

REthinking low Carbon hYdrogen production by Chemical Looping rEforming RECYCLE



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Feasibility Study Technical Report - Final

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2. Abbreviations And Definitions

Abbreviation	Definition
AACE	Association for the Advancement of Cost Engineering
BEIS	Business, Energy, and Industrial Strategy
BFD	Block Flow Diagram
BFW	boiling feed water
CAC	Carbon Avoidance Cost
CAGR	Compound annual growth rate
CAPEX	Capital Expenditure
CCR	Carbon Capture Rate
CCUS	Carbon Capture, Utilisation and Storage
CHP	Combined heat and Power
CLC	Chemical Looping Combustion
CLR	Chemical Looping Reforming
DMR	Dry Methane Reforming
EPC	Engineering, Procurement and Construction
FEED	Front-End Engineering and Design
FT	Fischer-Tropsch
GHG	Greenhouse Gas Emissions
GTL	Gas-to-liquid
HP/IP/LP	High/Intermediate/Low Pressure
HPLC	High-performance liquid chromatography
HT/IT/LT	High/Intermediate/low Temperature
KER	Key Exploitation Results
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCOH	Levelised Cost of Hydrogen
LHV	Lower Heating Value
MEA	Mono-Ethanol Ammine
MeOH	Methanol
NG	Natural Gas
NLPM	Normal litre per minute
OC	Oxygen Carrier
OPEX	Operating Expenditure
P&ID	Process and Instrumentation Design
PFD	Process Flow Diagram
PSA	Pressure Swing Adsorption
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
TCR	Total Capital Requirement
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
WGS	Water Gas Shift

3. Executive Summary

The development of new disruptive technologies with low-carbon intensity for the production of hydrogen is imperative to secure economic growth and competitiveness of UK industries.

Responding to the above challenge, REthinking low Carbon hYdrogen production by Chemical Looping rEforming (RECYCLE) has demonstrated during Phase I of the H₂ supply competition 2 the technical feasibility and opportunity to scale up and demonstrate during Phase II a new chemical looping technology for syngas generation with inherent CO₂ capture. 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.

This feasibility study is divided into 4 parts.

Experimental campaign to demonstrate the scientific and technical hypotheses beyond the concept: cumulative >1000 hours of testing three formulations supplied by Johnson Matthey close to relevant industrial conditions in terms of pressure, temperature, gas composition and gas velocity have provided an extensive amount of data used to validated advanced process modelling tools.

Process modelling and simulation: in collaboration with TotalEnergies, the integration of the process and comparison with conventional steam methane reforming with and without CCS have demonstrated the high performance of the technology in terms of energy efficiency, hydrogen yield and improvement of LCA KPIs. The complete design and pre-FEED engineering for the demonstration unit have also been provided for Phase II.

Economic study: an unbiased AACE Class 4 estimate study has been carried out by an external contractor (KENT plc) to assess the cost of the technology. Following a conservative design choice, the total capital requirement (TCR) and levelised cost of hydrogen (LCOH) are estimated to exceed the counterfactual SMR with CCS by 25% and 13% respectively. However, pathways to reduce the costs have been identified and they are going to be implemented in the next Phase. Following an optimistic scenario for the CAPEX, the RECYCLE process would result in a lower LCOH by 12% than the SMR counterfactual.

Market study and stakeholder analysis: while the feasibility study has focused on large-scale H₂ production (300 MW), the market analysis provided by Element Energy has demonstrated the huge opportunity at different scales, including 1-20 MW capacity to provide heat and energy. In these ranges, RECYCLE technology could develop a positive business case and results more cost-competitive than other technologies that rely on electrification.

4. Overview of the project

The key objective of RECYCLE is demonstrating the enhanced auto-thermal reforming process for the cost-effective production of hydrogen with a minimum CO₂ capture rate of 95% and CO₂ avoidance cost at least 20% lower than existing benchmark solvent technologies.

The technology proposed is based on dynamically operated gas-solid reactors which can produce syngas from natural gas (and other fossil fuel or biogenic sources) and inherently capture the CO₂ generated from the process.

The “RECYCLE” process operates using modular units which are also scalable and therefore it can be applied to both large-scale and small-scale applications. Other very relevant processes such as bio-based conversion, waste valorisation and gas-to-liquids (methanol, ammonia, sustainable aviation fuels) can also be integrated, thus de-risking the cost of implementation and development, especially for disruptive high-risk high-gain blue sky technology.

Building from the existing research carried out in the last four years over national and international research projects that have consolidated the technology to mature TRL4 level, this consortium will accelerate the scale-up of the technology aiming to demonstrate the integrated process to a pre-commercial scale. This will bring the technology effectively to a pre-commercial scale (in case of smaller units) with a horizon to build and operate the first unit in 5 years.

The RECYCLE technology will be studied from a techno-economic point of view using the specific industrial settings and requirements provided by industrial partners and end-users. The techno-economic, environmental and feasibility assessment will be carried out and used for market and policy-related analyses.

5. Description of The RECYCLE Technology

5.1 Theoretical background

Chemical looping reforming is considered one of the most promising technologies for syngas generation with inherent CO₂ capture because of higher efficiency than conventional CO₂ capture technologies^{1,2}. The term 'chemical looping' is used to describe the process in which a reaction breaks down into individual reactions in which the intermediates are in a continuous cycle of reaction and regeneration using a solid oxygen carrier (OC). To make the process feasible, the OC should have catalytic properties which can apply to the steam reforming process³. Some of the potential oxygen carriers are Ni, Fe, Cu, Mn, and other mixed oxides. For each case, there are several advantages but also disadvantages. In the case of steam methane reforming, the most common material is Ni-based catalyst⁴ which provides high reactivity and also a high mechanical strength at high temperature. On the other hand, Fe has relatively low performance for the process and also low reactivity with CH₄^{5,6} despite it being a cheaper option.

5.2 Process Description (the RECYCLE process)

The RECYCLE concept relies on a chemical looping process operated at high pressures in adiabatic packed bed reactors. It consists of three dynamically operated reactors as shown in Figure 5-1. Each reactor is sequentially exposed to:

1. Oxidation (exothermic, e.g., $\Delta H_{298K}^p = -479.4 \text{ kJ mol}^{-1}$ for Ni oxidation) of the oxygen carrier using air to generate heat, which remains stored inside the bed;
2. Reduction of the oxygen carrier using any available low-grade offgas which is converted into CO₂ and H₂O mostly heat neutral (e.g., $\Delta H_{298K}^p = -43.26 \text{ kJ mol}^{-1}$ with CO and $\Delta H_{298K}^p = -2.13 \text{ kJ mol}^{-1}$ with H₂ for Ni reduction);
3. Reforming (endothermic, $\Delta H_{298K}^p = 205 \text{ kJ mol}^{-1}$ in case of CH₄) of a CH₄-based gaseous fuel into syngas (CO and H₂) and cooling the reactor to result overall thermally balanced. This intensified process represents a high level of novelty since it combines syngas generation, direct heat transfer and CO₂ capture in a single unit. It was first introduced by Spallina et al.⁷.

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- ¹ M. Luo, Y. Yi, S. Wang, Z. Wang, M. Du, J. Pan, Q. Wang, Review of hydrogen production using chemical-looping technology, *Renew. Sustain. Energy Rev.* 81 (2018) 3186–3214. <https://doi.org/10.1016/j.rser.2017.07.007>.
- ² D. Li, R. Xu, X. Li, Z. Li, X. Zhu, K. Li, Chemical Looping Conversion of Gaseous and Liquid Fuels for Chemical Production: A Review, (2020). <https://doi.org/10.1021/acs.energyfuels.0c01006>.
- ³ V. Spallina, F. Gallucci, M. van Sint Annaland, Chemical Looping Processes Using Packed Bed Reactors, in: *Handb. Chem. Looping Technol.*, Wiley-VCH Verlag GmbH & Co. KGaA, 2018; pp. 61–92. <https://doi.org/10.1002/9783527809332.ch3>.
- ⁴ L.F. de Diego, M. Ortiz, J. Adánez, F. García-Labiano, A. Abad, P. Gayán, Synthesis gas generation by chemical-looping reforming in a batch fluidized bed reactor using Ni-based oxygen carriers, *Chem. Eng. J.* 144 (2008) 289–298. <https://doi.org/10.1016/j.cej.2008.06.004>.
- ⁵ P. Hamers, F. Gallucci, P.D. Cobden, E. Kimball, M. Van Sint Annaland, A novel reactor configuration for packed bed chemical-looping combustion of syngas, *Int. J. Greenh. Gas Control.* 16 (2013) 1–12. <https://doi.org/10.1016/j.ijggc.2013.02.021>.
- ⁶ A. Cabello, A. Abad, F. García-Labiano, P. Gayán, L.F. de Diego, J. Adánez, Kinetic determination of a highly reactive impregnated Fe₂O₃/Al₂O₃ oxygen carrier for use in gas-fueled Chemical Looping Combustion, *Chem. Eng. J.* 258 (2014) 265–280. <https://doi.org/10.1016/j.cej.2014.07.083>.
- ⁷ V. Spallina, B. Marinello, F. Gallucci, M.C. Romano, M. Van Sint Annaland, Chemical looping reforming in packed-bed reactors: Modelling, experimental validation and large-scale reactor design, *Fuel Process. Technol.* 156 (2017) 156–170. <https://doi.org/10.1016/j.fuproc.2016.10.014>

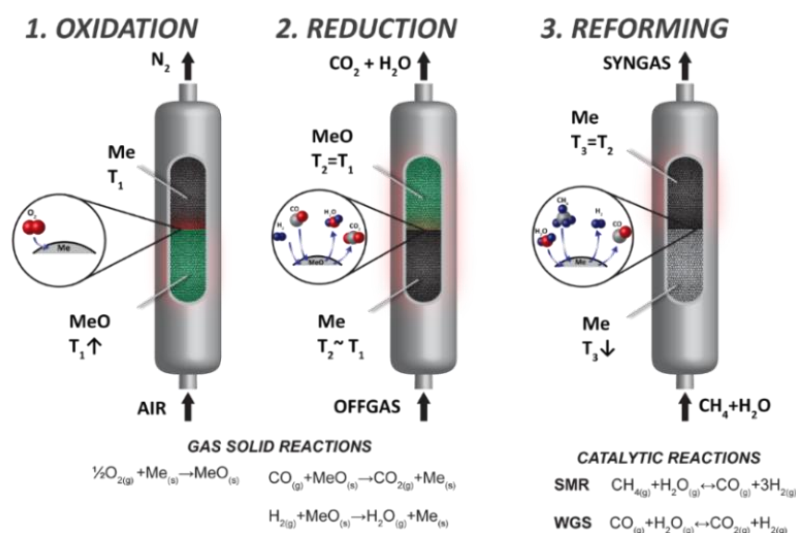


Figure 5-1 Chemical Looping Reforming in Packed Bed reactors process

5.3 Process Integration

The RECYCLE technology can be applied to **hydrogen production** with flexible design for other syngas-based products that make this **process suitable for several energy and carbon-intensive processes** (Figure 5-2) such as:

- Direct Reduction of Iron (steel manufacturing)
- Methanol synthesis (alternative transportation fuels such as maritime sector)
- Liquid fuels via Fischer-Tropsch for transportation (e.g. aviation)
- Ammonia synthesis which is a viable option to reduce the hydrogen storage intensity.

Feed fuel for the RECYCLE process **can be fossil fuel-based feedstock** such as natural gas, light hydrocarbons and waste streams from refineries or chemical plants such as flare gases. **Alternatively, bio-based feedstocks can be integrated** such as biogas and bio-waste liquids like glycerol or downstream 2nd generation biomass syngas (Figure 5-2 and Figure 5-3).

In the case of hydrogen production, the RECYCLE process does not need a 2nd expensive LT-WGS as the H₂ yield is enough in the reformer, not the selective CO₂ separation process at high purity (e.g. solvent technology) because CO₂ is inherently separated from the PSA offgas stream after the REDUCTION and delivered at high purity. The PSA is needed (as for conventional SMR plant without CO₂ capture plant) to deliver hydrogen at the required purity >99.9%. Therefore, the RECYCLE technology is primarily a syngas generation process that recovers the offgas stream from other processes such as the H₂ PSA. This is an intrinsic advantage of this technology as it could retrofit existing Reforming without changing the downstream units, reduce the overall cost of implementation and it could rely on commercial technologies (as in the case of WGS and H₂ PSA) reducing the risks and cost uncertainties.

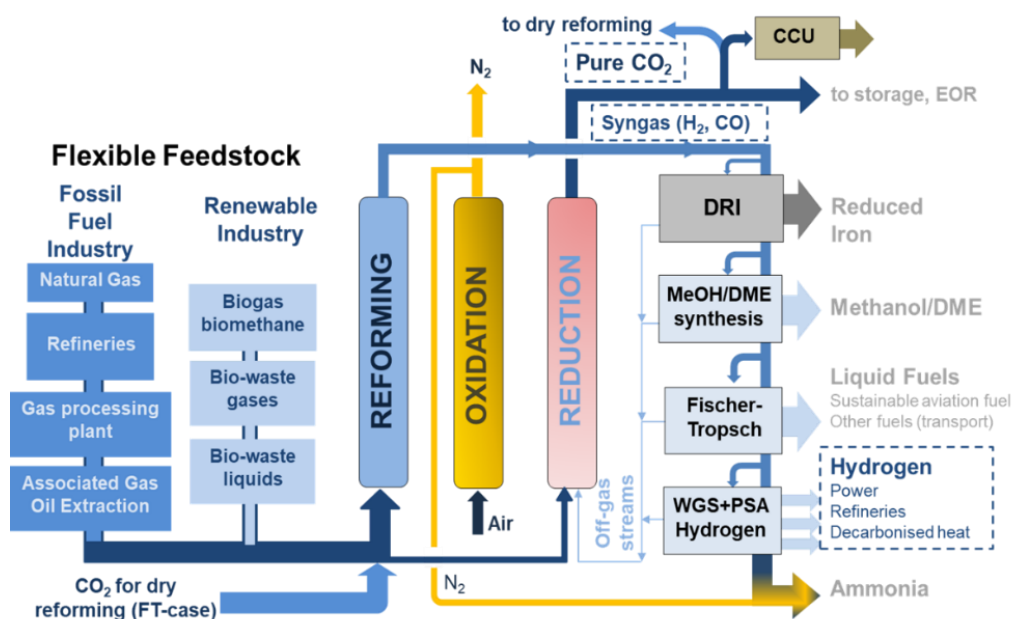


Figure 5-2 The RECYCLE process provides a flexible method for hydrogen or syngas production

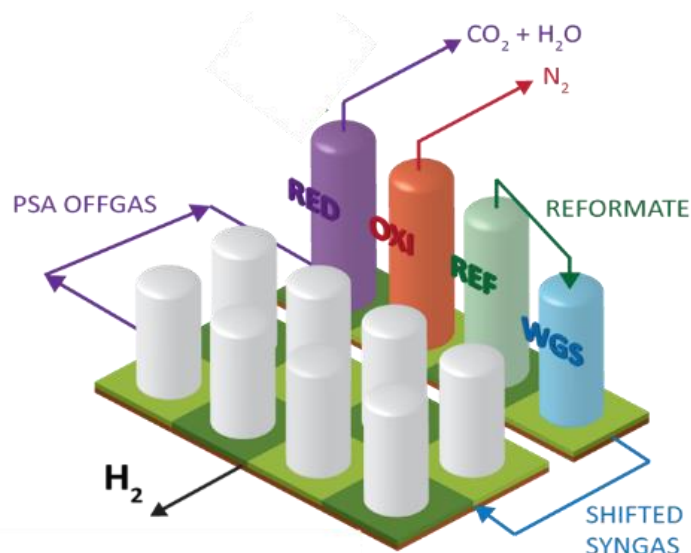


Figure 5-3 Potential plant configuration for RECYCLE⁸

The Feasibility study presented in this report focus only on hydrogen production. As **RECYCLE technology is modular, the application at different scales makes it suitable for different uses and applications** are currently under consideration given the impact on costs, market, technology challenges and relevance with respect to technology development and demonstration.

⁸ P.A. Argyris, A. Wright, O. Taheri Qazvini, V. Spallina, Dynamic behaviour of integrated chemical looping process with pressure swing adsorption in small scale on-site H₂ and pure CO₂ production, Chem. Eng. J. 428 (2022) 132606. <https://doi.org/10.1016/J.CEJ.2021.132606>.

6. Experimental and modelling results

6.1 Material and methods

The experiments have been conducted in the lab facility located at the University of Manchester. The overall experimental system is divided between two adjacent walk-in fume cupboards (Figure 6-1a and b). A schematic of the chemical looping packed bed reactor is shown in Figure 6-1c. The set-up consists of a high-temperature resistant SS tube (253MA material manufactured by Array Industries B.V) with inner diameter and length of 35 mm and 1050 mm respectively. Inside the reactor, there is a thermowell of 1050 mm in length and 6.3 mm in diameter having 10 K-type thermocouples.

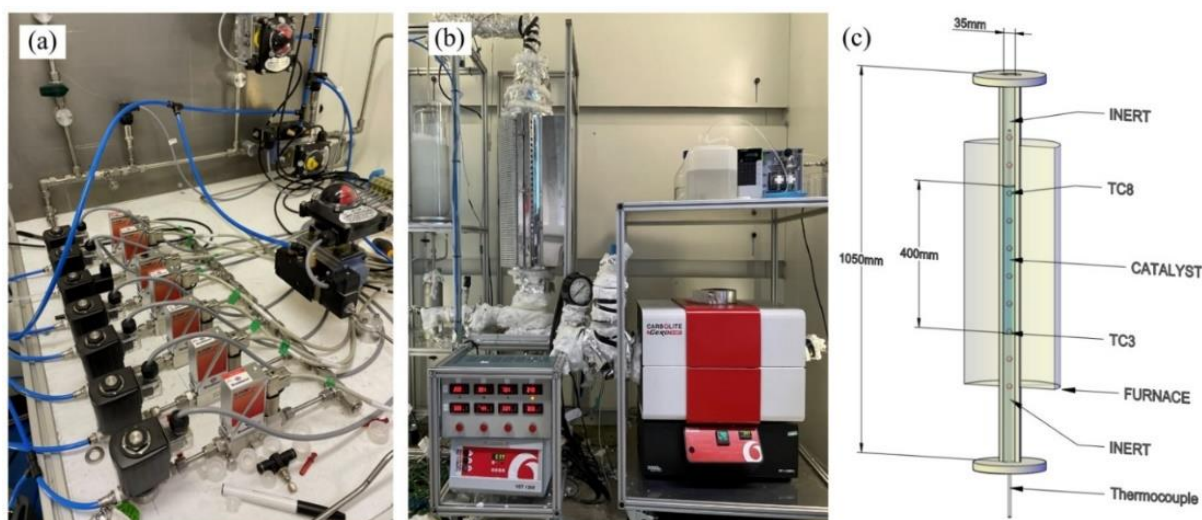


Figure 6-1: The TRL4 packed bed reactor set-up located at the University of Manchester having (a) a gas feeding system in FC-1; (b) a packed-bed reactor enclosed in a furnace placed in FC-2 and (c) schematic of a cross-section of the packed-bed reactor unit⁹

The RECYCLE concept has been firstly tested over dry reforming to produce syngas rich with H₂ and CO using Ni on CaAl₂O₄ provided by our project partner Johnson Matthey and the extensive laboratory campaign is reported in Argyris et al, 2022⁹. A P&ID of the whole system is presented in Figure 6-2.

⁹ P. A Argyris, C. de Leeuwe, S.Z. Abbas, A. Amieiro, S. Poulton, D. Wails, V. Spallina, Chemical looping reforming for syngas generation at real process conditions in packed bed reactors: An experimental demonstration, Chem. Eng. J. 435 (2022) 134883. <https://doi.org/10.1016/J.CEJ.2022.134883>.

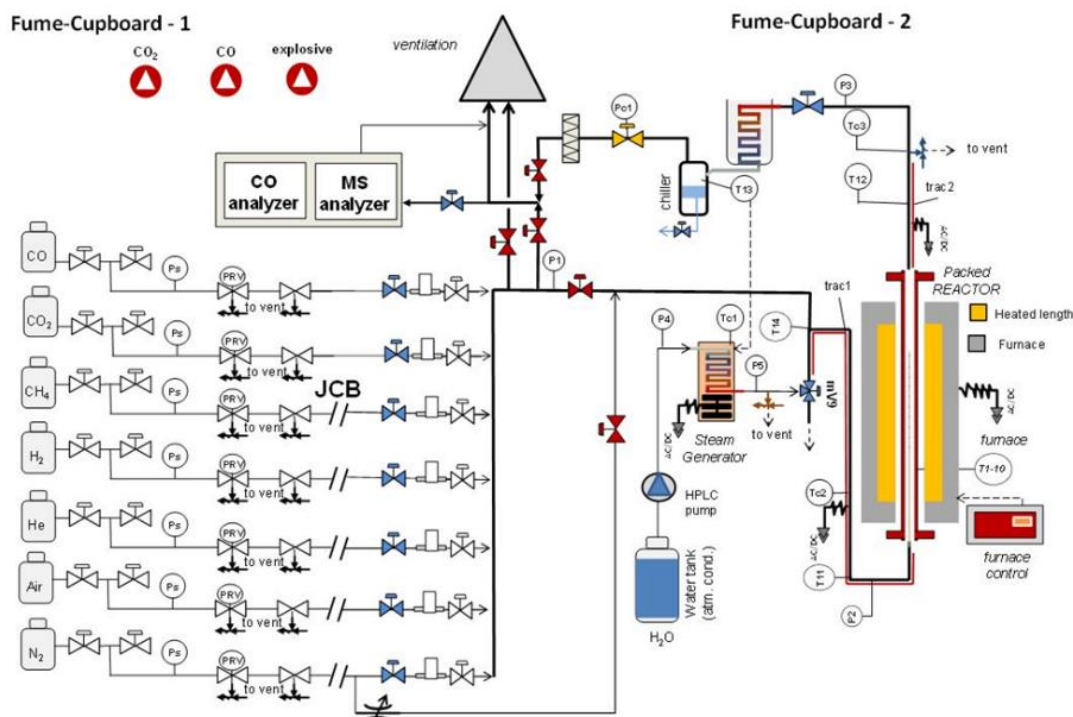


Figure 6-2 P&ID diagram of the large rig chemical looping setup at the University of Manchester

During Phase I of the Hydrogen Supply Competition 2, two new materials have been tested over dry and steam methane reforming as well as glycerol reforming to validate the concept also in presence of a waste stream from a bio-based process. For the next series of experiments both Fe and Ni-based OCs were tested with different shapes and compositions provided by Johnson Matthey to benchmark the 1st generation OC.

6.2 Results of the experimental campaign

A comprehensive experimental campaign has been carried out collecting overall more than 1000 hours testing. The testing has considered sequential oxidation, reduction, and reforming. The main achievements are reported as follows:

- 1) Oxidation: at increased temperature (and at $T > 600^\circ\text{C}$), the oxygen breakthrough becomes very sharp, and the material utilisation is $>90\%$ as demonstrated by the oxidation and maximum temperature rise inside the bed. The effect of pressure, oxygen content and flowrate (at $T > 600^\circ\text{C}$) are marginal, mostly influenced by the resulting gas velocity (thus residence time) while the kinetics do not show differences within the examined range.
- 2) Reduction: at increased temperature (and at $T > 800^\circ\text{C}$) the gas breakthrough is well defined, the material utilisation is $>80\%$, and both H_2 and CO are very reactive with the oxygen carrier, while in the case of CH_4 content ($>8\%$) some slip occurs at the very beginning. As the material tested (Ni, Fe) are catalysing the water gas shift reaction, after the oxygen carrier has been fully reduced, the breakthrough composition differs from the feed gas composition because of catalytic

conversion (in presence of H₂, CO and CO₂). The effects of pressure and gas flowrate do not impact significantly the conversion of the materials.

- 3) Reforming: the reforming has been demonstrated over a wide range of operating conditions including steam and dry condition with a H₂O-CO₂ over to CH₄ ratio from 3 to 7; pressure 1-9 bar, temperature 600-900°C and flowrate up to 10 NLPM.

The overall process has been run continuously for 4 complete cycles at the conditions reported in Table 6 at 1 bar and 5 bar. In this analysis, the furnace set-point was selected equal to 600°C (considered as the minimum temperature of the process at industrial scale). This has been required to compensate for the heat losses of a laboratory-scale rig. N₂ was also used as carrier gas, however, being an inert gas of the process, its presence did not affect the results.

Table 6-1 Inlet operating conditions for the CLR complete cycle (furnace temperature at 600 °C and p = 1-5 bar)

Inlet conditions	Oxidation	Purge	Reduction	Reforming	Purge
Flow Rate (NLPM)	10	5	14	14	13
Feed time (s)	250	120	180	600	120
NLPM in feed					
N₂	3.95	5	5	5	5
O₂	1.05	-			-
He	1	-			-
CH₄	-	-	-	1	-
H₂	-		2	-	
H₂O	3	3	3	3	3

The results are reported in Figure 6-3. The sequence is well defined, each step can provide a clear trend in the products. The CH₄ breakthrough during reforming is about 1% (at 1 bar) while it increases slightly at 5 bar (because of thermodynamic limitation). No carbon deposition was detected. The tests were repeated 4 times showing very good repeatability and temperature stability over time.

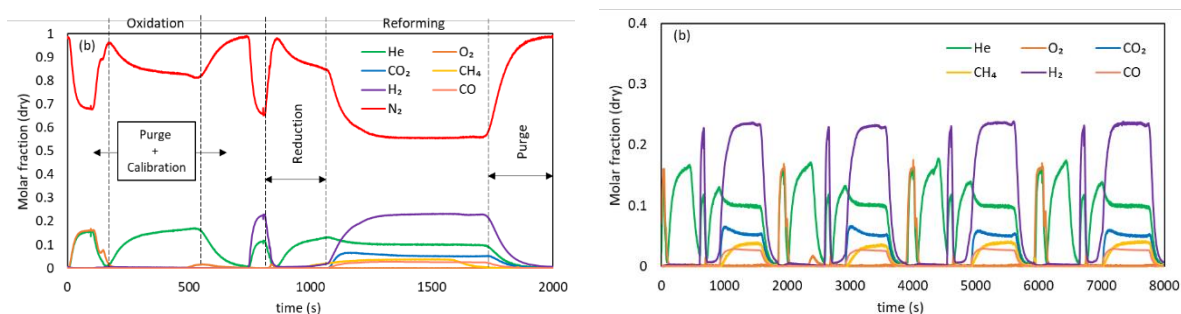


Figure 6-3: left: outlet molar fractions (dry) during complete CLR cycle at 5 bar, steam-to-carbon ratio = 3; right) recoded outlet molar composition and repeatability of the cycles during the experimental campaign.

The results reported below are the first and largest testing campaign ever carried out on chemical looping reforming with steam and CO₂ as other chemical looping processes (especially fluidised bed reactors) are hindered by solid circulation and operation at high pressure is extremely challenging.

6.3 Reactor modelling and validation

The experimental campaign has been supported by comprehensive phenomenological modelling aiming to understand the reactor behaviour and performance. In this study, one-dimensional (1-D) and two-dimensional (2-D) models have been developed to describe the dynamic operation of RECYCLE process. **The model results have been validated using the experimental data** discussed in section 6.2 and widely discussed in Argyris et al., 2022¹⁰. Both models have been validated presenting very good agreement with the experimental results. The comparison between modelling and experimental results has been carried out in terms of thermowell temperature and the gas composition breakthroughs, with the 2-D model capturing the thermowell temperature recordings with high accuracy, while the 1-D model delivered results that underestimated it by 2.5%. Nonetheless, the predicted average bed temperature presented a difference limited to 1% lower estimation of the 1-D to the 2-D model. Thermowell tends to be unable to capture big sharp temperature variations due to its thermal inertia, with temperatures during oxidation being higher even as 181 °C inside the bed, emphasizing the importance of the model in the proper design and safe operation of the reactor. The 1-D model, due to the significantly lower computation times (~21 times faster than 2-D), has been selected to be tested against a range of operating conditions for oxidation (500–600 °C, 1–5 bar, 10–40 NLPM, 10-20% O₂), reduction (600–900 °C, 1-5 bar) with H₂, syngas and CH₄-rich reduction agents and dry reforming (700–900 °C, 1-5 bar), delivering results with good agreement, especially for high temperature conditions where solid conversion is high and at conditions which resemble the expected industrial ones. Key results are reported in Figure 6-4, Figure 6-5, and Figure 6-6. The developed model shows a very good agreement with experimental results; thus, it provided reliability and accuracy to be used in the design of larger scale reactors (at pilot and industrial scale) and can be used to assess the heat management of the process.

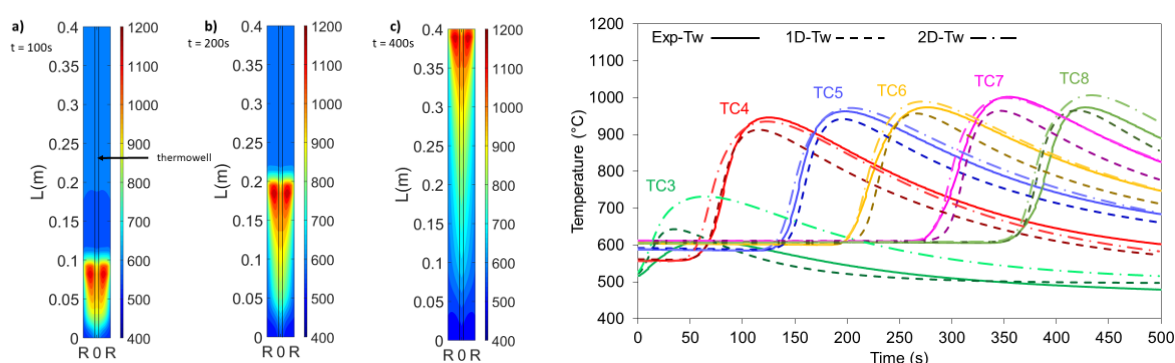


Figure 6-4: Oxidation: Left) 2D temperature profile (radial and axial) during oxidation at different times. Right) comparison of the axial temperature profile of experiments, 1D and 2D models for the different thermocouples available in the reactor¹⁰.

¹⁰ P.A. Argyris, C. de Leeuwe, S. Zaheer Abbas, Vincenzo Spallina, Mono-dimensional and two-dimensional models for chemical looping reforming with packed bed reactors and validation under real process conditions, *Sustain. Energy Fuels*. (2022). <https://doi.org/10.1039/D2SE00351A>.

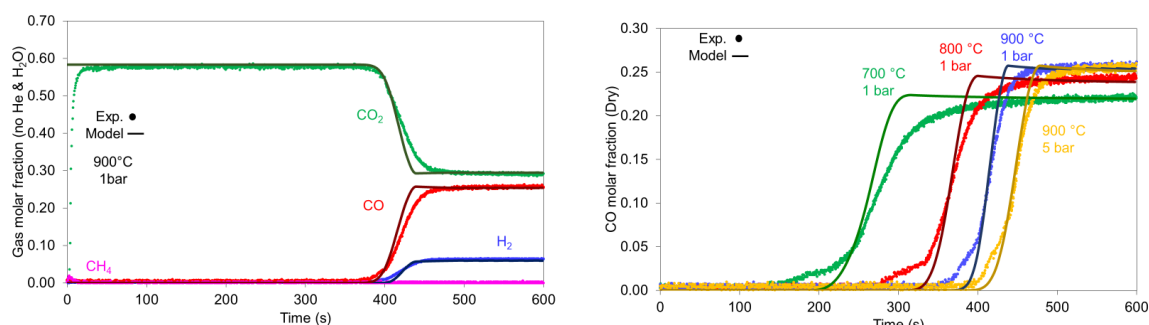


Figure 6-5: Reduction: Left) comparison of the 1D model and experiments for the gas breakthrough during reduction between experiments and the 1D model with CH₄/CO₂ mixture. Right) CO breakthrough during reduction at different pressure (1-5 bar) and temperature (700-900°C)¹⁰.

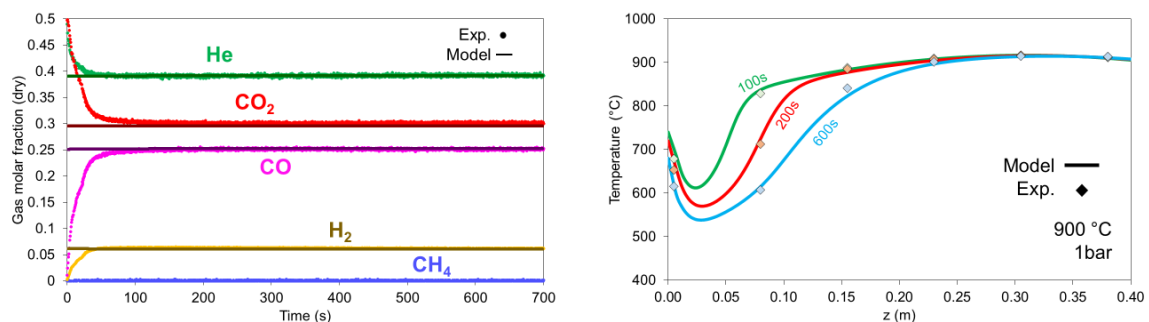


Figure 6-6: Reforming: Left) comparison of the 1D model and experiments gas composition at steady state operation; Right) Comparison of the axial temperature profile from the thermocouples during experiments and the model¹⁰.

6.4 Large Scale RECYCLE process

The schematic process flow diagram of the RECYCLE process is reported in Figure 6-7. The process presented in the feasibility study is related to hydrogen production from natural gas with capacity of 300 MW_{LHV,H₂}. This plant capacity corresponds to around 216 tons of H₂ per day (equivalent to 100 kNm³/h) and it can deliver H₂ with a purity of 99.99% as required in refineries and main industrial processes and for fuel cells where H₂ is required or will be required in the near future (see Market analysis section for further details).

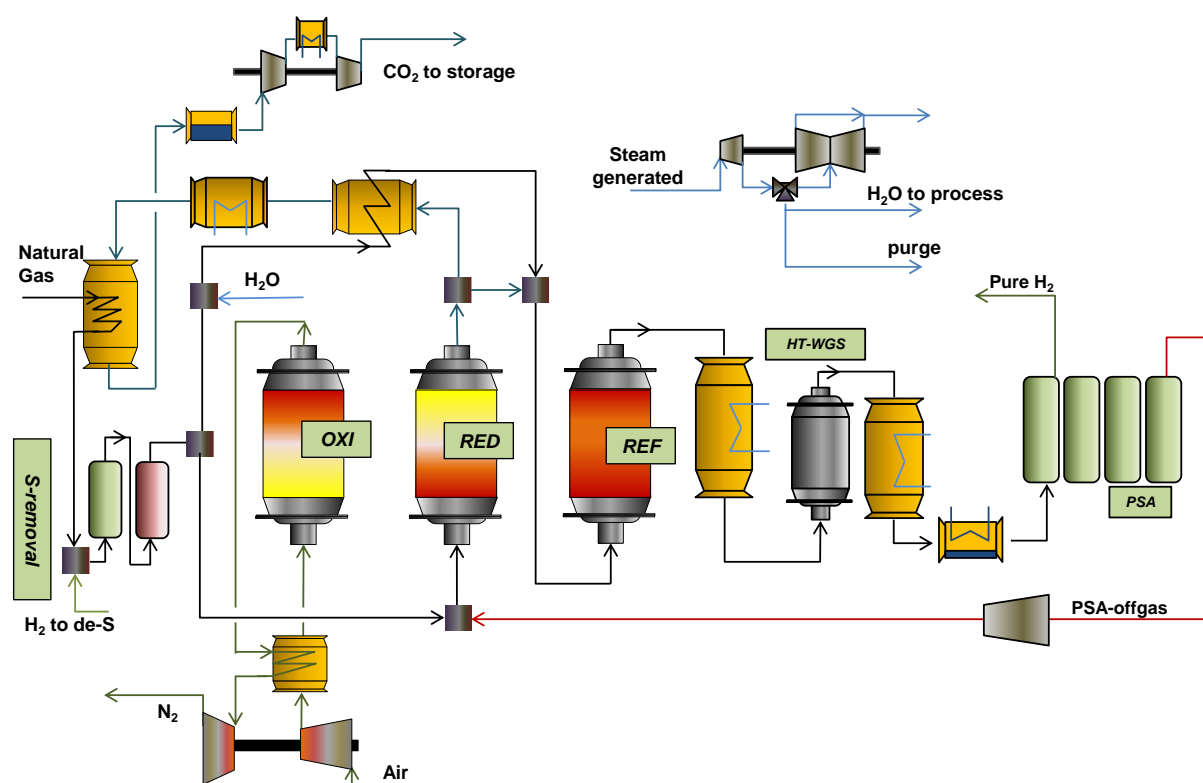


Figure 6-7 Process flow diagram of the RECYCLE process for H₂ production

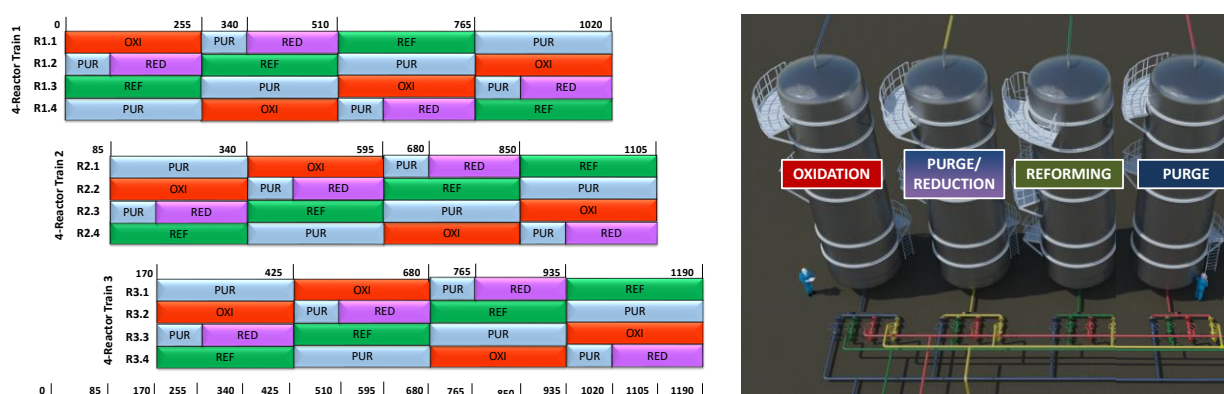
The natural gas is initially pre-treated to remove any sulphur present in the feedstock in the desulphurisation unit, after that, is mixed with steam heated up to 370 °C and fed to the reactors operating in reforming cycle. The syngas produced exits at average temperature of 1050 °C and it is cooled in syngas cooler heat exchangers down to 320 °C prior to entering the water gas shift reactor. The shifted syngas is further cooled down to 40 °C and sent to the PSA unit. The H₂ PSA achieves an 89% recovery of product gas at a purity of 99.99%. The tail-gas from the PSA unit (40 °C and 1.1 bar) is compressed in a tail-gas compressor mixed with some additional natural gas and distributed in the reactor operated in reduction (using NiO-supported on CaAl₂O₄ which is one of the materials successfully tested in the experimental campaign). To avoid fuel slip, the reduction is limited to achieve 96% of the total oxygen carrier capacity. The exit gas from the reduction reactors (containing H₂O and CO₂) is cooled by providing heat to the reforming feed, and the reduction inlet with the residual heat is recovered through preheating BFW. After H₂O condensation, the CO₂-rich stream (99.2 % purity) is sent to de-hydration and compressed to 110 bar for final transportation and storage. Oxidation is carried out using ambient air which is first compressed to 31 bar through a compressor. The compressed air is heated to 600 °C prior to being distributed to the reactor(s) in oxidation, with the exiting N₂-rich stream at T > 770°C first cooled and then expanded down to 1.05 bar in a N₂ turbine to recover energy and vented to the atmosphere. Finally, purging with steam before and after oxidation is carried out to avoid any mixing inside the reactor between air and fuel. Purging could also be done with recycled CO₂ instead of steam accepting some little fugitive emissions but at reduced energy and cost saving of steam production. This scenario will be considered in Phase II.

The operation of RECYCLE in packed bed reactors results in a pseudo-continuous operation of repeating process cycles as it is referred conventionally for dynamic processes such as PSA, TSA, and catalytic processes and also proposed and widely discussed for gas-solid reactors operated at high temperature^{11,12}. The cycle stages for the reactors are presented in Figure 6-8 for large scale plant with H₂ production output of 300 MW_{LHV}. The design and operation of the process have been carried out using the reactor model developed and discussed in section 6.3 using the operating condition reported in Table 6-2.

Table 6-2 RECYCLE reactor and simulation specifications

Parameter	Units	RECYCLE			
Reactor Length	(m)	10.0			
Reactor Diameter	(m)	2.0			
Bed porosity	(m ³ _g m ⁻³ _r)	0.4			
Particle Porosity	(m ³ _g m ⁻³ _s)	0.41			
Particle Diameter	(mm)	3.7			
Inlet conditions		Oxidation	Reduction	Reforming	Purge
Temperature	(°C)	600.0	540.0	600.0	350.0
Pressure	(bar)	31.0	31.0	31.0	31.0
Flow Rate	(kg s ⁻¹)	14.58	6.07	9.02	3.00
Feed time	(s)	255	170	255	85
Molar Fraction	(mol%)				
N ₂		79.05	0.63	0.22	-
O ₂		20.95	-	-	-
H ₂ O		-	-	74.59	100.00
H ₂		-	24.18	0.55	-
CO		-	15.51	-	-
CO ₂		-	45.74	0.50	-
CH ₄		-	13.94	24.14	-

The reactor network comprises 3 trains which can operate as a stand-alone unit and in combination with other trains Figure 6-8(left). According to the time displacement proposed, the process will result in a pseudo-continuous process with 3 reactors in Oxidation, 2 reactors in Reduction, 3 reactors in Reforming and 4 reactors in Purge.


Figure 6-8 left: Reactor operation strategy throughout a whole RECYCLE process; right) single train reactor network.

The outlet gas conditions from each reactor are presented in Figure 6-9 using an existing model already presented in Argyris et al 2021⁸.

¹¹ V. Fridman, M.A. Urbancic, Dehydrogenation process with heat generating material, US 2015/0259265 A1, 2015

¹² M.M. Bhasin, J.H. McCain, B. V. Vora, T. Imai, P.R. Pujadó, Dehydrogenation and oxydehydrogenation of paraffins to olefins, Appl. Catal. A Gen. 221 (2001) 397–419. [https://doi.org/10.1016/S0926-860X\(01\)00816-X](https://doi.org/10.1016/S0926-860X(01)00816-X).

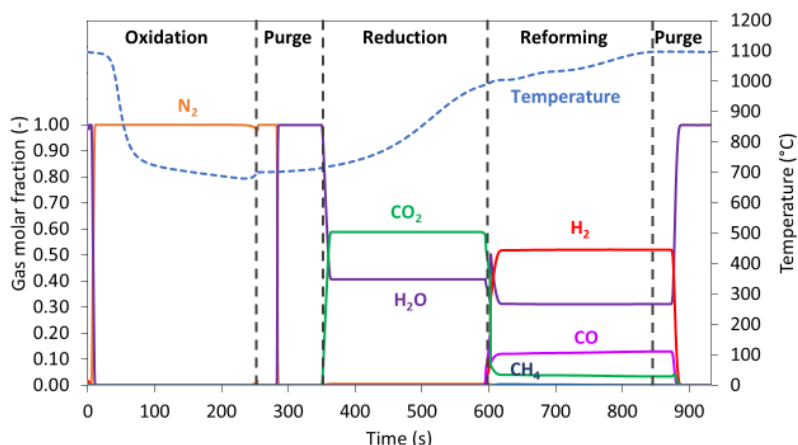


Figure 6-9: RECYCLE outlet each reactor after 1 complete cycle as predicted from the model.

The PSA dimensions were chosen based on the experience of the maximum size of vessels that are easily shipped, so as to keep the unit cost low¹³. The adsorbent bed was assumed to comprise of a feed inlet layer of activated carbon to remove primarily CO₂ and CH₄, with 5A molecular sieve added on top to remove the residual impurities (i.e., N₂ and CO) to achieve a 99.99 % H₂ product purity. For the RECYCLE case, a single H₂ PSA train would be sufficient to process all the feed syngas Figure 6-10. This was modelled as a 10-bed unit based on the designs suggested by Weist et al.¹⁴. On the feed step, syngas is introduced into the bottom of the vessel and a H₂ product gas obtained from the top. On the equalisation steps, gas is removed from the top of the vessels and added back into the top of another vessel on the same numbered re-equalisation step. During the provided purge step (PP) gas is removed from the top of the vessel and used for purging other vessels. After the equalisation and provide purge steps, the bed is reduced to the chosen regeneration pressure by removing gas from the bottom during the blowdown step. The adsorbent is then purged in a downwards direction using gas from vessels on their provided purge steps. After regeneration, the vessel is brought back up to the feed step via the re-equalisation (RE) steps followed by a final re-pressurisation step (RP) that uses part of the H₂ product gas. The outlet gas from the blowdown and purge steps constitutes the combined tail gas from the H₂ PSA which is sent to the reactor operated in reduction as explained in the syngas generation part.

1	F				E1	E2	E3	E4/PP	PP	BD	P				RE4	RE3	RE2	RE1	RP	
2	RE1	RP	F				E1	E2	E3	E4/PP	PP	BD	P				RE4	RE3	RE2	
3	RE3	RE2	RE1	RP	F				E1	E2	E3	E4/PP	PP	BD	P				RE4	
4	P	RE4	RE3	RE2	RE1	RP	F				E1	E2	E3	E4/PP	PP	BD	P			
5	P		RE4	RE3	RE2	RE1	RP	F				E1	E2	E3	E4/PP	PP	BD	P		
6	BD	P		RE4	RE3	RE2	RE1	RP	F				E1	E2	E3	E4/PP	PP	BD		
7	PP	BD	P		RE4	RE3	RE2	RE1	RP	F				E1	E2	E3	E4/PP			
8	E3	E4/PP	PP	BD	P				RE4	RE3	RE2	RE1	RP	F				E1	E2	
9	E1	E2	E3	E4/PP	PP	BD	P				RE4	RE3	RE2	RE1	RP	F				
10	F	E1	E2	E3	E4/PP	PP	BD	P				RE4	RE3	RE2	RE1	RP	F			

F = Feed; E = Equalisation PP = Provide purge; BD = Blowdown, P = Purge; RE = Re-equalisation; RP = Re-pressurisation

Figure 6-10: 10-vessel H₂ PSA cycle

¹³ S. Hall, [Rules of Thumb: Tanks and Vessels - Features - The Chemical Engineer](#)

¹⁴ E.L. Weist, D. Wu, J. Xu, B.E. Herb, B.C. Hoke, US9381460B2 - Pressure swing adsorption process, US9381460B2, 2016. <https://patents.google.com/patent/US9381460B2/en?q=US9381460>

7. RECYCLE demonstration project

7.1 Description of the demonstration project

Phase II of the BEIS Hydrogen Supply 2 Competition is aiming at the construction and demonstration of a low-carbon hydrogen plant replicating the RECYCLE process at pilot scale, thus fully integrating syngas generation via chemical looping technology, water gas shift reactor and H₂ purification plant via PSA. **The demonstration project in Phase II aims to operate the fully integrated plant to produce up to 110 NLPM of syngas, with an expected H₂ production of 11 kg per day (corresponding to 15 kW_{LHV}).**

Location site: The James Chadwick Building (Manchester)

The demonstration of the RECYCLE technology will be carried out in the James Chadwick Building (JCB), Figure 7-1. The JCB is a 4-floor building built in 2009 in which we have currently ≈400 m² available to accommodate a pilot scale unit. The JCB building is located beside the new engineering building of the University of Manchester. It is located in front of the Graphene Institute and the Henry Royce Centre within a walking distance of most of the centres of excellence in advanced materials, energy, and bioengineering. It is part of the University of Manchester innovation cluster. In June 2022, the Wolfson Foundation granted £ 1M to build the **Industrial Hub for Sustainable Engineering**¹⁵ which has been top up with an additional £1.7M from the University as a strategic investment to develop next-generation technologies and demonstration up to pre-commercial scale to support industries and small business to flourish and move the research from academia to market. The existing investment will look at H₂ economy and CO₂ chemistry to build two integrated rigs for fuel synthesis (mainly methanol and liquid fuels) for the first phase with a clear vision of chemicals and commodities. The building will be a unique location in the UK fully integrating the *PCS NeO system* developed by Siemens for the automation and control of chemical and manufacturing processes. In addition, the University will provide advanced instrumentation to improve the research capacity of the department in new material development, testing and characterisation. **The RECYCLE process will be installed and tested in the pilot area of the JCB, fully integrated with the existing rigs for liquid fuel synthesis to provide further testing and validation of the technology for hydrogen and low-carbon fuels (as explained in the market analysis).** Moreover, the demonstration during Phase II will have access to the existing resources of the University (control, instrumentation, laboratories, instrumentation) to work closely for the improvement and optimisation of the performance.

During Phase I, the University of Manchester carried out a cost estimation and requirements to install a fully automated hydrogen plant based on RECYCLE concept and subsequently to interconnect the new system with a centralised control room based on the ultimate Siemens PCS Neo system.

¹⁵ [Sustainable Hub for Chemical Engineering | StaffNet | The University of Manchester](#)

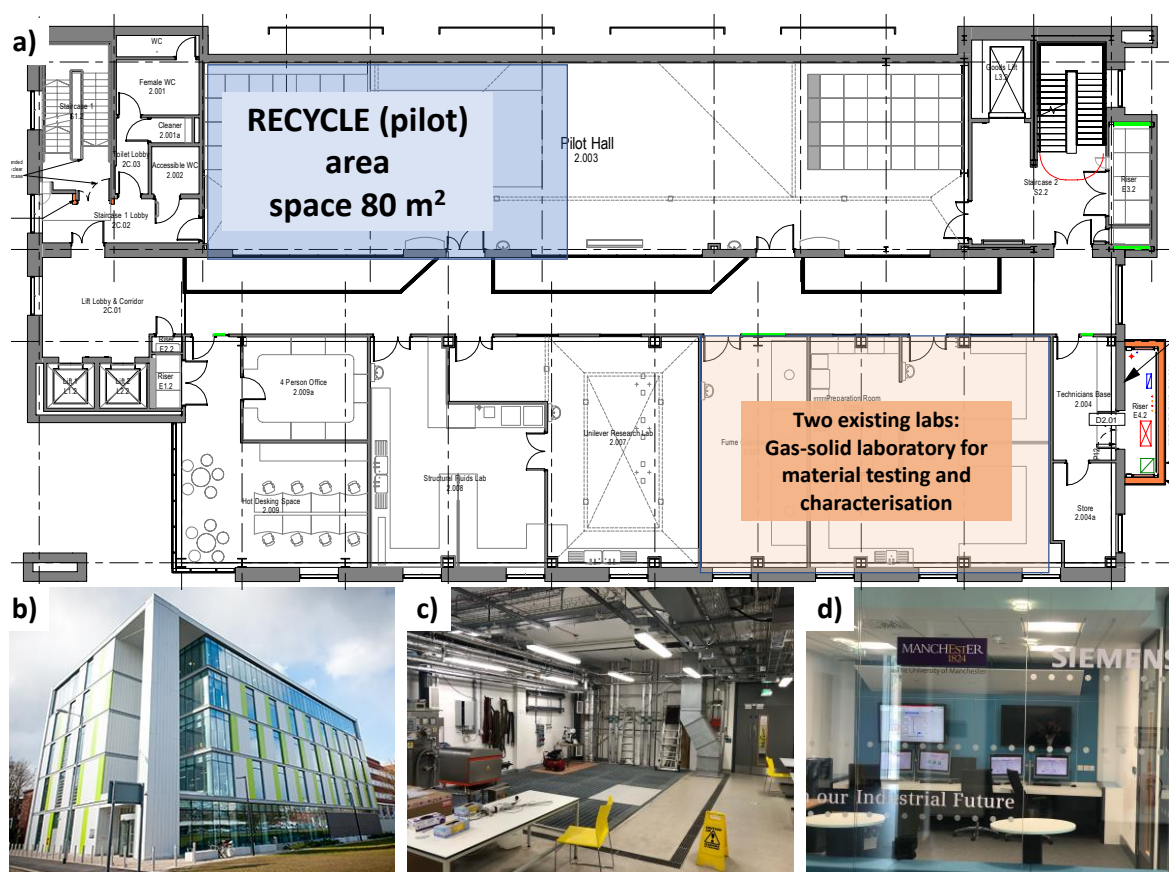


Figure 7-1: a) pilot area identified for the building and construction of the RECYCLE demonstration during Phase II; b) view of the James Chadwick Building (JCB); c) pilot all area in the JCB; d) central control room of the pilot area.

Syngas Generation: chemical looping reforming

Syngas generation will be carried out using three reactors fully interconnected and dynamically operated filled with oxygen carrier materials provided by Johnson Matthey. The overall syngas generation unit will operate up to 30 bar and in a temperature range of 600-900°C. Each reactor will include a furnace/heating elements that are needed to provide initial heat for the activation of the materials/catalyst, and start-up while the process is expected to run thermally balanced. Compared to Phase I, the scale-up of the technology will increase by a factor >20 (Table 7-1) with a schematic 3D design available in Figure 7-2. In terms of process operation, the 3-reactor rig will be integrated with downstream units and the experimental campaign will be carried out close to real industrial operation (pressure, temperature, gas velocity, reduced heat losses, composition).

Table 7-1 RECYCLE syngas generation comparison between Phase I and Phase II

	Phase I (feasibility study)	Phase II (demonstration)
Reactor in operation	1	3
Reactor volume (single)	1 litre	20 litres
Amount of Oxygen carriers	400-500 grams	30 kg (3 reactors)
Flowrate (in case of CH ₄)	1 NLPM	30-40 NLPM
H ₂ output (syngas)	2.7 NLPM (500 W _{LHV})	80-100 NLPM (20 kW _{LHV})

The temperature along the reactor is controlled using a multipoint thermocouple as in the case of the laboratory scale reactor. The syngas generation unit has been designed to operate with the following flowrates:

Oxidation: 100-200 NLPM (design 150 NLPM) of air. Air will be available at 2 bar from the pipelines in the JCB building compressed up to the operating pressure of the reactor operated in oxidation pressure. Air for oxidation will be pre-heated at the beginning of the reactor where inert solid material is present.

Purge: up to 100-200 NLPM (design 150 NLPM) of inert nitrogen. Nitrogen will be available at 2 bar from the pipelines in the JCB building compressed up to the operating the plant.

Reduction: 100-200 NLPM (design 150 NLPM) of mixed gases with variable composition of (H_2 : 10-50%, CO : 2-20%, CO_2 : 5-50%, CH_4 : 1-10%, N_2 : 0-20%; H_2O : 0-30%). The composition during reduction is not fixed as it will depend on a case basis (industrially relevant) that will be considered where different waste offgas could be available. The design of the feeding system has been chosen to operate flexibly. Moreover, at industrial scale, the reduction will occur using tail gas from a PSA unit and therefore the stream will be connected from the H_2 purification unit (multi-bed PSA) to the feeding system of the reactor operated in reduction.

Reforming: a combination of CH_4 , H_2O and CO_2 will be used to produce a syngas flowrate of 110 NLPM. For the RECYCLE process, a design condition of H_2O/CH_4 ratio of 3 will be used as this is the most suitable for the syngas generation in hydrogen production plant. However, the demonstration campaign will consider also different H_2O/CH_4 content as well as the mixture of H_2O/CO_2 with CH_4 to obtain different syngas compositions with variable H_2/CO ratios. Those campaigns will demonstrate the feasibility of chemical looping as a viable route for MeOH and FT-liquid fuels which are among possible solutions in the hydrogen economy. The gas will be compressed up to the operating pressure of the reactor operated in reforming and mixed with steam.

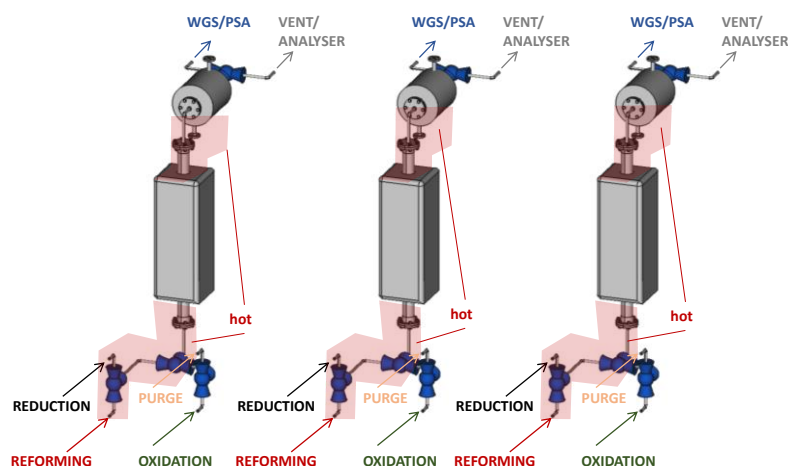


Figure 7-2: 3D drawing of the Chemical looping reactors

After the syngas generation unit, the flow leaving the reactor operated in reforming is sent to a WGS reactor (SS 316L). The reactor size will be also approximately 80 mm and length of 2 meters. The reactor design will be up to 450°C and 30 bar.

H₂ purification: design and list of equipment

For the design of the H₂ PSA test unit, the following assumptions have been made.

The PSA unit is designed to operate up to 150 NLPM with a molar composition is assumed to be: CO₂ (10-20%), CH₄ (0-2%); CO (6-10%); N₂ (0-2%); H₂ (50-90%).

1. Experiments will be performed where the outlet pressure on the feed step can lie between 6 bar and 30 bar.
2. The regeneration pressure is 1.1 bar, but this can be increased during testing if required.
3. The adsorbent particles are 2.0 mm diameter spheres. The adsorbent bed is a split of 75 % activated carbon followed by 25 % 5A molecular sieve.

For a more representative design of the H₂ PSA compared with a full-scale process, a 4-bed unit was evaluated. This design includes an equalisation step to the cycle which aids with H₂ recovery. The P&ID of the PSA unit is presented in Figure 7-3. Different options have been evaluated to perform the control of the process as shown in Figure 7-4. The selected design is based on the use of control valves. Apart from the 4 beds, the PSA unit also includes a blowdown tank to stabilise pressure and flowrate before sending it to the unit operated in reduction.

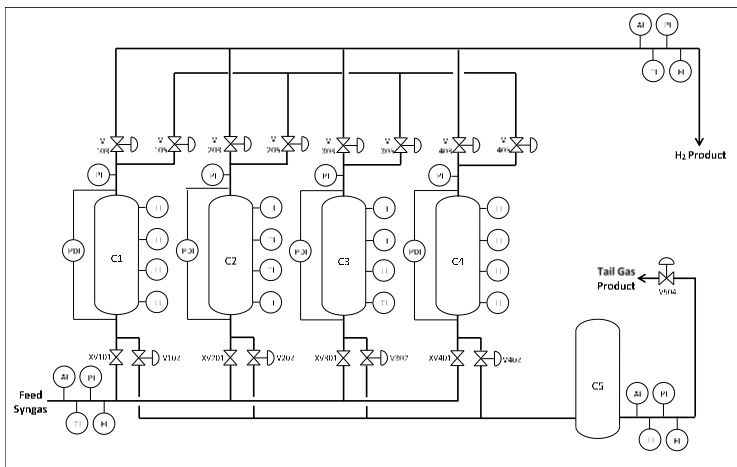


Figure 7-3: Schematic of a 4-bed design using control valves

The sequence of steps for this 4-bed design is reported in Figure 7-4.

Bed	t _{feed}		t _{feed/2}	t _{feed/2}	t _{feed/2}	t _{feed/2}	t _{feed/2}	t _{feed/2}
1	F		E	PP	BD	P	RE	RP
2	RE	RP	F		E	PP	BD	P
3	BD	P	RE	RP	F		E	PP
4	E	PP	BD	P	RE	RP	F	

F = Feed, E = Equalisation, PP = Provide Purge, BD = Blowdown, P = Purge, RE = Re-equalisation, RP = Repressurisation

Figure 7-4: PSA 4-bed design cycle

The bed size was fixed at 2.0 m in length and 63 mm in diameter (2 ½ inch piping). For feed pressures from 30 bar down to 12 bar, this provides sufficient adsorbent to process all the feed gas in a reasonable cycle time. Below 12 bar the cycle time starts to become too short for a typical large scale H₂ PSA unit. The design is based on a target H₂ purity of about 99.99 %. The calculated H₂ recovery in turn ranges from 70 % up to 84% which is close enough to the 89% purity targeted in industrial scale PSA.

7.2 RECYCLE project team

The **RECYCLE team for Phase II will include three additional partners**: HELICAL Energy, KENT plc and Element Energy. They will cover the full value chain to ensure the commercial feasibility of the technology. Roles and responsibilities are reported in Table 7-2.

Table 7-2 RECYCLE: consortium partners and roles during Phase II

Partner	Responsibility
The University of Manchester	Project Coordinator Testing and Demonstration
Johnson Matthey	Material Supply and technology provider
TotalEnergies	End users of the technology, market requirement
Helical Energy	EPC company Responsible of design and manufacture the pilot scale unit
KENT plc	EPCM Contractor: - responsible for the techno-economic study and process benchmarking
Element Energy	Exploitation, Dissemination and Communication

The presence of an Industrial **Advisory Board** (to be set in the first 6M) will reinforce the technological and industrial orientation of the project and provide a wider industrial roadmap and exploitation plans. The industrial advisory board will be part of the stakeholder engagement task and will host potential end-users interested to use RECYCLE for their process.

The total cost for Phase II is estimated to be £ 5.2M for a 2 years project. Design, engineering, and procurement of Demonstrator (20%); Material and construction of the Demonstrator (28%); site preparation and design engineering costs, commissioning: (8%) additional onsite equipment (5%); testing and demonstration step: (9%) technology at industrial scale (21%); Exploitation, communication and dissemination (5%); Management and reporting (4%).

8. Benefits and barriers

8.1 The economic analysis

TotalEnergies and the University of Manchester have requested to an external contractor (KENT plc) to develop an unbiased techno-economic assessment of the RECYCLE technology (block diagram available in Figure 8-1 and Table 8-1) and compare with a counterfactual SMR with CCS by using mono ethanol ammine (MEA) as presented in an IEAGHG study performed by Wood)¹⁶.

- Complete an unbiased techno-economic study assessment of the RECYCLE technology in the capacity of producing blue hydrogen. The estimate provided by the study is an AACE Class 4 estimate (accuracy range +50%/-30%), based on the 4Q2021 price level, in Pound Sterling (£).
- Compare the RECYCLE technology with a benchmark process for blue hydrogen.
- Gain an understanding of the operational flexibility.
- Gain an understanding of the trade-off between different CO₂ capture rates, Levelised Costs of Hydrogen (LCOH), utility costs and Carbon Avoidance Cost (CAC).

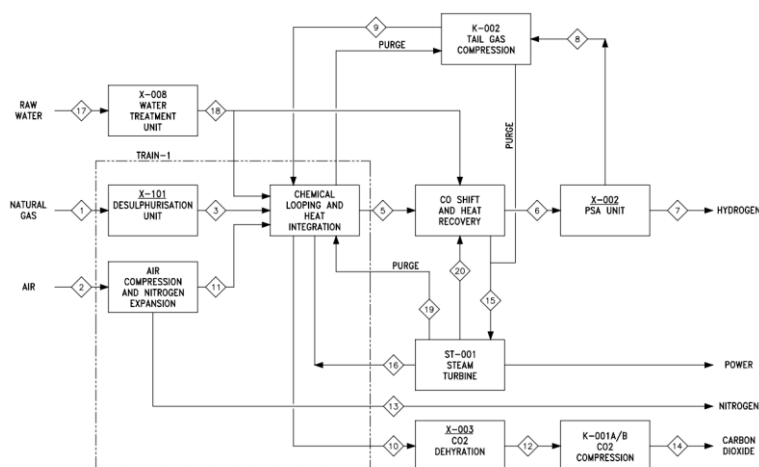


Figure 8-1: The Block Flow Diagram of the overall arrangement for the RECYCLE

Table 8-1: Process considered in each plant

Plant area	Associated Units	Description	Package Item Tag	
Hydrogen plant	100	Air compression	GT-101	Train
	200	Nitrogen expansion	GT-101	Train
	300	Natural gas feedstock/ desulphurisation	X-101	Train
		Chemical looping	R-101/102/103/104	Train
		Water Gas Shift reactor	R-001	Common
		Hydrogen purification	X-002	Common
			K-002	Common

¹⁶ IEAGHG 2017-02 report “Techno-Economic Evaluation of SMR Based H₂ Plant with CCS” available at [2017-02.pdf \(ieaghg.org\)](https://www.ieaghg.org/)

		Tail gas compression		Common
Power island	600	Steam turbine	ST-001	Common
CO₂ delivery	400	CO ₂ compression CO ₂ dehydration	K-001A/B X-003	Common Common

The RECYCLE plant has been positioned in a site located in an undisclosed area in the UK, with no major site preparation required which is typical for an industrial cluster. It was assumed that there are no restrictions on plant area and no special civil works or constraints on the delivery of equipment. Rail lines, roads, fresh water supply and high voltage electricity transmission lines, and high-pressure natural gas pipelines are considered available at plant battery limits. An area may be required in addition to the Site Plan for Construction activities, materials delivery/storage, and fabrication/erection facilities. This is not included within the current overall footprint.

The overall Total cost of the Plant is divided into the Hydrogen plant, CO₂ treatment unit, Power Island, utilities and balance of plant. The Hydrogen plant accounts for 81% of the TPC.

A breakdown of the costs is as follows (Figure 8-2). **Chemical looping reactor trains represent 41% of the total cost of the Hydrogen plant cost.** The reactors are expected to be constructed in carbon steel with refractory material to reduce heat losses. Reactors also include a heat exchanger to cool down the gas (and generate steam) before reaching switching valves. This design would allow the valves to operate at a lower temperature. This is a conservative design choice, and it provides a worse-case cost scenario. Furthermore, The WGS reactor considered for this first study is based on an advanced shift reactor (thus 20% of the total cost of the hydrogen unit). The current design is not optimised; some equipment designs would require further analysis in terms of heat integration and component sizing as well as opportunities for unit retrofitting within the existing plant (e.g. PSA, WGS, feedstock pre-treatment).

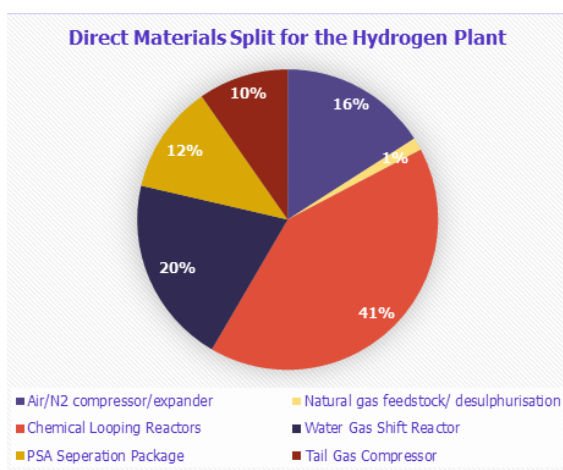


Figure 8-2: cost breakdown of Direct Material costs

However, this would be more accurately estimated once the technology is validated at a larger scale, therefore this study has provided conservative figures for the capital expenditure. With the current design, the total capital requirement (TCR) is estimated to exceed the counterfactual SMR with CCS by approximately 25%. The OPEX of the SMR+CCS has been updated according to the BEIS¹⁷. The annual O&M costs are shown in Figure 8-3.

The total plant costs for the RECYCLE plant range from £ 280-400M. The total operating costs are approximately between £ 115-140M per year.

¹⁷ [Hydrogen Supply Competition - ITT and Guidance Notes \(publishing.service.gov.uk\)](https://publishing.service.gov.uk)

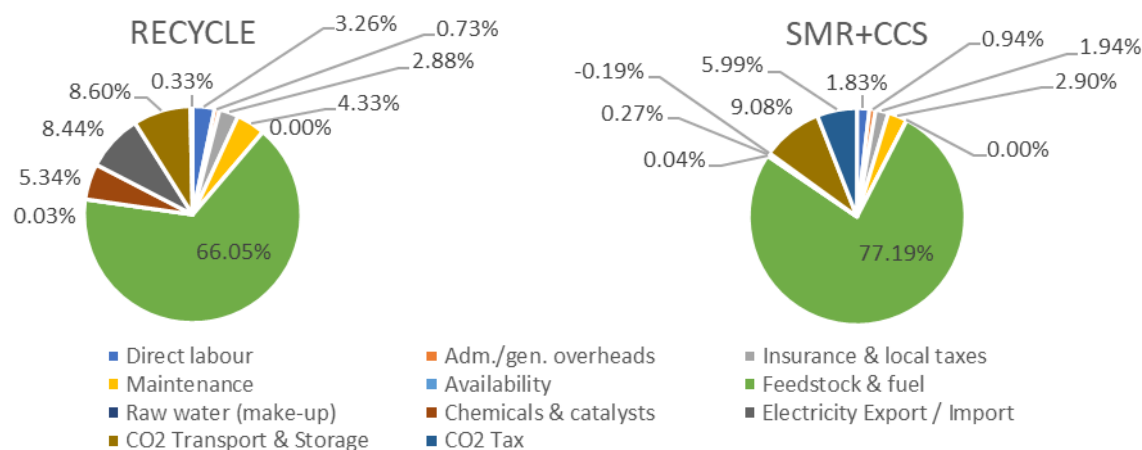


Figure 8-3: Cost comparison of the operating costs

In terms of job creation, RECYCLE will support the deployment of the hydrogen economy at scale, and it will take part in the new job creation related to renewable energies. During Phase II, the business model developed per each industrial partner and non-industrial partner will take into account how the deployment of RECYCLE at scale could provide new jobs and skills including both direct and indirect opportunities. The techno-economic study has estimated that a plant of 300 MW (as the one presented in the feasibility study) will require 63 operators.

8.2 Life Cycle Assessment

A preliminary LCA has been performed on the RECYCLE process and the results compared against SMR with CCS for the production of blue H₂. **The LCA results show that the RECYCLE technology could reduce GHG emissions by 53% compared to conventional SMR with post-combustion CO₂ capture MEA-solvent.** RECYCLE also results in lower eutrophication and acidification as no solvent is used. Despite a large amount of Ni-based catalyst/oxygen carrier required, this has a very low impact on the environment compared to energy (electricity + natural gas); water scarcity is also less damaged thanks to a lower water consumption compared to SMR. Some other impacts, such as toxicity and land occupation, are damaged due to the import of electricity in the RECYCLE process although RECYCLE will require a land footprint 40% smaller than SMR+CCS.

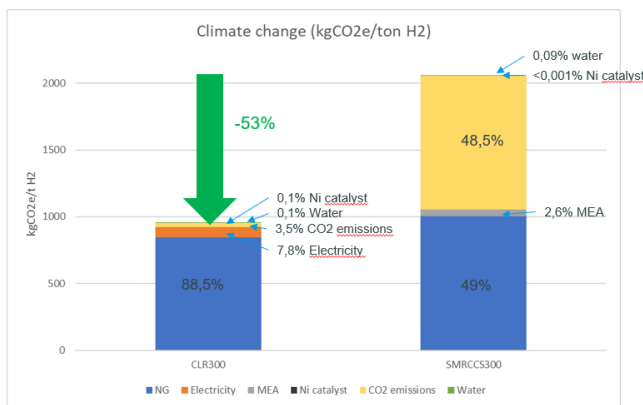


Figure 8-4: Impact on climate change

Overall, the RECYCLE process has a 50% lower impact on human health compared to SMR+CCS, but with a slight increase in the impact on ecosystem quality due to the electrical grid composition (UK). Figure 8-4 shows a reduction of **GHG emissions by 53% with RECYCLE process** compared to the SMR+CCS process when 99.8% of CO₂ is captured by the RECYCLE process.

For the 300 MW plant, the amount of equivalent CO₂ emitted is 0.077 Mt_{CO_{2,e}}/year (RECYCLE) versus 0.151 Mt_{CO_{2,e}}/year (counterfactual), considering a different plant availability. Due to the low maturity level of the RECYCLE process, there is a high level of uncertainty about the level of fugitive emissions that could result from the process. For this reason, a sensitivity has been performed by considering a lower capture rate for the RECYCLE process (98%). **When 98% of CO₂ is captured, the share of CO₂ emissions goes from 3.5 to 19% in the global RECYCLE process.** This reduction is mainly due to the very low amount of direct CO₂ emissions by the RECYCLE process, representing only 3.5% of the GHG emissions of this process. On the other hand, 48.5% of GHG emissions of the SMR+CCS process are due to its direct CO₂ emissions. **Natural gas is the main contributor** to GHG emissions. Ni-based catalysts and water consumption have a comparable low impact on climate change.

8.3 Key Performance Indicators

Technical Performance

The comparison of energy consumption and main KPI associated with technical performance is presented in Table 8-2. for 1) SMR without CO₂ capture; 2) SMR with MEA CCS 3) the RECYCLE process as simulated and discussed in Section 6.4. The performance parameters of the counterfactual SMR with and without CO₂ capture are taken from an IEAGHG study performed by Wood¹⁶.

Table 8-2: Comparison of energy performance

Plant Performance Results	UNITS	SMR	SMR-CCS counterfactual	RECYCLE
		No capture	Post-comb	
Energy producers (-)/consumers (+)				
Steam turbines	MW _{el}	-18.5	-12.3	-5.54
Gas turbine	MW _{el}	-	-	7.7
Syngas Production	MW _{el}	0.6	2.2	0.1
Air separation unit	MW _{el}	-	-	-
CO ₂ plant	MW _{el}	-	1.2	-
CO ₂ compressor	MW _{el}	-	6.3	1.8
Tail-gas compressor	MW _{el}	-	-	6.9
Utilities	MW _{el}	2.2	2.6	0.1

Net electricity consumption	MW _{el}	-15.7	0.0	11.18
H ₂ flowrate	kg/h	8994	8994	8993
	Nm ³ /h	99996	99996	99989
	MW _{th} (LHV)	299.6	299.6	299.6
NG flowrate	kg/h	34578	34578	29174
	MW _{th} (LHV)	446	446	377
Net NG flowrate	kg/h	32368	34578	30769
Thermal Efficiency (LHV)	%	69.1	69.1	79.5
Net Efficiency (LHV)	%	71.8	69.1	75.4
CO ₂ emissions	kg _{CO2} /hr	80910	8880	614
SPECCA (based on net efficiency)	MJ _{LHV,NG} /kgCO ₂	-	1.21	-1.33

Levelised Cost of Hydrogen (LCOH)

Based on the cost estimation, the levelised cost of hydrogen (LCOH) with respect to the counterfactual SMR case has been calculated with and without carbon tax (£ 119/ton of CO₂) and presented in Table 8-3.

Table 8-3: Levelised cost of hydrogen comparison. Costs are relative to the SMR without CCS (and carbon tax implemented) assumed equal to 100 a.u.

LCOH Case	Tax	No Tax	units
SMR without CCS (base 100)	100	61	a.u.
SMR with CCS	90	86	a.u.
RECYCLE	103	102	a.u.

8.4 Reflection on barriers for technology deployment

RECYCLE process has shown a large margin of improvement **outperforming the SMR with and without CCS by 10.4% (thermal efficiency) and 3.6-6.3% (net efficiency)**. Moreover, the CO₂ capture rate is above 99%. In terms of LCA, the environmental indicators show a reduction of 53% of the climate change impact compared to the SMR with post-combustion CCS. In terms of economics, these performances have shown lower operating costs of the process due to a reduced cost of fuel and cost of CO₂ taxes. In summary:

- *Higher thermal efficiency, among the highest reported for low-carbon hydrogen production.* This makes RECYCLE more resilient to increases in NG price. It is also expected to result in lower upstream (NG) emissions, and overall lower GHG emissions per kg_{H2} produced.
- *High carbon capture rates (>98%)* – more resilient to increases in CO₂ taxes
- *Import of electricity* – opportunity to decrease further GHG emissions of H₂ from NG through the utilization of green electricity. Not possible with conventional SMR technology.

The two main operating costs of the RECYCLE process are associated with the chemicals which heavily depend on the oxygen carrier replacement and on the electricity consumption. **The unbiased economic analysis has shown a high total capital requirement. This cost is affected by the conservative design choices and the uncertainty associated with the low TRL level of the technology.**

It must be noted that RECYCLE is a modular technology which could be adapted at smaller scale with similar specific costs which is not the case with SMR technologies. Therefore, the cost of H₂ production at small scale will be partially affected by the plant size and will compete with the cost of H₂ and energy supply that currently exceed 100 £/MWh as in the case of electrolyzers or the case of H₂ injected in the NG grid and transported.

Moreover, **with Phase II utility prices defined by BEIS¹⁸** as in the case of natural gas fuel (3.15 pence/kWh vs 2,98 pence/kWh of the present study), higher carbon tax (302 £/tonCO₂ instead of 119 £/tonCO₂) and low cost of electricity (11.5 vs 12.6 £/kWh) and lower carbon intensity, **the difference (positive) in OPEX between RECYCLE and the SMR +CCS will increase from 1 to 11%** and it could result advantageous at large-scale against competing technologies in view of the CLASS IV uncertainty associated to the TCR estimated in this first of in-kind study.

The unbiased study has therefore demonstrated that the development and optimisation should focus on the reduction of the capital costs of the plant and the lifetime of the materials as key enabling cost-effective economics, as well as pursue exploitation routes at smaller scale where H₂ would be required by several stakeholders for different uses as highlighted in the Market analysis presented in section 9.2.

¹⁸ [Low Carbon Hydrogen Supply 2 Competition: Stream 1 Phase II - Rules and Guidance \(publishing.service.gov.uk\)](https://publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/974122/low-carbon-hydrogen-supply-2-competition-stream-1-phase-ii-rules-and-guidance.pdf)

9. Rollout potential and route for Exploitation

9.1 Key Exploitable Results

A list of main Key Exploitable Results that would arise from RECYCLE has been already identified and reported in Table 9-1.

Table 9-1: Exploitable results

KER1 (material)	New oxygen carrier formulations and manufacturing routes, including catalysts, multi-functional materials for syngas generation
KER2 (reactor)	Intensified chemical looping reactors for syngas generation at high pressure
KER3 (process)	modular processes for small-medium on-site H ₂ and pure CO ₂ generation
KER4 (process)	Development of reforming processes for blue NH ₃ production, clean MeOH, liquid fuels from NG, flaring gas and renewable-based sources

The main conclusions on how **RECYCLE technology could supply hydrogen to several sectors in the UK** are reported below and summarised in Table 9-2.

Table 9-2: Grid assessment of the potential market route

Option	Economic Feasibility	Potential Market Size
1 – In large cluster competitive with blue H₂	Yellow	Green
2 – In cluster, not cost competitive with blue/green H₂	Green	Yellow
3 – Dispersed sites with CO₂ storage	Yellow	Yellow
4 – Dispersed sites with CO₂ utilisation	Green	Yellow
5 – Fuel production from biogenic feedstock	Yellow	Green

- Small-scale sites located outside of industrial clusters are less likely to have infrastructure connections directly to large-scale hydrogen producers.
- Sectors such as fuel production, food and drink, mineral production and chemicals could all be potential sources of hydrogen demand for the RECYCLE technology in the future.

RECYCLE can tap into large demand sectors that require syngas to develop other low-carbon products.

- Low-carbon fuels such as methanol and ammonia could see significant demand by 2050 for the decarbonisation of long-distance transport methods.
- RECYCLE has the potential to produce both hydrogen and syngas streams, therefore unlocking the ability to access a greater share of future markets.

RECYCLE is adaptable to small scale, thus relevant for the manufacturing industries that are needed to decarbonise their process in terms of high temperature heat decarbonisation. According to market analysis, there are several different options/configurations for a feasible deployment of RECYCLE technology.

- In light of the above market analysis, the **5 options considered in Table 9-2 are assessed** with colour codes for the likely economic feasibility and potential market size of each option.
- It should be noted that the below estimation is **based on the current status of the technology** and depending on future cost reduction, the role of RECYCLE may change. Furthermore, **more detailed techno-economic and feasibility studies are needed** to explore these options.

9.2 Market Analysis

At this stage, RECYCLE has been evaluated with this reference market by 2050, however, based on further development this capacity may vary.

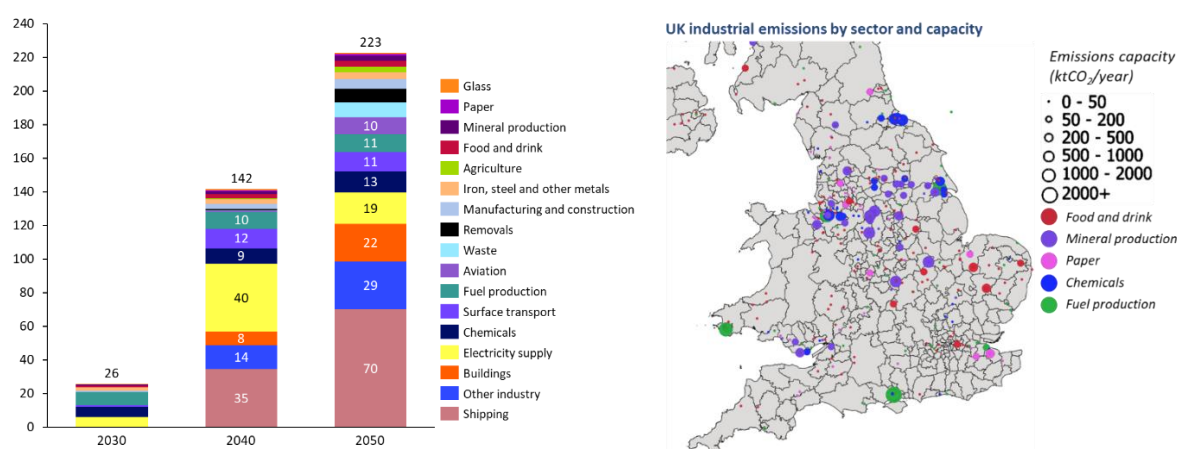


Figure 9-1: left) UK hydrogen demand forecast by sector¹⁹ right) Stakeholders that are most suitable to adopt RECYCLE technology as part of their processes can be identified in key sectors/locations by GIS mapping²⁰

RECYCLE has already strong industrial participation and commitment to ensure that the project has a follow-up. The partners have performed a preliminary study on key exploitable results, analysing the following aspects: i) reference market for the project; ii) how the products developed in the project could be introduced into the market as new product applications; iii) main economic advantages.

The industrial partners will cooperate to scale up the technology progressively to have it mature and with multiple applications over 10 years. The main phases of development can be grouped as follows:

- ⇒ **Phase-A:** In this phase, the first small unit for H₂ will be built and operated including a follow-up research project at TRL>7
- ⇒ **Phase-B:** As further investments by the partners proceed, more medium-scale plants and the technology reach commercial scale (<50 MW_{LHV} size)
- ⇒ **Phase-C:** As the scale-up is completed, the technology can adopt new feedstock for increased scalability: medium-large and then large size units are commercialized by JM, while large Oil and Gas end-users could develop, commercialise, and build large-scale H₂ plants.

¹⁹ [UK Hydrogen Strategy \(publishing.service.gov.uk\)](https://www.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/90123/uk-hydrogen-strategy.pdf)

²⁰ [Mapping Global Carbon Dioxide Emissions - GIS Lounge](https://www.gis-lounge.com/mapping-global-carbon-dioxide-emissions/)

10. Dissemination

Dissemination activities have been focused on:

- 1) Participation in thematic conferences and workshops ([UKCCSRC, April 2022](#), [Energy Challenge Event in Manchester April 2022](#), UKCCSRC September 2022, Chemical Looping Conference September 2022, [link to program](#))
- 2) Press release to specific journal (Open Access Government, pag. 356-357, July 2022), [link to publication](#).

For these events, presentation of the preliminary results, pitch presentation of the technology and conference proceeding have been delivered.

11. Conclusions

Phase I of the project has demonstrated the feasibility of the RECYCLE technology for low-carbon hydrogen production and provided valuable inputs for the development and implementation of Phase II.

The techno-economic assessment of the industrial scale process has demonstrated that RECYCLE **has very favourable performance in terms of thermal and net efficiency** reducing the operating cost significantly compared to benchmark technology and being more resilient in view of high NG price and carbon tax. On the other hand, the uncertainty associated with the CAPEX will impact the LCOH and could reduce economic performance. **In terms of environmental LCA, the climate change index related to carbon capture rate near 100% makes the environmental impact of RECYCLE from 45 to 53% lower than the SMR post-combustion CCS counterfactual.** In terms of economics, the CLASS IV study has shown an increase of the total capital requirement by 25% compared to the counterfactual plant which is mostly dictated by the uncertainties associated with the cost of the RECYCLE reactors at scale and the associated contingencies. Additionally, the cost of the oxygen carrier replacement could also have an impact on the LCOH (approximately 5% of the annual operating cost). **A sensitivity analysis has demonstrated that the LCOH will be comparable to the counterfactual ($\pm 4\%$ difference)** by using the new costs from BEIS. In case the RECYCLE TCR is reduced by 30%, the LCOH will be 5% lower while the optimal scenario could result in a **cost reduction of 12%** for large scale plants (>300 MW). At larger plant sizes, these costs should be compared with advanced reforming technology (e.g. ATR-GHR licensed by Johnson Matthey). As modular and flexible technology, **RECYCLE could operate at different scales, including small and medium size hydrogen production (1-20 MW, H₂ capacity)** for the decarbonisation of heat and small scale hydrogen uses in industries. The market analysis has demonstrated that there will be a large demand for hydrogen at that scale (≈ 4300 relevant pieces of industrial heaters using natural gas >1 MW_{th} accounting for $\approx 70\%$ of industrial gas consumption). RECYCLE could compete in terms of LCOH with electrolyzers or electrified with an expected **cost-saving of 20-30%**. To scale up the technology, and gain confidence in performance and costs a new fully integrated plant will be built and operated to produce up to 100 NLPM pure hydrogen (20 kW H₂ output) at relevant conditions which would include all the conversion and separation steps. Based on the results and performance obtained during the demonstration stage, it would be possible to **adjust the plant cost assessment and extrapolate the material lifetime.**

Besides, the RECYCLE consortium will carry out the economic analysis of the technology following the recommendation of the market analysis thus following on small scale plants, **alternative feedstock** such as biogas and waste gases from industrial processes and also assess the feasibility **to produce other hydrogen-based products** such as MeOH and NH₃ which are going to play a big role in the transportation or DRI technology for steel manufacturing.