishments	60
Occupied buildings, Air compressor intakes, air conditioning, Place of public assembly	20
Technical and unoccupied buildings, Any combustible liquids and solids, Open flame, smoking, welding, Railroads, roads, property boundaries, Overhead power lines	10
Flammable gas storage	8
Liquid oxygen storage	6
Other LH_2 tanker	3
90 min fire resistive walls	2.5
Other LH_2 fixed storage	1.5

Implementing these distances on the current deployment site may be too conservative as the National Fire Protection Association Code 55 on Compressed Gases and Cryogenic Fluids [3] recommend the following safety distances for pressures from 0.1 – 103.43 MPa:

- 4 - 6 m for lot lines, air intakes, operable opening in buildings, and ignitions sources.
- 3 - 6 m for exposed persons other than those servicing the system and parked cars.
- 3 - 5 m for hazardous materials storage systems, slow burning combustible solids, fast burning solids, overhead utilities,

The right to install a gasification system for hydrogen production will be subject to planning permission for South Tyneside Council and all the relevant legislation. It may be necessary to identify an alternative site for installation if planning and operation permission cannot be obtained.

2.5 Digital Representation of Proposed Installation

Figure 6 shows a labelled model of the potential layout for the NEW_2H_2 system that coincides with the heat and mass diagram (Figure 7).

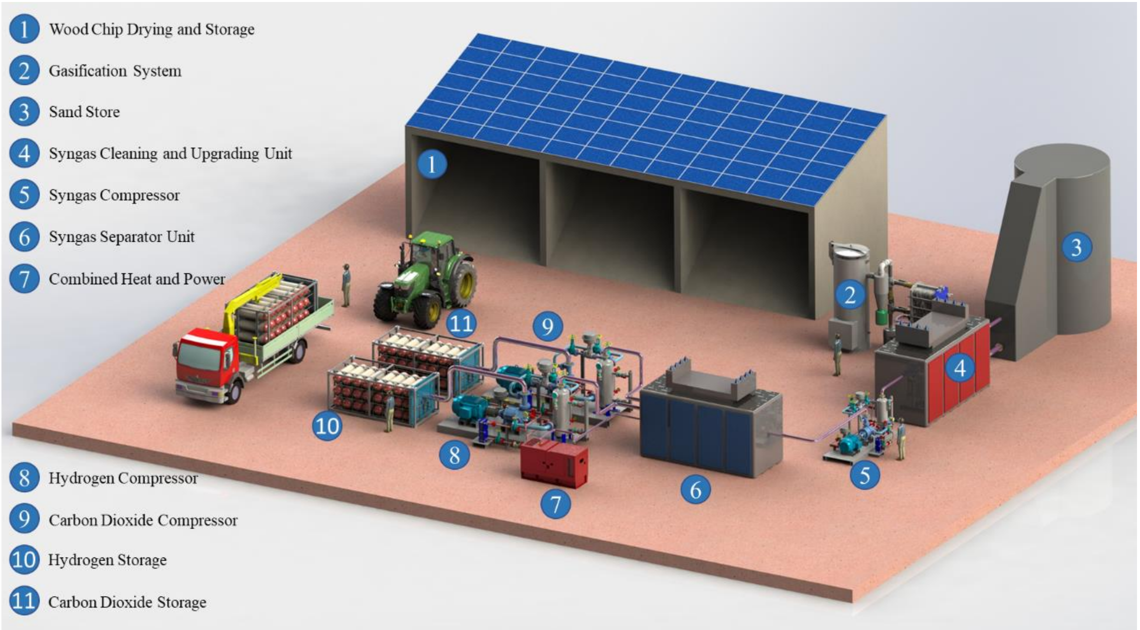

Figure 6: Digital Representation of the Layout for NEW$_2$H$_2$ Concept 3

Heat and Mass Balance

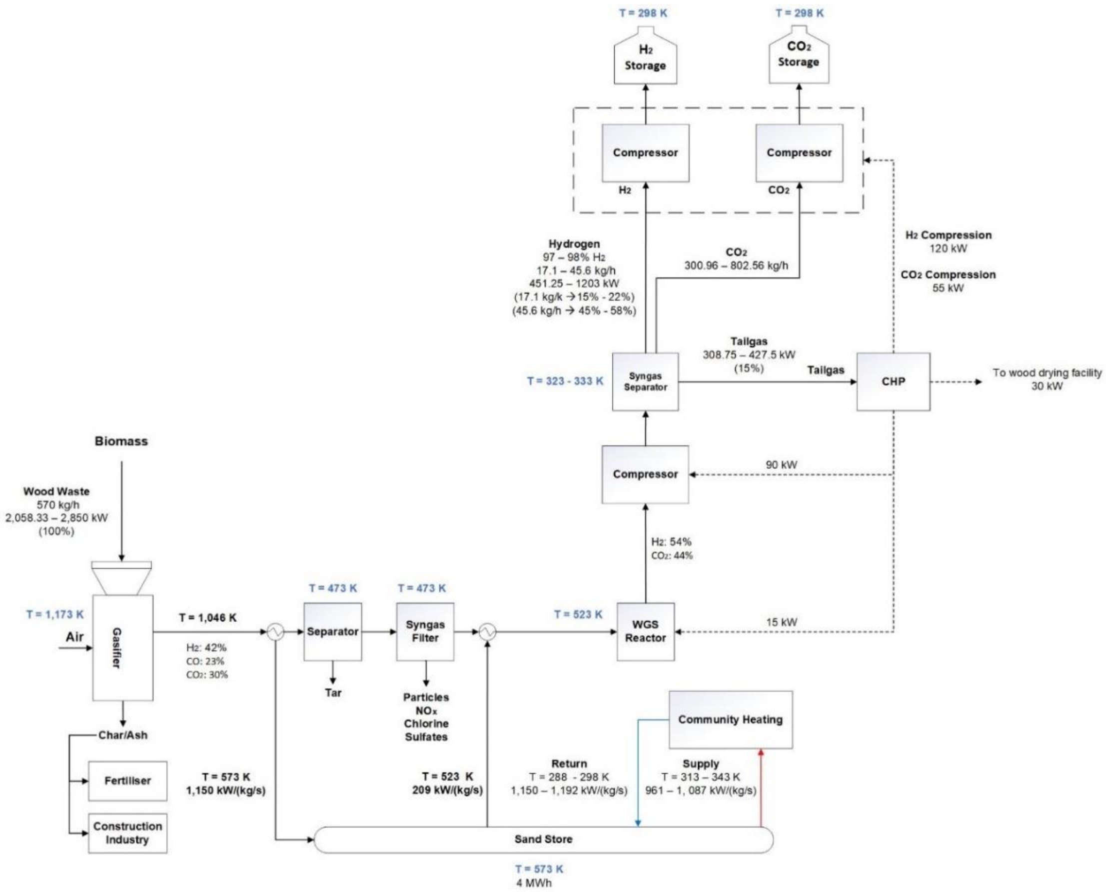

Figure 7: Heat and Mass Balance Diagram for the Proposed NEW2H2 Concept 3 Installation

The heat and mass balance were calculated for a system with a hydrogen yield of 55g per kg feedstock and a 42% hydrogen volume content in the raw syngas. The mass flow rates were determined using representative data from existing gasification systems as discussed in the Feasiblity Report Section 2.2. Additional data were calculated in the Feasibility Report Section 2.4, Section 5 and obtained from the techno-environmental analysis of hydrogen production from wood gasification with CSS done by Antonini et. al [4].

The mass flow rates of the heat exchangers in the sand store is expressed as kW/(kg/s).

3 System Test Planning

The detailed test plan for the biohydrogen system is to be completed as part of the system commissioning process of the demonstration project and entails both functional testing and performance testing. The system test plan is designed to be applied to the Concept 3 biohydrogen system, but can be adapted for the other systems or reduced concepts.

3.1 Functional Test Planning

The functional test plan includes lists of inputs and associated desired outcomes to define clear ‘pass’ or ‘fail’ criteria. The full details of this plan for the testing of each sub-system are available in the feasibility report. This report shows the testing requirements of the main system components. The requirements for the gasifier, syngas filer, syngas separator, waste wood processing and H_2 and CO_2 Storage tests are shown in Table 6 - Table 10. The emissions limits and provisions compliance requirements for the gasification system are will be done in compliance with DEFRA Statutory guidance for combustion of waste wood [5].

Table 6: Gasification Processing Requirements for System Test Planning

Component	Pass Condition	Fail Condition
Gasification operation temperature	More than 800°C	Lower than 800°C
Raw syngas yield rate	More than 30%	Less than 20%
Gasification heat recovery efficiency	More than 85%	Less than 65%
Gasification continuous operation	More than 6 weeks	Less than 5 weeks
Gasification operation rate (utilisation)	More than 310 days operation per year (85%)	Less than 274 days operation per year (75%)

Table 7: Syngas Cleaning Requirements for System Test Planning

Component	Pass Condition	Fail Condition
Separator unit pressure	Between 20 bar to 50 bar	Less than 20 or more than 50 bar
Particulates	More than 98% removed Almost removed	Less than 98% removed
Sulphur, Ammonia	More than 98% removed < 1 ppm	Less than 98% removed > 1 ppm
Chloride, Alkali	More than 98% removed < 10 ppb	Less than 98% removed > 10 ppb

Table 8: Syngas Separation Processing Requirements for System Test Planning

Component	Pass Condition	Fail Condition

Syngas separator	Between 20 – 50 bar	Less than 20 bar
Hydrogen yield	More than 30 g hydrogen per kg biomass	Less than 20 g hydrogen per kg biomass
Hydrogen yield rate	More than 55 kg per day (based on 310 days operation)	Less than 25 kg per day (based on 310 days operation)
Hydrogen separation	More than 85% vol%	Less than 70% vol%
Hydrogen purity	More than 85% vol%	Less than 70% vol%
Carbon dioxide yield rate	More than 997 kg per day	Less than 453 kg per day
Carbon dioxide separation	More than 70% vol%	Less than 50% vol%
Carbon dioxide purity	More than 85% vol%	Less than 70% vol%

Table 9: Waste Wood Processing Requirements for System Test Planning

Component	Pass Condition	Fail Condition
Wood delivery capacity	Over 5 tonnes per day	Less than 4 tonnes per day
Wood chip size	Between 40 mm to 80 mm	Smaller than 40 mm and larger than 80 mm
Wood chip moisture content	Wood chip moisture less than 10% after 3 days drying process	Wood chip moisture over 15% after 3 days drying process
Wood chip drying speed	Over 7 tonnes per day	Less than 4 tonnes per day
Wood store capacity	Over 3 days of feeding stock, 21 tonnes store	Less than 3 days of feeding stock, 12 tonnes store
Wood chip feeding speed	Over 0.29 tonnes per hour	Less than 0.17 tonnes per hour

Table 10: H_2 and CO_2 Storage Processing Requirements for System Test Planning

Component	Pass Condition	Fail Condition
H_2 storage pressure	Between 50 - 80 bar	Less than 50 bar or over 80 bar
H_2 storage temperature	Less than 25 °C (298K)	More than 25 °C (298K)
H_2 storage capacity	Less than 2 tonnes on site	Over 2 tonnes on site
CO_2 storage pressure	Less than 65 bar	Over 65 bar
CO_2 storage temperature	Between 15 °C (288 K) ± 25 →C (298 K)	Below or over 15 °C (288 K) ± 25 °C (298 K) range
CO_2 storage capacity	Over two weeks production - 100 tonnes	Less than two weeks production - 60 tonnes

3.2 Performance test planning

This report proposes a short Alpha test (Figure 8) and an extended period Beta test (Figure 9) for system performance evaluation and optimisation for the proposed gasification system. A long term extended field test would follow a successful Beta test to establish viable commercial operation of the gasifier system and to enable experimentation with specific gasifier fuel types.

Alpha testing is the first complete system test. Its objective is to identify equipment faults, monitoring faults and process failures that require correction.

The Beta test is designed as a first fully operational test to verify performance and allow for optimisation to be achieved. Reliability, Security and Robustness are checked during Beta Testing. Any faults detected during the Beta test are corrected. The extended field test is the first commercial operation following a successful Beta test. The gasification system will be monitored rigorously, and further optimisation applied, particularly to the maintenance cycles that need to be applied to the system.

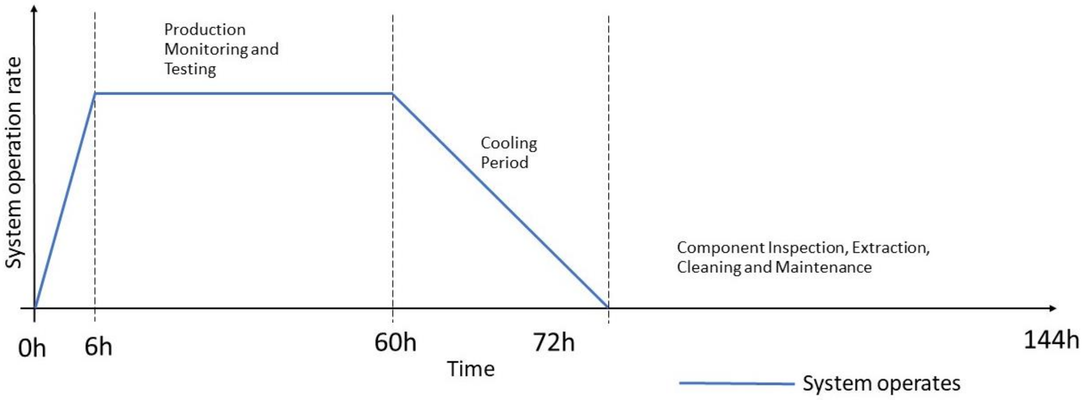

Figure 8: Alpha Test Timeline Illustration

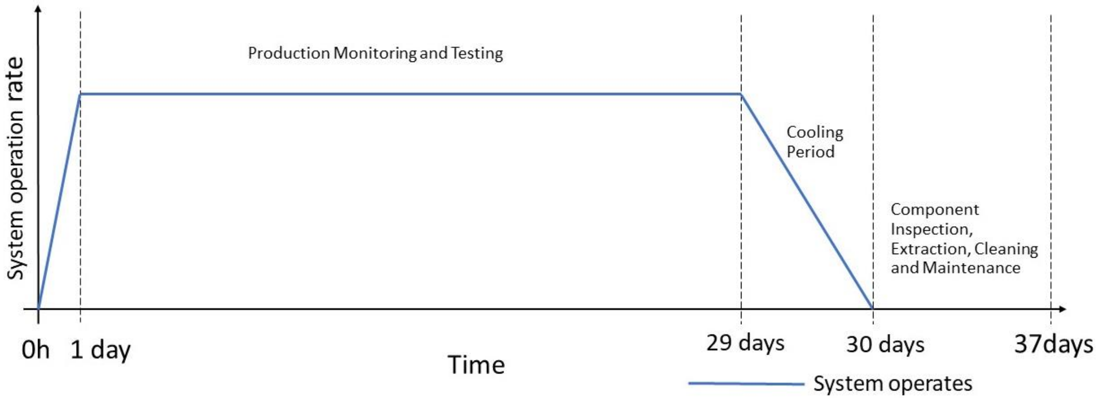

Figure 9: Beta Test Timeline Illustration

4 System Modelling and Simulation

Converting biomass into a more usable form of energy through gasification is a complicated process and conducting experiments to determine the results is expensive and problematic. Often it is more worthwhile modelling the process for simulation and prediction of performance as many parameters need to be considered such as the type of gasifier, the type of biomass and other relevant input parameters. Simulations offer a more cost-effective way of evaluating the benefits and risks associated with a system as well as providing a comprehensive overview of the physical and chemical mechanism of the gasifier.

A kinetic model was developed for a downdraft gasification system to determine the performance in terms of the hydrogen yield. In this model the chemical reaction rates were considered to be proportional to the difference between the actual reactant/product ratio and the equilibrium ratio and to have an Arrhenius-type temperature dependence. Mass and energy balances were applied to the system along with equations for pressure drop and the variation of velocity, from which nine differential equations were obtained and solved using the MATLAB ODE45 solver. The modelling process is shown in Figure 10.

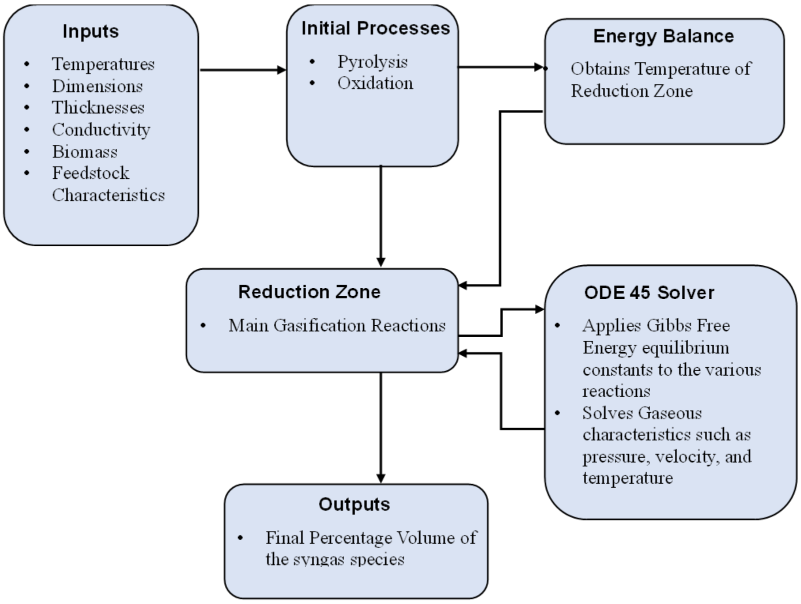

Figure 10: Schematic Diagram of the Gasification Code Structure

To ensure that the model developed is working as expected within acceptable parameters, the biomasses simulated within the model were compared with the real-world equivalent. The validation was conducted against experimental data as well as real world industry data. The two biomasses, rubber wood and wood chips, were validated against experimental data available in the open literature. The rubber wood experimental data was obtained from Jayah [7] while the wood chip data were obtained from an experiment conducted by Ong [8]. A comparison between the developed model and the experimental data for wood chips is shown in Figure 11.

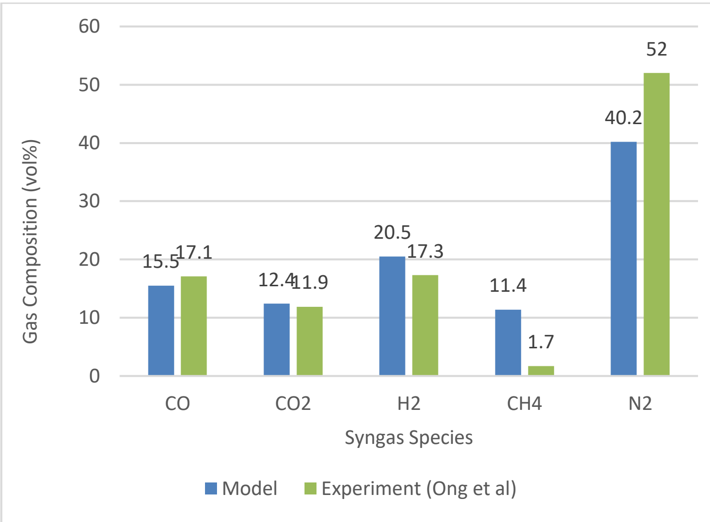

Figure 11: Validation Comparison Between the Developed Model and the Experimental Data for Wood Chips

The simulation using wood chips as feedstock have indicated that the hydrogen volume percentage is overpredicted by 18.5 %. The model produces a volume of 20.5 %, while the experiment indicated a value of 17.3 %. The carbon monoxide value was underpredicted by 9.3 % and the carbon dioxide over predicted with 4.2 %. The same trends as in the previous case with rubber wood persist where the methane production is overestimated, and the nitrogen content is underestimated.

Between the two validation cases the uncertainty in the modelled hydrogen production ranges from 5.8 to 18.5 %. The general trends in over prediction and underprediction of the other components is consistent. It should be noted here that the experimental results were given in the literature as absolute values without reference to an uncertainty margin in the experimental measurement.

Comparison of modelled values against absolute values is not ideal since it may appear that the numerical results obtained through modelling are less accurate. Modelling should be used as part of a validation process and is most useful for comparing permutations of operational parameters that can then be tested in a real system, thus aiding the system optimisation process.

The predicted syngas composition was compared with down draft gasification systems available on the market from Refgas [9] and SpannerRe^2 [10]. These results are presented in Table 11. It shows that that developed model produces results that are comparable with real world systems.

Table 11: Downdraft Gasification System Data Industry Validation

	CO	CO_2	H_2	CH_4	N_2
Refgas	17 - 21%	12 - 17%	12 - 17%	2 - 4%	45 - 54%
SpannerRe^2	17 - 20%	7 - 12%	13 - 16%	1 - 5%	46.5 - 61.9%
Model	15.5%	12.4%	20.5 %	11.4%	40.2%
Experiment	17.1%	11.9%	17.3%	1.7%	52%

Different feedstocks were modelled to determine the trends in the performance of wood chips, rubber wood and wood pellets. The syngas output results for the carbon monoxide and carbon dioxide content are comparable between the different feedstocks. The hydrogen composition was the largest with wood pellets (23.1%), second largest with wood chips (20.5%) and the smallest with rubber wood (18.2%).

The input parameters that can be varied in the model to determine their effect on the composition of the syngas includes, but is not limited to, the inputs listed in Figure 10 as well as the ambient temperature, oxidation chamber depth, reduction chamber depth, char fraction, ash fraction and moisture content.

The gasification modelling code developed here is a useful tool that can be used for system performance prediction and optimisation of gasification systems.

5 Economic Analysis and Forward Planning

This feasibility report describes a gasification system that produces hydrogen and is capable of consuming the 2,500 tonnes of wood per annum from South Tyneside Council and Port of Tyne. All of the gasifier system concepts are capable of generating hydrogen that can either be converted to another chemical or stored for sale as a gas. Concept 3 is our favoured configuration for a demonstrator system; the gasifier would produce syngas from which the hydrogen and the carbon dioxide would be extracted and stored to generate revenue. The costs of candidate gasifier systems capable of consuming the 2,500 tonnes of available wood per annum greatly exceed the £5 million available budget from BECCS for a Phase 2 gasifier. The preferred EQTEC gasifier would cost £6 – 7 million and the Refgas gasifier would cost £8 – 9 million; to which would need to be added the wood storage, treatment and drying systems, various gas filter and separation solutions and the gas storage systems. The overall cost of a full capacity Concept 3 system would be £13 – 15 million. The maximum budget for a Hydrogen BECCS Phase 2 project is £5 million.

The purpose of the Hydrogen BECCS Phase 2 project is to build a demonstration system capable of producing hydrogen that can be extracted from the wood gasification process and must conform to the strict £5 million maximum budget envelope. A demonstrator system conforming to the Concept 3 design will now be proposed.

The demonstrator system will be based on a commercially available wood gasifier system, the Spanner Re^2 HKA-49 wood chip gasifier. The HKA-49 gasifier is an integrated system where the produced syngas is filtered and fed into a CHP to generate electricity. Our proposal is to use a HKA-49 unit and to insert hydrogen capture technology between the gasifier's filter system and the CHP. The residual syngas (now without hydrogen), which will be rich in carbon monoxide and with a trace of methane will be fed into the CHP to generate electricity. The HKA-49 unit already has a heat exchanger to scavenge some heat for facility heating applications; we will incorporate an additional heat exchanger to scavenge more heat from the system. The demonstrator system will also include the building of a sand store for the storage of excess heat. We will also include an electrolysis system that will consume some electricity to convert the carbon dioxide emitted from the exhaust of the CHP to carbon monoxide. The carbon monoxide produced will either be bottled or re-used as fuel to be fed back into the CHP to generate electricity. The electricity produced from the CHP can be used for the community or fed into the national grid system.

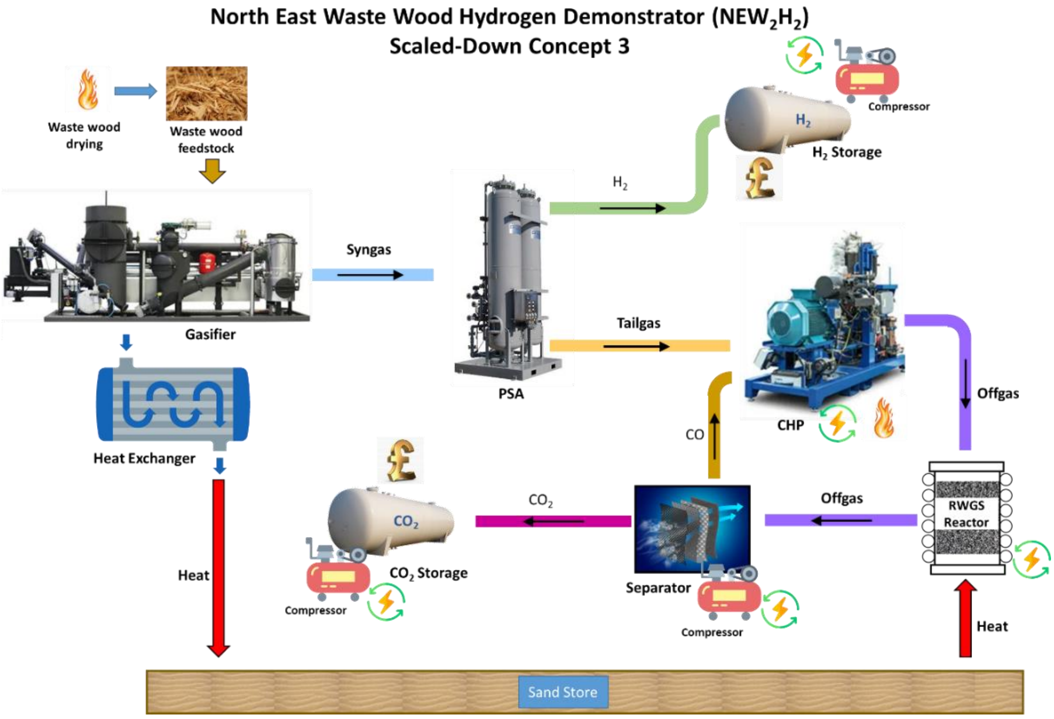

Figure 12: Scaled-Down Concept 3 Pictorial Diagram

The HKA-49 gasifier is capable of consuming up to 44.1kg of wood chips per hour, or up to 1058 kg of wood chips per 24 hours of operation. The annual wood chip consumption for a HKA-49 gasifier with 85% ultilisation will be around 328 tonnes. Hydrogen will make up to 17% of the syngas composition from the HKA-49 gasifier unit. We will extract the hydrogen for storage in gas bottles, but we will not enhance the hydrogen content through the use of a water gas shift reactor. The captured hydrogen will most likely be burnt as a fuel for community heating purposes or it can be sold as a commodity.

The demonstrator project is planned to run for one year from the commissioning of the gasifier system (Table 12). The one-year period will allow much testing of the hydrogen extraction system, sensitivity of the gasifier to wood chip type and quality, as well as enabling the detailed study of sand store and CHP performance. Spanner Re[2] recommend that the HKA-49 be run for between 1 – 2 months where all of the syngas is consumed by the CHP to establish the correct performance of the system. After the two month 'burn-in' period, the hydrogen extraction, carbon dioxide capture and sand store systems will be incorporated for detailed testing. Once the demonstrator period has been completed, the unit can be re-configured so that all of the gasifier's syngas can be consumed by the CHP to generate electricity. Alternatively, the system can be expanded by the addition of more gasifiers and ancillary equipment to make a much larger modular system.

Table 12: Gannt Chart of Demonstrator Gasifier Project

ACTION	DESCRIPTION	PROJECT YEAR 1				PROJECT YEAR 2				DELIVERABLES
		Q1 4 months	Q2 4 months	Q3 4 months	Q4 4 months	Q1 4 months	Q2 4 months	Q3 4 months	Q4 3 months	
Activity 1	Project Management									
A1.1	Overall project co-ordination									
A1.2	Governance committee meetings		Quarterly				Quarterly			
A1.3	Progress meetings (management and technical teams)		Monthly				Monthly			
A1.4	Reporting to BEIS: financial, progress and final reports		Quarterly				Quarterly			Monthly Minutes of Meetings
A1.5	Recruitment of university research assistants									Quarterly Reports
WP0	Further Engineering Work following from Phase 1									
Task 0.1	Refinement of the Final Design									Technical Note on Final Design
Task 0.2	Site Selection and Confirmation									Safety Plan
Task 0.3	Refinement of the HAZOP Study									Installation Plan
WP1	Procurement, Build and Commisioining of Gasifier Site and Equipment									
Task 1.1	Identify and obtain quotations for agreed demonstrator system components									
Task 1.2	Develop legal and contractual agreements with key equipment and lease providers									
Task 1.3	Raise purchase orders for equipment									
Task 1.4	Site preparation and construction									
Task 1.5	Delivery, assembly and construction of key components to site: sand store, wood chipper and dryer									Invoices and Delivery Notes from Suppliers Legal Documentation
Task 1.6	Assembly and commissioning of gasifier system									Reports from Site Inspections
WP2	Gasifier Test Programme									
Task 2.1	Initial run of gasifier and CHP									
Task 2.2	Installation and initial testing of H_2 capture and CO_2 capture systems									
Task 2.3	Installation of additional system measurement systems									
Task 2.4	Alpha test - fundamental system componet functional test verification									
Task 2.5	Beta test - fundamental system test verification									
Task 2.6	Fuel selection testing of gasifier product performance									
Task 2.7	Sand store heat charging and heat recovery testing									
Task 2.8	CO_2 to CO conversion system testing									Installation Reports
Task 2.9	Electricity production evaluation									System and Sub-System Test Specifications
Task 2.10	Long term gasifier system performance evaluation									Test Execution Reports
Task 2.11	Decomissioning hydrogen capture - revert to syngas generation of electricity									Decommissioning and Disposal Report
WP3	Dissemination of Results: Public, Industrial & Academic Engagement									
Task 3.1	Creation/Modification of project website									
Task 3.2	Maintenance of website									
Task 3.3	Writing and publication of articles for appropriate trade magazines									
Task 3.4	Writing and publication of scientific papers									
Task 3.5	Attending industry and engineering conferences									
Task 3.6	Public engagement events at Holborn Energy Centre									Project Website
Task 3.7	Development of gasifier monitoring system at Holborn Energy Centre									Academic Articles
Task 3.8	Facilitate university, technical college and school projects at Holborn Energy Centre									Trade Articles

CAPEX cost of each item has been included, along with the Annularised CAPEX cost, which is calculated by dividing the CAPEX cost of each item by the number of years over which the item is expected to be depreciated (i.e. the number of years when which you would expect to have to replace that component of the system). The total CAPEX required to establish the demonstrator system is expected to be: £2,347,000. The annual depreciated CAPEX cost is expected to be: £230,200. The annual operating expenditure is expected to be: £296,000. The annual cost of the system (annual depreciated CAPEX cost + annual operating expenditure) is expected to be: £526,200.

The levelized cost of hydrogen (LCOH) for the system was calculated in accordance with the Department for Business, Energy & Industrial Strategy Guidance for Hydrogen Production Costs 2021 [11]. The calculated values were measured against the BEIS LCOH targets [11]to determine the commercial viability of the design. The LCOH was determined for a hydrogen yield of 20 g per kg wood waste. This yield will produce 6.56 tonnes of hydrogen and 118.5 tonnes of carbon dioxide per year. The higher heating value of the hydrogen is taken as 141.7 MJ/kg as per BEIS guidance. The system will therefore have a hydrogen energy content of 929,552.00 MJ per year which can also be expressed at 258.2 MWh. The annualised CAPEX is £230,000.00 which leads to a levelized capital cost of 891.56 £/MWh. The annual OPEX is £296,000.00. The selling price of the hydrogen was deducted from the annual OPEX. The hydrogen produced in the system can be sold at a price of 6,218 £/tonne resulting in an annual income of £40 790.08. The net annual OPEX was subsequently taken as £255,209.92 leading to a levelized fixed operating cost of 998 £/MWh. A value of £20,000.00 per year as assumed for the variable OPEX. The levelized variable operating cost was estimated at 77 £/MWh.

The carbon dioxide costing was done at £28/kg as per the BEIS guidance. This cost was subsidised by the selling price of the produced carbon dioxide which at 321 £/tonne gave an income of £ 38,038.50 per year. The levelized cost associated with the transport and storage of the captured carbon dioxide was altered in this calculation to accommodate the sales associated with the product as well. This design does not rely on carbon storage, but rather on the utilisation of carbon dioxide as a commodity. This cost therefore has a negative value, since it represents an income stream for the design at a value of 293 £/MWh. The standard costs for carbon dioxide emitted to the atmosphere was kept at the same level as the baseline. Although this design does not emit carbon dioxide directly to the atmosphere during the production of hydrogen, there is still the carbon associated with site operations such as the transport of the feedstock to the processing facility, the processing of the feedstock and the transport to the gasification site. This was estimated at 49.2 £/MWh. Similarly, the levelized cost of carbon dioxide sequestered, was kept at the baseline of -55.7 £/MWh. This led to a LCOH with CCUS of 1,657.5 £/MWh (HHV) (Table 13).

Table 13: Levelised Cost of Hydrogen for a Hydrogen Yield of 20 g per kg Wood Waste

LCOH baseline reference	Biomass Gasifier with CCUS_59 MW HHV2030			
Cost Elements	**Baseline (£/MWh HHV H2)**	**With applicant's technology (£/MWh HHV H2)**	**Change (%)**	**Description**
Capex £/MWh	38.3	891.56	2229%	Levelised capital cost
Fixed Opex £/MWh	12.6	988.4	7758%	Levelised fixed operating costs eg rent, salaries
Variable Opex £/MWh	7.8	77	889%	Levelised variable operating costs eg feedstock, energy consumption
CO2 T&S cost £/MWh	13.2	-293	-2314%	Levelised cost associated with the transport and storage of the captured CO2*
Carbon cost emitted (fuel) £/MWh	49.2	49.2	0%	Levelised carbon cost for CO2 emitted to atmosphere.*
Total £/MWh (excl. carbon cost)	121.0	1713.2	1315%	Levelised cost of hydrogen without cost of sequestered carbon.
Carbon cost sequestered (fuel) £/MWh	-55.7	-55.7	0%	Levelised carbon cost for CO2 sequestered*
Total £/MWh (incl. carbon cost)	65.3	1657.5	2437%	Levelised cost of hydrogen with cost of sequestered carbon.

The LCOH may seem excessive in in comparison with the BEIS targets for 2030, but it is comparable and even more economic than the estimates for hydrogen production through both electrolysis and methane reformation as shown on Page 18 of the BEIS guidance document [11]. The estimates for the levelized capital cost can be as much as 1,800.00 £/MWh which is double the cost for this installation. The LCOH can be improved by increasing the hydrogen yield of the system. As the exact yield is currently unknown, the values were determined for yields of 40g/kg feedstock (LCOH 366.7 £/MWh (HHV)) and 80g/kg feedstock (LCOH - 689.9 £/MWh (HHV)). These figures show that should NEW$_2$H$_2$ be able to achieve a hydrogen yield of 80g/kg feedstock, it will exceed the net

LCOH targets for 2050. However, a more achievable target, for this design, given the use of a downdraft gasifier, it is more realistic to aim for a hydrogen yield of 40g/kg feedstock.

Table 14: Levelised Cost of Hydrogen for a Hydrogen Yield of 40 g per kg Wood Waste

LCOH baseline reference	Biomass Gasifier with CCUS_59 MW HHV2030			
Cost Elements	Baseline (£/MWh HHV H2)	With applicant's technology (£/MWh HHV H2)	Change (%)	Description
Capex £/MWh	38.3	445.78	1065%	Levelised capital cost
Fixed Opex £/MWh	12.6	494.2	3829%	Levelised fixed operating costs eg rent, salaries
Variable Opex £/MWh	7.8	19.25	147%	Levelised variable operating costs eg feedstock, energy consumption
CO2 T&S cost £/MWh	13.2	-586	-4528%	Levelised cost associated with the transport and storage of the captured CO2*
Carbon cost emitted (fuel) £/MWh	49.2	49.2	0%	Levelised carbon cost for CO2 emitted to atmosphere.*
Total £/MWh (excl. carbon cost)	121.0	422.4	249%	Levelised cost of hydrogen without cost of sequestered carbon.
Carbon cost sequestered (fuel) £/MWh	-55.7	-55.7	0%	Levelised carbon cost for CO2 sequestered*
Total £/MWh (incl. carbon cost)	65.3	366.7	461%	Levelised cost of hydrogen with cost of sequestered carbon.

6 Commercialisation Planning

6.1 Target Market Analysis

The focus of these installations is to improve the ability of clients to generate energy and/or income from waste products especially for deprived communities. Three categories of target markets have been identified: Category 1 - Councils of deprived communities in UK [12], Category 2 - Councils that do not currently have a climate action plan to reach Net Zero [13], and Category 3 - Developing Countries.

6.2 Potential Deployment Locations

The original deployment location for NEW$_2$H$_2$ in South Shields may not be suitable for this installation based on the analysis conducted here. Not only does the production of hydrogen pose a potential safety risk to the nearby estates, but emissions from the gasifier makes it an undesirable location. Negotiations are underway to make use of the large stretch of derelict land adjacent to the original site. This is the preferred location since it is already classed as industrial land and it is removed from any occupied buildings or residential areas.

6.3 Concept Upscaling Projections

Upscaling of the concept will require an increase in the hydrogen yield. Using the current system, this can be accomplished by either increasing the temperature in the gasifier or by upgrading the syngas using a water gas shift reactor. Increasing the temperature of the system may not be a viable option since the material selection and the flow rates is designed around a specified operating temperature. The best option for increasing the production rate, is the upgrading of the syngas using a water gas shift reactor. These components can easily be integrated into the system, as it was design for modularity and flexibility. Upscaling of production can also be achieved by duplication of the facility where more than one gasifier is used to feed the system. This option allows for redundancy where phased maintenance can be applied to ensure continued production of hydrogen.

6.4 Sale Strategy Development

The inbound sales method will be used to present this solution to the target market. The sales philosophy of NEW$_2$H$_2$ is unique in that the consortium is not a commercial entity that has the aim of generating income, but it consists of public entities that will promote a solution to deprived communities for achieving their net zero targets while subsidising community heating and with the potential to generate income. We will be a personalised and helpful partner for the target market to become aware of this solution for their wood waste sources. We will act as consultants during the decision-making process to determine the best implementation for the design taking their unique environments into account. Since we will mostly be working with other public entities that is reliant on public funding, we will also assist them in identifying the funding routes for their own installations. The ultimate aim is to create a network of councils around the United Kingdom that uses similar technologies for hydrogen production form waste wood processing into hydrogen.

6.5 Intellectual Property Strategy Formulation

It is too early to decide whether any new IP will be created during Phase 2 of this project. It is unlikely that IP will be created for any individual component of the system that we define because we are seeking to integrate existing solutions from third-party providers. IP may be created when we consider specific component requirements, but this is unlikely to happen. IP is most likely to be in the form of a system patent, where the IP involves the system integration of the components that already exist.

6.6 Review of Alignment with Net Zero and Hydrogen BECCS

A recent study from Imperial College proposed the implementation of a framework for negative emissions technology in the UK [14]. It included the implementation of Hydrogen Bioenergy with Carbon Capture and Storage (BECCS). It was determined that in the UK, BECCS can play of role in the removal carbon dioxide to in the order of 5 Mt. NEW_2H_2 falls not only falls directly within this framework, but it goes further in that the captured carbon is not stored, but either converted to carbon monoxide and used to generate heat and electricity or sold to generate income. This directly supports the UK Government's legal commitment to achieve New Zero by 2050. The ability of NEW_2H_2 to support the Net Zero goals and integrate with BECCS relies on the large-scale adoption of this method by councils across the country for generating hydrogen from biomass feedstocks through gasification. This will require an overall adjustment in current methods of disposal where the waste wood that is sent to the landfills are rerouted to processing sites and prepared for gasification. The public image of gasification is not favourable, and this will have to be activity managed through community engagement.

7 Conclusions

The goal of this project was to conduct a thorough feasibility analysis to determine the technoeconomic viability of a demonstration model of a scalable, adaptable system that produces biohydrogen through the gasification of waste wood. The system is designated the 'North East Waste Wood Hydrogen Demonstrator' – NEW_2H_2.

A number of options were defined and after analysis the option listed as Concept 3 was selected. This solution will increase the hydrogen content in the syngas by making use of a water gas shift reactor that at the same time will convert the carbon monoxide in the gas to carbon dioxide. The hydrogen will be separated from the syngas stream using a pressure swing adsorber and will be store in a medium pressure tank. Similarly, the carbon dioxide will be captured through a membrane system and stored. The tail gas will be burned in the CHP to supply the system with the energy it requires to the self-sustaining. Hydrogen and carbon dioxide will be sold as commodities. This system is designed to consume the 2,500 tonnes of waste wood available per year and will produce 138 tonnes H_2 and 2,493 tonnes CO_2. There are a number of gasification solutions from EQTEC, Refgas, ABLS and Kew Technologies that can be used in this system. However, cost of a full capacity Concept 3 system would be £13 – 15 million which is beyond the maximum budget for a Hydrogen BECCS Phase 2 project of £5 million. Although this system is technically viable, the full-scale version is not economically possible.

The purpose of the Hydrogen BECCS Phase 2 project is to build a demonstration system capable of producing hydrogen that can be extracted from the wood gasification process and must conform to the strict £5 million maximum budget envelope. A scaled-down demonstrator system that conforms to the Concept 3 design is proposed for Phase 2 implementation. This system will make use of a Spanner Re2 HKA-49 gasifier with a waste wood feed rate of 44.1 kg/h and an estimate hydrogen yield of 20 g per kg feedstock. The total CAPEX required to establish the scaled-down demonstrator system is expected to be £2,347,000 and fits will within the Phase 2 budget.

The novelty in this project resides in the system's level approach where the design will make use with commercial off the shelf components to build a low-cost demonstrator capable of producing hydrogen from waste wood gasification. The scaled-down system proposed here is both economically and technologically feasible.

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