

# Materials for Nuclear Enabled Hydrogen

A landscape report exploring the technologies, recommended research, and wider enablers for the development of a nuclear enabled hydrogen sector.

ROYCE

## Foreword

**There has been much focus on direct electrification as the answer to lowering our carbon emissions, and of course, with regard to transport, this is the most attractive solution for cars, vans and light goods vehicles. However for areas such as shipping, aviation and the heavier end of our manufacturing industries, an alternative energy vector is urgently required.**

The capacity of [green hydrogen](#) to meet such demands has now moved much further up the energy agenda – indeed the Committee on Climate Change (CCC) foresees an expansion of low-carbon hydrogen production equivalent to nearly a third of the current power sector by 2035, as outlined in the [Sixth Carbon Budget](#). Significant progress is already being made towards adoption of hydrogen worldwide, but we need to act quickly to ensure it becomes an integral part of the UK's industrial future. We recognise that a significant bottleneck to this wide-scale hydrogen deployment is assurance and availability for materials compatible with its production, storage, and distribution.

In 2021 Royce commissioned its [Materials for End-to-End Hydrogen report](#) which identified the most valuable materials research areas to accelerate the transition to hydrogen as an energy vector. As a result a number of Royce facilitated materials related activities are now underway including routes to funding such as the [Royce Hydrogen Accelerator](#)

Now, nuclear enabled hydrogen is gaining interest, with a focus on nuclear power as a low carbon source of energy. In the same year Royce produced its Hydrogen Roadmap, the National Nuclear Laboratory (NNL), a Royce Partner, also published its own [Roadmap on how nuclear enabled hydrogen](#) could support the UK achieving its net zero targets.

This Roadmap Report was clear that low carbon hydrogen production from today's grid connected nuclear is possible using current technologies. However, it also recognises that nuclear power is not only a source of electrical energy, but also of process heat; by utilising the heat from a nuclear reactor, there is the potential to tap into existing technologies that could also generate hydrogen at greater efficiencies.

Royce and NNL were therefore pleased to compile this latest [Royce Landscape Report](#). It contains an overview of the materials challenges ranging from materials issues that could impact the performance of the technologies required to generate hydrogen from nuclear, through to the risks associated with coupling nuclear reactor heat outlets with downstream plants. It concludes:

- The technical maturity for conventional electrolysis routes for hydrogen synthesis from grid connected nuclear is already high. The materials challenges that do exist are well covered in the Royce Materials for End-to-End Hydrogen Roadmap.
- For intermediate maturity technologies including solid oxide and PEM electrolyzers there will be materials challenges associated with the non-nuclear aspects of the technology including scalability and lifetime.
- For low maturity, high temperature thermochemical hydrogen production, there needs to be clear targets around operating temperatures and target efficiencies so that the nuclear systems can be designed with maximum performance and reliability. The materials challenges associated with delivering these technologies are considerable.

This Landscape Report recognises that significant technology gaps remain and these will need to be addressed as a UK strategy around nuclear enabled hydrogen evolves. It also identifies a pressing need for different areas of the research community to work together to advance this understanding, particularly regarding manufacturing and catalysis.

It is therefore hoped that this latest Royce Landscape Report will catalyse such interactions across the UK R&D base to enable further momentum around nuclear enabled hydrogen.

On a final note, Royce and NNL would like to thank Delta H for their hard work in compiling the input from a diverse range of stakeholders and literature sources.

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## Acknowledgements

The project team wishes to thank all the individuals and organisations that took the time to support and contribute to the study.

Robert Alford (National Nuclear Laboratory), Mark Bankhead (National Nuclear Laboratory), Andrew Bowfield (Henry Royce Institute), Nigel Brandon (Imperial College London), Qiong Cai (University of Surrey), Bo Chen (University of Leicester), Brian Connolly (Henry Royce Institute), Paul Connor (University of St Andrews), Peter Donnelly (Office for Nuclear Regulation), Nadimul Faisal (Robert Gordon University) Jonathan Hawes (National Nuclear Laboratory), Mamdud Hossain (Robert Gordon University), Stefan Hotomega (Ceres Power), John Irvine (University of St Andrews), Fran Jones (Frazer-Nash Consultancy), Sam Knight (UK Atomic Energy Authority), Alexander (Sandy) Knowles (University of Birmingham), Ewa Marek (University of Cambridge), Juan Matthews (University of Manchester), Jiawei Mi (University of Hull) Robin Morris (Henry Royce Institute), Oliver Posdziech (Sunfire), Oliver Postlethwaite (Ceres Power), Chris Rowe (Ceres Power), Allan Simpson (Equilibrion), Bob Sorrell (Henry Royce Institute), Karl Whittle (University of Liverpool), Dan Wolff (UK Atomic Energy Authority)

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## Executive Summary

The UK has announced plans to vastly expand its nuclear fleet by 2050, with a proposed 24GW of nuclear capacity by the middle of the century. Tangentially, the UK's Hydrogen Strategy forecasts the UK's low carbon hydrogen demand to be between 250 and 425 TWh per year by 2050 representing 20-35% of the UK's total energy demand. The use of nuclear power to produce hydrogen has been proposed to help meet 2050 net zero hydrogen production targets. Thermally enabled hydrogen production technologies would make use of combined nuclear heat and electricity outputs to reliably produce low carbon hydrogen. Given the speed and scale of development required in these sectors, a clear understanding of the materials challenges which may act to hinder the delivery of nuclear enabled hydrogen technologies is needed to direct research and development if nuclear enabled hydrogen is to play a role.

This study, led by the Henry Royce Institute and National Nuclear Laboratory (NNL), gathered expertise across the nuclear, materials, and hydrogen sectors in industry and academia to identify the status of candidate technologies for nuclear enabled hydrogen production and the materials challenges related to the development of these technologies. It follows from questions posed within the 2021 Henry Royce Institute study on End-to-End Hydrogen which explored the entire hydrogen value chain and proposed an application of nuclear energy to high temperature electrolysis technologies: "By coupling solid oxide electrolyzers to a source of high temperature heat, such as from nuclear power or solar heat generators, solid oxide electrolyzers will be able to produce more hydrogen per kWh of input energy than other electrolyser types." As well as indicating (in Appendix A) the importance of the future research topic of "Hydrogen thermolysis from nuclear power" not covered as a part of the previous report. The basis of the current study is formed from a consultation, with input sought across industry and academia, through a series of bilateral discussions, a workshop, and written and verbal feedback from sector specialists to confirm the study's findings.

The report sets out a technology landscape of reactor and thermally enabled hydrogen production technologies which may form the basis for a nascent nuclear enabled hydrogen sector and explores their relative levels of technological maturity. Four key research fields for the development of nuclear enabled hydrogen are identified in this report and their associated materials challenges are explored. Proposed research paths are discussed for the identified materials challenges and the five most pressing materials research challenges are identified. These five pressing research challenges are presented as key areas of research for the development of the sector. The objective of this identification is to focus industry and research goals to allow nuclear enabled hydrogen to become a mature component of the UK's low-carbon hydrogen production and to focus development in areas where the UK has a good potential to establish technological expertise. The five key research challenges identified are:

- **Model tritium concentrations arising from next generation reactor technologies** and develop materials to limit tritium transfer to a hydrogen production plant and downstream to end-users.

- **Investigate Solid Oxide Electrolyser (SOE) degradation mechanisms** and develop materials-led solutions to extend the operational lifetime of SOEs from less than 5 years to over 10 years.
- **Develop techniques to improve phase separation of products within the Sulphur-Iodine Cycle**, and catalysis methods to reduce the operating temperature of the sulphuric acid decomposition reaction, to inform materials choices and materials development for thermochemical reaction vessel materials.
- **Test superalloy and other candidate materials (RHEAs, ODS alloys, ceramics) for use within heat exchangers of next generation High Temperature Gas-cooled Reactors (HTGRs)**, and in conjunction with alternative coolant materials such as helium and molten salts.
- **Develop a materials research database with the use of AI tools to accelerate new materials development** and compile prior research on the high temperature and corrosive environments likely to be encountered by nuclear enabled hydrogen materials.

In addition to the key research challenges, the study identified the need for further work to develop sectoral and governmental understanding of the business case for nuclear enabled hydrogen. The paper calls for a detailed techno-economic study to compare the cost of hydrogen produced via renewable power and nuclear power. Importantly, the study should look to capture the value to end users of a reliable supply of hydrogen produced from nuclear power at sites where renewable capacity may be limited. This study would further inform the prioritisation of materials research in the nascent nuclear enabled hydrogen sector and could form the basis of a specific nuclear hydrogen strategy for the UK.

This study aims to inform both short-term and long-term materials research into nuclear enabled hydrogen. By outlining the UK's expertise on the materials challenges of this sector, the development of domestic nuclear hydrogen will be accelerated. The industrial and research collaborations initiated by this project are expected to enable further sectoral development.

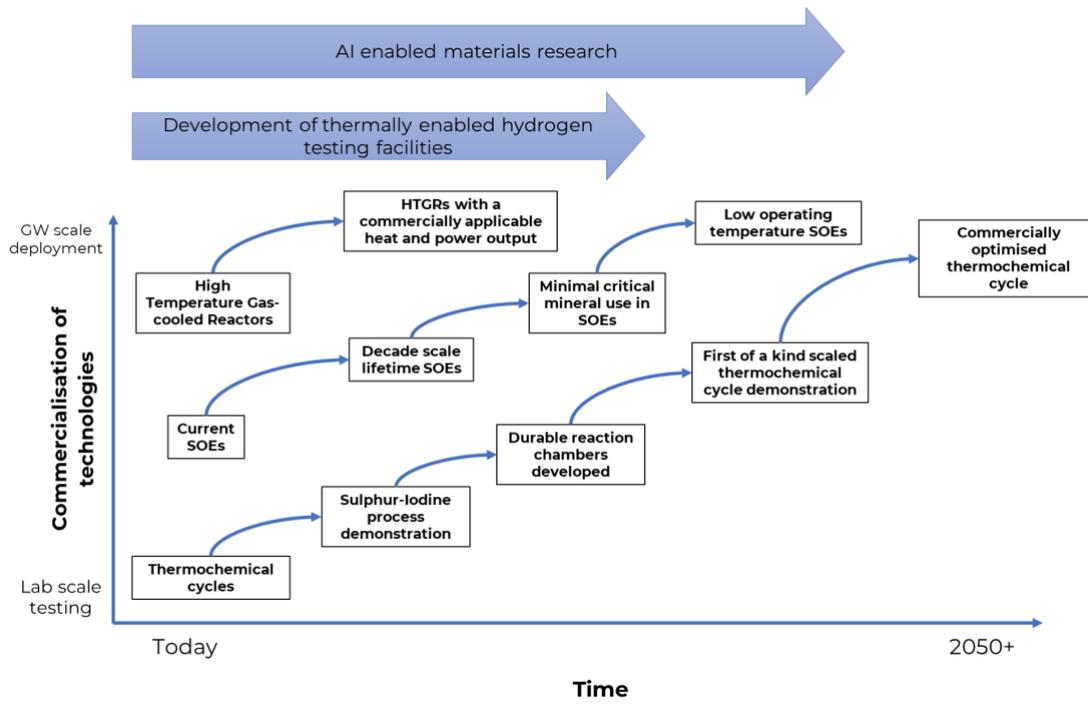


Figure 1 - A graphical summary of the development pathways for nuclear enabled hydrogen technologies and enablers presented in this paper. Pathways presented are indicative only.

# Contents

Acknowledgements.....	4
Executive Summary.....	5
1. Introduction.....	10
1.1. Study context and objectives.....	11
1.2. Scope and methodology.....	11
1.3. Report Structure.....	12
2. Technology landscape.....	13
2.1. Reactor Technologies.....	14
2.2. Proton Exchange Membrane (PEM) electrolysis.....	15
2.3. Solid Oxide Electrolysers (SOEs).....	16
2.4. Thermochemical cycles.....	16
2.4.1. S-I.....	17
2.4.2. HyS.....	17
2.4.3. Cu-Cl.....	17
2.5. Chemical looping.....	18
2.6. Low TRL thermally enabled hydrogen technologies.....	18
2.6.1. Proton-conducting SOEs (H-SOEs).....	18
2.6.2. Supercritical electrolysis.....	19
2.7. Summary.....	20
3. Key Research fields.....	22
3.1. Introduction.....	22
3.2. Heat exchange and transfer.....	22
3.3. Tritium Removal.....	24
3.4. Improvements to SOE lifetime and efficiency.....	26
3.4.1. Degradation mechanisms in SOEs.....	26
3.4.2. Mitigation strategies for anode degradation.....	28
3.4.3. Chemical poisoning of SOEs.....	28
3.4.4. Limiting critical mineral utilisation in SOEs.....	29
3.5. Developing a full-scale demonstration of thermochemical cycles.....	30
Stage 1: Developing techniques to improve the performance of the Sulphur-Iodine cycle.....	30
Stage 2: Demonstrator scale S-I thermochemical cycle running as a closed loop.....	33
Stage 3: Large scale S-I prototype development: Emergent materials challenges.....	34
Stage 4: Heat recovery from process.....	34
4. Key enablers.....	34

4.1.	Introduction .....	34
4.2.	Critical mineral utilisation and recycling.....	34
4.3.	AI enabled materials research database.....	35
4.4.	Develop understanding of nuclear enabled hydrogen’s business case .....	37
4.5.	Improved testing facilities for thermally assisted hydrogen production .....	38
4.6.	Growing within regulatory constraints .....	39
5.	Conclusions and next steps.....	40
5.1.	Developing techno-economic studies for nuclear enabled hydrogen.....	40
5.2.	Materials research challenges identified in this study .....	40
5.2.1.	Tritium profiling and exploring materials to limit tritium transfer .....	40
5.2.2.	Develop lifetime of SOEs.....	41
5.2.3.	Sulphur-Iodine Cycle development.....	41
5.2.4.	Testing of materials for high temperature heat exchangers.....	41
5.2.5.	Develop an AI enabled materials database .....	42
	Glossary.....	43
	Bibliography .....	45

# 1. Introduction

The UK's Net Zero Strategy, published in October 2021, detailed a radical change to national power, heat, and transport, with the target of an entirely decarbonised electricity grid by 2035 and achieve net zero carbon emissions in the UK by 2050.<sup>3</sup>

As part of the Energy Security Strategy, a vast extension of the UK's nuclear capacity is planned to grow the current 6.5GW of nuclear power to 24GW of capacity by 2050.<sup>4</sup> New nuclear capacity is already under development at Hinkley Point C, while next generation Small Modular Reactor (SMR) and Advanced Modular Reactor (AMR) technologies are being developed which have the potential to reduce the capital costs of nuclear power plants significantly.<sup>5</sup>

In tandem with the growth of the UK nuclear sector, the UK has set ambitions of developing 10GW generation capacity of domestic low-carbon hydrogen production by 2030 as part of the UK's updated Hydrogen Strategy published in December 2022.

Forecasted demand for low-carbon hydrogen in the UK is expected to be between 250 and 460 TWh by 2050, representing between 20-35% of the UK's total energy consumption.<sup>6</sup>

## Load Factor Explainer

An electrolyser's load factor is the ratio of its average hydrogen output to its maximum capacity hydrogen output. A 5MW electrolyser has the capacity to utilise 5MWh of electricity per hour to produce hydrogen but may on average only be provided with 3MWh per hour resulting in a load factor of 60%.

Higher load factors are desirable as the levelised cost of hydrogen generally decreases with higher load factors (the capital costs of an electrolyser are spread across the total hydrogen production; the more hydrogen produced, the lower the capital cost contribution in each kg of hydrogen) but due to intermittencies in direct electricity supply, such as solar panels at night and the variable price of grid electricity throughout a day, electrolysers may not be run every hour of a day. In DESNZ's 2021 Hydrogen Production Costs report, the capital cost contribution to the price of hydrogen increased from £0.40 /kg-H<sub>2</sub> by around £1.50 /kg-H<sub>2</sub>, when a 25% load factor scenario was considered. The total modelled price of hydrogen in the study across all scenarios was around £6 /kg-H<sub>2</sub> or less.

*Load Factor*

$$= \frac{\text{average hydrogen output } \left(\frac{\text{kg}}{\text{day}}\right)}{\text{maximum potential hydrogen output } \left(\frac{\text{kg}}{\text{day}}\right)}$$



Figure 2 - Anticipated development of nuclear technologies and hydrogen demand in the coming decades.

Strategies for meeting the ambitious targets for low-carbon hydrogen production are greatly enhanced by the coupling of nuclear power with hydrogen production technologies.<sup>4</sup>

Coupling hydrogen production with nuclear power plants presents an opportunity to deploy thermally enabled hydrogen production technologies: a more electrically efficient, and often more energy efficient route to produce hydrogen gas, which would utilise the cogeneration of heat and power from a nuclear power plant. The availability of power over any continuous 24hr period provided by nuclear plants (compared to fluctuating power sources like wind and solar) may also offer an economic advantage for the production of low carbon hydrogen by enabling a high electrolyser load factor.<sup>7</sup>

### 1.1. Study context and objectives

The materials for nuclear enabled hydrogen study follows from research questions posed in the Materials for End-to-End Hydrogen report commissioned by the Henry Royce Institute in 2021.<sup>2</sup> The study considered the materials research needs to support the entire hydrogen value chain and raised the application of Solid Oxide Electrolysers (SOEs) to nuclear power as a method of hydrogen production with a lower specific energy consumption as compared to low temperature electrolysis. This landscape study aims to present the status and key materials challenges related to nuclear enabled hydrogen production. It is expected that the conclusions drawn from this study will be used to develop the UK's strategy for deploying commercial nuclear enabled hydrogen production. The UK's world-leading expertise in energy materials research and key enabling technologies, such as catalysis, places it in a strong position to develop a reliable domestic supply of low-cost, low-carbon hydrogen from nuclear power and to export industrial expertise internationally.

### 1.2. Scope and methodology

A focused scope was adopted for this study, which explored the material considerations for heat transfer within the secondary circuit of a nuclear power plant through to the hydrogen production technologies. Upstream considerations of nuclear materials and reactor types were not included within the scope of the study, while downstream applications of hydrogen were equally considered beyond scope.

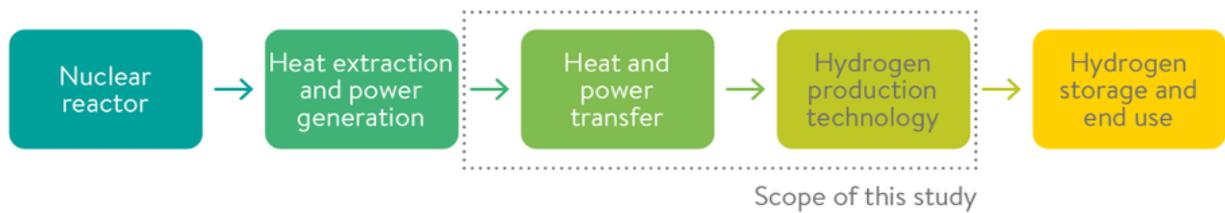


Figure 3 - The scope of this landscape paper is limited to materials challenges of heat transfer beyond the primary circuit of a nuclear reactor and thermally enabled hydrogen production technologies.

The study was led by the Henry Royce Institute - the UK's national advanced materials research and innovation institute, the National Nuclear Laboratory, and zero carbon consultancy Delta H, however the findings and recommendations contained in this report reflect feedback from the research and industrial communities of the nuclear, materials and hydrogen production sectors. The engagement exercise employed through April-July of 2023 consisted of:

- A series of bilateral discussions with academic and industrial groups
- A workshop with representatives of industry and academia across the nuclear, materials, and hydrogen generation sectors
- Written and verbal feedback from the identified experts to develop and confirm the main findings of the landscape study.

The study team made efforts to consult as widely as possible within the UK to collect a representative range of opinions and to develop a consensus of the foremost materials challenges in developing nuclear enabled hydrogen. This was supported by the Knowledge Transfer Network (KTN) using their extensive network of contacts in UK academia and industry.

### 1.3. Report Structure

The following sections present the current thermally enabled hydrogen technology landscape as understood from discussions with experts in the field, and the materials challenges in developing technologies towards commercial nuclear enabled hydrogen. [Section 2](#) presents an introduction to nuclear reactor technologies in the UK and thermally enabled hydrogen production technologies which could feasibly be coupled to nuclear combined heat and power plants. [Section 3](#) details the main materials research challenges identified by the landscape contributors that will enable the development of commercial nuclear enabled hydrogen. [Section 4](#) provides an overview of the key enablers for the development of commercial nuclear enabled hydrogen identified by the landscape contributors, and conclusions are presented in [section 5](#).

## 2. Technology landscape

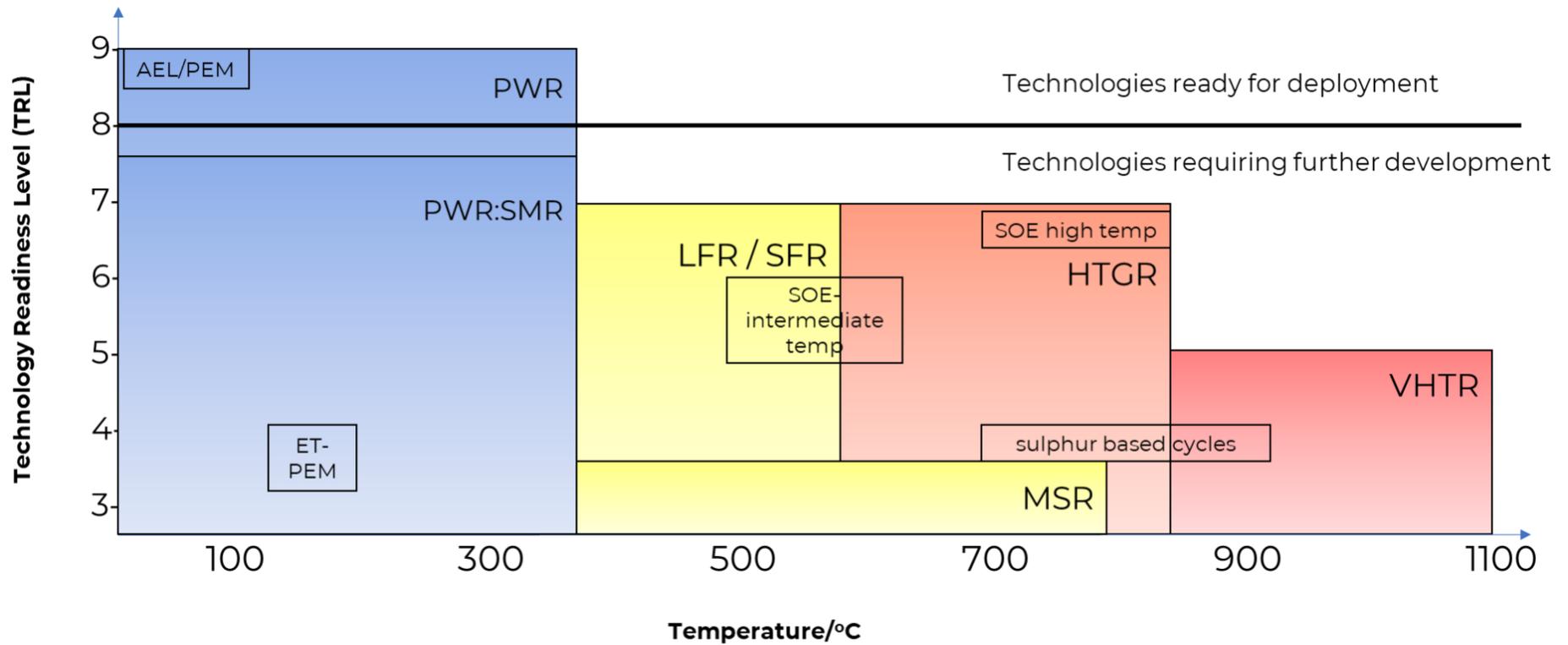


Figure 4 - Technology landscape of nuclear reactors and hydrogen production reactions Summary of terms: AEL – Alkaline Electrolysis , PEM – Proton Exchange Membrane Electrolysis, ET-PEM – Elevated Temperature PEM, SOE – Solid Oxide Electrolysis, PWR – Pressurised Water Reactor , SMR – Small Modular Reactor, LFR – Lead-cooled Fast Reactor, SFR – Sodium-cooled Fast Reactor, HTGR – High Temperature Gas-cooled Reactor, MSR – Molten Salt Reactor, VHTR – Very High Temperature Reactor.

## 2.1. Reactor Technologies

### Specific energy consumption explainer

Specific energy consumption is defined in this paper as the thermal energy required to produce a kilogram of hydrogen using a given production technology.

The specific electrical energy consumption by contrast is the electrical energy required to produce a kilogram of hydrogen with electrically enabled production technologies. A distinction is drawn between these as the specific electrical energy consumption is dependent upon the operating temperature of the process as can be seen with the temperature dependent electricity consumption of SOEs.

To give a fair comparison of different technologies, both the thermal and electrical consumption per kilogram of hydrogen must be known and combined to give a normalised specific energy consumption as demonstrated in Table 2.

Nuclear reactors technologies are split into discrete generations based on advances in performance and technologies.<sup>8</sup> Currently, generation IV reactors are in development. A summary of the six main generation IV Advanced Modular Reactors (AMRs) technologies being developed internationally compared with Generation III technologies is given in Table 1. The UK's fleet of Advanced Gas-Cooled Reactors (AGRs) are expected to be retired

before the end of the decade so are not included here. The Department for Energy Security and Net Zero (DESNZ) have chosen High Temperature Gas-cooled Reactors (HTGRs) as the preferred AMR technology for the UK, in support of reaching Net Zero by 2050. This decision was backed by an assessment of six main AMR technologies carried out by the Nuclear Innovation and Research Office (NIRO) who evaluated each reactor type against multiple criteria, with each criterion being weighted depending on importance to the programme.<sup>9</sup> DESNZ have set out an aim to have a UK-based HTGR demonstration by the early 2030s.

Table 1- Overview of AMR technologies compared with PWRs<sup>9,10</sup>

Reactor System	Coolant	Outlet Temperature (°C)	Technology Readiness Level
<b>PWR – Pressurised Water Reactors</b>	Water	300-330	9
<b>PWR:SMR – Small Modular Reactors</b>	Water	300-330	7-8
<b>HTGR / VHTR (AMR) High / Very High Temperature Gas Reactors</b>	Helium	700 – 850 / 900 – 1000+	7 HTGR 5 VHTR
<b>SFR – Sodium-Cooled Fast Reactors (AMR)</b>	Sodium	500 – 550	7
<b>SCWR – Supercritical Water-Cooled Reactors (AMR)</b>	Water	510 – 625	2
<b>GFR -Gas-cooled Fast Reactors (AMR)</b>	Helium	850	2
<b>LFR – Lead-cooled Fast Reactors (AMR)</b>	Lead	480 – 530	4
<b>MSR – Molten Salt Reactors (AMR)</b>	Fluoride / Chloride Salts	700 – 800	4 Thermal 3 Fast

## 2.2. Proton Exchange Membrane (PEM) electrolysis

PEM electrolysis is a low temperature and high Technology Readiness Level<sup>11</sup> (TRL) electrolyser technology capable of producing high purity hydrogen gas. PEM benefits from higher operating temperatures with reductions in specific electrical energy consumption of the cell on the order of 3% when operating at 87°C and 1 amp/cm<sup>2</sup> current density as compared to a cell under standard conditions (0°C and 1 atmosphere of pressure).<sup>12</sup> PEM electrolysers are generally limited to a 100°C maximum operating temperatures as the ability of the polymer membrane to transport protons, and thereby split water, is dependent upon the presence of liquid water.<sup>13</sup> PEM electrolysis is not set to take advantage of the high temperature outputs of nuclear plants, yet four out of ten of the nuclear enabled hydrogen demonstrator plants being developed globally will make use of PEM electrolysers due to their relative maturity compared with other heat-enabled electrolysis technologies (such as solid oxide electrolysers).<sup>14</sup> Low operating temperatures below 100°C allow PEM to be paired with modern LWRs and next generation HTGRs but they would utilise the electrical power output of these reactors rather than their thermal output.

Elevated temperature PEM (ET-PEM) electrolysis is under investigation where the use of pressure or steam allows PEM electrolysers to function at temperatures as high as 170°C and

are capable of lower specific energy consumption as compared to 80°C PEM.<sup>15</sup> ET-PEM represents a viable method of employing LWR heat outputs to improve hydrogen production efficiencies. Concerns raised in the previous Royce landscape study on Materials for End-to-End Hydrogen highlight the reliance on Platinum group metals in PEM electrolyzers.<sup>2</sup>

### **2.3. Solid Oxide Electrolyzers (SOEs)**

SOEs are a lower TRL electrolysis method where the oxygen ion of water is transferred through a solid oxide electrolyte. Operating temperatures for high-temperature SOEs are typically in the 700-850°C range and are based on Yttria stabilised Zirconium (YSZ) ceramic electrolytes.<sup>16,17</sup> Alternative chemistries have been explored such as Ceres Power's SOEs which employ a Cerium Gadolinium Oxide (CGO) electrolyte enabling commercial ion conductivities at intermediate temperatures of 500-620°C.<sup>18</sup>

While typical SOE operating temperatures (700-850°C) are above those of LWR outlet temperatures, the provision of a source of low temperature steam (100-300°C) to an SOE which is subsequently heated to the operating temperature of the SOE will result in a lower specific electrical energy consumption than PEM or alkaline based electrolyzers (as described in Table 2). For example, Bloom Energy's SOE stack, which operates at 850°C, makes use of a 150-200°C steam input and has a system-level specific electrical energy consumption of 37.5 kWh/kg-H<sub>2</sub>.<sup>19</sup> This is much lower than low-temperature electrolysis specific electrical energy consumption of ~52kWh/kg-H<sub>2</sub>.<sup>20</sup> A 1MW low-temperature SOE is planned to be in trial at Heysham for the production of hydrogen from one of the UK's second-generation AGRs.<sup>21</sup>

Concerns regarding SOEs stem from their relatively high degradation rates which are in the region of 1%/1000hrs, limiting lifetimes to less than 5 years.<sup>22,23</sup> Targets for SOE lifetimes are in the region of 7-10 years.

### **2.4. Thermochemical cycles**

The direct thermal decomposition of water into hydrogen and oxygen streams requires temperatures in excess of 2000°C. Thermochemical cycles for hydrogen production are substitute reaction pathways to the direct thermal decomposition of water operating at less challenging temperatures. Hundreds of thermochemical cycles have been explored, though these all remain at TRL of below 4. This report will focus on two of the most promising thermochemical cycles in development:

- The Sulphur Iodine cycle (S-I cycle)
- The Hybrid Sulphur cycle (HyS cycle)

The justification for this selection is the high TRL of these cycles relative to other cycles explored, though it is noted that other cycles such as the Cu-Cl cycle continue to be investigated worldwide. The S-I cycle stands as the most well researched and tested thermochemical cycle to date, while the HyS cycle, utilising the same initial step of the decomposition of sulphuric

acid as the S-I cycle, also benefits from the research conducted into the S-I cycle. Heat and power for thermochemical cycles can be provided by nuclear power plants making these technologies well suited for nuclear enabled hydrogen.

#### 2.4.1. S-I

The S-I cycle is a three-step process:

- |  |  |
|--|--|
| 1. <b>Bunsen reaction</b>              | 20-120°C exothermic reaction<br>( $I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$ ) |
| 2. <b>Sulphuric acid decomposition</b> | 600-900°C endothermic reaction<br>( $2H_2SO_4 \rightarrow 2H_2O + 2SO_2 + O_2$ )   |
| 3. <b>Hydriodic acid decomposition</b> | 300-450°C endothermic reaction<br>( $2 HI \rightarrow H_2 + I_2$ )                 |

The S-I cycle has been most recently under development as part of a nuclear enabled hydrogen demonstration plant conducted by the Japanese Atomic Energy Association (JAEA). In 2016 a bench-top demonstration of a closed S-I cycle was demonstrated which ran for eight hours.<sup>24</sup> Research into the S-I cycle in the UK has slowed since around 2008, though recent interest has gathered around this technology again as demonstrated in the NNL feasibility study on Hydrogen from Thermochemical and Nuclear (HyTN) report of 2022.<sup>25</sup>

#### 2.4.2. HyS

The hybrid sulphur cycle is a combined thermochemical and electrochemical cycle, with the sulphuric acid decomposition step being common to the S-I cycle.

- |   |                                    |  |
|---|------------------------------------|--|
| 1. <b>Sulphuric acid decomposition</b>    | 600-900°C endothermic reaction     | ( $2 H_2SO_4 = 2H_2O + 2 SO_2 + O_2$ ) same as the S-I cycle |
| 2. <b>Electrolysis of sulphur dioxide</b> | 80-120 °C electrochemical reaction | ( $SO_2 + 2H_2O = H_2SO_4 + H_2$ )                           |

The most recent development work on a paired nuclear power and HyS cycle was conducted by the Savannah Rivers National Laboratory in 2009 where single cell PEM electrolyser testing of the HyS electrolysis step was developed.<sup>26</sup> More recently, in 2016, the SOL2HY2 European project concluded their exploration of the HyS cycle's application to concentrated solar power enabled hydrogen.<sup>27</sup>

#### 2.4.3. Cu-Cl

The Copper Chlorine cycle (Cu-Cl cycle) was also initially considered in this report primarily due to its low operating temperature of around 500°C which would make it compatible with intermediate temperature reactors such as Sodium-cooled Fast Reactors (SFRs) or Lead-cooled Fast Reactors (LFRs). However, the low production efficiencies and slow reactions involving solid state phases, and relatively high voltage electrolysis steps involved in the Cu-Cl cycle are a

challenge to commercialisation at present, though longer-term research could address some of these shortcomings.

Several variations of the Cu-Cl cycle have previously been considered. A four-step hybrid copper-chlorine cycle is presented below:

1.  $2\text{Cu} + 2\text{HCl} \rightarrow 2\text{CuCl} + \text{H}_2$  (430–475°C)
2.  $2\text{CuCl}_2 + \text{H}_2\text{O} \rightarrow \text{Cu}_2\text{OCl}_2 + 2\text{HCl}$  (400°C)
3.  $2\text{Cu}_2\text{OCl}_2 \rightarrow 4\text{CuCl} + \text{O}_2$  (500°C)
4.  $2\text{CuCl} \rightarrow \text{CuCl}_2 + \text{Cu}$  (ambient-temperature electrolysis)

## 2.5. Chemical looping

Chemical looping technologies operate in a similar manner to thermochemical cycles with a cycle of thermally enabled reactions aiding the production of desired by-products at less challenging temperatures.

Chemical looping technologies for hydrogen production make use of redox reactions of organic inputs (such as methane) and metal oxides to produce hydrogen and carbon dioxide gases. The metal oxides are catalysts that act as oxygen carriers undergoing redox reactions with organic compounds to release hydrogen before a second stage redox reaction leads to the generation of  $\text{CO}_2$ . The two gases are produced in separate chemical reaction chambers enabling separate carbon capture and storage (CCS) and hydrogen collection with high purities of both gas streams. Metal oxide chemical looping technologies are at a very early stage of development and require temperatures in the range of 600-900°C, similar to thermochemical cycles explored above. Chemical looping research is focused on developing mixed metal oxides as oxygen carriers to combine desirable oxygen carrier properties.<sup>28</sup>

Chemical looping technologies are also being explored to enable a low carbon steam methane reformation process, Chemical Looping Steam Methane Reformation (CL-SMR). The steam methane reformation process accounts for the majority of global hydrogen production and the capture of  $\text{CO}_2$  from this process is being explored as a “blue” hydrogen alternative to the technologies explored above.<sup>29</sup> As such, another focal area of research is on metal oxide catalysts for CL-SMR.

## 2.6. Low TRL thermally enabled hydrogen technologies

In addition to the more developed thermally enabled hydrogen production technologies presented above, innovative technologies also exist which may enable improved performance of nuclear enabled hydrogen production in the long term.

### 2.6.1. Proton-conducting SOEs (H-SOEs)

A new strand of SOE research that has garnered much attention in recent years is proton conducting SOEs. Instead of transporting the oxide ion, the hydrogen ion (a proton) is

transported through the electrolyte. The protons can be conducted more efficiently at lower temperatures than the oxygen ion meaning that the H-SOE could operate at temperatures as low as 300°C.<sup>30</sup> This is hot enough to achieve improved electrical efficiency over low-temperature hydrogen production methods such as PEM and AEL and could be combined with all generation IV reactors considered in this report. H-SOE's low operating temperature compared with oxygen conducting SOEs would mean that the technology would avoid many of the thermally enabled degradation methods inherent to high temperature oxygen conducting SOEs. However, H-SOEs remain at a very early stage of development and challenges with the stability of the proton conducting electrolyte have been observed. So far, studies have been limited to 100hr degradation tests of H-SOE electrolyte materials.<sup>31</sup> H-SOEs offer a novel thermally enabled hydrogen technology to bridge between less electrically efficient low-temperature electrolysis technologies and high-temperature electrolysis technologies which suffer from thermally enabled materials degradation mechanisms. However, further research developing the stability of electrolytes used in H-SOEs is required before a commercial deployment of this technology can be considered.

### **2.6.2. Supercritical electrolysis**

Supercritical electrolysis takes advantage of the behaviour of supercritical water and the higher electrical efficiency of electrolysis at high temperatures to produce hydrogen with less electrical power input than PEM and alkaline electrolysis.<sup>32</sup>

Water requires less energy to bring it to high pressures compared to steam or hydrogen. Additionally, electrolysis of water or steam conducted at higher temperatures requires less electrical power input as a portion of the process energy is provided by heat. Both properties can be leveraged to improve the electrical efficiency of hydrogen production. Under high enough temperatures and pressures, water will become supercritical, a state of matter which has properties of both a gas and liquid. Supercritical water electrolysis introduces a high pressure (220 Bar minimum) and high temperature (373°C minimum) water stream into an electrolyser, resulting in hydrogen produced at equivalently high pressures and theoretical specific electrical energy consumption as low as 39kWh/kg-H<sub>2</sub>.<sup>33</sup> Certain end use applications of hydrogen, such as in hydrogen vehicles, require the gas to be compressed to pressures of around 350 or 700 Bar post-production. Supercritical electrolysis would largely eliminate the cost of post-production compression as the gas stream will already be compressed. Supercritical electrolysis systems are at an early stage of development but could offer reductions to total production costs of hydrogen where a compressed gas stream is required.<sup>34</sup> Small scale demonstration projects for supercritical electrolysis are in development in the UK.<sup>35</sup> Further techno-economic assessments of this technology are required to develop sectoral understanding of the application of supercritical electrolysis technologies.

## 2.7. Summary

Within their HyTN report, NNL summarised the anticipated lowest specific energy consumptions that could be attained by a range of technologies, based on their modelling of the processes.<sup>25</sup> Similarly, in this study, a comparison of the specific energy requirements of different hydrogen production technologies based on existing data sources was produced and is presented in Table 2 below. It was found that compared to alkaline/PEM electrolysis, steam enabled SOEs could increase hydrogen production output by up to 25% from the same reactor with 20a process which has a moderate TRL. Thermochemical cycles offer a potentially significant gain with a possible maximum increase of 160% in hydrogen production from the S-I cycle compared to electrochemical processes, though the range of uncertainty in these performance figures is considerably higher due to the low TRL of these technologies.

Table 2. Energy required to produce 1 kg of hydrogen (assuming a uniform reactor thermal efficiency of 40%)

a) Practical specific energy requirements taken from real-world technologies

Technology	Operating Temperature (°C)	Electricity Use (kWh/kg-H <sub>2</sub> )	Heat Use (kWh/kg-H <sub>2</sub> )	Specific Energy Use – Normalised Heat* (kWh/kg-H <sub>2</sub> )	TRL
Alkaline Electrolysis	40–90	51 <sup>36</sup>	0	128	9 <sup>37</sup>
PEM	40–90	51 <sup>38</sup>	0	128	9 <sup>37</sup>
SOEs	600	37 <sup>18</sup>	10	102	6 <sup>18</sup>
SOEs	850	38 <sup>39</sup>	10	105	7 <sup>37</sup>

b) Theoretical specific energy requirements of low-TRL technologies

Technology	Operating Temperature (°C)	Electricity Use (kWh/kg-H <sub>2</sub> )	Heat Use (kWh/kg-H <sub>2</sub> )	Specific Energy Use – Normalised Heat* (kWh/kg-H <sub>2</sub> )	TRL
S–I Cycle	720	0 <sup>25</sup>	48	48	4 <sup>25</sup>
HyS Cycle	720	16 <sup>25</sup>	41	81	4 <sup>25</sup>
ET-PEM	120-170	49 <sup>15</sup>	unknown	unknown	4 <sup>15</sup>

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\* Comparisons between electrical energy and thermal energy are achieved by assuming a 40% thermal efficiency in the production of electricity. Each kWh electricity is equivalent to 2.5kWh thermal. Specific Energy Consumption- Normalised Heat converts table values to thermal energy required to produce 1kg of hydrogen with different production technologies.

### 3. Key Research fields

#### 3.1. Introduction

In developing the overview of nuclear heat enabled hydrogen production technologies, key research challenges to enable the commercial coupling of these technologies to nuclear power were discussed. These research fields are presented in order from upstream to downstream. The key materials research topics in each field were considered on a metric of their relative importance in delivering nuclear enabled hydrogen and the urgency of research required and this is presented in Figure 5.

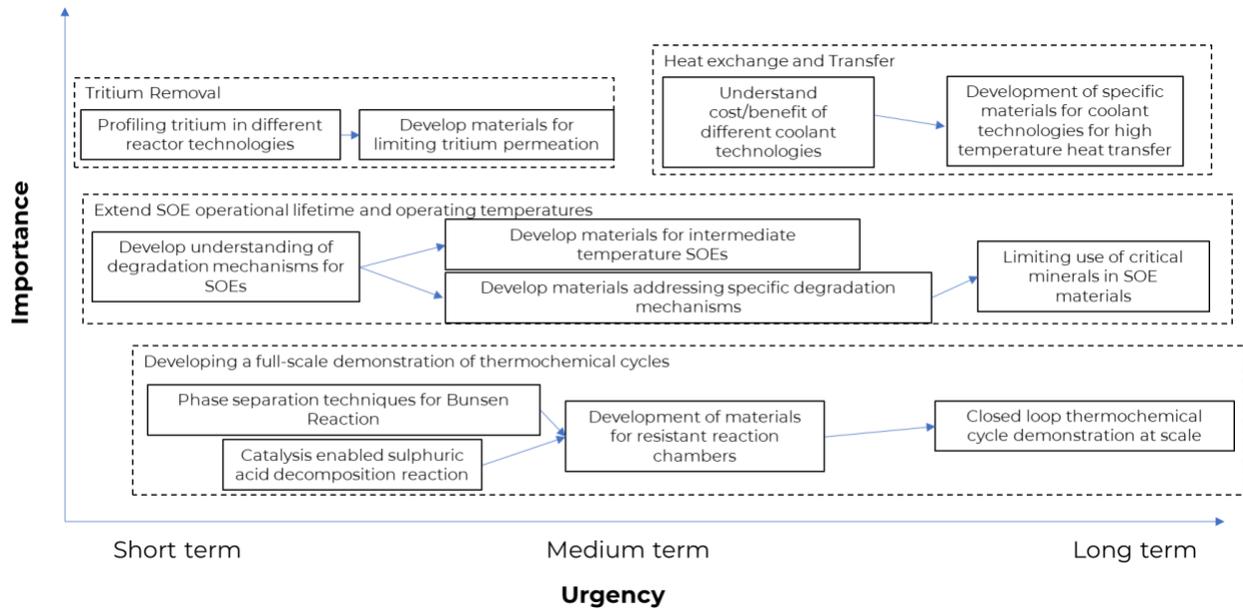


Figure 5 - Key research topics identified through landscape study for the development of nuclear enabled hydrogen. Research pathways for the key research topics are presented against metrics of importance and urgency.

#### 3.2. Heat exchange and transfer

High temperature thermally enabled hydrogen production technologies such as high-temperature SOE and thermochemical cycles require sources of heat on the order of 700-900°C. As such they require high temperature reactors such as HTGRs and VHTRs and efficient methods of heat extraction from these reactors. An intermediate heat exchange system can be used to take advantage of the high outlet temperatures of an HTGR up to 950°C while limiting the contamination of the coolant with radioactive materials. The intermediate heat exchange acts as a secondary heat cycle isolating the primary coolant and hydrogen production plant steam cycle.

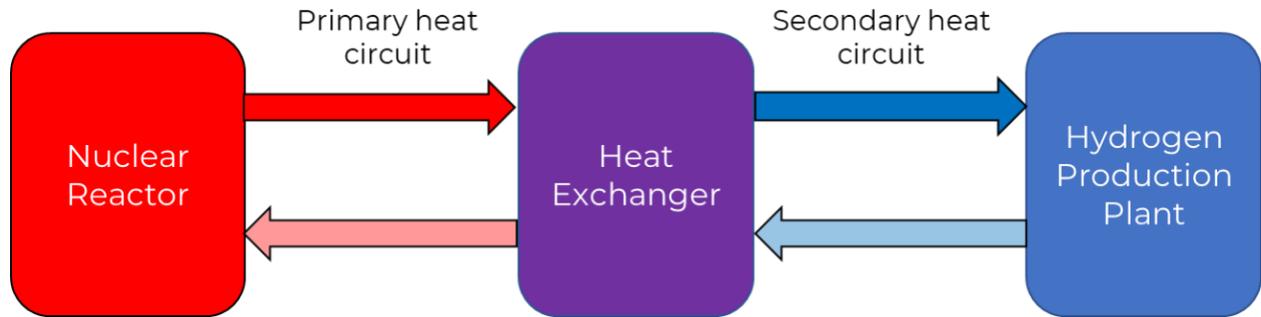


Figure 6 - Intermediate heat exchangers separate coolants in different heat circuits while allowing heat to be transferred between them. The trade-off for this separation is a loss of heat in each additional heat circuit. In this graphic, a heat exchanger is placed on the primary heat circuit with coolant used within the nuclear reactor. The secondary circuit will be cooler than the primary circuit. Other configurations exist where additional heat exchangers are placed on secondary or tertiary heat circuits and do not interact with coolants directly in contact with the reactor core, but these suffer from further heat losses.

An intermediate heat exchange system can be made using various coolant materials. The type of coolant used will impact the materials used in the heat exchange system as well as the direction of research on the materials used. For example, the use of molten salts such as FLiBe (a mixture of lithium fluoride and beryllium fluoride) require the use of materials resistant to corrosion. Literature discussions of heat exchange coolants currently revolve around the use of helium, as is used in the HTTR in Japan, and novel molten salt coolants.

Helium has been demonstrated to function in intermediate heat exchange (IHX) systems and the related materials are relatively well understood. The inert gas sees limited reactions with IHX materials. However, helium has been shown to leak easily from test reactors which is associated with severe pressure drops which can damage the IHX. The helium IHX has also suffered problems with carburisation and decarburisation linked to helium interactions with certain super-alloy materials. Appropriate long duration and high temperature testing of materials for helium IHXs must be performed.

Molten salt IHXs present three benefits when compared with helium IHXs:

1. The energy losses from molten salt IHXs are as much as three and a half times lower than for helium IHXs as less energy is required to pump the liquid around the IHX as compared to the helium gas.<sup>40</sup>
2. The molten salt IHX is more compact, with pipe-diameters typically a fifth the diameter of helium IHX pipes, allowing compact IHXs to be produced reducing material use and costs.
3. The lower operating pressures of molten salt IHXs result in a lower risk of leaks and less extreme pressure differentials in plants when leaks occur and therefore less mechanical stress on IHX materials.

However, candidate molten salts are highly corrosive meaning that corrosion resistant IHX materials will need to be developed for their application. Molten salts must be maintained above their melting point to avoid blockages and damage within the IHX. The melting point of

FliBe is 459°C. Techniques to maintain the high temperature of molten salts will be required as well as methods of maintaining temperature when the plant is undergoing maintenance. Development of molten salt chemistries should be undertaken to improve the range of operating temperatures of molten salts and less corrosive materials.

Materials challenges are relatively well understood for helium IHXs and failure mechanisms and materials have been explored internationally. Whilst the pressure vessel of the IHX can be manufactured from steel (such as SA508) the tubes carrying the coolant would have specific material requirements including high mechanical strength at temperatures up to 950°C, resistance to oxidative reactions (as at least one side of the IHX will be used to heat steam for a hydrogen production plant), low thermal expansion and high thermal conductivity, and minimal reactive interactions with coolant technologies employed.<sup>41</sup>

Superalloys that have been explored and employed for helium IHXs include alloy 800H, a nickel-iron-chromium alloy, for temperatures below 800°C, and alloy 617, a nickel-chromium-cobalt-molybdenum alloy for temperatures up to 950°C. Both are certified for use in nuclear settings and demonstrate good mechanical strength at high temperatures and resistance to corrosive environments.<sup>42</sup> For even higher operating temperatures than 950°C, ceramics, refractory metal alloy coatings or Nickel-based oxide dispersion-strengthened (ODS) alloys are presented as candidate materials for application in an IHX.<sup>43</sup> Refractory high-entropy alloys (RHEAs) are presented as an excellent candidate material for use with next generation HTGRs in combination with molten salt heat exchangers due to their resistance to corrosion and high temperatures.<sup>44</sup> However, heat exchangers employing RHEAs remain at a very low TRL.<sup>45</sup> ODS materials present a challenge to manufacture but have cross-sectoral applications to the nuclear fusion industry. Testing of these alloys for specific use in HTGR helium IHXs is needed. The HTTR makes use of Hastelloy XR, a nickel-chromium-iron-molybdenum alloy, in its helium IHX. Similar to the previous alloys this has good mechanical performance at high temperatures and is a nuclear certified material.<sup>46</sup>

Molten salt IHXs are at a lower TRL than helium IHXs, but similar superalloy materials are considered including Haynes 242, Alloy 800H, and Alloy 617. Alloy 617 is presented in review papers as a particular material for consideration due to its resistance to initial corrosion testing with molten salts alongside low TRL RHEAs. Molten salt testing of alloys under operating conditions of the IHX for long duration is required to develop this technology.<sup>41</sup>

### **3.3. Tritium Removal**

A specific challenge for nuclear-enabled hydrogen is the presence of tritium in the inlet water/steam stream. Tritium is a radioactive isotope of hydrogen with a half-life of just over 12 years. Several production mechanisms of tritium exist within nuclear fission reactors, including ternary fission reactions and neutron absorption and decay of lithium and helium isotopes. Tritium is a relatively weak beta emitter; however, it is readily exchanged into water and organic molecules meaning it can easily be incorporated into human tissues. For this reason,

strict regulatory limits are imposed on streams leaving the site boundary, and any water that is used in hydrogen production must have tritium concentration less than 100Bq/kg.<sup>47</sup>

HTGRs are a particular area of concern for tritium contamination as the mechanism for tritium's transport through heat exchanger materials is diffusion, which is temperature driven. Tritium contamination is thus more prevalent in higher temperature reactor technologies such as HTGRs as compared to LWRs, however limited data is available on the concentration of tritium in the various cooling circuits of different reactor systems. An initial area of research into tritium cross-over should focus on the profile of tritium within the cooling circuit fluids from different reactor technologies, and the rate of tritium diffusion into a steam loop for a downstream hydrogen production plant. Initial explorations of the tritium contamination of the helium heat exchanger within the Japanese HTTR and Chinese HTR-10 reactor suggest that the concentrations of tritium are well within the regulatory limits of the UK.<sup>48-50</sup> However, profiling tritium concentrations associated with different reactor and heat exchange technologies is still needed to ensure that regulatory limits on tritium concentration are not exceeded, exposing end users and site workers to dangerous conditions. Furthermore, ensuring that concentrations of tritium within hot reactor effluent which will be directed to the hydrogen production plant are below regulatory limits enables off-site hydrogen production, reducing the regulatory burden of a hydrogen production plant and the associated time and financial costs of that regulatory burden.

Should mitigating measures to limit tritium and hydrogen permeation through the cooling circuits be required, a materials-based solution is recommended. Mitigation methods would consist of reducing tritium concentrations within the nuclear plant's primary circuit or reducing the permeability of heat exchangers to tritium and thus reducing the concentration of tritium downstream of the primary circuit. These would result in an additional benefit of reducing the risk of hydrogen embrittlement on heat exchange materials and piping materials used to transport heat in secondary and tertiary heat loops.<sup>51</sup> Removing tritium from the primary circuit could result in an additional value stream for a nuclear plant, as tritium is currently priced at \$30,000 per gram and concerns with the supply of tritium for the nuclear sector already exist.<sup>52</sup>

Silicon Carbide (SiC) coatings are presented as good materials for reducing tritium transfer across heat exchangers and pipes. They exhibit good strength at high temperatures and offer protection from oxidation and hydrogen embrittlement. Furthermore, SiCs have been explored as a material with good radiation damage tolerance.<sup>53</sup> Metal oxides are more recently under consideration as hydrogen permeation barriers. Aluminium oxides such as commercially produced corundum offers excellent properties as a hydrogen permeation barrier, however its limited mechanical strength at high temperatures presents a concern for applications linked to HTGRs. Recent exploration of alumina nanolattices suggests greater mechanical strength at higher temperatures may be achieved.<sup>54</sup> Titanium nitride is another promising material for consideration as a hydrogen permeation barrier and has seen application in the fusion sector.<sup>55,56</sup>

UK research into all these materials is ongoing but not necessarily exploring their properties as a tritium barrier. Long duration testing of these materials exposed to tritium under high temperature conditions should be conducted. The harnessing of commercially viable materials free of critical minerals such as aluminium oxides should be of particular interest as the UK already has an established aluminium recycling industry.<sup>57</sup>

### **3.4. Improvements to SOE lifetime and efficiency**

SOEs represent the most well developed thermally enabled hydrogen production technology. Companies such as Ceres Power in the UK, Bloom Energy in the US, and European leaders such as Sunfire and Haldor Topsoe have developed market leading SOE systems. However, the high operating temperatures of SOEs present a challenge to the durability of the cells. Current SOEs have high degradation rates leading to stack lifetimes on the order of five years or less. The commercial application of SOEs is reliant on reducing the cell's degradation rate to reach operational lifetimes on the order of 10 years. Ceres Power expects that this is possible and further developments in their SOE cell could extend the operating lifetime from around 5 years (for the first commercial products) to 10 years within the next 5 years.<sup>18</sup> This is in line with the US Office for Energy Efficiency and Renewable Energy's technical targets for high temperature SOEs in 2026 and beyond.<sup>58</sup>

The Levelised Cost of Energy (LCOE) from nuclear power is typically more expensive than comparable renewable power sources such as offshore wind and solar.<sup>59</sup> Extending the lifetime of SOEs is thus of particular importance to the nuclear enabled hydrogen sector as the business case for this technology will be largely driven by the efficiency of the hydrogen production process.

Extending the lifetime of SOEs not only reduces capital costs for electrolyser replacement, but also allows for increased electrolyser efficiency over its lifetime thereby decreasing the cost of power per kg of hydrogen. Beyond its applications to the nuclear sector, extending the lifetime of SOEs will develop the application of this technology to the renewable power sector. SOEs are already being considered for application alongside concentrated solar power systems.<sup>60</sup>

#### **3.4.1. Degradation mechanisms in SOEs**

Degradation mechanisms in SOEs are varied in cause, but largely relate to ion migration enabled by oxygen partial pressure distribution and heat for high-temperature SOEs. Migration of ions within the SOE lead to the formation of unwanted minerals at electrode-electrolyte interfaces which generate microstructural deformations. Eventually, delamination of the electrodes and electrolyte can result. Different SOE manufacturers and researchers have seen degradation at both the anode and cathode. At high temperatures and currents, degradation is largely focused on the oxygen producing anode where a high oxygen partial pressure evolves.<sup>61</sup>

Lanthanum strontium manganese (LSM) perovskite based porous anodes when combined with yttria-stabilized zirconia (YSZ) electrolytes see the formation of Lanthanum Zirconium Oxide

$\text{La}_2\text{Zr}_2\text{O}_7$  at the anode-electrode interface, while Lanthanum strontium cobalt ferrite (LSCF) porous anodes suffer from  $\text{La}_2\text{Zr}_2\text{O}_7$  formation and the formation of  $\text{SrZrO}_3$ .<sup>61</sup> Both formations are thermally enabled and lead to degradation of SOE performance. Decreases in anode porosity, such as results from  $\text{SrZrO}_3$  formation on LSCF anodes, reduces oxygen migration at grain boundaries or along the electrolyte boundary. An increase in localised oxygen partial pressure leads to localised pressure and eventual delamination.

For the hydrogen cathode, Ni-YSZ cermet is typically used, and nickel migration is the chief degradation mechanism at play. The specific mechanism for nickel migration is not well understood yet, though several mechanisms are proposed in the literature. These involve steam enabled diffusion and are driven by high operating temperatures.<sup>62</sup>

Considerations of the SOE cell system as a whole are important as interactions between electrodes and electrolytes can lead to SOE failures. For example, using a Lanthanum Gallate based electrolyte leads to rapid degradation with a nickel-based hydrogen cathode due to the formation of  $\text{LaNiO}_3$ , which leads to fractures at the cathode electrolyte boundary.<sup>63</sup>

Failure mechanisms of SOEs are largely driven by the choice of materials employed and these materials' interactions under high temperature and oxidative conditions. Two materials led solutions to these failure mechanisms are currently being investigated:

1. Developing materials which enable SOEs to function at lower temperatures, thereby reducing the impact of temperature driven degradation mechanisms. This would allow a greater field of "low temperature" (below  $600^\circ\text{C}$ ) less exotic and cheaper materials to be employed in SOEs, which will reduce capital costs of the SOE stack. However, the efficiency of ion transfer in SOEs is also driven by temperature, meaning that a lower operating temperature will likely impact the hydrogen production rate of an SOE cell. Ideal operating temperatures of SOEs are based on the tension between these two parameters and new SOE materials will enable ideal operation at different temperatures. For example, SOEs based on a Cerium Gadolinium Oxide electrolyte have been demonstrated to operate well at temperatures between  $500\text{-}620^\circ\text{C}$ .<sup>18</sup>
2. Developing materials resistant to specific degradation mechanisms at high temperatures, thereby extending the operational lifetime of SOEs in current use practices. The requirement for this route is a firm understanding of failure mechanisms and the development of strategies to mitigate such mechanisms. While several degradation methods have been explored, some of which are presented below, further exploration of degradation methods is required before materials led solutions can be developed. Identifying specific failure mechanisms is hindered by the lack of opensource testing data for industrially developed SOEs and the lack of testing facilities for SOEs in the UK.

A capability map of testing facilities within the UK for SOEs is recommended to identify specific gaps in the UK's material testing capabilities. Secondly, greater opensource testing of modern

SOE materials, while respecting industrial intellectual property, is called for to identify specific degradation mechanisms for the advancement of the sector as a whole.

### 3.4.2. Mitigation strategies for anode degradation

Mitigation strategies for SOE degradation at the anode-electrolyte interface (the main contributor to SOE performance degradation at high temperatures) have focused on nanoparticle infiltration and microstructure developments in anode materials.

The infiltration of nanoparticles has been demonstrated to reduce degradation rates. The use of RuO<sub>2</sub> anchored to the surface of YSZ/LSM composite electrodes improves the rate of the oxygen evolution reaction while reducing oxygen gas partial pressure (pO<sub>2</sub>) at the anode-electrolyte interface. Similarly, the use of LSCN\* impregnated CGO/LSM\*\* composite sees improved maintenance of pore structures in the anode thus maintaining sites for the oxygen evolution reaction and reducing pO<sub>2</sub>.

Harnessing materials' microstructure to improve oxygen dispersion and reduce pO<sub>2</sub> is an active strand of research. Ruddlesden-Popper (R-P) phase perovskites are explored as a replacement for perovskite materials used in SOEs. The layered R-P structure-infiltrated electrodes provide improved capacity for accommodating oxygen ions as compared to perovskite-based materials. A porous YSZ boundary layer between the electrolyte and anode has also been explored as a method to allow improved routes for oxygen degassing as opposed to transport along grain boundaries and the electrolyte-anode interface. Similarly, Wu et al has explored a honeycomb microstructure which offers greater porosity and thus improved capacity for accommodating oxygen ions and degassing routes, reducing pO<sub>2</sub>.<sup>61</sup> These materials techniques all offer improved stability of the anode-electrolyte interface and thus improved SOE degradation rates.<sup>61</sup>

While demonstrations of reductions to SOE degradation rates through these techniques have been achieved in a laboratory, these techniques will need to be implemented by SOE industrial manufacturers. Mitigation techniques identified must be adapted to the materials and manufacturing processes of industry where possible. Collaborations across research and industry for the development of next generation SOEs is required.

### 3.4.3. Chemical poisoning of SOEs

While degradation methods of SOE cells based on ideal operating conditions have been considered, a systemic perspective of SOEs' application to nuclear enabled hydrogen presents further materials challenges. SOEs are susceptible to chemical poisoning from impurities carried by their gas input stream (steam in the case of nuclear enabled hydrogen). In previous studies, sulphur, chlorine and chromium were among the impurities explored for their effects on the

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\* Lanthanum Strontium Chromium Nickelate

\*\* Cerium Gadolinium Oxide/ Lanthanum strontium manganese

performance of Solid Oxide Fuel Cells and by extension would impact the performance of SOEs.<sup>64</sup> Sulphur and Chlorine impurities at very low concentrations had demonstrable impacts on the performance of nickel based components of SOFCs. Formation of strontium chromate and chromium oxides on LSM based electrodes form the main method of chromium poisoning within SOEs. While sulphur impurities are not expected with a steam infeed, other impurities likely to be found in the secondary and tertiary cooling loops of nuclear reactors may impact SOE performance.

Further to limiting sources of impurities from the gas input steam, materials used in the SOE stack must themselves be free of sources of impurities. State of the art hermetic glass seals are commonly used in the production of Solid Oxide Fuel Cell stacks.<sup>65</sup> While glass sealants are a source of silica-based impurities in the presence of high temperature steam, this is not problematic for Solid Oxide Fuel Cells. However, when operating as an SOE, silica will concentrate at or near to active sites of the cathode degrading the performance of the SOE cell.<sup>66</sup>

Methods of limiting chemical poisoning in SOEs consist of purifying the gas input stream to the SOE and ensuring that all materials in the steam loop and the SOE stack do not provide a source of impurities which could damage SOEs. This can be achieved through desalination technologies, such as reverse osmosis, applied to water before heating and supply to the SOE.<sup>67</sup> Chromium and silica poisoning present a particular areas of concern however given the use of chromium containing superalloys which may be applied in IHX and piping materials such as Alloy 617 and 800H and the common use of glass sealants in Solid Oxide cell stacks. A systemic approach to nuclear enabled hydrogen using SOE technologies should be taken. Materials used in the hydrogen plant heat loop should be assessed for impurities which may impact the performance of SOEs. For example, materials used in these loops should either not contain chromium or new materials should be developed for use in SOEs which are resistant to chromium poisoning. Alternative sealant materials should be explored for SOE cell stacks.

#### **3.4.4. Limiting critical mineral utilisation in SOEs**

SOEs in development today make use of materials at risk of limited supply in the future including yttrium, scandium, lanthanum, cerium and gadolinium. According the Royal Society of Chemistry, all of these metals have been assessed to have a relative supply risk of 9.5/10.<sup>68,69</sup> The USGS reports that 87% of the US' supply of yttrium is sourced from China which has been presented as a concern for the resilience of the SOE supply chain and energy independence. Similarly, while nickel only scores a 6.2 on the Royal Society of Chemistry's relative supply risk, demand is expected to be driven up by this element's application to battery technologies. Supply limits have seen volatility in the price of nickel, rising as high as \$100,000 / tonne from a baseline of around \$25,000 / tonne in a single day.<sup>70</sup>

Reducing SOEs dependence on critical minerals will be a requirement for the commercial deployment of large-scale nuclear enabled hydrogen employing this technology as the volatility of the critical mineral market will impact the commercial case for hydrogen derived from SOEs. SOE manufacturers should focus research on limiting critical mineral use in their cells while maintaining cell performance.

### 3.5. Developing a full-scale demonstration of thermochemical cycles

As a potential zero-electrical power hydrogen production technology, thermochemical cycles are uniquely placed to take advantage of the high temperature output of next generation nuclear reactors. Materials research on thermochemical cycles (TCs) is intertwined with the development pathway of a full-scale prototype of the sulphur-iodine cycle. Challenges in the reaction process at different stages must be overcome to achieve the commercial deployment of the S-I cycle and will shape the materials research on thermochemical cycles. A four-stage suggested development process for a full scale-demonstration of thermochemical cycles is presented below along with the materials challenges to be prioritised.

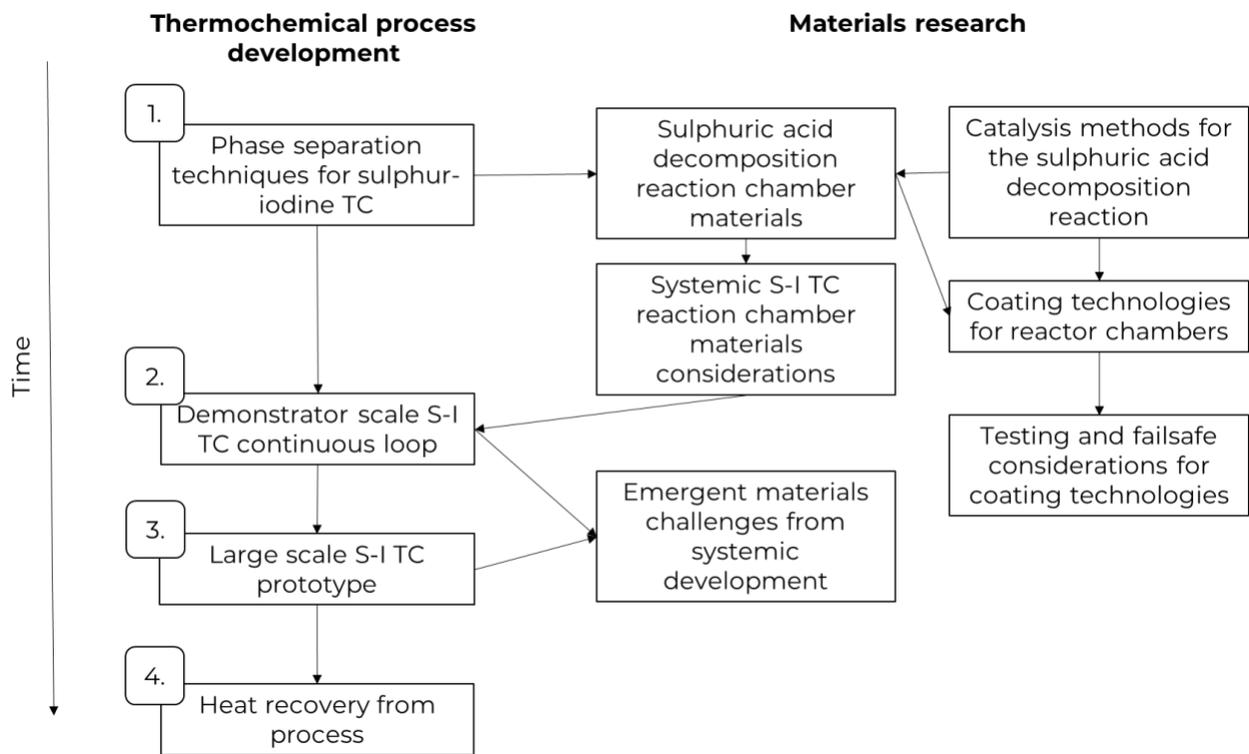


Figure 7 - Suggested development process of a scaled thermochemical demonstrator.

## Stage 1: Developing techniques to improve the performance of the Sulphur-Iodine cycle

### *Phase separation of the sulphur-iodine Bunsen reaction*

A challenge to the commercialisation of the sulphur-iodine process lies in the phase separation of H-I and H<sub>2</sub>SO<sub>4</sub> acids of the Bunsen reaction.<sup>71</sup> To develop appropriate phase separation, excesses of iodine and water are required for the Bunsen reaction which in turn lowers the efficiency of the H-I decomposition reaction making the cycle prohibitively energy intensive.<sup>71</sup> A recommended prerequisite for materials research to enable S-I thermochemical cycles is the development of techniques to improve phase separation of the Bunsen reaction without use of excess water and iodine, as the concentrations of chemicals used in the reactions will inform the range of appropriate materials for the reaction vessels. Previous research on phase separation has centred on the use of alternative solvents in place of water, such as tributylphosphate which promotes phase separation of the acids without the need for excess iodine.<sup>72</sup> Alternatively, a technique pursued in the closed loop demonstrator developed by the JAEA makes use of electro-dialysis to concentrate hydroiodic acid from the azeotrope of hydroiodic acid, water and iodine resulting from the Bunsen reaction.<sup>73,74</sup> Challenges surrounding phase separation should be addressed alongside catalysis methods to improve low-temperature cycle efficiencies. Only once these challenges are investigated should materials challenges relating to chemical reaction chambers be explored more completely.

### *Catalysis enabled sulphuric acid decomposition reaction*

Another strand of research related to the S-I cycle process development is a catalysis-enabled sulphuric acid decomposition reaction stage with a reduced operating temperature. The endothermic sulphuric acid decomposition reaction requires temperatures of around 850°C to achieve efficient rates of conversion.<sup>75</sup> Catalysis methods have been explored to reduce the efficient conversion rate temperature of this reaction. At temperatures of around 600°C, less exotic materials can be used for reaction chamber materials and lower temperature nuclear reactors could be employed as sources of heat, which would enable the development of commercial S-I hydrogen.

Platinum-based catalysts have shown promise in reducing the operating temperature of sulphuric acid decomposition. However, many of these catalysts degrade under the high temperature and corrosive conditions of 600-900°C sulphuric acid. For example, leaching of platinum from SiC-supported Pt catalysts has seen a deactivation of the sulphuric acid decomposition reaction at low temperatures.<sup>76</sup> Pt-impregnated anatase TiO<sub>2</sub> presents a recent avenue of further research as this has been demonstrated to suffer no degradation after 100hr exposure to sulphuric acid at temperatures ranging from 650-850°C.<sup>77</sup> Conversion rates of a low-temperature catalysis-based reaction remain a concern as the rate of conversion of sulphuric acid decomposition decreases with lower operating temperatures.<sup>78</sup>

Further development of catalysts resistant to the high temperature and corrosive environments of sulphuric acid is recommended as a first step of research development. Pt-impregnated anatase  $\text{TiO}_2$  is suggested as an important catalyst to consider in depth and sulphuric acid performance testing should be conducted on longer than 100hr timescales. The UK is a global leader in catalysis development, having the research facilities, personnel, and production capacities for catalysis development. Industrial stakeholders such as Johnson Matthey and research consortiums such as the UK Catalysis Hub should be engaged to develop catalysis methods for the decomposition of sulphuric acid.

Catalysis research into reducing the operating temperature of the sulphuric acid decomposition reaction is recommended as part of the initial stage of development alongside research into the S-I phase separation challenges as interactions between reaction chamber materials and catalysts will be important to consider. An understanding of the catalysts likely to be developed will inform reactor chamber materials as discussed in the subsequent section.

#### *Materials challenges for S-I cycle reaction vessels*

Materials challenges for S-I cycle revolve around the development of appropriate reaction vessels for thermochemical cycles. Materials must be resistant to both high temperatures (up to  $900^\circ\text{C}$ ) and corrosive environments. However, the use of exotic materials which provide resistance to these challenging conditions such as tantalum or niobium are often prohibitively expensive or difficult to source. Greater understanding of the S-I process and how it may be developed at scale for commercial hydrogen production, particularly in relation to phase separation, is required to inform which materials may be appropriate for reaction vessels.

Being common to both the HyS and S-I cycles, the development of a reaction chamber capable of withstanding the high temperature and corrosive conditions of the sulphuric acid decomposition reaction is a recommended focal point for materials research in the delivery of S-I thermochemical cycles. This research should be informed by technologies used for Bunsen reaction phase separation and catalysis methods for sulphuric acid decomposition. Silicon Carbides (SiCs) have been employed in the JAEA's S-I testing facility for the sulphuric acid decomposition reaction chamber.<sup>24</sup> Materials previously under exploration for reaction chambers include tantalum alloys, niobium alloys, tantalum coatings, Silicon carbides, and mullite ceramics.<sup>79</sup> Recommended first materials tests would be to design a corrosion resistance experiment for a series of materials exposed to high temperature sulphuric acid over 100hrs and perform economic studies for the deployment of each of these materials to an industrial scale thermochemical reaction chamber. Recommendations on the materials to be pursued in the development of a skid demonstrator could then be proposed.

#### *Coating technologies for reaction chambers*

Materials research into the application of resistant coatings to reaction vessels is an important avenue of exploration. Materials capable of withstanding high temperatures and corrosive

environments of the sulphuric acid decomposition step, involving long term resistance to  $\text{H}_2\text{SO}_4$  at temperatures in excess of  $800^\circ\text{C}$  typically involve rare and expensive materials such as tantalum and niobium.<sup>79</sup> These particular minerals present additional challenges as both are listed on the UK's critical mineral strategy.<sup>80</sup>

By applying resistant coating to reaction chamber walls, significant reductions in the quantities of these critical minerals are required with the main body of the reaction chambers then being made of thermally resistant alloys of steel.<sup>81</sup> Once an understanding of material requirements for thermochemical reaction chambers is developed, coating technologies and best practice coating techniques should be explored.<sup>82</sup> Alternative materials for coatings which do not make use of critical minerals should also be researched to eliminate reliance on critical and conflict minerals.

Important additional considerations when developing coatings are the development of fail-safes and methods of assessing the condition of resistive coatings during production. Electrochemical impedance spectroscopy presents an avenue for testing coatings during plant operation whereby the impedance of a reaction vessel is continually monitored and changes to the impedance would indicate damage to the protective coating system employed within the reaction vessel.<sup>83</sup> Maintenance of protective coating systems can be regulated as part of prototype and commercial thermochemical hydrogen production plants. Expertise in protective coating systems from the chemical industry should be applied to thermochemical reaction chambers to understand appropriate precautions and testing methods.

## **Stage 2: Demonstrator scale S-I thermochemical cycle running as a closed loop**

### *Systemic perspective to reaction chambers*

Demonstrators for the S-I cycle have been developed globally. A skid experiment involving the three reaction steps of the S-I cycle was developed in 2008 by General Atomics with the aim of demonstrating a laboratory scale method of hydrogen production via the S-I cycle, however this was not run as a closed loop cycle which limited the exploration of inter-reaction chamber interactions.<sup>84</sup> The development of the S-I cycle was picked up by the JAEA where in 2016, a benchtop scale demonstration operating successfully as a closed loop thermochemical cycle.<sup>85,86</sup> The JAEA S-I demonstrator, with capacity of around 7kg/hr, was run as a closed loop cycle for eight hours and plans have been developed to scale this demonstrator for inputs from the Japanese HTTR reactor.<sup>24</sup> To date, closed loop demonstrations capable of scaled production have not been developed in the UK.

The interactions of reaction chamber materials for different stages of the S-I cycle need further research to ensure that materials used in each of the reaction chambers are compatible and that degradation of the closed loop system can be controlled. Longer running experiments should be conducted to ensure the stability of the closed loop cycle for extended operational periods. While the operating regime for next generation nuclear reactors has not been fully

determined, thermochemical plants may be expected to run for 12-24 months between maintenance periods based on typical refuelling cycles for an HTGR.<sup>87</sup>

### **Stage 3: Large scale S-I prototype development: Emergent materials challenges**

The development of demonstrator scale and subsequent large-scale S-I thermochemical cycles will reveal emergent materials challenges surrounding continuous operation and allow the interactions of materials in separate reaction vessels to be tested. For example, the incomplete phase separation of the Bunsen reaction may result in side-reactions occurring in other reaction chambers and vessels must be resistant to products of these side-reactions.

### **Stage 4: Heat recovery from process**

With the development of a prototype scale S-I cycle, thermal optimisation of reactions can be developed. Waste heat from the different reaction vessels can be passed through heat exchangers to reuse this waste heat for alternate purposes or be used to heat the other reaction vessels. Reductions in the specific energy consumption of hydrogen production can be achieved via this optimisation decreasing the operational costs of the S-I hydrogen production plant. Development of materials for heat exchangers within this waste heat recovery system will be required. Material requirements will be similar to those of the IHX system described in a previous section.

## **4. Key enablers**

### **4.1. Introduction**

In addition to investigating key research fields, the technology landscape study discussed key enablers for the development of nuclear enabled hydrogen. The enablers are considered to be areas important for accelerating the commercial development of a broad range of materials to support nuclear enabled hydrogen.

### **4.2. Critical mineral utilisation and recycling**

A growing area of concern for materials research for hydrogen production is the use of rare earth elements.<sup>88</sup> As discussed in the End-to-End Hydrogen report and more recent studies, the use of iridium in PEM electrolyzers poses a risk to the commercial application of that technology due to volatilities in the supply and thus price of iridium.<sup>89</sup> Similarly, for the technologies explored for nuclear enabled hydrogen production, rare earth element-dependent solutions are often developed for lab scale demonstrations but may not be suitable for the commercial roll out of those technologies.

Assessing the risk of critical mineral supply limitations is an important first step in understanding this issue. The diversity of electrolyser technologies that are being explored present an opportunity for the UK to build a critical mineral resilient electrolysis market. SOEs,

PEM electrolyzers, Alkaline electrolyzers, and potentially AEM electrolyzers have different requirements for critical minerals and are suited to different hydrogen production applications (e.g. high temperature enabled hydrogen production is better suited to SOEs while PEM electrolyzers are better suited to utilise the variable electricity supply from renewables<sup>90</sup>). As such, a dependence on a particular set of critical minerals for domestic hydrogen supply can be avoided by employing a variety of electrolysis and hydrogen generation technologies.<sup>91</sup> Furthermore, the requirement of new materials within high temperature SOE components and thermochemical cycle reaction vessels for nuclear enabled hydrogen presents an opportunity to avoid dependencies on any particular critical mineral. A model of global critical mineral demand and supply should be developed to assess the risk of using critical minerals in nuclear enabled hydrogen technologies.

Should it be required, the foremost step that must be taken to reduce risk from critical mineral supply is to reduce the dependence on critical minerals as part of hydrogen production technologies. Where critical minerals are needed, diversity of supply is an important step in reducing their supply risk. End of life planning as part of thermally enabled hydrogen technologies development to recycle rare earth elements, and other components, is recommended to produce a domestic supply of these elements in the long term.

Materials research should take critical mineral limitations into account when developing novel materials. New materials should limit critical mineral use and be designed to ease end of life recycling.

### **4.3. AI enabled materials research database**

Development of new materials from initial research to commercial application has historically taken around 20 years.<sup>92–94</sup> The UK's Net Zero and hydrogen strategies present a challenge for nuclear enabled hydrogen materials development as demand for low-carbon hydrogen will necessitate deployment of these technologies and materials before 2050.

Given the speed and scale of deployment required to commercialise nuclear enabled hydrogen by 2050, making use of existing materials research is an important method of accelerating research in the sector and enabling deployment of nuclear hydrogen in line with decarbonisation targets.

Fortunately, a great deal of research has already been conducted in the field of materials sciences in developing materials resistant to high temperatures (towards 1,000°C) and under challenging conditions such as corrosive environments, radiation bombardment, and exposure to erosive surfaces.

Exploring the full landscape of materials research and extracting useful data from this literature will be time consuming if conducted manually. However, the development of new Artificial Intelligence (AI) tools has the potential to revolutionise data research and extraction. New natural language-processing AIs have the capacity to process and extract data from literature

papers at incomparable speeds to manual research.<sup>95</sup> These tools could accelerate materials research in four ways:

1. Parsing research papers from across industries for materials with key properties. Materials used or discarded within one industry could be brought to bear on another industry where their properties are useful. For example, FeCrAl alloys were initially explored and disregarded for use as a cladding material in high temperature reactors in the 1960s. The alloys demonstrated good resistance to oxidative conditions but did not maintain appropriate mechanical strength at high temperatures. However, following the 2011 Fukushima reactor incident where an oxidative reaction precipitated the core meltdown, interest in FeCrAl alloys for nuclear applications was renewed. Novel techniques are being developed to improve the mechanical performance of these alloys at high temperatures while maintaining their resistance to oxidative conditions.<sup>96</sup> An AI is capable of parsing far greater numbers of papers than can be conducted manually which will precipitate more 'reapplications' of previously researched materials.
2. Focusing materials research on the development of a few materials for the application to nuclear enabled hydrogen. There are many materials that could meet the requirements of nuclear enabled hydrogen commercialisation. AI presents a tool for synthesising the state of research on materials and applying tests to present the most suitable materials. While tests criteria would need to be designed by a researcher, the AI could perform an initial screening of materials thus narrowing the focus of materials research towards specific materials for development.
3. AI could be used to extract and synthesise data on the performance of materials under challenging conditions conducted globally.<sup>97</sup> The synthesis of larger data sets would in turn allow more complete conclusions on the performance of materials and greater data inputs for modelling the performance of materials digitally prior to development. This will allow many materials to be easily screened, saving investments of time and money.
4. AI enabled modelling software can be used to test and identify new alloy compositions. With a well-developed modelling software, AI tools can be used to test many thousands of alloy compositions in a fraction of the time that would be required if the testing were conducted manually. For certain novel alloy materials such as High entropy alloys (HEA), where a "trial and error" method of alloy testing is applied, AI is already being explored as a tool to identify promising new alloy materials for testing.<sup>98</sup>

By compiling previous research and identifying the most promising materials for further exploration through AI tools, previous materials research can be built on directly and research can accelerate down the pathway to commercialisation of existing and novel materials. The UK Science and Technology Facility Council (STFC) has already recognised the role that AI can play in advancing scientific research. The STFC Scientific Computing department has assembled cutting-edge skills and expertise in scientific software research and development.<sup>99</sup>

Engagement with the STFC in the development of an AI enabled materials research database is

recommended.

#### **4.4. Develop understanding of nuclear enabled hydrogen's business case**

Developing wide-spread understanding of the business case for nuclear enabled hydrogen is important in driving funding and interest into early-stage research and allowing researchers to contextualise the potential value of specific research topics in a nascent sector.

The levelized cost of hydrogen (LCOH) from nuclear power is projected to be cost-competitive with renewable energy sourced hydrogen. The OECD predicts that the LCOH from newly built nuclear power plants would be around \$3.3/kg-H<sub>2</sub>, matching the LCOH of offshore wind and the upper-bound predictions of solar LCOH in the EU.<sup>7</sup> Nuclear power's capacity to produce a reliable supply of hydrogen presents added value to critical industries which will be reliant on a steady supply of hydrogen such as steel and cement manufacture, or future production plants for green chemicals such as ammonia and sustainable fuels. Nuclear enabled hydrogen demonstration projects are being developed at sites across the world, including in the UK, using today's hydrogen production technologies.<sup>14</sup>

Furthermore, the value and cost of heat from different nuclear reactors must be better understood. High temperature reactors are in development but understanding of how best to utilise this heat is required. High temperature reactors open the door to high temperature hydrogen production technologies but may be used for power generation too or industrial heat applications also.

As explored in this report, high temperature hydrogen production technologies will require the advancement of existing materials and the development of new materials. The cost and performance of novel materials underpins the economic performance of thermally enabled hydrogen technologies. For example, the economic performance of thermochemical cycles will be highly dependent on material development within catalytic methods to reduce the operating temperature of thermochemical cycles and in the development of durable materials for reaction chambers which can withstand the high temperature and corrosive conditions of the thermochemical cycle. Materials development underpin the business case for thermally enabled hydrogen technologies, and they may in turn underpin the business case for high temperature nuclear reactors.

A study to determine the value of a guaranteed hydrogen supply from nuclear power sources should be conducted. For specific applications, such as the production of hydrogen for industrial feedstock, reliably produced nuclear enabled hydrogen would require less storage capacity than hydrogen produced from a variable renewable source such as wind or solar.<sup>7</sup> Following this, a study into the potential value and cost of heat from different nuclear reactor types will be required to understand the potential market applications of high temperature

reactor heat. Finally, the development of a specific nuclear enabled hydrogen strategy is recommended to demonstrate the capabilities of nuclear enabled hydrogen technologies for developing resilience within the UK energy sector.

#### **4.5. Improved testing facilities for thermally assisted hydrogen production**

The UK has limited capacity for high and intermediate temperature testing of hydrogen production technology as explored in a series of blueprints by the Royce Institute following the publication of the End-to-End Hydrogen landscape.<sup>100</sup>

Nuclear enabled hydrogen technologies such as thermochemical loops and high temperature SOEs should be developed and tested at scale ahead of their application to nuclear facilities to better understand the materials and engineering challenges that these technologies face. Currently, limited testing of hydrogen production technologies on existing nuclear facilities is being developed.

While bench-top tests of these technologies can be delivered, a scaled facility mimicking the combined heat and power of a nuclear facility would provide thermally enabled hydrogen production technologies a space to develop and demonstrate their capabilities for TRL 4-7. A proposal as part of the Low Carbon Hydrogen Supply 2 Competition called for a scaled combined heat and power facility for the testing of nuclear enabled hydrogen technologies.<sup>101</sup> The facility would be capable of producing steam up to temperatures of 900°C and power outputs of up to 6MW. The facility would have the capacity for multiple configurations, where multiple intermediate sized experiments could be tested simultaneously, or a single larger scale demonstration. Such a facility would enable materials for high temperature heat exchangers to be tested as well as hydrogen production technologies. Degradation mechanisms in materials of high temperature steam cycling at scale could be demonstrated and tested at this facility prior to deployment in commercial settings. Intermediate-sized testing facilities (on the order of 600°C and 1MW output) would also provide development and demonstration spaces for thermally enabled hydrogen technologies.

Enabling early phase testing of hydrogen production technologies at scale without the regulatory constraints of a nuclear power plant will enable faster development of technologies. The Heysham project will see the deployment of intermediate temperature SOEs with a nuclear facility, but testing could be replicated for a broad number of different configurations at a combined heat and power testing facility without the regulatory constraints of a nuclear facility.

It is important to note that the combined heat and power facility will not eliminate the need for nuclear testing capabilities for hydrogen production technologies (as it will not have the capacity to test nuclear specific materials challenges such as tritium production), but it will provide a path to accelerate the development of these technologies. As previously discussed, nuclear site testing of hydrogen production technologies is in development through the

Heysham project. Given that the UK's fleet of AGRs is expected to be retired by the end of the decade, the Heysham project will need to be resolved in the near term if it is to have a positive impact on the development of the nuclear enabled hydrogen sector.

#### **4.6. Growing within regulatory constraints**

The UK's nuclear site regulatory framework does not make provisions for chemical or hydrogen productions on a nuclear site. As such, constrictions of the nuclear site will be applied to a hydrogen production facility within a nuclear site boundary. Examples of regulations which will be applied to the hydrogen production plant include the following conditions from the Office for Nuclear Regulation (ONR):

- ONR License conditions 9 and 10 relating to instruction and training of staff must be applied to operators, installers, and repair workers of the hydrogen production plant.
- ONR license conditions 19 and 20 detail the need for site plans to be developed and no changes permitted without consulting ONR which will extend to the hydrogen production facility.
- ONR License conditions 28 through 31 detail the requirement of plant shut down planning for maintenance and inspection and hydrogen production will be required to comply with inspection schedules.

In addition, hydrogen production facilities will require a nuclear site to be compliant with COMAH regulations as on-site hydrogen production will likely meet the 5-50 tonne range of permitted hydrogen storage for this regulation to apply. A report detailing the regulatory requirements for a hydrogen production facility within a nuclear site license should be compiled to understand the challenges related to on-site nuclear hydrogen production.

Following an assessment of the regulatory requirements for an on-site hydrogen production plant, moving the hydrogen production facility outside of a nuclear site boundary may prove to be a more cost-effective option. However, novel materials challenges are presented by off-siting a hydrogen production plant. A hydrogen production plant may be sited several kilometres from a nuclear plant, and transporting heat with limited losses will be required. A report detailing the estimated costs for off-site heat transport should be developed. Tangentially, the capacity to off-site nuclear heat could be applied to broader process heat applications in industry as well as district heating projects. Engagement with regulatory bodies to understand the regulatory challenges related to off-site heat transport is recommended. For example, fluids used to transport heat off of a nuclear site will need to meet radiation limits detailed in the Environmental Permitting Regulations.<sup>102</sup>

A comprehensive engagement with regulatory bodies is required to ensure project proposals for nuclear enabled hydrogen do not run counter to regulatory requirements for the nuclear sector.

## **5. Conclusions and next steps**

Nuclear enabled hydrogen production presents an opportunity to produce reliable low-carbon hydrogen at scale. Demonstrators for nuclear enabled hydrogen are already in progress in the UK and internationally but the majority of these make use of low temperature electrolysis technologies. The role of nuclear enabled hydrogen in the UK's future energy system is not yet well understood. To improve governmental and sectoral understanding of the potential coupling of these technologies, techno-economic studies must be carried out exploring the next generation nuclear reactors application to thermally enabled hydrogen technologies, particularly HTGRs, the UK's AMR technology of choice.

### **5.1. Developing techno-economic studies for nuclear enabled hydrogen**

The OECD's study into the LCOH from different renewable power sources presented nuclear enabled hydrogen as a viable and cost-competitive route of hydrogen production. However, to date, publicly available studies have not considered the additional advantages of nuclear derived hydrogen such as its capacity to produce a reliable and adjustable stream of hydrogen. A reliable and adjustable stream of hydrogen has the potential to eliminate the requirement of extensive hydrogen storage facilities under specific use cases, such as in the supply of hydrogen to industries such as steel and cement production.

As a first step towards developing broader understanding of the potential of nuclear and thermally enabled hydrogen coupling, a detailed techno-economic analysis of nuclear enabled hydrogen production for applications in archetypal use cases should be developed. The study should go beyond the scope of this paper and consider the set-up costs of new nuclear reactor plants as well as the end-use applications of hydrogen and compare this to the application of green hydrogen derived from renewable power to the same end-user archetypes. The study will help to inform the direction of materials research in this nascent sector.

### **5.2. Materials research challenges identified in this study**

Thermally enabled hydrogen technologies combined with intermediate and high-temperature reactors can drive down the electrical energy demands of reliable low-carbon hydrogen, but greater materials development is needed for these technologies to become commercially viable. In this landscape the materials challenges in delivering nuclear enabled hydrogen have been presented and an outline of the key research areas to be considered are outlined. The materials challenges considered to be a priority are:

#### **5.2.1. Tritium profiling and exploring materials to limit tritium transfer**

Profiles of tritium concentrations associated with different reactor and heat exchange technologies should be conducted with proposed generation IV reactor designs. Models of tritium diffusion associated with different reactor types should be developed using these

profiles and used to determine whether tritium concentrations in effluent is likely to result in radiation in excess of the regulatory limits of 100Bq/kg. Should radiation levels exceed this limit, long duration testing of promising materials for limiting tritium transfer should be carried out where materials will be exposed to tritium under high temperature conditions. Aluminium oxides are a promising area to focus on due to recent advances in nano-lattice performance at high temperature and the UK's established recycling industry.

### **5.2.2. Develop lifetime of SOEs**

As the most mature thermally enabled hydrogen production technology, extending the lifetime of SOEs without impacting their performance is a priority area of research. Current SOE technologies fall short of targeted degradation rates required to be commercially competitive. Modelling degradation mechanisms within intermediate temperature Cerium Gadolinium Oxide based SOEs (500-600°C) and high temperatures Yttria stabilised Zirconium based SOEs (700-850°C) should be undertaken. Once degradation mechanisms are understood, alternative materials for use in intermediate temperature SOEs should be developed to extend the operational lifetime of these cells. Advanced SOEs should then be developed with industrial partners making use of new materials to improve operational lifetimes.

### **5.2.3. Sulphur-Iodine Cycle development**

Developing methods for phase separation of the sulphuric acid and hydroiodic acid products of the Bunsen reaction and catalysis methods for reducing the operating temperature of the sulphuric acid decomposition reaction are key process developments required to inform the materials challenges of developing resistant chemical reaction chambers. Material development should then focus on the sulphuric acid decomposition reaction chamber. Tantalum and niobium-based materials are suggested for consideration though alternative chemistries or development of coating materials using these minerals is encouraged due to the scarcity of these minerals and to limit the UK's reliance on critical and conflict minerals. It is important to note that the UK currently does not have the facilities to carry out experimental work to optimise the S-I cycle.

### **5.2.4. Testing of materials for high temperature heat exchangers**

Testing of likely superalloy material candidates for IHX use should be tested for durations longer than 100 hours and under IHX conditions. Materials should be exposed to temperatures up to 950°C and tested for degradation when exposed to different coolant materials including helium and molten salts. Candidate materials include Haynes 242, Alloy 800H, and Alloy 617. Alloy 617 is highlighted as of particular interest and should form the focus of initial research but development of alternative materials such as ceramics, RHEA and ODS alloys should also be conducted.

### **5.2.5. Develop an AI enabled materials database**

The database would make use of an AI tool to parse materials research papers extracting data on materials testing. Data sources should be compiled across academia and industry where possible. The AI would compile the materials testing data to form more complete datasets on specific materials. Follow-up studies should be conducted on this database and datasets should be used to prioritise materials research. The database would help to improve knowledge sharing and reduce manual research requirements required as part of academic studies. By developing this tool, the UK would reaffirm itself as a centre for global research collaboration.

These areas together provide an opportunity for the UK to maintain its world-leading position in materials research, and benefit from the environmental and economic opportunities with developing new technology pathways for low carbon hydrogen production.

## Glossary

AEL	<i>Alkaline Electrolysis</i>
AGR	<i>Advanced Gas-cooled Reactor</i>
AI	<i>Artificial Intelligence</i>
AMR	<i>Advanced Modular Reactor</i>
CCS	<i>Carbon Capture and Storage</i>
CGO	<i>Cerium Gadolinium Oxide</i>
CL-SMR	<i>Chemical Looping Steam Methane Reformation</i>
COMAH	<i>Control of Major Accident Hazards</i>
Cu-Cl Cycle	<i>Copper-Chlorine Cycle</i>
DESNZ	<i>Department for Energy Security and Net Zero</i>
ET-PEM	<i>Elevated Temperature PEM (Electrolysis)</i>
FLiBe	<i>Lithium Fluoride and Beryllium Fluoride based molten salt</i>
GFR	<i>Gas-cooled Fast Reactor</i>
HEA	<i>High Entropy Alloys</i>
H-SOE	<i>Proton conducting Solid Oxide Electrolysis</i>
HTGR	<i>High temperature Gas-cooled Reactor</i>
HTTR	<i>High temperature Engineering Test Reactor</i>
HyS Cycle	<i>Hybrid Sulphur Cycle</i>
HyTN	<i>Hydrogen from Thermochemical and Nuclear Report</i>
IHX	<i>Intermediate Heat Exchanger</i>
JAEA	<i>Japanese Atomic Energy Association</i>
KTN	<i>Knowledge Transfer Network</i>
LCOE	<i>Levelised Cost of Energy</i>
LCOH	<i>Levelised Cost of Hydrogen</i>
LFR	<i>Lead-cooled Fast Reactor</i>
LSCF	<i>Lanthanum Strontium Cobalt Ferrite</i>

LSM	<i>Lanthanum Strontium Manganese</i>
LWR	<i>Light Water Reactor</i>
MSR	<i>Molten Salt Reactor</i>
NIRO	<i>Nuclear Innovation and Research Office</i>
NNL	<i>National Nuclear Laboratory</i>
ODS	<i>Oxide-Dispersion Strengthened (alloys)</i>
OECD	<i>Organisation for Economic Co-operation and Development</i>
ONR	<i>Office for Nuclear Regulation</i>
PEM	<i>Proton Exchange Membrane (Electrolysis)</i>
PWR	<i>Pressurised Water Reactor</i>
RHEA	<i>Refractory High Entropy Alloy</i>
R-P phase	<i>Ruddlesden-Popper phase</i>
SCWR	<i>Supercritical Water-cooled Reactor</i>
SFR	<i>Sodium-Cooled Fast Reactor</i>
S-I Cycle	<i>Sulphur-Iodine Cycle</i>
SiC	<i>Silicon Carbide</i>
SMR	<i>Small Modular Reactors</i>
SOE	<i>Solid Oxide Electrolyser</i>
SOFC	<i>Solid Oxide Fuel Cells</i>
STFC	<i>Science and Technology Facility Council</i>
TCs	<i>Thermochemical Cycles</i>
TRL	<i>Technology Readiness Level</i>
USGS	<i>United States Geological Survey</i>
VHTR	<i>Very High Temperature Gas Reactor</i>
YSZ	<i>Yttria stabilised Zirconium</i>

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This report was commissioned by the National Nuclear Laboratory (NNL) in partnership with the Henry Royce Institute for advanced materials as part of its role around convening and supporting the UK advanced materials community to help promote and develop new research activity.

The overriding objective is to bring together the advanced materials community to discuss, analyse and assimilate opportunities for emerging materials research for economic and societal benefit.

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