

# OISH – Hydrogen from steelmaking waste as green fuel for steel production

Industrial Hydrogen Accelerator Programme: Stream 2A



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## Abbreviations and Glossary

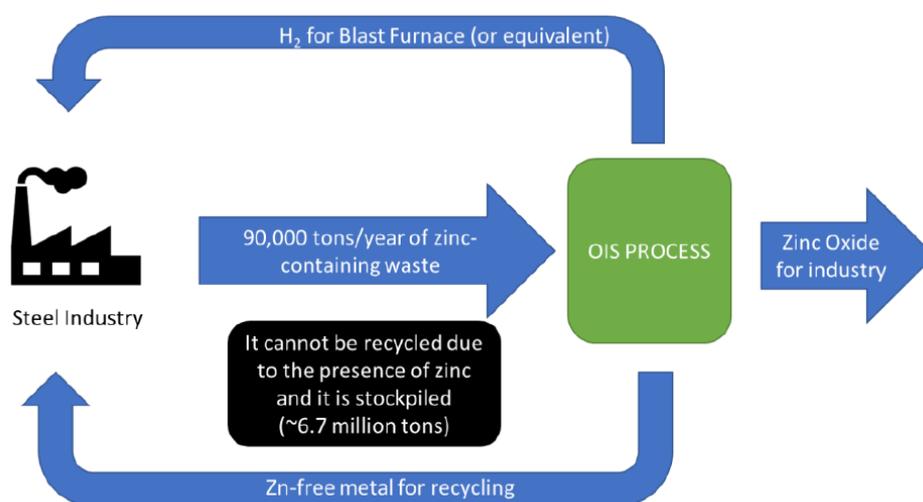
2BACT	Second best available current technology
°C	Degrees Celsius
AACE	Association of Advancement of Cost Engineering
ASTM	American Society for Testing and Materials
BACT	Best available current technology
BOS	Basic oxygen steelmaking
cm <sup>3</sup>	cubic centimetres
CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide
CO <sub>2</sub> e	carbon dioxide equivalent
CCS	Carbon capture and storage
CAPEX	Capital expenditure
CH <sub>4</sub>	Methane
COMAH	Control of major accident hazards regulations
DESNZ	Department for Energy Security and Net Zero
DRI	Directly reduced iron
DSEAR	Dangerous substances and explosive atmospheres regulations
EBITDA	Earnings before interest, taxes, depreciation, and amortization
FAT	Fixed equipment testing
FEED	Front end engineering design
FIs	Foundation Industries
GHG	Greenhouse gas
g	grams
Gt	Giga tons (billion metric tons)
GW	Gigawatt
H <sub>2</sub>	Hydrogen
h	hour
HBI	Hot Briquetted Iron
HCl	Hydrochloric acid
HS&E	Health, Safety & Environment
ILs	Ionic liquids
ISBL	Inside site battery limits
Gt	Giga ton (billion metric tons)
kg	kilogram
kW	Kilowatt
kton	kilotons

L	Litres
LCA	Life cycle assessment
LCOA	Levelised cost of abatement
LCOH	Levelised cost of hydrogen
LHV	lower heating value
LME SHG	London Metal Exchange - Special High Grade
m <sup>3</sup>	Cubic metres
min	minute
MPI	Materials Processing Institute
MJ	Megajoule
MSDS	Material Safety Data Sheets
NaOH	Sodium Hydroxide
NPV	Net present value
OIS	Oxidative ionothermal synthesis
OISH	Oxidative ionothermal synthesis for hydrogen
OPEX	Operating Expenditure
OSBL	Outside site battery limits
PER	Pressure equipment (safety) regulations
PPE	Personal protective equipment
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
RA	Risk assessment
REACH	Registration, evaluation, authorisation and restriction of chemicals
STP	Standard Temperature and Pressure
SOP	Standard operating procedure
TW	terawatt
tCO <sub>2e</sub>	tons of CO <sub>2</sub> equivalent
Ton	Metric tons
TRL	Technology Readiness Level
UK	United Kingdom of Great Britain and Northern Ireland
wt%	weight percent
yr	year
Zn	Zinc
ZnO	Zinc Oxide

## Executive Summary

The worldwide use of fossil fuels for electricity generation, transport, heating and industry leads to the release of about 37 gigatons (Gt) of CO<sub>2</sub> annually. A significant part of these emissions, about 3.3 Gt CO<sub>2</sub>, or 9 % of all CO<sub>2</sub> emissions, can be attributed to the iron and steel production industry. Decarbonisation of this industry will therefore be a key part of the overall effort towards reaching net-zero emissions in the near future.

In this project, a feasibility study was conducted to explore the integration of a new process, Nanomox's Oxidative Ionothermal Synthesis (OIS), for metal-rich slag waste and the use of co-produced hydrogen in steel manufacturing at the same site (Figure 1). The OIS process, which is patent pending, uses green catalytic solvents to efficiently oxidize metals, co-producing hydrogen. By converting steelmaking waste into saleable materials and using the co-produced hydrogen as fuel, the process has the potential to reduce landfilling, decrease reliance on energy-intensive pyrometallurgical processes, and to minimize CO<sub>2</sub> emissions from steel manufacturing.



*Figure 1. Schematic of the Oxidative Ionothermal Synthesis for Hydrogen (OISH) integration with the steel industry.*

With approximately 6.7 million tons of zinc/iron-rich slag stockpiled in the UK and 90,000 tons produced annually, this project presents a double benefit with significant cost savings and energy efficiency gains. It not only addresses the ongoing and legacy waste issue but also leverages the co-production of hydrogen to improve the environmental and economic performance of steel manufacturing.

During Stream 2A, lab-scale experimental work was performed using slag materials obtained from different industries to gather the data needed for a detailed assessment, such as measurement of hydrogen production rates and quality, and optimization of process conditions. The lab-scale work demonstrated that the OIS process can treat different slag materials and produce hydrogen from it. This was followed by a process design to determine the OPEX/CAPEX for recovery, buffer storage and use of the produced hydrogen on the same site. The first techno-economic modelling and life cycle assessment (LCA) show the OIS process for ZnO production needs to be integrated with a chlor-alkali process to regenerate the chemicals used in the process to be viable from a commercial

and environmental point of view. Using the OIS process with the chlor-alkali process, advanced ZnO can be produced at £3,383/ton (compared to up to £60k/ton using existing methods of advanced ZnO production), while co-producing hydrogen with a carbon footprint of 2.84 gCO<sub>2</sub>/MJ(LHV). OIS hydrogen is below the green hydrogen threshold of 20 gCO<sub>2</sub>/MJ(LHV), in accordance with the [UK Low Carbon Hydrogen Standard](#). Green hydrogen can be produced at a cost of £2.85/kg H<sub>2</sub>.

This work has led to a future work programme, which will be carried out onsite at the Materials Processing Institute (MPI) steelmaking pilot works, where an OIS zinc removal pilot plant is in place. Furthermore, the MPI has a facility for oxyhydrogen combustion and testing in 400 kW burners where combustion of the produced hydrogen will be tested (Main steelmaking end-use). A specially modified instrumented steel ladle and mobile thermal imaging equipment, along with mass spectroscopy will be used to compare heating performance of the OIS hydrogen with the performance of the regular supply of merchant hydrogen, and with the baseline of natural gas to confirm heating values, flame characteristics and products of combustion. The successful project outcome will lead to demonstration/commercial plants in the future with the goal to deliver a flexible end-to-end solution as soon as 2025. A second steelmaking use under consideration for the hydrogen is as a reductant in iron making.

The industrial implementation of the OIS process will:

- Contribute to the hydrogen economy by producing green hydrogen from metal-containing waste streams at a competitive cost.
- Increase the competitiveness and sustainability of the UK steel and metals sector by providing 1) a UK-based mechanism for treating existing and on-going waste streams from steelmaking and 2) a recycle-route returning valuable iron-containing material to steel manufacturing, (3) producing additional saleable products from the non-iron component of the waste stream, and 4) providing low carbon hydrogen to replace existing fossil fuel usage on steel sites.
- Contribute to the Government's NetZero goals by replacing energy-intensive pyrometallurgical processes used in zinc oxide production while also contributing to various waste reduction and circular economy strategies by using and treating steel manufacturing waste as an input material.
- Improve the sustainability and product efficiency of existing and developing applications using zinc oxide.

In conclusion, this feasibility study has shown that the end-to-end solution is technically viable. It has also shown the economic and environmental potential of an integrated OIS process with a steel plant for metal processing and green hydrogen generation. The main limitation of the technology is the quantities of hydrogen generated, which are a function of the availability of metal-containing waste streams and their composition, and/or the demand for inorganic materials such as zinc oxide. It is estimated that at least 55 ton hydrogen can be produced annually from waste streams (~90 kton/y of waste per year with a 2% Zn content w/w). At least 495 ton of hydrogen can be produced in a 20 kton ZnO/y plant from pure zinc. It is unlikely that the OIS process can provide the entire hydrogen requirement for green steel production. However, as there is an urgent need to treat waste streams generated in the steel industry, as well as to remediate large amounts of legacy waste, the

OIS process can be implemented quickly for this purpose. In future steel plants, the OIS process will co-exist with other hydrogen generation technologies, paving the way to green hydrogen steel plants.

Specific technical challenges remain regarding the hydrogen generation through the OIS process. Managing the variability of input materials, which affect the hydrogen quality and solvent recyclability, will be a priority for further scale-up. Next steps will also have to include the safe integration of auxiliary systems in the chain (including chlor-alkali process or equivalent) to demonstrate all aspects of the end-to-end solution for green hydrogen production at pilot scale.

Nanomox will continue to work on the optimisation of the OIS process, and generate technologies and knowledge around the process, to expand to other waste streams, and other metals beyond zinc. There is a vast potential for technology roll-out, carbon savings across sectors and integration with other sectors beyond steel manufacturing. This work should include how the process could be scaled and replicated more widely, including in different applications.

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## 1. Introduction and Overview

### 1.1 Project overview

Around 9% of all global CO<sub>2</sub> emissions can be attributed to the iron and steel production industry. Decarbonisation of the iron-making process includes transitioning from solid fossil carbon in the iron reduction reactions to direct gas reduction by hydrogen, as well as decarbonisation of high temperature heating used to prepare vessels or heat treat steel. In both cases there is a need to scale-up and invest in the production of low-carbon hydrogen to support the transition to low-carbon steelmaking.

Slag is a by-product material that is produced during the process of smelting or refining ore in metallurgical industries, such as iron and steel production. It consists of impurities and non-metallic components that are separated from the desired metal during the refining process. During steelmaking, zinc-containing slag and zinc-rich filter dust is produced, where the presence of zinc prevents it from being recycled into the iron industry's internal processes, requiring it to be treated or landfilled.

In this project, a feasibility study was conducted to explore the integration of a new process, Nanomox's Oxidative Ionothermal Synthesis (OIS), for the treatment of metal-rich slag waste and the use of co-produced hydrogen in steel manufacturing at the same site (Figure 2). The OIS process, which is patent pending, uses green catalytic solvents to efficiently oxidize metals and also co-produces hydrogen gas. By converting steelmaking waste into saleable materials and using the co-produced hydrogen as fuel, the process has the potential to reduce landfilling, decrease reliance on energy-intensive pyrometallurgical processes, and minimize the CO<sub>2</sub> emissions of steel manufacturing.

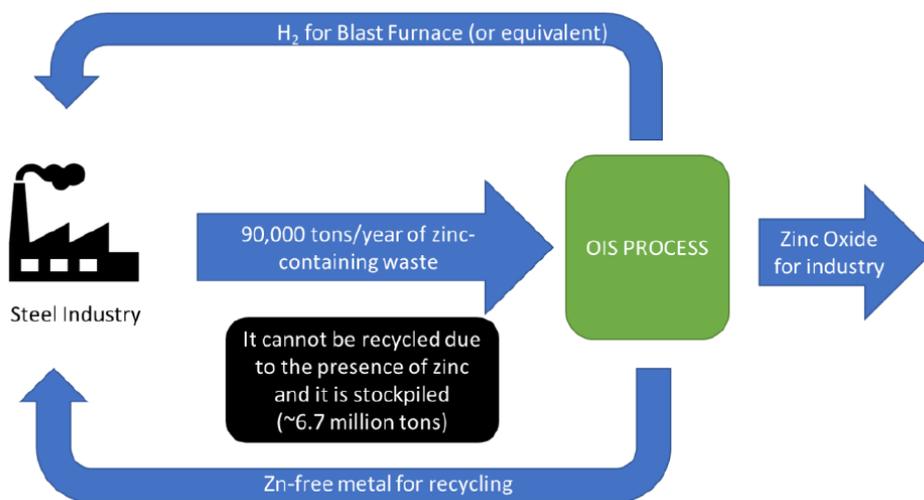


Figure 2. Schematic of the Oxidative Ionothermal Synthesis for Hydrogen (OISH) integration with the steel industry.

With approximately 6.7 million tons of zinc/iron-rich slag stockpiled in the UK to date and 90,000 tons produced annually, this project presents a double benefit with significant cost and energy efficiencies. It not only addresses the ongoing and legacy waste issue, but also leverages the co-production of hydrogen to improve the environmental and economic performance of steel manufacturing.

The hydrogen end-use at commercial scale would be to displace natural gas in steelmaking vessel pre-heating, or in semi-finished product reheating for rolling. The pre-heating combustion application will be demonstrated in a commercial mid-scale (400 kW) oxy-fuel steel ladle preheater burner at the Materials Processing Institute (MPI) which has been modified to run on 100% oxy-hydrogen. An alternative application for the hydrogen would be to supplement hydrocarbons used in iron reduction. This application will be demonstrated using the OISH hydrogen in standard test equipment for Blast Furnace iron reduction and for Directly Reduced Iron. Since the OISH technology is already incorporated in a 2-year study of zinc removal options for the UK's major steelmakers, the final end-use of the hydrogen will depend on the site selected for any commercial scaleup and is most likely to be a combustion fuel switch whereby hydrogen collected from the OISH process is stored in pressurised vessels and moved across site to the point of use.

In this project, the technical and economic feasibility of the OISH process is explored as an end-to-end system for green hydrogen to be used as a green fuel in the steel industry (Figure 3).

The system includes:

1. Hydrogen generation: OISH process using slags from the steel industry as feedstock.
2. Hydrogen collection, purification and storage: upgrading OISH hydrogen to a fuel-grade specification; buffer capacity to match production with consumption.
3. Hydrogen end-use: As a green fuel to provide heat for the OISH process and export to steel-making plants for use as a blend with natural gas for steel pre-heating operations. This end-user has been selected as it will require little modification of existing hardware. Other uses within the steel industry are also explored.

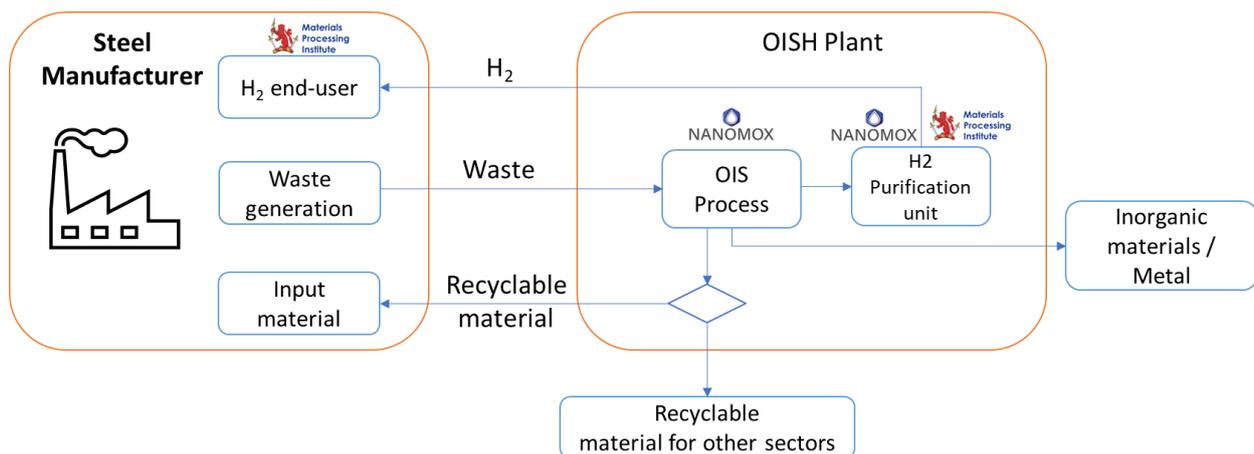


Figure 3. Schematic of the end-to-end solution using OISH hydrogen.

Stream 2A experimental work was performed to gather the data needed for a detailed assessment, such as measurement of hydrogen production rates and quality, and optimization of process conditions. This was followed by a process design to determine the OPEX/CAPEX for hydrogen recovery, buffer storage and use on the same site. This led to a

proposal for a subsequent project to begin onsite at the MPI steelmaking pilot works where there is an OIS zinc removal pilot plant and facility for oxyhydrogen combustion and testing in 400 kW burners. Successful project outcomes will lead to demonstration/commercial plants in the future. The implementation of the technology will reduce CO<sub>2</sub> emissions of steel manufacturing, both through the use of green hydrogen and recycled slag in the process replacing fossil fuels and virgin ore, whilst improving profitability and environmental credentials through the remediation of ongoing and legacy steelmaking waste.

The system is currently at a technology readiness level (TRL) of approximately 5, with the lowest TRL component being the OIS reactor at TRL 4. We hope to reach TRL 7 for the system after demonstration by 2025. See Appendix for details.

## 1.2 Decarbonisation

The [UK Hydrogen Strategy \(August 2021\)](#)<sup>1</sup> stated that low-carbon hydrogen has a critical role to play in the UK's transition to net zero and set out the ambition to rapidly ramp up the production and use of hydrogen over the coming decade. The [British Energy Security Strategy \(April 2022\)](#)<sup>2</sup> doubled this ambition to up to 10 GW (~84 TWh/yr) of low carbon hydrogen production capacity by 2030, subject to affordability and value for money, with at least half of this coming from electrolytic hydrogen.

The worldwide use of fossil fuels for electricity generation, transport, heating and industry leads to the release of about 37 gigatons (Gt) of CO<sub>2</sub> annually. A significant part of these emissions, about 3.3 Gt CO<sub>2</sub>, or 9 % of all CO<sub>2</sub> emissions, can be attributed to the iron and steel production industry. Decarbonisation of this industry will therefore be a key part of the overall effort towards reaching net-zero emissions in the near future, and it is the selected end-use case for stream 2A. The annual production of steel worldwide amounted to about 1.8 Gt in 2018. About half of that is produced in China, while the EU-28 accounted for 9% of the global steel production. Within the EU, about a quarter of the steel was produced in Germany, another quarter in Italy and France, a further quarter in Belgium, Poland, Spain and the UK, and the remaining quarter mainly distributed over nine countries (Austria, Czech Republic, Finland, Hungary, Luxembourg, the Netherlands, Romania, Slovakia and Sweden).<sup>3</sup>

Decarbonisation of the iron-making process requires replacing carbon/carbon monoxide in the iron reduction reactions with an alternative gas, such as methane or hydrogen, that would lead to lower or zero carbon emissions. The anticipated switch in the late 2020s and through the 2030s will be away from coal-based iron reduction in the Blast Furnace route, to Directly Reduced Iron (DRI) using natural gas and later hydrogen. The use of methane (CH<sub>4</sub>), a chemical compound containing both carbon and hydrogen, would allow a reduction in CO<sub>2</sub> emissions, partially replacing them with water vapour (H<sub>2</sub>O). The use of green

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<sup>1</sup> UK hydrogen strategy, 2021: ISBN 978-1-5286-2670-5, CCS0621687164 08/21, CP 475

<sup>2</sup> British energy security strategy, 2022: <https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy>

<sup>3</sup> The potential of hydrogen for decarbonising steel production (PE 641.552 – December 2020): [https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS\\_BRI\(2020\)641552\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf)

hydrogen (H<sub>2</sub>) would make it possible to completely decarbonise the process, since it would only produce water vapour as a chemical by-product.

The methane alternative is technically well understood, with methane or coal-gas, DRI accounting for approximately 20% of the global primary iron production as sponge iron or hot-briquetted iron (HBI). The hydrogen equivalent process is fast approaching commercialisation in Scandinavia where plentiful affordable green electricity and high-grade ore deposits have led several companies to developing hydrogen DRI with electric melting units. Several European steelmakers in Scandinavia have also announced plans to replace blast furnace ironmaking with natural gas DRI which then transitions to green hydrogen once the supply is available. Methane is the main component of natural gas and is thus available in great quantities. It is already used to a limited degree in steel production, but a more widespread use would allow for a partial decarbonisation of the processes. Methane can also be produced from biological sources using anaerobic digestion, potentially offering a full decarbonisation route (the emitted carbon would be biogenic, while combining it with Carbon Capture and Storage (CCS) could lead to a carbon negative process). Hydrogen makes it possible to completely decarbonise these processes. Hydrogen, however, is so far only being produced in limited quantities, and its use for steel production still needs to be further fine-tuned for industrial-scale production.

Downstream steelmaking processes (reheating and rolling solid steel into commercial products such as construction beams, rails, bars or sheets) are responsible for up to 25% of the embodied energy and CO<sub>2</sub> emissions of the final product. A further 1-2% is also associated with preheating the vessels (primarily 'ladles' which are large refractory-lined buckets) used to transport liquid iron and steel during refining and casting. This energy input is primarily through natural gas combustion in reheating furnaces. Available decarbonisation options are a relatively straightforward decarbonisation of the combustion gas (by blending or substituting green hydrogen and/or green hydrocarbons), or by transitioning to direct electrical heating from radiant heating elements, and in some specific cases, electrical induction heating. In both cases the challenge for the coming decade is one of scale and cost since sufficient green fuels are not yet available and electrical heating options, well known in smaller scale heat treatment furnaces of metals and ceramics, are also not yet commercially widespread. The relative net costs of using industrial electricity or gas have been coming closer in recent years but the markets remain volatile and in need of a reform. Capital investment in infrastructure and furnace upgrades or replacements needed to make a transition to electricity or hydrogen are quite site-specific. Major steel producers are likely to require agreements for a dedicated hydrogen supply, either from natural gas cracking with CCS or from electrolysis powered by wind, hydroelectric or nuclear energy.

Another technical challenge is to understand of pure hydrogen combustion, the heat transfer modelling, its effect on furnace refractories and the steel product itself, and the lifetimes of equipment at risk of degradation from hydrogen infiltration. For this reason, the learning from the next phase of work recommended in this report contributes to the wider body of knowledge by using an instrumented modified steel ladle acting as a research furnace to demonstrate both the ladle preheating use case and the more general oxy-hydrogen combustion environment.

### 1.3 Green hydrogen

Hydrogen gas is currently used in the chemical industry in a rather limited way, e.g., for the production of ammonia or in petroleum refining. Most of this hydrogen is presently produced by steam reforming, a process that uses natural gas and emits CO<sub>2</sub> as a by-product. The cost of producing hydrogen from natural gas ('grey hydrogen') depends mainly on the price of gas, which varies from one region of the world to another. On the basis of gas prices in Europe, typical hydrogen prices are of the order of £1.34/kg (rising to £1.77/kg when including the cost of carbon emission avoidance through CCS – then becoming 'blue hydrogen') (2020 values).<sup>4</sup>

Hydrogen can also be produced through electrolysis. This process uses electricity to split water into hydrogen and oxygen. If the electricity is produced from carbon-free sources, this allows production of carbon-free hydrogen gas, also called 'green hydrogen'. This process transforms about 70-80% of the electrical energy into chemical energy of the hydrogen gas. It takes about 50 to 55 kilowatt hours (kWh) to produce 1 kg of hydrogen. The production cost of green hydrogen has fallen by 60% over the last decade and is now typically in the range of £3.19-£4.69/kg (2020 values).<sup>5</sup> With the high energy prices in Q1 of 2023 (also the time of writing this report), the selling price for green hydrogen has temporarily increased to £6.00/kg. However, apart from the currently high energy prices, this price is expected to fall further, as investment costs for production facilities decrease with mass production, and electricity prices from renewable energy, such as wind and solar, continue to drop. Under conservative assumptions, the price of green hydrogen could fall to £1.59/kg by 2030 (2020 values).<sup>6</sup>

With 50-55 kWh required to produce 1 kg of hydrogen, and 50 kg of hydrogen required to produce 1 ton of steel, in the case of Germany (the EU's largest steel producer), it would require about 100 terawatt-hours (TWh) of renewable energy to fully decarbonise the annual production of 42 megatons (Mt) of steel. This 100 TWh of additional electricity demand would correspond to a 20 % increase in the total demand for electricity in Germany (PE 641.552 – December 2020). In the UK, 17 TWh would be required to decarbonize the UK steel production (7.2 Mt), which represents 5.5% increase in the total electricity production.

The current production costs of one ton of steel is in the order of £355, which includes about £45 for the coal used. Replacing this coal with hydrogen would require around £160 worth of hydrogen at 2020 best prices (£3.19/kg), which would increase the total price of a ton of steel by about one third. If the large-scale production of hydrogen drives down the price of hydrogen to £1.59/kg by 2030, the price difference between conventional steel and steel produced by green hydrogen would drop to the order of 10%.

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<sup>4</sup> The potential of hydrogen for decarbonising steel production (PE 641.552 – December 2020): [https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS\\_BRI\(2020\)641552\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf)

<sup>5</sup> The potential of hydrogen for decarbonising steel production (PE 641.552 – December 2020): [https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS\\_BRI\(2020\)641552\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf)

<sup>6</sup> The potential of hydrogen for decarbonising steel production (PE 641.552 – December 2020): [https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS\\_BRI\(2020\)641552\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf)

## 1.4 Zinc oxide production

Zinc oxide (ZnO) has one of the greatest assortments of different particle structures among all known materials. This compound is one of the most important nanomaterials today – a multifunctional material with a breadth of achievable physical and chemical properties, which depend on particle size, dimensions, and morphologies. ZnO is used in a wide range of applications, including cosmetics, tyre manufacturing, ceramics, glass, paints, batteries, catalysis, optoelectronics, sensors, transducers, energy conversion and for medical sciences.

The ZnO market is mainly supplied by ZnO produced from energy-intensive pyrometallurgical processes, such as the French Process operating at a temperature above 1000°C. In the French (also known as “indirect”) process, metallic zinc is melted in a furnace and vaporized at >1000 °C. The zinc vapour reacts with oxygen from the air to produce ZnO. The ZnO particles are transported via a cooling duct and are collected at a bag filter station. The product consists of agglomerates with an average particle size ranging from 0.1 to a few micrometres. As morphological control of the particles cannot be achieved with the French Process, the ZnO produced cannot be used in high-tech applications.<sup>7</sup>

As an alternative, many wet chemistry methods have been developed. One example is the hydrothermal method, where a mixture of substrates is heated gradually to a temperature of 100–300 °C and left for several days in an autoclave. These processes have the advantage of carrying out the synthesis at lower temperatures compared to pyrometallurgical process (French process). They also offer the possibility to obtain a diversity of shapes and dimensions of the resulting crystals depending on the composition of the starting mixture and the process temperature and pressure.<sup>8</sup> However, these methods for ZnO production have not demonstrated adequate scalability and, therefore, have not been serious competition to the current mass manufacturing methods.

## 1.5 The OIS Process

Ionic liquids (ILs) are a type of salt that is liquid at room temperature. Unlike traditional salts, which have a high melting point, ionic liquids have a low melting point, allowing them to exist in a liquid state at or near room temperature. They are often used as solvents due to their unique properties, including high thermal stability and non-flammability. Ionic liquids have a wide range of applications, including those in electrochemistry, organic synthesis, and separations.

Nanomox developed a novel state-of-the-art synthesis, OIS, for inorganic material production (such as metal oxides). OIS uses ILs and water solutions to convert metals (pure or waste) into advanced metal oxide materials ranging from nano to micro-sized particles and thin films (Figure 4). The OIS process offers environmental benefits over the incumbent processes as the reaction is carried out at low temperatures (<120°C) and the catalytic solvent is recycled with negligible losses to the atmosphere due to its low vapour pressure.

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<sup>7</sup> Materials (Basel). 2014 Apr; 7(4): 2833–2881.

<sup>8</sup> Kołodziejczak-Radzimska A, Jesionowski T. Zinc Oxide-From Synthesis to Application: A Review. Materials (Basel). 2014 Apr 9;7(4):2833-2881. doi: 10.3390/ma7042833. PMID: 28788596; PMCID: PMC5453364.

The process co-generates hydrogen, which can be isolated as a by-product. Metal oxidation reactions in water for hydrogen production are well known, but one of the main challenges is the metal surface passivation due to metal oxide deposition over the surface of the metal, halting the reaction. Preliminary results show that in the presence of ILs, and specifically with zinc, oxidation goes to completion, suggesting that the OIS process is a suitable method for hydrogen production.

The OIS process has been demonstrated up to TRL 5, and activities to reach TRL 6 are planned as a next step following this project.

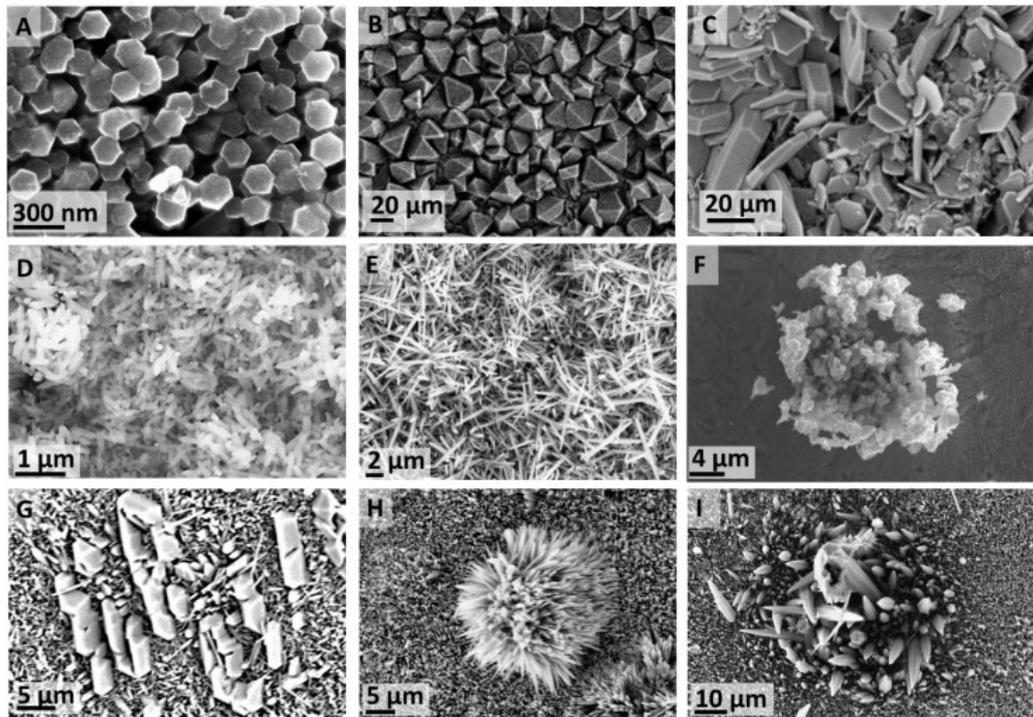


Figure 4. Summary of the most representative structures. [A] ZnO flat-topped hexagonal rods. [B]  $\epsilon$ -Zn(OH)<sub>2</sub> octahedrons. [C] ZHC plates. [D] ZnO short rods (round and sharp ended). [E] ZnO needles. [F] ZnO polycrystalline structure. [G] ZnO thick crystals. [H] ZnO 3D needle flower. [I] ZnO 3D thick crystal flower. Imagen taken from the Royal Society of Chemistry.<sup>9</sup>

In contrast to the incumbent processes for ZnO production, the OIS process offers a path to decarbonize the production of ZnO while generating materials with targeted morphologies and properties for the different applications, resulting in lower quantities of ZnO needed to achieve the same performance (resource efficiency). A comparison of the OIS technology for ZnO production compared to other production methods is presented in the appendix (Table 17).

<sup>9</sup> Mater. Adv., 2020,1, 3597-3604.

## 2. Hydrogen production

### 2.1 Technical feasibility

#### 2.1.1 OIS hydrogen from zinc oxide production

It was previously demonstrated at the laboratory scale that the OIS process can generate a diversity of zinc oxide and other materials with controlled morphology from pure zinc (Mater. Adv., 2020,1, 3597-3604). During this feasibility study, it was confirmed that pure hydrogen (saturated with water) is co-formed alongside ZnO. In this section, the technical feasibility of recovering the hydrogen produced from the oxidation of pure zinc into ZnO is explored. In this scenario, the hydrogen is used to provide the heating duty for the OIS process and the excess is exported to a steel mill.

A 20,000 ton/y production plant was modelled, corresponding to the estimated annual demand of ZnO in the United Kingdom. A proportion of the produced hydrogen is used as a green fuel to provide heat for the process (ca. 51%), with the excess being available for export. It is worth mentioning that further process integration, including with waste heat sources, will result in lower heat demand for the OIS process and, therefore, higher hydrogen exports. A mass balance comparing the OIS process against industry-standard processes for zinc oxide production is given in Table 1.

Table 1. Mass balance for an OIS ZnO plant compared to the French Process.

\*Performance for the French Process taken from a zinc oxide furnace supplier's website [A. H. BURNS ENERGY SYSTEMS LTD].<sup>10</sup> †Electric consumption for process users only. It is assumed that the electrical consumption of non-process users (lighting, control systems, laboratory, buildings, etc) will be the same regardless of the production technology.

Parameter	Units	Technology		
		OIS	French Process (2BACT)	French Process (Burns, BACT)*
Zinc	ton/ton ZnO	0.8	0.8	0.8
Fuel [Natural gas]	GJ/ton ZnO	-	9.5	3.2
	kWh/ton ZnO	-	2,639	889
Electricity†	kWh/ton ZnO	65.0	-	-
Total H <sub>2</sub> produced	kg/ton ZnO	24.7	-	-
	kWh/ton ZnO	823 (LHV)	-	-
H <sub>2</sub> consumed internally in the OIS process	kg/ton ZnO	12.6	-	-
	kWh/ton ZnO	421 (LHV)	-	-

<sup>10</sup> <https://www.burnsenergy.ca/>

Parameter	Units	Technology		
		OIS	French Process (2BACT)	French Process (Burns, BACT)*
Excess H <sub>2</sub>	kg/ton ZnO	12.1		
	MJ/ton ZnO	1448.7 (LHV)	-	-
	kWh/ton ZnO	402 (LHV)		
ZnO Production per year	ton ZnO/y	20,000	20,000	20,000
Excess H <sub>2</sub> production	ton/y	242	-	-
Excess H <sub>2</sub> -eq energy (LHV)	GJ/y	29,061	-	-
	kWh/y	8,072,509		

The main reagents, consumables and utility requirements for the OIS process for zinc oxide production from pure zinc are given in Table 2 and Table 3. In this scenario, wastewater is disposed of via municipal drains.

Table 2. Chemical Consumption

Consumable	Consumption kg/ton ZnO
NaOH (50%)	1,966
HCl (32%)	2,800
Amine	37

Table 3. Utility requirements and wastewater production

Item	Consumption /ton ZnO
Water (process water + cooling tower make-up water)	9,962 kg
Wastewater	10,333 kg
Electricity (imported)	65.0 kWh
Heat (imported)	0 kWh

### 2.1.2 OIS hydrogen from waste slag materials

Experimental work was carried out as part of this feasibility to study hydrogen production from waste slag materials. Several types of metal-containing waste from the ironwork

industry were used for these experiments, and an experimental set-up designed to measure gas production flowrates. The gas composition was analysed. It was found that hydrogen was produced alongside CO<sub>2</sub>, and different starting materials resulted in different overall gas yields as well as different gas compositions.

The effect of treatment temperature during the OIS was studied. It was found that temperature not only affects the rate of reaction but also the amount of gas produced. The highest tested temperature (80°C) resulted in the fastest production rates as well as the highest yields. It is unclear at this stage if lower temperatures result only in a reduction of the rate or selectively limit the reaction with certain materials. This will be investigated in the future through trace element analysis to gain more mechanistic understanding and optimise for hydrogen production while limiting the production of undesirable products, such as CO<sub>2</sub>.

## 2.2 Environmental performance

### 2.2.1 OIS hydrogen from zinc oxide production

The environmental performance of the OIS process for ZnO production was assessed and compared to the French process. A grid average emissions factor of 38.4 gCO<sub>2</sub>/MJ (start year 2025) was used for the impact of the electrical consumption (Climate Change Committee’s Sixth Carbon Budget).<sup>11</sup> The emission factor for natural gas consumption used is 0.243 kgCO<sub>2</sub>/kWh based on a direct footprint of 201.9 g/kWh from BEIS<sup>12</sup> GHG conversion factors, and an indirect footprint of 15.8 g/kWh, based on Econinvent estimate.<sup>13</sup>

Table 4 summarises the CO<sub>2</sub> emissions associated with ZnO production using the OIS process. Table 5 compares the emissions from the OIS process with those of the French Processes. For both the OIS and French Processes, emissions from the zinc starting material are omitted as they are the same for both technologies.

Table 4. CO<sub>2</sub>eq. emissions from the OIS process including embedded CO<sub>2</sub> emissions from the consumed chemicals as well as the energy input required.

Input	Carbon intensity	Kg CO <sub>2</sub> e/ton ZnO
NaOH	1.95 kg CO <sub>2</sub> eq/kg	3,831.4
HCl	1.87 kg CO <sub>2</sub> eq/kg	1,677.5
Amine	3.74 kg CO <sub>2</sub> eq/kg	136.6
Heat	0.243 kg CO <sub>2</sub> /kWh	0
Electricity	38.4 g CO <sub>2</sub> /MJ	9.0
<b>Total</b>		<b>5,654</b>

<sup>11</sup> The CCC, The Sixth Carbon Budget: <https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-Charts-and-data-in-the-report.xlsb>

<sup>12</sup> Greenhouse gas reporting: conversion factors 2022: <https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022>

<sup>13</sup> Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230.

Table 5. Energy (heat and electricity) related emissions for zinc oxide. \* Performance for the French Process taken from a zinc oxide furnace supplier’s website [A. H. BURNS ENERGY SYSTEMS LTD]<sup>14</sup>

Parameter	Unit	Technology		
		OIS	French Process (2BACT)	French Process (Burns, BACT)*
Normalized CO <sub>2</sub> emissions	kg CO <sub>2</sub> eq/ton ZnO	5,654	665	224
ZnO Production per year	ton ZnO/y	20,000	20,000	20,000
Total CO <sub>2</sub> emissions	ton CO <sub>2</sub> e/y	113,080	13,300	4,480

While the emissions from the required energy are substantially lower for the OIS process compared to the Best Available Current Technology (BACT) (which rely on energy-intensive pyrometallurgical processes), they have the advantage of not requiring chemical inputs. Indeed, the carbon footprint of the OIS process exceeds that of the pyrometallurgical processes by around an order of magnitude, with virtually all emissions coming from the embedded CO<sub>2</sub> footprint of the chemicals. The major contributors are the high NaOH and HCl consumption. NaOH and HCl can, however, be produced directly onsite using the chlor-alkali process. The chlor-alkali process is a well-established chemical process that uses sodium chloride to produce caustic soda (NaOH), hydrogen and chlorine gas. The latter two can then be used to produce hydrochloric acid. Since sodium chloride is formed as the neutralisation product in the OIS process, the chlor-alkali process not only offers a lower emissions route to NaOH and HCl, but potentially makes the OIS process more circular. If these chemicals are produced on-site from NaCl (with a carbon intensity of 0.2 kgCO<sub>2</sub>eq/kg if bought in and 0 kgCO<sub>2</sub>eq/kg if recycled internally) in a chlor-alkali process, the emissions linked to electricity use increase, but are more than compensated by the avoidance of embedded emissions from the NaOH and HCl used (Table 6). The CO<sub>2</sub> intensity for the produced ZnO therefore drops to 493 kgCO<sub>2</sub>e/t, which is between the BACT and second-best available technology (2BACT), using the French process. While the OIS process can be further decarbonised using greener electricity, the pyrometallurgical processes for ZnO production are more difficult to decarbonise since switching the required fuel to e.g. green hydrogen would be cost prohibitive.

<sup>14</sup> <https://www.burnsenergy.ca/>

Table 6. CO<sub>2</sub> footprints for ZnO production using the OIS process with and without the chlor-alkali process add-on, with NaCl as a consumable and recycling the NaCl internally.  
\*Not including Zn starting material.

Scenario	Base line OIS process without chlor-alkali add-on	OIS process with chlor-alkali add-on, NaCl as consumable	OIS process with chlor-alkali add-on, NaCl recycled
Chemicals footprint* [kg CO <sub>2</sub> e/ton ZnO]	5,645	1,161	137
Electricity footprint [kg CO <sub>2</sub> e/ton ZnO]	9.0	356	356
Total CO <sub>2</sub> intensity /ton ZnO [kg CO <sub>2</sub> e/ton ZnO]	5,654	1,517	493

Additionally, unlike traditional methods for ZnO production, the OIS process produces hydrogen in addition to the ZnO. To analyse the carbon intensity of the OIS process for hydrogen production, two methods have been defined: Case 1, in which carbon emissions allocated to the hydrogen production have been normalized by weight of the products (*i.e.*, ZnO & hydrogen) (H<sub>2</sub> mass fraction = 1.2%); and Case 2, in which carbon emissions allocated to the hydrogen production have been normalized by product cost. ZnO and hydrogen prices fluctuate so for the economic easement an average ZnO selling price of £2,516.13/ton and a price of £6,000/ton of hydrogen (\$7.5/kg)<sup>15</sup> has been assumed based on market research (hydrogen value fraction = 0.0217). The carbon intensity of pure zinc has been excluded as it is added exclusively to the ZnO CO<sub>2</sub> footprint. The carbon intensity was calculated for three scenarios: (1) purchasing NaOH and HCl (baseline), (2) using the chlor alkali process and purchasing NaCl, and (3) using the chlor alkali process where the NaCl is internally recycled. The results are shown in Table 7.

Table 7. OIS H<sub>2</sub> carbon intensity. Case 1: figure based on weight fraction. Case 2: figure based on value fraction. Figures include the impact of chemicals (not including Zn) and energy inputs.

<sup>15</sup> Statista - Green hydrogen - statistics & facts: <https://www.statista.com/topics/7783/green-hydrogen/#topicOverview>

Scenario	OIS H <sub>2</sub> carbon intensity in kgCO <sub>2</sub> /kg [gCO <sub>2</sub> eq/MJ(LHV)]	
	Case 1	Case 2
NaOH & HCl as feedstock	5.59 [46.6]	13.10 [109.2]
NaCl as feedstock	1.50 [12.5]	3.52 [29.4]
NaCl recycle	0.14 [1.17]	0.34 [2.84]

The results shown in Table 7 show that in order to meet the green hydrogen threshold of 20 gCO<sub>2</sub>/MJ(LHV), in accordance with the [UK Low Carbon Hydrogen Standard](#),<sup>16</sup> NaCl (purchased or recycled) has to be used to produce the chemicals required on site. Process optimization, process integration with other industries and the use of green electricity would result in even lower carbon intensities, which demonstrates that the OIS process is a viable method for green hydrogen and ZnO production.

### 2.2.2 OIS hydrogen from waste slag materials

A Life Cycle Assessment (LCA) was carried out for the OIS process for hydrogen production from waste slag materials in a plant processing 45 kt/year of input material (zinc-containing slag). CO<sub>2</sub> formed from the slag material in the process was assumed to be captured, whereas the CO<sub>2</sub> from burning of natural gas for the heating requirement was not captured. Table 8 summarises the flow-rates and carbon intensity that were used to calculate the overall carbon intensity of zinc and hydrogen produced.

Table 8. Mass flow rates and associated CO<sub>2</sub> footprints of chemicals and materials used in the OIS slag LCA.

Process input	Value	Unit	Notes and assumptions	CI value	Unit	Total impact [kg CO <sub>2</sub> e/h]
Slag (dry)	3,850	kg/h	Waste stream of no economic value. Thus, no LCA impacts are attributed to the slag waste.	-	-	-

<sup>16</sup> UK Low Carbon Hydrogen Standard: emissions reporting and sustainability criteria: <https://www.gov.uk/government/publications/uk-low-carbon-hydrogen-standard-emissions-reporting-and-sustainability-criteria>

Process input	Value	Unit	Notes and assumptions	CI value	Unit	Total impact [kg CO <sub>2</sub> e/h]
Triethanola mine	28.8	kg/h	<a href="http://sitemap.design-4-sustainability.com/ecocosts/47716">http://sitemap.design-4-sustainability.com/ecocosts/47716</a>	3.742	kg CO <sub>2</sub> / kg mass	107.9
HCl	42.8	kg/h	The production carbon intensity from GREET, based on a US production plant reference.	1.872	kg CO <sub>2</sub> / kg mass	80.1
NaOH	9.5	kg/h	The production carbon intensity from GREET, based on a US production plant reference.	1.95	kg CO <sub>2</sub> / kg mass	18.5
Electricity	2,689,200	kJ/h	Grid electricity requirement for the OIS process using 2025 as the start year.	0.000038	kgCO <sub>2</sub> / kJ	103.29
Heat energy	208,800	kJ/h	Supplied by natural gas in a boiler – direct footprint of 201.9 g/kWh from BEIS GHG conversion factors 2022. Indirect footprint of 15.8 g/kWh, based on estimates from the Ecoinvent database. A boiler efficiency of 90% by LHV is assumed. This is the heat requirement for the OIS process.	0.2	kgCO <sub>2</sub> / kWh	14.1
Heat needed to capture CO <sub>2</sub>	45167	kJ/h	Supplied by natural gas in a boiler – direct footprint of 201.9 g/kWh from BEIS GHG conversion factors 2022. Indirect footprint of 15.8 g/kWh, based on estimates from the Ecoinvent database. A boiler efficiency of 90% by LHV is assumed. This is the heat requirement for the CO <sub>2</sub> capture	0.2	kgCO <sub>2</sub> / kWh	3.05

Process input	Value	Unit	Notes and assumptions	CI value	Unit	Total impact [kg CO <sub>2</sub> e/h]
			unit, which is needed to send CO <sub>2</sub> to the cement production facility.			

Similar as for the ZnO case, the carbon footprint can be allocated in different ways. Based on a mass allocation, a CO<sub>2</sub> footprint of 7.23 kgCO<sub>2</sub>/kg for both hydrogen and zinc has been calculated. This is a reduction compared to the incumbent “carbon-intensive” production technologies for hydrogen production, with a CO<sub>2</sub> footprint of around 9 kgCO<sub>2</sub>/kg H<sub>2</sub> using steam methane reforming<sup>17</sup>. Zinc can be procured with a carbon footprint of 2.55 kgCO<sub>2</sub>/kg Zn<sup>18</sup>, so the OIS-produced zinc is above the reference value. The main contributors to the CO<sub>2</sub> footprint are the embedded emissions from the amine and the electricity use. In particular, grinding and sieving of the slag feedstock is modelled to use a lot of electricity. Switching to a lower-carbon source of electricity can therefore afford significant CO<sub>2</sub> savings overall.

It should be noted that in this scenario, the zinc-free slag is not taken into account as a usable product. If we do count the zinc-free slag as a product, the carbon footprint of all three products falls to 0.085 kgCO<sub>2</sub>/kg, a very low value due to the large amount of zinc-free slag isolated compared to the very small quantities of zinc and hydrogen. The zinc-free slag is projected to have a similar iron content as iron ore and is expected to be recycled into the steelmaking process. Iron ore has a carbon intensity of 4.8 kgCO<sub>2</sub>/kg, therefore the OIS process derived zinc-free slag offers a 98% CO<sub>2</sub> saving vs. iron ore.

## 2.3 Technoeconomic assessment

### 2.3.1 Methodology

#### 2.3.1.1 CAPEX estimates

Costs for the major equipment items were estimated with Nanomox’s database, cost literature and vendor consultation to provide a Class IV estimate<sup>19</sup> consistent with a (AACE) feasibility-level study. The basis for the capital cost estimate for commercial plants was a high-level equipment list (CAPEX Class IV). All other costs were factored off the installed mechanical equipment costs to account for direct and indirect costs. The factors, where possible, were selected by equipment type, which generally provides a higher level of accuracy, rather than a blanket factor, such as a Lang factor. This method has an estimated accuracy of ± 30%, consistent with a (AACE) feasibility-level study.

<sup>17</sup> A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation, M. Khan *et al.*, International Journal of Hydrogen Energy, 2021.

<sup>18</sup> GREET Lifecycle Calculator, USA.

<sup>19</sup> Note that the costs of individual process units were derived from various cost sources, ranging from Class III to Class IV. However, the overall quality of this assessment has been conservatively deemed Class IV.

The structure of Nanomox’s total CAPEX investment is presented in Table 9. This includes hydrogen generation, purification and export. As the hydrogen is going to be diluted with natural gas, it will require minimal modification of the steel plant, therefore, the CAPEX for the end-user has not been taken into account for the estimate.

Table 9 Structure of Nanomox's total CAPEX investment

Inside site battery limits (ISBL): i.e., the core technology			Outside site battery limits (OSBL)
Direct costs		Indirect costs	Land cost
Equipment cost	Equipment installation cost (materials + labour) Structural steel Piping Electrical systems Instrumentation Concrete / foundations Insulation Paint Equipment setting	Engineering design Installation equipment rental Freight Field office Supervision Contractor profit	Contingency (10% of combined direct and indirect costs) Site preparation Storage of feedstock and products Shipping and receiving facilities Administrations buildings Laboratories

### 2.3.1.2 OPEX estimates

The basis for OPEX estimates, including the sources of the costs and their methodologies, is presented in Table 10 for the variable costs and in Table 11 for the fixed costs.

Table 10. The basis for variable cost estimates.

Cost category	Cost item	Cost*	Reference
	LX/EW Chemicals	0.105 £/kg	Vendor quote
Chemicals and reagents	NaOH (50%)	0.567 (0.609) £/kg	Vendor quote adjusted for scale
	HCl (32%)	0.258 (0.276) £/kg	Vendor quote adjusted for scale

Cost category	Cost item	Cost*	Reference
	Triethanolamine	1.640 £/kg	Vendor quote adjusted for scale
	Zinc	2.506 £/kg	Nanomox internal database
	Process water and cooling water	0.81 £/m <sup>3</sup>	Northumbrian Water's wholesale charges 2022/23 for customer bands consuming >175 ML/year; drinking-water grade
	Wastewater	0.98 £/m <sup>3</sup>	Sewage water, charged according to Northumbrian Water's Household charges 2023/24
Utilities	Natural gas	0.024 £/kWh	According to Department for Business, Energy & Industrial Strategy (2022): Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal; 10-year average between 2025 and 2035; Scenario B, industrial use.
	Electricity	0.1129 £/kWh	According to Department for Business, Energy & Industrial Strategy (2022): Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal; 10-year average between 2025 and 2035; Scenario B, industrial use.

\*Where costs between the OIS Zinc Oxide Plant and the OIS Zinc Plant differ, the cost in brackets indicate the cost in the OIS Zinc Plant. The difference is due to discounts applied to higher purchase volumes.

Table 11. The basis for fixed cost estimates.

Fixed cost category	Method of calculation	Reference
Maintenance	5% of Total Fixed ISBL CAPEX investment	Sinnott (2005): Chemical Engineering Design. Volume 6, 4th edition. Chapter 6.9.1 Estimation of operating costs
Operating labour	20 workers in OIS Zinc Oxide Plant (or 25 workers in OIS Zinc Plant) over 5 shifts @ £35k/y	Peters and Timmerhaus (1991): Plant Design and Economics for Chemical Engineers. 4th edition. Pages 197-198
Laboratory costs	20% of operating labour cost	
Supervision	1 supervisor per shift + 2 managers @ £60k/y	
Plant overheads	50% of the total labour costs	Sinnott (2005): Chemical Engineering Design. Volume 6, 4th edition. Chapter 6.9.1 Estimation of operating costs
Insurance	1% of Total Fixed ISBL CAPEX investment	
Local taxes	1% of Total Fixed ISBL CAPEX investment	

The operating costs are presented to an accuracy of  $\pm 30\%$  consistent with an Order of Magnitude estimate (Class IV).

## 2.3.2 Economic estimate

### 2.3.2.1 OIS zinc oxide production plant (with chlor-alkali process)

The total CAPEX investment for a 20 kton/y production plant using the OIS technology has been estimated at £106.2m. This figure includes the chlor-alkali process, conservatively costed at £67.5m. This estimate carries a significant uncertainty as estimates ranging from £9m to £67.5m were found using different sources.<sup>20</sup> It is very likely that a revised cost estimate (e.g. from a vendor) would significantly reduce the actual CAPEX of a chlor-alkali process package, thus making the total investment more financially attractive.

<sup>20</sup> 1) doi: 10.1149/2.F062021F; 2) doi:10.1021/acs.iecr.9b03970 page 22721

By comparison, the total CAPEX investment of BACT French Process Plant is about £15.3m. Despite the higher investment costs, the OIS process produces high-performance inorganic materials (not achievable with the French Process) with a higher commercial value and co-produces green hydrogen (Table 7), which results in higher profitability.

A summary comparison of the OPEX estimates for the OIS Process plant and the two French Processes is provided in Table 12. A detailed breakdown of the OPEX is presented in the attachments.

Table 12. OPEX comparison for zinc oxide production [2025].\* Performance for the French Process taken from a zinc oxide furnace supplier's website [[A. H. BURNS ENERGY SYSTEMS LTD](#)].

Parameter	Unit	Technology		
		OIS	French Process (BACT)	French Process (BURNS)
LME SHG Zinc feedstock	£/ton ZnO	2,116.55	2,116.55	2,116.55
Variable and fixed cost (minus Zinc feedstock)	£/ton ZnO	872.74	347.7	304.3
Total OPEX	£/ton ZnO	2,989.29	2,464.26	2,420.86

The average ZnO selling price for bulk market applications is £2,516/ton. With current energy prices, the estimated margins for the French Process range from £81.21 - £101.41 per ton of ZnO. These low margins result in high undiscounted payback periods EBITDA (7-8 years). Such projects are not financially attractive in the UK, especially with the expected increase in natural gas prices in the future and pressure to switch to low-carbon technologies.

For the OIS plant (with chlor-alkali process) to achieve zero Net Present Value (NPV; for 30-year plant life and 10% discount rate) under this assessment, the minimum ZnO selling price is £3,383.85 /ton. By comparison (and despite a significantly lower total CAPEX investment), the corresponding price for an OIS plant without a chlor-alkali process is £4,212.35 /ton.

Importantly, the OIS process, unlike the French Process, allows to control the crystal morphology of the ZnO particles. As a result, a range of different particle sizes and morphology can be produced, ranging from nano-sized to micro-sized particles. These advanced ZnO materials have a higher selling price than bulk ZnO and can go up to £60k/ton); therefore, even without process optimization, the OIS process is viable to supply the advanced ZnO market.

The hydrogen production costs are summarized in Table 13. The production cost was calculated as the total OPEX of the plant attributable to hydrogen either by weight fraction of hydrogen in the total product output (case 1), and by revenue fraction (case 2). Ultimately, the addition of a chlor-alkali process makes the hydrogen revenue stream profitable, compared to an assumed retail price of £6/kg. For these calculations, the minimum ZnO selling price for each scenario was used.

Table 13. Hydrogen production cost. Case 1: figure based on hydrogen weight fraction. Case 2: figure based on revenue fraction.

Plant type		Case 1		Case 2	
		£/kg	£/MWh (LHV)	£/kg	£/MWh (LHV)
OIS plant with chlor- alkali process	NaCl internally recycled	2.85	85.37	5.00	149.99
	(THE BASIS OF THIS ECONOMIC ASSESSME NT)				
	NaCl not recycled	2.99	89.71	5.04	151.21
OIS plant without chlor-alkali process		4.06	121.89	7.14	214.15

### 2.3.2.2 OIS zinc production from slag (without chlor-alkali process)

The total CAPEX investment for a 357-ton Zn/y production plant using the OIS technology has been estimated at £39.3m. This figure does not include the chlor-alkali process, because the consumption of caustic soda and hydrochloric acid is significantly lower than in an OIS Zinc Oxide Plant, thus lowering the appeal of a high-CAPEX add-on that is the chlor-alkali process. A gate fee has been assumed for the slag material since the alternative is landfilling it, which is highly taxed in the UK. The zinc-free slag is returned to the steel industry to partially replace iron ore. The plant generates a positive NPV, which is expected to be further improved if the zinc content in the starting material is higher (resulting in a larger income stream from zinc and hydrogen).

### 2.3.3 OIS hydrogen performance

#### 2.3.3.1 Levelised cost of hydrogen (LCOH)

The levelised cost of hydrogen (LCOH) is the discounted lifetime cost of building and operating a production asset, expressed as a cost per energy unit of hydrogen produced (£/MWh). It covers all relevant costs for the OIS process, including capital, operating (maintenance, labour, consumables and insurance) and electricity.

For the LCOH calculation, the CAPEX and OPEX have been corrected using the UK GDP deflator index provided in the Green Book supplementary appraisal guidance: Table 19: GDP deflator. A discount rate of 10% was used.

The base case is a ZnO production plant running at approx. 3 t/h, i.e., with a capacity of 20 kton per year, which corresponds to the estimated UK demand. The generation of product has continued at this level during the lifetime of the project. The base for the slag processing case is 3.85 t/h (zinc-free slag).

To take into consideration the fraction of the CAPEX/OPEX that is used for material production, the CAPEX/OPEX allocated to the hydrogen production has been normalized by weight of the products.

Table 14. LCOH results for a plant commissioned in 2035 operating for 30 years.

Feedstock	Product(s)	Chlor-alkali Process	H <sub>2</sub> export mass fraction	LCOH [£/MJ(HHV)]	LCOH [£/kWh(HHV)]
Pure Zinc	Zinc Oxide	No	0.0119	0.0359	0.1290
Pure Zinc	Zinc Oxide	Yes	0.0119	0.0285	0.1026
Slag	Pure Zinc / Slag for recycling	No	6.36x10 <sup>-5</sup>	0.0011	0.0038

#### 2.3.3.2 Levelised cost of abatement (LCOA)

The LCOA was calculated using a similar methodology to the LCOH, considering the overall lifetime costs of the project and the overall carbon abatement (for any near-term demonstration and estimated for a commercial scale solution in 2035). Carbon costs were not included in the lifetime costs. The carbon abatement calculation is based on the carbon savings for using the excess green hydrogen as an alternative fuel to natural gas. The carbon saving from zinc oxide production compared to pyrometallurgical processes was also taken into consideration for the LCOA calculation for the ZnO production mode. For the slag case, the CO<sub>2</sub> saving arising from using the zinc-free slag as input material for steel making, as opposed to importing iron oxide ores, is taken into account in the LCOA

calculation. The emission reduction benefit from using zinc-free slag as input material for steel making is 4.8 gCO<sub>2</sub>eq/kg iron, which correspond to the impact of procuring iron ore (data from Ecoinvent).

In the model, it is assumed that hydrogen is diluted with natural gas already in use within the steel plant, resulting in minimum CAPEX investment. Moreover, the OIS process alone cannot supply the totality of the hydrogen required to decarbonize steel manufacturing, as the quantities are limited by the availability (and chemical composition) of the waste streams and/or the demand for inorganic materials. Therefore, the cost for an end-user conversion to hydrogen is not included in the LCOA calculation.

Finally, 2 cases are considered for the OPEX calculation. In Case 1, no credit for the products is considered. In Case 2, credit for the products is considered. For this, the breakeven selling price was used for each case. ZnO without Chlor-alkali process £4,212.35/ton ZnO. ZnO with Chlor-alkali process £3,383.85/ton ZnO. Zinc-free slag £107.90/ton of slag (based on current iron ore prices). For the slag case LCOA calculation, contributions due to gate fees and zinc metal are not included as a conservative approach.

Table 15. LCOA for the end-to-end solution results for a plant commissioned in 2035 operating for 30 years. Case 1 (no credit for products). Case 2 (credit for products).

Feedstock	Product(s)	Chlor-alkali Process	LCOA [£/tonCO <sub>2</sub> ]	
			Case 1	Case 2
Pure Zinc	Zinc Oxide	No	4,863	879
Pure Zinc	Zinc Oxide	Yes	4,089	0.0014
Slag	Pure Zinc / Slag for recycling	No	7,191	5,458

When credit for by-products is taken into consideration, the LCOA of the end-to-end solution is low and competitive. Further process optimization and heat integration could further reduce these figures.

## 2.4 Regulatory considerations

Chemical manufacturing is a very regulated activity, with a series of legislations, regulations and standards that cover all aspects of production (UK, EU and International). Points covered by these include construction/building strength, ventilation, risk assessment, hazardous areas, metering, pipework design and installation, appliance installation, testing, purging and commissioning, inspection and maintenance, identification and labelling, detection and response, and emergency response.

Chemicals, such as zinc oxide, need to be REACH registered before they can be sold in or imported to the EU at large scale (over 1 ton per year). Different levels of registration are required depending on the annual quantities.

In the UK, the primary regulations that will govern the handling of hydrogen and the associated infrastructure are Dangerous Substances and Explosive Atmospheres (DSEAR), Control of Major Accident Hazards (COMAH), Pressure Equipment (Safety) Regulations (PER) and the Carriage of Dangerous Goods Regulations all of which arise from implementation of EU directives. Storage of hydrogen is regulated by The Planning (Hazardous Substances) Regulations 2015 and/or the COMAH Regulations 2015 depending on the quantities involved. COMAH sets high requirements for operators to take all measures necessary to prevent a major accident and limit consequences for human health and the environment. The operator must have in place various strategies, including safety plans, emergency plans and a Major Accident Prevention Policy.

Under the Hazardous Substances Regulations, consent is required to store two or more tons of hydrogen, and a further consent is required where storing five or more tons of hydrogen. In the integrated OIS process with a steel plant, the hydrogen produced will be used on site to provide the heat duty for the OIS process and as a green fuel for steel making. The quantities on site will be minimized to ensure an inventory less than 2 tons to minimize the risks linked to hydrogen storage.

No regulatory barriers have been identified.

### 3. Scale-up and hydrogen use

#### 3.1 Scale-up

This Stream 2A study assessed the feasibility of scaling-up and operating an end-to-end pilot industrial hydrogen process at the MPI, with the following components:

- A. OIS Hydrometallurgical reactor ('Hydromet') to generate hydrogen from steelmaking wastes
- B. Collection, purification, compression and storage of the hydrogen
- C. Connection to and delivery through short low-pressure pipeline to the steel plant
- D. Industrial oxy-hydrogen burner to preheat steelmaking vessels

Procurement of the main components at the MPI has been taking place under separate funding streams: at the time of reporting (March 2023) components A, C and D have already been delivered or installed and are awaiting commissioning, and component B is in the procurement stage. This study, therefore, assumed that of all the components would be available by mid-2024 since the commissioning will be complete in Q1 2024.

Since the hydrogen combustion use case involves an established technology (Linde Oxygen 400 preheat burner) with a fuel switch to hydrogen which has itself at least been demonstrated by the manufacturer, and since the compression and capture technology can also be assembled from commercially available elements, the largest area of R&D focus in Stream 2A and in the initial stages of any future work has to be on the challenges of scaling up the OIS hydrogen production technology itself. The process has been verified at laboratory scale, and with the OIS hydrometallurgical reactor ('Hydromet') is being scaled

up, providing a joint source of high value zinc oxide, low-zinc residuals to return to steelmaking, and useable hydrogen.

The purchase of the Hydromet equipment is part of a joint steel industry ‘De-Zincing’ collaborative programme run by the Materials Processing Institute and the UK’s four largest steel producers (Tata Steel UK, British Steel, Celsa Steel UK, and Marcegaglia UK (formerly Outokumpu)), with core equipment capital funding and matched operational funding from the 2020-25 Innovate UK PRISM programme [Programme of Research and Innovation for Steel and Metals]. The De-Zincing programme will demonstrate and develop low-energy materials recovery pathways specifically for the separation of zinc from steelmaking waste streams to enable separate recycling of both zinc and iron.

The first generation 100 L Hydromet unit (Figure 5) has a 100-litre reaction vessel which allows a daily consumption of a few kg of waste products by cycling the ionic liquids between the reactor where they are generated and the modular ‘dissolution reactor’ chambers containing the wastes. Hydrogen volumes will be too low to attempt a use case and will be safely vented, but the gas composition will still be continuously monitored and sampled. The second generation 2400 L unit simply adds a hydrogen offtake valve and a 2400-litre reactor vessel to allow for several kg of waste to be treated per hour in the same chambers.



Figure 5. Hydromet first generation unit (100 L reactor) at the Material Processing Institute.

It was planned to use the first generation (100 L) Hydromet unit within Stream 2A to generate operational process data on reaction rates and hydrogen gas quality for the feasibility case. Unfortunately, due to a series of supply chain and engineering delays the Hydromet unit was still under construction and commission during the timeframe of the Stream 2A study. Considerable time was, however, spent within Stream 2A by research, engineering, and process safety staff to assess the feasibility of operating the first and second generation units, based on data from the laboratory experiments, process safety

reviews and practical experience gained with suppliers during the build and early commissioning.

The practicalities and HS&E compliance of scale-up to pilot operation of the Hydromet unit, capture and purification of hydrogen, and integration with the hydrogen network have been assessed, and proposals made for a further work programme. A full DSEAR study on the industrial use case of hydrogen in a ladle preheater has been carried out ahead of its commissioning.

Laboratory scale experiments applying the OIS process to solid feedstocks (finely crushed slag, and zinc oxide powder as a control) have confirmed the likely range of hydrogen production rates within the pilot plant (see Table 16), and also the expected gas chemistries, since some waste feedstocks (slags) will evolve a mixture of hydrogen and CO<sub>2</sub>. Filter plant dust/sludges are, however, not expected to generate CO<sub>2</sub> and should be the focus of the first round of trials on the first generation 100 L Hydromet unit. A further matrix of laboratory experiments is required to confirm the reaction kinetics and thermodynamics of the range of waste streams from De Zincing partner sites. In particular, slag and sludge wastes from all four partner sites need to be included, and the influence of the size fraction of crushed/ground slags (three different size fractions) and temperature (four different temperatures) studied. The data from the laboratory experiments will then be used to inform the conditions to be used in the Hydromet pilot plant.

The Hydromet pilot plant will be in operation during 2023 to treat steelmaking wastes and, once the 2400 L reactor is added, will co-produce hydrogen in sufficient volumes to enable purification, compression and storage prior to use in the reheating equipment of the pilot steel plant, and also in the iron ore reduction. These are the two pathways identified by steel plant operators as the best match for hydrogen co-produced during materials recovery on commercial steelworks.

### 3.2 Demonstration programme proposal

The programme of pilot campaigns set out in the following sub-chapters is proposed for future work.

#### 3.2.1 Demonstration part 1 (months 1-9)

Prior to commissioning the 2400 L (expected 1.5 kg of hydrogen per day) pilot hydrometallurgy reactor, the base unit will first be run with a 100 L reactor, assessing a matrix of waste samples and operating parameters. This scale of operation allows:

- reaction parameters (flow rates, concentrations, temperature, feedstock particle size) to be further defined;
- operator safety training to be conducted; and
- a dataset of feedstock characteristics (chemistry, particle size) vs reaction performance to be rapidly developed before larger batch processing.

This first demonstration can be carried alongside procurement and integration of the hydrogen collection and storage equipment using the pre-existing hydrogen supply network

and pilot equipment at the MPI. Although the plant uses off-the shelf equipment and components, the recent experience with long lead times for some components (e.g. hydrogen pressure relief valves) suggests that this issue will also constrain the demonstration phase.

### 3.2.2 Demonstration part 2 (months 6-21): 2400 L reactor campaigns with hydrogen collection

The 2400 L reactor will batch-process feedstock from the commercial partners: filter dusts/sludge from filter plants and slag from legacy stockpiles. Hydrogen will be collected and used in the ladle preheater of the pilot steelmaking plant, and also tested for compatibility within a Blast Furnace or for use in producing Directly Reduced Iron, using iron ore reduction standards equipment. The physical equipment is either already installed (see above) or there are clear procurement, hazard study and commissioning timelines established for 2023 within existing programmes at the MPI, to enable demonstration of the integration of the OIS process with hydrogen use at the pilot scale.

### 3.2.3 Demonstration part 3 (months 1-22): FEED Study for flagship commercial scale plant

The industrial collaborative ‘De-Zincing’ programme is due to conclude in December 2024 with recommendations for a joint investment by the steel industry in zinc separation technology. The OIS process plays an important part in this programme, but still needs to be proven in a pilot operation. Therefore, committing to a full-scale plant on a steelmaking host site within the next 2-year demonstration cycle is not realistic. It will likely be mid-2024 before steel industry collaborators are ready to discuss such a plant. The most realistic, manageable and strategically effective use of follow-up funding for the final stage of the demonstration will be to conduct a FEED study on a commercial scale (tons per hour) materials recovery and hydrogen co-generation plant, in preparation for scale-up to commercial scale in 2025.

Input to the FEED study will come from operating experience of the core Hydromet pilot plant, as well as the construction and integration of the three extension modules: a continuous dissolution reactor, a regeneration unit for the ionic liquids, and a module to recover the zinc oxide precipitates from the process for subsequent sale.

### 3.2.4 Alternative use case (Cement integration)

Whilst an alternative use case for the next phase has also been explored during the Stream 2A work and raised with the monitoring officer and DESNZ during the feasibility study (dryout and conditioning heat for geopolymers cement precursor production in a new build plant), the plant in question is still in the development stages. There are several synergies with this proposed plant in terms of material feedstocks (steelmaking slags can potentially be repurposed as aggregates in geopolymers concretes, and nanoparticle products of the OIS process may also be compatible in fillers), and energy demand is of a similar order of magnitude to the hydrogen output from a slag treatment OIS unit. However, the timelines for the end-use plant as a standalone commercial demonstrator are not defined enough to switch from the initial steelmaking focus to this new application for the demonstration phase.

### 3.3 Integration of hydrogen source, collection, storage and delivery

#### 3.3.1 Integration: collection

Laboratory-scale experiments showed that the hydrometallurgy reactors produce gas streams of variable composition ranging from 50 mol% to 100 mol% hydrogen (5 wt% to 100 wt %), plus CO<sub>2</sub> depending on the nature of the feedstock source. The variability in CO<sub>2</sub> content is related to the composition of the feedstock being reprocessed and will be more consistent for a fixed source of input material. In the lab test, the sample where zinc was the only active reactant (zinc powder control) produced pure hydrogen; materials containing carbonates (e.g. steel slags), including calcium and magnesium carbonates, produced a mixed gas stream of hydrogen and carbon dioxide. The reactivated calcium and magnesium oxides in the residuals should be able to subsequently re-entrain the same amount of atmospheric CO<sub>2</sub>, or be re-used as fluxes, but this was outside of the scope of the Stream 2A study to quantify. A more in-depth LCA during the demonstration phase will address this and the most economically or environmentally preferred routes for capturing CO<sub>2</sub> and exploiting the reactivated limes (gas capture and use or storage as gas or by direct carbonation of the limes, vs re-use of CO<sub>2</sub> and Ca/Mg oxides in separate markets), with the aim of making that part of the process carbon negative.

If the feedstock is zinc fume dust/sludge, the CO<sub>2</sub> evolution is less of an issue since the carbonate content is much lower, though it may still occur if there are unconsumed calcium carbonate particles present in the dust collection from a steel furnace. This varies depending on furnace practice and what has been charged into it – typical electric arc furnace dusts compositions have been found to range from 3.5-15 wt% CaO, 1.7-9% MgO, along with 17-32 wt% Zn and 23-45 wt% Fe.<sup>21</sup> There is the added complication of mixed compounds forming, e.g. zinc ferrite. Gas collection and treatment, therefore, needs to be capable of separating CO<sub>2</sub> from the hydrogen stream, and the end-use should be assessed for tolerance to residual CO<sub>2</sub>.

Initially, the gas coming off the OIS reactor will contain N<sub>2</sub> purge gas during startup, which will be flushed out before hydrogen collection begins. The gas will also be saturated with water vapour since it originates from a hot aqueous chemical reaction, and will, therefore, be dried after collection using a conventional condensation cooling loop. Other organic residuals are not anticipated, since zero evaporative losses are claimed for the ionic liquid solvents, but these will still be tested for by mass spectroscopy in case of some carry over of ionic liquids or precursors. However, even if these species are present, it would be expected that they are also removed by the condensation loop. Final hydrogen purity will be confirmed by local independent laboratories as well as in-house spectroscopy.

Projections for the 2400 L reactor, scaled up from the laboratory tests, showed the maximum and minimum boundaries of expected gas evolution (

**Table 16).**

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<sup>21</sup> Antrekowitsch, Rösler & Steinacker “State of the Art in Steel Mill Dust Recycling” Chem. Ing. Tech. 2015, 87, No 11, 1498-1503

Table 16. Gas production projections based on the lab results provide by Nanomox Ltd for the 2400 L reactor.

Parameter	Pure zinc (4 kg/h consumed)	Slag (4 kg/h consumed)
Initial Gas Flowrate (kg/h)	0.125	0.055
Initial Gas Flowrate (nm <sup>3</sup> /h)	1.39	0.61
Initial Gas Flowrate (L/min)	23.2	10.2
Hydrogen Composition (mol%)	100	50/50
Pressure (mbarg)	16	16
Temperature (°C)	80	80
Time to fill one 47 L hydrogen bottle (h)	86.4	196
Days (8 h campaigns) for an 18-bottle pack	10.8	24.5

Prior to commissioning the 2400 L pilot hydrometallurgy reactor, the base unit will first be run with a 100 L reactor, where the offgas composition will be continuously monitored using a commercially available Optical Interferometric Gas Concentration Meter (FI-8000) capable of real-time inline measurement of the gas composition. This scale of operation allows reaction parameters to be further defined and a dataset of feedstock characteristics (chemistries, particle size, dissolution chamber packing rate) vs reaction performance to be rapidly developed before larger batch processing.

Figure 6 shows the 100 L reactor and the method of sampling the generated gases. The method and designs were developed during the Stream 2A project and will be used in the first phase of subsequent work to optimise processing conditions and derive the reaction rate equations for the next phase scale-up to the 2400 L reactor. During this phase, hydrogen will be generated in sufficient quantities to allow 1-2 standard 47 L bottles to be filled per daily campaign, with the plant operating in a batch mode during a single day shift.

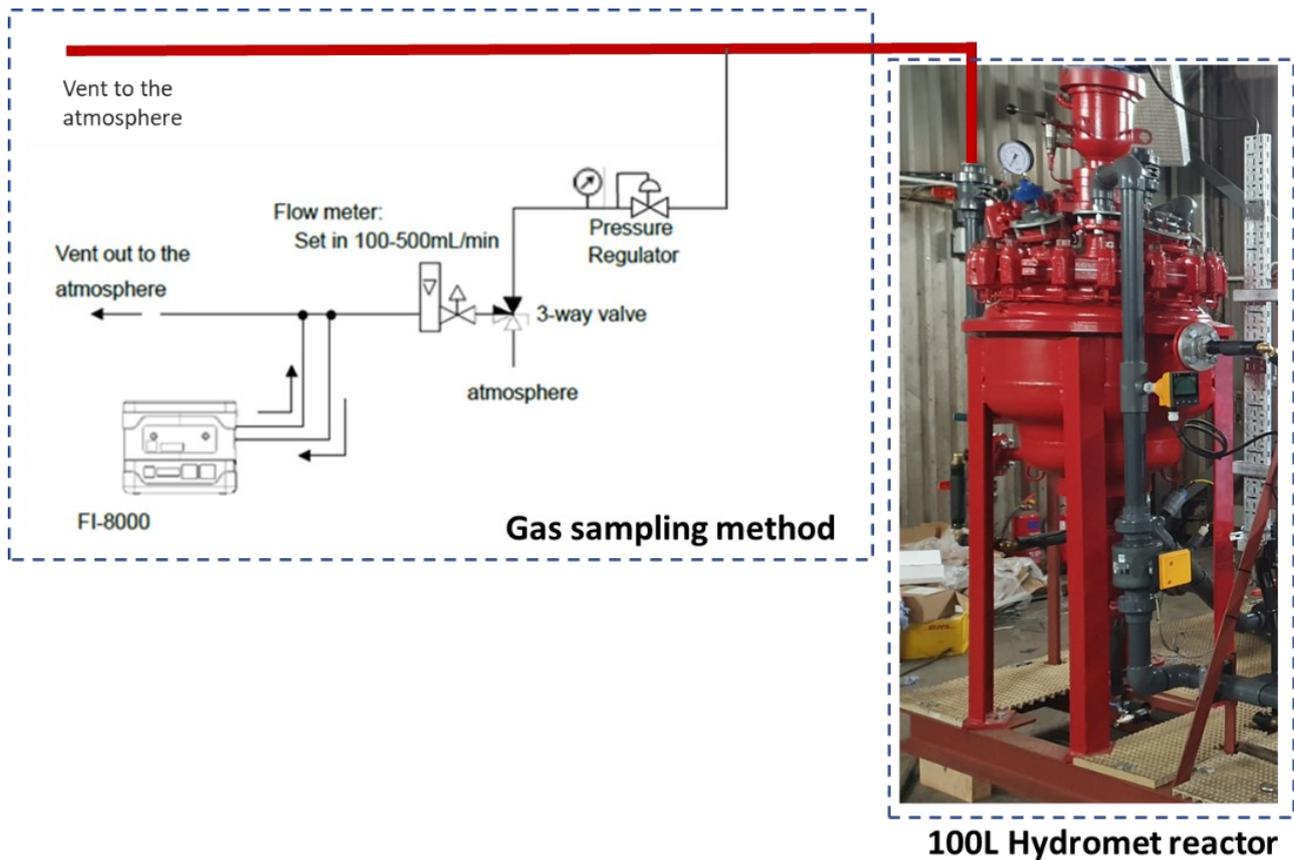


Figure 6. 100 L reactor and gas sampling schematic.

Given the variability of the reaction initiation phase, initial collection runs from the pilot plant batch runs will begin after 60 minutes of operation to allow stable conditions.

The gas evolution rates will be measured first in the 100 L reactor outside the scope of stream 2A. This data will be used in the next phase of the project to optimise processing conditions for the 2400 L reactor. The 100 L testing will also provide validation of the reaction rate equations and the process conditions for the range of feedstock chemistries and particle sizes.

The overall mass balance of the OIS reaction is such that  $Zn_{(s)}$  to hydrogen $_{(g)}$  molar ratio is 1:1. Translating this to mass units, the equivalent mass ratio is 33:1.

- This means that 30 g of hydrogen is evolved per 1 kg of Zn atoms present. [pre-compression, i.e., normal volume 336 cm<sup>3</sup> at STP, 1 kWh low heating value energy content [ HHV is 1.18 kWh]].
- At scaled-up volumes, 1 ton of pure Zn (reacted fully) produces 30 kg hydrogen = [33.33 kWh/kg x 30 kg, with an LHV of 1000 kWh if burned].

The 2400 L reactor operating at 60°C will treat material bearing up to 4 kg of zinc per hour, evolving 0.125 kg of hydrogen per hour. The latter is a significant safety consideration to handle since, despite its dilution with water vapour and CO<sub>2</sub>, this equates to hourly volumes

of 1.4 normal m<sup>3</sup> with 4.2 kWh (15.12 MJ) of heat release should the gas auto ignite and/or explode. Faster reaction times are achievable with higher temperatures (up to 120°C), which necessitate an upgrade of pipework from PVC to PTFE-lined steel, so the assumptions in this report are based on the worst case, i.e. continued operation at 60 °C using existing equipment.

Given a 0.6 kg fill-capacity of a 47 L compressed hydrogen cylinder, that translates to 20 kg Zn required per cylinder filled (representing 23.6 kWh energy value of hydrogen). In other words, the compressor for the 2400 L reactor will be filling 1.5 compressed hydrogen bottles every 8 hours on most runs. From the point of operation management, in order to stagger the introduction of medium hazard processes the first runs will fill one bottle per day and then switch to venting and flaring the excess hydrogen, before introducing bottle changes to the operational regime once the operators are more familiar with routine operation of the OIS plant. Operational safety assessment of the Hydromet plant is underway and includes control measures for hydrogen venting/flaring.

Reaction temperatures and pressures will be maintained between 50°C and 60°C and up to 1 barg vessel pressure. Ionic liquids have negligible vapour pressure, and this will also maintain safe operating temperatures for the PVC pipe material used throughout the first-generation reactor. Value engineering during the design phase of the (first generation) Hydromet pilot plant in 2022 ascertained that the higher operating temperatures (120°C, desired for faster commercial operation) would require switching to PTFE-lined steel pipes with a ten-fold price increase and very long lead times (> 6 months) due to an international supply chain. Consequently, this was ruled out for the first-generation plant – both on the grounds of value for money and availability. With appropriate funding, the material switch could be incorporated during the upgrade to the second generation 2400 L pilot, enabling significantly faster reaction times.

### 3.3.2 Integration: compression and storage

Collection of the co-produced gas from the 2400 L reactor will be via a special hydrogen approved ½ inch stainless steel medium-pressure tubing (ASTM A213/A269) PE, to reduce the hydrogen adsorption and prevent embrittlement. After the generated gases exit the reactor from the top, the mixture will pass through the following units before being compressed and stored in standard hydrogen bottles:

- **Desiccator** unit to remove the moisture from process gas;
- Zeolite membrane **separator** unit to separate hydrogen from CO<sub>2</sub>;
- **Compressor** (for compression up to 300 bar);
- Cooling unit (**cooler**); and
- Standard 47 L hydrogen gas cylinders.

Process flow diagram is presented in Figure 7.

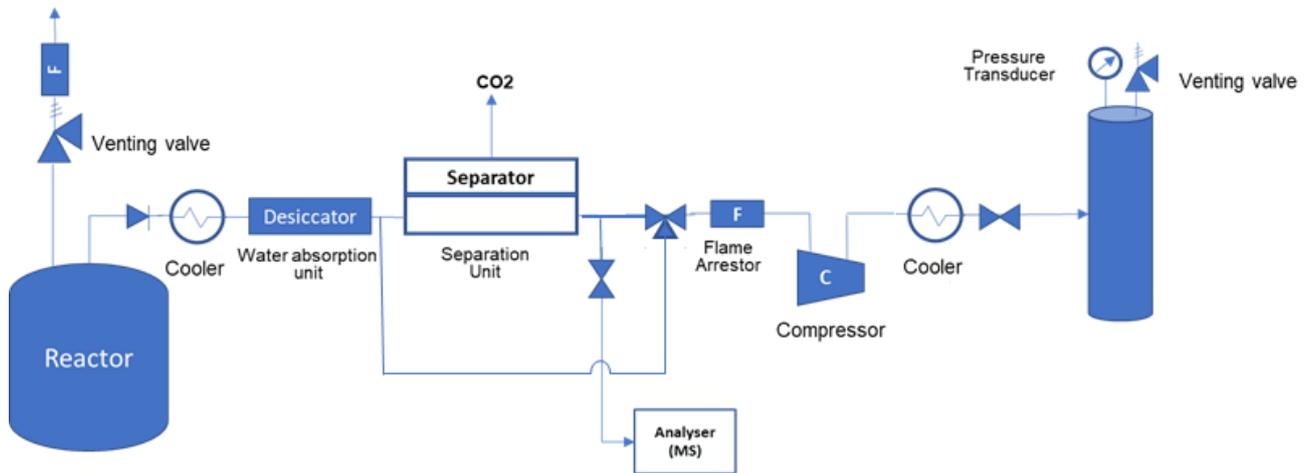


Figure 7. Process flow diagram for hydrogen collection

### 3.3.3 Integration: transport/delivery to point of use

Hydrogen generation using the OIS process is part of a larger by-product reclamation process, and, therefore, a commercial OIS plant will be co-located with the raw material source / stockpiles rather than the point of hydrogen use in a busy steelmaking plant. Steelworks typically have 1-2 km distance between their solid 'waste' settling lagoons/stockpiles and the iron or steelmaking plant. Continuation of the pilot demonstration and the FEED studies based around transportation of bottled hydrogen to shorter, local pipe runs rather than direct pipeline from the processing plant to the point of use is, therefore, valid and relevant. It also allows for a greater flexibility in the eventual outlet for hydrogen, which could be for transportation, as well as heating or iron reduction.

Hydrogen gas will be collected from the OIS reactor, purified, compressed and stored in standard compressed gas cylinders (47 litre) which comprise a caged 'maxipack' (an 18-cylinder unit). The maxipacks are subsequently transported to the network injection point by forklift with suitable static /spark suppression. This arrangement was considered the most suitable for several reasons.

This form of hydrogen supply is already in use at the MPI as a standalone supply and integrated into the bulk supply system as a back-up for tube trailer and let-down into the hydrogen pipe network (Figure 8). Staff are familiar with such an arrangement and have developed site-appropriate safe handling and storage procedures. It is modular, portable and uses commercially available pressure control valves and connectors. Additionally, based on existing estimates the £50,000 cost of adding an extra 50-metre partially buried pipeline spur from Hydromet facility to the hydrogen network simply for a few months of pilot trial was not considered good value for money compared to £9-10 per day for bottle pack hire. In any event, the 1:100 production volume:demand volume mismatch would require a storage buffer anyway at this scale, which can be provided by the use of bottle packs.



Figure 8. Gas bottle pack in situ supplying Rotary Reduction Furnace, Materials Processing Institute.

### 3.4 Industrial use case – feasibility and conclusions

#### 3.4.1 Quality of hydrogen generated

As described in Chapter 3.3.1, the OIS process is expected to generate a mixture of hydrogen and carbon dioxide, with hydrogen content varying from 50% to 100% by volume (5% to 100% by weight) depending on the feedstock in use. Processed slag feedstocks will generate the highest volumes of CO<sub>2</sub> over the course of the dissolution reaction (dependent on their lime content), whereas filter dusts will generate less but with rapid evolution in the early stages of dissolution. Further laboratory work is required to quantify these reaction products, using a larger range of samples, and it is recommended that a rapid laboratory evaluation of reaction rates and products remain a standard part of the preparation for the batch runs in the Hydromet plant. For this reason, a Hydromet support laboratory is now planned next to the reactor building to analyse feedstock and residuals, as well as in-line laser monitoring of approximate gas composition and gas mass spectroscopy to refine the accuracy of the results. The reactivity of 'free' lime (CaO and MgO) residual products post treatment will also be assessed by standard wet chemical analytical methods, so that their potential to re-capture an equivalent amount of CO<sub>2</sub> from the atmosphere can be quantified and included in the LCA.

Hydrogen quality has an impact on its use as a green fuel (first end-use case). As well as representing an emission of CO<sub>2</sub> to atmosphere, high-level CO<sub>2</sub> content in the hydrogen stream has an impact on the combustion efficiency by lowering the flame temperature and the flame speed, and reducing the fuel heating value. There is a lack of data for hydrogen

but an equivalent effect is observed in biogas where varying CO<sub>2</sub> concentration from 0 to 0.4 decreases the burning temperature by ~127°C. Should there be significant residual CO<sub>2</sub> in the purified OIS hydrogen, this effect will be determined experimentally and the data published and incorporated in the combustion models.

It is, therefore, essential to:

- reduce the content of CO<sub>2</sub> from the gas stream by optimising the reaction kinetics and the operating conditions of the process; and
- develop a separation process for CO<sub>2</sub> and hydrogen.

The latter will involve benchmarking the different separation technologies for continuous separation at scale, and selecting the most suitable route, considering the energy required to separate CO<sub>2</sub> from the gas stream. A membrane-based CO<sub>2</sub> separation loop has already been specified for the compressor, for ease of operability at these relatively small scales. These findings will also improve the confidence in the LCA model.

The level of purity of hydrogen required in the steel vessel reheat process will be set based on a trade-off study of the energy needed to separate CO<sub>2</sub> versus the combustion heating value gained and the penalty of increased CO<sub>2</sub> emissions to atmosphere. This study will cover the use of collected hydrogen in combustion processes involving atmospheric air as well as pure oxygen (oxy-combustion) and will provide valuable data on the adequacy of the two alternatives. The majority of the equipment is being procured under separate funding (items A, C and D described in Section 3.1) in order to be available in Q2 of 2023.

The second steelmaking use under consideration for the hydrogen is as a reductant in iron making, either as:

- an augmentation to blast furnace hot gas (which is a mixture of CO and hydrogen, and reduces iron oxides to form H<sub>2</sub>O and CO<sub>2</sub>); or
- for Directly Reduced Iron (DRI) in which iron oxides are reduced by pure hydrogen to release H<sub>2</sub>O; or
- a mixture of CH<sub>4</sub>/CO/H<sub>2</sub> to release CO<sub>2</sub> and H<sub>2</sub>O.

Neither process will be affected by traces of CO<sub>2</sub> in the hydrogen since it is part of the standard gas mix encountered in iron reduction.

The blast furnace process and the DRI process can be simulated during the pilot demonstration phase by adding the hydrogen gas to the hydrogen feed on the MPI's iron Oxide Reducibility rig (Figure 9) (Carbolite Gero Split Tube Iron Ore Test furnace calibrated to run ISO 4695:2015 Iron Ore Reducibility, ISO 7215:207 – Determination of reducibility of iron ores and various other Standards). These tests trace the reduction of a 500 g ore sample over a fixed time period under standardised gas mixtures, temperatures (typically 650-900°C) and flow rates of up to 20 L/min.

In addition, the DRI process can be demonstrated at 50-100 kg iron ore batch scale using the MPI's Rotary Microwave Reduction Furnace. This unit is an experimental 3-metre

furnace with variable radiant electrical temperature zones and additional microwave heating, which uses the equivalent of one 18-bottle hydrogen gas pack (10-12 kg) per 4-hour, 50-kg iron ore reduction run at typical temperatures of 500-850°C.



Figure 9. Left: iron ore reducability rig. Right: rotary reduction furnace at the MPI.

In both cases, the end product (metallised iron) can be analysed before and after melting to establish the composition of the liquid iron entering a steelmaking furnace and confirm the suitability of OIS hydrogen as a reductant gas in ironmaking.

#### 3.4.2 Hydrogen quantity – scale and match with use case

There is a 1:100 scale match between the amount of hydrogen produced from the OIS process at the pilot scale (up to 0.125 kg/h) and the amount which could be consumed during a continuous use in the industrial equipment at the MPI (up to 12 kg/h at full power). However, this reheat equipment is, by nature, in intermittent use: particularly, in the pilot steel plant at the MPI which typically runs ladle heating using natural gas on a 6-12 hour programme, once or twice per week, preheating a single 7-ton capacity ladle per arc furnace melt (Figure 10). Commercial steel plants have a more regular demand with hour-to-hour fluctuations on individual ladle preheat stations.

The solution proposed for the pilot demonstration phase is the same as would be on any commercial scale-up: compress and store the hydrogen at the point of generation, transport the compressed hydrogen tanks to the point of use, and connect it to supply the variable demand. Decoupling supply and demand allows for variability in the profile of each and removes the dependency and the risk of minute-to-minute variations in the hydrogen plant affecting steelmaking vessel availability in the steel plant, which is important in order to maintain a smooth steel production.

A further benefit of the pilot plant is the flexibility for choosing the preheating vessel and its duration of the operation:

1. Hydrogen preheating can be used as part of a single shift production campaign to heat a production ladle, if necessary, using the available hydrogen for a 1-2 hour final heat (from 1000 °C up to 1250°C) after the ladle temperature has been raised from ambient using a separate natural gas burner.
2. Preheating can also be studied over a longer time in a special, purpose-modified, instrumented ladle which shares thermal characteristics with the production ladles

but is constructed to enable refractory lining temperature profiles, flame characteristics and off-gas compositions to be observed. Such an instrumented test ladle could be fired for shorter periods of time simply to assess the heat transfer, without holding up any steelmaking operations. Whilst the pilot demonstration phase will demonstrate pure hydrogen combustion, the uptake of hydrogen at a commercial scale is expected to be gradual. At first, the hydrogen will be blended with natural gas before a complete phase-out of natural gas. Blending can also be explored to improve the comparison with the natural gas baseline, but the current R&D focus is on demonstrating pure oxy-hydrogen combustion.



Figure 10. Steel ladles and preheater stations in the MPI Normanton Pilot Plant: (top) 7-ton steelmaking ladle at a preheater station (foreground RHS) ready to receive tapped steel

(Electric Arc Furnace in the background on LHS); (bottom) Horizontal ladle preheat station which is being converted to oxy-hydrogen firing.

The projections of generation and subsequent use allows several days of OIS plant operation in 8-hour batches producing 0.1 kg hydrogen per hour. Following subsequent collection and storage, this quantity can then be used to heat a steel ladle at a rate of 2-10 kg hydrogen per hour.

### 3.4.3 Considerations and implications for transferring to a commercial steel plant

This Stream 2A report has focused on the feasibility of generating sufficient hydrogen from the OIS process to demonstrate potential steel plant end-uses rather than attempt to link it immediately to a commercial scale end use. This is for two reasons:

Firstly, the hydrogen is a co-product of the OIS process but as a side-effect rather than the main aim of the process and so the economies of scale for the main process (hydrometallurgical removal of zinc from wastes) must take priority in the commercial scale-up planning, siting of the plant and marketing the refined zinc oxide. Beneficial use of the secondary product, i.e., co-produced hydrogen, would improve the overall economic and environmental impact of the process but would not be the controlling factor in decision making. For this reason, collection, storage, and delivery of the hydrogen elsewhere on site is anticipated, where it could be blended with existing hydrogen-bearing off-gases (coke oven gas, blast furnace top gas, reformed syngas), natural gas, or used in isolation. The use case will depend on the volumes available which are not yet proven above laboratory scale, and so the scale-up development plan for the next stage must involve sustained demonstrations of the pilot equipment before steel users will view the process as a credibly significant source of hydrogen.

Secondly, the most realistic acceptable scenario for introducing local hydrogen use within a commercial steel plant is analogous to the proposed roll-out of hydrogen in domestic gas networks: blending up to 20% by volume with existing heating gas supplies to partially decarbonise them and establish familiarity and confidence, followed by phased introduction of 100% hydrogen use.

A pure hydrogen end case can therefore be demonstrated at pilot scale, to represent potential practice in the 2030s when hydrogen availability is anticipated to be matching potential demand on large industrial sites that currently deploy GW scales of fossil fuels, or to demonstrate the validity of one or two pure hydrogen installations during the 2020's within a plant which still functions largely on fossil gas. Doing so will enable assumptions about this type of rollout to be validated with smaller scale equipment, since multi-MW hydrogen burners are still under development.

Many questions are still unquantified and under research and so it is hard to make reliable predictions about their scale-up, hence the recommendation that a clearly defined piece of the puzzle should at least be demonstrated first – the pure hydrogen end-use case. This is borne out in other studies including those supported by BEIS, now DESNZ. Feasibility studies carried out in 2022 by the Materials Processing Institute as a partner in- the 'Green Hydrogen in Steel Manufacture' project of the BEIS/DESNZ Industrial Fuel Switching Programme Phase 1 [public report not yet published at the time of writing]-examined the potential for converting some zones of a commercial steel rolling mill to 100% hydrogen

firing and recommended further burner design work and combustion modelling to verify operation and emissions at multi-MW scale, since commercial hydrogen-ready burners were not yet available to test. One recommendation was the deployment of oxy-hydrogen combustion to limit NO<sub>x</sub> emissions and improve combustion efficiencies and heat transfer profiles. However, this was recognised as adding a further degree of capital cost and operational complexity to any such project. Such modifications are possible since oxygen is already supplied in bulk to integrated steel works that use the Basic Oxygen Steelmaking (BOS) process, but they illustrate the complexity of optimising a new fuel supply such as hydrogen. Even rolling out pure hydrogen to ladle preheating bays should be evaluated alongside oxy-firing upgrades to all burners (natural gas and hydrogen) to optimise combustion efficiencies and CO<sub>2</sub> emissions across all the fleet.

The introduction of pure hydrogen flame (in-air or oxy-fired) in refractory (ladle or other vessel lining) preheating or steel reheating is still very much a live research topic in terms of the impact of a different set of flame and atmospheric conditions on the equipment, refractory or steel product. The Materials Processing Institute purchased the experimental oxy-hydrogen ladle preheater for the purpose of carrying out several campaigns of demonstration and verification, which are planned for 2023 in co-ordination with other foundation industry research bodies, and will enable manufacturers to proceed to commercial deployment with confidence. The flame spectra and heat transfer characteristics [higher UV, much lower IR and visible, faster flame speeds and therefore different gas flows around the heating zones] will impact the heating rates and differential thermal expansion of refractory linings. The potential for free hydrogen or associated radicals to infiltrate or react with refractory binding phases and cause weak spots needs to be studied in case redesign of some of the mid-range temperature products (12-1600 °C) is necessary. However, the main issue to model and verify is the increase in H<sub>2</sub>O in the combustion atmosphere, both in terms of potential increased scale build up on steel stock (if hydrogen flame is used in reheating ) and impact on refractories, particularly high silica phases or sections where current design could lead to condensation zones and potential spalling. In all these considerations the option of direct electrification rather than a combustion fuel switch also needs to be considered by any responsible research team and a clear CO<sub>2</sub>-based case for the latter needs to be made, since carbon prices will gradually become dominant in the economics of steel manufacture in the years towards the 2030 and 2050 climate stabilisation targets.

#### 3.4.4 Variability

The OIS process is best suited to a decoupled supply and demand to allow sufficient buffering capacity to purify the gas stream, since the composition of the gas stream (H<sub>2</sub>:CO<sub>2</sub> ratio) depends on the feedstock. As a process dependent on potentially variable feedstock there is an estimated 10-25% variability in gas evolution rates for precipitated fines (filter cake/sludge where the reactant is predominantly zinc oxide fines) and a 25-50% variability when the feedstock is processed steel slag since the feedstock will vary in reactivity, free alkali levels, and other metal contents.

### 3.4.5 Safety considerations of use case

The ladle preheat equipment and networked supply, and the iron ore reduction facilities have been subject to thorough DSEAR assessments (Appendices 1 & 2 in D3.1) conducted during 2022 by subcontractors 6 Engineering, who are also directing the hazard studies and providing DSEAR assessments on the Hydromet plant.

Materials Processing Institute engineering and site services staff, the Site Safety Advisor, and research staff have been involved in several weeks of discussions, hazard and operational assessments, trouble shooting and plant facility modifications as the first generation Hydromet plant has been assembled on site and the commissioning process begun, following several months of supply chain delays for the suppliers to obtain and test components. This preparatory activity is crucial to safe and successful operation since a multidisciplinary team will be required to complete the commissioning, operate the plant and analyse the performance to allow for improvements in between each campaign.

The full hazard review including risk matrix is still underway, but in terms of safety of the Hydromet plant, the issues have been many and varied:

#### 1. Equipment fitness and design:

- a. Although the pipework and dissolution vessels are new, the 100 L reactor is a reconditioned vessel and so certification was only available for its integrated heating system, not the whole reactor, necessitating detailed part-by-part checks of gaskets and gauges, with some replacements to ensure confidence in resistance to the acids which will be used, and to enable the system as a whole to pass pressure testing.
- b. Accessibility of the dissolution pots, which must be manually isolated, disconnected and charged with each batch of solid reactant, has room for improvement. Manual handling, operator stretching, twisting and lifting, mitigation of liquid spill hazards during removal (by addition of bunding).

#### 2. Utilities integration:

- a. Electrical Fixed Equipment Testing , services integrity and capacity of distribution boards has been carried out and confirmed but additional earthing was required to mitigate static shock risk.

#### 3. Facilities upgrades:

- a. Extra venting of the equipment was recommended to mitigate gas explosion risk. Based on previous air change calculations in similar sized buildings (although with higher temperature hydrogen operating environments) it is likely that forced ventilation will be recommended for operation of the 2400 L reactor to mitigate spark ignition.
- b. Drainage connections were required to the below-ground IBC containers which will be used to capture spent liquids from the first-generation plant and

comply with waste handling and disposal regulations (the second-generation plant allows for greater regeneration and re-use of solvents).

- c. These issues must be addressed before operation begins so they have been prioritised by site engineering colleagues, to occur in parallel to final pressure checks on the equipment itself; however these factors together have put the earliest start date for running the actual OIS process back to April 2023.

#### **4. Chemical hazards:**

- a. Material Safety Data Sheets (MSDS) have been obtained for the ionic liquids, hydrochloric acid (HCl) and sodium hydroxide (NaOH), and some constituents of the waste materials.
- b. The initial plan to dilute several hundred kg of HCl and NaOH on site from solid precursors has been replaced by purchase of pre-mixed solutions with standard molarities, since suitable facilities could not be identified for this scale of chemical preparation. NB: Later development stages of the technology anticipate on-site electrolysis to regenerate the HCl and NaOH but this is not feasible at pilot plant quantities.
- c. The normal mitigation measures for chemical injury are required: overalls, goggles or face visors, gloves, and boots. Wash bottle and emergency shower accessibility (already present), and an appropriate training regime including operator competence assessments and authorisation for each method statement.
- d. The steelmaking waste feedstock materials hazards are being assessed based first on elemental analysis and then on known handling requirements for the actual compounds present in what are largely inert or passivated materials. Some pre-reaction crushing and milling of slags is required however, so the risks presented by active metal species including lead, cadmium are magnified by the possibility of dust being generated close to the operator.
- e. The same sets of hazards need also to be considered in the support laboratory environment where waste samples will undergo initial assessment.

#### **5. Fire and explosion risk (in the Hydromet plant room):**

- a. Principal areas for consideration are related to safe management of the main gas stream (from the reactor vessel, where the offtake / flare vent will be) and then the mitigation of spark ignition or autoignition risks of hydrogen building up locally around other parts of the equipment or building to unsafe concentrations (i.e. above 4% in air, risking ignition even by static spark discharge).

- b. Hand-held Crowcon detectors [calibrated for flammables including hydrogen] are in use on site already and will be the first line of defence for regular Standard Operating Procedures (SOPs) for checking of valves and components for leaks, and operators will also carry personal gas monitors; however, the building will also be fitted with permanent hydrogen sensor equipment linked to localised alarm sirens, and to the central alarm controls via the site Delta management system. Current trigger settings in use on site are at 20% of explosive level threshold, based on the advice of the detector suppliers and standard steel industry practice for other explosive atmosphere safety (principally CO).
- c. Anti-static PPE and other spark risk mitigation such as leaving mobile phones out of the building will be standard practice here as in other hydrogen areas on site. General staff training on hydrogen safety awareness is planned across the site including for other site tenants, and a new section on hydrogen safety awareness for the mandatory staff and contractors' site safety induction video is in preparation.
- d. Further mitigation will be provided by adequate forced and passive ventilation calculations (see (a) above within this section) to ensure sufficient air changes, and thorough appraisal of the building architecture.
- e. Facility to vent and flare offgas from the 2400 L reactor will be part of the upgrade (through a modified flame arrestor similar to that already installed on site for the Rotary Reduction Furnace).

## **6. Fire and explosion risk (compressor and hydrogen bottle pack):**

- a. Additional to the above measures, the Hydromet pilot plant DSEAR assessment will include consideration of the location of gas cleaning and compression equipment and any potential additive effect of hazard zones from this and around the Hydromet unit itself. The unit and the compressed gas bottles will be sited outside the Hydromet building to maximise ventilation. Extraction pipe connection from the Hydromet reactor to the compressor will be through the external cladding of the building, to maintain a safe 8 m linear distance from any doorway or electrical distribution boards and will be caged off with authorised access only and gas safety zones indicated on the ground around it. Based on calculations currently in use on site for the hydrogen bottle pack installation feeding the Rotary Reduction Furnace this is likely to include 11-12 m of exclusion zone for combustion engines when the equipment is in use, and a 2-3 m exclusion zone when compressed hydrogen is present but isolated from the compression equipment.
- b. Transport of the hydrogen bottle pack from the compressor compound to the point of connection will be by forklift truck following the measures laid out in the internal Risk Assessment 20230208-ID-A for moving large multi-bottle hydrogen packs around site; the final manual movement of the packs within the restricted gas compound is laid out in Risk Assessment 2023-0207-ID-A.

- c. The focus of the mitigation measures in these cases is on avoiding spark ignition of stray or leaking hydrogen, through carefully planned bottle pack handling, lifting and moving; through use of gas detection monitors on the packs and operators themselves; through anti-static PPE and through training, advance communication and clear visual warnings (temporary internal road closure, personnel visible to other site users) when moving hydrogen around on the site.
- d. Further risk mitigations are standard physical safety measures for moving and handling loads on manual pallet trucks, for movements involving 2 or more staff, and on staff awareness around forklift trucks.
- e. The conditions for the bottle pack connection to the hydrogen pipe network are the same as the current installation of bottle packs at the same feed-in point, where they are used to supply the Rotary Reduction Furnace covered in the DSEAR assessment, a restricted access compound requiring anti-static PPE, no mobile phones, portable gas detection.
- f. Since this input point is at the end of the hydrogen network, the demonstration phase will require some additional manual and solenoid valves to enable the integration of this with the network section leading from the rotary furnace compound to the steelmaking pilot plant (a 30 m pipe run 3 m above ground along external walls) will require pressure checks via gauges on solenoid valves following each changeover.
- g. And to blend into network we need a 200 to 15 bar pressure reducer with a vent, isolation valves, (solenoid valve, isolation valves on both sides of the system, i.e. after bottle, and on network, and a venting system in between.

## **7. Fire and explosion risk (ladle preheater):**

- a. The standard operation of the ladle preheater in the steel plant on natural gas was developed. The hydrogen preheater station will be commissioned later in 2023 the next revision of preheater Risk Assessment is scheduled alongside preparatory training with the steel plant operational crew as that station swaps over from natural gas-air firing to oxy-hydrogen.
- b. This preheat station was installed as an additional station in 2022 to enable hydrogen and/or upgraded natural gas preheating alongside the existing natural gas preheater. The location is as close to the north plant entrance as feasible as a precaution, to allow maximum natural ventilation and dilution of any stray hydrogen but several active measures are also being installed to mitigate combustion or explosion risks.
- c. Pressure testing with nitrogen and then with helium during final commissioning.

- d. Nitrogen purge of gas lines within the steel plant (i.e., downstream of the external wall isolation valve) before and after use.
- e. Robust isolation regime (solenoid and manual valves) with controlled key manual lock-off as the final step.
- f. Fail-safe flame shutoff when ladle heating lid is not fully closed or if the flame fails to ignite.
- g. Hydrogen network shutoff via central control system in the event of pressure drops anywhere in the network.
- h. Oxygen supply from the plant oxygen main has similar shutoff procedures, and staff will be trained on the differences between air firing and oxy-firing, with refresher training on oxygen handling and hazards and the use of combustible atmosphere detection devices.
- i. Staff training on ladle preheating SOPs for the standard operation under natural gas.
- j. Procedural safety practice and communication (verbal, written and with temporary signage during use) with plant supervisors and staff to ensure no naked flame or other heating or welding/cutting activity is taking place within a 12 m safety zone during preheater operation and to ensure that all personnel, contractors and visitors on the shop floor and adjacent areas are aware when hydrogen heating trials are planned.
- k. Anti-static PPE as for all other hydrogen areas.

**8. Other risks (ladle preheater):**

- a. The current RA covers mitigation of risks from radiative heat due to proximity to hot vessels up to 1250°C and conducted heat through contact with hot surfaces up to 400°C; also mitigation of the risks from overhead crane lifting, noise from burners, and the maintenance of safety systems including fail-safe shutoff flame detection equipment and purging gas (nitrogen) lines.
- b. All personnel coming onto the steel plant floor during active operations wear heat or molten metal resistant clothing, helmets, eye and ear protection as mandatory and must be trained and signed off as competent in each individual procedure on the plant which they are required to operate.

## Verification of performance:

### 3.4.6 Hydrogen generation

Gas composition from the OIS process will be measured continuously and logged by an in-line monitor as will exhaust gas from post-combustion carried out when it is not being collected (e.g., during start-up and shut-down). Gas samples will also be taken for analysis offline by mass spectroscopy.

The OIS plant control system data, energy consumption will be measured and logged on a 10s frequency integrated with the MPI's Thingworx platform.

Data analytics of plant data plus feedstock characterisation results will be carried out by the Materials Processing Institute digital technologies group, with interpretation by the project partners. This will enable a performance matrix to be established and operational rate equations verified for the plant, net energy and mass balances and GHG impact to be calculated, and a predictive model to be established. Parameters to be collected for input into the matrix will be:

- Feedstock source and composition: elemental and phase characterisation by X-Ray Diffraction, X-Ray Fluorescence, Mass Spectroscopy; variability of these for each source.
- Feedstock morphology: particle size distribution.
- Residual solids composition and morphology.
- Process conditions: reactor and dissolution vessel temperature, system pressure, heat inputs, mixing and reaction times.
- Emitted gas rates, total volume per kg of material treated, composition (hydrogen, water vapour, CO<sub>2</sub>, N<sub>2</sub>).
- Gas flare or venting losses.

### 3.4.7 Hydrogen compression and storage

Commercially available hydrogen diaphragm compressors have been identified, as having standard gas cleaning and membrane filtration elements capable of handling the gas volumes, and an invitation to tender for the compressor system has been published based on expected gas volumes. The compressor will be rated for 1-5 Nm<sup>3</sup>/hr but a larger unit may also be procured under the Materials Processing Institute's internal hydrogen development centre budget.

Compressor energy consumption will be logged (standard energy meter connected to Thingworx), and compositional testing of the compressed hydrogen will be carried out both in-house and by independent analytical services.

Hydrogen mass balance model will be established for the whole system, incorporating losses through flaring, non-combusted emissions to atmosphere, and fugitive losses -

based on extrapolation of exhaust data, volume of gas supplied to the end-use (from mass-flow controller data), theoretical hydrogen volumes expected from analysis of the pre-and post-reaction solids. This will be related to industry norms for fugitive losses from compressed tanks [in 300 bar compressed 47 L bottles, suppliers have quoted this at 2-5% per week] to show deviation from “best possible” performance.

### 3.4.8 Hydrogen in use

A specially modified instrumented steel ladle and mobile thermal imaging equipment, along with mass spectroscopy will be used to compare heating performance of the OIS hydrogen with the performance of the regular supply of merchant hydrogen, and with the baseline of natural gas to confirm heating values, flame characteristics and products of combustion. Steel ladles (Figure 10) in use at this plant are bucket-shaped vessels approximately 2 m high x 1.5 m diameter, lined with alumino-silicate refractory cement which can withstand and contain 7 tons of molten steel and slags up to around 1600 °C while they are being transported (by crane) to secondary steelmaking or casting areas. The modified ladles a standard 7-ton ladle shell which has been relined to create a 1m+ flat-bed domed combustion testing space rather than to hold molten metal. It was redesigned in 2022 and rebuilt in February-March 2023 and is scheduled for commissioning in Q1 of 2023-4 to demonstrate commercial oxy-hydrogen combustion equipment for a range of clients.

The preheater burner is a Linde Oxygen 400 commercial preheat burner, originally designed as a natural gas oxy-fired burner, and modified by the OEM to run on pure hydrogen plus oxygen, ie with the gas flows increased and nozzles tested to ensure comparable thermal output and flame characteristics vs natural gas. Due to capital funding availability, it was purchased in 2021 ahead of the hydrogen network and ladle preheat station installations and will be commissioned in mid 2023. The maximum rated output is 400 kWth and it operates on a pulsed modulation control. It is fitted into the centre of a close-fitting insulating refractory lid which swings across the ladle top during operation and has a double exhaust gas extraction flue integrated into the lid.

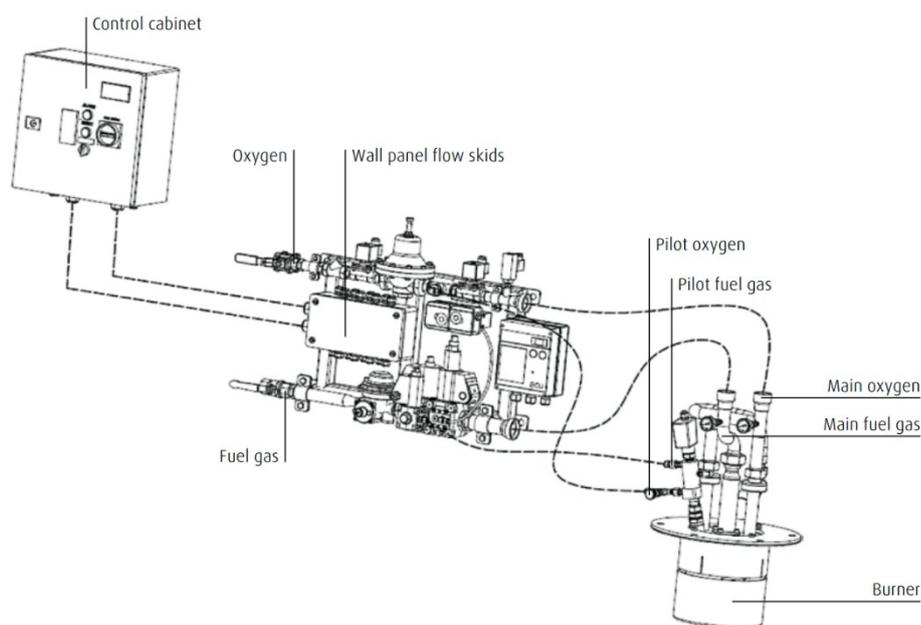


Figure 11. Linde Oxygen burner.

Preheating the ladle to 1250 °C or higher for steel plant operation typically takes 6 hours due to the thermal mass and expansion characteristics of the ladle lining and shell, and is normally conducted using a natural gas burner. This preheat is essential to enable the ladle to receive tapped hot metal at temperatures between 1550-1650 °C without thermal shock cracking the lining, and without the steel charge cooling and solidifying in the ladle. It is claimed that oxy firing can reduce heatup times vs air firing, through a more even heat distribution and hotter flame temperatures, as well as the economic and environmental benefits of removing air from the combustion zone, with the combustion efficiency gains, and the vast reduction in nitrogen converting to NO<sub>x</sub> and/or absorbing and carrying away thermal energy.

Computational fluid dynamic models of hydrogen combustion are established on the Materials Processing Institute Ansys modelling server and so these can also be linked to experimental performance data to improve predictions about scaled up end uses.

The expected outputs would be a combustion model of a commercial size (150-200 t) ladle preheat burner which would model the options for blending or substituting hydrogen in the fuel supply. This would incorporate heat transfer rates and consistency (i.e., evenness of heating), turnaround times, running costs, emissions of CO<sub>2</sub>/H<sub>2</sub>O/NO<sub>x</sub> and any expected changes in refractory lining life as a result of more even heating and/or potential hydrogen combustion atmosphere impacts. It would compare it to current practice to make a case for decarbonisation options for the ladle fleet.

During demonstration, following initial combustion studies the instrumented ladle will be swapped for a standard production ladle once the performance is established, so that the hydrogen vessel preheating is demonstrated integrated into a full standard steel production cycle (i.e., the hydrogen-heated steel ladle is being used to transport molten metal within the steel plant as it would do on a commercial steelworks). Combustion offgas from the exit flues (primarily H<sub>2</sub>O) will be monitored for composition by in-line instruments, and samples analysed in-house by mass spectroscopy for trace components including NO<sub>x</sub>. Since this set-up is already under commission and most components are on site the timescales are feasible within 12 months.

The other steelmaking use identified by commercial stakeholders is the use of the hydrogen in iron ore reduction. This will be demonstrated first using hydrogen, a pure reductant, to compare with merchant hydrogen in a pilot scale direct reduction furnace. Thereafter, a low percentage blend with CO and CO<sub>2</sub> in standard ore reducibility testing equipment will be tested to mimic hydrogen enhancement of the Coke Oven Gas which is used as a supplementary reductant to reduce coke consumption in blast furnace use. Reducibility mass loss-time curves, thermodynamic calculations and metallurgical comparisons will be used to verify the performance and value-in-use of this form of hydrogen as a reductant in conventional steelmaking. Again, the equipment necessary is already on site and under commissioning as this report was written.

Transferring this learning to a full-scale site would involve augmenting the tuyere gas supplied to a blast furnace with a few percent of hydrogen, starting below 1% and holding

each incremental increase in hydrogen concentration steady for several days to allow internal conditions in the furnace to adjust and be analysed before proceeding to the next increment. Existing furnace and topgas monitoring systems would be able to track any changes and the main modifications would be a bleed-in control to add hydrogen before the gas heaters. This approach is TRL 8 since the behaviour of hydrogen within blast furnace reduction is well understood, as it is part of the reducing atmosphere which occurs as fossil hydrocarbons break down. The hydrogen-iron oxide reduction reaction is endothermic, unlike the carbon-iron oxide reaction, i.e., it is known to extract heat from its surroundings and this property is exploited as part of the furnace control strategy. However, the development of hydrogen for ironmaking is now focused on transitioning to direct reduction of iron rather than extending the operating life of blast furnace assets. For this reason, the working assumption for this study has been that a preheating or reheating combustion fuel switch will be a more sustainable end-use for the 'green' hydrogen produced by OIS or similar processes, since these processes (reheating for rolling, in particular) will continue to be essential for steelmaking.

Out of scope for funding within this call, but should opportunity be found to verify the performance as a fuel for hydrogen plant vehicles, e.g., in combustion engine mobile plant equipment in use around the waste reprocessing site, suitable quantities of verified composition OIS hydrogen will be supplied to the relevant third-party research groups. As Teesside is a national hub for future transport hydrogen demonstrators there may be easy opportunity to participate. The purity of fuel cell grade hydrogen is not required for the main applications so this is not a priority for the output, hence any transport demonstrations would have to assume combustion engines and go ahead with 99.9% OIS hydrogen as-supplied.

#### 4. Value, future plans and dissemination

##### 4.1 Values and benefits

###### 4.1.1 Economic

The OIS project will create a new form of industrial symbiosis in the supply chain for the Foundation Industries (FIs), keeping waste out of landfill and increasing productivity with limited resources. Green hydrogen is produced at a very low cost and can be used as a green fuel to replace fossil fuels and accelerate reaching Net Zero.

Valorising zinc waste into functional ZnO will reduce imports, create exports, reduce waste, and advance the UK circular economy. Domestic manufacturing of this sustainable form of ZnO will give Nanomox's customers access to a stable, secure supply of a critical raw material, which is particularly important in times of supply chain disruption.

The OIS process has the potential to create new advanced materials and improve the profitability of the FIs, positioning the UK as a leader in sustainable innovation. New, affordable morphologies of ZnO enabled by OIS create an unprecedented opportunity for emerging sectors, such as solar photovoltaics, advanced construction materials, and aerospace engineering.

The UK economy will benefit from reduced imports of ZnO and reduced exports of waste zinc, contributing positively to the GDP. Domestic manufacturing of sustainable ZnO will reduce dependence on unstable supply chains and secure UK jobs in high-value industries.

It is worth mentioning that with the OIS process, the crystal morphology of the ZnO particles can be controlled, and a diversity of materials are possible ranging from nano-sized to micro-sized particles. This morphological control cannot be achieved through the French Process which only produces bulk ZnO. These advanced ZnO materials have a higher selling price than bulk ZnO of up to £60k/ton. Therefore, even without further process optimization, the OIS process is viable to supply the advanced ZnO market at a very competitive price.

#### 4.1.2 Environmental

Due to the R&D nature of the feasibility study during Stream 2A, no emission savings were achieved. However, this project contributes to decarbonisation of the foundation industries, producing green hydrogen, improving circularity and significantly reducing GHG emissions to move the UK towards Net Zero. The OIS process produces ZnO with an excess of co-produced hydrogen, eliminating the need for external fuel input for the heat requirements. Relying largely on electricity for the process, the OIS process can easily be fully decarbonised. The process further has the ability to convert low-grade industrial wastes from batteries and steel manufacturing to high-quality products, creating an industrial symbiosis that reduces landfill waste and consumption of energy-intensive mined materials while co-producing green hydrogen.

#### 4.1.3 Government Priorities

This project supports the government's Build Back Better plan by contributing to the core pillar of Innovation, as well as Net Zero and a Global Britain. The sustainable, high-quality ZnO and green hydrogen produced by Nanomox moves the UK toward a high-growth, sustainable and secure economy. Scale-up of this process will build a new domestic, low-carbon manufacturing industry, creating jobs and export opportunities.

#### 4.2 Dissemination activities

Throughout Stream 2A, Nanomox and the Material Processing Institute created awareness of the importance of NetZero via conference attendance and presentations and, social media and public broadcast media activity. Engagement will continue with targeted third parties, including those with general interest in hydrogen and materials circularity, such as environmental regulators, regional hydrogen economy promoters (e.g., Teesside Net Zero Hydrogen Innovation Centre, South Wales Industrial Cluster), foundation industry academic researchers and umbrella groups (TransFIRE, SUSTAIN, TFI), recycling operators, local schools and the general public.

Nanomox attended UK Metals Expo from 13-14 September 2022 at the Birmingham NEC and participated in one of the flagship events organised by the Greater London Authority (City Hall) during COP27 to promote student engagement in the climate crisis and clean/green technology at the Royal Institution on Tuesday 8 November 2022.



Figure 12. Nanomox participation in the events organised by The Greater London Authority (City Hall) at the Royal Institution on Tuesday 8 November 2022.

Nanomox is committed to disseminate the findings on Stream 2A in future conferences and peer-reviewed scientific publications.

### 4.3 Hydrogen fuel switching

The iron and steel industry are a major contributor to the overall anthropogenic CO<sub>2</sub> emissions worldwide, and therefore a significant driver of climate change. The iron and steel industry are responsible for about 4% of anthropogenic CO<sub>2</sub> emissions in Europe, and 9% worldwide, due to the massive use of coal (PE 641.552 – December 2020).

This project explored the possibility for decarbonising iron and steel production processes by replacing fossil fuels with green hydrogen produced with an innovative process, the Oxidative Ionothermal Synthesis (OIS). OIS not only produces green hydrogen but contributes to intrinsic decarbonisation of steel making by avoiding landfill of zinc-rich slags which can be recycled for steel making, and used as a source of zinc.

The switchover from coal to green hydrogen on a worldwide scale will also have implications for the geospatial distribution of the global steel industry. Access to domestic coal or easy shipping facilities for imported coal were key considerations in the past for the construction of new steel mills. With the transition to green hydrogen, the local availability of cheap renewable electricity, or the existence of transport facilities for hydrogen (pipelines, port facilities) will become important aspects of steel industry competitiveness. This feasibility study showed that integration of Oxidative Ionothermal Synthesis for Hydrogen (OIS) within a steel mill is technically feasible. Even though the hydrogen quantities are limited to the zinc content in the waste stream, it can be implemented faster than other technologies under development for green hydrogen production, as it allows the monetization of waste streams.

### 4.4 Future plans

The end-to-end solution proposed in this project will continue to be developed after funding ends. The next steps include:

1. Validation of process scalability: Finalize pilot trials at the Materials Processing Institute (100 L and 2400 L reactor trials), recovery and purification of the OIS hydrogen, and its safe use in the steel industry .
2. Validation and selection of technologies for commercial plants based on pilot trials performance .
3. FEED study to confirm technical, economic, and environmental performance of the end-to-end solution .
4. Detailed engineering design for the flagship plant (capacity and location to be confirmed in the future, post-project).
5. Construction, commissioning, and operation of the flagship plant (post-project).

Nanomox will continue to work on the optimisation of the OIS process, and generate technologies and knowledge around the process, to expand to other waste streams, and other metals beyond zinc. There is a vast potential for technology roll-out, carbon savings across sectors and integration with other sectors beyond steel manufacturing. This should include how the process could be scaled and replicated more widely, including in different applications.

## APPENDIX

## Appendix I: Comparison of several processes for zinc oxide production.

Table 17. Qualitative comparison of the main methods for ZnO production. The best process per criteria has been highlighted in green while the worst has been highlighted in red. The symbol +?/-? were used to indicate that more research/analysis is needed to reach a conclusion.

Criteria	French Process	OIS	Hydrothermal Methods
Hydrogen	<b>[-]</b> Not produced.	<b>[+]</b> Produced.	<b>[-]</b> Not produced.
Particle Quality	<b>[-]</b> Morphology not controlled.	<b>[+]</b> Morphology, size and chemical composition can be controlled.	<b>[+]</b> Morphology, size and chemical composition can be controlled.
Energy consumption (Environmental footprint)	<b>[-]</b> High temperatures required to vaporize metallic zinc. Difficult to decarbonise as green hydrogen is cost prohibitive in this low-margins process.	<b>[+?]</b> Reaction can be carried out at low temperatures (no phase changes). Hydrogen produced can be used as a fuel. Main energy input is electricity, which can be easily decarbonised. Some process conditions will result in Zn(OH) <sub>2</sub> (or others), which will require high temperature calcination for ZnO production.	<b>[-]</b> Reactions can be carried out at low temperatures but in most cases calcination of Zn(OH) <sub>2</sub> at high temperatures is required.
Safety	<b>[-]</b> Risk of explosions and fires due to the high temperatures and the use of fossil fuels.	<b>[+?]</b> Ionic liquid/water mixtures are not flammable and have negligible vapour pressure. Toxicity and effect on the environment will need to be studied, but is expected to be in line with the properties of	<b>[-]</b> Precursors used in hydrothermal methods are in general more dangerous than metallic zinc.

Criteria	French Process	OIS	Hydrothermal Methods
Operating Cost	<p style="text-align: center;"><b>[-]</b></p> <p>High energy demand but no chemical consumption.</p>	<p>the underlying amine and acid.</p> <p>Hydrogen is produced. Refer to section 3 for Safety considerations.</p> <p style="text-align: center;"><b>[+?]</b></p> <p>Ionic liquid is not consumed in the process and can largely be recycled. IL losses will significantly impact the OPEX. High chemicals consumption can be managed through the chlor alkali process, which can potentially recover all chemicals from the aqueous waste stream.</p>	<p style="text-align: center;"><b>[-?]</b></p> <p>These methods were not modelled in detail. However, high energy demand is expected due to the calcination step and increased cost to process aqueous waste streams.</p>
Capital Investment	<p style="text-align: center;"><b>[+?]</b></p> <p>Expected lower CAPEX than the OIS process but has not been modelled in detail.</p>	<p style="text-align: center;"><b>[-?]</b></p> <p>The OIS process is likely to require integration with a chlor alkali process, increasing the overall capital investment required.</p>	<p style="text-align: center;"><b>[+?]</b></p> <p>Not modelled but should be similar to the OIS process excluding wastewater treatment plants and chlor alkali add on.</p>
Process	<p style="text-align: center;"><b>[+]</b></p> <p>Well established technology.</p>	<p style="text-align: center;"><b>[-]</b></p> <p>Novel process. Large scale separation of nanoparticles from the IL/water mixtures needs to be validated.</p>	<p style="text-align: center;"><b>[-]</b></p> <p>Industrial experience for the production of ZnO via wet chemistry methods, but very poor scalability of the process steps.</p>

## Appendix II: Technology Readiness Levels (TRL) predictions

The TRL was calculated for before and after the proposed demonstration phase. For the current calculation, the system was separated into component technologies, each with an individual TRL, and with a weighting assigned to each of those numbers to obtain a reasonable average TRL.

### **OIS 1st Generation reactor plant [40% of total system, at overall TRL-4]**

This is assessed as TRL-4, since reactions have been proved at bench scale but require further optimisation for various feedstocks. Crucially, solvent recycling needs to be demonstrated. A small pilot plant is installed and to be commissioned imminently (100 L main reactor), which was built from commercially obtained components following a rigorous design phase, and can be scaled-up to the 2400 L scale. A standard 3-phase reactor philosophy was used. Materials handling uses established technology but materials extraction and beneficial re-use is undemonstrated with this solid feedstock.

### **Gas monitoring and Hydrogen capture [30% of total at overall TRL-8]**

Gas monitor and components are at a TRL 8 because they are commercially available but not yet integrated in the OIS pilot plant. Hydrogen separation is a TRL 9, since this is commercial condensation and membrane technology, and can easily be applied to the gas mixture produced in the OIS process. Equally, hydrogen compressor and storage are at a TRL 9, including commercial compressor, regulators and bottles.

The hydrogen interface with existing hydrogen supply gas pipes is at TRL 7, since it uses commercial components but is not yet integrated with the supply network. Blending for first round commercial integration has not yet been demonstrated with hydrogen from this source.

### **Oxy-Hydrogen burner [30% of total at overall TRL-7]**

The oxy-hydrogen burner is at TRL 7 since it is a burner adapted from commercial standard technology now beginning to see market applications using natural gas, and it has been demonstrated by the manufacturer in pilot use with hydrogen, but is not yet mainstream technology.

**Overall starting point TRL calculation** = {average weighted total at start} – 1 for novelty of integration

$$= \{[40\% \times 4] + [30\% \times 8] + [30\% \times 7]\} - 1 = 5.2$$

i.e. the estimate for the system as a whole at the start of demonstration is **mid TRL 5**

### **Development of the component TRL levels during demonstration:**

Development of the OIS reactor: increasing the TRL from 4 to 6 occurs will be achieved by operating the 100 L reactor for small batch (kgs), followed by replication of the conditions in the 2400 L large batch (100 kg) reactor during year 1. This will feed into the optimisation of the continuous reactor design. A small proof of concept continuous reactor is planned to be built at the same facility in year 2. This will be followed by a FEED study on the commercial tons-per-day continuous process.

Development of the hydrogen integration from 8 to 9 in year 1-2 occurs by demonstration of the commercial technologies in combination in the novel reactor and integrated with the hydrogen delivery trains.

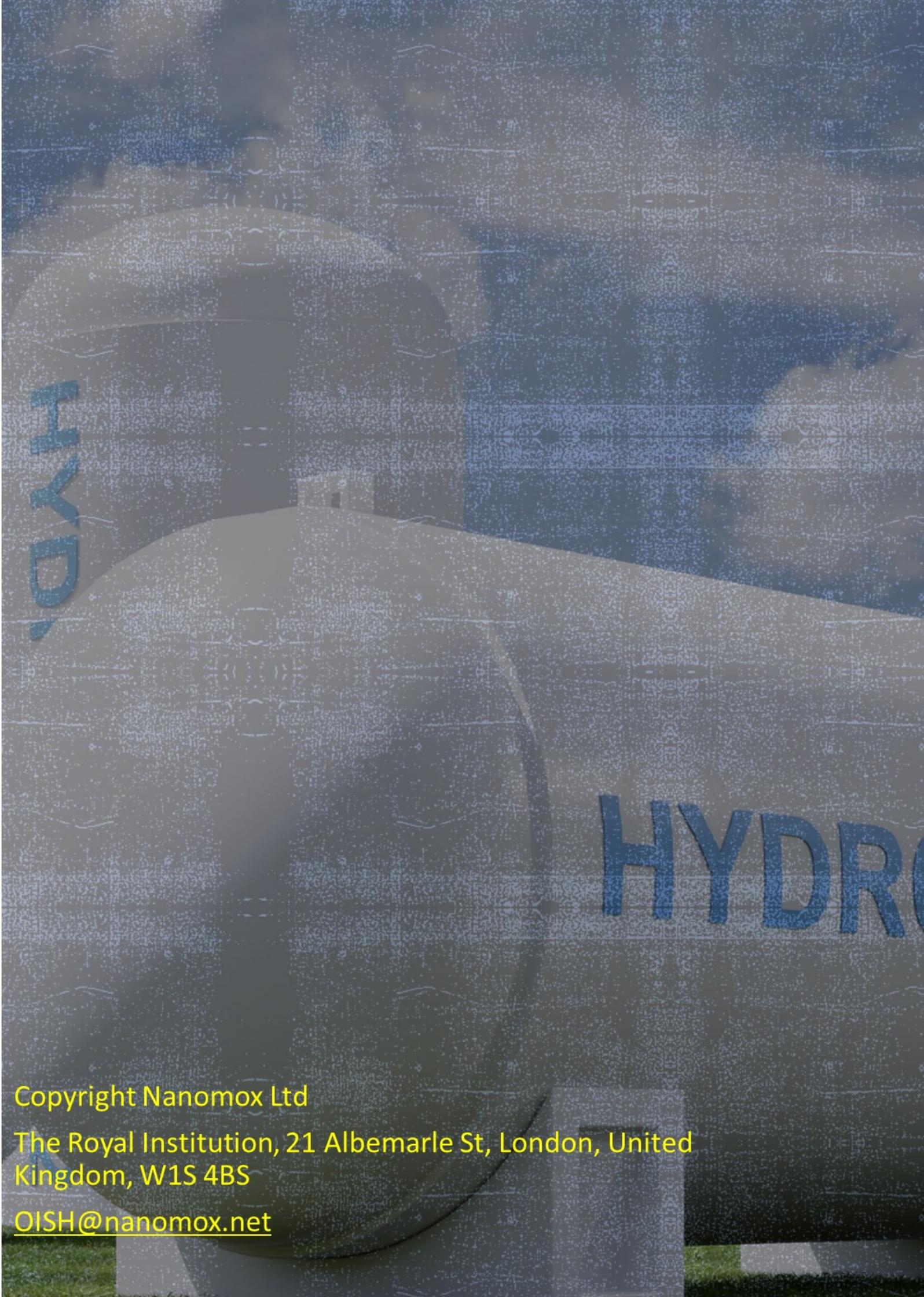
Development of the end-use burner: demonstration at TRL 8 will be achieved through the use of the burner as an integrated technology in a small production plant (MPI steelmaking plant). Other potential end use options can also be demonstrated on site: a small pilot iron ore reduction and small steel/ceramics heat treatment furnaces are available, moving the demonstration of OIS hydrogen for reduction or heat treatment to TRL 6.

**Overall end point TRL calculation** (i.e., FEED and demonstration complete but commercial plant not built) raises the combined TRL predicted to:

$$\{[40\% \times 6] + [30\% \times 9] + [30\% \times 8]\} - 1 = 7.3$$

This will thus confirm the readiness to build a TRL 7 flagship plant and deliver hydrogen to pilot verified industrial uses at the 1MW scale.

Successful operation of the flagship plant will result in a TRL-9.



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