UK Government

RECYCLE Phase 2:

Rethinking Low Carbon Hydrogen Production Via Novel Chemical Looping Reforming Process

Final Report

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Executive Summary

The UK set the world's most ambitious emissions target by aiming to slash its GHG emissions by 81% by 2035 compared to 1990 levels, becoming carbon neutral by 2050. These ambitious targets set a requirement to the Industry to reduce its dependence on fossil fuels. This will require both efficiency optimisations, and further integration of renewable energy sources in to production processes.

The development of new disruptive technologies with low-carbon intensity for the production of hydrogen is imperative to secure economic growth and the competitiveness of UK industries. Responding to the above challenge, REthinking low Carbon hYdrogen production by Chemical Looping rEforming (RECYCLE) project demonstrated the technical feasibility and opportunity to scale up during Phase I of the DESNZ-run Low Carbon Hydrogen Supply 2 competition. In Phase II, the project aimed to demonstrate operation of the new chemical looping technology. The process features a modular design and flexible operation and therefore can be operated with different feedstocks to produce hydrogen and other syngas-derived products at different plant sizes.

RECYCLE project is the joint effort of six partners from Industry and Academia: *The University of Manchester, Johnson Matthey*, *TotalEnergies OneTech*, *Kent Plc, Helical Energy* and *Environmental Resources Management (ERM)*.

The main objective of RECYCLE was to design, manufacture and commission a demonstration plant for three chemical looping reactors dynamically operated within an industrial environment. Among the objectives were also defining business cases, market needs, exploitation routes and commercialisation steps, identifying key sectors and stakeholders through market & policy analysis.

Due to the complexity of the tasks, the Project ran longer than initially planned. A demonstration pilot rig was constructed and installed at The University of Manchester's Industrial Hub for Sustainable Engineering, novel catalyst materials were developed and tested, business cases for large and small hydrogen production plants, steel industry and bio-methanol production were developed, and market analysis and exploitation plans were developed.

The demonstration plant commissioning is currently finalising the control part and the demonstration expected to start in Q4 2025.

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Glossary/Abbreviations/Acronyms

AACE	Association for the Advancement of Cost Engineering
ACCR	Annualised Capital Charge Ratio
ATR	Autothermal Reformer
BioMeOH	Biomethanol
CAPEX	Capital Expenditure
CLP	Chemical Looping Plant
CLR	Chemical Looping Reforming
DESNZ	Department for Energy Security and Net Zero
DRI	Direct reduced iron
FT	Fischer-Tropsch
GHR	Gas-heated Reformer
IP	Intellectual Property
JM	Johnson Matthey
KPI	Key Performance Indicator
KTPY	Kilotonnes per year
LCH	Low Carbon Hydrogen
ML	Machine Learning
MTPY	megatonnes per year
NG	Natural gas
OC	Oxygen Carrier
OPEX	Operating Expenditure
NZIP	Net Zero Innovation Portfolio
RECYCLE	REthinking low Carbon hYdrogen via Chemical Looping rEforming
SMR	Steam Methane Reforming

TRL	Technology Readiness Level

1. Background

1.1 Company/consortium information

RECYCLE project is the joint effort of six partners from Industry and Academia funded by Department for Energy Security and Net Zero's Net Zero Innovation Portfolio (NZIP) under the: "Low Carbon Hydrogen Supply 2 Stream 1 Phase 2" DESNZ Programme.

The project was co-ordinated and led by *The University of Manchester,* part of Russel Group. The university is renowned for its global research impact, high-quality teaching, and strong focus on social and environmental responsibility. The university provided their expertise in RECYCLE technology, design of the pilot plant, modelling and techno-economic assessment. RECYCLE pilot plant was constructed at the premises of the university's Industrial Hub for Sustainable Engineering.

Johnson Matthey, multinational speciality chemicals and sustainable technologies company, acted as technical consultants, material developers and technology providers for TRL5 demonstration of RECYCLE process

TotalEnergies OneTech as a large industrial company were involved as an end-user of the technology and they contributed to modelling, techno-economic analysis, maturity level and risk assessment of the technology.

Kent Plc supported the project by completing a Class IV (AACE) techno-economic study assessment of the RECYLE technology (in Phase I), developed the process design and economic assessment of the RECYCLE plant based on four commercial scale applications: large scale and small-scale hydrogen production, methanol synthesis and direct reduction of iron.

Helical Energy was instrumental in construction of the pilot unit. Together with The University of Manchester they were the key partner involved in designing the pilot unit.

Environmental Resources Management (ERM) as the world leading global sustainability consultancy supported the project by conducting an assessment of the hydrogen demand in the United Kingdom, conducted stakeholder engagement, dissemination of findings, business case analysis and strategy development.

1.2 Project background

Phase I

In Phase I, RECYCLE project was awarded £288,688 by the Department for Energy Security and Net Zero's Net Zero Innovation Portfolio (NZIP). Phase I was running from January 2022 till December 2022 and included the following activities:

Experimental campaign to demonstrate the scientific and technical hypotheses beyond the concept: cumulative >1000 hours of testing different oxygen formulations supplied by Johnson Matthey.

Process modelling and simulation: in collaboration with TotalEnergies, the integration of the process and comparison with conventional steam methane reforming with and without CCS.

Economic study: An AACE Class 4 estimate study has been carried out by KENT plc to assess the cost of the technology with respect to the conventional steam methane reforming integrated with CCS.

Market study and stakeholder analysis: while the feasibility study has focused on large-scale H2 production (300 MW), the market analysis provided by ERM has demonstrated the huge opportunity at different scales.

Phase II

In Phase II, RECYCLE project was awarded £5,110,204.52 by the Department for Energy Security and Net Zero's Net Zero Innovation Portfolio (NZIP). Phase II started in March 2023 and finished in September 2025. During Phase II of RECYCLE project, a fully integrated innovative *hydrogen production pilot unit was designed and constructed, delivered and commissioned* at the University of Manchester, to demonstrate a new technology to produce syngas and pure hydrogen in a relevant environment with near-zero direct carbon dioxide emissions. This plant is designed to continuously produce 0.8 kg/h of hydrogen and capture 7 kg/h of pure carbon dioxide from natural gas. It includes critical components such as a syngas generation unit, a Water Gas Shift Reactor (WGSR), and a Pressure Swing Adsorption (PSA) system. In addition to the construction and commissioning efforts, the project was also pursuing the following activities: expanding *research into industrial applications*; exploring *market opportunities*; developing *large-scale reactor design and techno-economic analysis*.

2. Project Overview

2.1 Scope and objectives

Scope

- The RECYCLE process provides a flexible method for hydrogen and/or syngas production, while also showing economic potential benefits over other blue hydrogen production pathways.
- RECYCLE technology can supply hydrogen to several sectors in the UK, focusing on smaller-scale industrial sites, with its ability to tap into large demand sectors that require syngas to develop other low-carbon products.
- RECYCLE optimises energy integration of the process while preserving high thermal efficiency and the CO_2 capture for different scenarios.
- Market analysis shows there are several different options for the feasible deployment of RECYCLE technology.

Objectives

The key objective of RECYCLE is to demonstrate the enhanced auto-thermal reforming process for the cost-effective production of pure hydrogen that could be applied in refineries, chemical production and iron and steel industries with a minimum CO_2 capture rate of 99% and reduced costs of production. The project objectives are as follows.

- To design and assess the performance of a new process at industrial scale and optimise the design and operating conditions of key components at laboratory scale.
- To define the business cases, market needs, exploitation routes and commercialisation steps required to reach the market of the technology.
- To identify key sectors and stakeholders through market & policy analysis.
- To build and operate a demonstration of next-generation net-zero technology at the University of Manchester.
- To cooperate with stakeholders and other related projects within hydrogen, CCUS and industrial decarbonisation to cluster research synergies with UK and European institutions.

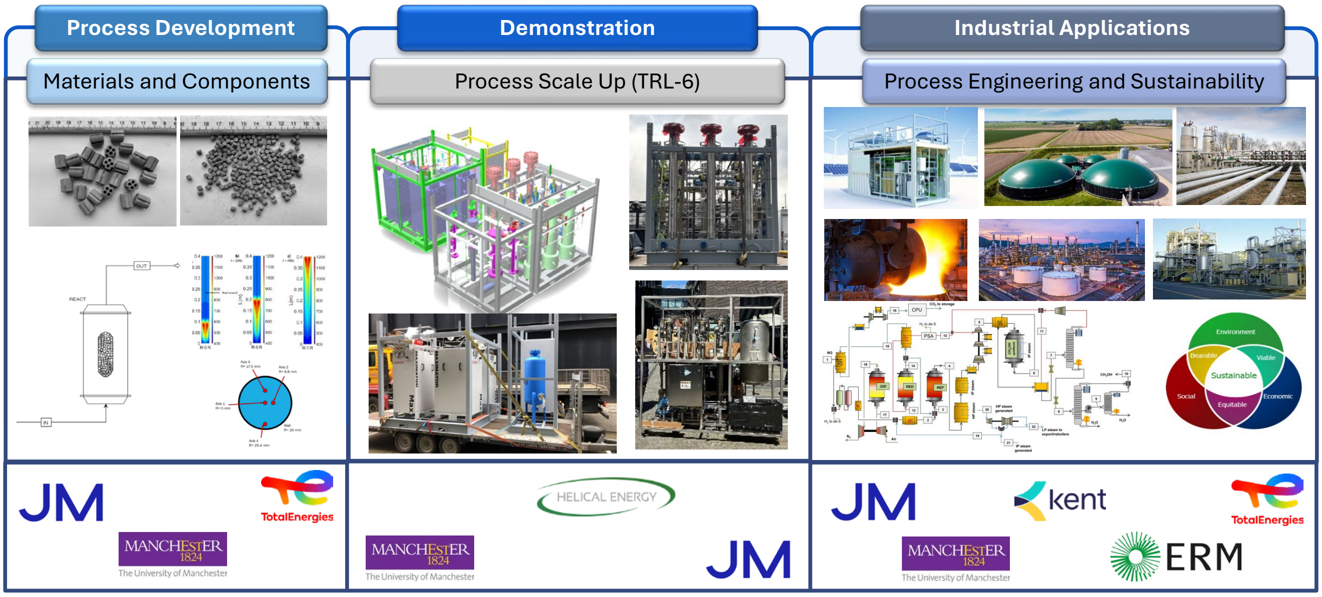

Figure 1: RECYLE project value proposition

2.2 Schedule, deliverables and financial information

Phase II of the RECYCLE project started in March 2023 and ended in September 2025. Plant design and specifications of the demonstration rig were completed by October 2023. Procurement started in parallel with the design and continued till end-2024 with long-lead items procured in the early stages of the project. Simultaneously, the site at The University of Manchester was being prepared for the installation of the rig skids. The rig Factory Acceptance Test was carried out in November 2024.

The demonstration of RECYCLE is expected to be completed in Q4 2025.

Materials development, characterisation and manufacturing were being done from the start of the project till end-January 2025. Reactor modelling, techno-economic assessment of different scenarios, market analysis, dissemination and communication activities continued throughout the duration of the project.

Deliverables, eighty-eight in total, were grouped in line with the work packages and included design and construction of the rig, site preparation, testing and demonstration, scenario analysis, materials development, market analysis, exploitation strategy development, dissemination and communication and management-related reporting. Responding to the variations in running the project, the consortium had to adjust deliverables’ deadlines and costs and to include some additional deliverables through contract change request procedures closely monitored and accepted by DESNZ.

The budget of the project and the actual spent were £5,110,204.52. Some adjustments to the costs of particular deliverables and payment milestone amounts within the budget limit proved to be necessary.

3 Design Considerations and Challenges

3.1 FEED/system design

The activities for the front-end engineering and design are summarised in the work carried out in WP4.

The main sections of the pilot unit are split into:

- Inlet component flow and composition control
- Gas compression
- Gas heating
- Chemical looping reaction in 3 reactor vessels followed by aftercooling
- Water gas shift (WGS) reaction, including preheating and aftercooling
- H_2 PSA for high purity H_2 production and tail gas recycle
- Analytical system
- Process gas venting

The first 6 of these are exemplified in Figure 2 which shows how these sections are connected together. Gas samples are taken from various positions throughout the plant and analysed using a mass spectrometer, a dedicated carbon monoxide analyser (to help distinguish between N_2 and CO), an O_2 analyser for the gases from the oxidation step and a H_2 analyser for the PSA product. The process and relief vents are combined (not shown in Figure 2) to allow all product gases to be released safely to the atmosphere. In addition, continuous gas analysis will be in place around the unit to monitor for any leakages of flammable, toxic and asphyxiating components.

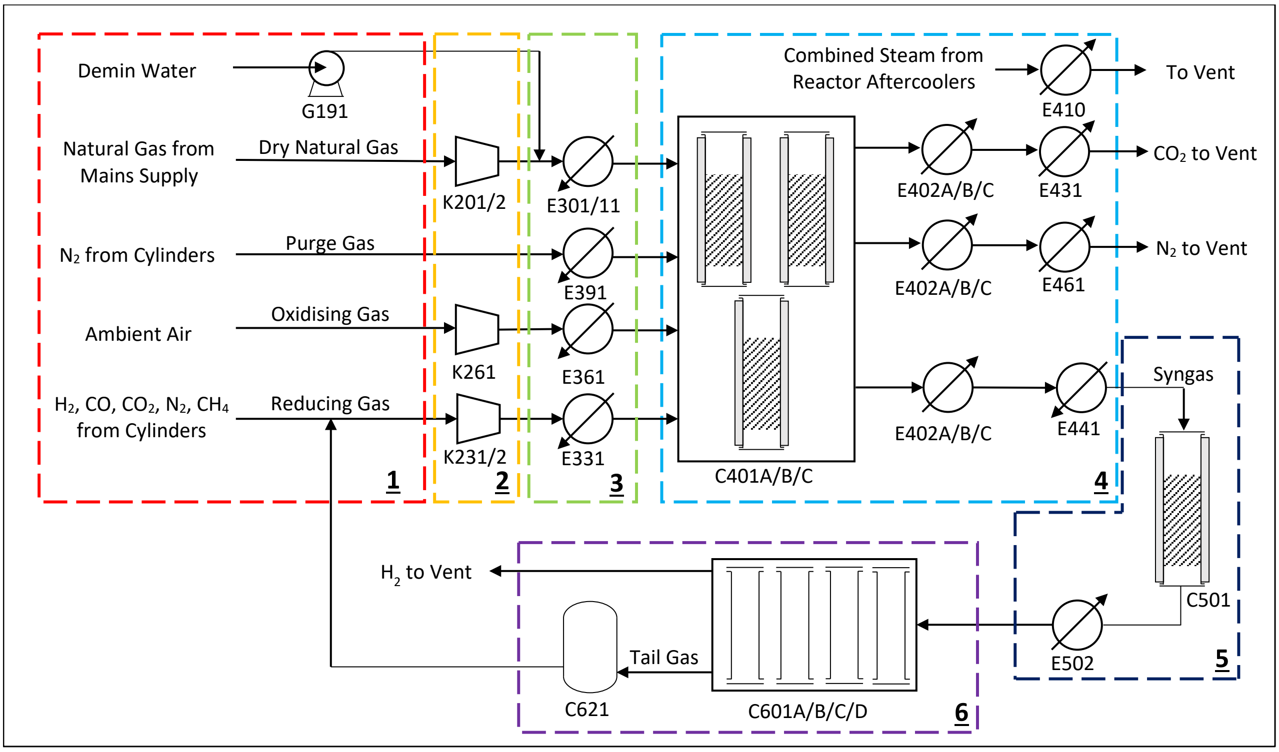

Figure 2: Block diagram of the RECYCLE demoplant

The process flow diagram was developed based on the specification as well as the P&ID that served as a document to develop the Safety Assessment, and detailed engineering, which resulted from the HAZOP.

The RECYCLE demoplant has been installed inside the Pilot Hall of the James Chadwick Building (JCB) at the University of Manchester (Figure 3). The design, construction, and commissioning have been performed by Helical Energy, with support from the UoM. The UoM will take over the operation after the commissioning is completed and Site Acceptance Test is formally signed. These tests will allow data to be collected on different feed compositions and the results validated against lab-scale experimental work and process simulations.

Figure 3: James Chadwick Building at the University of Manchester

3.2 General Process Description

The main technology under investigation in the RECYCLE demoplant is a dynamically operated fixed bed chemical looping reforming [1] to convert a hydrocarbon feed stream into syngas (i.e. a mixture of H_2, CO, CO_2 and H_2O). This syngas then passes through a water gas shift (WGS) reactor to maximise the amount of H_2 produced, and a H_2 pressure swing adsorption (H_2 PSA) unit is subsequently used to purify the H_2 to 99.9% [2].

The fixed bed chemical looping reforming stage requires 3 reactors operating in parallel in order to convert a continuous flow of feed gas into syngas. Each reactor is filled with a catalyst/oxygen carrier that allows reforming of the hydrocarbon feedstock when mixed with steam. The process works by allowing this reaction to take place in one reactor for a set period of time (which depends on the reactor size, here considered approximately 15 minutes) at a temperature of around 800 °C. However, as the reaction is endothermic, heat energy is extracted from the bed, which in turn cools down the process. If the temperature gets too low, then this negatively impacts the reaction kinetics.

To bring the temperature of the catalyst/oxygen carrier bed back up to operating temperature again, the hydrocarbon feed gas is stopped, and air is introduced. The O_2 in the air reacts with the metal(s) in the catalyst in a highly exothermic reaction, thereby increasing the bed temperature. As the oxygen in the supplied air is consumed by the catalyst bed, the product gas from the reactor at this time is primarily N_2.

After oxidation, the oxygen carrier/catalyst is sufficiently hot enough to be used for reforming, but it is only active for the CH_4 reforming reaction in the reduced state. Therefore, following the oxidation step a reducing gas, i.e. one rich in CO, H_2 and/or CH_4, is fed into the reactor, which gives a product gas comprised primarily of CO_2 and H_2O. The heat of reaction during the reduction step is small and does little to change the temperature of the materials (and bed). Once the oxygen carrier/catalyst has been reduced, then the hydrocarbon feed gas (e.g. CH_4+H_2O) can be reintroduced into the reactor and syngas production restarted.

Either side of the time air is brought into the reactor, the system is flushed through with N_2. This is to prevent the air combusting directly with the flammable gases (both the reduction and reforming gas streams) as this will result in rapid reaction and excessively high temperatures occurring.

As any single reactor is only producing syngas part of the time, 3 reactors are used to enable continuous production. The feed gases are switched from one reactor to the other, allowing the material inside the reactor to perform all steps (reforming/pure-oxidation-purge/reduction) of the cycle in a synchronous but offset manner. This is exemplified in Figure 4 and Table 1. This means that there are 3 concurrent product streams from the chemical looping process: a syngas stream, an N_2-rich stream and a CO_2/H_2O-rich stream. A continuous feed of hydrocarbons and reducing gas also needs to be provided, whilst the overall oxidation step consists of switching back and forth between supplying air and N_2. Therefore, whilst there is always a feed of gas to one of the vessels during the overall oxidation step, the individual feeds of air and N_2 are themselves discontinuous.

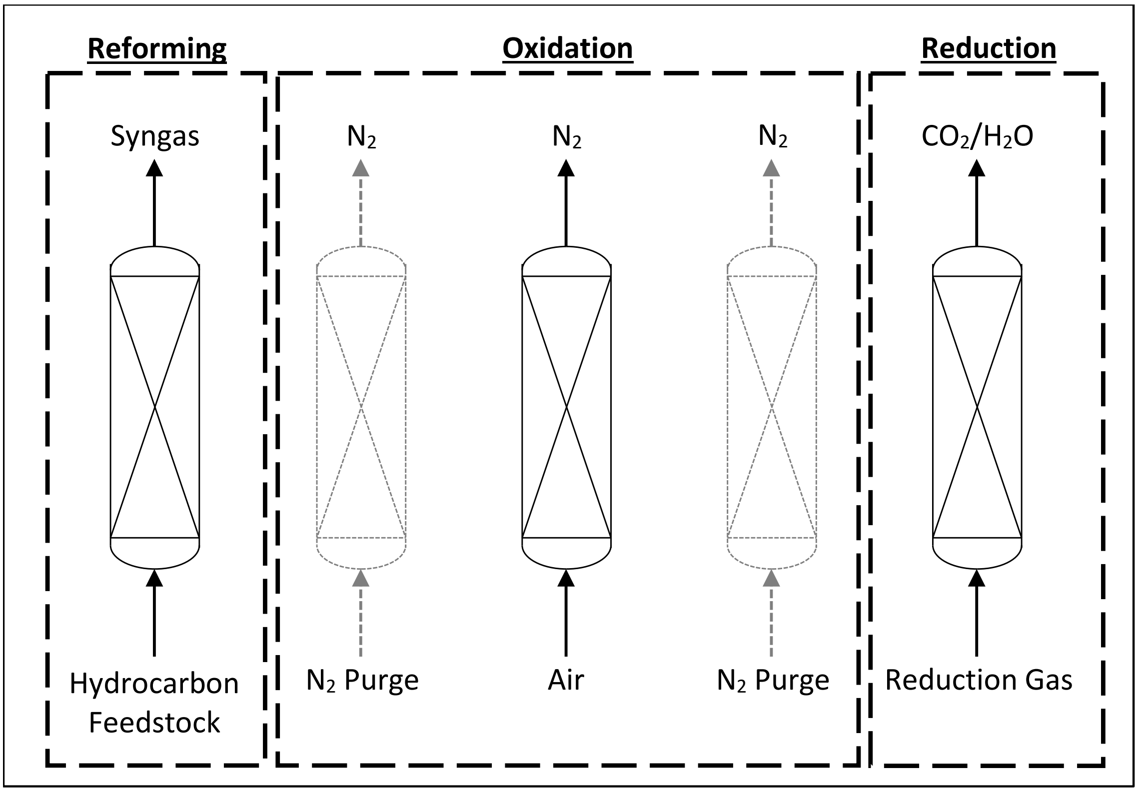

Figure 4: Representation of the 3-bed fixed bed chemical looping reactor system showing feed and product gases

Table 1: The sequence of steps experienced by the 3 reactors over the course of a chemical looping cycle

	Reactor		
	1	2	3
Step 1	Reforming	Reduction	N_2 Purge
Step 2	Reforming	Reduction	Oxidation
Step 3	Reforming	Reduction	N_2 Purge
Step 4	N_2 Purge	Reforming	Reduction

Step 5	Oxidation	Reforming	Reduction
Step 6	N_2 Purge	Reforming	Reduction
Step 7	Reduction	N_2 Purge	Reforming
Step 8	Reduction	Oxidation	Reforming
Step 9	Reduction	N_2 Purge	Reforming

3.3 Description of the Demonstration Plant

The 3D design of the plant is provided in Figure 5 representing the combination of all skids that comprise the full integrated plant.

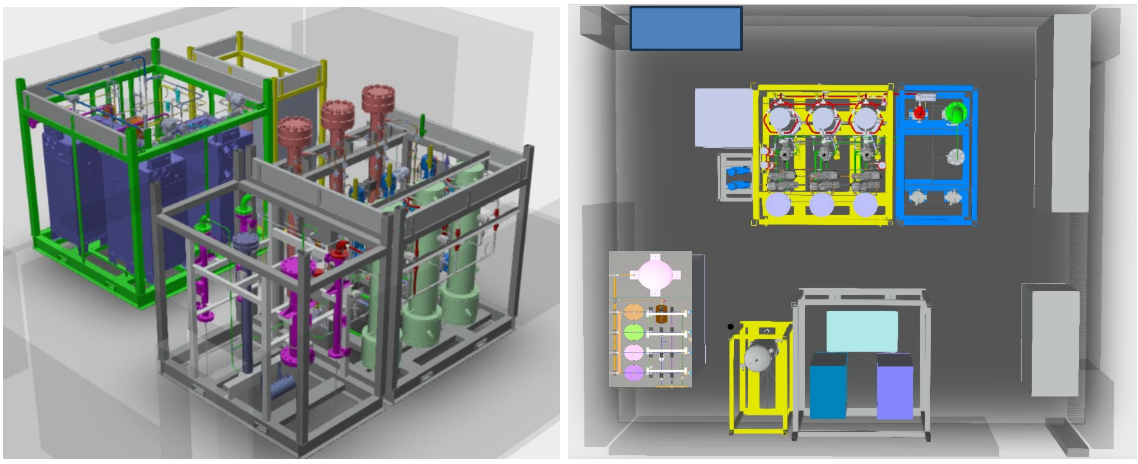

Figure 5: 3D view of the RECYCLE plant

3.3.1 Gas boosters

Four gas boosters were required in the demonstration plant to allow the process to operate above 30 bar (Figure 6). These boosters were manufactured by Maximator UK.

Booster Natural Gas (1): the first booster is needed to increase natural gas from city gas grid to be increased up to 4 bar and reach a fixed bed desulfuriser (blue vessel in Figure 6 left).

Booster Natural Gas (2): the second booster receives desulfurised natural gas at approximately 2 bar(a) and compresses it to 30 bar and sends to the feed heating section, where steam is also generated.

Booster Natural Gas (1) and (2) are instrumental to the operation of reforming at high pressure (K201/2 in Figure 2).

Booster Reducing gas: this is a 2-stage booster with an intermediate cooling gas compressor, which is needed to compress the reducing gas from the PSA buffer tank to 30 bar. These boosters (indicated with K231/2) are also used to operate the demonstration with different modes, such as WGS + H_2 PSA or just H_2 PSA. This functionality is relevant during single skid commissioning and also in case of material/catalyst activation or separate check and testing.

Booster Air: this booster is required to compress air from 10 bar to 30 bar for oxidation (K261)

Figure 6: Gas booster skids and NG desulphuriser and right) Air Compressor(s)

These are Air-Driven High Pressure boosters, hence they require as input energy large air flowrate. Given the demand, two parallel Air Compressors (Avelair, Figure 6 right) were added in the plant to provide the diving force to all boosters. In this configuration, utility air is compressed up to 10 bar and sent to the air side of gas boosters, where a piston periodically pumps each gas to its desired pressure.

3.3.2 Syngas Generation (chemical looping)

Chemical looping syngas generation is occurring in three reactors manufactured by Helical Energy (Figure 7) with a design temperature of 900°C and 36 bar, and able to operate all steps described in Figure 4. Hence, they are made of a special alloy material (800HT material).

The three reactors are identical, and the volume is approximately 25 litres. Each reactor also contains a heating jacket to allow vessel pre-heating (e.g. for startup operation) and mitigate heat losses. In each reactor, a multipoint thermocouple is provided to record the temperature profile during gas-solid reduction and oxidation and during the catalytic steam reforming. After each reactor, there is a syngas cooler to cool down the gases to approximately 200 °C. The gas temperature is controlled by boiling water (at 15 bar). Each reactor (line) requires 3 switching valves to direct the right feed stream to the proper reactor.

Figure 7: Chemical looping reactors from fabrication to installation in the plant (left to right)

3.3.3 WGS and cooling systems

Downstream the syngas coolers, a high temperature water gas shift reactor manufactured by Helical Energy is provided to convert any CO from syngas generation into H_2 and CO_2. This reactor is designed to operate at 400 °C and 36 bar.

This skid contains all heat exchangers (as represented in Figure 2) which are operated with cooling water: low temperature syngas coolers (E502); N_2 coolers after oxidation (E461), CO_2-rich stream after reduction (E431) and the heat exchanger that condenses all process water/steam (E410).

Figure 8: Water gas shift (WGS) reactor skid

3.3.4 H_2 Pressure Swing Adsorption

In order to achieve pure H_2, a Pressure Swing Adsorption has been integrated in the system (Figure 9). The system comprises 4 beds which are operated sequentially in adsorption, purge, desorption and re-pressurisation (C601A/B/C/D in Figure 2) with a tail gas buffer tank (C621) which collects the tail gas and sends it to the Gas booster for the reduction step.

The PSA is designed to operate maximum at 20 bar (ambient temperature), it has its own control system which will be integrated and operated centrally with the remaining control and operation parts. The plant has been manufactured by Amnis Pura (Portugal).

Figure 9: H_2 Pressure Swing Adsorption

3.3.5 Gas Analysers

In order to have continuous measurement of the gases generated in the plant 2 gas analytical units are available (Figure 10).

Mass Spectrometer (HIDEN) can provide composition up to 12 different sampling points. The other gas analysers are required to have continuous recording and monitoring of pure H_2 (Siemens CALOMAT), CO_2 from reduction (Siemens ULTRAMAT), N_2 from oxidation (Siemens ULTRAMAT) and syngas after the WGS reactor.

Figure 10: Gas analytical system

3.4 Consents, permitting applications and other regulatory approvals/considerations

The demonstration plant is located at the University of Manchester. As a research unit, no specific regulatory approvals were required.

In order to comply with Health and Safety Requirements, services were modified to accommodate gas feeding, increase the extraction capacity and install new sensors (Figure 11).

In order to achieve a safe design, each skid has been fabricated with ATEX-rated components. This is required because the plant operated under an enclosure and with flammable gases, where complete dilution with air below the flammable limits cannot be guaranteed. ATEX-rated components include electric items (e.g. heaters, compressors, electric cables and connections) and sensors (pressure, flow, temperature).

In addition to that, multiple sensors were installed inside the skids, which could trip the plant in case of H_2 or CO detection.

In case ATEX-rated components were not available, the design has been modified to accommodate safety measures such as hydrogen and carbon monoxide sensors, and limited gas temperature.

Figure 11: Extraction design and sensors installed in the RECYCLE plant site

4. Experimental Testing and Demonstration

4.1 Material Development

The main objectives of Work Package 3 (Process Components) were to synthesise, test and characterise 2nd generation multi-functional materials, perform lab testing with new materials under relevant conditions and validate process modelling data.

4.1.1 Materials and Scale up

RECYCLE's modular technology, which utilises a chemical looping process operated at high pressure in adiabatic packed bed reactors to produce syngas from multiple feedstocks, requires a material with good redox and reforming capability.

In this Work Package Johnson Matthey prepared, developed and supplied bespoke materials tailored to RECYCLE specifications. These were designed to address the challenge of producing robust dual materials which can be fully integrated and fulfil the catalytic and chemical looping oxygen mobility requirements of the demonstrator. The cost of filling a packed bed with e.g., a Ni-based material is prohibitively high, so it is important to reduce the cost of the oxygen carrier for RECYCLE to be viable at larger scales. Ease of manufacturing was also an essential consideration in these activities [3].

Proprietary Johnson Matthey routes were used to prepare materials.

The main technical achievements resulting from the material development work were i) synthesis of promising new materials from viable commercial routes, ii) successful development of mixed Ni- and Fe-containing materials (replacement of Ni with Fe to cut costs while retaining performance), iii) demonstration of feasibility of using Fe-containing materials as a low-cost alternative to Ni-based OCs for chemical looping reforming (CLR) applications [4] .

Materials were successfully developed, showing good oxygen transport capacity and reforming activity as required for the RECYCLE process.

The feasibility of using the novel developmental material was core to the design process. The most successful developed materials can be manufactured at scale by conventional industrial methods, which are cost-competitive. These materials can therefore be formed into pellets or granules using an active material precursor powder or impregnated over a preformed support.

4.1.2 Cost-effective materials

The feasibility of producing cost-efficient, novel mixed Ni and Fe materials - bespoke to the RECYCLE process - capable of oxygen carrying, reforming and cycling was successfully demonstrated during Phase II. This research has been carried out during Phase II in parallel to the scale up and demonstration at TRL6 by testing small samples produced by Johnson

Matthey, at laboratory scale. Such materials were designed to reduce the content of Ni by increasing Fe content (more environmental and health-friendly).

Materials were scaled up and formed to meet contact times, fulfil pressure drop requirements, and endure the demanding temperatures and exotherms through catalysis and chemical looping processes. Developmental materials were scaled up from powder to pellets, maintaining more than 90% of the selectivity and conversion values required by the project KPIs.

To achieve implementation of these novel materials into RECYCLE processes, they must undergo further material development. This could improve the durability and strength of the catalyst while further reducing its cost (Figure 12).

Figure 12: material used to fill the demonstration plant reactor

4.1.3 Lab Scale Testing

The University of Manchester has two experimental rigs for 1-10 g TRL3 and 500 g TRL4 reactors (Figure 13) that can be used to test the suitability of materials in RECYCLE. In this project, commercial benchmarks, developmental materials, and mixtures of each were assessed for efficacy towards the RECYCLE process. In each case, materials were tested for cycling, oxygen capacity, reforming and looping capability. The laboratory large-scale reactor is equipped of a multipoint thermocouple in which up to 10 different measurement points are considered along the axial direction (Figure 13, right).

Figure 13: lab scale testing: left) 1-10 grams material development and center) 500 grams reactor testing; right) schematic of the thermocouple location inside the reactor.

It has been confirmed that Fe-based materials are not effective methane steam reforming catalysts [5]. It has, however, been shown that combining materials, e.g., Ni-based steam reforming catalysts with Fe-based oxygen carriers, yields a performance comparable to Ni-based materials alone. Mixtures of materials were found to achieve the same conversions and oxygen transfer capacity as proven Ni-based oxygen carrier.

Combining Ni and Fe can reduce costs and lower the carcinogenic dangers of chemical looping reforming oxygen carriers while maintaining catalytic activity and delivering sufficient oxygen carrier capacity. The combination of Ni- and Fe-based materials is suitable for steam chemical looping reforming at TRL4, in which the material underwent full cycles with high reforming conversion, showing no drop in capacity or large-scale structural changes indicative of degradation (Figure 14, Figure 15 and Figure 16).

The recommended next phase of work is an assessment of the RECYCLE performance of commercial materials and mixtures of Ni- and Fe-based materials in the demonstration plant being commissioned.

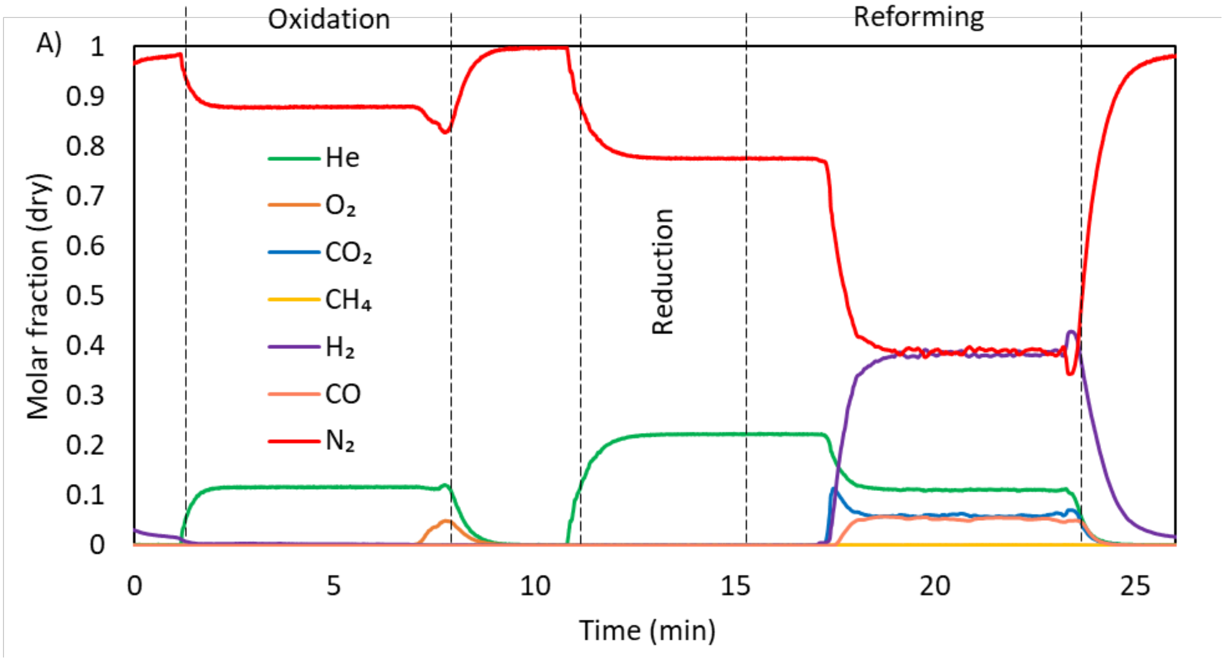

Figure 14: Outlet gas composition during a complete cycle

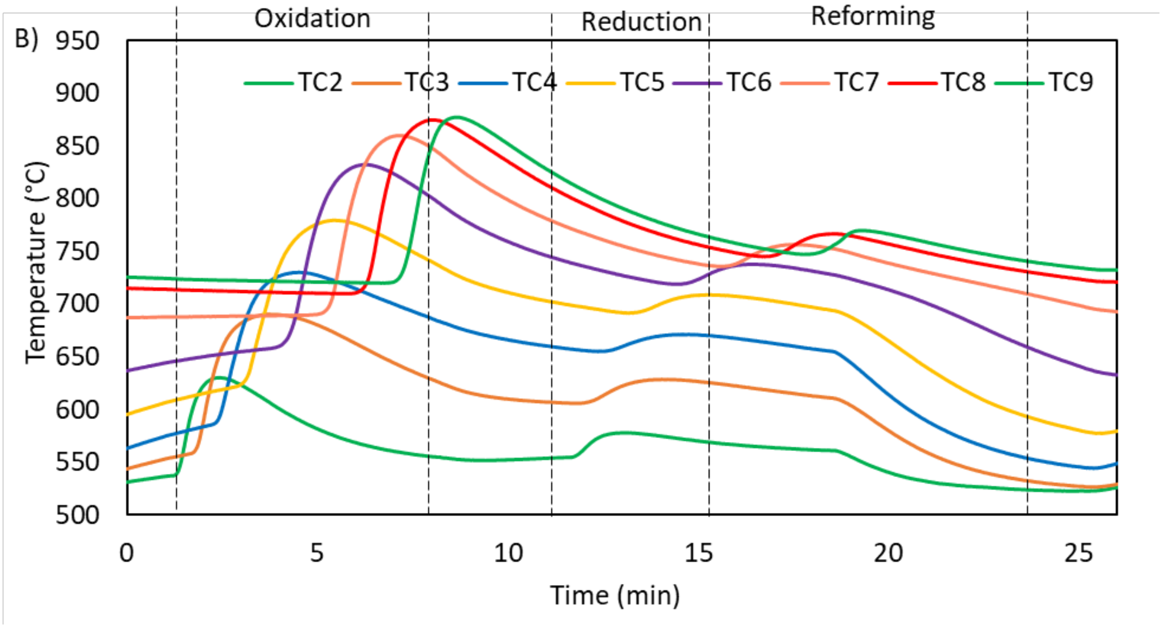

Figure 15: Reactor axial temperature profiles during a complete cycle

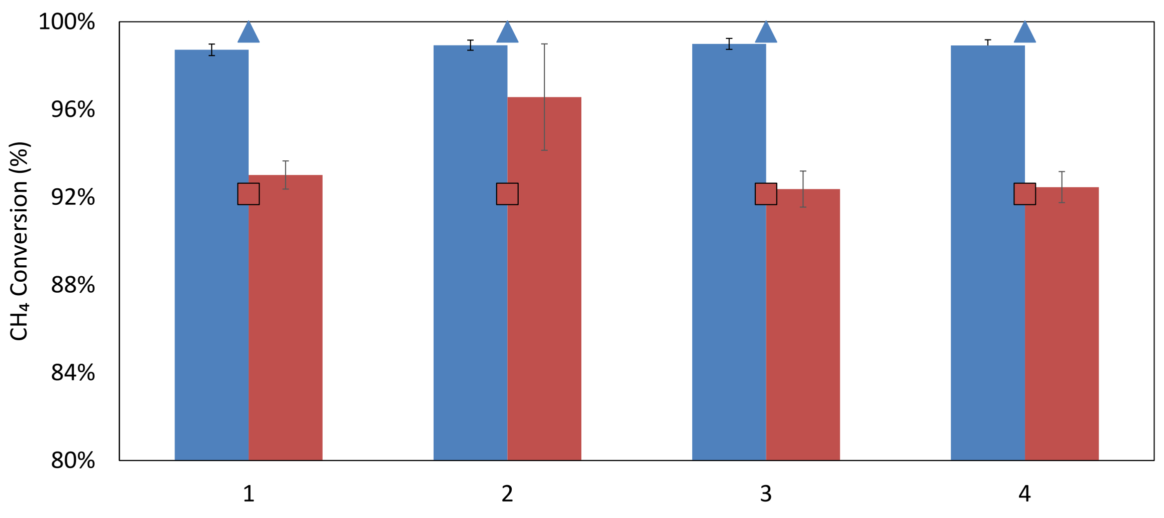

Figure 16: CH_4 conversion during repeated cycle (1-4) at H_2O/CH_4 = 4 and pressure 1 bar (blue) or 5 bar (red)

4.2 Modelling Development

4.2.1 1D-mono dimensional model

The primary objective of this modelling work was to develop an intricate reactor model for the design and scale-up of a chemical looping reactor. The reactor, featuring a dynamically operated fixed bed layout, is intended to produce syngas with inherent CO_2 capture. The detailed sub-models and comprehensive integration allow for a nuanced understanding of the reactor behaviour, facilitating its application in reactor design and scale-up. A series of models was used in this work.

The mono-dimensional 1D model (derived from a previous work from the University of Manchester [6]) was used to anticipate the testing campaign with the demonstration plant and was required to design the testing campaign, material dilution and calculate the KPIs.

Several scenarios of the chemical looping reactor system were simulated (Table 3) for the DESNZ RECYCLE project based on these design conditions (Table 2)

Table 2: Time-averaged flowrates of the feeds for the chemical looping reactors as calculated in the heat and mass balances detailed in previous deliverables.

Description	Units	Oxidation	Reforming	Reduction	Purge
Phase		Vapor Phase	Vapor Phase	Vapor Phase	Vapor Phase

Temperature	°C	350	347.9	349.9	350
Pressure	bara	27.9	26	27	27
Mole Flows	kmol/hr	0.74	0.65	0.42	
Mole percent					
H_2	%	0.00	0.00	45.98	
H_2O	%	0.00	79.17	0.15	
CH_4	%	0.00	19.79	5.66	
CO	%	0.00	0.00	3.58	
CO_2	%	0.00	0.00	43.03	
N_2	%	78.50	1.04	1.61	
O_2	%	20.50	0.00	0.00	
Ar	%	1.00	0.00	0.00	
He	%	0.00	0.00	0.00	
Mass Flows	kg/hr	21.4	11.5	9.3	21.04
Volume Flow	l/min	23.1	20.7	13.5	

Table 3: Summary of tests performed

Test	Stage duration (s)	Flowrate to reforming (fraction of the original design)	Heat transfer coefficient **10 W·m^{-2}·K^{-1}**
Test 1	300	0.5	10, 15, 20

Test 2	150	1	10, 15, 20
Test 3	150	1 (diluted with N_2)	10, 15, 20

In Figure 17, simulations were conducted with the reforming gas feed diluted with N_2. This was carried out to lower the concentration of H_2 in the flue gas and to decrease the amount of air extraction required to ensure that the plant operated below the lower explosion limit of H_2. The flow rate during reduction, oxidation and CH_4 and H_2O during reforming were kept consistent so that the cycle time remained at 150 s with the addition of an equal mass flow rate of N_2 to the reforming gas mixture.

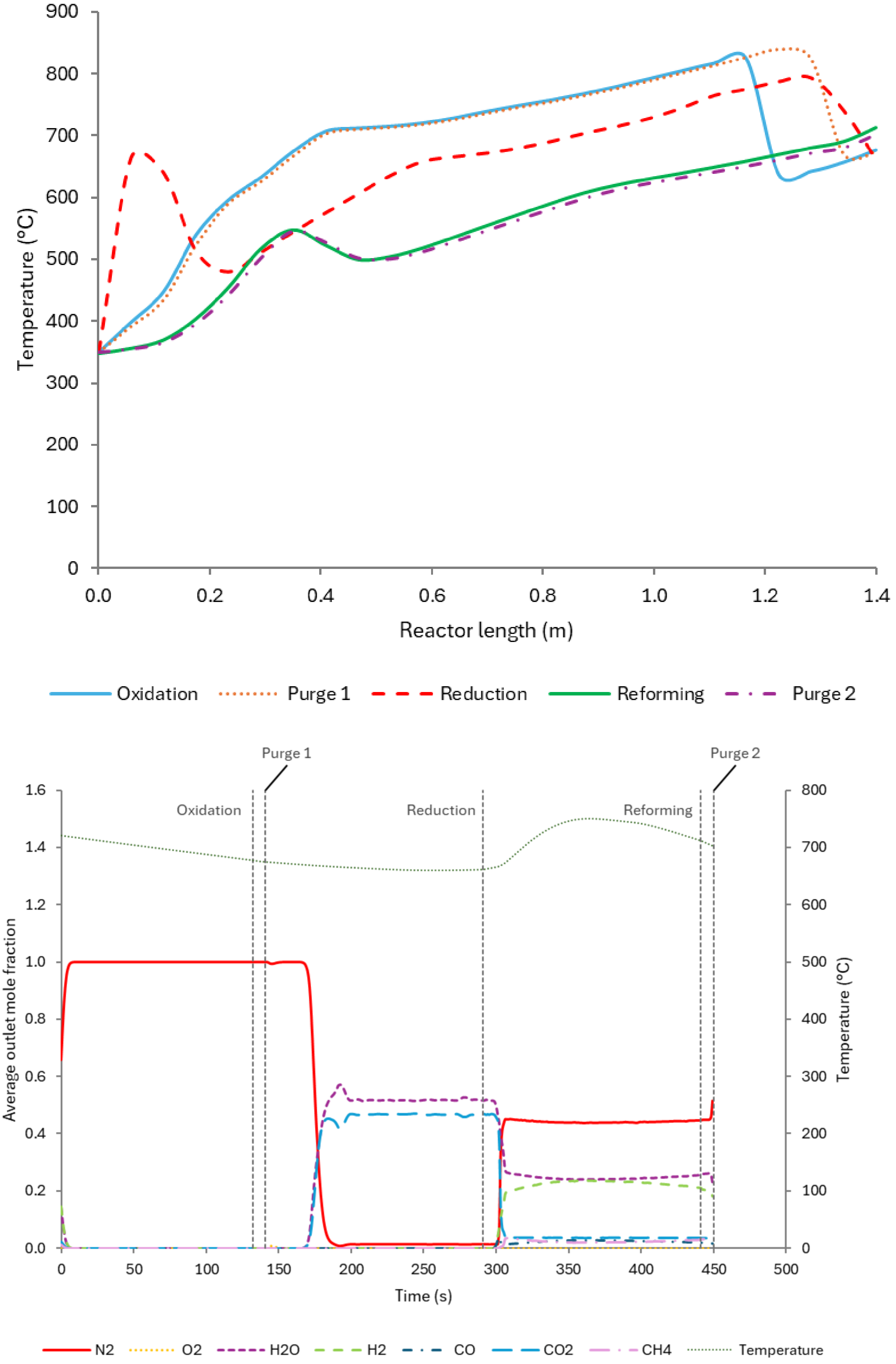

Figure 17: top) Axial bed temperature at the end of each stage of the chemical looping process and, bottom) outlet gas composition for the duration of the cycle. Using a cycle

duration of 150 s and the flowrates of the heat and mass balance with additional N_2 added to the reforming stage such that the concentration of CH_4 was half that of the values in section 5.2. U = 20 $W\cdot m^{-2}\cdot K^{-1}$

The results in Figure 17 show that these conditions are suitable for the reactor with a slight variation depending on the heat transfer coefficient. The lower the value of heat transfer coefficient U, the larger the temperature rise seen during oxidation and the less heat loss. This doesn't affect the outlet gas composition during the oxidation, purges and reduction stages, but the lower temperature results in the lower CH_4 conversion. The highest temperature in the reactor is considerably larger than the proposed highest temperature (850°C), but it does not exceed the maximum safe operating temperature (900°C), while these higher temperatures do result in a considerably better CH_4 conversion. Overall conversion during these stages shows that these are suitable operating conditions regardless of the overall heat transfer coefficient.

Final consideration on modelling-assisted reactor design

Several scenarios of the chemical looping reactor system were simulated for the DESNZ RECYCLE project. For the full range of overall heat transfer conditions studied, conditions were found to achieve suitable conversions for the plant without exceeding the reactor design temperature. However, as the maximum temperature in the reactor is increased, the average CH_4 conversion increases, which means that during operation, there needs to be a careful balancing of temperature and CH_4 to ensure that the project's aims are obtained without risking damage to the reactors.

4.2.2 Other models developed during the project

Analysis of this data was conducted in relation to factors impacting the temperature rise of the system and cycle times. This has also been compared to correlations/observations made in the literature, and the validity of these previous correlations has been carefully scrutinised to analyse their validity with respect to systems where radial flow and heat transfer mechanisms cannot be ignored.

This highlighted conditions which will be impactful at larger scales, especially concerning mechanisms relating to heat transfer, heat management, and the formation of hotspots.

COMSOL Multiphysics 6.1 software, a 2D non-isothermal model was developed and used to explore the flow dynamics and chemical reactions. This tool combines Multiphysics properties of different components and it solves material, momentum and energy equations over time, replicating the real behaviour of the system (such as temperature/composition changes,etc…).

Once the COMSOL model has been validated against the experimental data collected, it will be possible to scale up this model to an industrially sized RECYCLE reactor and analyse how these lab-scale trends would translate into industrial applications. CFD's ability to simulate transient and dynamic behaviour is essential for scaling up cyclic processes, like in the RECYCLE project. By modelling the reactor's response to changing conditions and disturbances, we can identify potential challenges and develop strategies to mitigate them. This knowledge is invaluable for designing and operating larger-scale reactors, ensuring stable and efficient performance.

A second model, which is currently under development, involves the use of Machine learning techniques. Machine learning applications in chemical engineering were investigated, with the formulation of surrogate models to use for optimisation or optimal control being the most popular use case. Different architectures can be used to formulate surrogate models.

An algebraic model was developed that showed some agreement with experimental data. The statistical model was trained using synthetic data generated by the algebraic model.

Very good results were achieved for a single inference step, with the model growing unstable after some tens of seconds. This was remedied by running several models in parallel and averaging their outputs.

Deficiencies of current approaches and how to remedy them were analysed, and a plan for future work has been created out of that.

The development of this model is at its preliminary stage, and the purpose is to improve the performance in terms of accuracy and speed once real data from experimental units will be made available (small reactor and large reactor unit in DESNZ).

This work is embedded in the activity carried out in the DESNZ project through a PhD project externally funded by the University of Manchester. The activity is relevant to the overall purpose of the development of the RECYCLE process. The potential of this model, once fully formulated and validated, could be exploited in multiple applications, and as such, the activity from this work could lead to potentially exploitable results.

4.3 Plant commissioning and preliminary activities

Some activity in the WP on demonstration has been carried out.

1) The air compressor and gas boosters have been commissioned, and they could reach the required operating pressure (30 bar) in inert nitrogen environment.

Those units are equipped with a dedicated control system, therefore, it was possible to start them up and operate by venting the gases to the atmosphere.

2) In order to proceed with the installation of lagging and insulation, the plant has gone through a leak test. The leak test procedure has been designed to isolate various sections of the plant and pressurise to the expected operating pressure (30 bar_a) and keep the pressure overnight to determine the extent of the leak. Before doing it, leak points are determined using soap as leak detector in all fittings and connections. Some examples of leak points that require reinstallation and replacement are provided in Figure 18.

The skids were left overnight, and the pressure difference recorded over 24 hours was used to estimate the amount of gas leak and the equivalent hole size that would be required to achieve such a pressure loss.

If the equivalent hole size was lower than the one accepted during the design conditions to avoid excessive release of flammable gases to risk the ignition of potential flammable atmospheres, the pressure test was considered passed, hence any leakage present in the skid is acceptable and it would be too small to be detected or the gas lost would be too little to reach any flammable limit. Additional pressurisation of different parts and leak checks were completed to find out any possible points that were still leaking.

Figure 18: Examples of leak points identified during the pressure test carried out in the Syngas Generation and WGS-cooling system skids

The pressure tests were successfully completed for the Syngas generation (chemical looping) skid (Figure 7) and WGS and cooling skid (Figure 8).

A leak rate 25 times smaller than the design conditions for the syngas generation reactors and pipes (0.0102 mm^2 vs a design of 0.25 mm^2) was obtained.

A leak rate of 250 times smaller than the design conditions for WGS + cooling heat exchanger and pipes (0.00102 mm^2 vs a design of 0.25 mm^2) was obtained.

For both cases, leaks were very small compared to what the ventilation was designed for.

Following the leak tests, hot pipes in both skids were insulated with thermal-resistant material.

The insulation that was installed prior heat tracing is shown in Figure 19.

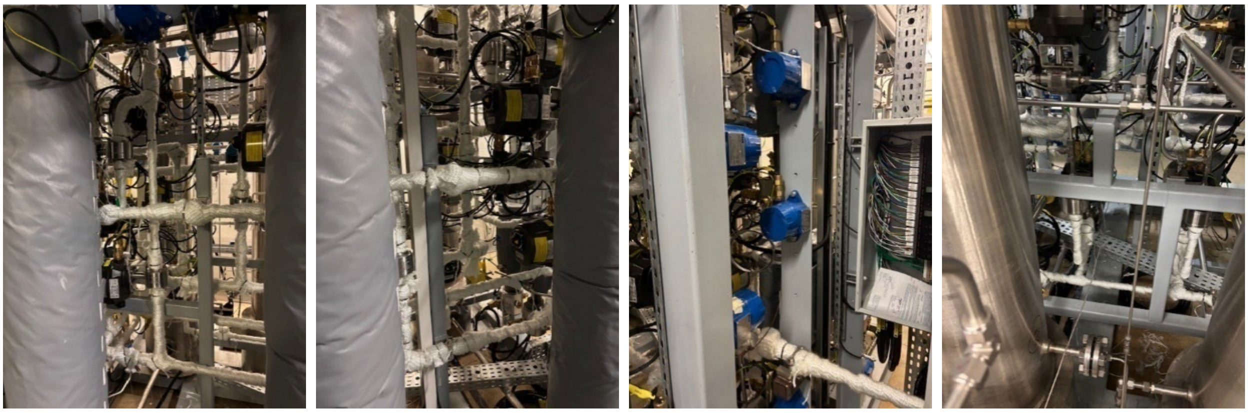

Figure 19: installation of pipe insulation

The remaining tasks to complete the commissioning include:

- Heat tracing connection to the electric panel, to embed their operation with the control system

- Final commissioning and Site Acceptance Test of the Pressure Swing Adsorption.

- Connect the cooling water system.

- Complete the commissioning of the control system.

- Safety loops tested and verified based on remarks and indications in accordance with the HAZOP assessment.

- Cold commissioning on the integrated plant, which is carried out by feeding nitrogen into the plant and bringing the whole plant to the operating pressure.

- Hot commissioning of each skid and the integrated plant under inert conditioning (using nitrogen).

- Start up operation under reactive conditions.

In terms of the testing campaign, the key tasks will include:

- Carry out the start-up operation to understand the dynamics of the plant and the procedure to bring all units to nominal conditions.

- Continuous operation of the process under nominal conditions by feeding natural gas from the city gas pipeline to produce pure hydrogen and inherent carbon dioxide. The testing campaign was originally designed for 2 weeks of continuous (and overnight operations). Once the plant is ready for testing, the University of Manchester (supported by other partners) will schedule a new plan to ensure long-term testing in accordance with existing resources.

- During the testing campaign, variation of the operating conditions within the boundaries of safety will be considered, such as partial load operations, low pressure, and higher/lower steam-to-carbon.

- In order to gain knowledge and familiarise with the skid, the plan was expected to be operated for a maximum 500 hours; however, the aim of the testing campaign is to operate the plant as long as possible based on available resources and components’ integrity.

5. Industrial Implementation

5.1 Metrics for calculation

- Energy Efficiency: calculated as the thermal flowrate of H_2 divided by the total thermal flowrate of NG into the plant and cost for power generation (assuming a natural gas combined cycle with electric efficiency of 59%)

$$Energy\ efficiency = \frac{\dot{m}_{H_2} \cdot LHV_{H_2} - \frac{\dot{E}_{El}}{\eta_{NGCC}}}{(\dot{m}_{NG} \cdot LHV_{NG})_{CLR} + (\dot{m}_{NG} \cdot LHV_{NG})_{heating}} * 100$$

- Cold Gas Efficiency calculated as the thermal flowrate of H_2 divided by the thermal flowrate of NG to the reforming unit. In case of methanol this is not provided because the conversion includes both biogas and green H_2 which are converted into methanol.

$$Cold\ gas\ reforming\ efficiency = \frac{\dot{m}_{H_2} \cdot LHV_{H_2}}{(\dot{m}_{NG} \cdot LHV_{NG})_{CLR}} * 100$$

- CO_2 capture rate: percentage of the CO_2 emissions captured from the specific emissions stream that the capture technology is applied to, without considering the emission from the whole site or the additional emission created by providing heat and power to the capture plant (Carbon Capture, Usage and Storage: An update on the business model for Industrial Carbon Capture (publishing.service.gov.uk))

$$capture\ rate = \frac{\left(\dot{m}_{CO_2}\right)_{CO_2\ product}}{\left(\dot{m}_{CO_2}\right)_{CO_2\ product} + \left(\dot{m}_{CO_2}\right)_{leak,purge}} * 100$$

- CO_2 capture (Application rate): Percentage of the carbon emissions from the whole site

$$\text{application rate} = \frac{\left(\dot{m}_{CO_2}\right)_{CO_2\ product}}{\left(\dot{m}_{CO_2}\right)_{CO_2\ product} + \left(\dot{m}_{CO_2}\right)_{leak,purge} + \left(\dot{m}_{CO_2}\right)_{\text{flue gases}}} * 100$$

- Specific CO_2 emissions

$$E_{CO_2} = \frac{\left(\dot{m}_{CO_2}\right)_{CO_2,emitted}}{\left(\dot{m}_{\mathrm{i}}\right)_{product}}$$

- With i being the produced hydrogen, the iron produced from the Reducer plant or bio-methanol

-

Assumptions for cost analysis are taken from the baseline information Table 4.

Table 4: List of assumptions as provided in the baseline information from DESNZ [7].

Item	Unit	Values

Natural Gas Industrial Retail Price	p/kWh	3.15
Biogas price (100 €/MWh)	£/MWh	83.91
Electricity Industrial Retail Price	p/kWh	11.5
Carbon Price	£/tCO_{2e}	302
CO_2 T&S	£/tCO_2	28
Operational hours per year	h/year	8000
Emission factor CO_2 from NG	kg CO_2/MJ	0.05035

5.2 Industrial Assessment

5.2.1 Process Integration and technical performance

RECYCLE has been studied with 4 different applications. These are:

- Large scale hydrogen production (600 MW)
- Small scale hydrogen production (2 MW)
- Direct Reduction of Iron (2.5 MTPY DRI)
- Biomethanol from biogas (10 KTPY biogas)

All these configurations require syngas generation. Their deployment in industrial settings is sensitive to plant size and scale; therefore, the use of RECYCLE being available at small and large scales is relevant to developing one or more relevant business cases.

In this section, an example of the RECYCLE process description is provided for the Large Scale Hydrogen application, which is represented in Figure 20.

Desulphurised natural gas is heated utilising process heat and mixed with steam. The natural gas steam mixture is routed to the reforming reactor (R-105 in Figure 18) at 600°C and 31bar(a). The syngas mixture exits reforming at 872°C and 29 bara. It is then routed to waste heat recovery and then the high temperature WGSR (R-106 in Figure 18), exiting at 396 °C before further cooling and water removal. Thereafter, the cooled gas is routed to the PSA where high-purity Hydrogen is recovered. Low-pressure Tail gas is compressed in the Tail Gas Compression C-104 and heated using hot process streams and routed back to the Chemical

Looping Reactors, to the reactor, which is in Reduction mode of operation. This is R-104 in Figure 18 above.

The reduction feed temperature is 605°C at a pressure of 31 bara. In the reduction step, the tail gas, which is rich in CH_4 is converted to CO_2 and H_2O. This stream is cooled from an exit temperature of ≈1000 °C before undergoing phase separation to remove water and then dehydration to generate CO_2 ready for compression. The dry CO_2 is compressed and cooled and routed to sequestration.

The reactor that has completed the reduction step is ready to be used as the Reforming reactor, and thereafter it is purged with steam and undergoes Oxidation. This is in reactor R-102 in Figure 20. Oxidation occurs by feeding compressed air to the Oxidation reaction step at 500°C and 31 bara. The oxygen carrier catalyst is oxidised, becoming hot and producing O_2-depleted air (≈N_2) which exits at 608°C. The gas is cooled by heating process streams and then routed through an expander before being released to the atmosphere.

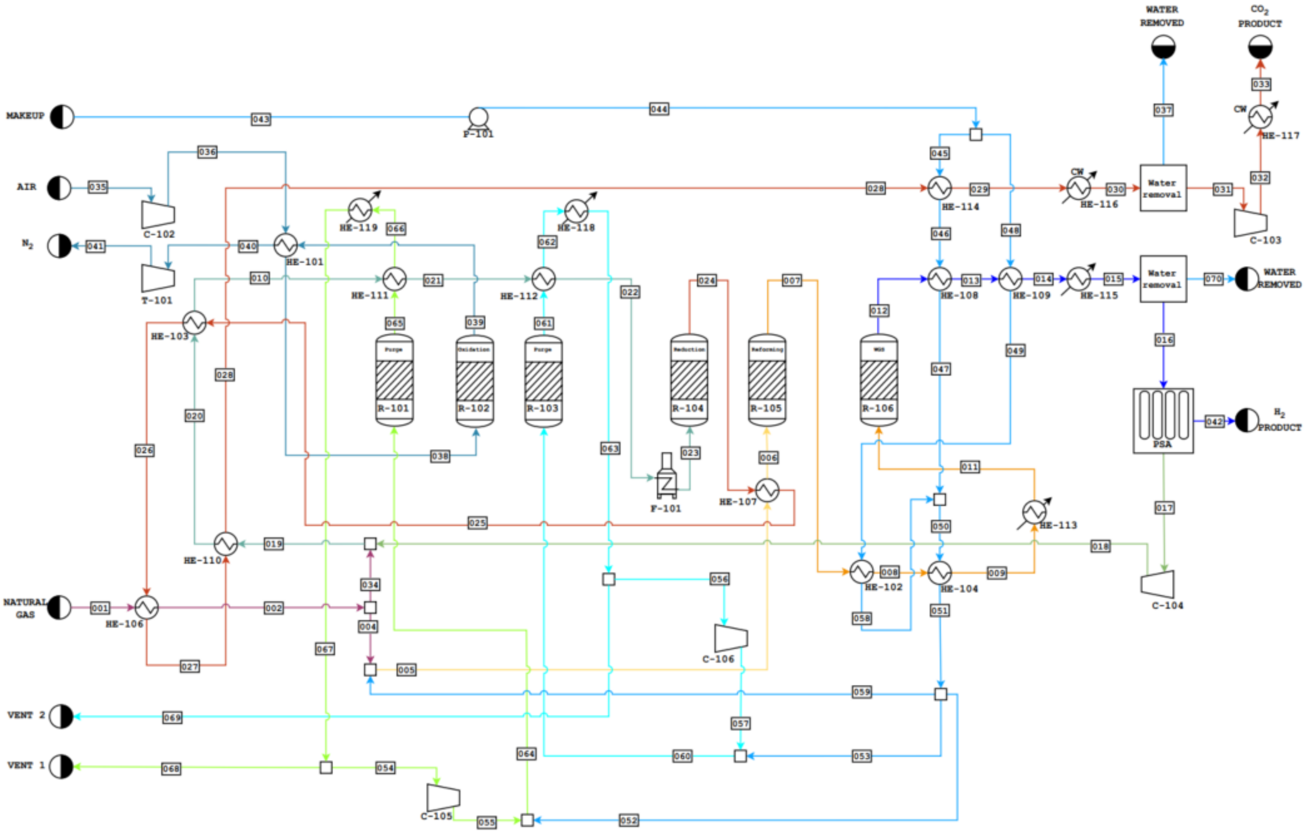

Figure 20: Process Schematic of the Large Scale Hydrogen production process using RECYCLE process

Other processes were simulated based on industrial end-user feedback, product specifications and specific requirements. The technical performances are presented in Table 5.

It is important to highlight the following differences among different cases:

- Small Hydrogen plant configuration has lower performances that Large hydrogen because of a simplified heat recovery and use of low temperature valves which requires at the same time more fuel for direct heating (natural gas), hence higher CO2 emission and fuel demand

- In case of DRI, the energy demand and performance (indicated) outperform other processes developed [8]. CO2 emissions reduction (application rate) is currently limited to 55% because the process was designed to replicate the same inlet/outlet conditions from the DRI Fe-reduction unit. In case of a more specific design, fuel/Fe ratio may be decreased improving the efficiencies and CO2 emissions.

- In case of biomethanol, the energy efficiency accounts for the fact that some hydrogen (green source from water electrolysis) is needed to convert the CO2 in the biogas and obtain the required (H2-CO2)/(CO+CO2) ratio which is optimal for methanol synthesis. Any resulting CO2 from the process are biogenic and any concentrated CO2 (>99%) is from biogenic origin therefore the plant can results overall carbon neutral (CO2 emitted) or carbon negative (if CO2 is sent for storage).

Table 5: Key Performance Indicators (based on modelling of industrial scale processes) for RECYCLE

Parameter	**Units**	**Large Hydrogen**	**Small Hydrogen**	**DRI**	**Bio-methanol**
Energy efficiency	%	72.9	59.5	66.1	66.5
Cold gas reforming efficiency	%	82.1	78	70.4	N/A
CO_2 Capture rate	%	>99.99	99.87	99.83	99.8
Application rate	%	>99.1	94.2	55.0	62
Primary Energy Intensity	-	0.082 MJ/MJ_{H2}	0.1 MJ/MJ_{H2}	8.93 MJ/kg_{DRI}	39.47 MJ/kg_{MeOH}
Specific CO_2 emissions	-	0.079 g_{CO2}/MJ_{H2}	0.13 g_{CO2}/MJ_{H2}	0.181 t_{CO2}/t_{DRI}	0.4 t_{CO2}/t_{MeOH}

The following techno-economic assessments were based on achieving hydrogen at specifications and standards required for pipeline or refinery (Large Scale RECYCLE), for PEM fuel cells (Small Scale RECYCLE), or syngas suitable for conventional Direct Reduction of Iron (RECYCLE DRI) and raw biomethanol (RECYCLE bio-MEOH).

5.2.2 Economic Assessment

This section presents the economic assessment of four plant configurations evaluated in the RECYCLE project (Phase II). These configurations were evaluated under consistent assumptions for natural gas (NG), electricity, and carbon pricing, as specified in the Low Carbon Hydrogen Supply 2 Stream 1 Phase 2 Guidance. The relative contributions are based on a AACE Class IV estimate.

Relative Capital Expenditure (CAPEX) contributions across the different configurations are shown in Figure 21. The distribution reveals that cost contribution varies depending on the process and the scale. For example, hydrogen plant & steam components are the dominant cost across the hydrogen technologies, and a significant component in the syngas producing configurations, which have DRI and methanol as a final product, respectively. The chemical looping reactors constitute a relatively small proportion of the cost, while the cost of catalysts and/or oxygen carriers depends on the scale of the operation.

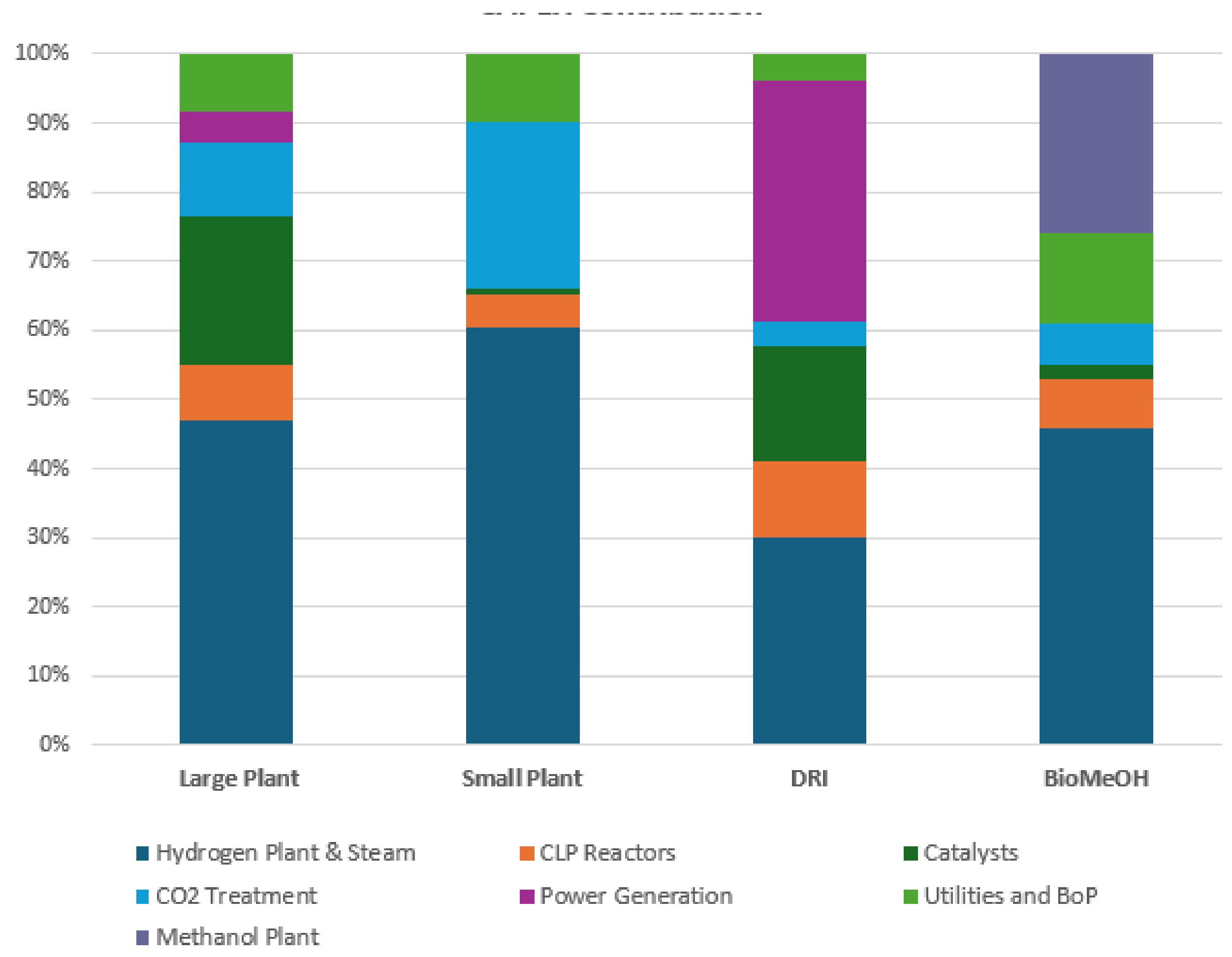

Figure 21: relative cost of plant units in terms of CAPEX for all cases

CO_2 treatment is the second largest contributor to CAPEX for the small hydrogen plant because the design concept assumes that CO_2 will be liquified to be transported by truck. This assumption was made given the size of the plant, which may not be located close to a CO_2 pipeline. Reassessing this configuration with a different destination for the CO_2 captured may decrease this contribution substantially.

Power generation is a significant cost contribution for DRI production, where high-temperature gas streams are used to produce steam, and with additional superheating, electricity is produced in a steam turbine. As a result, in the DRI case, there is no power imported, and the facility produces all the power required with the remaining exported. This is reflected in the cost of the products generated by different operating and fixed costs for each case Figure 22.

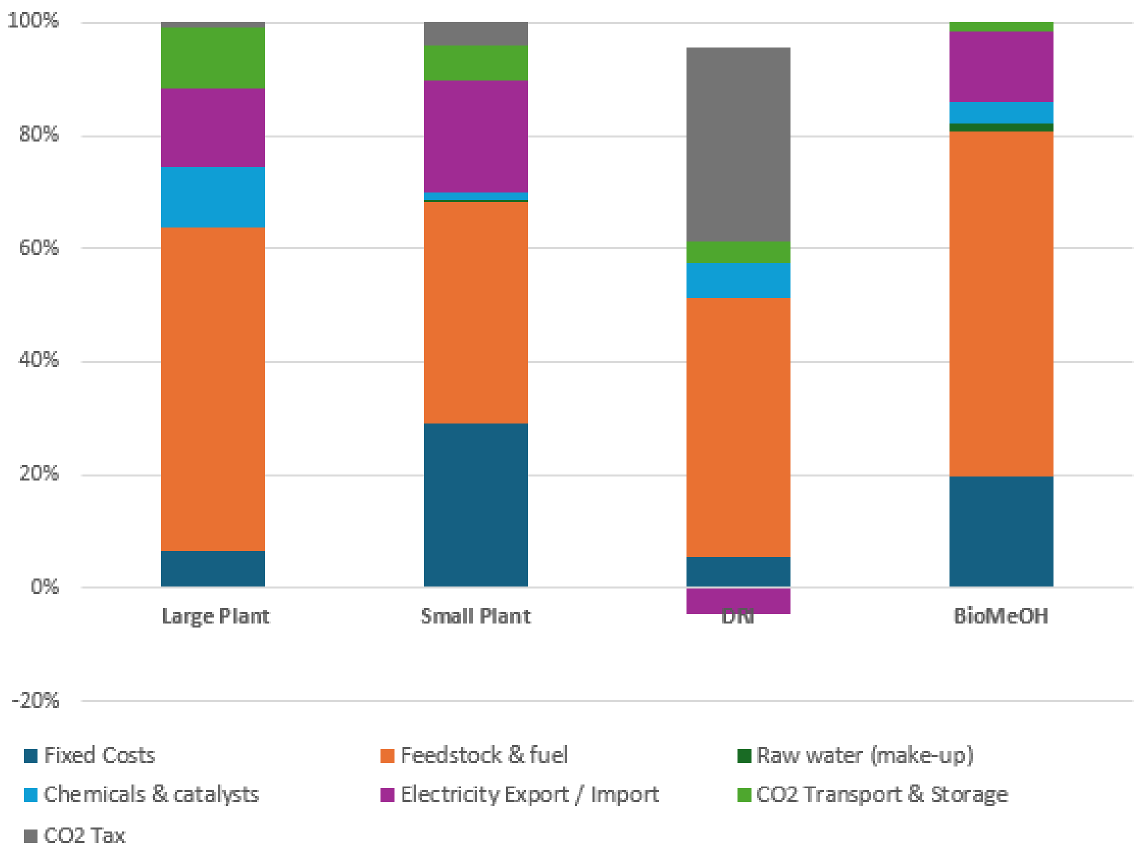

Figure 22: Cost of the products in terms of percentage contribution

The CO_2 Tax contribution and Transport & Storage contribution to OPEX reflect the proportion of capture achieved. For example, in the large plant, there is a small contribution for the CO_2 tax due to high capture rates, with an associated larger contribution due to transport and storage. In the Bio-Methanol case, due to biogenic feedstock, there is no CO_2 Tax cost.

Operating expenditure (OPEX) analysis highlights that Feedstock & Fuel is the dominant cost driver across all cases, emphasising the economic sensitivity of these technologies to commodity prices. This cost dominance aligns with the energy-intensive nature of hydrogen and syngas production processes.

5.2.3 A comparative study with other H_2 benchmark technologies

A comparison with benchmark technologies for hydrogen production at large scale has been carried out, and the key results are proposed in Table 6. *In Table 6, the technical KPIs and the cost model are different from the one adopted for the detailed cost analysis (in Table 5) to have the same terms of comparison as the benchmark plant.*

Table 6: Techno-economic comparison of the RECYCLE process with respect to other traditional solutions based on Steam Methane Reforming (SMR) with and without CO_2 capture and Autothermal Reforming (ATR) with CO_2 capture

Key Performance Indicators	Units	SMR No CC	SMR with CC	ATR with CC	RECYCLE

Technical Performance					
CO_2 emissions	kg_{CO2}/kg_{H2}	9.3	0.4	0.5	0.009
CO_2 capture rate	%	0.0	95.7	94.6	99.9
Energy efficiency	%	70.5	63.5	63.3	76.8
Economics					
CAPEX (2023)	£/(kg_{H2}/day)	810.5	1971.5	1558.3	1208 – 3020
ACCR (i = 10% n = 20 years)	£/kg	0.29	0.69	0.55	0.43 – 1.06
Fuel (£8.75/GJ_{HHV})	£/kg	1.61	1.72	1.61	1.42
Variable **(electricity 115 £/MWh)**	£/kg	0.07	0.19	0.29	0.26
CO_2 Transport and storage (28 £/t_{CO2})	£/kg	0.00	0.25	0.25	0.26
Levelized cost of H_2 (with carbon tax 302 £/t_{CO2})	£/kg	4.83	3.13	2.94	2.52 – 3.16
CO_2 avoidance cost *(51 £/t_{CO2})*	*£/kg*	*110.7*	*86.5*	*82.3*	*51.5-120.8*
Levelized cost of H_2 (without carbon tax)	*£/kg*	*2.02*	*3.01*	*2.78*	*2.5 – 3.14*

5.2.4 Environmental assessment

Simapro 9.3.0.3 associated with EcoInvent 3.8 database is used to perform the LCA. Impact World + method was used. Process data used to perform the LCA come from the Techno-Economic Analysis (TEA) (Table 7).

Table 7: Process data for 4 processes

		Small H_2 plant		**Large H_2 plant**		**SMR 2 with CCS**		**SMR1 w/o CCS**	
		/year	**/t_{H2}**	**/year**	**/t_{H2}**	**/year**	**/t_{H2}**	**/year**	**/t_{H2}**
H_2	t	526	1	142,200	1	161,280	1	161,280	1

NG	m^3	2,410,256	4,582	576,000,000	4,051	775,384,615	9,847	727,384,615	4,510
CO_2 emissions	%	5.8	5.8	0.9	0.9	4	4	100	100
	t	267	0.508	10,854	0.076	64,512	0.819	1,499,904	9.300
CO_2 captured	%	**94.2**	**94.2**	**99.1**	**99.1**	**96**	**96**	**0**	**0**
	t	4331	8.23	1,195,200	8.41	1,548,288	19.66	0	0.00
Electricity	MWh	3382.2	6.43	389,628	2.74	329,011	2.04	104,832	0.65
Water	t	3992.34	7.59	2,407,446	16.93	3,894,912	24.15	2,548,224	15.8

The amount of CO_2 captured reported in this table is the one defined as application rate, and it refers to the total amount of direct CO_2 emissions from the plant (including furnaces and external combustion) and not just related to the chemical looping reforming process (conversion of fuel into syngas). All water is consumed during the process.

According to Electricity Maps website (https://app.electricitymaps.com/zone/GB), the carbon footprint of consumed electricity in the UK in 2024 is 164 g_{CO2e}/kWh. To align with DESNZ competition guidelines, a prospective electricity mix for the UK was modelled in Simapro (Table 2). The objective is to consider the increase of renewable energies in the electric consumption of the UK. For the chosen scenario, more than 75% of electricity comes from wind and nuclear sources.

Table 8: Prospective grid UK composition

	Prospective Grid UK
Natural gas	5
Nuclear	40
Wind	37
Hydro	5

Solar	13
Oil	0
Climate change (gCO2e/kWh)	63

EcoInvent 3.8 assumptions for the consumed natural gas origin in the UK were used as a reference for this study. The composition as well as its carbon footprint are presented in Table .

Table 8: Natural gas GHG emissions

EcoInvent 3.8	**Natural Gas UK (%)**
Offshore gas production	39.5
Import from NO	44
Import from RU	2
Import from NL	14
Others (transport)	0.5
Climate change (gCO2e/MJ)	4.41

5.2.5 Impact on climate change

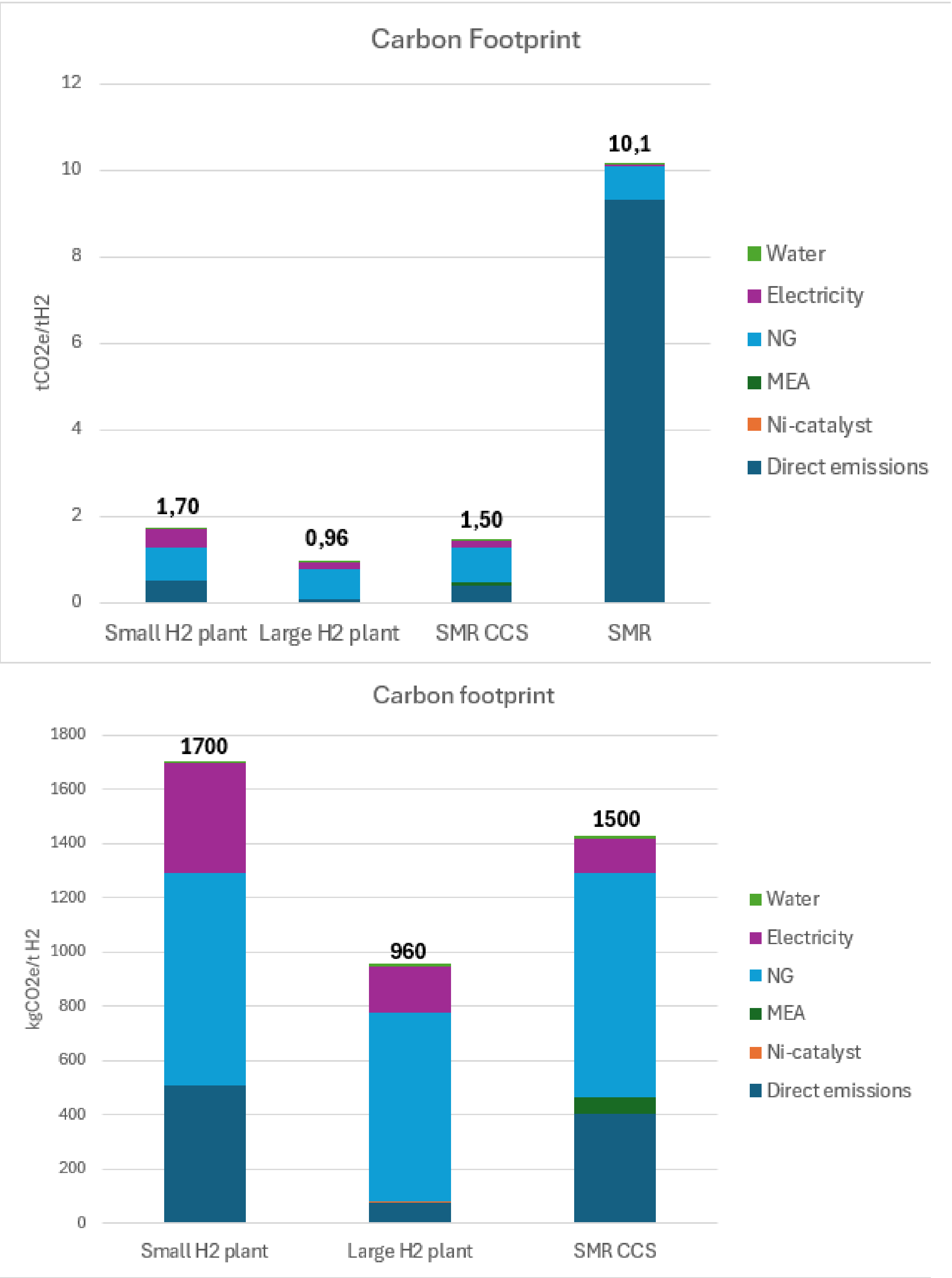

Figure 23: left) Impact on climate change for the 4 processes and right) Focus on the 3 least emitting processes (1b)

Both the small (RECYCLE) H_2 plant and the large (RECYCLE) H_2 plant and the SMR combined with CCS have a lower impact than the SMR without CCS, with a reduction of approximately 85% of GHG emissions. This is linked to the SMR direct CO_2 emissions (Figure 23).

When looking at the 3 processes emitting less CO_2, the small (RECYCLE) H_2 plant has the highest impact on climate change (1700 kg_{CO2e}/t_{H2}) while the large (RECYCLE) H_2 plant has the lowest one (960 kg_{CO2e}/t_{H2}). The large (RECYCLE) H_2 allows decreasing GHG emissions by 36% compared to the SMR+CCS base case (1500 kg_{CO2e}/t_{H2}). Very low direct CO_2 emissions from the large (RECYCLE) H_2 allow decreasing the global carbon footprint of this technology.

The third most important contributors to GHG emissions are, in order of importance, and for all studied processes, natural gas use, direct CO_2 emissions and electricity use. The use of Ni-catalyst and water, and the use of MEA for the SMR+CCS case, have a very low impact on GHG emissions.

A single score indicator in LCA is a composite measure that aggregates multiple environmental impact categories into a single numerical value. This approach simplifies the interpretation of LCA results by providing a clear, overall assessment of the environmental impact of a product or process.

It is used to more easily communicate complex LCA results to stakeholders, including non-experts. And facilitate comparison between different products or scenarios, aiding in decision-making processes. In addition, it highlights the most significant impacts, single score indicators help prioritise areas for improvement.

In order to calculate the single score indicator, environmental impacts are first classified into various categories (e.g., global warming, acidification) and characterised to quantify the potential impacts within each category; after that, the characterised results are normalised to a common scale, often based on a reference value such as the average environmental impact per person in a specific region. Then, the normalized results are weighted according to the relative importance of each impact category. Weighting factors are typically derived from expert judgment, stakeholder input, or policy priorities. Finally, the weighted results are summed to produce a single score, representing the overall environmental impact.

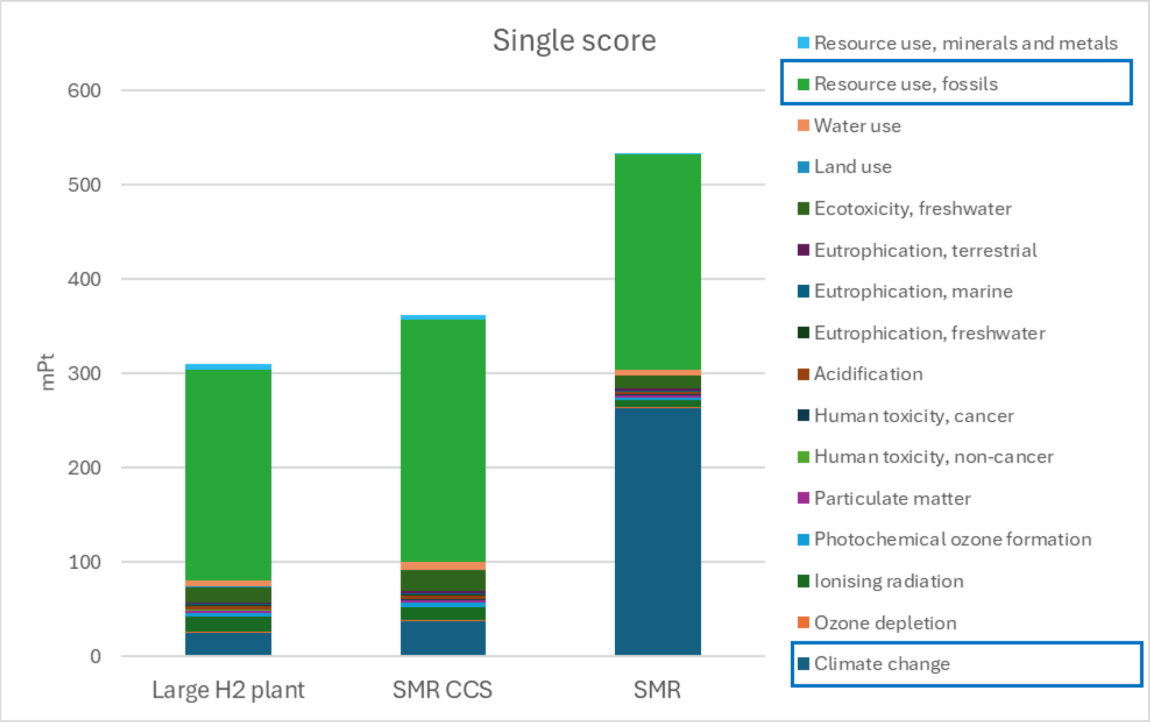

Figure 24: Single score results

Single score is another interpretation of the LCA results (Figure 24). It shows a global environmental footprint reduction for the large (RECYCLE) H_2 compared to both the SMR with and without CCS. The main impact here is the use of natural gas for both the large (RECYCLE) H_2 and the SMR with CCS. However, the main impact is climate change for the SMR without CCS.

In conclusion, the LCA of the RECYCLE processes demonstrates significant environmental benefits compared to the conventional SMR technology. The large (RECYCLE) H_2 shows a 36% reduction in greenhouse gas emissions and a 30% reduction in global environmental impact. These improvements are primarily due to the inherent very low direct CO_2 emissions of the RECYCLE process. The use of natural gas is the main contributor to environmental impacts for the scenarios studied.

6. Secondary Project Benefits

6.1 Dissemination activities undertaken including media coverage

RECYCLE project adopted a strategy aimed at amplifying the project's core messages through a range of targeted communication channels, in particular including the project website (Phase 2 | H2Recycle), LinkedIn, and two industrial workshops. These workshops were key touchpoints for direct stakeholder engagement. The first event (24.04.2024) showcased the preliminary results of RECYCLE technology, providing an opportunity to gather valuable feedback from stakeholders involved in the NZIP Low Carbon Hydrogen Supply Competition. The second workshop (18.03.2025) presented the up-to-date project results. It brought together key industry stakeholders and facilitated discussions on potential deployment pathways for the technology. Representatives of project partners delivered presentations and participated in discussions at several conferences and other related events.

The list of publications and dissemination items is provided in Appendix A1.

6.2 IP generated from the project

Key IPs generated by the project include:

- Materials synthesis and formulation

- Reactor and process design and engineering

- Process integration

- Process control and optimisation

Partners have put in place specific actions to protect the generated IPs (including patent applications which are in progress) through the Exploitation plan.

6.3 Number of jobs created and improving skills/experience in sector

At different stages, the project fully or partially supported the creation/maintaining of 32 jobs of which five in Academia and the rest in Industry. Upon the completion of the project, all participants – from the Project Lead to young employees – gained valuable experience in their respective fields. Early researchers in Academia progressed in their careers, and collaborators in Industry acquired the knowledge and skills necessary for advancing the technology across the sector. A university spin-off company is currently in the process of being set up, which could additionally create 3-5 highly qualified positions in the near term.

6.4 New partnerships formed from the project (UK and International)

RECYCLE project Partners established strong collaboration links between themselves. Those links will be – and already are being – used for further collaboration and pushing ahead the technology to upper TRLs. Some of the partners are currently participating in a Horizon Europe project, which is partly related to exploiting some of the achievements generated during RECYCLE. The University of Manchester is currently looking to spin off a company that will be closely collaborating with other project partners to build and operate a pre-commercial plant in a potential end-user identified through the market analysis and stakeholder engagement.

6.5 Supply chain development

During RECYCLE pilot rig development and construction, the project partners established links with new suppliers and strengthened links with their existing suppliers. 55 suppliers provided their items to the rig. Setting up a supply chain was crucial for the project, and it was a priority but also a risk item (see section 7.2) for the duration of the design and construction stage. Long lead items were of particular concern, and they were addressed at the initial stages of the design.

During the project implementation, few relevant issues related to the supply chain have been identified:

- R&D equipment: some of the sensors or equipment were not available off-the-shelf because of the size/capacity. As an example, IT valves with pipe diameter of ½” were hard to find in the market, and they were a key component for the process.
- Several sensors and plant components were not easy to find, especially in the case of ATEX, unless a long lead time or high costs.
- Similarly, no electric compressors/boosters could be found due to the relatively low flowrate required; therefore, air-driven gas boosters were instead used, which have also increased the overall cost and complexity of the plant
- The presence of Helical Energy, with longstanding experience in pressure vessel and exotic components manufacturing, was pivotal to designing and installing the reactors for chemical looping

7. Project Management

7.1 Brief description of structuring and scheduling of project, recruitment activities

RECYCLE project structure is shown in Figure 25.

Project start date: 01/03/2023

Project end date: 30/09/2025

Project duration: 31 months (including 7 months extension)

The project includes 6 Work Packages

WP1: management (M1-M31), partners: University of Manchester

WP2: Industrial Applications (M1-M24), partners: TotalEnergies, University of Manchester, Kent, Johnson Matthey

WP3: Process Components (M1-M27), partners: Johnson Matthey, TotalEnergies, University of Manchester

WP4: Prototype design and construction (M1-M31), partners: Helical Energy, University of Manchester, Johnson Matthey

WP5: Demonstration (M20-ongoing): University of Manchester, Helical Energy, Johnson Matthey

WP6: Exploitation, Dissemination and Communication (M1-M31): ERM, TotalEnergies, University of Manchester, Kent, Johnson Matthey, Helical Energy

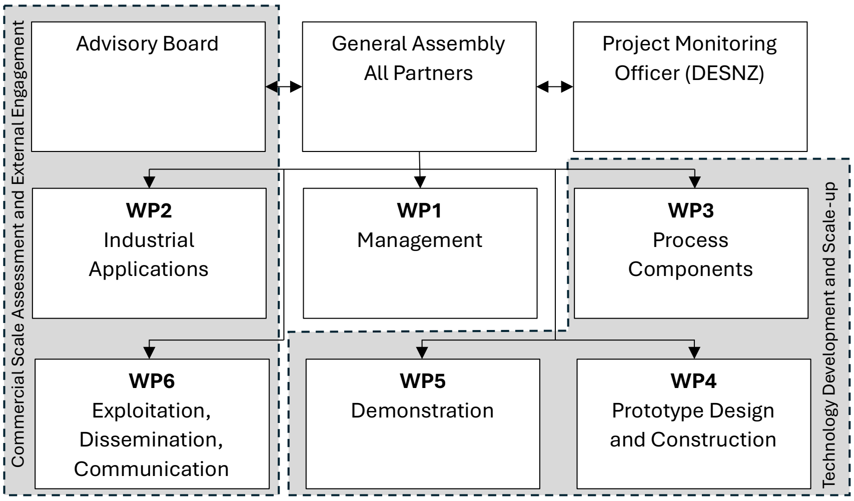

Figure 25: RECYCLE project structure

7.2 Brief description of key risks and mitigations, and detail of any risks that materialised into issues

The major risks indicated in Table 9 were anticipated by the Consortium, mitigations measures were planned and implemented when the risks materialised.

Table 9: Major risks which materialised during RECYCLE project

Description of the risk	Proposed risk-mitigation measures	Residual risk (after mitigation)
Delays in the completion of demonstrator design and construction. The fabrication of the skids were delayed because of: **Delays in ordering items;** **Delays in receiving items;** **Delays in skid assembly.** **Unforeseen events during the procurement, construction and fabrication process.**	Mitigating actions associated with cost control and item procurement. Partners closely involved in the control of the plant the status of skid fabrication by weekly and bi-weekly meetings to receive an update on the status, plant layout, commissioning plan, and spare parts ordering. Contractors were continuously updated about the status of the skid; the project plan is frequently revised and discussed between the partners involved.	Delay in construction (WP4) and testing (WP5) - risk materialised
Unconventional items/equipment not available on the market	In some cases, such as valves or instrumentation, several revisions were required (e.g. valves and mass flowmeters, etc). In this case, actions included: i) revision of the P&ID; ii) revision of the control strategy. For some of those items which may be on a long lead, installation and calibration can be done in Manchester.	The risk materialised for some instrumentation and valves. To mitigate the problem, items from different suppliers have been purchased, thus delaying the order for some of them This also delayed the delivery of the skids.
Start-up/testing and operation delayed	Actions in place to mitigate the risk of additional delays to start the testing campaign. Follow up projects funded or partly funded by project partners to continue the demonstration after the end of the funding	Residual risk exists in case of unforeseen issues associated with the start-up and operation of the plant.

8. Commercialisation Plans

8.1 Discussion on scalability and applicability to other sites

An assessment of the hydrogen vs other decarbonisation routes has been carried out during the project and it is summarised in Table 10. This assessment is needed to understand, among sectors which require the implementation of decarbonisation technologies.

Three possible solutions were considered: decarbonisation by hydrogen (as fuel or chemical for the relevant process to replace natural gas); electrification to provide energy for heat and power via renewable sources; carbon capture, utilisation and storage to substantially remove the CO2 from flue gases and do not emit into the atmosphere.

For each sector, the likelihood of the implementation of each technology has been classified into viable (green), potential with some challenges (amber), and difficult (red). The scale and feasibility of each technology are contextualised to UK market, taking into account also plant size, existing industry in the territory, presence of industrial clusters, etc…

Table 10: The technical suitability of hydrogen versus other decarbonisation routes varies depending on an industry's process requirements

Sector	H2	Elec.	CCUS	Additional notes
Paper	🟡	🟢	🟡	Electrification will likely be the dominant route due to its technical feasibility and high efficiencies at raising the required steam with industrial heat pumps. However, hydrogen fuel-switching and CCUS may be of significant interest in major industrial clusters where there is supportive infrastructure nearby.
Cement	🔴	🟡	🟢	CCUS is critical for capturing unavoidable process emissions from clinker production. Combustion systems can be fuel-switched to burn hydrogen with some modifications, but process emissions will remain. Electrification complements CCUS but is currently at a low TRL.
Chemicals	🟡	🔴	🟡	These sites have some high-temperature requirements. Internal fuel use can make fuel-switching difficult. CCUS enables continued operation but is only suitable for a portion of site streams. Electrification is disruptive and low TRL.

Primary Iron & Steel	🟢	🟢	🟠	Hydrogen and electrification can significantly decarbonise the Iron production process if there is a shift away from blast furnaces – for which CCUS may be more relevant.
Refining	🟢	🟠	🟢	Many high-temperature processes. High internal fuel use makes fuel-switching difficult. CCUS is only suitable for some site streams but is required for process emissions. Existing demand for H_2, currently supplied by SMR & site processes such as catalytic naphtha reformation. Electrification could supplement the use of hydrogen and CCUS.
Glass	🟠	🟢	🟠	Hydrogen fuel-switching achieves the necessary high temperatures for glass production, but NO_X emissions and differences in flame emissivity make retrofitting challenging. Electrification is favoured for new builds due to operational benefits, higher energy efficiencies, and better product quality. CCUS can help capture process emissions and may be relevant in industrial clusters.
Food & Drink	🟠	🟢	🔴	These sites have low-to-moderate steam requirements, and electrification is likely to be the dominant route due to its technical feasibility and high efficiency at raising the required steam with industrial heat pumps. Hydrogen fuel-switching is likely not cost-competitive. CCUS is uneconomical for such small sites.

The market and replication analyses of the RECYCLE technology for use in different industrial contexts and sites provided the following key advantages, which could give it a competitive edge over alternative technologies, but would be limited to bio feedstocks for sustainable aviation fuel and sustainable methanol production (Table 11).

Table 11: Comparison of RECYCLE technology vs other conventional processes in the syngas value chain.

	Summary of key advantages with potential applications (RECYCLE vs traditional/Benchmark technologies)

Blue H_2 production	Lower CH_4 consumption compared to SMR, which will allow it to directly compete with traditional reforming once mature Air is used as an oxidant which eliminates the need for an ASU to provide high-purity O_2, as in the case of ATR. CO_2 is inherently captured at high rates and purity within RECYCLE, eliminating the need for expensive solvent-based capture. RECYCLE claims to have a lower levelised cost of H_2 production than SMR coupled with carbon capture and storage. RECYCLE’s own life cycle assessment indicates a significantly lower climate change impact than SMR+CCS for hydrogen production.
Blue ammonia	RECYCLE can produce a high-purity H_2 stream along with a nitrogen-rich stream, which can be used for NH_3 synthesis. Air is used as an oxidant which eliminates the need for an ASU to provide high-purity O_2, as in the case of ATR. CO_2 is inherently captured at high rates and purity within RECYCLE, eliminating the need for expensive solvent-based capture. RECYCLE claims to have a lower levelised cost of H_2 production than SMR coupled with carbon capture and storage. RECYCLE’s own life cycle assessment indicates a significantly lower climate change impact than SMR+CCS for hydrogen production.
Fischer – Tropsch to SAF	RECYCLE can produce syngas with a suitable H_2:CO ratio for FT synthesis. The modular design can simplify the siting of SAF plants and fit with FT modular designs, which are currently being developed. RECYCLE can produce SAF if bio-based feedstock is used. However, most SAF developers are targeting electrolytic H_2 and RWGS, rather than reforming technology due to the lack of biomethane feedstock available in large volumes.
Low-carbon methanol	Lower CH_4 consumption compared to SMR, which will allow it to directly compete with traditional reforming once mature RECYCLE can produce syngas at a suitable H_2:CO ratio for methanol synthesis.

	RECYCLE claims to have a lower levelised cost of H_2 production than SMR coupled with carbon capture and storage. Sustainable methanol can be produced if bio-based feedstock is used. However, most low carbon methanol developers are targeting electrolytic H_2, rather than reforming technology due to the lack of biomethane feedstock available in large volumes.

8.2 Considerations around access to revenue support mechanisms

Based on the techno-economic study and current industrial landscape, low-carbon hydrogen production through new technologies such as RECYCLE would require the following support mechanism to reach confidence from investors and potential end-users:

- The implementation of a new or similar mechanism to deploy a pre-commercial unit and operate it in conjunction with existing operators/end users who are looking at hydrogen as a decarbonisation route for their process (manufacturing or utilities).
- At commercial scale, the cost of low-carbon hydrogen production would require subsidies or policies in place to be competitive with respect to unabated fossil fuel traditional routes
- General policy implementation to favour low-carbon hydrogen use for small scale emitters which are very frequent (especially for boilers and furnace replacement) and they do not have a system in place ot decarbonise their process

8.3 Outcome(s) of conversations with prospective end users

Two industrial workshops have been organised during the project. the main outcomes of both events are summarised below:

- Strong progress in Teesside valley, with advancements in carbon capture, utilisations and storage (CCUS) projects, as well as the development of hydrogen production facilities to support industrial decarbonisation.
- Good progress in HyNet Northwest, driving the development of a low-carbon hydrogen economy and supporting industries in the region to switch from fossil fuels to hydrogen.
- Acceleration of industrial decarbonisation projects ahead of the 2030 goals, supported by increased investment and collaboration between government and the private sector.

- Increased collaboration between governments, industries, and research institutions, fostering greater innovation and technological advancements in industrial decarbonisation.
- High energy costs in Europe, making industrial decarbonisation more expensive and reducing competitiveness.
- Frequent delays in UK-funded projects due to bureaucratic hurdles, permitting issues, and regulatory challenges.
- Safety concerns around hydrogen production, storage, and transportation, requiring further infrastructure investment.
- Difficulties in establishing resilient supply chains for sustainable technologies, affecting project timelines.
- Lack of sufficient financial incentives for companies taking risks on decarbonisation initiatives.
- External geopolitical factors such as Brexit, Russia-Ukraine war, and US policy shifts creating market instability.
- Rising interest rates increasing the cost of financing large-scale decarbonisation projects.
- Provide stable and well-designed regulations, creating long-term market certainty to encourage private sector investment in decarbonisation technologies.
- Ensure clear and fair rules on intellectual property (IP), allowing companies to choose between multiple suppliers and foster innovation.
- Introduce targeted financial incentives and subsidies, such as tax credits, grants, and low-interest loans, to help companies scale up low-carbon technologies without excessive financial risk.
- Support scale-up efforts by reducing barriers to commercialisation, including streamlined permitting processes and funding mechanisms to help pilot projects transition to full-scale deployment.
- Encourage collaboration between similar decarbonisation projects, sharing best practices, technical insights, and lessons learned to accelerate progress.
- Adjust natural gas pricing structures, ensuring fair market conditions that encourage industries to transition to lower-carbon alternatives.

8.4 DESNZ acceleration support

At the final stages of RECYCLE project, DESNZ provided NZIP Acceleration 1-to-1 support to the Lead Partner in the form of consulting. The main aim was to assist the Lead Partner in understanding the target market segments, applications, customers, value proposition and possible business model. That support was a welcome addition to the market analysis and exploitation plan developed by the consortium members during the Project.

9. Conclusions and Next Steps

9.1 Was the project able to achieve its objectives?

The following objectives of the project were achieved in full.

- To design and assess the performance of a new process at industrial scale and optimise the design and operating conditions of key components at laboratory scale.
- To define the business cases, market needs, exploitation routes and commercialisation steps required to reach the market of the technology.
- To identify key sectors and stakeholders through market & policy analysis.
- To cooperate with stakeholders and other related projects within hydrogen, CCUS and industrial decarbonisation to cluster research synergies with UK and European institutions.

The following objectives were partly achieved:

- To build and operate a demonstration of next-generation net-zero technology at the University of Manchester.

In this case, the demonstration plant has been designed following safety requirements and best engineering practices. The key components have been procured, installed in multiple skids and delivered in Manchester, where the mechanical and electrical commissioning has been completed. Some of the units have already been operated as stand-alone with inert gases and as soon as the plant has the control system fully operational, the demonstration will start.

Since the demonstration has not started yet, the original demonstration objective of operating the plant for 500 hours to produce 20 kW of hydrogen while concurrently sequestering 80 kg/day of carbon dioxide was not reached within the project timeframe. However, we have already secured follow-on funding from project partners to continue the work of the project after the end date and to disclose non-confidential results of the testing campaign in the website and in the LinkedIn page. Those results will be also disseminated through research papers and attendance to international conferences in the area.

9.2 Lessons learned

The development of the RECYCLE project has overall confirmed the hypotheses beyond the scientific and commercial relevance of the technology and its potential for hydrogen and syngas generation. As with any new developing technology, new aspects, typically less scientific, have been discovered and will need to be considered for any follow up.

9.2.1 Technical Aspects

Plant complexity and challenges to design and build a small-scale demonstration plant. This aspect involves the low maturity of the supply chain and relevant components, such as valves, which require specialists on board to have a comprehensive and solid design. On the other hand, the possibility to operate the plant fully integrated, despite the associated risk, along with the positive numbers related to process performance and costs, would provide the necessary confidence to all industrial partners and end-users to invest in this technology. Furthermore, most of the technical challenges identified so far do not present a hard barrier to the deployment of the technology.

9.2.2 Economic Aspects

In the case of the RECYCLE project, the cost for fabrication and commissioning of the plant was primarily affected by the ATEX requirements which were found after the HAZOP and DSEAR assessment. Under these circumstances, the consortium had to go through repeated iterations with the DESNZ to find the best way to deliver the project while mitigating any circumstances generated by cost increases.

In terms of process development at large scale, the techno-economic study of different configurations (and different markets) provided some promising scenarios to deploy RECYLCE at scale. The main advantage of the technology is dictated by the relatively low costs of the chemical looping reactor units to generate syngas compared to existing reforming technology and the possibility to operate at small scale. On the other hand, to generate the product at the required specifications, several components are needed as balance of plant, and they are affecting the overall CAPEX and consequently, the cost of the products, especially at a small scale. The costs from the demonstration plant may not be reliable for larger scale CAPEX due to the difference in some design and selection of components, which were dictated primarily by the limited supply chain at small/experimental scales. To overcome this existing limit, detailed engineering for a pre-commercial plant is required to ensure that the costs of the RECYCLE are in line with expectations and more reliable, and the costs for other parts of the plant may be reduced by looking at specific suppliers and off-the-shelf units.

9.2.3 Policy and Regulatory aspects

With the existing market, policy and regulatory landscapes, low-carbon hydrogen will require substantial measures and resources to unlock market potential and uptake from consumers as recently highlighted by DESNZ [9].

This is due by the obvious costs compared to more traditional unabated hydrogen production routes. As long as policy and regulation are not implemented, the existing work exploitation may be limited to R&I and niche applications. For a wide deployment of the RECYCLE technology, two main conditions must be satisfied: 1) implementation of Hydrogen Market and Supply Chain; 2) implementation of CO_2 credits, transport and storage mechanism and related infrastructures.

To partially mitigate these existing barriers, RECYCLE technology, as syngas generation plant, could be used already in other traditional syngas technology or gas-to-liquids process using fossil fuels. However, unless CO_2 is removed and not emitted in the atmosphere, the expected advantage is limited with existing, established technologies already commercially available, hence reliable.

9.2.4 Project management

DESNZ funding scheme in terms of payment vs submission was somewhat different and unfamiliar to the Lead Partner from Academia at the early stages of the Project. The initial plan proved to be not adequately reflecting the actual cost expenditures (over invoicing periods) and deliverables and reports required adjustment to avoid financial imbalance and long payment intervals from The University of Manchester to partners and from DESNZ to The University of Manchester. This required initial change requests. Multiple partners with their specific cost/payment requirements also added to the complexity of the financial management of the Project.

The complexity of the plant and variety of suppliers, which became evident during the design and construction phase, required further change requests. Risk management was prioritised as some anticipated risks – delays - materialised during the design and procurement/payment process.

The complexity of the integrated process and the number of components showed the need for additional safety measures to be considered. Close interaction between partners hugely mitigated the risk of cost increase.

Systematic contacts with and support from DESNZ representatives were instrumental in the successful completion of the Project. Raising issues at the earliest stages and informing DESNZ representatives about them helped solve many problems before they might have become critical.

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Appendices

A1 List of Publications

Category of Activity	Author’s name and activity title	Journal / Conference	Key Achieve-ments / Outcomes	Date
Publication	The University of Manchester leading innovation in hydrogen economy. Initial Project Press Release	The University of Manchester Link here	General information about the project	06/2023
Publication	Vincenzo Spallina ‘Building the largest chemical looping plant in the UK from lab scale: the successful development in Manchester’	UKCSSRC Community Link here	General information about the project	10/2023
Presentation	Luigi Crolla ‘Comparative Assessment of New Emerging Chemical Looping Technology for Pure Hydrogen Production’	Abu Dhabi International Petroleum Exhibition and Conference (ADIPEC), Abu Dhabi	International Industrial Engagement	10/2023
Policy and comm. event	Vincenzo Spallina ‘Fuelling the Future: Using Low Carbon Hydrogen to Decarbonise’	House of Commons, London	Policy communication	10/2024

Presentation	Christopher de Leeuwe, Nicola Element ‘Combining Ni and Fe to lower the cost and environmental impact of Chemical Looping Reforming of CH4’	7th International Conference on Chemical Looping, Banff, Canada Link here	Scientific dissemination	10/2024
Presentation	Christopher de Leeuwe ‘RECYCLE: REthinking low Carbon Hydrogen production by Chemical Looping Reforming’	7th International Conference on Chemical Looping, Banff, Canada Link here	Scientific dissemination	10/2024
Presentation	Isabel Pazmino Mayorga ‘Hydrogen Production Via Chemical Looping: Modelling, Design and Techno-Economic Analysis’	7th International Conference on Chemical Looping, Banff, Canada Link here	Scientific dissemination	10/2024
Presentation	Vincenzo Spallina ‘High-Pressure Chemical Looping with Packed Bed Reactors: Challenges, Advances and New Process Configurations’	7th International Conference on Chemical Looping, Banff, Canada Link here	Scientific dissemination	10/2024
Presentation	Isabel Pazmino Mayorga ‘Chemical looping reforming: An emerging player in the hydrogen economy’	APEN-DISCO 1st Applied Energy Discovery Workshop on System integration of Hydrogen	Scientific dissemination, Industrial engagement	09/2025