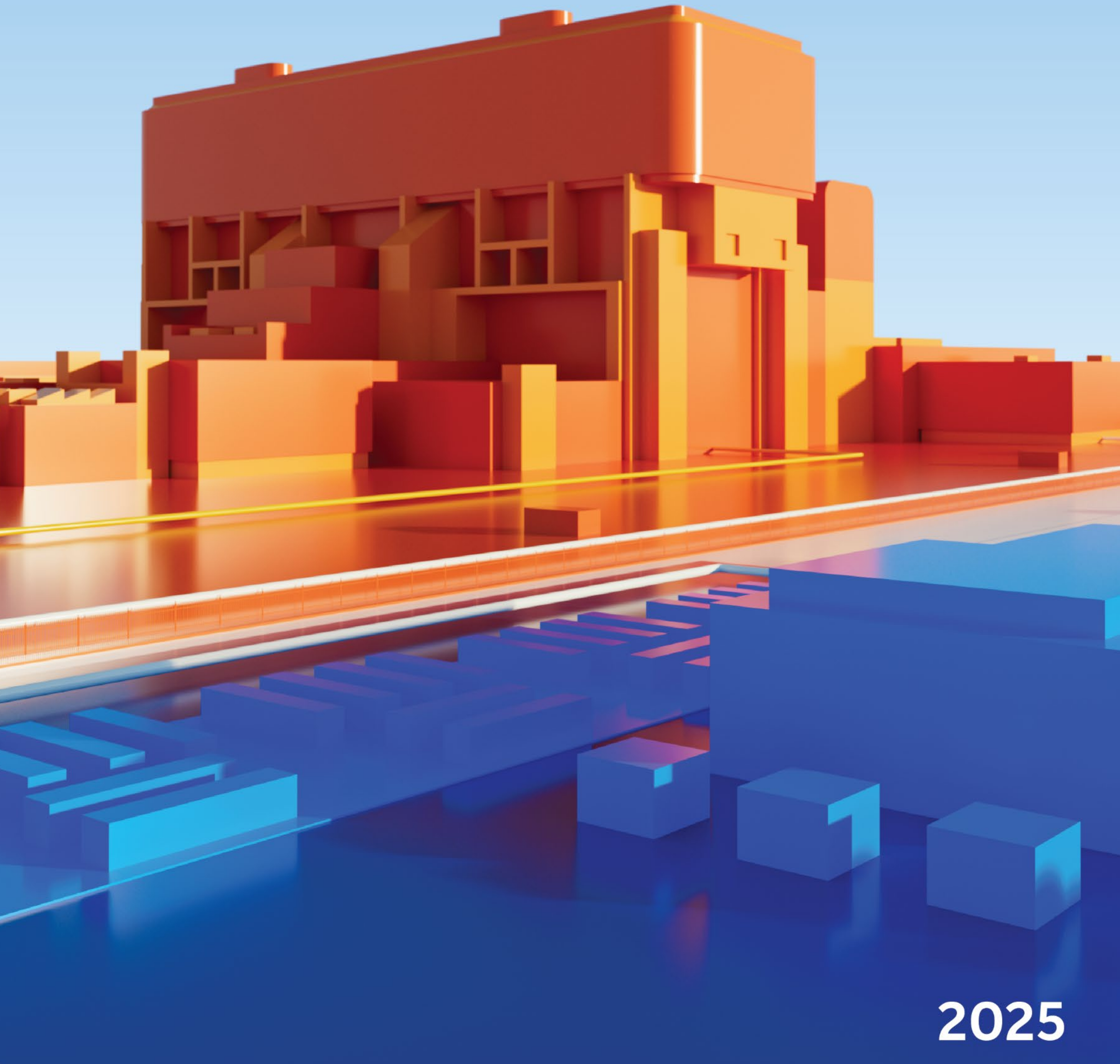
Nuclear Enabled Hydrogen Handbook



2025

Quality information

Document Title:	Nuclear Enabled Hydrogen Handbook
Document Reference:	EDF-SCD-BHH-NEH-001
Revision:	Final
Authors:	Stephen Tutin, Peter Smith, Olga Dubinin, August Pandey, Andrew Nairn, Arman Kuraishy, Matthew Bennion, Christopher Kiely, Daisy De Selliers, Olayinka Ayo, Ann Boyd, John Logue, Aline Leon, Martyn Mills, Paul Kaine, Robert Alford, Jonathan Hawes, Jonathan Macdonald-Taylor.
Reviewers:	Ian Morgan, Jim Kershaw, Andy Pyle, Rebecca Rosling, Roy Collins, Kent McCord, David Stevens, Alistair Wasey, Katie Baverstock-Hunt, Howard Chapman, Christopher Connoly, Richard Gibson, Jennifer Smart.
Approver:	Sophia Czuprynski
Email Contact:	rdoperations@edfenergy.com

Acknowledgements

The successful delivery of this Nuclear Enabled Hydrogen Handbook was made possible with the support of the Department for Energy Security and Net Zero.

We are deeply grateful to the individuals and teams outside our project group who played a crucial role in shaping this Handbook. Their knowledge, perspectives, and unwavering support significantly strengthened our work, helping to create a resource that is both thorough and valuable for its readers:

- United Kingdom National Nuclear Laboratory (UKNNL)
- FuelCell Energy
- Alfa Laval
- Department for Energy Security and Net Zero (DESNZ)

The Nuclear Enabled Hydrogen Handbook has been produced as part of the Bay Hydrogen Hub project, which has been supported by the UK's Department for Energy Security and Net Zero Industrial Hydrogen Accelerator Programme.

Disclaimer

This Nuclear Enabled Hydrogen Handbook was prepared by EDF Energy Nuclear Generation Limited ("EDF") and provides a summary of information that is intended to be a helpful starting point for future projects. When accessing this publication, you on your own behalf and on behalf of any person with whom you share any part of this publication agree to the terms of this disclaimer. This publication does not constitute legal, financial, technical or other professional advice. Whilst EDF believes that the information given in this document is correct as at the date of publication, it does not guarantee that this is so, nor does it guarantee that the information is suitable for any particular purpose.

None of EDF, its group companies nor any of their respective directors, officers, members, employees, advisers, partners, agents or representatives (together the "EDF Group"), nor any other contributor to this publication, their respective group companies nor any of their respective directors, officers, members, employees, advisers, partners, agents or representatives, makes any guarantee, warranty or representation, express or implied, regarding the accuracy, completeness, suitability or reliability of the information or any analyses, assumptions, opinions, conclusions or recommendations contained in or referred to in this publication. Users of this publication must satisfy themselves as to, and conduct all checks they deem necessary to verify, the accuracy, completeness, suitability and reliability of the information and any analyses, assumptions, opinions, conclusions and recommendations contained in or referred to in this publication. EDF is under no obligation to update or correct any inaccuracies which may become apparent in this publication. None of the EDF Group, nor any contributor to this publication nor any of their respective directors, officers, members, employees, advisers, partners, agents or representatives accepts any liability whatsoever for any loss, expense, cost, damage or any other liability arising from any use of, receipt of, reliance on, or otherwise in connection with, any of the information or any analyses, assumptions, opinions, conclusions or recommendations contained in or referred to in this publication, and any such liability is expressly disclaimed. This publication and the information contained in or referred to in this publication are protected by copyright and other laws.

© 2025 Published in the United Kingdom by EDF Energy Nuclear Generation Limited. All rights reserved.

Executive Summary

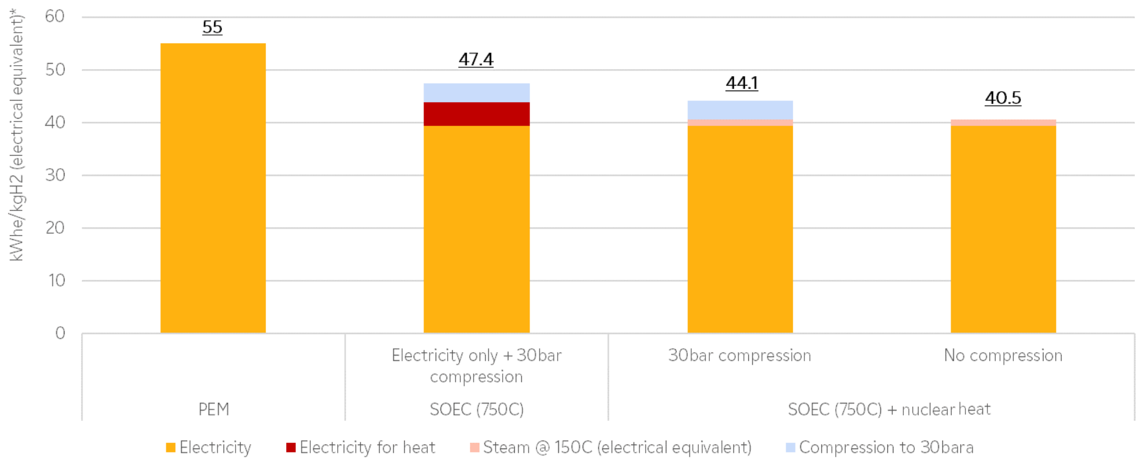
Nuclear Enabled Hydrogen (NEH) is where the heat and/or electricity produced by a nuclear power station (NPS) are used to produce low carbon hydrogen[1]. This handbook outlines the benefits of NEH, and aims to provide a practical and accessible guide to demonstrate how a NEH project could be delivered. It identifies key considerations with developing a hydrogen production project near a nuclear site, and how these could be addressed. A summary of the key findings is included below.

Nuclear Enabled Hydrogen can make low carbon hydrogen more cheaply

- NEH can deliver a 20-30% improvement in the efficiency of hydrogen production compared to alternative low temperature electrolysis technologies.
- NEH with high-temperature electrolysis can achieve up to a 30% efficiency gain compared to other electrolytic technologies. This is achieved when heat is extracted from the NPS steam cycle and supplied to the electrolyser.
- Using the technologies available today, the cost to produce NEH using solid oxide electrolysis is estimated to be around £6-7/kg of hydrogen, depending on off-taker requirements. This compares very favourably to the strike prices agreed in the Hydrogen Allocation Round 1 (HAR1) of ~£9.50/kg of hydrogen.
- There is an opportunity to further reduce costs by tailoring the system to meet the needs of specific off-takers, by creating a private wire electrical connection between the nuclear plant and electrolyser, and through further technology improvements and economies of scale.

Solid Oxide Electrolysis unlocks greater efficiencies, and pairs well with nuclear

- Solid Oxide Electrolysis Cells (SOEC) allow steam from the NPS to be supplied, via a heat exchanger, directly to the electrolyser. This enables the increased efficiencies.
- Nuclear provides reliable and continuous supply of clean electricity, which offsets the reduced flexibility of SOEC relative to other electrolysis technologies.
- Whilst SOEC modules currently are expected to have greater degradation rates than alternative technologies such as Proton-Exchange Membrane (PEM), these rates should diminish with time. Degradation rates can be minimised if the electrolyser is kept operating consistently. Reliable electricity from nuclear can enable this.



[1] *Low carbon hydrogen in the UK is defined by Low Carbon Hydrogen Standard, which sets a maximum threshold for greenhouse gas (GHG) emissions associated with hydrogen production (must have GHG of 20gCO_2e/MJ LHV or less)*

Hydrogen production and storage would best be sited outside the nuclear site licence area

- This enables most of the project to be similar to any other hydrogen project, by minimising additional nuclear safety and security related requirements.
- This also minimises the impact on the NPS's Site Licence Condition compliance arrangements, and reduces the number of modifications that would be required for a NPS to enable NEH.
- A heat exchanger, and isolation valves, would be installed within the nuclear site security fence. This gives the NPS control over the heat export and ensures steam from the NPS steam cycle never leaves the site.
- As the NEH facility is outside the NPS the Health & Safety Executive are the relevant regulator. The Office for Nuclear Regulation would regulate activities within the NPS. Early engagement with both regulators should start before detailed design begins.

Updates to the nuclear safety case will be required, but they can be achieved

- A Front-End Engineering Design (FEED) has shown SOEC and its supporting systems can be integrated with heat and power supplies from a nuclear reactor, and this FEED is presented within the handbook.
- The hazard from the NEH facility should be treated as an off-site industrial hazard when incorporated into the reactor safety case. This would be similar to existing industrial hazards that are already present near some nuclear sites in the UK. Emergency plans may also need to be updated to maintain site licence condition compliance.
- There is a history of having small scale electrolysers and hydrogen storage on nuclear sites in the UK, as hydrogen is used as part of nuclear plant operations. This demonstrates that a safety case can be made.
- Having a separation distance between the NPS and the hydrogen production facility can significantly reduce the complexity of the safety case. Indicatively, for a 24MW plant, the SOEC electrolysers could be sited 15-20m away from the nuclear site fence [because of the low operating pressure and hydrogen volumes contained in the electrolysers]. Storage would likely be located further from the site, such as 50-150m depending on the storage volume and pressure and other design considerations. Detailed design would need to include an assessment to determine more accurate distances, based on the specifics of the final design
- Additional mitigations could be used to reduce the separation distance, such as raised land barriers, blast walls, or the use of hydrogen storage technologies with lower pressures (e.g. metal hydrides, such as depleted uranium).
- Updating the electrical connections to the NPS will also require a safety case assessment.

Adequate security can be achieved if it is considered as part of the design

- Minimising digital communication between the NPS and the NEH facility simplifies the cyber security assessments, allowing remote operations at the NEH facility.
- Plant design needs to consider the potential for malicious acts. Information from the safety case can be used to help assess the potential consequences of any malicious acts.
- By designing the NEH facility to operate as a separate entity from the NPS, it reduces the security burden on the NEH facility, such as by reducing the potential for an insider threat.

Nuclear plant modifications are required, but would not delay a hydrogen project's end date

- If NEH is considered during design of new nuclear projects, less modifications will be required than for existing sites.
- Estimates show the time required for modifications to the NPS can be accommodated within the schedule for building a 24MW hydrogen production facility, even for existing NPS sites, without causing an overall delay.
- During design future nuclear new build projects should plan for electrical connections to NEH projects. This could include ensuring transformers have sufficient footprint and connection interfaces to enable modifications.

- In circumstances where the NEH Facility is proposed as part of a new nuclear development, it may be possible to include it in the wider planning application process for the new nuclear development. On an existing operational nuclear site, a separate Town and Country Planning Act (TCPA) application will likely be required, although it may also be possible to use permitted development rights of a NPS to perform the modifications.

Higher upfront costs are required, but this is outweighed by higher revenues

- The costs for any nuclear plant modifications required for the NEH facility are estimated to be a small proportion of total capital costs – less than 7% for the example 24MW commercial facility considered in the handbook.
- In the long term (e.g. by 2030), capital expenditure (CAPEX) costs for SOEC are estimated to be similar or lower than other electrolysis technologies, due to using cheaper and more widely available electrode materials.
- Whilst SOEC stack modules are currently expected to be replaced more frequently than PEM stack modules, the better efficiency of the technology, and comparative lower material costs of the stacks, is expected to offset this cost, and the life of the stack modules should increase with time with technology developments.

This handbook provides an accelerated start for future NEH projects

- The information within this handbook should provide the basis for early project and design development of a NEH facility and thus a future application into the UK government's hydrogen production business model scheme.
- A 24MW commercial scale project is used as an example to demonstrate the principles discussed throughout the handbook. This example builds on work done during the Bay Hydrogen Hub feasibility study and FEED at Heysham 2 power station.
- For the 24MW example, information such as block diagrams, plant layouts, and other technical information have been included within the handbook.
- Information on how to scale a project beyond 24MW has been included, as well as a case study illustrating the potential for NEH longer term, such as part of a nuclear modular reactor project at Hartlepool.

The summaries within the handbook are underpinned by many public and proprietary documents, which have been referenced throughout and are listed at the end. If you wish to understand the underpinning detail, you can reach out to the EDF team at rdoperations@edfenergy.com

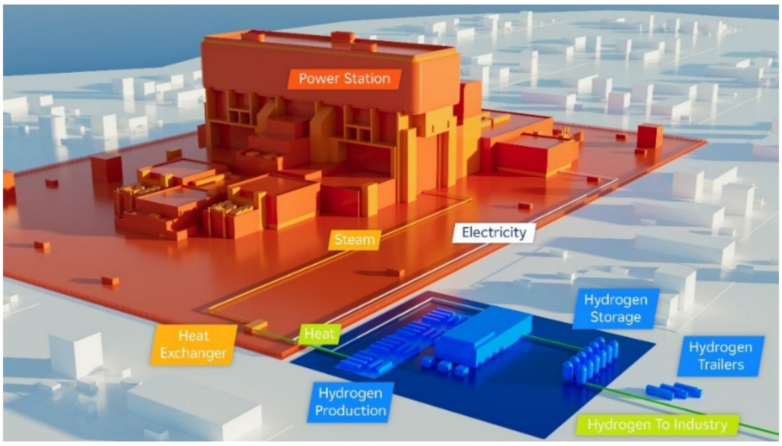


Image representing the concept of hydrogen production integration with a nuclear power station.

Contents

1. INTRODUCTION

A practical handbook for Nuclear Enabled Hydrogen

The Nuclear-Enabled Hydrogen (NEH) Handbook is a practical guide designed to help bring a NEH project to life. The goal is to help equip a project developer with the knowledge and tools necessary to confidently design a NEH facility. Although each project is unique and will require a tailored business case, detailed design and regulatory compliance, this handbook provides a foundation to commence work.

This handbook provides a concise summary of the most important factors to consider in a NEH project, including key messages at the beginning of each section. For more in-depth analysis, a list of references has been provided at the end, directing readers to additional resources.

Note that the handbook was produced in 2025 and is not intended to be kept updated over time.

Key messages are provided at the start of each chapter. The detail which justifies these messages is then contained within the chapter. In addition, a checklist is provided at the end of the handbook. This checklist focuses on elements of a project specific to NEH, it is intended to be a tool a project developer could use to ensure they have addressed key considerations specific to a NEH project.

The handbook is structured into four broad sections:

- First, a general introduction is provided to define NEH, its history and current status, as well as the benefits of NEH.
- Then information is provided on the design of a system. A high-level concept is provided, before more detailed engineering is presented, using a 24MW project as an illustrative example.
- After the design, an overview of the regulatory considerations is provided, with specific attention on how to demonstrate the nuclear safety case and the impact on the nuclear site licence.
- Finally, the handbook provides information on other topics, ranging from schedule, economics, commercial analysis, and how to scale up from the 24MW example.

This flow is illustrated in the diagram below. Whilst the handbook is intended to be approachable for a more general audience, some subsections do go into a bit more detail to provide helpful information for practitioners. Depending on their areas of specialisms, some readers may find this detail unhelpful or distracting. In such cases, it is generally possible to skip ahead to the next subsection and still understand the information, as the handbook has not been written with the expectation all readers will read it cover-to-cover. However, it is particularly helpful to read Chapter 3 (3. OVERVIEW OF PLANT DESIGN CONCEPT) prior to reading any later chapters.

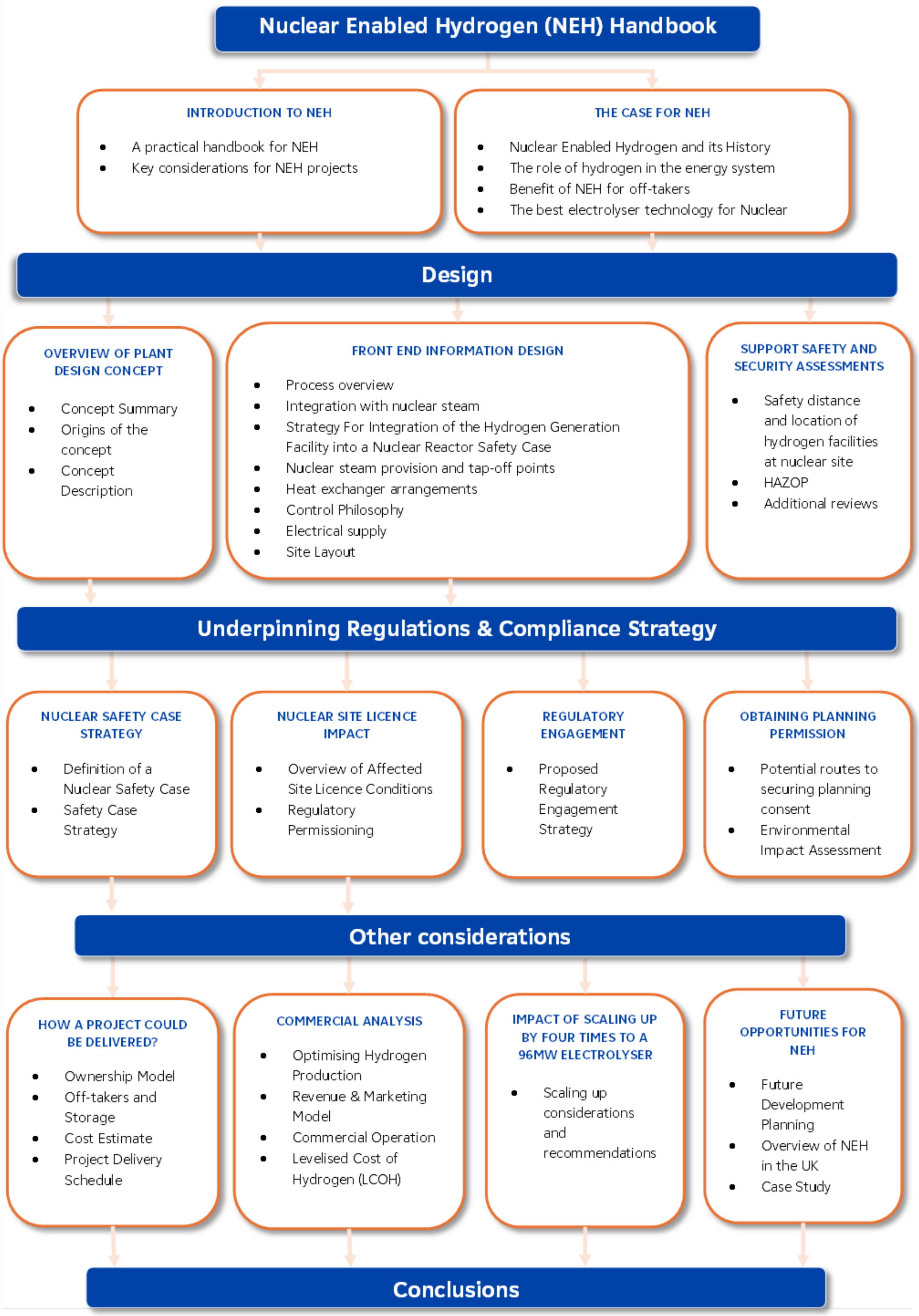


Figure 1 Nuclear Enabled Hydrogen Handbook content.

2. THE CASE FOR NUCLEAR ENABLED HYDROGEN

Key messages

- There is a history of small electrolysers located on nuclear stations to provide hydrogen used for generator cooling.
- Hydrogen considered one of the key decarbonisation solutions, especially in hard-to-electrify sectors (heavy industry, long-haul transport and high temperature processes).
- Providing nuclear power and heat for hydrogen production has several benefits: low carbon, large-scale production, high-utilisation, consistent and stable source of electricity and heat.
- Hydrogen can be produced via various methods, including water electrolysis using PEM, Alkaline, or SOEC electrolysers. Using nuclear energy, SOEC can produce c.20-30% more hydrogen with the same overall energy input, than PEM/alkaline electrolysis.
- Providing heat reduces the amount of electricity required for electrolysis improving overall efficiencies to provide hydrogen at a competitive price.

Nuclear Enabled Hydrogen and its history

NEH refers to hydrogen produced using nuclear energy, leveraging the unique capabilities of nuclear technology to generate low carbon hydrogen. This can be achieved through high temperature water electrolysis, where nuclear-generated electricity is used to split water into hydrogen and oxygen.

There is international precedence for powering electrolysis with electricity derived from nuclear, including here in the UK. Historically, both Heysham 2 and Torness Advanced Gas Reactors (AGR) NPSs installed small scale low-temperature electrolysers on site to provide hydrogen for generator cooling. Today, hydrogen is delivered to site and stored for use when needed. In Sweden low-temperature electrolysers have been used to produce hydrogen using electricity from two NPSs (Oskarshamn and Ringhals) since 1992 and 1997 respectively. Recently, several small-scale international projects have been exploring hydrogen production using electricity from existing NPSs. These projects aim to build on the success of historical electrolyser plants at nuclear sites, demonstrating that this method is both technically feasible and, to some extent, economically viable.

Currently, 12 major nuclear hydrogen projects are underway across the USA, Sweden, Finland, China, Russia, Canada, Japan, and Korea. These projects are shown in Figure 3 below,:: green indicates those already producing hydrogen, while orange represents those still under development. Most nuclear hydrogen initiatives worldwide, except for the two Swedish plants, remain in early demonstration phases. Among them, only the Nine Mile Point project in the USA has begun hydrogen production beyond the experimental stage. However, several projects are in detailed planning as shown in Figure 3, including Davis-Besse NPS and Prairie Island NPS in the US[2], Bruce NPS in Ontario Canada[3], Japan Atomic Energy (JAEA) at the High temperature test reactor site[4], Hanul NPS in Korea[5] and the Loviisa NPS in Finland[6].

Most of the advanced projects that have chosen electrolysis technology are opting for Low-Temperature Electrolysers (LTEs). This represents eight of the currently twelve active projects. Of these, six use PEM electrolysers, while the Oskarshamn plant employs an alkaline LTE. The type of LTE at Ringhals is unclear. Russia is the only country using an Anion Exchange Membrane (AEM)

---

[2] Nuclear Power Plants Gearing Up for Clean Hydrogen Production | Department of Energy
[3] Bruce Power supports study exploring potential to produce hydrogen through nuclear - Bruce Power
[4] Japan Eyes World First Hydrogen Production Using Nuclear Reactor
[5] Korea's first demonstration of hydrogen production using nuclear power 'start' < Nuclear < Energy < Article Text - Electric News
[6] Fortum to pilot hydrogen production in Loviisa | Fortum

electrolyser at the Kola site, and only one project has deployed SOECs beyond an experimental level at Prairie Island in the US, due to commence operaiton in 2025.. There are also plans to implement SOEC technology in Korea and China, where experimental tests have taken place.[7]

Several other countries, including Brazil, Argentina, the United Arab Emirates (UAE), France, Indonesia, Poland, and Turkey, are exploring nuclear hydrogen production, though their initiatives remain in early development. Additionally, some nations, such as Hungary and Czechia, have expressed interest in NEH and have incorporated it into national policies. See Reference 1 (History of Nuclear Enabled Hydrogen) for additional information.

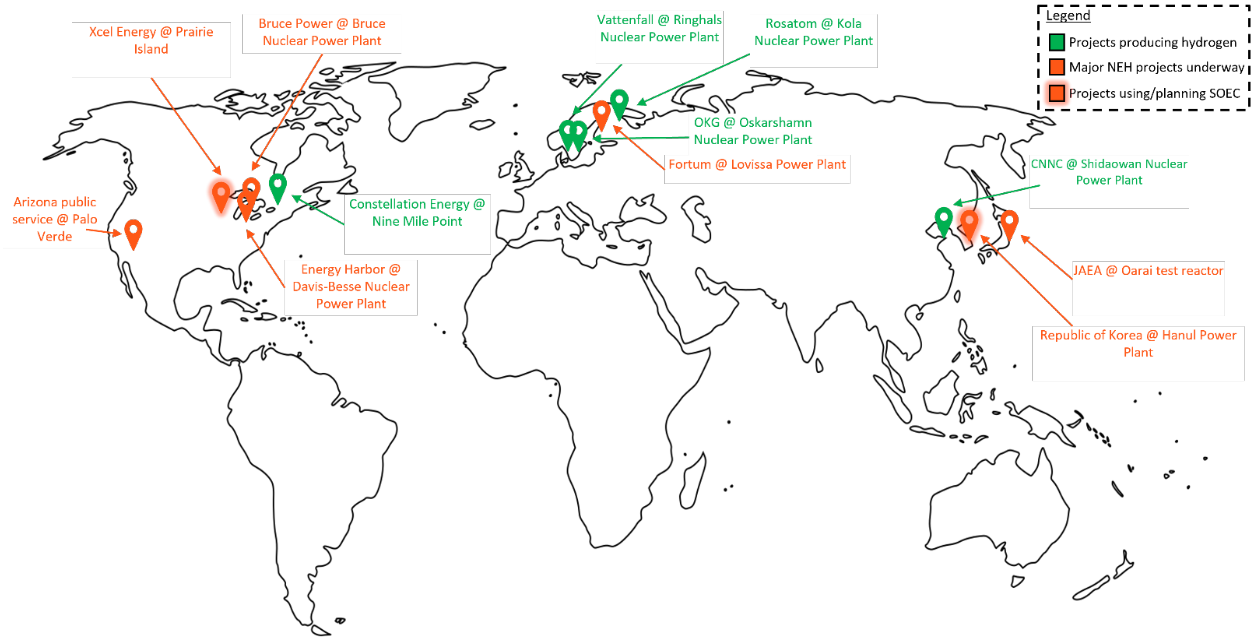


Figure 2 Graphic of world map with locations of NEH projects marked. Projects where SOEC technology is planned or used have a glow effect to highlight.

The role of hydrogen in the energy system

Hydrogen, a versatile energy vector, is recognised as a key solution in decarbonising sectors which are hard to electrify. Its unique properties – such as high specific energy and the ability to produce high combustion temperatures (flame temperature in air up to 2,127°C[8]) – make it a very attractive option to decarbonise certain energy-intensive industries currently reliant on fossil fuels.

Today, hydrogen plays a crucial role in several industrial processes –It is used extensively in crude oil refining for desulphurisation and hydrocracking, essential in producing low-sulphur fuels. However, as the world moves towards net-zero, the demand for hydrogen in oil refining is expected to decline. Despite this, hydrogen's role in chemical industries remains vital. This industry is essential for producing fertilisers (where ammonia synthesis through the Haber-Bosch process is fundamental), polymers, and other materials required for modern life.

[8] Thermodynamics glossary – Adiabatic Flame Temperature, University of Princeton

In the future, hydrogen is expected to play a much broader role in decarbonising the global energy system. In the UK, currently between 10 and 27TWh of hydrogen in produced annually[9], production could reach up to 393TWh per annum by 2050 (according to UK National Grid Electricity System Operator's (ESO's) Future Energy Scenarios Hydrogen Evolution scenario - shown in Figure 3 – although it is recognised this scenario has the largest hydrogen demand). Hydrogen and hydrogen-based fuels could be very useful in areas that are difficult to electrify, such as heavy industry, long-distance transport (i.e., aviation and shipping), and high temperature industrial processes.

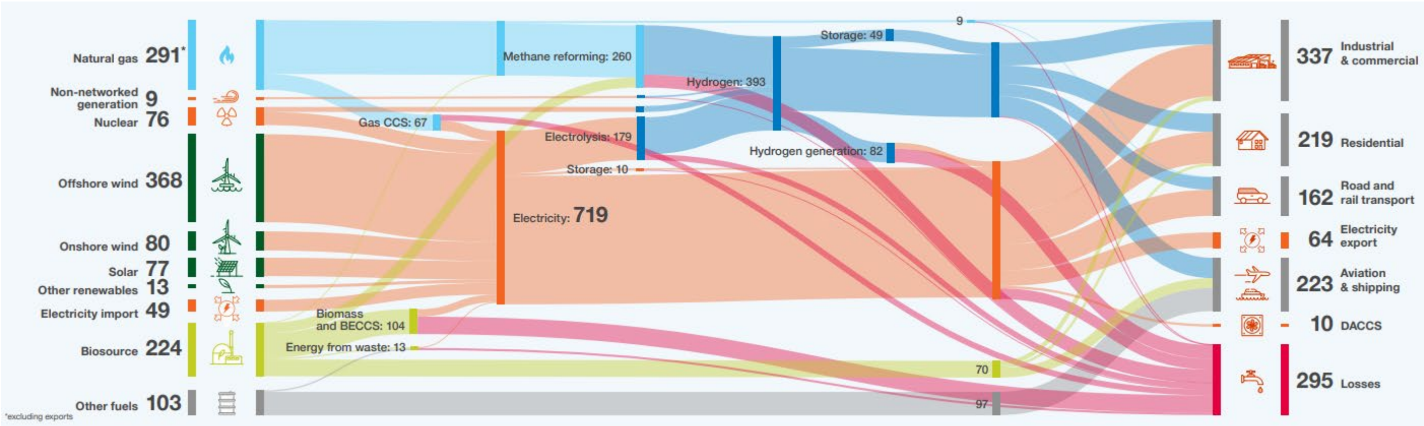


Figure 3 Hydrogen Evolution scenario - energy supply and demand in 2050, Future Energy Scenarios. Total energy supply: 1292 ***TWh****.*

Moreover, hydrogen can help enhance the resilience and flexibility of the energy system. Its role as an energy carrier and its ability to store energy (e.g. produced by renewable sources) for long periods could make it a key enabler for integrating large volumes of renewables like wind and solar into the electricity system. Hydrogen can also support nuclear power generation by absorbing excess electricity and heat (especially through heat-assisted electrolysis) during periods of low electricity demand or surplus renewable output, converting it into a storable fuel, thereby increasing flexibility. The 2024 edition of National Grid's annually published Future Energy Scenarios presented several strategic, whole energy system pathway projections for the United Kingdom to reach net zero by or before 2050[10]. Both in the Electric Engagement and Hydrogen Evolution scenarios, nuclear electrolysis plays an important role in decarbonisation. The projected hydrogen production range from nuclear electrolysis is between 8-25TWh p.a. as shown in Figure 4.

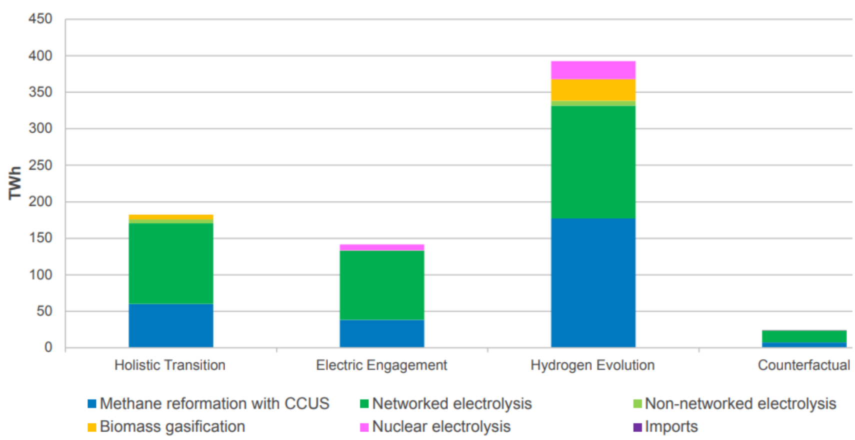


Figure 4 Hydrogen supply by technology in 2050, Future Energy Scenarios[11]*.*

[9] UK Hydrogen Strategy

[10] *Future Energy Scenarios – ESO Pathways to Net Zero, July 2024.*

[11] ***Holistic Transition*** *(HT): net zero achieved mainly through a mix of electrification and hydrogen;* ***Electric Engagement*** *(EE): net zero met by electrified demand + active consumers using smart technologies;* ***Hydrogen Evolution*** *(HE): Robust hydrogen economy, with hydrogen playing major role in industry and heat, lower consumer engagement. High hydrogen in HGVs;* ***Counterfactual*** *(CT): net zero missed with continued reliance on fossil fuels*

Benefits of Nuclear Enabled Hydrogen

Coupling nuclear energy with hydrogen production offers several advantages:

- **Low carbon emissions**: utilising nuclear energy in hydrogen production results in minimal greenhouse gas (GHG) emissions (well below the low carbon hydrogen standard threshold in the UK, 20gCO_2e/MJ LHV (Lower Heating Value)). This makes it a good alternative to fossil-fuel based hydrogen production methods and equivalent in full life cycle emissions to electrolytic hydrogen produced from renewable power such as wind energy.
- **Cost effectiveness**: Co-locating hydrogen production with nuclear enables the option to access a private wire electrical connection, and/or to use heat to improve the efficiency of hydrogen production. This can lead to lower costs per unit of hydrogen produced.
- **Low risk**: All technologies required to produce NEH are proven (however, SOEC is yet to be deployed at scale).
- **High electrolyser utilisation**: Nuclear plants operate continuously at high capacity, providing a stable and reliable supply of energy, which is crucial for maintaining high utilisation rates of electrolysers, and ensuring customers have a reliable supply of hydrogen.
- **Large-scale hydrogen production**: The combination of stable energy supply, high utilisation rates of electrolysers, and cost-effectiveness position nuclear energy as a promising option for large-scale hydrogen production. Nuclear reactors can produce the required energy at a large scale.
- **Existing infrastructure:** Nuclear sites already have grid connections for both export and off-take of electricity, as well as a supply of water (towns and demineralised). They also tend to have good road (and sometimes rail) connections, and some are located close to industrial off-takers.
- **Skilled staff**: A NPS requires technically skilled and safety conscious staff, some of whom also have an oil & gas industry background. As hydrogen is already used within the sites, there are some transferable skills both within the NPS site staff and the supply chain.
- **Integration with industry**: Co-locating nuclear energy and hydrogen production with industries can help optimise logistics. It enables a reduction in transportation costs while providing a steady supply of low carbon fuel for energy intensive industries. Some sites, such as Hartlepool, are located near industrial clusters, where there are already plans to develop a hydrogen pipeline system.

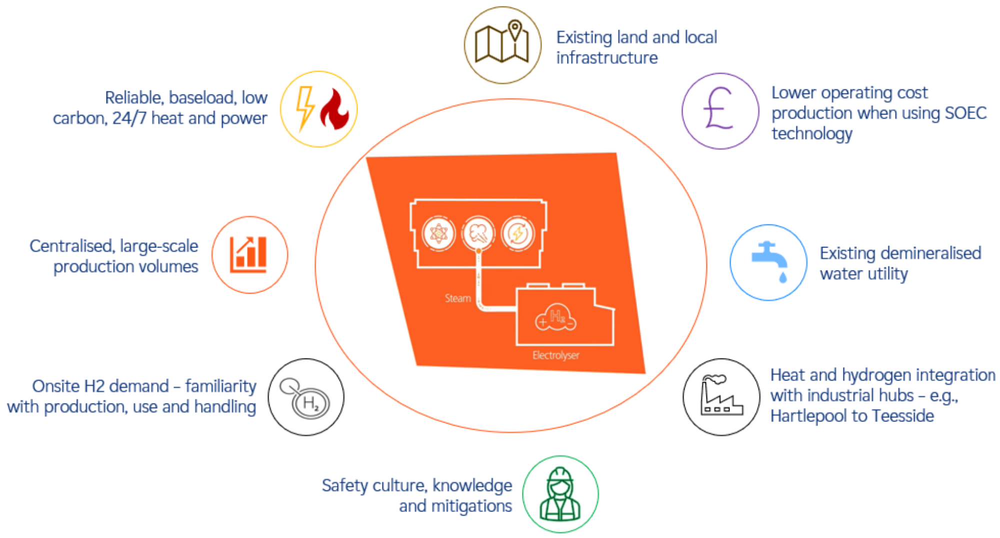


Figure 5 Benefits of hydrogen production integrated with nuclear power.

The best electrolyser technology for nuclear

There are three main types of electrolysers, two technologies operate at low temperature: PEM and alkaline electrolysers (AEL), and one operates at high temperatures based on steam electrolysis (High Temperature Electrolysis - HTE). For PEM and AEL, a NPS can provide the low carbon electricity to produce hydrogen on-site or off-site which is then stored and distributed. For HTE, nuclear reactors can supply both the electricity and heat required for the process, significantly enhancing hydrogen production efficiency compared to traditional electrolytic methods.

The electrical efficiency of water electrolysis improves as reaction temperature increases (with a corresponding increase in heat required). At a temperature of c.700 °C, the cell electrical consumption is 20 percentage points less than conventional electrolysis at lower temperatures (c.<100 °C), with a correspondingly lower thermoneutral voltage. Heat input is required to convert the inlet water to steam and raise the steam temperature to the cell operating temperature. The key hurdle to overcome is the latent heat of water vaporisation. As such, any plant that can provide steam c.>150 °C can benefit from HTE technology, available from all current and future nuclear reactor designs. Further temperature increases can be achieved by heat recovery from the hydrogen and air/oxygen cell outlet streams and a small electrical heating input (c.1-2% of total energy demand) to reach the cell operating temperature.

To achieve high-temperature electrolysis, SOECs based on low-cost ceramic materials are utilised. Currently available SOEC technologies generate hydrogen at near atmospheric pressure, below the 20-30bar outlet pressures of PEM and AEL. If an off-taker requires pressures ≥30bar, then a single stage of compression is required to compare SOEC with PEM and AEL. Figure 6 below shows an indicative equivalent electrical efficiency comparison of PEM and SOEC, demonstrating that even with 30bar compression, SOEC produces >20% more hydrogen for the same equivalent energy input.

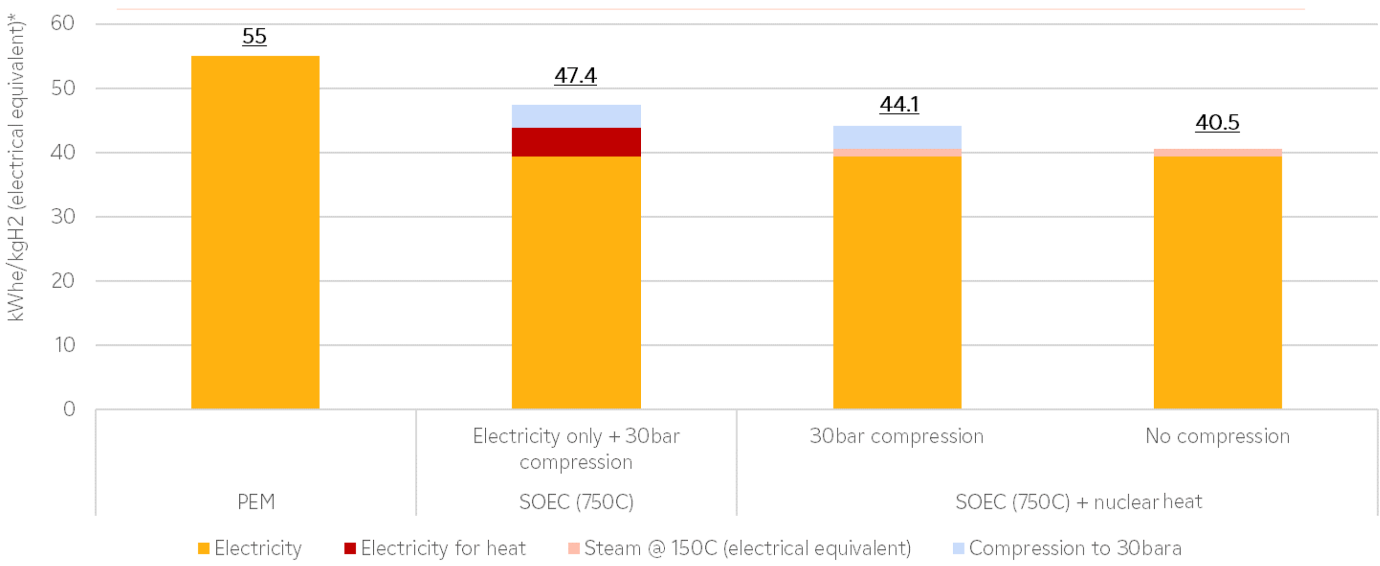


Figure 6 Energy required to produce 1kg of hydrogen via PEM and SOEC technology under different input conditions (electrical and thermal). Indicative numbers based on average performance.

As of 2023, the International Energy Agency defines SOEC as in commercialisation, at a technology readiness level (TRL) of 8[12]. Further development offers the future possibility of:

- Pressurised outlet, reducing reliance on external compression
- Reversible operation: either producing hydrogen (electrolysis) or electricity (fuel cell) using the same cell and stack architecture
- Co-electrolysis of steam and CO_2 to produce a syngas for downstream fuel or chemical production

See Reference 3 (Details about Solid Oxide Electrolysers) for additional information.

[12] *International Energy Agency, ETP Clean Energy Technology Guide – Data Tools - IEA*

3. OVERVIEW OF PLANT DESIGN CONCEPT

Key messages

- The concept is site and nuclear technology agnostic and assumes that both electricity and heat from a nuclear power plant provide the energy inputs to the SOEC.
- It is preferred to site the NEH facility outside of the nuclear site fence, and outside the nuclear site licence boundary, particularly for a commercial scale plant.
- To minimise risk to nuclear safety, a separation distance is included between the NPS and the NEH Facility.
- A heat exchanger is placed within the NPS, to keep steam from the reactor secondary circuit within the NPS. Steam or water is the recommended heat transfer fluid, to reduce cost and complexity.
- A broad range of offtakers has been included, to show the flexibility of NEH. This increases costs due to additional equipment requirements, so projects can be further optimised around specific offtakers.
- Whilst a 24MW example is used to illustrate the concept, NEH can be scaled up to larger sizes.

Concept Summary – How to integrate solid oxide electrolysis and nuclear

In Chapter 2, it has been examined how nuclear energy can unlock greater cost efficiencies, and how SOEC is a complementary technology. This concept explores the practicalities of how these technologies can be integrated for commercial use.

The plant concept described in this handbook is representative of how a first-of-a-kind (FOAK) commercial scale high SOEC plant could be coupled to a NPS. It incorporates insights from the Bay Hydrogen Hub feasibility study and FEED at Heysham 2 power station. Given its objective to provide a realistic foundation for developing a new NEH project, the concept considers the full value chain and integrates requirements from potential off-takers. The HTE technology selected is SOEC because of its high efficiency, and its ability to use heat from an NPS to further increase electrolyser efficiency with the objective of keeping the production cost of hydrogen down.

The concept is not based on a particular nuclear technology or a specific site location. However, the steam supply conditions adopted for the provision of heat, and the electrical supplies, are consistent with those currently available at a UK NPS. These conditions are described in more detail in Chapter 4 (4. FRONT-END-ENGINEERING-DESIGN).

The plant size of 24MW was selected to meet the hydrogen off-take requirements of a range of potential off-takers including a direct pipeline supply to a cement plant, offsite trailer deliveries of hydrogen to 2 asphalt plants and NPSs for generator cooling and provision of high purity hydrogen supplies for transport purposes. However, 24MW is just intended to be an illustrative example, and the same principles could be used for smaller or larger plants. Chapter 12 describes in more detail additional considerations for larger sizes.

The concept also includes the use of hydrogen for a peaking power plant and includes the capability to provide hydrogen into a gas pipeline network. The range of potential off-takers is deliberately broad, however is still consistent with opportunities available within the UK. The breadth of off-takers illustrates the flexibility in how NEH can be used, and enables the commercial analysis in Chapter 11 (11. COMMERCIAL ANALYSIS) to provide more insightful results.

Origins of the concept

Hydrogen is typically used on a NPS for generator cooling and chemistry purposes. Later Advanced Gas Cooledf NPSs in the UK were built with their own hydrogen production plants employing electrolysers. This was to ensure the stations were self-sufficient in hydrogen. Today, these plants have been shut down because of their age and high maintenance costs and have been replaced with tanker supplies of hydrogen.

Following an initial safety assessment, it was determined that the greatest nuclear safety concerns were the storage of large volumes of high-pressure hydrogen. Whilst it was believed that these risks could be mitigated for a smaller plant, it was concluded that it would be more appropriate to site a larger commercial scale hydrogen plant further from nuclear plant. As nuclear sites are usually compact, this would require siting the storage outside the NPS.

For some sites, the nuclear site licence area extends beyond the main nuclear site security fence. Therefore, the storage could potentially be sited within the nuclear site licence area, or outside it. It was decided that the storage should be sited outside the nuclear site licence area, as this simplifies the regulatory arrangements. This benefit could also be achieved for the hydrogen production facility (i.e. the electrolysers and associated balance of plant). Therefore, it was decided the hydrogen production facility should also be sited outside the nuclear site licence area. However, because the greater nuclear safety risk was with the storage rather than the production (due to the higher volumes and pressure), that provides the potential for the hydrogen production facility to be located closer to the NPS than the storage. This leads to the concept shown below.

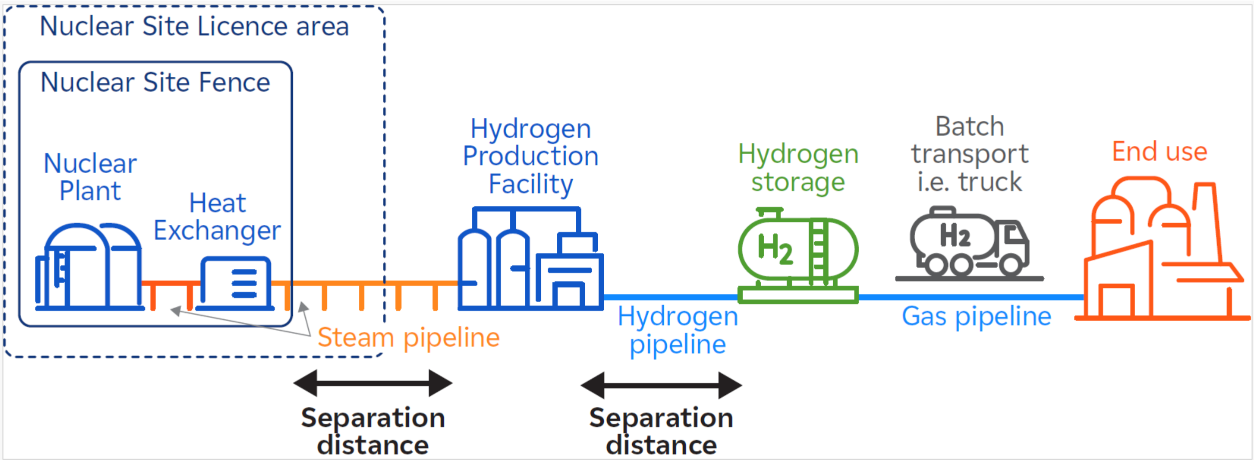


Figure 7 Potential design strategy to reduce risk from NEH Facility to reactor and nuclear island.

Concept description

Key elements of the concept are described below.

Nuclear Plant

Most reactor designs could be used. For this concept, the nuclear plant is assumed to produce electricity, and to have a tap-off for steam from the NPS secondary steam circuit.

Heat Exchanger

Instead of sending the NPS secondary steam off-site, a heat exchanger is used to ensure it remains always within the NPS. This keeps the NPS secondary steam and within the control of the NPS (e.g. so it could not be contaminated from outside the site). The heat exchanger also provides a barrier to contamination leaving the site, such as from trace amounts of tritium within the steam. The NPS will have isolation valves it can use to shut off the heat supply off-site when needed, to ensure the NPS retains full control over everything within the nuclear site. Chapter 4 (4. FRONT-END-ENGINEERING-DESIGN) describes the heat exchanger in more detail.

Nuclear Site Fence

The fence is a key security measure for the site. The heat exchanger is placed within the fence to ensure it, and associated equipment (such as valves) remains secure. The output pipe for the heat exchanger will however need to go past the fence. Therefore, a trench will need to be dug under the fence for the pipe, as it is unlikely to be acceptable from a security perspective for the pipe to go over the fence. As this involves an interface with the site fence, this activity requires its own security assessment (in addition to a more general security assessment of the impacts of the NEH Facility, as described in Chapter 5 (5. SUPPORTING SAFETY AND SECURITY ASSESSMENTS).

Steam Pipeline

In principle, there are lots of heat transfer fluids that could be used. Consideration was given to using both heat transfer oil and water/steam for the secondary side of the heat exchanger. Commercially, water/steam was cheaper except for very short distances (e.g. a few metres). Technically, oil had minimal benefits, as water/steam had acceptable material properties, lower consequences in the event of a leak, and is generally a well understood fluid on nuclear sites. Therefore, it was determined that water/steam was the better option.

Hydrogen Production Facility

This includes the majority of the NEH facility equipment, everything excluding the bulk storage and high-pressure compression. As the hydrogen produced by the electrolysers is close to atmospheric, an intermediate pressure compression system is included, to raise the hydrogen to approximately 30 bar. This pressure enables the hydrogen to either be sent directly to an end user (e.g. via a pipeline), or to be sent for further compression and storage.

Hydrogen Storage

This includes high pressure compression and bulk storage. The quantity of storage would be determined by specific off-takers. The storage presents the greatest potential nuclear safety risk, as the higher pressures and volumes of hydrogen could lead to a more significant worst-case scenario (even if it is unlikely). Therefore, the minimum distance the storage can be sited from the NPS is further than for the production equipment. How far away would be dependent on the specific location and project which would need to assess factors including:

- Volume and pressure of hydrogen stored
- Employment of physical or geological barriers between hydrogen storage and the NPS
- Hydrogen Tanker movements
- Land availability

Batch Transport and Gas Pipeline

A filling station would need to be sited for the trailers. As with hydrogen storage, higher pressures are used, so the filling station is likely to be sited further from the NPS than the hydrogen production. However, if possible, a pipeline is preferred, as it would lower the distribution costs. This pipeline could be direct to a specific end user, or part of a local or national network.

End Users

A variety of end users could be supplied with NEH. However, the different end users will have different quality requirements for their hydrogen, which influences cost.

Figure 32 (can be found in the SUPPORTING FIGURES) shows the 24MW concept in more detail, in particular how the requirements of different end users are met. A commercial project is likely to want to focus on a smaller number of end users than shown here, to reduce the upfront CAPEX required.

4. FRONT-END-ENGINEERING-DESIGN

Key messages

- FEED has shown that SOEC and its supporting systems can be integrated with heat and power supplies from a nuclear reactor.
- Steam to the Nuclear Steam Exchanger Plant can be bled off at a suitable quality from the nuclear plant. Steam from the NPS does not leave site, and heat is transferred off site (across the nuclear site boundary) through a heat exchanger ensuring that the interaction between NPS and NEH facility is minimised.
  A process flow diagram can be found in this chapter.
- The design assumes an 11kV supply for the hydrogen generation site. The transformer is a major cost factor. Increasing plant size and load will increase costs and lead times, with grid transformers having a lead time of multiple years.
- There must be isolation points between the reactor systems and NEH Facility, so that the equipment on the NPS can be fully isolated from the NEH Facility.
- One of the key factors in determining the layout for a NEH plant is the safe distance of nuclear critical plant (calculating by consequence modelling). Additional mitigations could be used to reduce the separation distance, such as raised land barriers, blast walls, or the use of hydrogen storage technologies with lower pressures (e.g. metal hydrides, such as depleted uranium).
  An example of site layout for the 24 MW hydrogen production facility is shown in this chapter.

A FEED is crucial for transitioning a concept into the design phase. The following sections will explore various options to determine the most effective process layout and components configuration, and will provide a comprehensive exploration of these options, ensuring that the design is optimised for functionality and efficiency.

The work completed in the feasibility study and engagement with technology providers has confirmed SOEC electrolyser technology as a good fit with nuclear energy. This is due to the inherent higher process efficiency of the technology and the additional benefit of taking a heat off-take from the plant. This provides an overall efficiency benefit of 20-30% which brings down the cost of hydrogen production significantly when compared with the low temperature electrolyser technologies such as PEM and Alkaline[13].

The FEED study work completed in this phase of the Bay Hydrogen Hub project has highlighted that a small 1MW demonstration plant could potentially be accommodated within a nuclear licenced boundary, it does present some challenges particularly around the hydrogen risk and traffic movements of large volumes of high pressure compressed hydrogen. For a commercial scale it is clear that building the plant outside of the nuclear licenced boundaries in many respects is more straight forward although it does introduce a heat exchanger inside the licenced area with a pipeline conveying heat in the form of steam to the electrolyser along with an electrical supply.

[13] The Levelised Cost of Hydrogen (LCOH) produced via SOEC has been calculated and compared to other electrolytic methods during the feasibility study of the Bay Hydrogen Hub project. It has been concluded that at scale, in 2030s hydrogen cost produced via SOEC could be lower or at a similar level to PEM and alkaline electrolysers. This is further supported in the literature, e.g. Comparative optimization study of three novel integrated hydrogen production systems with SOEC, PEM, and alkaline electrolyser. Nejadian et al.(2023)

Because hydrogen production in the current generations of SOEC electrolysers occurs at low pressure, just above ambient, the electrolyser itself can be built close to the nuclear station with high pressure compression and volume hydrogen storage further away depending on pressures and storage volumes. This section considers the front-end design considerations for such a plant.

Process overview

The concept process considered for the FEED took waste heat from the secondary circuit of a nuclear reactor and used solid oxide electrolysers to generate hydrogen. The process was split into the following sub systems:

- The nuclear power plant steam supply system – this supplies the waste heat to the intermediate loop via a heat exchanger.
- The intermediate heating loop – transfers the heat from the nuclear steam supply system to the electrolyser feed system using a pump and heat exchangers.
- The electrolysers – split the steam into the hydrogen product and oxygen waste streams using solid oxide electrolysis.
- Hydrogen purification – steps to dry, compress and cool the low-pressure hydrogen from the electrolyser ready for purification, high-pressure bulk storage and distribution.
- Hydrogen storage and distribution – equipment for storage of the high-pressure hydrogen and for transferring the hydrogen to pipework or vehicle trailers for transportation to the end user.

The electrolyser plant includes:

1. Power conditioning equipment including transformers and rectifiers;
2. Water treatment system(s);
3. Heat exchanger/steam boiler(s) for providing heat to the water/steam fed to the electrolyser;
4. Electrolyser package which houses the solid oxide stack(s);
5. Electrolyser hydrogen vents and electrolyser exhausts;
6. Electrolyser heat exchange equipment, such as heat exchangers, fin fan coolers and external chiller units;
7. Hydrogen purification system(s) including medium pressure compression, drying, pressure swing absorption and high-pressure compression;
8. Hydrogen storage system(s);
9. Hydrogen off-take (including pressure reduction, metering, odorisation and export pipelines);
10. Nitrogen system (for purging and compressor seal system); and
11. Mains water and sewerage connections (pipeline connections and break tanks).

The main process steps are as follows:

1. The electrical balance of plant (EBOP) package converts Alternating Current (AC) input power to Direct Current (DC) power for supply to the electrolyser package.
2. An inlet water supply feeds the water treatment system, in turn delivering low conductivity water to the mechanical balance of plant (MBOP) package, which preheats the water using waste heat from the stacks.
3. The preheated water is fed to a process steam boiler which converts the water to steam using heat (steam) from the NPS. If steam from the NPS is unavailable an electric boiler is used to raise the necessary steam.
4. The steam is fed back to the MBOP and then to the SOEC, which produces a hydrogen-rich stream and oxygen-rich exhaust.
5. Excess water is removed from the hydrogen stream by cooling it, after which it exits the electrolyser package.
6. The hydrogen is compressed from atmospheric pressure to a medium pressure (MP) level, where it is dried to a dew point of -10 °C.
7. Further processing by purification and compression is carried out according to the requirements of each off-taker (see chapter 10 (10. HOW A PROJECT COULD BE DELIVERED), off takers and storage).

8. The hydrogen can be stored before being dispatched. The amount of hydrogen storage required is based on the optimum size as calculated using the estimated hydrogen demand profiles (see chapter 10, off takers and storage).

A simplified version of the process is provided in the block flow diagram below.

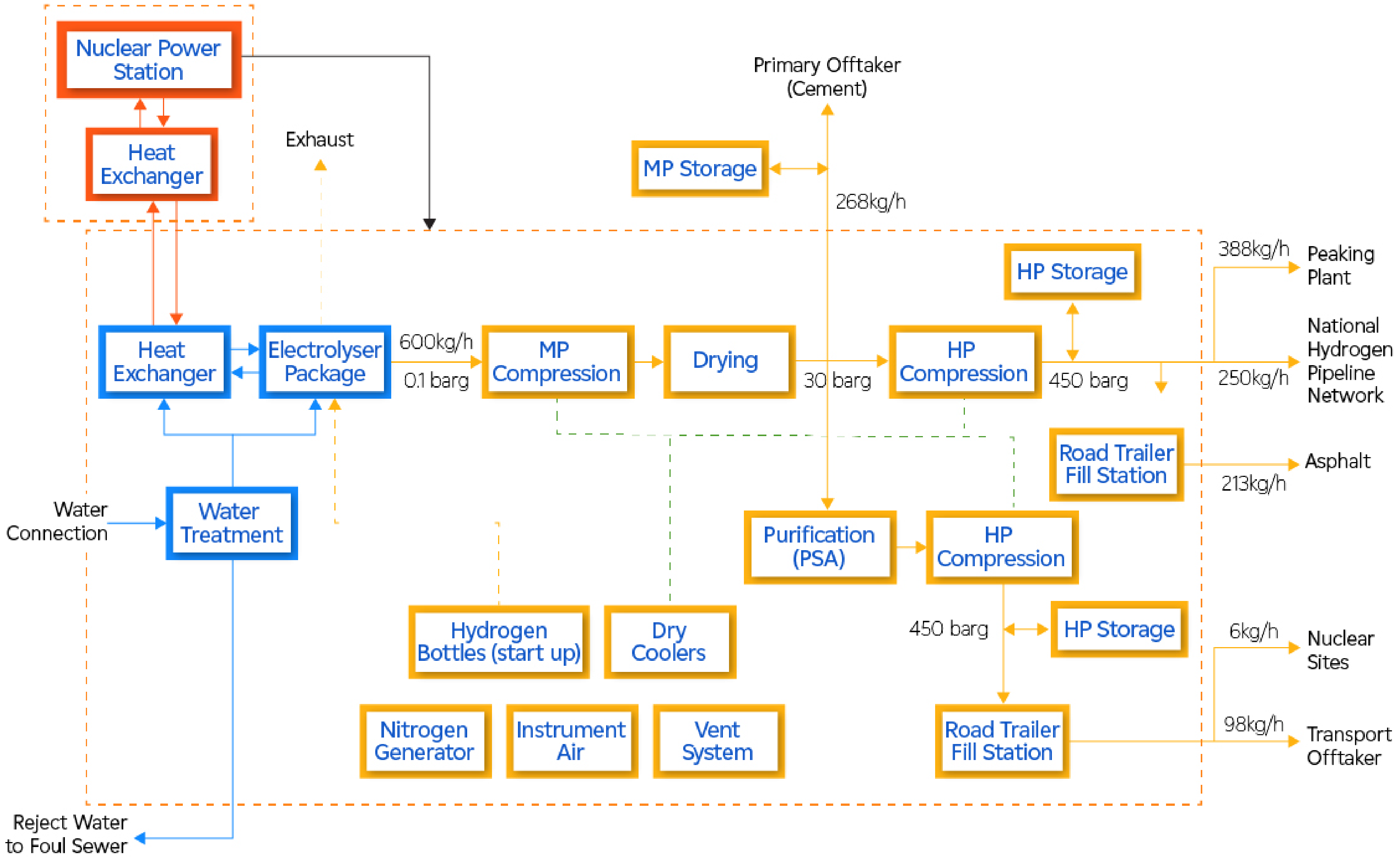


Figure 8 Block Flow Diagram of the proposed Nuclear Enabled Hydrogen facility concept.

Integration with nuclear steam

Heat from the nuclear steam will be supplied from the NPS (e.g. Turbine Steam Cycle) to the SOEC using a separate closed intermediate heat transfer circuit so that the reactor steam is kept within the reactor site boundary and not directly connected to the electrolyser feed water.

The intermediate circuit incorporates a pump, the Nuclear Steam Heat Exchanger, and the SOEC External Heat Steam Boiler Steam to the Nuclear Steam Heat Exchanger Plant will be bled off from a suitable location in the secondary steam circuit of the NPS to provide a low carbon source of process heat.

The Nuclear Steam Heat Exchanger is installed on the reactor site and takes the steam from the reactor's secondary circuit and transfers the heat into an intermediate circuit before returning the condensate back to turbine steam cycle. Whilst this would reduce the electrical output of the site, overall energy efficiency is improved, as the losses of converting heat to electricity are not incurred.

The heat from the Nuclear Steam Heat Exchanger is transferred into the water in the intermediate circuit pipework which pumps the high temperature water through the site boundary to the SOEC External Heat Steam Boiler. The heat is transferred into the electrolyser feed water from the intermediate circuit by the SOEC External Heat Steam Boiler. The water is then returned to the Nuclear Steam Heat Exchanger to be reheated and pumped back round the intermediate circuit. Heat losses within the intermediate loop (Reference 12 - Heat Loss Calculations) were calculated to be negligible. For example, for temperatures to drop by 1 °C an intermediate loop length of ~800m would be required.

The process heat is used to convert the feedwater for the electrolyser and produce high quality steam and increase process efficiency. If there is no steam supply available (or process heat), the SOEC unit can use Primary Electrical Steam Boiler for this process.

Hydrogen is produced at low pressure within the electrolyser. To allow for the product to be transported (or stored for transportation), compression stages will be required. The details on compression stages will be determined through the detail design process.

An example of ground layout for the 24 MW hydrogen production facility is shown in Figure 25 (SUPPORTING FIGURES). The key features of this facility will include:

- 6 x 4 MW electrolyser blocs, each including 4 SOEC electrolysers, 1 MBOP and 1 EBOP units, these will be supplied by the SOEC supplier
- The rectifiers, low voltage power and controls are contained with the EBOP containerised units
- Process air and heat recovery are contained within the MBOP containerised units
- One water treatment plant provides the demineralised water supply required for the facility
- One primary electric steam boiler and one external heat steam boiler are used to provide the saturated steam at 3-4bar(g) (121 °C – 152 °C) to the superheater unit; the primary electric steam boiler and external heat steam boilers could be combined within the same unit; the external heat steam boiler uses nuclear plant steam
- Hydrogen processing (separation, compression and purification) is done through 2 stages separators and compressors feeding into a dryer/purification unit; this will also include a condensate system
- Plant switchgear is fed through a 11kVsupply from the nuclear site feeding into the low voltage transformer which feeds the low voltage switch gear and control system
- Stacks for purging and venting
- Instrument air system
- Provision for storing bottled nitrogen and hydrogen
- Cooling water system
- Hydrogen is fed into a high-pressure storage vessel or into high pressure trailers for transportation offsite

Strategy for integration of the hydrogen generation facility into a nuclear reactor safety case

The Nuclear Reactor safety case will need updating to include the hydrogen generation facility as a new industrial hazard. The hydrogen generation facility could impact the following aspects of the reactor fault and hazards schedules.

Plant Faults

Plant faults are those faults that originate from failures of the systems, structures and components on the reactor plant systems. Initial investigation suggests that faults such as Spurious Trip, Feed System Faults and Loss of Electrical Supplies will need to be considered. It is recommended that the impact of the hydrogen generation facility on the remaining plant faults is also assessed.

Internal Hazards (Hazards that originate within the Reactor Site Boundary)

Internal hazards are those which originate inside the reactor plant boundary. They include, but are not limited to, Fire and Steam release faults. It is judged that all other internal hazards are likely to be unaffected as the reactor equipment is protected by its location. This will need to be confirmed once the design has matured, and the safety case is developed.

External Hazards (Hazards that originate outside the Reactor Site Boundary)

External hazards cover the impact of external disturbances on the reactor plant. They include seismic events, extreme weather conditions and external man-made hazards e.g., aircraft crash, hazards from industrial facilities. The impact of the hydrogen facility on the reactor site during these hazards will need to be reviewed and confirmed as part of developing the safety case. Faults with the hydrogen facility (in particular hydrogen fire) will need to be assessed to confirm they do not change the "standard" external hazards case.

Further information on the strategy for the development of a safety case is contained in Reference 9 (Nuclear Safety Case Strategy).

Nuclear steam provision and tap-off points

During normal operation the heat is provided from the NPS steam cycle. Steam from the NPS does not leave site, and heat is transferred off site (across the nuclear site boundary) through a heat exchanger. By keeping the steam within the nuclear site boundary, it is ensured that any potential release from site is minimised (e.g., trace amounts of tritium). The designer should consider the provision of an appropriate system to monitor for any radioactivity that may be present in the nuclear steam heat exchanger and could be transferred into the intermediate loop.

Potential tap-off[14] steam conditions shown below (mass flows dependent on SOEC requirement) for three typical NPS designs in the UK.

Table 1 Potential tap-off steam conditions for different reactor types in the UK (LPT: Low Pressure Turbine, IPT: Intermediate Pressure Turbine, HPT: High Pressure Turbine).

Location	Pressure	Temperature	Saturation Temperature	Comment
Sizewell B Power Station (SZB) Post HPT	6.14 bara	159.7 °C	159.7 °C	No superheat – Could use a Gasket Plate Heat Exchanger solution.
SZB Pre LPT (post reheat)	6.14 bara	275.3 °C	159.7 °C	Superheated –could use a Compabloc type (welded heat) exchanger solution.
European Pressurised Reactor (Sizewell C) Pre IPT (post reheat)	11.47 bara	276.6 °C	185.9 °C	Superheated –could use a Compabloc type (welded heat) exchanger solution.

[14] A 'tap-off' point refers to the point at which the steam for the hydrogen facility will be taken for the nuclear steam heat exchanger. At the time of writing, a design has not been established and therefore potential options for 'tap-off' points have been presented throughout the report.

Key considerations when choosing tap-off points

- Practical limitations of access to appropriate tap-off locations
- Energy required at particular temperature
- Impact on electricity generation at the NPS (lost electricity dependent on tapping points)
- Cost and performance of available heat exchangers
- "Future proofing" of the tap-off points design to allow flexibility to integrate with other hydrogen or net zero technologies and industrial decarbonisation (direct heat supply)

When choosing tap-off points it will be necessary to assess the impact of changes in load on the NPS steam system. Operation of the electrolysers will require the ability to function between full capacity, part power, complete shutdown, and back to power to accommodate hydrogen facility operational states. The design for the tap-off points and the supporting steam supply and condensate return system must be able to accommodate these changes without unduly affecting safe reactor operation.

This decision will be a balance of all these factors. Tap-off point locations that have been considered include options with and without superheat[15]. There are pros and cons to steam flow with superheat including:

- Higher grade heat, ensuring future options are kept open for other technology couplings
- Lower steam flow rates and smaller heat exchanger
- Potentially slightly higher electricity loss factor
- Potentially higher cost heat exchanger design: moving from gasket sealed at saturation temperature to welded flanges.

Furthermore, consideration of the temperature at which steam/water is fed back into the NPS (e.g. at the condenser) is required, and superheat could lead to higher temperatures. A further subcooling heat exchanger may be required, similar to the desuperheater system used to control bled steam temperatures during load changes on the existing nuclear steam systems.

Heat exchanger arrangements

The heat transfer arrangement between nuclear steam and heat for the 24MW electrolyser facility will involve two heat exchangers. One heat exchanger within the nuclear site boundary and the other on the hydrogen plant facility. A typical arrangement is shown below.

Use of a compact welded heat exchanger such as conventional welded shell and tube heat exchanger is recommended on the nuclear site. A compact welded exchanger saves space, is easier to install, and designed for quick access, making maintenance simpler. Consultation with manufacturers has identified suitable examples such as the Alfa Laval "Compabloc" as being available. However, this heat exchanger is currently not available for nuclear code requirements and could be a future opportunity.

For this NEH 24MW concept a gasketed plate heat exchanger is considered. This heat exchanger is suitable for operating with saturated steam at around 160 °C.

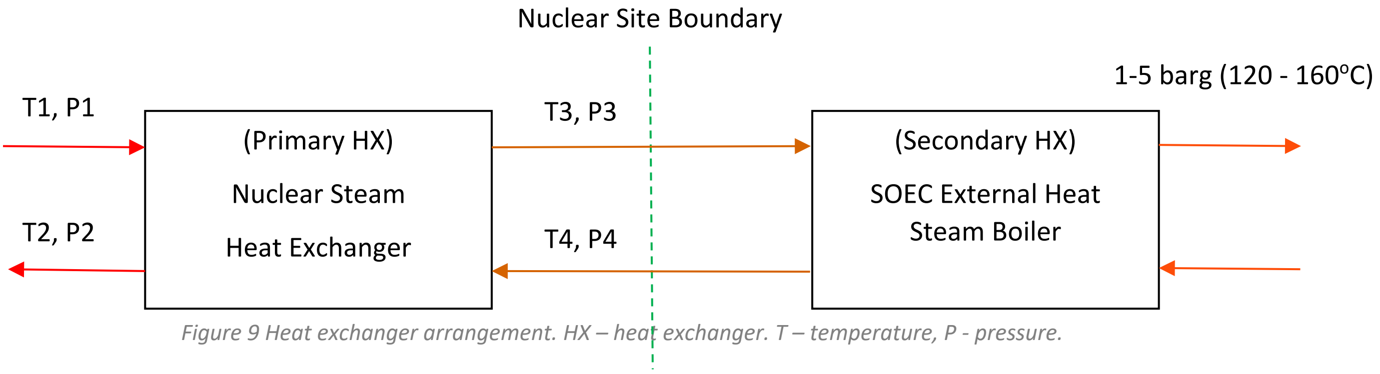


Figure 9 Heat exchanger arrangement. HX – heat exchanger. T – temperature, P - pressure.

---

[15] *Superheat refers here to superheated steam – steam that is at a temperature higher than its saturation temperature.*

Inlet steam conditions (T1, P1) for the primary heat exchanger (within the nuclear site boundary) will depend on the feasible tap-off points within the NPS.

Steam exit conditions (T2,P2) should be optimised though a cost benefit analysis and suitable connection point within the NPS. It is assumed that the outlet from the primary heat exchanger could be returned to the condenser.

Heat from the Primary Heat Exchanger (T3 P3) to SOEC External Heat Steam Boiler (Secondary Heat Exchanger) could be transferred through a heat transfer fluid or water/steam. Feasibility of a suitable intermediate heat transfer fluid should be assessed in accordance with the specific design (separation distance). A high-level optioneering review showed that steam would be a more suitable heat transfer fluid for longer distances (more than 30m) of pipework.

Control philosophy

The electrolyser and its subsystems are complex and cannot be controlled solely by operators. This section describes the high-level principles of a potential control philosophy to operate the Nuclear Steam Supply and Return System, the Intermediate Circuit, and the Electrolyser and its sub systems. Further details can be found in Reference 5 (Approach to Ensuring Nuclear Site License Compliance).

Nuclear Power Plant Steam Supply and Return Loop Control Philosophy

The Nuclear Steam Heat Exchanger will be controlled and maintained by NPS site personnel and will need to have the capability to be fully isolated from the NPS. The heat exchanger and supporting equipment will also interface with non-essential site power and control systems. It is expected that the system will operate independently with no requirement for the NPS reactor desk operator to interact routinely with the system.

There will be no requirements for control from the electrolyser. The intermediate loop and electrolyser control systems will not be connected to the Nuclear Steam Supply and Return Loop. Indication of temperature, pressure and flow will be fed to the intermediate loop and electrolyser control systems. The steam loop will always be under the control and supervision of the reactor operator through local to plant operation by an operator.

The system will be operated continuously at steady state conditions when the reactor and electrolyser are operating. Automatic control will be provided to control the steam conditions and the conditions in the condensate and blow down systems during normal operation. There will be no automatic control for start-up, this will be completed manually according to the plant operating instructions. Shut down of the system will be required during controlled conditions and during emergency conditions. Controlled shutdowns will be completed under manual control. Emergency shutdowns can be either by manual trip or as a response to the control system, the system will need to be designed to fail to a safe state under these conditions. Return from emergency conditions will be controlled by manual actions once the fault has been rectified.

Intermediate Heating Loop Control Philosophy

The intermediate loop will be controlled and maintained by the Electrolyser site personnel. Where the system enters and leaves the nuclear licensed site there will be isolating valves to allow the system to be isolated from the nuclear site.

The intermediate loop will operate continuously providing heat to the electrolyser feed water. The system will have instrumentation for temperature, pressure, flow and fluid level within the system. The instrumentation will be used to manually operate the intermediate circuit according to defined instructions. Manual control is acceptable because it is not directly connected to the reactor secondary circuit or the electrolyser feed. Faults will be revealed by the instrumentation which raise appropriate alarms for the local to plant operator to respond to. For example, if there was steam leak from the reactor system into the intermediate circuit it would be revealed by a pressure increase which, if not recognised by the operator, would be revealed by the high-pressure alarm. There will be no automatic trip, the operator will respond to the alarm to shut the intermediate circuit down.

Operation and Control of the Electrolyser and the Supporting Systems

This section provides a high-level description of the operation and control of a single Solid Oxide Electrolyser system. Where multiple electrolysers are used, the design will need to accommodate the changes where individual electrolysers are taken out of service and returned to operation as individual units.

Individual electrolysers and their supporting systems will be controlled automatically using a Programmable Logic Controller (PLC). For larger facilities the individual PLCs will then feed into a larger distributed control system with a centralised Supervisory Control And Data Acquisition (SCADA) system for the combined plant. Individual electrolysers should be designed to operate autonomously once requested by the operator i.e., start up, operate and shutdown once requested by the operator. The control system will handle fault situations, it will automatically shutdown the plant to protect equipment and prevent unsafe operation. A Human Machine Interface (HMI) will be provided for the whole facility and each electrolyser so the operator can monitor and control the plant and the sub systems as required.

The electrolyser control philosophy will be based around operating modes that cover all potential states. The modes will range from shutdown/disabled through to normal operation/electrolysis, with various intermediate states such as standby/idle and fault conditions. The control system must be able to manage these states and respond to changes as well as keep the operator aware of the health of the system and the faults that might occur. Development of the control philosophy will be an integral part of the design and safety case for the hydrogen generation facility.

There are several sub systems that are essential to the operation of the hydrogen electrolysers that will need to be integrated into the overall control system architecture. How the systems will interact will need to be confirmed during the detailed design of the systems. The key sub systems that will need to interface with the electrolyser are:

- Water treatment system – ensure that there is a supply of water at the correct quality and flow rate to support electrolysis
- Steam boiler system – control the generation of steam from the feedwater to feed the electrolyser
- Hydrogen compression and storage system – the electrolyser will need to monitor the condition of the buffer tank, compressors, and storage to ensure they are ready to accept the hydrogen product
- Electrical systems and back-up power – the control system will need to react to faults on the electrical systems and use back up power sources where necessary

The overall control system architecture will also need to consider control during emergency conditions both on the electrolyser and the sub systems to ensure that fault conditions are appropriately responded to. The key emergency conditions that will need to be incorporated into the overall control scheme are:

- Hydrogen gas detected by the gas analysers
- Heat/fire detected
- Fire suppression system activated
- Safety Relief Valves lifting
- Emergency stop button signals

The design of the electrolyser systems is not sufficiently detailed to identify all of the potential emergency conditions and the exact nature of these control signals. Despite this it is evident that the electrolyser and its sub systems will be required to immediately trip and shutdown under these circumstances. Where larger installations that have multiple electrolysers are concerned there will need to be consideration given to how these signals are handled as there may be a requirement to trip all the systems in extreme events e.g., fire and/or explosion.

Electrical supply

The outline design provided within the handbook assumes an 11kV supply being made available to the hydrogen generation site. The infrastructure required to provide an 11kV supply will depend upon the source of supply. Based on a review of existing UK NPS, supplies taken for an ~ 30MVA load could potentially be taken from the station isolated phase busbars, this would be a significant modification to the existing station infrastructure. The cost and availability of the additional equipment required would be dominated by the transformer being typically of the order of £1M in cost and 12-month lead time. In relation to increasing the size of the plant and hence load as expected the cost would increase, with lead times for grid transformers presently being ~ 48 months (as of 2024). Costs and lead time could only be firmed up once a design has been chosen and the feasibility of electrical connections established and hence the figures given are provided as a guide.

The provision of construction electrical supplies has not been considered at this stage. The site could employ temporary power generation; however, this option is relatively expensive and entails emissions considerations. Furthermore, fuel storage and transportation present additional risk to the site. The availability of a lower rated supply from the nuclear site has not been reviewed at this stage as the construction requirements are unknown. Any lower rated supply from 3.3kV supplies as an example would still be subject to existing infrastructure constraints i.e. the availability of spare switchgear, load constraints from the existing infrastructure (transformer load) or the modification of electrical infrastructure, cable routing and breach of the station security fence. All of which would require a safety case to be presented.

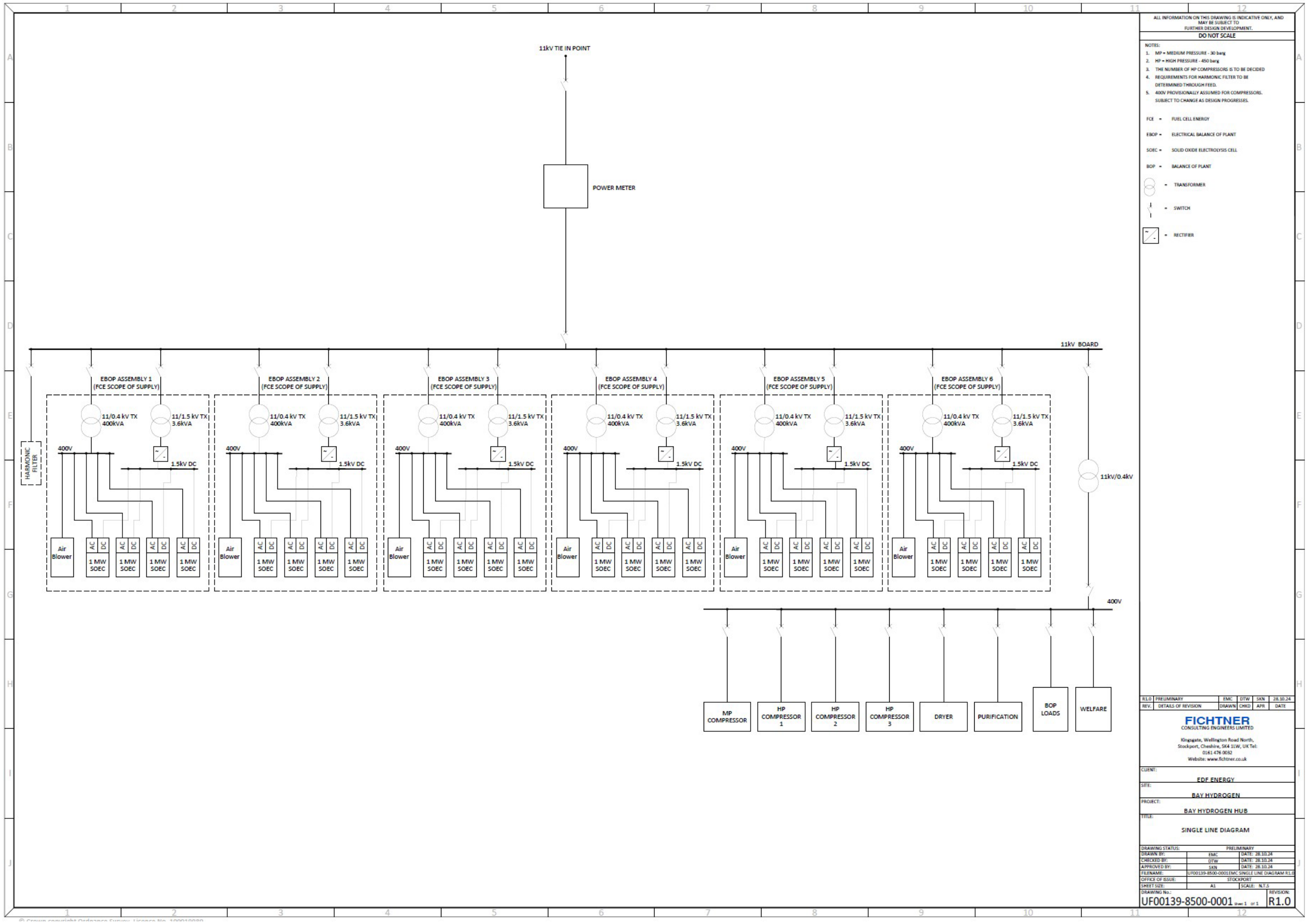


Figure 10 Concept - Example of Electrical Line Diagram for a 24MW hydrogen plant

Site layout

One of the key factors in determining the layout for a NEH plan is the safe distance of nuclear critical plant (Please see Chapter 5, 5. SUPPORTING SAFETY AND SECURITY ASSESSMENTS). The agreed 2D layout for the electrolyser plant is shown in Reference 4 (Health and Safety Considerations). The layout follows a systematic approach with equipment grouped into areas based on the hydrogen pressure, and in accordance with the separation distances estimated using PHAST assessment, details can be found in Reference 8 (Additional Assessments).

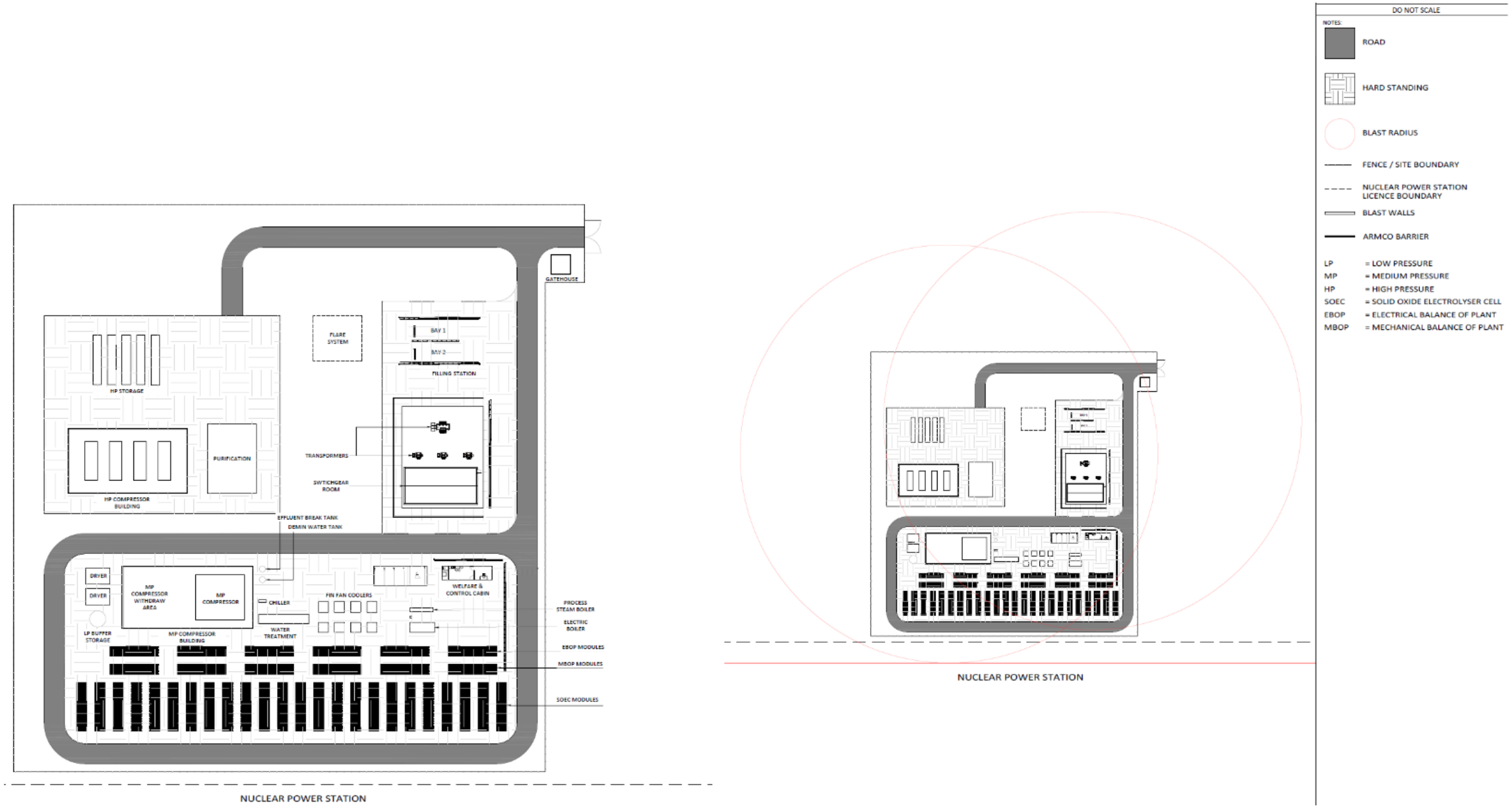


Figure 11 Concept - Layout with minimum distances based on 24MW hydrogen plant for a 12.5mm bore release

Separation distances for this concept have been calculated using consequence modelling. The leading driver for separation distance in this layout is from maximum overpressure in case of a large bore leak which is ignited, causing an explosion.

The modelling assumes a worst case 12.5 mm bore release. Two scenarios have been examined:

- 0.138 bar overpressure, which is likely to lead to structural damage
- 0.3 bar overpressure, which gives a 30% risk of fatality for outdoors personnel

The modelling approach undertaken here to determine separation distances is to ensure safe distances between each of the key pieces of infrastructure for the hydrogen production facility and the NPS, reducing the impact of each on the other. The relative locations of different plant equipment that forms part of the hydrogen production facility are determined by the design approach, which is influenced by the consequences of failure and the available space. An alternative approach, where space is limited, could group the hydrogen production infrastructure together, accepting the risk that a failure in one part of the plant (e.g., high-pressure compression) could impact another part (e.g., electrolyser). Whichever design approach is adopted the designer must maintain a safe separation distance between all plant equipment and the nuclear boundary. The modelled approach does not consider catastrophic equipment failure leading to missiles, nor does it account for physical barriers, walls, bunds, etc., which may be employed to reduce the risk to the nuclear reactor.

Indicatively, using this modelling approach for the concept, the SOEC electrolysers could be sited 15-20m away from the nuclear site fence as they only process small volumes of hydrogen at just above atmospheric pressure. Storage would likely be located further away, such as 50-150m, depending on the storage pressure. Detailed design would need to include a full assessment of the consequences, e.g., jet fire, blast waves and missiles, to determine more accurate distances, based on the specifics of the final design[16]. If necessary, other mitigations could be used to reduce the separation distance, such as raised land barriers, blast walls, or storage technologies with lower pressures (such as metal hydrides).

Key plant parameters

Table 2 Key process parameters (24MW SOEC).

Item	Process Data	Units	Input
1	Hydrogen output at 100% load (plant)	kg/h	600
2	High Pressure Storage Pressure	Barg	450
3	Maximum hydrogen storage	tonnes	Below the COMAH Upper Tier Threshold (<50 tonnes)[17]
4	Electrolyser water (steam) specification	-	Conductivity < 1 µS/cm; Total Organic Carbon < 50 µg/L; Sodium < 5 µg/L; Chloride < 5 µg/L; Silica < 3 µg/L.
5	Hydrogen output pressure from electrolyser	Barg	0.1
6	Hydrogen output temperature	°C	40
7	Connection voltage to hydrogen facility	kV	11
8	Electrical connect capacity for hydrogen facility	MVA	34

A detailed requirements summary is available in Reference 13 (NEH Requirements Summary).

[16] The initial explosion assessment has analysed the consequences of a bounding leak that is ignited and explodes, it has not analysed catastrophic failure of equipment that could generate missiles following an explosion. The designer of the NEH facility will need to conduct a detailed explosion assessment that fully considers all credible initiating events, their frequency, and their consequences to understand the impact on the NEH Facility and Nuclear Safety.

[17] The COMAH regulations will require the NEH facility to assess the volume of hydrogen and any other chemicals stored on site to comply with the requirements for its own facility. The NEH facility developer will then be required to work with the competent authority and the Nuclear Site Licence holder to confirm the consequences of failure on both sites. This will include consideration of domino effects due to the proximity and inventories of dangerous substances on both sites.

5. SUPPORTING SAFETY AND SECURITY ASSESSMENTS

Key messages

- Software (such as PHAST) can be used to model hydrogen leak scenarios to estimate safe separation distances between the nuclear site & hydrogen facility, and storage & surrounding equipment.
  Note: a graph related to an indicative distance is included in this chapter.
- Indicatively, for a 24MW plant, the SOEC electrolysers could be sited 15-20m away from the nuclear site fence. Storage would likely be located further, such as 50-150m, depending on the storage pressure. Detailed design would need to include an assessment to determine more accurate distances, based on the specifics of the final design.
- Plant design needs to consider hostile acts for security purposes.
- Minimising digital communication between NPS and NEH facility, simplifies the cyber security assessments, allowing remote operations at the NEH facility.
- Different safety and security standards can be applied to the NEH facility and NPS. The equipment at the NPS must remain operational after extreme events, which is not a requirement for the NEH facility.

Safety distance and location of hydrogen facilities at nuclear site

Several aspects must be considered when locating hydrogen facilities around a nuclear site to use heat for hydrogen production:

- Emergency Planning Zones of the NPS, which are being assigned based on the nature and consequence of the hazard
- Site Licence Boundary of the NPS both for steam extraction systems and electrolysis facility
- Fire, explosion and missile risks as hydrogen is highly flammable
- Heat transfer to minimise heat losses and safety risks (included in Reference 8 – Additional Assessments)
- Activities on the nuclear site, which are critical to maintain safe operation
- Quantity of hydrogen to establish the separation distance between the nuclear site and hydrogen facility
- Credible events, such as evolving flammable atmosphere, heat wave from ignition or pressure wave from explosion
- Characteristics of the potential leak (size, thermodynamics properties of hydrogen)
- Physical barriers to reduce the separation distance between facilities
- Topography, which might provide additional protection against the spread of hydrogen gas and explosions
- Weather in the production area to prevailing wind patterns should be studied to determine the likelihood of gas cloud movement
- Assessment of explosion hazard – PHAST modelling

PHAST software was used to model hydrogen leak scenarios to estimate safe separation distances between the nuclear site & hydrogen facility, and storage & surrounding equipment. This software has been used previously for modelling hazards that could affect a nuclear site.

This assessment provides a guidance and highlights hydrogen's unique properties and potential hazardous events like jet fires, vapour cloud explosion and flash fires. Vapour cloud explosion has been established as the most meaningful parameter in hydrogen generation plant layout and its placement relative to targets such as the associated NPS. In the full design of a hydrogen generation plant, consideration must be also given to jet fires, flash fires and to catastrophic plant failures.

In designing a hydrogen generation plant, it is advised to maintain primary containment, implement passive and active protection measures and ensure adequate spacing between plant items to prevent event escalation. Gas detector system such as point gas detectors, MPS (Molecular Property Spectrometer) technology, and ultrasonic gas leak detectors, could be implemented to detect and isolate hydrogen leaks. The placement of detectors must consider hydrogen's buoyancy and the environment, aided by leak dispersion modelling to inform suitable locations.

This section discusses the hazard effect ranges, specifically explosion overpressures, to estimate the separation distances to avoid harm to people and damage to structures. The predicted hazard range depends on factors like leak size, pressure, inventory, release orientation, topography and environment conditions. The PHAST software was used for modelling outdoor releases predicting flammable envelopes and overpressure thresholds. Modelling included scenarios with 2mm, 12.5mm, and 25mm leaks, representing different failures. Fugitive emissions[18] are not explicitly considered, they are judged to be bounded by the leaks considered in the modelling and will be controlled as part of normal operation (e.g., purging hydrogen to vent during start up and shutdown).

The PHAST modelling has required the use of generic input parameters relating to plant design, local topography and climatic conditions as site specific data is not available. Increasingly detailed and productive modelling is required as a project moves from an outline scheme into detail design.

The plant layout proposals in the NEH Handbook have assumed that overpressures of 0.138 bar will not result in plant damage and further hydrogen releases, such that there is no escalation of a small initiating event (low pressure, small inventory) to involve major plant items (high pressure, large inventory). This also determines the allowable proximity of features, such as the security perimeter of the supplying NPS or it's utility connections. For example, if damage is sustained at 0.138 bar and above, then plant must be placed at least 56.1m from a 100 bar, 12.5mm leak, and it is referred to as the "stand-off distance". The standoff distances for any cut-set of scenarios may be graphed.

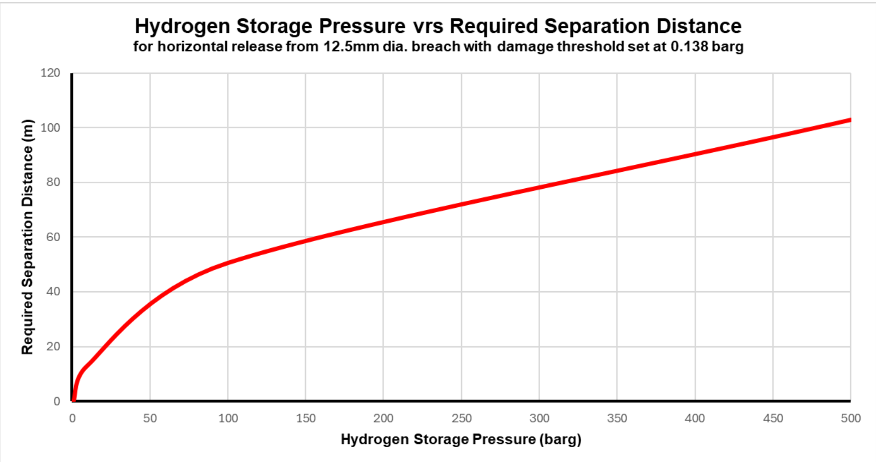


Figure 12 Relationship between process pressures and standoff distances for horizontal 12.55mm leaks, with a 0.138bar damage threshold. Note: it is necessary to use the log scale on the x-axis, for pressures from 1 bar through 500 bar.

When applied, to the 24 MW design, it was concluded the SOEC electrolysers could be sited 15-20m away from the nuclear site fence. Storage would likely be located further, such as 50-150m, depending on the storage pressure. Detailed design would need to include an assessment to determine more accurate distances, based on the specifics of the final design.

[18] *Fugitive emissions - defined as the unintentional and undesirable emissions, leakage, or discharge of gases or vapours from pressure-containing equipment or facilities, and from components inside an industrial plant such as valves, piping flanges, pumps, storage tanks, compressors, etc.*

Hydrogen venting and flaring are two methods[19] used to manage excess hydrogen (although rarely needed) at a production site, each with its own applications and considerations, which are outlined in Reference 8 (Additional Assessments).

HAZOP

A HAZOP (Hazard and Operability) study is a structured and systematic technique used to identify potential hazards and operability issues within complex systems, particularly in high-risk industries like chemical manufacturing, oil and gas, pharmaceuticals and nuclear. As part of producing a NEH project, a developer should consider holding one or more HAZOPs, to ensure the design addresses the risks[20].

As part of the HAZOP study, the design must be divided into smaller sections, referred to as nodes. Potential nodes that could be used as part of a HAZOP for a NEH project are:

- Steam side of Nuclear Steam Heat Exchanger
- Intermediate loop between the Nuclear Steam Heat Exchanger and External Heat Steam boiler
- Feed to the electrolyser
- Outputs of the electrolyser and compression and Intermediate storage
- Hydrogen export (e.g. via trailers or pipeline)

For this Handbook, this method was applied to the design of the hydrogen production facility. This involved a multidisciplinary team reviewing the system in detail, using guidewords to prompt the identification of deviations from the intended design. Further details on the HAZOP held can be found in Reference 8 (Additional Assessments). Below is a summary of the high-level findings & considerations that emerged.

Safety and Emergency Systems

- Implement automatic emergency shutdown systems
- Provide alarms, trip systems, and filters to protect against loss of flow, blockages, and leaks
- Provide interlocks, safety measures, and systems to monitor and detect leaks for example, startup not allowed unless appropriate purge gas is available
- Assess and minimise fire/ignition risks, and develop a site fire plan, including considering fire detection and suppression; the designer should consider limiting flammable materials, such as by considering non-flammable lubricants where possible
- Ensure design of equipment within the nuclear site prevents loss of containment and steam release during seismic events
- The hydrogen facility should be designed to fail to a safe state, to minimise the impacts on the NPS during faults or emergencies

Pressure and Temperature Management

- The system design must consider the arrangements for high system pressure such as pressure relief, use of filters, implementation of operational sequencing and alarm logic for pressure
- The system design will need to consider the safe startup and shutdown conditions and protection against low pressures; consideration will also need to be given to vacuum pressures where steam and water/steam mixtures are used

---

[19] Flaring is used to manage excess hydrogen that cannot be stored or exported during start-up, shutdown, and maintenance processes. It serves as a safety measure to prevent hydrogen from venting directly into the atmosphere.

[20] HAZOP is only one of the hazard identification and management techniques that should be used. The developer of a hydrogen production facility will need to consider which of the different hazard identification techniques it will use to make their safety case. See section 6 and References 4 & 6 for further detail.

- Identify safeguards for excess superheat, consider upstream pressure/temperature regulation failure, examine material properties, and monitor for failed heat exchangers
- Provide low temperature alarms and shutdown/trip; use glycol mix in cooling systems to prevent freezing
- Design to prevent negative pressure and reverse flows e.g., non-return valves; analyse plant response to pressure drop, install differential pressure instrumentation
- Evaluate the system's ability to endure high frequency of thermal cycles and how these can be minimised to reduce significant maintenance
- Design electric steam boiler for abrupt steam condition changes, use gasket-less HX, add condensate return system, evaluate strainer requirements, manage with robust maintenance

Monitoring and Control Systems

- Use conductivity sensors to monitor conductivity of feed water, agree on specification for feedwater dosing, include alarms for conductivity. Insert low point drains and steam traps for the steam system
- Review power requirements, ensure backup Uninterruptable Power Supply (UPS) if required, consider power supply redundancy to control loss of power situations and loss of heating
- Reduce operator intervention with automated trips and remotely operated valves

Product Quality and Contamination Prevention

- Review hydrogen quality requirements and select appropriate technologies to eliminate contamination of the electrolyser and provide the required product hydrogen purity; for example, oil-free compressors for hydrogen compression
- Set minimum action levels for increased radioactivity in the nuclear steam circuit, investigate impacts, review contamination handling, and identify safeguards and consequences for any transfer between the intermediate circuit and the nuclear steam supply circuit
- Consider the impact and handling of trace amounts of hydrogen in the recycled electrolyser feedwater

Maintenance and Inspection

- Conduct thorough pipework inspection and maintenance, assess pressure differential during maintenance, and plan for duty/standby requirements to ensure plant availability

Nuclear security implications

Due to the critical nature of nuclear facilities, comprehensive planning and stringent measures are necessary to prevent the potential security risks from development of a NEH facility adjacent to a NPS. Developing an understanding of the potential areas of concern early in the design allows the security implications to be addressed at a fundamental level where possible.

The sterile zone (SZ) must be considered when calculating the safe distance of the external plant from the NPS. As a minimum this should be at least 5 meters from the NPS fence. Additionally, other security factors could increase this minimum distance required. For example, tall buildings (which could create a vantage point/potential access route into site), or where destruction of plant (intentional or accidental) could create a hazard.

In Reference 5 Approach to Ensuring Nuclear Site License Compliance), the following areas of potential security considerations were analysed:

- Any hydrogen plant/hardware crossing the NPS SZ and immediately adjacent to outer fence
- Unauthorised access to the NPS, through hydrogen plant pipework or other structures
- Consequence on NPS arising from a malicious act to the offsite Hydrogen facility
- Access/Maintenance for the heat exchanger and any pipework located within Nuclear Site (Insider threat)

- Cyber Security considerations
- Hydrogen plant pipework within nuclear site boundary
- Station electrical supply feeding Hydrogen plant.
- By-products/Waste products
- Management of Thermal runaway of SOEC units to prevent fire risk.

Additional reviews

Several additional reviews were identified as important in relation to the design and installation of a hydrogen plant close to a NPS.

Environmental review provides guidance on what environmental aspects project developers and planners need to consider for an environmental license/permit to install a water electrolyser for hydrogen production adjacent to a nuclear power station. The environmental review will be used to satisfy the environmental regulators and will need to consider aspects such as the impact of the emissions from the plant on air quality, use of water and safe disposal of wastewater, and the ecological impact of the facility.

Electrical supply review, challenges in connecting into the electrical system at NPS, and potential electrical connection points were identified. A hydrogen generation facility developer will need to show they have a robust design for the electrical supply and connection points and that the impact on the electrical system's stability at the nuclear facility is understood. A safety case will be required to demonstrate that the design is acceptable and that the additional load will not compromise the existing electrical system and undermine nuclear safety.

Extreme weather conditions review examined the potential impacts of extreme weather events on the co-located facility and explored the possibility of applying nuclear safety regulations to the hydrogen production plant. The review will need to consider, but not be limited to, temperature extremes, flooding events, and extreme wind events.

Seismic review has been undertaken as the Office for Nuclear Regulation (ONR) safety assessment principles requires that the effects on a seismic event on a nuclear reactor facility, including nearby facilities like hydrogen generation plants, be considered to ensure they do not impact the reactor's safety. Hydrogen generation facilities must be able to safely shut down and maintain a safe state during and after a seismic event to prevent affecting the nuclear reactor's operation and safety systems. The NEH Facility must be capable of safely shutting down and maintaining a safe state during and after a seismic event. This safe shutdown needs to not impair systems that protect the nuclear site from severe accidents.

Full reviews mentioned above can be found in Reference 4 (Health and Safety Considerations).

6. NUCLEAR SAFETY CASE STRATEGY

Key messages

- In principle, a safety case for the integration of the NEH Facility with an NPS can be developed.
- A relatively small separation distance between the NPS and any hydrogen storage can significantly reduce the complexity of the safety case.
- Existing practices that are established and followed by the NPS would be suitable for the NEH Facility.
- The off-site hazards from the NEH Facility should be treated as an industrial hazard when incorporated into the reactor safety case.
- The NEH Facility will need to demonstrate the risks, from its operation on the nuclear reactor, have been reduced to ALARP
- The compliance with the site licence conditions can be demonstrated through a series of safety cases that justify the installation of the heat exchanger and the construction, installation and operation of the hydrogen generation plant outside the site boundary.

Licensing of a hydrogen generation facility in the UK will be dependent on the level of risk being managed and the location of the plant. Where the hydrogen generation plant is going to use waste steam and electricity from a nuclear reactor, and be adjacent to the reactor site, it will be necessary to demonstrate that the risks to the nuclear reactor have been reduced so far as is reasonably practicable in accordance with UK law. This will likely require demonstration that the risk is close to the broadly acceptable level. Demonstration that the risks have been reduced so far as is reasonably practicable is via a nuclear safety case.

Definition of a Nuclear Safety Case

The nuclear safety case is a term used to encompass the totality of the documentation developed by a designer, licensee or duty holder to demonstrate high standards of nuclear (including radiological) safety and radioactive waste management.

The nuclear safety case provides the information required to allow the UK's safety standards to be maintained. It is a logical and hierarchical set of documents that describes risk in terms of the hazards presented by the facility and the modes of operation, including potential faults and accidents, and those reasonably practicable measures that need to be implemented to prevent or minimise harm. It takes account of experience from the past, is written in the present, and sets expectations and guidance for the processes that should operate in the future if the hazards are to be controlled successfully. The safety case clearly sets out the trail from safety claims through arguments to evidence.

The UK regulations (Licence Conditions 14 and 23) require the licensee to produce an adequate safety case to demonstrate the safety of any operation that may affect safety. The term 'nuclear safety case' may be used in reference to a site, a facility, part of a facility, a modification to a facility or to the operations within a facility, or to one or more significant issues. The regulator (ONR) will expect that where multiple safety cases are provided to demonstrate the safety of the licensee's operations and the interfaces between these documents are clear and the totality of the documentation provides a holistic demonstration of safety across the overall undertaking (Ref. NS-TAST-GD-051, The Purpose, Scope and Content of Safety Cases, ONR, Issue 7.1 December 2024).

The Purpose and Scope of the Safety Case

Constructing and operating a hydrogen generation facility will affect the safe operation of the adjacent nuclear reactor. The primary purpose of a safety case is therefore to provide the duty holder (or intended duty holder) with the information required to enable safe management of the facility across its lifecycle, and to reduce risks to As Low As Reasonably Practicable (ALARP).

The safety case for the hydrogen generation facility should be understandable and useable and clearly owned by those with direct responsibility for safety. It should communicate a clear and comprehensive argument to its users that the facility can be operated or that an activity can be undertaken safely. It should demonstrate appropriate defence in depth in design, that the associated risk and hazards have been assessed, the appropriate limits and conditions have been defined, and adequate safety measures have been identified (Ref. NS-TAST-GD-051). In essence the duty holder should present a safety case that is:

- Explicit about the scope of the safety case and the interfaces to other safety cases/processes, i.e., what does the safety case cover (e.g., new site/facility, modification to site boundaries).
- Able to demonstrate the totality of the site safety case, i.e., it covers all site operations that may affect safety, and demonstrates consistency in the underpinning assumptions.
- Clear in its definition of scope of operations, plant operating modes, plant boundaries and interactions/interfaces and lifecycle assumptions.
- Explicit about the time period for which the safety case is valid for. The safety case for the hydrogen generation facility will therefore need to cover its effect on the licensed nuclear site for all operational phases during its life cycle.
- Clear about the implementable requirements of the case, for example limits and conditions, maintenance requirements etc., so that the facility can be operated and maintained in a safe manner i.e., the radiological risks are managed to reduce them to ALARP (Ref. NS-TAST-GD-051).

Safety case strategy

Overview of Safety Case Strategy

As the hydrogen generation facility will be located near a nuclear licensed site it is necessary to justify that this can be done safely, not just from a nuclear safety perspective but also a conventional safety perspective. Demonstration that this can be done safely will be through development of a safety case that covers the operation of the hydrogen generation facility throughout its life from initial design into construction and through to decommissioning. An overview of how this could be achieved is presented in this section, which provides a strategy for justifying the hydrogen generation facility that covers the design, construction, and operation of the new plant.

The nuclear safety risks from the hydrogen generation facility relate to the potential impacts from the hydrogen generation plant on the claimed nuclear safety equipment and any potential impact of the reactor on the hydrogen generation facility.

The principal risks are as follows:

- The risk of hydrogen gas being released leading to an explosive gas cloud which catches fire and damages or destroys nuclear safety claimed equipment.
- The risk of a hydrogen explosion that results in a pressure wave and missiles that damage or destroy nuclear safety claimed equipment.
- The risk of a small fire on the hydrogen plant that could escalate and lead to a larger hydrogen fire or explosion.
- The risk of disruptive failure of the heat transfer equipment on the nuclear reactor site that potentially damages nuclear safety related equipment.

At present the magnitude of the risk has not yet been fully determined as the design of the hydrogen generation and storage facility has not yet been completed. Despite this the strategy presented here will support development of a safety case so that once the design has matured sufficiently, and the details are known, a safety case can be made. An important part of developing an appropriate safety case will be to demonstrate compliance with the relevant conventional safety regulations such as Pressure Systems Safety Regulations (PSSR), Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) and potentially COMAH (COMAH regulations must be considered where the quantity of hydrogen on the facility exceeds 5 tonnes (HSE L111 The Control

Of Major Accident Hazards Regulations 2015, 3rd edition 2015). Where the proposed activities affect the environment and/or the security arrangements the safety case will also address aspects such as the Best Available Technique and aims to demonstrate the security risks have been reduced as far as reasonably practicable

In addition to the safety issues above the hydrogen generation facility will also need to demonstrate that the relevant internal and external hazards on the facility and its equipment are being adequately managed e.g., steam release from the Steam Supply and Return system could affect nuclear safety claimed equipment.

The nuclear reactor safety case will require updating to include the hydrogen generation facility as a new industrial hazard. The hydrogen generation facility could impact the following aspects of the reactor fault and hazards schedules.

Plant Faults

- Spurious Trip – inclusion of the impact of an emergency on the hydrogen generation facility requiring a reactor shutdown.
- Feed system faults – potential to affect the condensate system resulting in a reduction in condensate flow.
- Feed system faults – potential to contaminate the condensate system if heat transfer fluid or other contaminant enters the system. If this occurs the condensate system would be shutdown to protect the reactor's secondary cooling circuit, and this would trip the reactor.
- Loss of Electrical Supplies – NPS delivered electrical supplies have the potential to affect the electrical systems. This will need to be appropriately justified.
- Steam system faults have been discounted as the steam system will not be significantly affected by the changes. However, there is the potential for steam release impacting on people and plant (see below).

Internal Hazards (Hazards that originate within the Reactor Site Boundary)

- Fire – There is a risk that the new on-site equipment could affect the fire safety case. This will need to be reviewed as part of developing the justification for the heat exchange equipment that will be placed inside the nuclear site boundary.
- Steam release faults – there may be an increase in the frequency of steam releases dependent on the tapping-off point in the secondary system and the routing of the pipework across the reactor site. For example, increased risk of steam release in the turbine hall or effects on external plant that are adjacent to the pipe work as it runs across the site.
- All other internal hazards are judged to be unaffected as the reactor equipment is protected by its location (inside the site boundary remote from other hazards such as dropped loads etc.).

External Hazards (Hazards that originate outside the Reactor Site Boundary)

- Industrial hazards – this is where the biggest change to the reactor safety case is expected. The industrial hazards safety case will need to be updated to include the risks from the hydrogen generation facility on the reactor systems. These risks include the potential for drifting hydrogen gas clouds that could be ignited, blast waves, and missiles from catastrophic failure of hydrogen generation plant equipment. A review of the faults and hazards on the hydrogen facility should be carried out as part of the development of the industrial hazards case. The review shall confirm that all the faults and hazards that could affect the reactor safety case have been identified and appropriately managed.
- A review of the external hazards safety cases for the reactor should be carried out. The review should confirm that there are not any significant impacts on the other external hazards safety cases, or where there are, the interactions have been correctly identified and can be appropriately addressed. For example, the flooding risk and seismic interactions may require additional justification.

The hydrogen generation facility is complex and will be required to keep the risks from its operation As Low As Reasonably Practicable during its design, construction, commissioning, and operation. The approach to justifying the production and export of hydrogen must consider the following aspects:

- Design principles for the production, storage, and distribution of hydrogen.
- Identification of the key nuclear reactor plant modifications required.
- The safety case claims, arguments and evidence required to substantiate the proposed plant.

- The approach to control the risk to the nuclear reactor and how this will be presented in a safety case.
- Key project quality and nuclear safety administration arrangements.

Incorporation of the risks from the hydrogen generation facility into the design basis safety case for the nuclear reactor will be by treating the hydrogen generation facility as an external industrial hazard. External industrial hazards are a class of faults that cover industrial facilities that can impact the nuclear licensed site. Where the hydrogen generation facility is to be included in the original design it is anticipated that it should be considered as early as possible in the design and licensing of the reactor site (i.e., as part of the Generic Design Assessment (GDA) process).

Determination of Risks and their Management

Successfully managing the risk from the hydrogen generation facility to the Nuclear Reactor Site will require a comprehensive understanding of the design, faults and hazards associated with the hydrogen facility and the risks posed to the reactor site and the public. The following risks to the public from the hydrogen facility need to be reduced as low as reasonably practicable:

- The direct risks to the public from the hydrogen facility that do not affect the nuclear reactor site. This risk comes from faults or hazards that could impact the public due to failure of the hydrogen facility structures systems and components. They do not impact the nuclear reactor and there is no radiological release.
- The risks from the hydrogen facility that could affect the nuclear reactor site and potentially increase the risk of a radiological release. These risks are from system, structures and component failures on the hydrogen facility that affect the nuclear reactor e.g. fire/smoke, explosions/blast waves.
- The risks from the nuclear reactor site that impact the hydrogen facility causing a shutdown that may escalate to a fault on the hydrogen facility.

The first step to determining the risk from the hydrogen facility is to systematically understand the faults and hazards that are presented by the plant during all operational states. The details discussed below can be used to determine and manage the hazards and risks

- The individual faults and hazards are identified by an appropriate and systematic hazard identification process (e.g., Hazard Identification (HAZID), Hazard and Operability (HAZOP), Failure Mode and Effect Analysis (FMEA)).
- Faults and Hazards are presented in a schedule with a number of grouped fault and hazard sequences.
- Each fault sequence which could lead to unwanted effects has an appropriate safety function, initiating event and unmitigated consequence calculated.
- Where there is the risk of a radiological release, radiological safety assessments are produced to specify safety measures which can be engineered or administrative in nature. The designated safety measures need to reduce the consequence and/or initiating frequency to an appropriate level. The concept of Defence In Depth is also important to ensure nuclear safety.
- The various engineered safety measures are identified as Systems, Structures and Components (SSCs) in an Engineering Schedule, which also includes the safety function and any performance requirements.
- SSCs are then substantiated against their safety function(s) and performance requirements to ensure they will fulfil their safety role when required.

Development of the understanding of the faults and hazards will occur throughout the design of the facility, it is recommended that an initial safety assessment be prepared alongside the plant design and published as soon as the design has matured and been frozen. The incorporation of Safety Case development within the design process helps to ensure that the design develops with normal and fault condition safety in mind with the aim of minimising the hazards present and reducing the residual risk and ultimately the overall cost (Ref. atw volume 69 (2024) Research and Innovation – Nuclear Enabled Co-Generation from a Regulatory and Safety Case Perspective).

This initial safety assessment shall use the output of the stages discussed above i.e., the Hazard Identification, HAZOP, and FMEA studies carried out during the design to support the fault and hazards schedule. Alongside the development of the deterministic fault schedule, it is recommended that probabilistic safety analysis is carried out. Using both a deterministic and probabilistic approach provides a comprehensive understanding of the risks from the NEH facility and their likelihood. Where the risks are not acceptable, further work will be required to provide adequate protection and mitigation measures that will support and demonstrate the argument that the risk posed to the public and Reactor Site is reduced ALARP.

Demonstration that Risks Have Been Reduced ALARP

Once the risk reduction measures proposed have been designed and their performance assessed, it will be possible to understand the risk to the public and nuclear reactor site. It will then be necessary to demonstrate if further work is necessary to reduce the risk ALARP.

Determination that the risk has been reduced ALARP is through a systematic and structured decision-making process that considers the reasonable practicability of options to further reduce the risks. The options and solutions that are considered should be fit for purpose and formally documented. The options should include a comprehensive set of measures from complex engineering solutions through to administrative and human factors improvements. Assessment of the risks against the ALARP principle may also confirm that the risk is already acceptable or that a potential option is too costly and does not provide a significant reduction of the risk. The final decision should be clearly demonstrated, and the discussion recorded as part of the safety assessment.

The overall demonstration that the design of a hydrogen generation facility reduces the risk ALARP should consider the principles of defence in depth (Ref. IAEA Safety Report Series No. 46 Assessment of Defence In Depth for Nuclear Power Plants). The Defence In Depth principles represent good practice for nuclear reactor safety cases and it is recommended they are applied to the hydrogen facility. Potential design strategies that could be employed are:

- Design and build to appropriate codes and standards to ensure structural integrity and plant reliability thus minimising the risk of failure.
- Provision of engineered fault detection and protection measures that will automatically detect fault conditions and failures.
- Optimisation of the plant layout to ensure that plant is protected and segregated from faults and hazards. This may include passive protection measures.
- Provision of engineered safety features and dedicated procedures that cover abnormal conditions and maintain them within the design basis.
- Development of emergency procedures and accident management arrangements, including off site emergency response measures that interface with the nuclear reactor site.

It is anticipated that where a hydrogen generation facility is situated near a nuclear reactor that depending on the distance between the facilities the following risk reduction measures may be appropriate.

- Separation distance – the design of the facility should seek to maximise the distance where practicable including arranging the plant layout so that the higher risk items are as far away from the reactor as practicable.
- Raised land barriers – the design of the site could use berms to control the consequences of failure on adjacent equipment and the nuclear reactor site.
- Blast Wall – provide an engineered structure that protects the reactor site from the consequences of an explosion i.e., blast waves and missiles.
- Blast Panels – provide engineered structures that control the consequences of failure of the high-risk equipment and protect the other systems.
- Construction below ground level – construction of the hydrogen generation facility below ground level would reduce the risk from explosions and missiles. It should be noted that some new reactor designs could potentially be partially constructed below ground level.

This list is not intended to be exhaustive, and the designer will need to determine the risks from the specific design and location they are considering and utilise the most suitable mitigations for their application.

The final demonstration that the risk is ALARP must establish that the risks to the public have been minimised as far as reasonably practicable i.e., there are no more reasonably practicable options that can be pursued. For a new reactor site that includes the hydrogen generation facility in its design and safety case, demonstration of ALARP principles will be included from the outset alongside all the other risks.

Where a hydrogen generation facility is to be developed alongside an existing nuclear reactor site it must be shown that the combined risk from the hydrogen generation facility and the reactor site remain ALARP. Where the combined risk can be shown to be close to the level of risk from the reactor alone it is considered that the Safety Case would likely remain valid with moderate but manageable changes being required.

Where there is a risk increase the overall risk must be shown to be within the regulator's framework (i.e., the UK Health, Safety and Environment (HSE's) "Tolerability of Risk" decision making requirements). It will be the responsibility of the developer of the hydrogen generation facility to demonstrate their design has minimised the risk increase so far as reasonably practicable and to work with the nuclear site licence holder to demonstrate this to the regulators (ONR and HSE). Where the reactor site operates within the Tolerable Region it is expected that a robust demonstration will be required detailing how the risk has been reduced and why specific mitigations are not progressed.

Safety Case Management

To manage the change in risk to the reactor and the understanding of the risks the hydrogen facility presents to it, the justification should be presented as a series of stage submissions to provide detailed evidence for the various stages in the hydrogen generation facility lifecycle. Based on existing nuclear industry experience of major projects in the UK it is recommended that the justification is presented as a series of stage submissions as follows:

- Overarching Strategy and Principles Submission – this will outline the staged submissions that will present the detail of the justification.
- Stage Submission 1 – Design and ALARP justification for the facility
- Stage Submission 2 - Construction
- Stage Submission 3 - Commissioning
- Stage Submission 4 – Long Term Operation
- Final Report Submission – Confirmation the facility is operating as per the safety case and original design principles.

The overall structure and approach for controlling the permission for each stage will need to be agreed with the ONR. It is recommended the designer engages with the ONR at the earliest opportunity to allow the regulator time to understand the proposed scope of work and the safety case strategy for managing nuclear and conventional safety.

Each of these submissions will need to be categorised with respect to their nuclear safety significance. Categorisation is based on the risk of a radiological hazard if the change is inadequately conceived or executed, and the significance of the change to the safety principles on which the case is based. There are four categories with category 1 being the most significant change and category 4 having no impact on nuclear safety or risk of a radiological hazard. The overarching strategy and principles submission is likely to be the highest categorised submission as it justifies the overall arrangements for the project, it is judged that category 1 or 2 would be appropriate. The supporting stage submissions will be appropriately categorised and are judged to be category 2 and 3 submissions depending on the scope of work and nuclear safety risks. The final report submission will be submitted at the same category as the overarching strategy submission to confirm the design and arrangements align with the principles set out at the start.

Further detail of the stage submission structure can be found in Reference 5 (Approach to ensuring nuclear site license compliance).

Faults and Hazards Schedule

To demonstrate that a hydrogen generation facility can be operated safely, it is vital to understand how the design behaves during normal operation, faults, and hazards. The aim is to understand the consequences of equipment failure and the hazards they present to the hydrogen facility and the licensed nuclear reactor site.

It is recommended that a detailed systematic review is performed of the operating conditions on the plant to determine the functional requirements for safe and efficient operation, and to identify potential failure modes that have a safety impact and understand the likelihood of those failures.

Once the review is completed it will be possible to identify the error likely situations where the systems, structures and components contribute to fault avoidance (e.g., high standards of design prevent the fault) and where there is a requirement for fault mitigation (take reasonably practicable measures to minimise the consequences of any faults). The requirements and how they are provided and addressed should be recorded in a fault schedule which outlines the consequences of failures, the essential plant conditions or functions that must be protected, and the engineering safeguards that mitigate and/or minimise the consequences.

Development of the fault schedule will be specific to each development site and the hazards identified for a particular plant design. With respect to the hydrogen generation facility the fault schedule should include the following fault categories.

Table 3 Possible faults and hazards.

Fault Category	Design Basis Fault/Hazard
Faults at Operation	Water Supply System Faults. Steam System Faults, Air System Faults, Hydrogen Faults, Nitrogen System Faults, Electrical Faults.
Faults at Shutdown	Water Supply System Faults, Steam System Faults, Air System Faults, Hydrogen Faults, Nitrogen System Faults, Electrical Faults.
Internal Hazards	Fire/Explosion, Steam Release, Missile Impact, Dropped Loads, Gas Release (hydrogen and nitrogen), Vehicular Transport.
External Hazards	Seismic Event, Wind Loading, External Flooding, Aircraft Impact, Industrial Hazards, Extreme Ambient Temperatures, Loss of Off-site Power (LOOP).

This list of faults and hazards is not exhaustive, a comprehensive list will need to be developed for each plant design and location. For example, the risk of external flooding and industrial hazards will vary depending on the location of the nuclear reactor site and hydrogen generation plant.

The fault schedule should identify the initiating event, the affected equipment, the frequency of the event, the consequential loss of equipment, and assess the impact on any engineered safety features. It is recommended that the structure and hazards considered are aligned with the practice currently used for the reactor fault schedules. An example where this approach has been utilised is presented in Reference 4 (Health and safety considerations)

The fault schedule should be developed in parallel with the design of the facility so that the design can be updated to take account of the faults and hazards that have been identified and clearly demonstrate that there are engineered mitigations put in place to manage the faults and hazards. Mitigations may range from minor adjustments to significant design decisions that affecting the plant's operation and layout. When simple measures are insufficient to mitigate the risks, complex engineered safeguards will be necessary, and the plant layout may need optimisation. It is recommended to apply the principles used in nuclear reactor safety cases, such as redundancy, segregation, and diversity, where appropriate. Examples include:

- Redundant systems for hydrogen gas detection. Redundancy is required in case of system failure due to the fire and explosion risk from hydrogen releases.
- Segregation of the hydrogen storage from the reactor plant and electrolysers. Segregation should be used in the design to keep high risk systems and components apart from each other so they can't interact, and their failure escalate.
- Diversity in power supplies to the plant systems. There will need to be back up power systems to allow the plant to be safely shut down and monitored in the event of a loss of grid power supply.

Where possible the design should aim to prevent faults in the first place and if this isn't possible ensure that the plant layout, orientation, and design have been optimised to minimise the risk.

Once the faults and hazards that need to be addressed have been analysed, the operating conditions for the plant and the hazards it needs to be protected against will become clear. The design of each system, structure and component must consider these conditions and demonstrate their qualification for the full range of potential conditions during normal and abnormal fault scenarios. This qualification will be documented in the safety case, along with the strategy to maintain their qualification through an appropriate Examination, Maintenance, Inspection and Test Schedule.

See Reference 4 (Health and safety considerations) for details on the proposed categorisation of the Safety Case Engineering Changes.

7. NUCLEAR SITE LICENCE IMPACT

Key messages

- The NEH Facility should be built outside the nuclear site licence boundary to minimise the impact on nuclear safety and the impact on Site Licence Conditions.
- Site Licence compliance can be demonstrated by development of an appropriate safety case that clearly defines the impact of the NEH facility on the nuclear reactor including emergency arrangements.

  The licence conditions that could be affected are listed in this chapter.
- This review supports the judgement that a NEH Facility can be installed near to a nuclear reactor with the appropriate controls in place.
- Consider using completely separate resources to construct and operate the hydrogen generation facility, to reduce the impact on the nuclear licensed site and support compliance with Licence Condition 36.

Overview of affected site licence conditions

In the context of the NEH licence condition compliance will fall into two broad areas:

1. Compliance with the licence conditions within the nuclear licensed site – i.e., the installation and operation of the steam heat exchanger and intermediate heat transfer loop within the site boundary. Compliance will be demonstrated through Licence Condition 19 (construction or installation of new plant) and/or Licence Condition 22 (modification or experiment on existing plant) depending on the individual design of the reactor and hydrogen generation facility. The arrangements will need to consider the impact of a sudden shutdown of the hydrogen facility on the reactor plant, especially the impact of sudden changes in the heat load and electrical power from regular shutdowns of all or part of the hydrogen facility.
2. Demonstration that the hydrogen generation plant (electrolyser and the gas compression, storage and delivery systems) does not impact the site licence conditions or where they do the impact is minimal and has been appropriately justified.

It is anticipated that the compliance with the licence conditions will be demonstrated through a series of safety cases that justify the installation of the heat exchanger and services and the construction, installation and operation of the hydrogen generation plant outside the site boundary. They will cover aspects such as the electrical scheme and its impact on post trip cooling.

Where the hydrogen generation facility is outside the licensed nuclear site and it is not being constructed and operated by the nuclear site licence holder, it will be necessary for both organisations to work together to ensure the site licence conditions are adhered to. It will be essential that the hydrogen facility operator provides sufficient information regarding the risks the hydrogen facility poses to the reactor site, this is so that adequate licence compliance principles can be established.

An initial assessment of the Nuclear Site Licence Conditions[21] has been carried out for the NEH Handbook. The review is based on the experience gained during the Bay Hydrogen Hub project. The initial review is summarised below. As this is an initial review it should be treated as guidance. The approach discussed here would need to be subjected to review and agreement by the Licensee's internal regulators and the ONR to confirm the strategy is appropriate.

[21] *Licence condition handbook, Office for Nuclear Reaction (February 2017).*

This high-level review has confirmed that the majority of licence conditions can be complied with as part of normal business. This is based on the following assumptions:

- The risks from the hydrogen generation plant on the nuclear reactor, and its supporting systems, can be shown to have been reduced so far as is reasonably practicable.
- An appropriate safety case can be developed to the satisfaction of the internal and external regulators. The safety case must clearly define the limits and conditions the plant will be operated under therefore ensuring compliance with Licence Condition 23 (operating rules) & 24 (operating instructions).

The review has identified the following Licence Conditions as areas that require moderate levels of work to address the new risks for site licence compliance:

- **Licence Condition 2** – Marking of the site boundary.

  The site boundary will be modified to allow the pipework that transfers the heat from the reactor steam system to the hydrogen generation plant. The design of the modification, the security precautions required during the modification and the ongoing maintenance of the site boundary will need to be appropriately maintained.

- **Licence Condition 7 –** Incidents on the site.

  There will need to be robust arrangements in place to allow the impact of any hydrogen generation plant incidents that could affect the reactor safety systems to be recorded, notified to the authorities and investigated where necessary.

- **Licence Condition 26 –** Control and supervision of operations.

  Operation of the equipment that supports the hydrogen generation plant will need to be carried out according to the existing arrangements and procedures. There may also be additional requirements introduced by the hydrogen generation plant e.g., the response to issues on the hydrogen generation plant that affect the reactor site and over which they do not have direct control.

- **Licence Condition 27 –** Safety mechanisms, devices, and circuits

  The on-site installed plant will be fitted with appropriate safety related equipment. The requirements for off-site safety equipment that may be required to reduce the on-site risk will need to be determined by the designer.

- **Licence Condition 36 –** Organisational capability

  Operating the on-site equipment will impact the Suitably Qualified and Experienced resources on the licensed site. There will also be impacts on the organisational capability from the requirements to monitor and address the risks from the hydrogen plant. These will need to be considered once the design and operation of the hydrogen generation facility is more mature and will need to cover all phases of the project from construction into normal operations. It is recommended that there will be completely separate resources provided to construct and operate the hydrogen generation facility so as to reduce the impact on the nuclear licensed site. Any changes made to the organisational capability of the nuclear organisation will also need to be assessed against the Licensee's Management of Change procedures.

The review has identified the following Licence Condition as requiring a higher level of work to demonstrate site licence compliance:

- **Licence Condition 11** – Emergency arrangements

  There will be a requirement for emergency arrangements to be in place both within the licensed site and outside on the hydrogen generation facility. These arrangements will need to be designed so that where there is an impact across both facilities the roles and responsibilities are unambiguous and minimise the risk. The arrangements will need to provide appropriate mitigations for all credible emergency scenarios from both facilities.

For all the licence conditions discussed above the requirements of the nuclear reactor will take precedence and the detriment to nuclear safety will need to be minimised so far as is reasonably practicable.

The arrangements for compliance with these licence conditions can be addressed by further work to understand the detail of the hydrogen plant design and how it can be incorporated into the arrangements for a nuclear licenced site. For example, it has not yet been possible to fully confirm the impact on the emergency arrangements. As the design matures and the risks from the handling and storage of hydrogen become clearer, and it will be possible to mitigate the risk through development of a robust design that complies with the requirements of the affected nuclear licensed site. This review therefore supports the judgement that it is possible to install a hydrogen generation plant near to a nuclear reactor with the appropriate controls in place.

Regulatory permissioning

The ONR grants permission for specific activities across several core regulatory areas such as nuclear safety, security, transport and conventional health and safety. The permissioning process allows the ONR to control the duty holder's undertakings, and to respond to duty holders who require permission to commence, continue, modify or cease the specific activities covered by the relevant legislation and site licence. The ONR will conduct activities outlined in the Figure 13 when granting permission for a duty holder’s arrangements. Further information on the permissioning process can be found in the ONR guidance ONR/PER/PROC/001.

Reference 5 (Approach to ensuring site license compliance) for further details on the approach to ensuring site licence compliance.

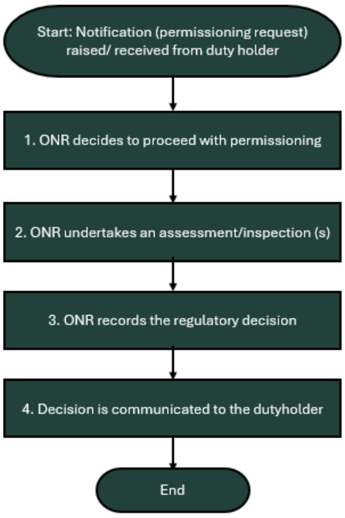


Figure 13 ONR permission process (ONR guidance ONR/PER/PROC/001).

8. REGULATORY ENGAGEMENT

Key messages

- The list of all relevant regulatory bodies is included in this chapter.
- Activities on the NPS and for the NEH facility will have different regulations. The NEH facility developer should engage with HSE and the appropriate environment agency. The NPS should engage with ONR.
- Early engagement with ONR is recommended, before detailed design begins. Use an approach similar to that adopted for nuclear new build. For example, the following steps are recommended: *Introductory engagement -> Technical and process engagements -> Preliminary design review*

As the NEH Plant connects a NPS and the Hydrogen Facility the scope of safety and environmental regulatory engagement should include all relevant regulators nuclear, industrial and environmental.

Table 4 below lists the key regulatory bodies in the UK which should be engaged for a NEH plant.

Table 4 Key regulatory bodies in the UK to be considered for a NEH project.

No.	Regulator	Scope	NEH relevance
1	Office for Nuclear Regulation (ONR)	The ONR regulates nuclear safety, civil nuclear security and safeguards and conventional health and safety at the licensed nuclear sites in the United Kingdom. This includes the existing fleet of operating reactors, fuel cycle facilities, waste management and decommissioning sites, as well as other licensed and, in part authorised defence sites, together with the regulation of the design and construction of new nuclear facilities. ONR also regulate the transport of civil nuclear and radioactive materials by road, rail and inland waterways.	The ONR will regulate (including Health and Safety) the part of the plant within the nuclear site boundary and directly connected to the site facilities. This will include the plant (e.g. heat exchanger, heat transfer fluid and associated pipework), people and processes.
2	Health and Safety Executive (HSE)	The Health and Safety Executive is the UK's national regulator for workplace health and safety. It prevents work-related death, injury and ill health. Other relevant areas of the Health & Safety Executive – Hazardous Installations Directorate (HID), Field Operations Directorate (FOD), may also provide additional guidance.	The HSE will regulate the non-nuclear site of the NEH plant. Engagement with the HSE could include the ONR as there will be overlap within the scope of both regulators.
3	Environment Agency (EA)	The Environment Agency is a non-departmental public body sponsored by the United Kingdom government's Department for Environment, Food and Rural Affairs (DEFRA). With responsibilities relating to the protection and enhancement of the environment in England. The Environment Agency is responsible for flood management, regulating land and water pollution, and conservation. The Environment Agency's stated purpose is, "to protect or enhance the environment, taken as a whole" so as to promote "the objective of achieving sustainable development" (Environment Act 1995).	The EA will regulate all NEH plant in the UK except in Scotland and Wales.

No.	Regulator	Scope	NEH relevance
4	Scottish Environment Protection Agency (SEPA)	The Scottish Environment Protection Agency is Scotland's environmental regulator and national flood forecasting, flood warning and strategic flood risk management authority. Its main role is to protect and improve Scotland's environment. SEPA does this by helping business and industry to understand their environmental responsibilities, enabling customers to comply with legislation and good practice and to realise the economic benefits of good environmental practice.	SEPA should be engaged for NEH plant in Scotland.
5	Natural Resources Wales (NRW)	The Natural Resources Wales are responsible for the environmental regulatory regime and flood forecasting for major industry and radioactive substances within Wales. New developments will need to show they comply with the Environment (Wales) Act. Any development will need to demonstrate it has recognised the social, economic, environmental and cultural wellbeing of Wales.	NRW should be engaged for a NEH plant in Wales.

Other regulatory and government bodies and licensees include:

- Department for Energy Security and Net Zero (DESNZ) – DESNZ is responsible for energy security an orderly transition from fossil fuels and reducing the UKs emissions towards net zero. DESNZ can support applications for government funding that support these priorities. DESNZ should identify the purpose and role of the department and how it would apply to NEH
- Department for Environment, Food & Rural Affairs (DEFRA) – Guidance on environmental protection, agriculture, fisheries and food production (discussion may be required with other food production regulators i.e. Food Standards Agency (FSA)) in the United Kingdom.
- Natural England - Non-departmental public body offering guidance on Environmental concerns
- Nature Scot – Guidance available for improving the natural environment in Scotland so that all nature in Scotland is maintained and enhanced and everyone benefits
- Marine Management Organisation (MMO) – Guidance on the protection and enhancing nature and the seas for the benefit of the society and economy.
- Marine Scotland – Guidance on the protection of aquatic life in Scotland
- Local Authorities – Regional guidance specific to each plant location
- Water utilities (e.g. in relation to a trade effluent or sewage agreement) – Discussion regarding discharge limits and viable solutions for waste treatment if required
- Nuclear Decommissioning Authority (NDA) – Discussions between the nuclear regulators and hydrogen plant facility should be maintained throughout the NPS lifecycle
- Civil Aviation Authority (CAA) – Updates may be required to the risk register to identify the site to any flying vehicles
- Department for Transport (DfT) – Guidance for the safe and secure handling and transportation of hydrogen

Depending on the location and scope of the NEH plant relevant regulator, government bodies and licensees should be identified and should be engaged as soon as possible.

For the purpose of this handbook, it is assumed that that the equipment (including pipework) on the NPS will be owned by the nuclear site (hence within the scope of the ONR) while the equipment/plant outside the nuclear site boundary will be owned by non-nuclear operator (scope of HSE) of the NEH Plant.

Proposed regulatory engagement strategy

Both ONR and HSE will be involved for the NEH system. HSE will be the main regulator for the hydrogen site assessment. All components within the hydrogen site are regulated by HSE, unless they can affect the NPS. ONR will perform the role of the HSE for hydrogen plants on nuclear sites. The regulatory approach will need to be defined for each project, it is likely there will be benefits in having the HSE regulate hydrogen production safety outside the licensed site, however, it is likely that ONR would want to be involved.

Case-by-case approach: The use of ONR and/or HSE needs to be considered on a case-by-case basis with HSE handling most of the hydrogen site's safety assessment but collaborating with ONR where interactions with the NPS are possible. For example, the impact of the hazards from the NEH facility on the nuclear reactor will be dependent on the design of the facility and must be carefully discussed and agreed between both safety regulators.

A process of early engagement with the regulators, to show them the technology and the latest knowledge on the subject, could be helpful to agree approaches and identify key issues. Proactively engaging ONR, HSE, and Environmental Agency (EA, or SEPA or NRW) on the hydrogen-nuclear integration would result in a more efficient regulatory process and save time and money. It will be of paramount importance to discuss the organisational aspects relating to the ownership, operation and maintenance of the hydrogen facility. Where the hydrogen facility is not going to be owned, operated or maintained by the nuclear site licence holder the arrangements for licence compliance must be addressed as part of the engagements between the site operators and the regulators. The requesting party is the organisation responsible for submitting a formal request or proposal to a regulator, such as ONR, HSE and environmental agency for review and approval. The arrangements for requesting permission e.g., the order and responsibility for the first proposal, will need to be discussed and agreed with all the regulators as early as possible during any future developments.

COMAH: Discussion with COMAH regulators is required to demonstrate the risk from the stored hydrogen is ALARP. COMAH limits were also a reason to not combine the nuclear and hydrogen sites. COMAH tiers depend mainly on how much high-pressure storage is required. The COMAH Regulations are enforced at an establishment by a Competent Authority (CA). Similar arrangements are in place for the PSSR and DSEAR regulations. Following agreement between the Health and Safety Executive, the Office for Nuclear Regulation, the Environment Agency, the Natural Resources Wales, and the Scottish Environment Protection Agency the relevant regulators for nuclear and other establishments have been defined as:

1. for a nuclear establishment: ONR and the appropriate environment agency acting jointly;
2. for any other establishment: HSE and the appropriate environment agency acting jointly.

Engagement plan: There is a need to develop a plan for early engagement with regulators and share an initial concept. The strategy should be to start exploratory conversations with ONR, then HSE on regulatory aspects, including site licensing, environmental and safety assessments, and systems for controlling the interfaces. Once the safety regulators have been briefed on the approach the other regulators and government bodies should be included in the relevant communications to raise awareness as the project progresses.

Utilising early engagement to improve the licensing and safety of new NPSs is already being recommended by the ONR and EA. Together they have developed high level guidance in their publication "New Nuclear Power Plants: Early Engagement for Regulatory Pathways" (ONR-GDA-GD-009), which aims to provide advice regarding early engagement with respect to the Generic Design Assessment of new nuclear reactor designs. It is recommended that a similar approach is followed.

The advice is not mandatory or prescriptive but recommends joint objectives for early engagement when the Generic Design Assessment is carried out. The advice is as follows:

- To facilitate access to regulators as early as possible, out with more formal processes, so that the project can benefit from advice and guidance early on in the design and licensing of a facility.
- To gain confidence that the potential development can meet regulatory expectations so that the regulator can make informed decisions how to deploy its regulatory resource.

The early engagement process should aim to use the following structure:

Introductory engagement: conduct a one-day engagement workshop to discuss the outline of the proposal with the regulators. This is seen as a pre-requisite for subsequent engagements allowing the regulators and developers to assess the next steps and areas of regulatory interest.

Technical and Process Engagements: these will allow more detailed discussions of the technology/design and the arrangements for its management. These engagements will be based on the areas of interest and the outcome of previous engagements.

Preliminary Design Review: this will be a technical review of certain aspects of the design based on submissions to the regulator by the applicant. This review allows the regulators to see what a future design might look like and give guidance on the next steps. The purpose of these engagements is not to provide indication that a design will be successfully accepted. A formal application for a licence will need to be made once the design has matured sufficiently and the initial safety assessments have been carried out.

Use of this structure is seen as best practice; a similar approach should be applied to the development of facilities where cogeneration of hydrogen and nuclear power is planned.

9. OBTAINING PLANNING PERMISSIONS

Key messages

- NEH Projects could obtain planning consent either via the same process as a new nuclear development (via the Planning Act 2008, as a Nationally Significant Infrastructure Project), or via a separate proposal (under the Town and Country Planning Act 1990).
- Whilst there is no relevant planning guidance on the size at which hydrogen production projects should be treated as Nationally Significant Infrastructure Projects, a 24MW would be unlikely to fall within this unless done as part of a larger new nuclear development.
- EN-6 (pre-existing National Policy Statement for nuclear generation) identifies sites suitable for new nuclear development. However, the government is consulting on EN-7 (the proposed new National Policy Statement for nuclear power generation), which is proposed to facilitate a more diverse range of sites by introducing a criteria-based approach for site identification.
- An Environmental Impact Assessment is likely to be required for a commercial scale facility. This could either be performed as a stand-alone assessment for the facility, or as part of the assessment for a nuclear development.

This chapter provides an overview of the key considerations that a prospective developer should be mindful of when looking to bring a scheme forward with respect to securing planning consent. The information provided is high-level and not intended to be exhaustive, noting each project will have its own individual considerations owing to the size, scale, design and setting of the development within the existing land use and surrounding environment.

Currently the Scottish government maintains an effective ban on new nuclear power related development. The information provided here is therefore focussed on the planning regimes relevant for developments in England and Wales.

Potential routes to securing planning consent

There are two potential scenarios which can be contemplated when considering the planning context for a NEH project:

- In the first scenario the NEH project is proposed from the outset as an integral part of a wider new nuclear development, and planning permission for the NEH project is sought at the same time and via the same overall process as the new nuclear development.
- In the second scenario the NEH project is a separate and later proposal, most likely in relation to an existing operational NPS or potentially to one which is still under construction, and planning permission for the project is consequently sought separately for the NEH project in isolation.

The routes to securing planning consent for the NEH project are likely to differ between these two scenarios.

In the first scenario, where the NEH project is an integral element of the main new nuclear development, consent for the new nuclear facility, including the NEH project element, would be sought via the Planning Act 2008 (PA 2008) as a Nationally Significant Infrastructure Project (NSIP).

In the second scenario, where approval for the NEH project is being sought at a later date on a stand-alone basis, this would most likely be via an application to the relevant local authority under the Town and Country Planning Act 1990 (TCPA). In principle a large NEH project could be treated as a NSIP in its own right – however as yet there is no relevant planning guidance on the size at which hydrogen production projects should be treated as NSIPs and the 24MW project considered in this handbook would not be of a scale necessary to justify or merit an NSIP application.

The following sections consider the planning context in a bit more detail for each of these scenarios.

NEH Project as an Integral Element of a New Nuclear Development.

The National Planning Policy Framework (NPPF) and corresponding National Policy Statements provide the strategic framework at a national level relevant for large scale energy infrastructure projects. EN-1[22] provides the overarching policy statement for energy development, and this should be reviewed in conjunction with EN-6[23] for new nuclear related energy. There is currently no hydrogen technology specific national policy statement.

EN-6 is currently under review by the UK government and covers implementation of new nuclear projects up until the period ending 2025. At the time of preparing this handbook the government is currently consulting on a new National Policy Statement for new nuclear developments – EN-7[24]. Key relevant proposals in the latest consultation are that:

- EN-7 will introduce a developer-led criteria-based approach for site identification. It will remove references to deployment time-limits
- EN-7 will encompass emerging new nuclear options such as Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs), as well as established large nuclear developments.
- Legislative changes – a proposed change to the Planning Act will mean the expansion of the scope of the Nationally Significant Infrastructure Project regime to include non-power outputs of new NPSs such as heat and synthetic fuels, which could include associated hydrogen production and hydrogen-derived fuels.
- Developers will now lead site identification and site assessments, instead of the government, requiring significant up-front engagement with planning and regulatory bodies on their proposed sites.

The approach adopted by the draft EN-7 aims to facilitate a more diverse range of potential new nuclear site options, while continuing to identify the sites identified in EN-6 as potentially suitable for new nuclear development.

Under the new EN-7 framework it will still be necessary for any new nuclear development to have secured GDA approval for its proposed design. The ONR working with Environment Agency (England) and Natural Resource Wales (Wales) manage the Generic Design Assessment[25] process which if successful provides Design Acceptance Confirmation. The objective of the GDA process is to provide confidence that the proposed design is capable of being constructed, operated and decommissioned in accordance with the standards of safety, security, waste management, safeguards and environment protection required. Whilst this is a separate process to obtaining a planning consent GDA approval should be undertaken first to provide the necessary technical assurances in support of a planning application.

Projects that constitute a NSIP are assessed against the National Policy Statements for energy infrastructure, alongside environmental and other principles. The Secretary of State is the decision-maker for onshore stations generating more than 50 MW in England and 350MW in Wales, with permission granted via a Development Consent Order (DCO). The developer should note the extended timeline in securing a NSIP consent is upwards of 3.5 years – this figure is based on indicative timescales set out for the NSIP process provided by the government. The government's National Infrastructure Planning website[26] provides further details on the planning process to be followed for NSIPs, the requirements for pre-application consultation and a wide range of other relevant guidance

NEH Project as a Stand-Alone application

In this scenario the project will likely seek to secure planning consent via an application to the relevant local planning authority under the TCPA. It is reasonable to assume that planning consent via the TCPA route could be secured in 12–24-month period on the basis a suitable level of design maturity being established early enough in the programme to support the preparation of a planning application. The Local Planning Authority are the decision-making authority for TCPA applications.

22. *Overarching National Policy Statement for Energy (EN-1), DESNZ (November 2023)*
23. *National Policy Statement for nuclear power generation (EN-6), DESNZ (July 2011)*
24 *https://www.gov.uk/government/consultations/draft-national-policy-statement-for-nuclear-energy-generation-en-7*
25. *Assessment of reactors, Office for Nuclear Reaction (2022-2023)*
26. *National Infrastructure Planning, The Planning inspectorate, 2014 edition (last version, January 2020)*

General guidance from the NPPF will remain relevant to the application and to the local authority's consideration of it, this will include relevant sections of the NPPF which highlight the national importance of developing sources of cleaner and lower carbon energy. In addition, the application should also be mindful of relevant local plans which are publicly available on local authority websites. These guide how the relevant local authorities are required to consider future development proposals that come forward to ensure the needs and opportunities of the local area are duly considered.

A NEH scheme therefore needs to be cognisant of the Local Plan relevant to the jurisdiction in which the development is proposed. The scheme should look to demonstrate how its implementation will support the objectives of the Local Plan on a range of cross cutting matters such as employment provision, infrastructure provision, climate change mitigation and adaption, conservation, and enhancement of the natural environment. Schemes that demonstrate attributes in support of the Local Plan objectives will stand an increased probability of successfully securing consent.

Environmental impact assessment

Irrespective of whether consent is sought as part of, and at the same time as, a wider National Policy Statement, or via a stand-alone application, some element of environmental impact assessment (EIA) relating to the NEH facility is likely to be required within the application. The aim of EIA is to protect the environment by ensuring that a determining authority when deciding whether to grant permission, which is likely to have significant effects on the environment, does so in the full knowledge of the likely significant effects, and takes this into account in the decision-making process. The extent of environmental assessment will depend on the size of the NEH facility and its corresponding scale of potential environmental impacts. Where an EIA is required then it is usually submitted in support of the planning application.

The EIA process requires applicants to systematically evaluate the potential for significant environmental effects to occur as a result of the proposed development. This is achieved through assessing the potential impacts of the proposed development against the current baseline i.e., pre-development and done through assessing tolerability i.e. sensitivity of associated receptors to any changes arising from the development. A broad range of topics can fall within the scope of an EIA and include but are not limited to; air quality, climate change, noise and vibration, traffic and transport, socioeconomics, major accidents and disasters, waste and raw materials, biodiversity, soils, geology and hydrogeology, surface water and flood risk, human-health.

EIA is mandatory for all commercial new nuclear power related infrastructure under The Infrastructure Planning (Environmental Impact Assessment) Regulations 2017 as Schedule 1 development[27]. Where a NEH facility is integrated into an application for a new nuclear development, the EIA would need to take account of any specific or additional environmental impacts of the NEH facility and ensure these are considered and addressed, with appropriate mitigations proposed where significant impacts are identified, within the overall EIA.

For hydrogen electrolyser schemes subject to a stand-alone application an EIA may well be required subject to an understanding of the description and the scale of the development against the threshold criteria stated in Schedule 2 of The Town and Country Planning (Environmental Impact Assessment) regulations 2017[28]. A 24 MW hydrogen electrolyser of the kind considered in this handbook would be likely to require some form of EIA.

---

[27] The Infrastructure Planning (Environmental Impact Assessment) Regulations 2017 – Paragraph 2, legislation.gov.uk
[28] The Town and Country Planning (Environmental Impact Assessment) Regulations 2017- Schedule 2, legislation.gov.uk

10. HOW A PROJECT COULD BE DELIVERED

Key messages

- A dedicated entity to deliver the NEH Facility (potentially including hydrogen storage) is recommended. This may or may not include the NPS. A legal entity that owns the NEH Facility could be made of nuclear power station, off-takers, distributors, landowners, and other funders/developers.
- Based on the 24MW concept, an indicative cost would be approximately £88m (£82m NEH facility, £6m for the NPS modifications). This makes the NPS modifications less than 7% of the total cost. Total costs could be reduced depending on off-takers requirements (purity, volume, distribution).
- Using information within the handbook, the indicative timeline for the project could be 36 months.

Ownership model

The ownership structure of a hydrogen production facility is not predetermined, and a number of different approaches could be adopted.

The facility could be fully owned and operated by the NPS owner, with hydrogen production powered by nuclear electricity and heat being viewed as an integral element of the energy and fuel production of the overall facility. This can sometimes be described as a "nuclear energy hub" model, where the nuclear facility is at the heart of a site which provides a range of energy products and services.

Alternatively, the NPS could simply provide electricity and heat under contract to the hydrogen production plant, with no wider commercial relationship between the two facilities. In this arrangement the NPS owner would own all the equipment within the NPS boundary fence and probably the steam pipelines up to the inlet to the SOEC electrolyser. A primary interest for the NPS owner would be to ensure that the hydrogen production plant was a safe distance from the NPS and did not present an unacceptable hazard. The primary commercial interest of the NPS owner would be to supply the plant with electricity and heat which would be done through an off-take agreement.

An intermediate option between these two scenarios could see the nuclear operator hold a partial stake in the hydrogen production plant.

Regardless of the precise ownership model, the development, construction and then operation of the hydrogen production project will require a range of contractual relationship to be put in place, as set out in Figure 14 below.

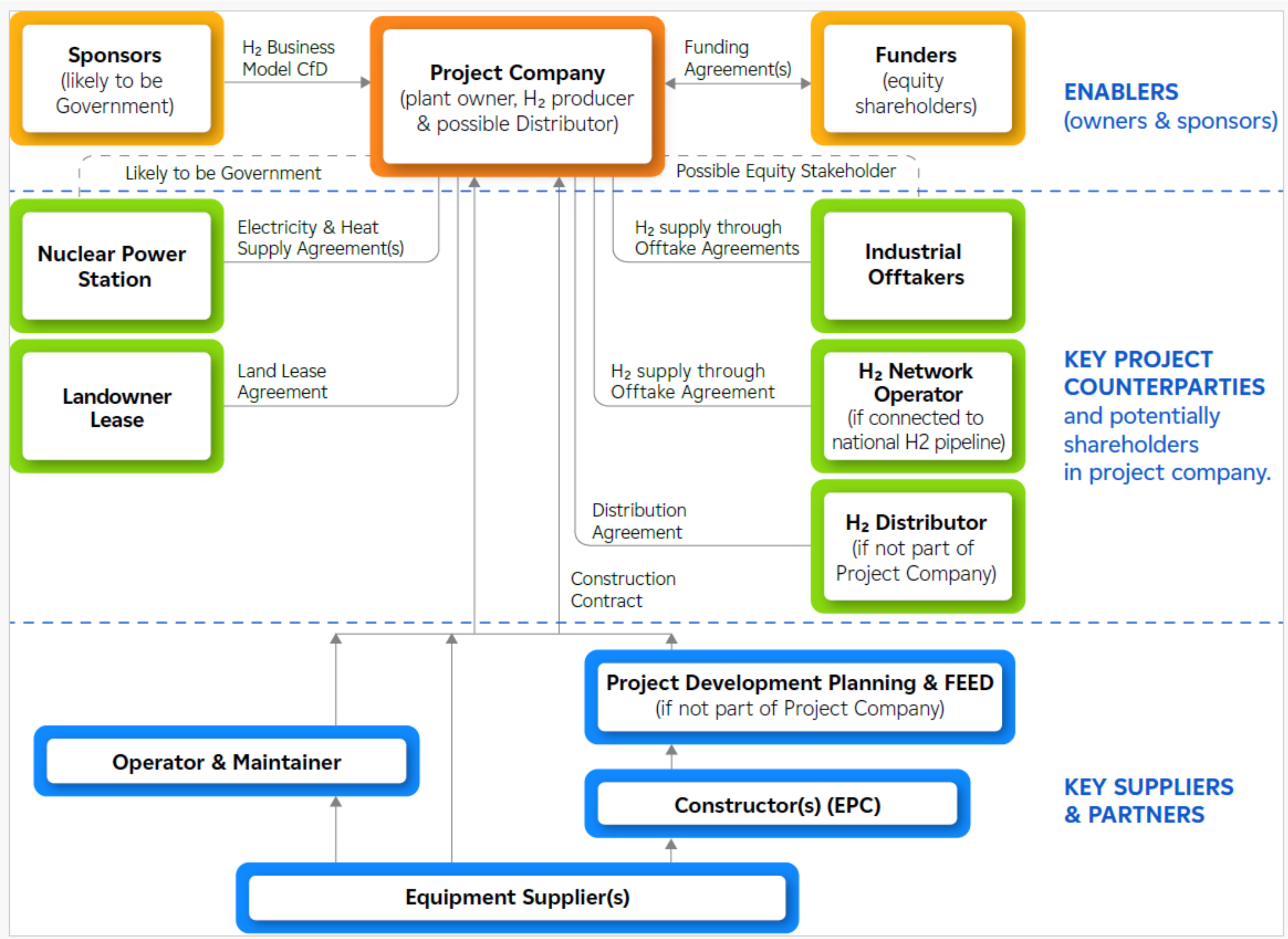


Figure 14 Diagram illustrating key contractual relationships for a Nuclear Enabled Hydrogen project.

At the heart of the structure is the project company, which as well as ownership of the production and storage facility could also be a distributor of the hydrogen produced. The project company will require funders (providing equity and potentially debt). Subject to the policy support framework applicable for hydrogen production at the time, the project could seek subsidy support from the government's Hydrogen Production Business Model (HPBM) scheme, which provides a form of Contract for Difference (CfD).

Key counterparties for the project company will be the hydrogen off-takers and energy supplier. Either or both the off-taker and energy supplier may have an equity stake in the project company. In addition, a land lease may be required and a hydrogen distribution agreement if that is not done directly by the project company. If the project includes a connection into a hydrogen pipe network, there will need to be an off-take agreement with the network operator.

The project company is typically responsible for developing the project but would often contract out a range of functions including planning, front-end engineering design and construction delivery. The project company could also appoint a developer to oversee the project development.

Importantly, this ownership model does not assume the NPS is the owner of the production and storage facility. This means that likely a separate operator would be appointed for the facility. For NEH, this both reduces the burden on NPS staff and means operators of the hydrogen facility would not necessarily need to have the same levels of nuclear training or security clearances as nuclear power station staff.

Off-takers and storage

The commercial concept models a range of possible off-takers, SUPPORTING TABLES, Table 12 (SUPPORTING TABLES), and reflects various needs for both asphalt and cement production industries (cement is illustrative of industry with continuous demand for fuel and asphalt for semi-continuous), along with other likely off-takers, including supplies to NPSs, that typically use hydrogen for generator cooling and chemistry purposes, and with other industrial uses, transport, pipeline and generation off-takers designed to reflect a future energy hub likely to develop as a hydrogen economy develops. The off-takers selected reflect the opportunities present in and around existing and future designated NPSs.

The storage volumes included in the concept, Table 13 (SUPPORTING TABLES), and the location and type of storage have been selected to match the industrial and flexibility requirements needed for an optimised hydrogen production and distribution centre. The actual storage requirements for a commercial project, will be strongly influenced by capital cost, future government support mechanisms for storage, the needs of off-takers and market conditions.

Cost estimate

The majority of costs for an NEH project would be the same as with a conventional hydrogen project. However, there is the additional cost of the work required on the nuclear site, such as to update the nuclear safety case and procedures, as well as install equipment to enable export of heat. This will increase the Development Expenditure (DEVEX) and CAPEX costs slightly. These costs have been estimated as the "Heat Supply costs" in the cost estimate provided below. Which partner is responsible for paying these additional costs could depend on the ownership arrangements adopted for the NEH facility and may be the subject of commercial negotiation. In exchange for these increased costs, operational costs per kg of hydrogen will be lower, due to the improved efficiency due to the provision of nuclear heat, and/or the reduced cost of electricity due to it being provided via a private network.

Cost estimates for an example 24MW Project have been presented below. Costs not included within the Heat Supply Costs have been described as "NEH Facility Costs". A more detailed cost breakdown is available in Reference 14 (NEH 24MWe Design Study). These costs do not include any site-specific costs, such as the purchase/lease of land or the cost of setting up a private network between the NPS and hydrogen plant (the cost of which is highly variable depending on the electrical infrastructure of the site).

The cost estimate has been produced as of December 2024, using a combination of Association for the Advancement of Cost Engineering (AACE) Class 3 and Class 4 methods. This includes using budgetary quotations from previous work, use of existing cost models, recent experience of similar projects, and cost estimation reference sources such as SPON's, CESK, and Compass International. An overall uncertainty of +30%/-20% is appropriate for NEH Facility Costs, whereas a higher uncertainty such as +50%/-30% should be assumed for the heat supply costs, due to the potential for site specific factors to affect the cost. Whilst there is potential for site specific factors to affect the NEH Facility costs too, the main area affected would likely be the civil costs, which are a relatively small proportion of the overall costs.

The contingency costs have not been included within the budget, although Reference 14 (NEH 24MWe Design Study) provides advice on potential contingency levels to consider for specific contracts. The advised contingencies are consistent overall with the uncertainty levels stated above. This cost estimate has been produced as of December 2024, and no allowance has been made for escalation.

Note that this is the cost for the whole 24MW system as presented in this handbook. In practice, it is likely that a smaller range of off-takers will be used than has been assumed. Therefore, it is likely that the CAPEX cost for NEH Facility equipment will correspondingly be lower.

Table 5 Estimated costs of a 24MW Nuclear Enabled Hydrogen facility connected to a nuclear power.

Description	NEH-Facility Costs	Heat Supply Costs	Notes
Process Equipment	£41,987,000	£218,000	Includes electrolysers, compressors, heat exchangers, dryers, purification, tanks, storage, trailer filling station, water treatment, chillers, pumps, air and nitrogen generation, odorising station
Civil works	£4,059,000	£1,095,000	
Pipework	£924,000	£414,000	
Electrical	£2,433,000	£235,000	Excludes costs of setting up private network.
Control & Instrumentation	£338,000	£469,000	
Install and Commissioning	£3,587,000	£1,481,000	
Equipment transport	£1,161,000	N/A	Transport costs for process equipment.
Design	£14,244,000	£1,331,000	Includes production of procurement specifications and safety assessments.
Project Management	£6,702,000	£871,000	Includes procurement management
Contractor markup	£6.894,000	N/A	Contractor markup already included within estimates for heat supply costs.
Permit applications	£120,000	£30,000	Very approximate costs as assessments required will vary based on site
Total Costs:	£82,449,000	£6,144,000	
Grand Total: £88.6M			

Project delivery schedule

A NEH project can be split into a number of key milestones:

Table 6 An example of a NEH project delivery schedule.

Milestone	Date
Agreements signed between Nuclear Power Site and Hydrogen Facility	Month 2
Site-Specific FEED Complete	Month 7
Planning Application Submission	Month 8
Key Contracts Signed	Month 9
Detailed Design Completed	Month 12
Begin work on Pre-Commencement conditions	Month 13
Planning Pre-Commencement Determination Completed & Environmental Permit issued	Month 17
Civil Works Start	Month 21
Civil Works Completed	Month 27
Mechanical & Electrical Works Start	Month 28
Mechanical & Electrical Installation completed	Month 34
Commissioning Completed	Month 35
Commercial Operations Start Date	Month 36

Whilst this handbook provides elements of a FEED study that can be used as a starting point, a further site-specific pre-FEED and FEED would be required prior to detailed design. This additional design work will need to tailor the information within the handbook to the specific project and analyse site specific conditions. A stage gate for the project should be held after this site-specific FEED, as shortly afterwards key contracts would be due to be placed and therefore there is a risk that significant spend would need to be committed to.

Work for the NPS includes tapping-off steam, installation of a heat exchanger, and update of the safety case for the site and implementation of any required risk mitigations identified by the safety case. This work would likely be delivered by the NPS site operator, to ensure the correct procedures are complied with to maintain nuclear safety. At minimum, the NPS will need to maintain intelligent client oversight of the work to comply with their site licence conditions, even if they subcontract out significant portions. A planning application under the TCPA regime has been included within the schedule as captured in Table 6. However, this may not be required to commence the work on the NPS if it falls within their permitted development rights. In any case, for work off the nuclear site, a planning application will still be required.

Work for the project company (including suppliers, such as the constructor) includes a planning application submission, procurement, installation, and commissioning of all equipment outside the site fence, and negotiation of commercial agreements (e.g. with the NPS or with end users), and installation of pipework between the hydrogen plant and the NPS (although this could be undertaken by the NPS too, depending on the details of the commercial arrangements). Information from the design phase of the NEH facility will need to feed into the safety case development for the NPS. Other than these additional interfaces, the schedule for the off-site work is broadly similar to any other hydrogen development project.

A Level 1 schedule, produced based on previous experience, is presented in Figure 33 (SUPPORTING FIGURES). A more detailed schedule is available Reference 15 (Project Delivery Schedule) - Level 2 schedule. The project schedule assumes work will be procured via two design & build contracts; civils scope, and mechanical and electrical (M&E) scope. The electrolyser would be procured by the Project Company and free issued to the M&E contractor. The M&E contractor would be responsible for procurement of all other process equipment.

11. COMMERCIAL ANALYSIS

Key messages

- Nuclear enabled hydrogen can provide reliable and cheaper low carbon hydrogen, to meet a range of off-taker needs. The Levelized Cost of Hydrogen (LCOH) would be £6-7/kgH2, using the technology currently available. This figure is underpinned by commercial modelling presented in the handbook, assuming a non-optimal set of diverse off-takers.
- The LCOH could be further reduced with economies of scale, future improvements in the supply chain, and optimising the production around the specific end user.
- Based on the concept developed within this handbook LCOH compares favourably to HAR1 (Hydrogen Allocation Round 1) of £9.5/kg.
- Modelled operation of a commercial-scale SOEC shows flexibility for a nuclear plant with power export. Hydrogen output can be varied, to minimise the cost of hydrogen, and enable export of electricity during periods of high demand. However, the SOEC's high-temperature process requirements, and the commercial need for a high-capacity, factor limit this flexibility somewhat.

The purpose of this chapter is to develop a business case for a commercial scale plant – 24MW SOEC integrated with a generic NPS to supply low-carbon hydrogen to various off-takers.

The 24MW plant concept was used for the commercial analysis work. This considered the off-taker demands for hydrogen and the hydrogen storage available as the parameters to calculate the cost of the hydrogen produced. In the commercial analysis actual power and heat prices (for 2023 and 2024) were used to calculate both the operational cost of the hydrogen produced and the levelised cost of providing hydrogen to a particular off-taker.

It should be noted that the concept was not designed to provide the lowest levelised cost of hydrogen but rather to reflect the range of possible off-takers. In addition, the volume of hydrogen storage available has not been optimised, instead what are considered reasonable, perhaps minimal storage levels have been used to demonstrate how storage can provide some production flexibility.

The proposed business model presented in this chapter adopts a holistic perspective on the entire supply chain, including interactions between the nuclear site and hydrogen production site, fluctuations in electricity prices, and the necessary equipment such as compressors, purification systems, and storage. Furthermore, a variety of off-takers, including continuous, semi-continuous, fixed and seasonal are considered to provide a comprehensive analysis.

Optimising hydrogen production

Hydrogen production needs to meet the requirements of off-takers as set down in an off-take agreement between the parties. When wholesale electricity prices are lower hydrogen production costs will also be lower as electricity price and the cost of heat combined are by far the greatest variable cost in the production of electrolytic hydrogen from SOEC.

In this concept there is a requirement to supply hydrogen to a cement works, a 24/7 business, on what is referred to as a semi-continuous basis. Semi-continuous because it is recognised there will be periods when the hydrogen production plant will be shut down for planned or unplanned reasons and the cement plant will need access to a back-up fuel. It is reasonable to assume that the periods when the cement plant is operating on backup fuel will be limited, either through legislation, if it is not a low carbon fuel, or commercially if it is a more expensive fuel than hydrogen.

The other off-takers do not require hydrogen on a continuous basis, and storage either at the hydrogen production site and/or at the industrial site will allow production flexibility, this is the concept adopted for asphalt sites. This ability to adjust the rate of hydrogen production allows the electrical demand from the NPS to be effectively decreased in times of system need or when power prices are high, by reducing the rate of hydrogen production.

In this concept we have included what are considered appropriate low levels of storage to support this commercial concept. The volumes included provide additional production flexibility. Looking ahead, there could be future support mechanism for hydrogen storage beyond geological solutions, which could influence actual levels of storage combined with location suitability and safety risks.

Revenue & market modelling

The assessment of market revenues for the NEH facility was completed using EDF's in house proprietary Nuclear Energy Hub optimisation algorithm, which models a NPS connected to the grid and co-located with a Solid Oxide Electrolyser. In this revenue and market optimisation algorithm, both the Day-Ahead (DA) market and hydrogen market were considered. Although power from British NPSs has traditionally been sold in forward markets as baseload, the Day-Ahead market is chosen for the modelling described here to study the impact of price variation over shorter timescales on electrolyser operation. The model decides on the quantity of electricity and hydrogen produced in response to pricing signals of the Day-Ahead electricity and hydrogen market, respectively.

All energy hub electric and thermal (heat) power is sourced from the nuclear plant (grid connection is export only). The modelled structure of the nuclear plant and SOEC is given by the diagram below.

The nuclear plant has full operational availability. The electric power generated is either exported to the grid or used by the SOEC. The changes in electric power generated are limited by a ramp rate and a minimum down time. Steam tapped for the SOEC reduces the electric power produced via loss rates dependent on tapping quantity and location.

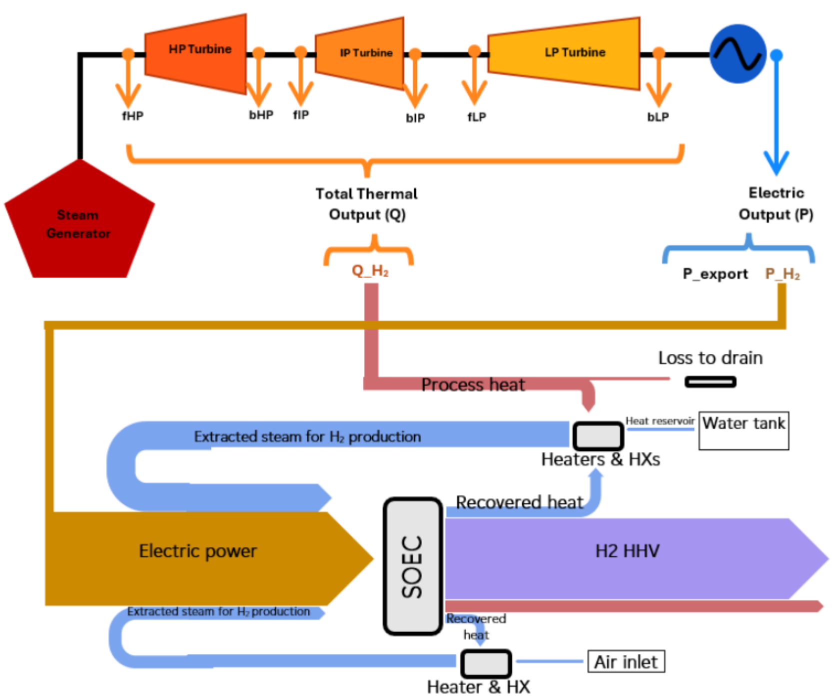


Figure 15 An example of a nuclear plant integrated with a solid oxide electrolyser – modelled structure. (High (HP), Intermediate (IP) and Low (LP) Pressure; f- (front inlet), b- (back inlet)).

The SOEC was modelled to be in 2 different states: On and Stand-by. In On state, the SOEC operates within its feasible electric power range to produce hydrogen. In Stand-by, the SOEC does not produce hydrogen but consumes the power needed to maintain its operational temperature so it can rapidly resume production when required. The Off state was not modelled because the SOEC is assumed not to be shut down more than 2-3 times a year. The electric and heat input from the nuclear plant cover electrolysis as well as the peripheral loads of heating devices for the water and air inlet streams. The specific load of non-heating devices is neglected as they have a much lower power requirement than the stack and heating devices, with overall system parameters capturing their efficiency impact. Hydrogen output is modelled as a piece-wise linear function of the input stack electric power which translates into a non-linear efficiency.

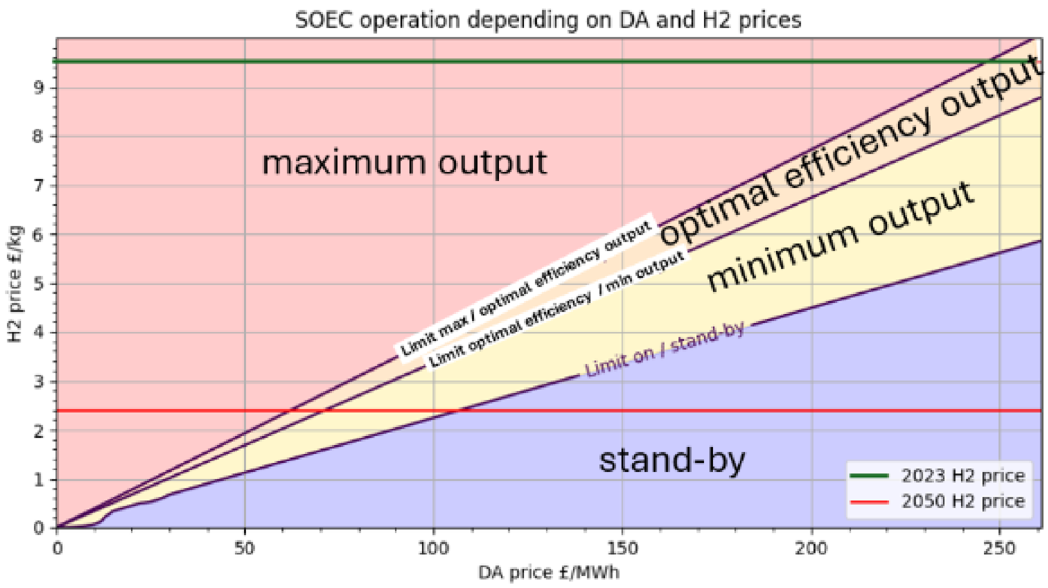
Several scenarios[29] were considered for the revenue and market analysis:

- a counterfactual scenario with the NPS alone (no electrolyser)
- scenarios with a typical AGR plant and a SOEC of a given capacity (1MW, 5MW and 100MW were considered)
- a scenario where the AGR was replaced by a typical European Pressurized Reactor (EPR), representative of SZC
- a scenario where the SOEC was replaced by a PEM electrolyser

Each scenario was run twice: once with 2023 observed Day-Ahead prices[30] and hydrogen prices, and once with 2050 projected Day-Ahead[31] and hydrogen prices. Since there is no existing hydrogen market, the 2023 hydrogen price was inferred from a government auction[32] and kept constant over the year, and the 2050 price was inferred from an Aurora report[33] and kept constant over the year.

An assessment of the listed scenarios showed that co-locating an electrolyser in the nuclear energy hub unlocks revenues from the hydrogen market, in addition to revenues from the Day-Ahead electricity market, compared to the counterfactual scenario. Further analysis shows that the additional revenues are proportional to the size of the SOEC and driven by Day-Ahead electricity and hydrogen prices. The relationship between Day-Ahead and hydrogen prices related to SOEC operation is summarised in Figure 16. A sensitivity analysis to evaluate the response of the system to different Day-Ahead electricity and hydrogen prices showed that hydrogen is produced, and at a given output level, when the flat rate hydrogen price is competitive with the Day Ahead prices, i.e. when the Day-Ahead prices are within a corresponding "hydrogen-competitive range (zone located above the blue area).

The diagram shows that hydrogen is produced at a given (minimum to maximum) output level when the Day Ahead (DA) prices are within a corresponding competitive range (yellow to red region). In the optimal efficiency (orange) region hydrogen is produced at the most efficient stack load according to the non-linear efficiency modelled (where the peak occurs between minimum & maximum loads). The minimum output region corresponds to higher revenues achieved from electricity sales, but not to a sufficient extent to cover the additional costs of electrolyser stand-by mode as the model excludes a full shut down state. Thus, our scenarios with 2023 DA and hydrogen prices led to more frequent production of hydrogen because DA prices stay in the hydrogen-competitive range more often than in 2050.



---

[29] Note: The scenarios have been chosen so both high temperature and low temperature steam is modelled, other reactor designs can be used.
[30] 2023, Nordpool prices.
[31] AFRY predicted prices.
[32] Hydrogen Production Business Model / Net Zero Hydrogen Fund: HAR1 successful projects, DESNZ (December 2023).
[33] Hydrogen for a net zero GB: an integrated energy market perspective , Aurora Energy Research (June 24, 2020).

Figure 16 The sensitivity analysis for each scenario - response of the system to the different Day-Ahead electricity and hydrogen prices.

This graph holds regardless of the type of NPS, SOEC capacity or choice of wholesale electricity market.
However, a sensitivity analysis conducted by varying the SOEC minimum output (from the lowest permitted stack load when the electrolyser is in its 'on' state) shows that the higher the minimum output, the steeper the limit between on and stand-by on the graph shown by the lowest of 3 black lines. This limit also changes with the type of electrolyser: with a PEM electrolyser, the stand-by region (which requires less electric energy) is larger due to its low efficiency and low temperature nature compared to the SOEC unit[34].

Commercial operation

Hydrogen off-taker modelling for the 24MW Solid Oxide Electrolyser plant concept builds on the original detailed SOEC dispatch model taking electrical & thermal power supply from a NPS, the development of which is described in the Revenue & Market Modelling section above. The main changes are as follows:

- Hydrogen plant scale: linear scaling applied to 1MW plant parameters to scale up to 24MW
- Optimisation approach: only electricity market revenues optimised, hydrogen off-taker demand must be met in full
- Hydrogen power cost: instead of hydrogen market revenues, output the £/kg contribution of electrolyser & auxiliary power to the cost of hydrogen production
- Nuclear output: restrict to constant reactor output (baseload operation), allow variable share of power generated available as supply to electrolyser

The hydrogen off-takers are configured as in the overall plant concept description – cement (primary off-taker), transport, asphalt & nuclear sites have total demand converted into half-hourly profiles, with peaking plant operation optimised for electricity market revenues and a "dump" off-taker (e.g. strategic storage) representing periods of spare electrolyser capacity in lieu of a defined demand or revenue incentive. Each off-taker has some storage associated as in the concept, either static tanks along with pipeline supply (cement & transport) or as tube trailers (asphalt & nuclear sites) allowing for flexible operation & production shifting to lower price periods. Auxiliary process power requirements are also included for compression (1 or 2 stages), drying & purification proportional to hydrogen production rates. Off-takers' configurations are summarised in the Table 7 below, with a chart showing weekly demand profiles in Figure 27 (SUPPORTING FIGURES).

Table 7 Off-takers hydrogen requirements details.

Off-taker	Hydrogen Demand Profile	Storage	Auxiliary Processes	Notes
Cement	Constant 268 kg/h across all periods	1t static tank Max flow 250 kg/h	2.34 kWh/kg (30 bar compression, drying)	Max flow rate less than 268 kg/h constant demand
Transport	Profile adapted from NREL Hydrogen Retail Station data[35] & scaled to give total of 10t per week	1t static tank Max flow 250 kg/h	4.84 kWh/kg (250 bar compression, drying, purification)	Static tank combines various filling station processes, allows simultaneous filling & discharge No seasonal or daily variation

[34] *Typically, in ON state, PEM electrolyser uses higher electric energy to produce hydrogen compared to SOEC due to its low efficiency. However, in the modelling, the stand-by mode is equivalent to OFF-mode since there is no need to heat the inlet air and water streams. This mode effectively gave PEM electrolyser the possibility to shut down, especially during long periods of negative day-ahead prices and when it was not valuable to produce hydrogen compared to the SOEC unit.*

[35] *Next Generation Hydrogen Station Composite Data Products: Retail Stations – Summer 2022: Data Through Quarter 2 of 2022, Saur et al. 2023. https://www.nrel.gov/docs/fy23osti/86247.pdf*

Asphalt	Total demand 212.5 kg/h only during 5 day working week, flat across assumed site operating hours 06:00-22:00	4x 1t tube trailers Max flow 125 kg/h 2 bays at SOEC facility	4.34 kWh/kg (250 bar compression, drying)	2 asphalt sites supplied, trailers operate 2x2 switching at site outside working hours & at 14:00 Minimum 3h for trailer transit
Nuclear Sites	Total 2.26 kg/h on average (required as 1 trailer change per site per month)	10x 0.33t tube trailers (for 5 nuclear sites) Max flow 110 kg/h, 1 bay at SOEC facility	4.84 kWh/kg (250 bar compression, drying, purification)	Total trailer movements 60/year, swap full/empty at facility during defined time & day windows

As the modelling described here optimises revenues from nuclear power dispatch while meeting hydrogen demand requirements, the resulting electrolyser operation minimises the cost of power for hydrogen production to supply the various off-takers. Values for each off-taker i cost of power for hydrogen production λ_i are calculated according to the following formula, where in each of the n periods λ_P is the wholesale electric power price, P_{H2} is the electric power supplied to the electrolyser accounting for heat if nuclear steam is in use, P_{aux} is the power supplied to auxiliary processes, and $m_{H2,i}$ is the specific mass of hydrogen supplied to off-taker i from the total m_{H2} produced by the electrolyser:

$$\lambda_i = \frac{\sum_n \lambda_P \cdot (P_{H2} + P_{aux}) \cdot \frac{m_{H2,i}}{m_{H2}}}{\sum_n m_{H2,i}}$$

The model is run for 2 electricity price scenarios (both from day ahead wholesale markets, shown in Figure 28)– for 2023 taking European Power Exchange (EPEX) hourly auction prices (same as Revenue & Market Modelling scenario) and for 2024 taking volume weighted average of EPEX & Nordpool N2EX hourly prices. Results from these 2 scenarios are given in Table 8 below:

Table 8 Modelled cost of power supplied to electrolyser to produce hydrogen for each off-taker.

Scenario Year	Off-taker Hydrogen Production Power Cost (£/kg)					
	Counterfactual	Cement	Transport	Asphalt	Nuclear Sites	Dump
2023	4.34	3.79	4.14	3.87	3.81	4.92
2024	3.35	2.90	3.13	2.97	1.96	3.90

The counterfactual results correspond to the average cost of electrolyser operation at a flat output level, and line up with the average power prices in £/MWh of 94.00 and 72.51 for 2023 and 2024 respectively. Overall result distributions are shown in Figure 29 (SUPPORTING FIGURES) as histogram, cumulative distributions and utilisation for prices and hydrogen production, from which the impact of production shifting within a narrow price distribution can be seen. The electrolyser operates with an average capacity factor of 72% in both years, with charts in Figure 30 showing this operation over single week periods with different price characteristics for the different off-takers.

Overall, for the core off-takers the presence of storage and some variation in demand profiles allows sufficient shifting of production to lower the power cost below the counterfactual, limited by time windows of higher price levels & low-price spreads. Through this, the model shows a benefit in introducing storage and flexible operation to overall hydrogen costs. Electrolyser operation during a sample 2-week period modelled in 2023 is shown by charts in Figure 17, with a mixed profile of power price spreads. While the modelled operation displays some flexibility particularly in response to the strongest price signals, the electrolyser never switches to stand-by mode, producing at least the volume of hydrogen corresponding to minimum stack load to meet semi-continuous demand. The model operates between minimum and maximum loads based on varying demand & efficiency, however results show this flexibility has a limited ability to shift production to lower price periods due the combination of restrictive off-taker demand requirements and sustained periods of high-power prices.

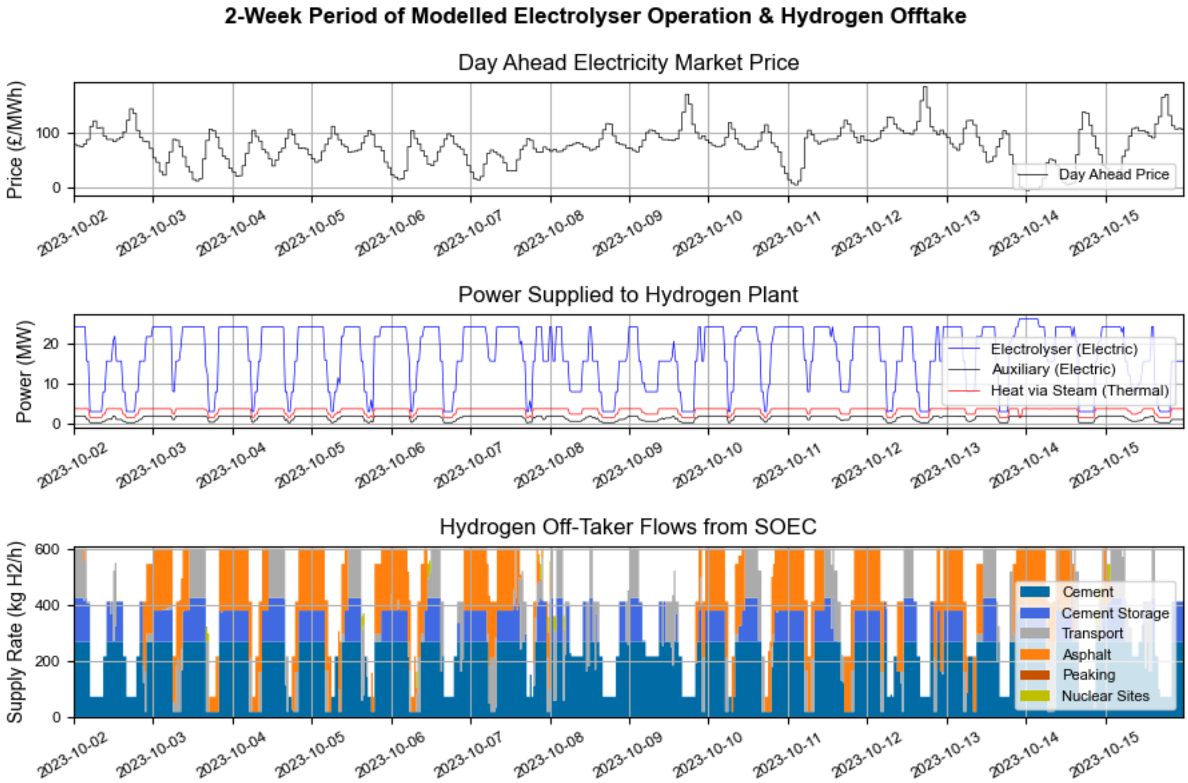


Figure 17 Charts showing modelled operation of commercial hydrogen plant to meet off-taker demand over a sample 2-week period.

The 5MW peaking plant exports power to be sold in the same market as the NPS and due to poor round-trip efficiency, single market choice & positioning last in off-take merit order only operated for 19 & 10.5 hours in 2023 & 2024, so results are not presented in the table for this off-taker. The distribution of periods with spare electrolyser capacity is shown in Figure 31 for the dump off-taker, which shows how the power cost for this falls above the counterfactual but with a large availability just above the average level.

The modelling described is limited by only using a single wholesale electricity market price which compromises between the NPS power trading strategy and peaking plant market position, where multiple markets would be available in both cases. Limitations also apply to auxiliary processes where most hydrogen losses and inefficiencies are neglected, and to the linear scaling from a 1MW to 24MW electrolyser capacity without considering process consolidation.

Levelised Cost of Hydrogen (LCOH)

Scenario 1: Various off-takers

The objective of this work was to calculate the LCOH for different off-takers taking into account that each of them has different requirements (hydrogen volumes, purity, pressure, etc.). This economic assessment aligns with the previously outlined concept in this handbook, focusing on supplying a variety of off-takers with low-carbon hydrogen produced by a 24MW SOEC integrated with a NPS.

The analysis has been developed using the CAPEX costs that have been presented in Chapter 10, plus ~£11m for other allowances and contingencies[36]. The load list has been produced as part of the Front-End Engineering Design for the 24 MW system. Electricity prices for the years 2023 and 2024 have been used for comparison, and the 10% discount rate of CAPEX have been assumed. Table 9 below captures the key assumptions for the LCOH.

Table 9 Assumptions for the LCOH calculations.

Data	Value	Unit
Life years	25	years
Load factor	73.4%	%
Fixed O&M electrolyser	1,863,000	£/yr
Fixed O&M other	5%	%
Hydrogen output	600	kg/hr
Steam supply by NPS	6.29	t/hr
Water supply	11.42	t/hr
Water cost	1.82	£/t
Steam energy density	2.76E+06	J/kg
Electric power	26.506	MWe

Figure 18 Levelised cost of hydrogen based on the concept of meeting a variety of off-takers' demand: cement, asphalt, transport, nuclear plant (hydrogen as a cooling agent), hydrogen peaking plant.

The electricity prices vary for each off-taker due to differences in their operating times - the figure above illustrates the LCOH for various off-takers under the 2024 electricity price scenario. When using 2023 electricity price, the LCOH is, on average, 14% higher.

[36] A value for contingencies has been calculated as part of Reference 14 (NEH 24MWe Design Study, by assessing percentages for each cost item. These contingencies are intended to cover design changes, performance issues, changes in market conditions, project delays, etc. The level of contingency to assume varies dependent on an organisations policies, judgement, and risk tolerance. Therefore, the value has not been included within the costs in Chapter 10 and instead an uncertainty level for the estimates was provided. However, to ensure a robust commercial analysis, a level of contingency has been assumed based on the Design Study's recommendations. The upper range of the uncertainty values has not been used, as it would result in an unduly pessimistic commercial assessment.

It is worth noting that the hydrogen cost for the peaking plant, faded in the graph, is relatively low due to the fact that the hydrogen for this specific off-taker is produced only when electricity prices are low (£10/MWh versus £60-£70/MWh). Apart from the hydrogen production cost at the exit of the electrolyser, the medium pressure (MP) compressor and the dryer have also been calculated as these additional costs are often included within the LCOH for competitive technologies (for example, PEM electrolysers produce hydrogen at higher pressures which does not require an additional compression). This approach allows to compare the LCOH with available hydrogen costs.

The results show that the hydrogen cost, to satisfy various off-takers' demand and requirements, goes from £6 (for the cement site) to £6.6/kgH_2 (for the transport off-taker) with the 2024 scenario as per Figure 18.

Scenario 2: one off-taker for the 24MW facility.

In addition to electricity prices, CAPEX significantly influences the total LCOH, hence the second scenario for the LCOH has been developed assuming that there is only one off-taker – an asphalt plant. The waterfall chart highlights the impact of an additional equipment needed for an asphalt site to meet its requirements (including drying, two-stage compression, storage and trailer filling station). It should be noted that the price presented on the figure below is different from the one presented in the scenario above as the electricity price at the exit of the electrolyser has been considered here (assuming all the hydrogen produced from the 24MW SOEC is directed to this one off-taker). The same electricity price has been considered for all the operating equipment in order to highlight the impact of various equipment's CAPEX on the hydrogen price.

The waterfall chart below illustrates step by step how the additional equipment increases LCOH due to CAPEX, electricity consumption (more power consumption) and fixed OPEX.

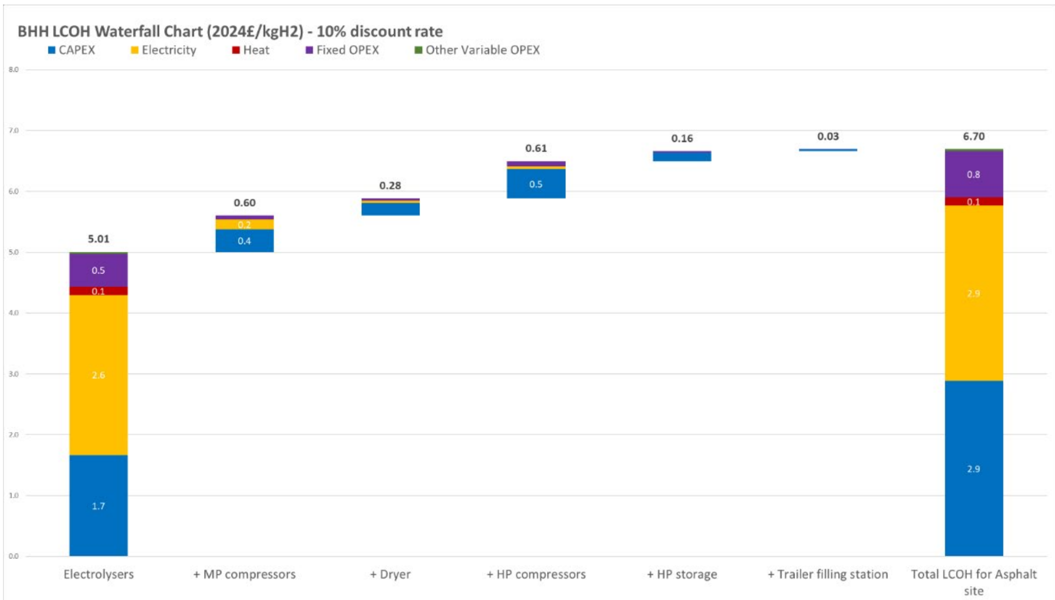


Figure 19 Levelised cost of hydrogen for an asphalt production plant (including all the equipment needed to satisfy the requirements of this off-taker).

In the long term, SOEC is expected to provide the competitive LCOH compared to other currently available technologies (PEM, alkaline, etc.). SOEC achieves higher efficiencies as mentioned earlier in this handbook, with 20-30% lower energy consumption than PEM and alkaline, due to its high temperature operation and ability to utilise external heat, which reduces electricity demand. While PEM and alkaline currently have lower capital costs and are more mature technologies, SOEC's efficiency gains and potential for cost reductions through economies of scale will make it highly competitive as deployment increases.

12. IMPACT OF SCALING UP BY FOUR TIMES TO A 96MW ELECTROLYSER

Key messages

- Consider pre-installing additional penetrations or a larger pipe tunnel to enable an easier scale up.
- Having multiple smaller HX or a single large HX, are both viable options depending on the land available and NPS layout.
- Multiple smaller compressors rather than one large compressor could be considered, to reduce upfront CAPEX and reduce operating temperatures, which provides a safety benefit.
- When determining the location of the hydrogen storage within the NEH facility, consider the potential for future scale up and the impact it may have on the separation distances to NPS and other equipment.
- Scaling up the NEH Facility could require an additional assessment to consider the impact on the NPS due to higher electrical and heat load.
- During the construction of the new nuclear power station, ensure there is an additional electrical connection capacity from the grid substation to easily enable an off-take to the NEH Facility.

Growing interest in and demand for hydrogen would lead to interest in larger-scale production of hydrogen. This section will explore the challenges developers may encounter during scale-up and highlight the benefits of incorporating installation requirements early on, which can significantly reduce costs. The current design outlined in this handbook is based on a 24MW facility. To fully grasp the potential of, and issues associated with, scaling up, a 96MW (4 x 24MW) facility has been evaluated in this section.

Three approaches for scaling up are discussed: modifying an existing 24MW facility, designing for future expansion, and building a full-scale 96MW plant, each with its own pros and cons. These are shown in Table 10 below.

Table 10 Three approaches for scaling up considered in this chapter.

Approach	Pros	Cons
Modifying an existing 24MW facility	Lower initial costs and effort for the 24MW plant.	Significant planning and potential operational disruptions during scaling up. Additional modifications needed for steam and electrical supplies.
Designing for future expansion	Enhanced potential for future scaling with pre-installed infrastructure (e.g., pipework, electrical capacity). Long-term land planning.	Higher initial investment and more time/effort in the design phase.
Building a full-scale 96MW plant	Immediate large-scale production, faster cost recovery due to increased hydrogen output.	Highest upfront costs, requiring a strong business case.

Having determined which option is most applicable, planning and the design of the plant can commence. To give investors an insight into what will be required during scale up, an analysis was completed on each site component. All site components were assessed, and for each, different layouts were visualised, the pros and cons, and provided recommendations, as shown in Table 11 below.

Table 11 Pros, cons and recommendation for the 3 scenarios of a NEH facility scale-up.

Component	Layout	Pros	Cons	Recommendations
Nuclear steam tap-off point	1- Multiple tap-off points	•Each unit having its own tap-off ensures a diverse supply of steam, reducing the risk of a single point of failure. •This setup provides redundancy, allowing the system to continue operating even if one of the tap-off points fails or requires maintenance. •Maintenance activities can be performed on one unit without shutting down the entire system, ensuring continuous operation.	•Installing multiple tap-off points can increase initial construction and installation costs. •The system's complexity is increased with multiple tap-off points, which may require more extensive monitoring and maintenance. • Adding more tap-off points may necessitate additional space, potentially complicating the facility layout and increasing encroachment on the NPS steam circuit	•Invest in advanced monitoring systems for efficient oversight to manage the multiple tap-off points •Carefully plan the facility layout to accommodate additional tap-off points without compromising space efficiency or safety. •Spread out the initial investment by using phased construction techniques.
Nuclear steam tap-off point	2 – Single large tap-off point	•Using one large tap-off point can reduce short-term construction costs by minimising the amount of pipework and associated infrastructure. •A single tap-off point simplifies the system design, making it easier to manage and maintain. •The larger pipework will encroach less on the NPS circuit, potentially easing regulatory and spatial constraints.	•This layout introduces a single point of failure. If the tap-off point encounters issues, the entire system could be affected. •With only one penetration, there is less redundancy, which could impact the system's reliability and maintenance flexibility. •Any maintenance or failure in the single tap-off point could require a complete shutdown of the system, affecting overall operational efficiency.	•Provision of safety equipment to measure, monitor and quickly address any issues with the single tap-off point to minimise the risk of a complete system shutdown. •Consider incorporating backup systems or alternative pathways to enhance reliability and maintenance flexibility, even with a single tap-off point, •Develop a comprehensive maintenance plan that includes regular inspections and preventive maintenance to reduce the likelihood of failure and ensure operational efficiency. •Conduct a cost-benefit analysis to explore the short-term construction cost savings against the potential long-term operational risks and maintenance costs.
Reactor site heat exchangers	1 – Four smaller heat exchangers	•Each plant having its own heat exchanger provides redundancy, ensuring that if one exchanger fails, the others can continue operating. •Maintenance can be performed on one heat exchanger without affecting the operation of the other plants. •Each plant can independently control its heat exchanger, allowing for more precise	•Installing multiple heat exchangers can increase initial setup costs. •Managing and maintaining multiple heat exchangers can be more complex and resource-intensive. •More equipment may require additional space, potentially complicating the facility layout.	•Design the facility layout carefully to accommodate multiple heat exchangers efficiently, minimising space constraints and potential complications. •Develop a comprehensive maintenance plan to manage the complexity and resource demands of maintaining multiple heat exchangers. •Conduct a thorough cost-benefit analysis to justify the initial setup costs, highlighting the long-term operational benefits and redundancy provided by having multiple heat exchangers.

Component	Layout	Pros	Cons	Recommendations
		temperature and pressure management.		
Reactor site heat exchangers	2 - Single Large Heat Exchanger Supplying All Four Electrolysers	•A single large heat exchanger can reduce initial construction costs by minimising the amount of equipment and infrastructure needed. •The system design is simplified, making it easier to manage and maintain. •A single large heat exchanger and pipeline will encroach less on the site boundary, potentially easing regulatory and spatial constraints.	•This layout introduces a single point of failure. If the main heat exchanger encounters issues, the entire system could be affected. •With only one heat exchanger, there is less redundancy, which could impact the system's reliability and maintenance flexibility. •Any maintenance or failure in the single heat exchanger could require a complete shutdown of the system, affecting overall operational efficiency.	•Implement additional reliability measures, such as backup systems or rapid repair protocols, to mitigate the risks associated with a single point of failure in the heat exchanger. •Conduct a thorough risk assessment to understand the potential impacts of a single heat exchanger failure and develop contingency plans to ensure operational continuity. •Compare the heat loss between using one large pipe versus multiple smaller pipes, and factor in pressure adjustments to optimise the design.
Intermediate Loop	1 - Four Penetrations through the nuclear site boundary with Four intermediate loops	•Ensures a diverse steam supply to the electrolysis plants •Reduces the risk of total system failure if one pipe is compromised.	•More complex infrastructure and higher installation costs. •Increased maintenance requirements due to multiple pipes. •Potentially higher heat loss over multiple transfer pipes.	•Design the infrastructure to balance complexity and cost, to identify if the benefits of a diverse steam supply outweigh the higher installation and maintenance costs. •Develop efficient maintenance protocols to manage the increased requirements due to multiple pipes, minimising downtime and ensuring reliable operation.
Intermediate Loop	2 – One penetration through the nuclear site boundary with one Intermediate loop with Buffer Tanks	•Simplified infrastructure in comparison to 4 intermediate loops which has the potential to lower installation costs. •Centralised control of steam and condensate distribution.	•Requires a buffer tank to maintain a constant steam supply. •Higher risk of total system failure if the single pipe or buffer tank fails.	•Implement robust monitoring and maintenance protocols for the intermediate loop and buffer tanks to reduce the risk of total system failure. •Design the buffer tanks with sufficient capacity and redundancy to handle fluctuations in steam/condensate demand and supply. •Conduct a cost-benefit analysis to weigh the lower installation costs and simplified infrastructure against the potential risks and costs associated with a single point of failure.
Hydrogen compressor	1- Four Compressor Units	•Allows for maintenance activities while the plant remains operational. •Provides redundancy and diversity, reducing the risk of total system failure. •Potentially less downtime, leading to higher overall efficiency.	•Higher initial installation costs. •Increased maintenance requirements due to multiple systems.	•Select a modular design that allows for easy scalability and maintenance. This can help manage higher output efficiently and reduce downtime. •Conduct a thorough cost-benefit analysis to balance the higher initial installation costs against the long-term benefits of redundancy and reduced risk of system failure.
Hydrogen compressor	2 - Single Large	•Simplified infrastructure with potentially lower long-term maintenance costs.	•Higher short-term installation costs.	•Enhance safety protocols to mitigate the increased fire and explosion risks

Component	Layout	Pros	Cons	Recommendations
	Compressor Unit	•Centralised control of the compression system.	•Increased fire and explosion risks due to larger compressed hydrogen volumes. •Potentially higher risk of total system failure if the single compressor unit fails.	associated with larger compressed hydrogen volumes. •Develop a robust risk management plan to address the potential for total system failure, ensuring quick recovery and minimal downtime.
Pressurised Hydrogen to storage	1 - Four Compressor Units with Dedicated High Pressure Transfer Lines	•Allows for maintenance without halting production. •Provides redundancy, reducing the risk of total system failure. •Enhances productivity by maintaining continuous operation.	•Higher initial installation costs. •Increased complexity and maintenance requirements.	•Develop efficient maintenance schedules to manage the increased complexity and maintenance requirements due to the number of components, ensuring minimal disruption.
Pressurised Hydrogen to storage	2 - One or Four Compressors (with HP buffer tank) and Single Pressurised Hydrogen Transfer Pipe	•Reduces the amount of pressurised pipework, lowering initial costs. •Maintains redundancy and diversity in the system. •Centralises hydrogen storage, simplifying management.	•Higher specification rating for the larger pipe may increase costs. •Potentially higher fire and explosion risks due to larger hydrogen volumes. •Requires careful assessment of cost feasibility and safety.	•Perform thorough safety assessments to evaluate and mitigate the fire and explosion risks associated with larger hydrogen volumes. •Carry out a detailed cost-feasibility analysis to balance the initial cost savings from reduced pressurised pipework against the potential higher costs of higher specification ratings for larger pipes. •Implement advanced monitoring systems and maintain redundancy in the hydrogen storage and distribution network to ensure reliability and safety, even with centralised storage.
Pressurised Hydrogen to storage	3 - Single Large Compressor with Direct Line to Storage	•Simplified construction and potentially lower initial costs. •Centralised compression and storage system.	•Lacks redundancy, increasing the risk of total system failure during maintenance. •Higher specifications and requirements for the single compressor and Transfer pipework.	•Implement alternative arrangements to reduce systems being taken offline during maintenance. •Design the single compressor and transfer pipework to meet higher specifications and requirements, whilst balancing cost and performance to ensure reliability. •Conduct a thorough cost-benefit analysis to weigh the lower initial costs and simplified construction against the potential risks and higher specifications needed for the single compressor and transfer pipework.
Hydrogen Storage	Larger Storage facility	•Costs associated with upgrading the site are small compared to increased revenue. •Potential to scale up even further if storage volumes can be increased	•COMAH regulations requirements may increase due to larger stored quantities, upgrading the site to a higher tier. •Expanded scope of DSEAR regulations for the larger site.	•Potentially may need to move the site or build blast walls if initial design did not consider scale up. •Updated zoning assessments due to larger amounts of stored hydrogen.

Component	Layout	Pros	Cons	Recommendations
Hydrogen Distribution facility	Larger Hydrogen Distribution Facility	•Costs associated with upgrading the site are small compared to increased revenue. •Potential to scale up even further if distribution network is efficient	Increased Hazards to manage. Potential to encroach nuclear site's access and egress routes.	•Clearly defined access and egress routes. •Routing that does not direct traffic towards the nuclear site. •Enhanced driver training. •Enhanced hazardous area classification assessments.

There were several other important factors that were discussed and were judged essential for scaleup. These have been identified in Table 14 (SUPPORTING TABLES).

13. FUTURE OPPORTUNITIES FOR NUCLEAR ENABLED HYDROGEN

Key messages

- Whilst this handbook focuses on UK application, NEH has the global potential to help decarbonise industry.
- Nuclear new builds are ideal for enabling NEH, as they can be designed with heat and electrical off-take in mind. This applies to both GW-scale new builds and modular reactors.
- Advanced Modular Reactors, with their higher temperature outputs, offer potential for further efficiency gains, including the ability to support future forms of hydrogen production, such as through thermochemical routes.
- Existing nuclear sites can provide access to the skills and infrastructure needed to accelerate the deployment of nuclear enabled hydrogen.
- Hartlepool is a particularly suitable site for Nuclear Enabled Hydrogen, with NEH having the potential to serve as the foundation of a wider energy hub.

Future development planning

This section explores strategic opportunities for future deployment of NEH technology, identifying unique challenges, pathways, and scenarios for growth that complement and expand on prior sections of the report.

Strategic Deployment Scenarios for NEH in Global Markets

The global potential for NEH technology is significant, especially in regions with nuclear infrastructure and rising hydrogen demand. Expanding NEH in these areas, particularly in the period 2030-2050, could support decarbonisation goals while meeting demand for clean energy alternatives. Countries like USA, Japan, South Korea, Canada, and select European nations with established nuclear sectors, are especially promising markets. Many of these countries, including several emerging economies, are exploring NEH to complement existing nuclear capabilities and help shift away from fossil fuels. Some projects, like those in Sweden (Oskarshamn and Ringhals) and the United States (Nine Mile Point), are already demonstrating that hydrogen production at NPSs is viable, using LTEs) for small-scale applications on-site. These are expected to build to larger scale industrial projects, for example co-located with energy clusters. In the longer term as the demand for hydrogen increases worldwide, the commercial opportunities for NEH may grow accordingly.

In addition to broader industrial uses, other applications for NEH could include high-temperature industrial processes, where nuclear heat and hydrogen production could serve industries such as steel and cement. NEH could also enable decarbonisation in sectors like maritime transport or aviation, providing low carbon hydrogen-based fuels. While most nuclear hydrogen projects worldwide are currently in demonstration or planning phases, the successful commercialisation of these applications could transform NEH into a critical component of the future energy mix. As renewables expand, NEH could occupy an important component within the hydrogen economy, providing consistent output complementing intermittent renewables.

Opportunities for Co-Location with Nuclear Plants

Co-locating NEH production with existing NPSs could offer strategic advantages, creating energy hubs where reactors, electrolysers, and complementary technologies (such as Direct Air Capture, batteries, and water supply systems) could operate in synergy. This setup not only optimises resource use but also enables cost efficiency, infrastructure sharing, and streamlined regulatory approval.

These energy hubs, modelled after hydrogen cluster initiatives seen in the US and South Korea, could anchor local industry, offering a stable supply of hydrogen and other energy vectors to various sectors.

These clusters foster cross-sector collaboration by linking NPSs, hydrogen producers, and end-use industries, thereby strengthening NEH's role in the hydrogen economy. This approach not only ensures cost-effective and scalable hydrogen production but also positions the UK and similar regions as leaders in the NEH field.

Strategic Partnerships, Cross Sector Collaboration, and Regulatory Development

Deploying NEH at a commercial scale will require extensive collaboration across industries and between nations. Strategic partnerships between nuclear operators, hydrogen producers, and emerging sectors—such as aviation and synthetic fuels—will drive technological and economic viability for NEH. Collaborative projects within sectors like aerospace, industrial heating, and marine transport can support the adaptation of NEH for a broader range of applications.

Further, international cooperation, policy frameworks, and harmonised regulations will be critical to realising NEH's global potential. Multinational agreements on hydrogen trade, cross-border hydrogen transportation, and co-funded NEH research could increase scalability and cost efficiency. Anticipated regulatory changes in transport, safety, and storage requirements will help streamline NEH deployment. For example, the alignment and clarity of hydrogen standards will simplify global trade and will facilitate project investment and public confidence in NEH technology.

Long-Term Technological and Financial Considerations

For NEH technology to mature, innovation must extend beyond electrolysers to include advances in hydrogen storage, transport infrastructure, and further more efficient production methods. As hydrogen demand grows, NEH systems will need to support flexible production that aligns with both nuclear baseload and intermittent renewables to stabilise the grid.

The financial viability of NEH projects will also depend on supportive mechanisms, such as carbon pricing, emission reduction targets, and net zero investment funds. Carbon pricing schemes, for example, could provide a significant economic advantage for NEH by raising the costs of more carbon-intensive alternatives. Further, international tax incentives and green bonds could attract investors to long-term NEH projects, helping to lower costs and support the transition to low-carbon economies. These mechanisms will play a vital role in fostering NEH as a competitive option in the global hydrogen market, alongside renewable-based hydrogen.

Supply Chain Scalability and Workforce Development

As NEH deployment progresses, a robust supply chain is crucial to prevent bottlenecks in sourcing critical components, such as rare earth elements and electrolyser parts. Rapid NEH scaling will necessitate secure supply chains and investments in manufacturing capacity. Additionally, a trained workforce with expertise in nuclear engineering and hydrogen production is essential to support NEH expansion. Developing this workforce, will support the UK's hydrogen objectives and bolster the future supply chain.

Market Evolution and Hydrogen Demand Growth Scenarios

Looking ahead, NEH's role in the hydrogen economy will depend on long-term hydrogen demand forecasts and its relative competitiveness with other production methods. As carbon taxes increase and more industries adopt hydrogen, sectors like aviation, heavy-duty transport, and energy-intensive manufacturing will require scalable hydrogen solutions. Chapter 2 has discussed hydrogen demand, and long-term trends for example, increased demand from carbon-intensive sectors and potential under-supply from renewables could place NEH at a competitive advantage.

In scenarios where renewable sources are unable to meet hydrogen demand independently, NEH's ability to offer stable, dispatchable, and efficient hydrogen production will ensure energy reliability and reinforce NEH's role in the UK's future energy strategy.

Overview of NEH opportunities in the UK

The UK's NEH opportunities are poised for substantial growth, particularly with large-scale projects like Sizewell C. Sizewell C has the potential to become a vital component of the UK's hydrogen economy by potentially using its significant power output for both electricity generation and clean hydrogen production. As part of its Clean Energy Hub initiative, Sizewell C is considering utilising excess nuclear power to produce low-carbon hydrogen via electrolysis, potentially supporting various industries, including transport, heavy industry, and residential heating. This hub is also designed to integrate renewable energy sources, offering a diversified energy mix that enhances grid resilience while producing hydrogen to decarbonise hard-to-abate sectors. The project's 3.2 GW of electricity output positions it as a cornerstone in the UK's clean energy transition, aligning closely with the nation's net-zero ambitions.

SMRs present another significant opportunity for NEH development in the UK. Great British Nuclear (now Great British Energy - Nuclear), formed in 2023, is leading efforts to deploy SMRs to meet the UK's future energy demands. A competitive process launched in 2023 which saw four SMR vendors shortlisted in September 2024, and the preferred bidder announced in June 2025. with the goal of reaching a final investment decision by 2029 and delivering projects in the mid-2030s. SMRs, are suited to hydrogen production through electrolysis. The Smaller SMR plant designs could provide a flexible, decentralised approach to hydrogen production, supporting local industrial hubs or regional energy needs.

Another promising area is the UK's Advanced Modular Reactor programme, which aims to demonstrate advanced nuclear technologies by the early 2030s. AMRs are designed to operate at much higher temperatures than conventional reactors, and this could enable even more efficient hydrogen production. This includes both high temperature electrolysis (with higher efficiencies than low temperature) and the potential to employ thermochemical processes such as the sulphur-iodine cycle or hybrid water-splitting methods. These processes can directly utilise the high heat produced by AMRs, reducing the energy losses associated with electrolysis. The government-backed AMR programme is exploring these high-temperature reactors as a future energy source capable of producing hydrogen at an industrial scale while minimising emissions. Demonstration projects in the 2030s could unlock the full potential of NEH using the higher temperatures from AMRs. In addition to using high-temperature electrolysis to produce hydrogen, AMRs also offer the potential of using thermochemical routes. This route is currently at a much lower technology readiness level than high-temperature electrolysis. However, this could become more efficient than electrolysis, and it could significantly lower the cost of hydrogen production. This innovation places AMRs at the forefront of the future hydrogen economy and offers the potential for large-scale, low-carbon hydrogen to become a key part of the UK's energy system. Much of the information in this handbook can be used to support thermochemical NEH production too.

Case study

EDF owns and operates a fleet of NPSs around the UK. The Advanced Gas Cooled Reactor fleet based on current forecasts are expected to cease generation by the early 2030s. EDF also operate Sizewell B (a Pressurised Water Reactor), which is currently scheduled to close in 2035, but is hoped can operate another 20 years subject to commercial and safety decision making. EDF is also constructing Hinkley Point C, and hope to see the construction of Sizewell C, both of which are anticipated to be operational for 60 years or more.

These sites also offer great potential for nuclear new build and/or development as Energy Hubs, including opportunities to produce hydrogen. The sites have an existing skilled workforce, relatively supportive local communities, and existing infrastructure such as grid connections, that could be used to accelerate a project.

Some of the sites also have potential off-takers for hydrogen located in the proximity. For example, Hartlepool is near the Teesside industrial cluster, Torness has a nearby cement site, Sizewell is located near an aviation fuel pipeline. Additionally, EDF is exploring e-fuel opportunities in Bristol, close to Hinkley Point.

To provide a more detailed example of NEH, a concept-level case study for Hartlepool is presented. This concept combines a new build modular reactor, with hydrogen production. The scale of hydrogen production is undefined but could be 24MW or larger.

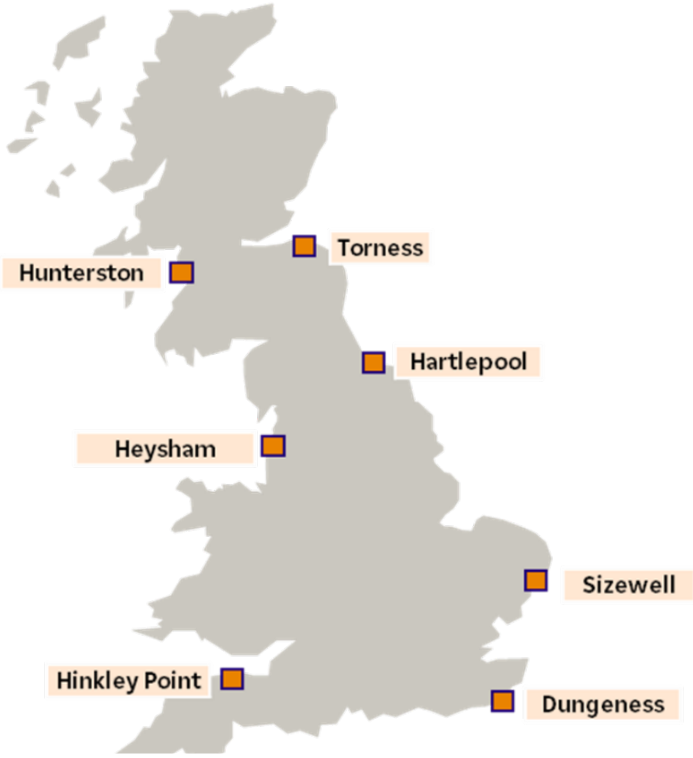


Figure 20 EDF Nuclear Power Stations.

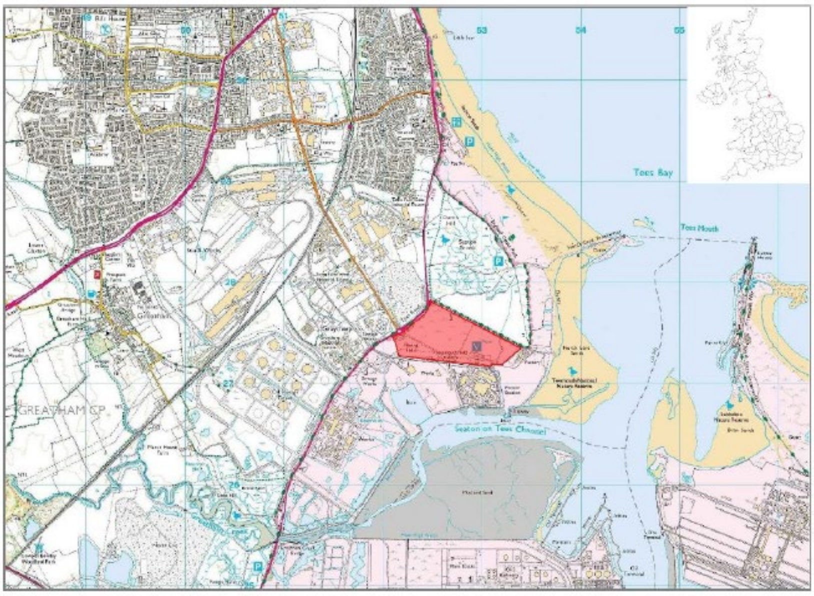


Figure 21 Map showing the area surrounding Hartlepool.

Hartlepool

Why Here: Teesside is at the forefront of delivering on the UK ambition to become Net Zero by 2050. The proposed land adjacent to the existing NPS has already been identified for new nuclear development through the National Policy Statement for nuclear (NPS designation).

- Deployment at Hartlepool represents an opportunity to use existing nuclear generation skills, site knowledge and local industrial relationships to provide project acceleration.
- The nearby Teesside industrial cluster is one of the top 5 carbon emitting zones and provides significant opportunity to decarbonise local industry [that requires high temperature process heat]
- Local public and political acceptance of new nuclear is high due to Hartlepool's AGR legacy and is expected to help de-risk the programme.

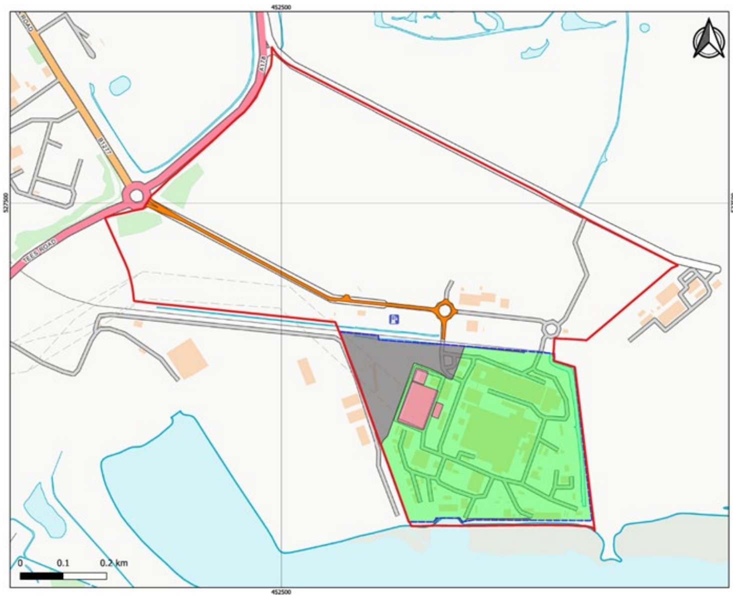


Figure 22 Map showing potential land for Hartlepool Heat Hub.

EDF Land and Location

Operational: 21ha (52 acres)

Non-Op: 48ha (118acres), which is mostly available for development

The size of the Hartlepool site and the extent of industrial demand in the area make it a prime site for a nuclear backed energy hub development future.

- The proximity of the site to existing large industrial consumers of high temperature heat and hydrogen.
- Existing heat and hydrogen service corridors provide opportunities for connection into existing networks with the appropriate agreements, and future expansion.
- Heat, electricity from nuclear and hydrogen from electrolysis would have zero scope 1 emissions
- There is existing hydrogen storage in geological cavern(s) which it may be possible to exploit.

Hydrogen Off-take Opportunities

The Teesside area has been a major draw for hydrogen development projects. The announced projects total ca. 3 GW of low carbon hydrogen, a mixture of fossil based and electrolytic projects[37].

- The existing hydrogen network might be further developed to provide a direct hydrogen supply to more customers.
- The Teesport freeport could be an off-taker for onsite vehicle and synthetic fuels for maritime purposes.
- The Tees area could become a distribution centre for low carbon hydrogen, including distributed hydrogen by tanker where transport distances are too great for pipeline investment.
- Depending on the extent of geological storage available the area could host a number of peaking power plants using hydrogen or hydrogen derived fuels in line with the climate change committee’s objectives.
- The area could become a production centre for e-fuels to be employed for applications such as sustainable aviation fuels (SAF) with Tees airport as an off-taker.

[37] *Hartlepool Heat Hub BEIS Phase A Pre-FEED Report HHH report.*

Other opportunities

In Teesside, there is a significant demand for low carbon heat up to 575 °C, which could be readily met by a High Temperature Gas Reactor (HTGR) nuclear station utilising current technology and heat distribution infrastructure.

There is currently limited need for industrial heat between 575 °C and 750 °C and for temperatures in excess 750 °C, there is potential for this to be met indirectly by use of hydrogen or low carbon electricity produced by HTGRs.

The area benefits from existing industrial heat networks and a hydrogen network, both of which could be further developed.

Overall, the total industrial heat demand on Teesside is greater than 15 TWh/year with an estimated average demand of 1781 MWt (megawatts thermal) and peak demand of 2200 MWt, details of this analysis can be found in the Reference 11 (Hartlepool Heat Hub Case Study).

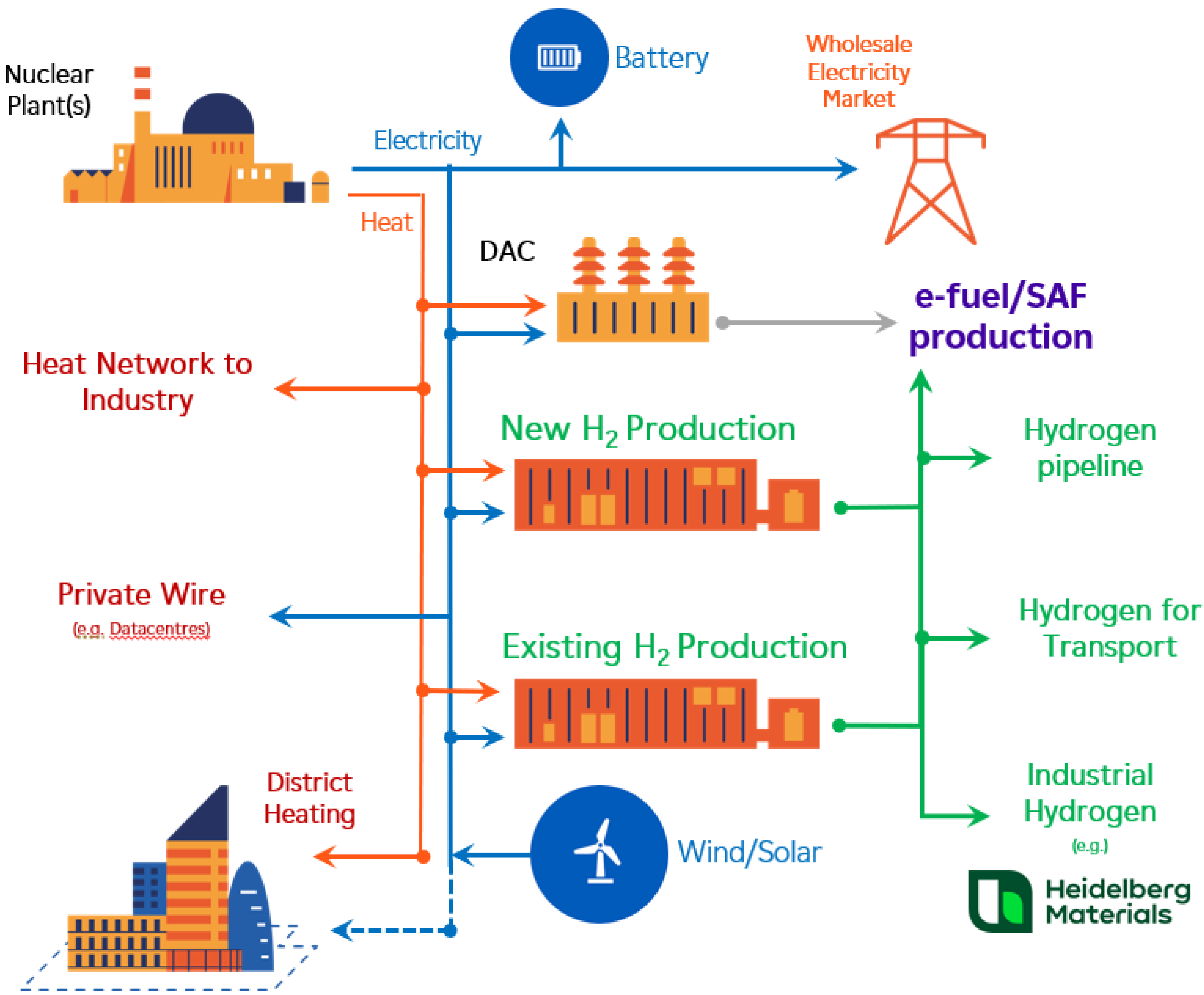


Figure 23 Concept for a Nuclear Heat Hub.

14. CONCLUSIONS

- A hydrogen production plant can be safely built adjacent to a NPS with the station providing low carbon electricity and heat to a SOEC electrolyser to optimise hydrogen production efficiency.
- In the long term, SOEC is expected to provide competitive LCOH compared to other currently available technologies (PEM, alkaline, etc.). SOEC, combined with heat from a NPS, can achieve 20-30% lower energy consumption than PEM and alkaline, due to its high temperature operation and ability to utilise external heat, which reduces electricity demand.
- The costs for any nuclear plant modifications required for the NEH facility are estimated to be a small proportion of total capital costs – less than 7% for the example 24MW commercial facility considered in the handbook. Relative to the improved efficiency of the technology, this small increase is CAPEX is commercially worthwhile.
- Using the technologies available today, the cost to produce NEH using solid oxide electrolysis is estimated to be around £6-7/kg of hydrogen, (using actual 2023 and 2024 electricity prices) depending on off-taker requirements. This compares very favourably to the strike prices agreed in the Hydrogen Allocation Round 1 (HAR1) of ~£9.50/kg of hydrogen.
- Utilising electricity provided by private wire directly from the NPS to the electrolyser allows grid export from the station to be reduced when wholesale prices are low. Similarly, when electricity wholesale prices are high, hydrogen production can be reduced, to enable the NPS to export electricity to the national grid instead.
- In this handbook we show how by varying hydrogen output in response to electricity price the average production costs of hydrogen can be brought down while maintaining high electrolyser utilisation. The ability to vary electrolyser operation is determined by hydrogen storage and off-take flexibility.
- Hydrogen is a potentially explosive gas and needs to be stored at a location where it does not present a hazard to the NPS, this can be achieved through physical separation or construction of physical or other barriers. The required separation distance is influenced by hydrogen volume and pressure, the higher the volume and pressure the greater the separation distance required. Additional mitigations could be used to reduce the separation distance, such as raised land barriers, blast walls, or the use of hydrogen storage technologies with lower pressures (e.g. metal hydrides, such as depleted uranium).
- The current generation of SOEC electrolysers operate just above ambient pressure and the hydrogen volumes within the electrolyser are low so they can be safely located close to a NPS boundary, although a minimum separation distance will be required for security reasons. Whereas high pressure hydrogen storage will need to be located further away.
- To deliver heat to the SOEC electrolysers, a heat exchanger, and isolation valves, would be installed within the nuclear site security fence. This gives the NPS control over the heat export and ensures steam from the NPS steam cycle never leaves the site. Instead, heat would be transferred off the NPS via another heat transfer fluid (likely water or steam).
- Updates to nuclear safety cases would be required but can be achieved. The FEED in this handbook has shown SOEC and its supporting systems can be integrated with heat and power supplies from a nuclear reactor. Within the nuclear safety case, the hazard from the NEH facility should be treated as an off-site industrial hazard. This would be similar to existing industrial hazards that are already present near some nuclear sites in the UK. For any new electrical connections that are installed, the electrical safety case for the NPS will also need to be reviewed.
- Adequate security can be achieved if it is considered as part of the design. Minimising digital communication between the NPS and the NEH facility simplifies the cyber security assessments, allowing remote operations at the NEH facility. Information from the safety case can be used to help assess the potential consequences of any malicious acts.
- Estimates show the time required for modifications to the NPS can be accommodated within the schedule for building a 24MW hydrogen production facility, even for existing NPS sites, without causing an overall delay

The information within this handbook should provide the basis for early project and design development of a NEH facility and thus a future application into the UK government's hydrogen production business model scheme. The handbook has identified several considerations and recommendations for Nuclear Enabled Hydrogen. The checklist below summarises these key considerations and associated recommendations.

The summaries within the handbook are underpinned by many public and proprietary documents, which have been referenced throughout and are listed at the end. If you wish to understand the underpinning detail, you can reach out to the EDF team at rdoperations@edfenergy.com.

Project Checklist

- Identification of the location of the electrolyser: best outside the licensed site.
  Consider: land availability, water source
  Consider: the volume of high-pressure hydrogen stored on site
  Consider: safe separation distance between NPS and NEH facility ensuring minimal impact on NPS

- Identification of the off-takers from the NEH facility.
  Consider: the amount of hydrogen in demand which feed into the decision about the electrolyser size
  Consider: the quality of hydrogen which will impact whether purification unit is required

- Identification of the H2 distribution methods
  Consider: nearby pipelines, number of trucks required to distribute hydrogen
  Consider: movement of trucks on site
  Consider: storage type, volume and location

- The Nuclear Reactor safety case needs updating to include the hydrogen generation facility as a new industrial hazard.

- Consider two heat exchangers: one within nuclear site boundary, one at the NEH facility. Investigate the suitable intermediate heat transfer fluid for the specific design.

- Electrical supply should be considered early (if possible, in the process of the design of the new nuclear power plant)

- Consider site specific assessment, included but not limited to:
  - Fire, explosion and blast waves
  - Electrical
  - Environmental
  - Extreme weather conditions
  - Seismic

  There could be other assessments needed depending on the location and size of the facility. The designer is responsible for identifying the relevant assessments.

- Security assessment needs to be considered
  Consider: both construction and operation

- As part of the design of the NEH facility, fault design would need to be shared with the NPS to enable them to support development of an appropriate safety case.

- The safety case for the NEH will need to identify the plant faults, internal and external hazards. The safety case must show that risks have been appropriately mitigated.

- Successful management of the risks from the NEH facility requires a robust approach to identify the risk and specify the safety measures and the performance required to mitigate them.

- Demonstration that risks have been reduced ALARP will be based on the application of appropriate engineering standards, robust design principles and practicable risk reduction measures.

Project Checklist

- Identify the impact on the site licence conditions and demonstrate that the new installations can be compliant via an appropriate safety case.
- Clearly define the operating rules, limits and conditions in the safety case (LC 23 & 24) and consider if incidents and emergency response plans for the nuclear power station need updating (LC11).
- A safety case will be used to introduce the new maintenance and operation procedures for the new heat exchanger equipment, and the transfer of heat off-site.
- Define and develop a plan for early engagement: depending on the location and scope of the NEH plant relevant regulator, government bodies and licensees should be identified and should be engaged as soon as possible.
- The designer must demonstrate compliance with the COMAH regulations based on the volume of hydrogen stored on site. Volumes should be minimised so far as is reasonably practicable in accordance with the ALARP principles.
- It is recommended the HSE regulate the off-site NEH facility and work closely with the ONR who regulates the impact on the nuclear licensed site.
- Familiarise yourself with the planning policy landscape: The National Planning Policy Framework (NPSF) and corresponding National Policy Statements.
- If a nuclear power station was to be built ensure the available land is compliant with EN-6 and EN-7 requirements.
- Agreement with the nuclear power station what's their role is in the NEH facility. Things to consider in the agreement: deliver safety case, heat exchanger(s), installation, connections, commercial arrangements, NPS resource.
- Whilst this handbook provides elements of a FEED study, a further site-specific FEED would be required prior to detailed design, to enable site specific conditions to be analysed in more detail and appropriate safety case developed.
- Optimise the system around the end user as there might be potential saving there.
- The LCOH is determined by a large numbers of factors, consider reaching out to EDF for more detailed analysis.
- Early definition of the future scaling up strategy of the NEH facility.
- Consider adding additional penetrations or a larger pipe when installing your initial NEH facility to enable an easier scale up.
- When determining the location of the H2 storage within the NEH facility, consider the potential for future scale up and the impact it may have on the separation distances to nuclear power station and other equipment.

GLOSSARY

AACE	Association for the Advancement of Cost Engineering
AEL	Alkaline Electrolysers
AEM	Anion Exchange Membrane
AGR	Advanced Gas-cooled Reactor
ALARP	As Low As Reasonably Practicable
AMR	Advanced Modular Reactor
ASME	American Society of Mechanical Engineers
BEIS	Department for Business, Energy and Industrial Strategy
BHH	Bay Hydrogen Hub
BLAST	Bled Auxiliary Steam
BoP	Balance of Plant
C&I	Commercial and Industrial
CAA	Civil Aviation Authority
CAPEX	Capital expenditure
CDM	Construction Design and Management
CDOIF	Civil Defence, Operational, and Industrial Framework
CfD	Contract for Difference
COMAH	Control of Major Accident Hazards
CSC	Electrode supported cell
DA	Day-Ahead
DBE	Design Basis Earthquake
DCO	Development Consent Order
DEFRA	Department for Environment, Food & Rural Affairs
DESNZ	Department of Energy Security and Net Zero
DEVEX	Development Expenditure
DfT	Department for Transport
DOE	Department of Energy
DSEAR	Dangerous Substances and Explosive Regulations
EA	Environment Agency
EBoP	Electrical Balance of Plant
EHSB	External Heat Steam Boiler
EIA	Environmental Impact Assessment
EPEX	European Power Exchange
EPR	European Pressurised Reactor
ESC	Electrolyte Supported Cell
ESO	Electricity System Operator
F&G	Fire and Gas

FCE	FuelCell Energy
FEED	Front-End Engineering Design
FID	Final Investment Decision
FMEA	Failure Mode and Effect Analysis
FOAK	First-of-a-kind
FOD	Field Operations Directorate
FSA	Food Standards Agency
GBN	Great British Nuclear
GDA	Generic Design Assessment
GHG	Greenhouse Gas
HAR 1	Hydrogen Allocation Round 1
HAZAN	Hazard Analysis
HAZID	Hazard Identification Study
HAZOP	Hazard and Operability Study
HHH	Hartlepool Heat Hub (project)
HID	Hazardous Installations Directorate
HPBM	Hydrogen Production Business Model
HPT	High Pressure Turbine
HRA	Habitat Regulations Assessment
HSE	Health and Safety Executive
HTE	High Temperature Electrolysis
HTGR	High Temperature Gas Reactor
HX	Heat Exchanger
HYA	Heysham A
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IPB	Isolated Phase Busbar
IPT	Intermediate Pressure Turbine
JAEA	Japan Atomic Energy Agency
LC	Licence Condition
LCOH	Levelised Cost of Hydrogen
LEMP	Lightning Electromagnetic Pulse
LHV	Lower Heating Value
LoM	Loss of Mitigation
LOOP	Loss of Off-site Power
LoP	Loss of Protection
LOPA	Layers of Protection Analysis
LPT	Low Pressure Turbine
LSELS	Load Shedding and Emergency Loading Sequencing Equipment
LTE	Low Temperature Electrolysis
LTE	Low Temperature Electrolyser

MAPP	Major Accident Prevention Policy
MBoP	Mechanical Balance of Plant
MMO	Marine Management Organisation
MP	Medium Pressure
MPS	Molecular Property Spectrometer
MSC	Metal supported cells
MV	Medium Voltage
MW	Megawatt
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NEH	Nuclear Enabled Hydrogen
NIST	National Institute of Standards and Technology
NPPF	National Planning Policy Framework
NPS	Nuclear Power Station
NPSF	National Planning Policy Framework
NREL	US National Renewable Energy Laboratory
NRW	Natural Resources Wales
NSHE	Nuclear Steam Heat Exchanger
NSIP	Nationally Significant Infrastructure Projects
NSLPA	Nuclear Site Licence Provision Agreement
OBE	Operating Basis Earthquake
OGP	Oil and Gas Producers
ONR	Office for Nuclear Regulation
OPEX	Operating Expenses and Expenditure
P	Pressure
PA	Planning Act
PEM	Proton Exchange Membrane
PEMEL	Proton Exchange Membrane Electrolyser
PESR	Pressure Equipment Safety regulations
PHAST	Process Hazard Analysis Software Tool
PLC	Programmable Logic Controller
PSSR	Pressure System Safety Regulations
PWR	Pressurised Water Reactor
REPPIR	Radiological Emergency Preparedness and Public information Regulations
RGP	Relevant Good Practice
SA	Safety Assessment Principles
SAF	Sustainable Aviation Fuels
SEPA	Scottish Environmental Protection Agency
SIL	Safety Integrity Level
SMART	Specific, Measurable, Achievable, Realistic and Timely
SMR	Small Modular Reactor

SOEC	Solid Oxide Electrolyser Cell
SQEP	Suitably Qualified and Experienced Person
SRV	Safety Relief Valve
SSC	Structures, Systems and Component
SZ	Sterile Zone
SZB	Sizewell B
SZC	Sizewell C
T	Temperature
TCPA	Town and Country Planning Act
TOR	Torness
TRL	Technology Readiness Level
UAE	United Arab Emirates
UGLD	Ultrasound Gas Leak Detection
UK	United Kingdom
UKNNL	United Kingdom National Nuclear Laboratory
WTS	Water Treatment System

FIGURES

SUPPORTING FIGURES

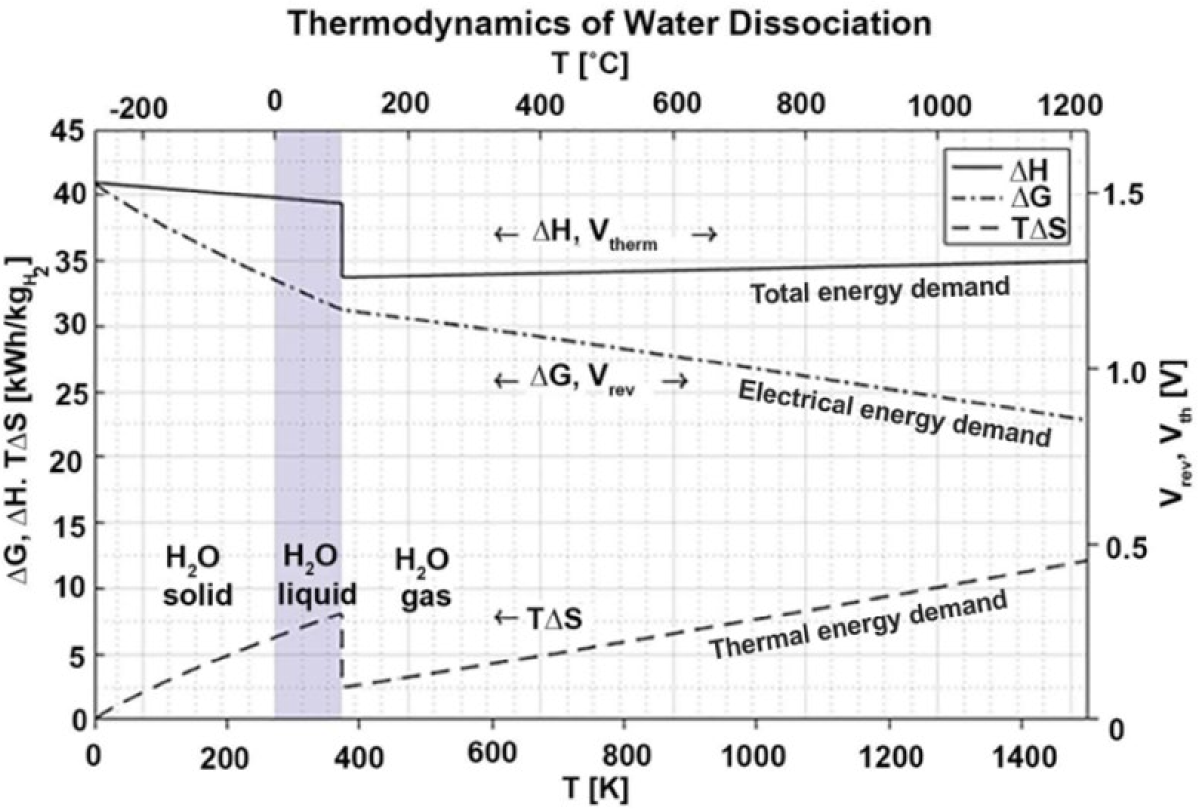


Figure 24 Thermodynamics of water dissociation.

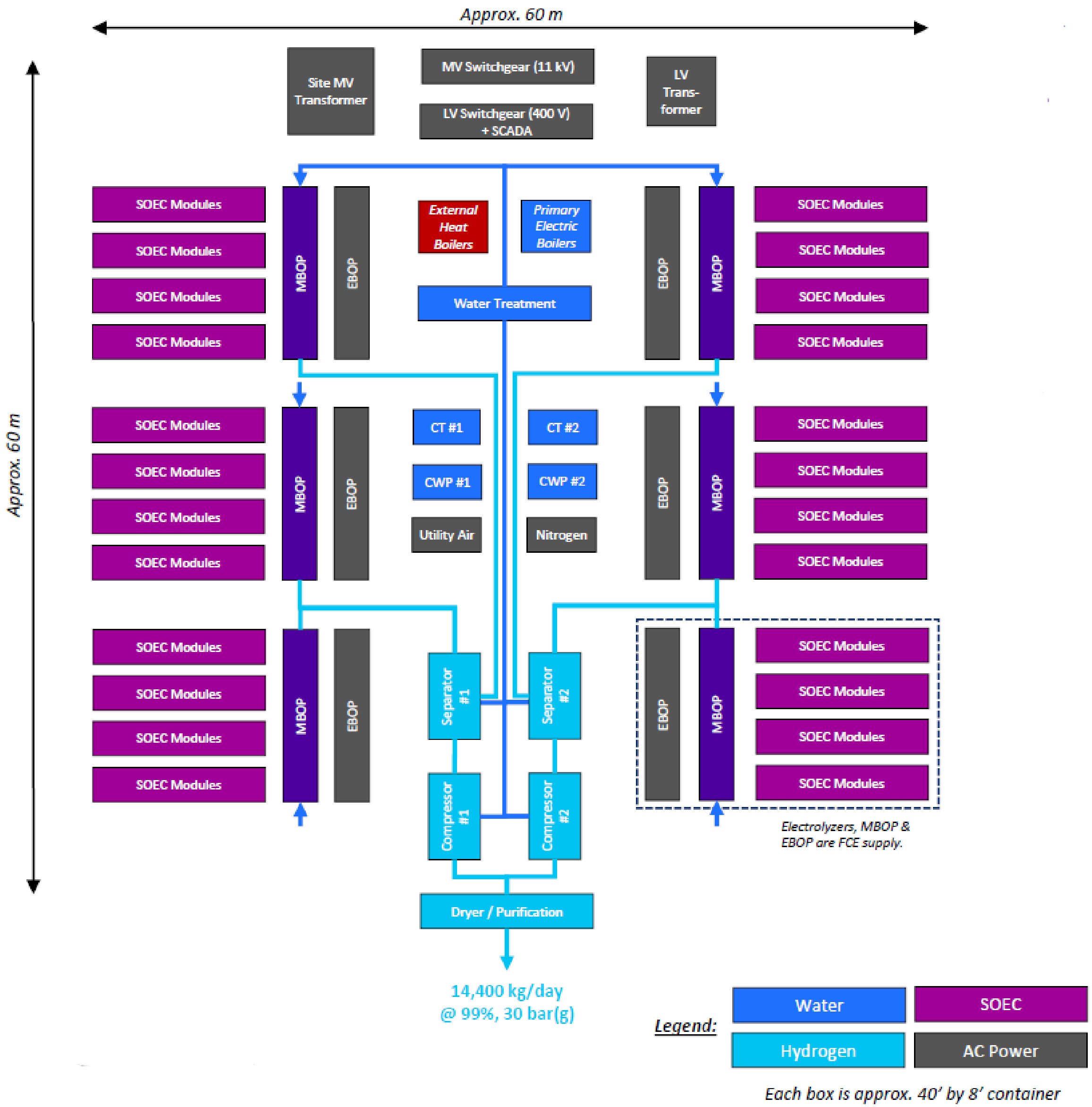


Figure 25 Illustration of a 24MW Nuclear Enabled Hydrogen plant concept.

Note: Any parameters noted on this drawing are based on general information and might not be the case at the point of delivery. The correct parameters for NEH Plant will be calculated through detail design processes.

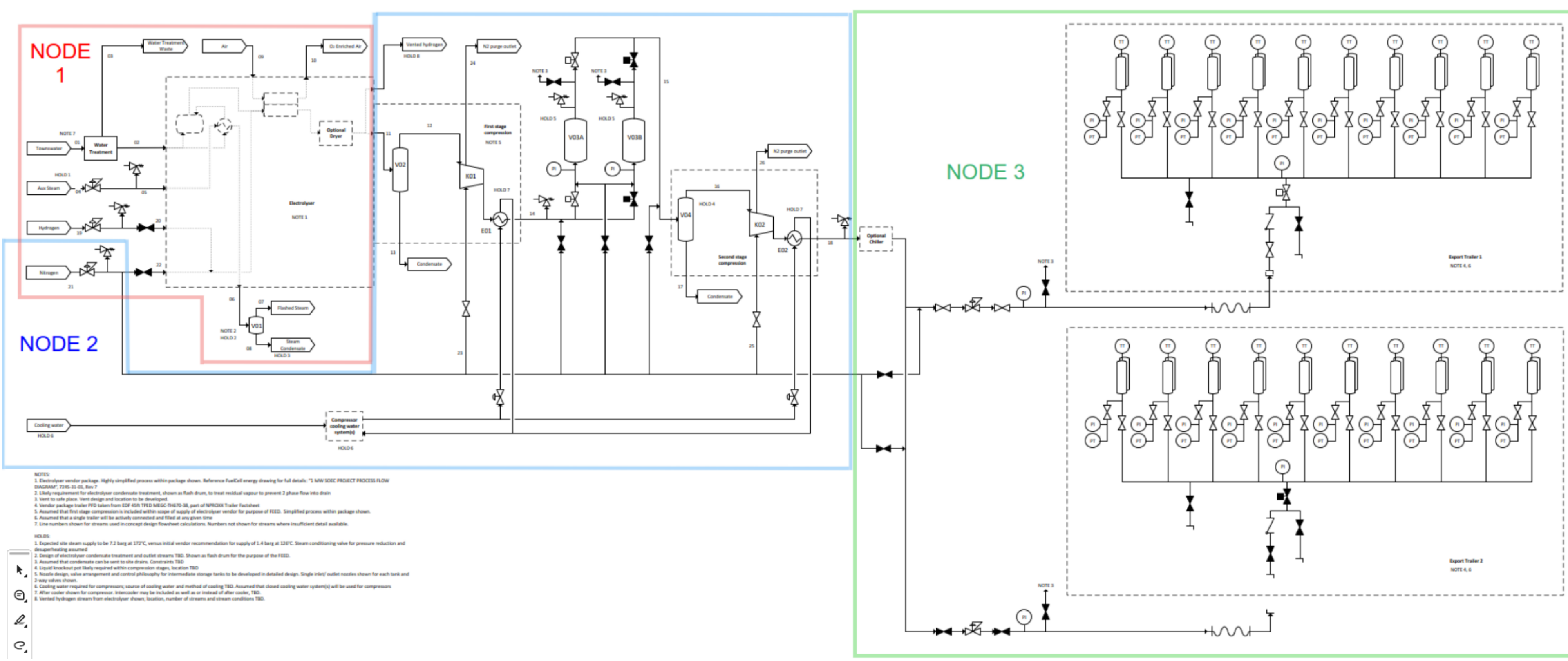


Figure 26 Nodes considered in HAZOP study.

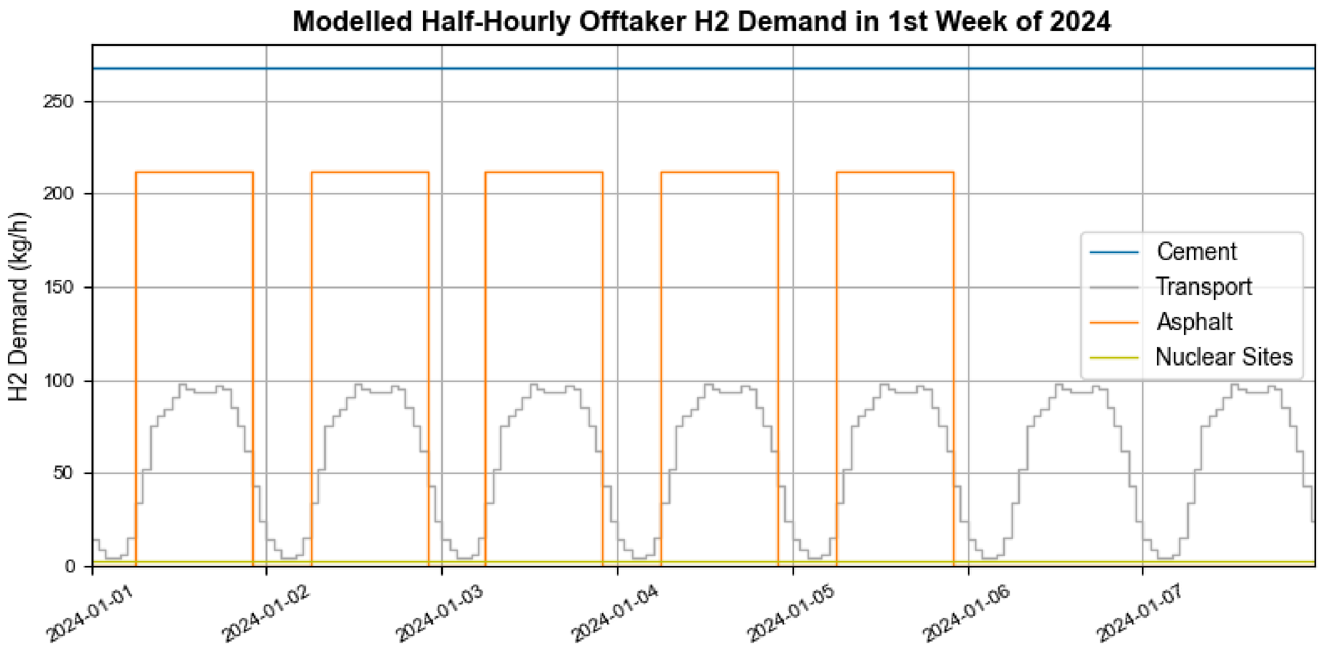


Figure 27 A single week of hydrogen off-take demand rates in kg/h.

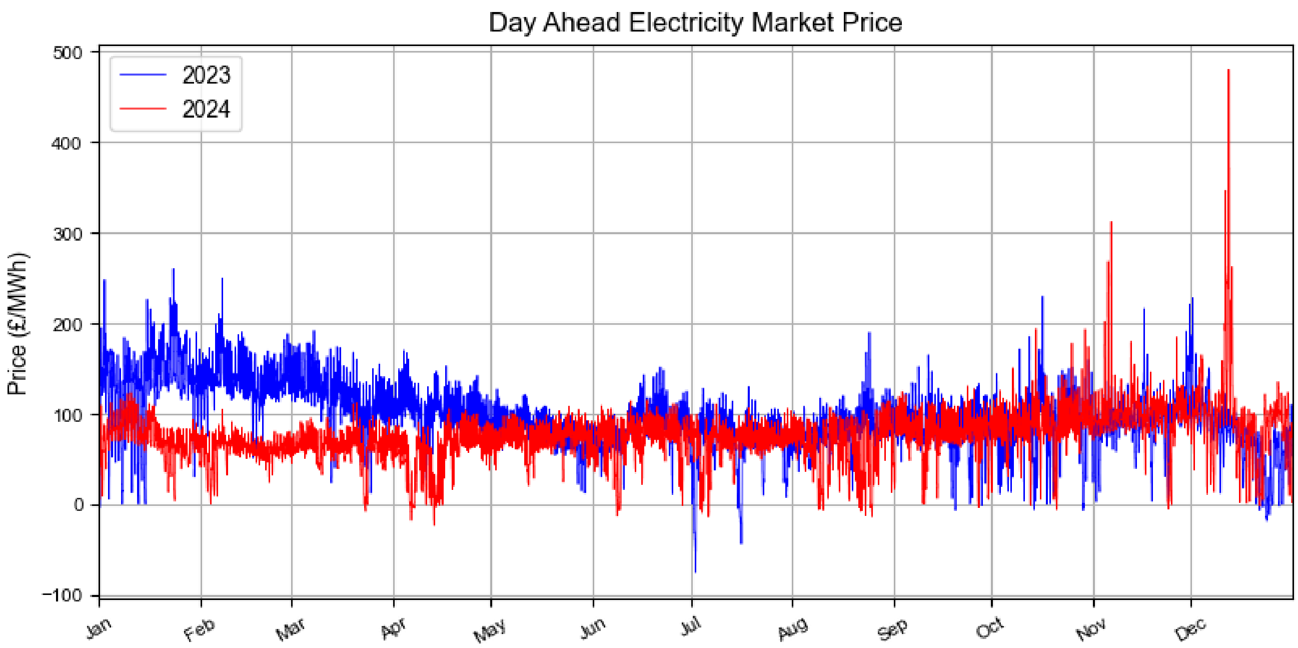


Figure 28 Day-ahead wholesale electricity prices for modelled 2023 & 2024 scenarios.

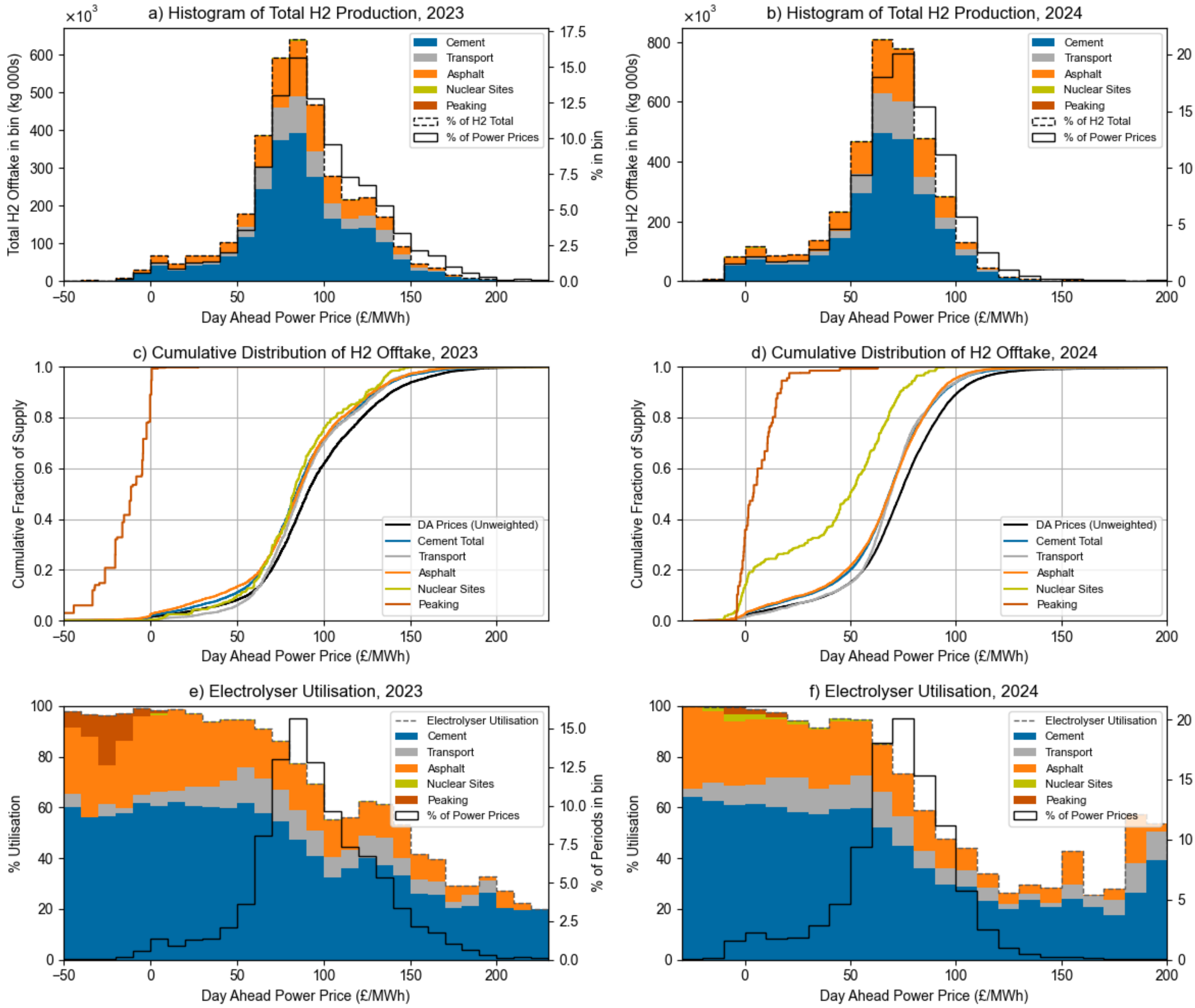


Figure 29 Charts showing in 10£/MWh bins histogram of total hydrogen production with off-taker components against power prices (a & b), cumulative distribution of hydrogen production per off-taker weighted by hydrogen volume against power prices (c & d), and electrolyser utilisation (e & f).

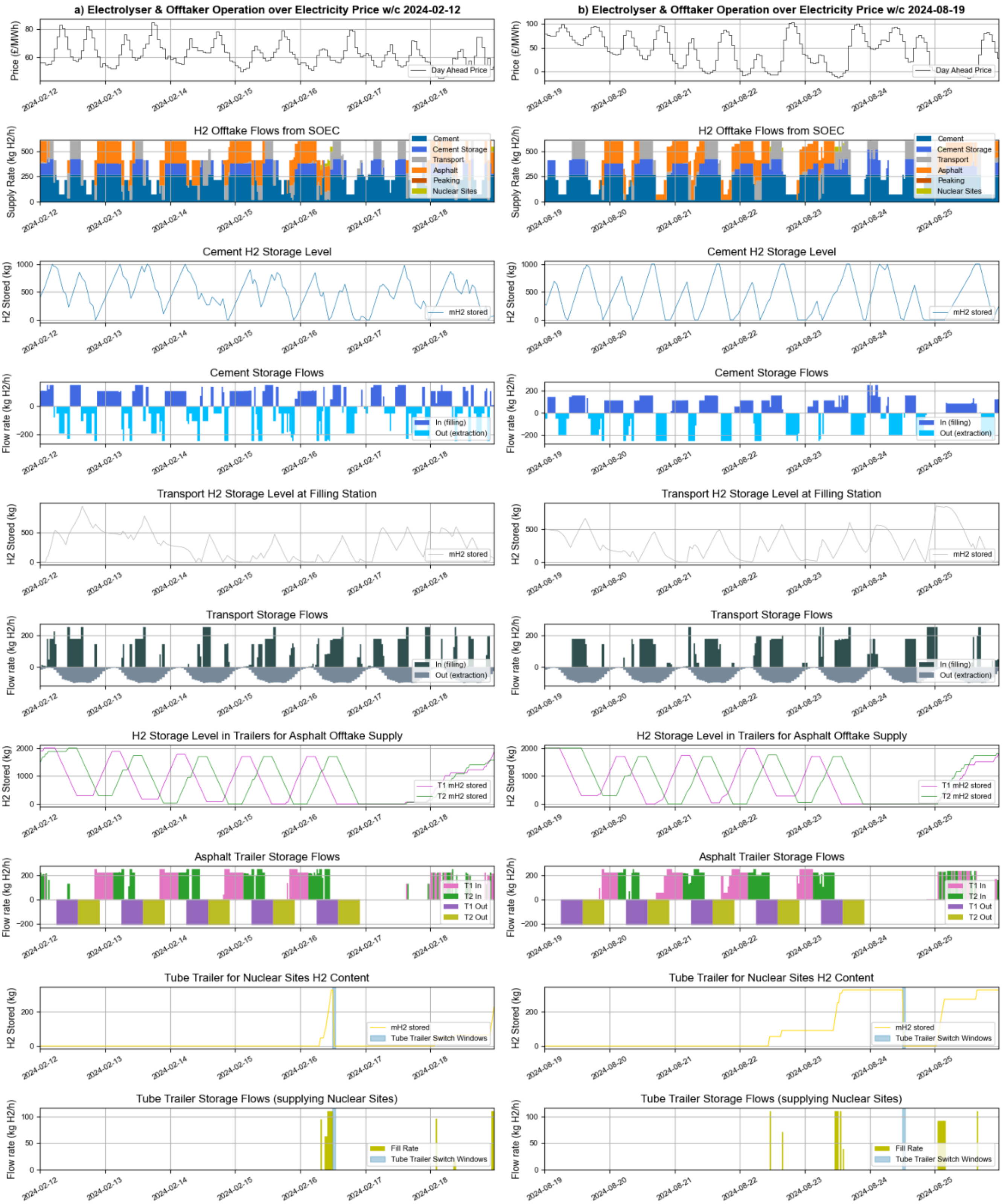


Figure 30 (a & b): Charts showing operation of electrolyser, off-taker supply & storage processes over 2 weeks based on the day-ahead prices for 2024: a) in February showing low spreads & high prices, b) in August with higher spreads.

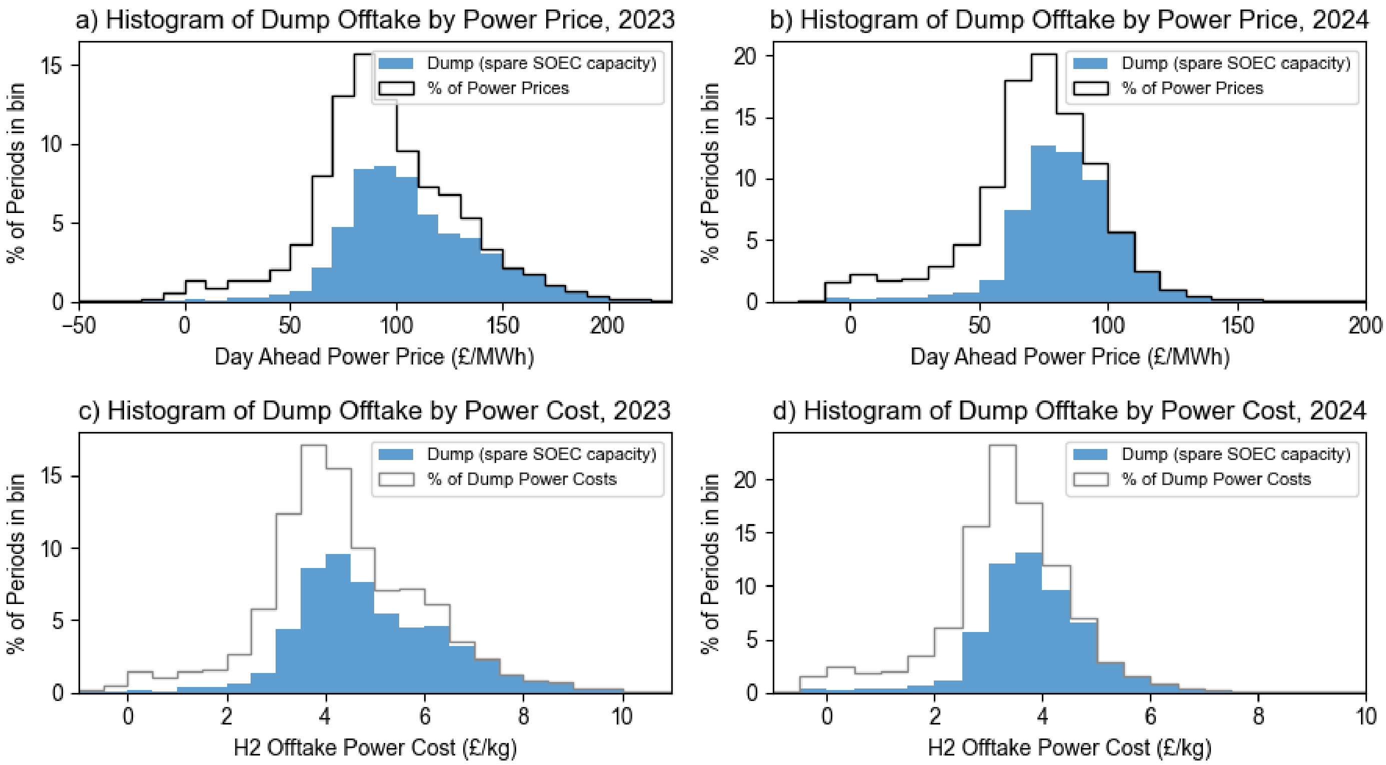
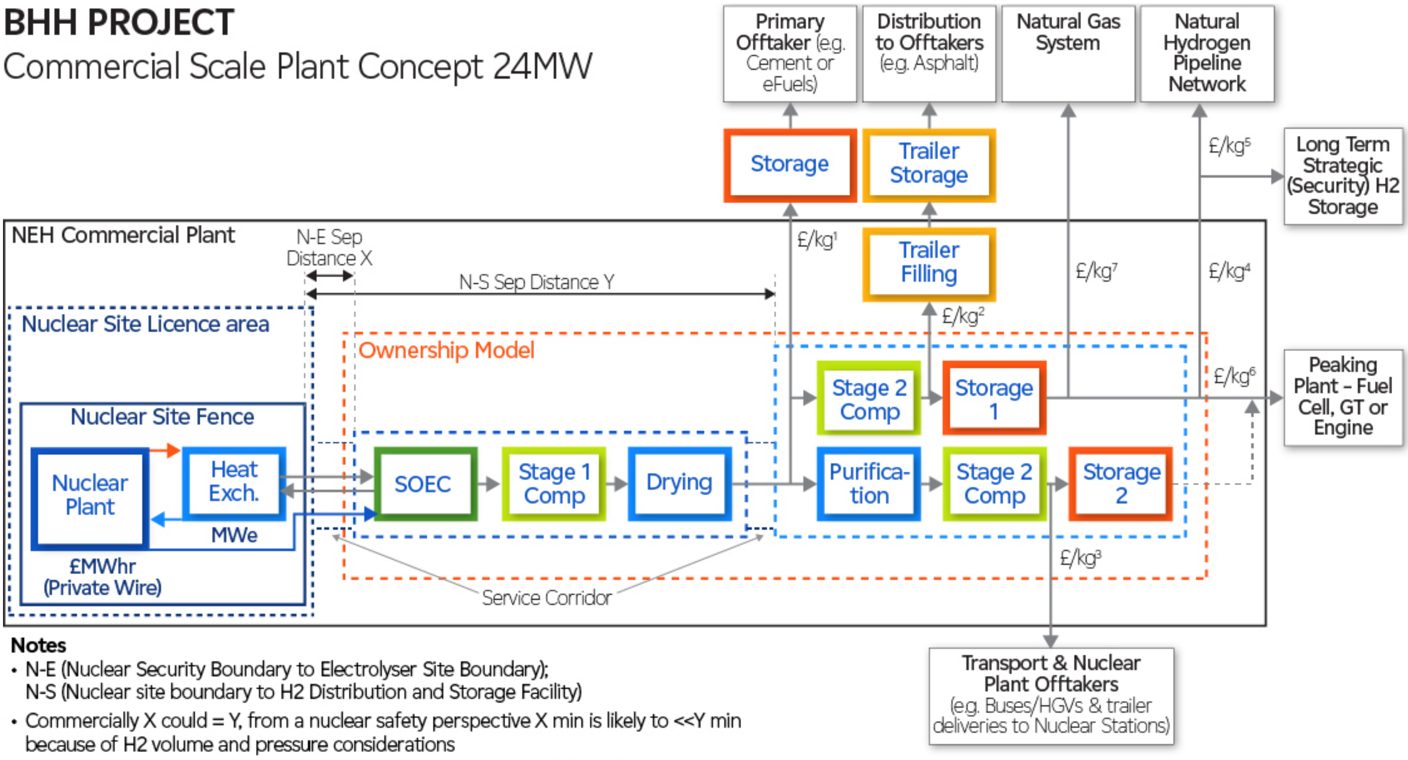


Figure 31 histogram charts of dump off-take availability against power prices (a & b) and power cost (c & d) for 2023 & 2024 price year results.

BHH PROJECT

Commercial Scale Plant Concept 24MW



Notes

- N-E (Nuclear Security Boundary to Electrolyser Site Boundary);
  N-S (Nuclear site boundary to H2 Distribution and Storage Facility)
- Commercially X could = Y, from a nuclear safety perspective X min is likely to <<Y min because of H2 volume and pressure considerations
- The primary side of the heat exchanger takes steam tapped off from the turbine, at in the range (T240 – 280C, P5-12bar)
- The secondary side of the heat exchanger is at lower pressure than the primary side (T 160 – 200C, P 1-5bar)
- The diagram does not include aux. plant, including demin. water, purge gases, etc
- The stage 1 compression outlet pressure (20 - 30bar), Stage 2 compression (250 – 500bar) dependent on distribution and transport requirements
- The distance between stage 1 and stage 2 compression facility could be long, up to 0.5km, dependent of explosion assessment risk
- The £/kg H2, 1 – 7, reflect the cost of production for the H2 to meet the off-takers requirements and is closely linked to wholesale electricity price

Figure 32 BHH Project - Commercial Scale Plant Concept 24MW.

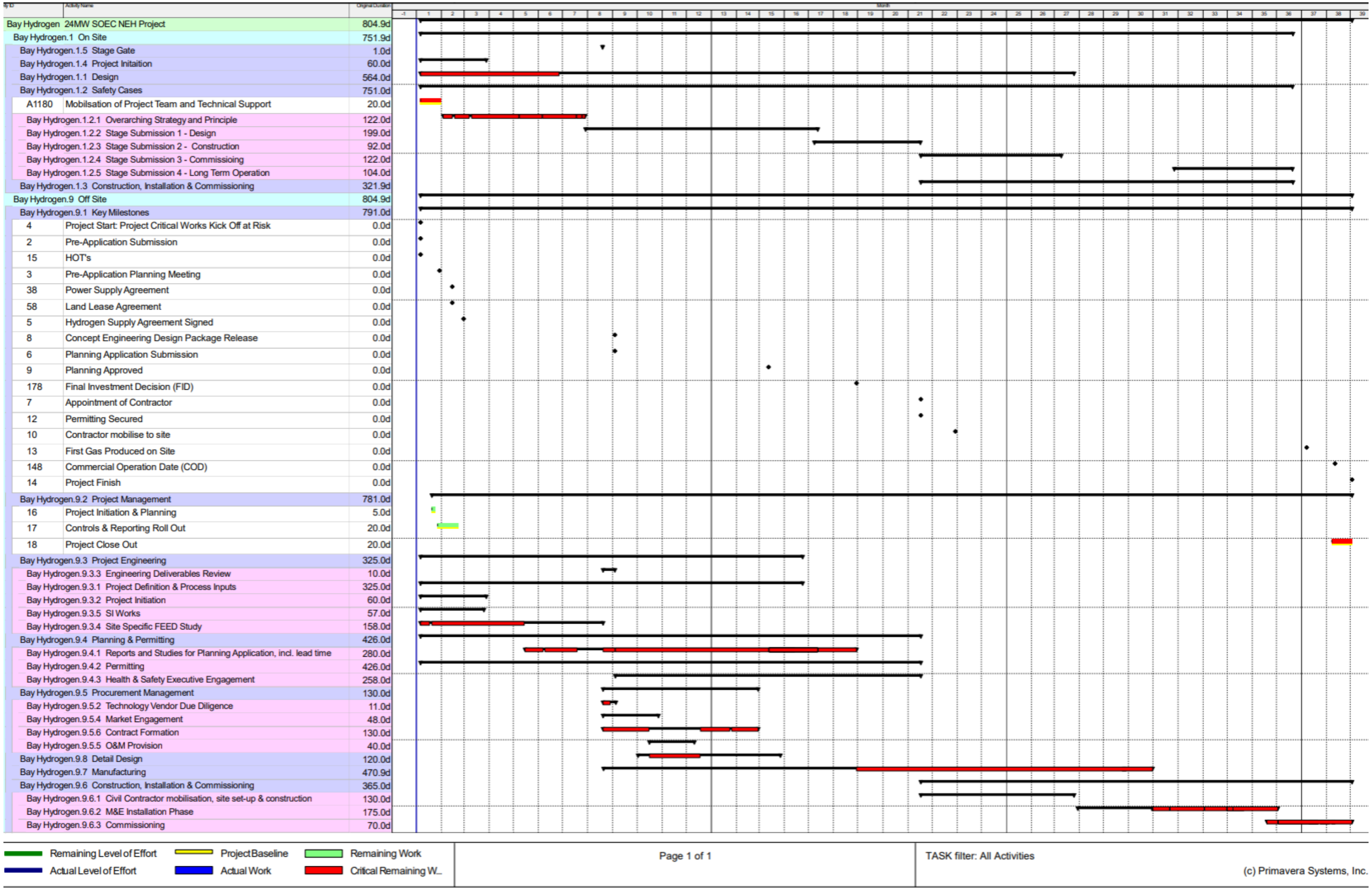


Figure 33 An example of a NEH project schedule.

SUPPORTING TABLES

Table 12: Off-taker demand profiles and criteria.

Off-taker	Nature of Offtake	% Annual Offtake*[1]	Weekly Production	Pressure	Notes
1. Cement	Semi continuous	45% (45t per week)	• 7 days per week • Site storage will allow supply to be curtailed for periods of up to 4hrs	20-30bar (pressure requirements at the plant much lower <2bar)	• Direct pipeline supply to cement plant operating 24/7 except when on outage (turnaround) • Offtake requirements are based on the H2 being a fuel enhancer making up 12.5% of the energy input with the remainder coming from biomass • Cement plant would have some H2 storage to allow for interruptions in supply for technical or commercial reasons (e.g. if power prices are very high it may make more sense to export the electricity to grid, perhaps during an evening peak or when there is limited renewable supply)
2. Asphalt	On demand	17.5% (17t/week)	• 48 – 96 hrs per week • Site storage (trailers) of 2t per site	200 to 500 bar	• Hydrogen is being supplied to 2 Asphalt sites • With on-site storage of 2 t per at each site and storage at the production site there is flexibility when H2 production is required • H2 production will be targeted to when electricity prices are low
3. Transport	On demand	10% (10t/week)	• 1- 4hrs per day • Storage on production site	200 to 500 bar (high purity)	• The demand for H2 will vary dependent on use of the Hydrogen Refuelling Station (HRS). H2 production to be targeted to when power prices are low!
4a. Natural Gas Pipeline* (Blending)	Intermittent	5%*[2]	• Only when H2 production cost is lower than counterfactual (NG + Carbon)	DNO - up to 14bar Trans – up to 100bar	• H2 can currently be introduced into the DNO gas system (intermediate/medium pressure) • H2 can't currently be introduced in the main NG Transmission system)high pressure) although this is being consulted on • [General consensus is that up to 20% H2 (by Energy?) can be safely introduced into the gas system, based on trial]
4b.National H2 pipeline network and Strategic* Storage	Intermittent	5%*[2]	• Only when H2 production cost is lower than counterfactual (NG + Carbon)	Dependent on geology and depth	• A strategic storage facility may be a salt cavern, aquifer or depleted hydrocarbon reservoir. • A suitable facility or pipeline connecting to a storage facility would need to be located relatively close to a nuclear power plant for this to be an option.
5. Peaking Plant	On demand	Up to 500hrs per year (c7%)	• Only when power prices justify operation	3 – 150 bar depending on technology (TBC)	• At times of peak electrical demand and if electricity prices are high, stored H2 can be used to fuel a 'peaking plant'. • There are several different competing technologies which could be used, including Gas Turbines, Fuel Cells or Combustion Engines.
6. Nuclear Station	On demand	<1.0% (15 to 20 t/year)	• When required, to replace a trailer on site	200 to 500bar	• Currently H2 is stored at 200 to 250 bar on stations in H2 trailers • Figures based on supplies to current stations

*[1] Assumes 85% utilisation of electrolyser
*[2] Assumes only one pipeline option (4a or 4b) is available, so total percentage annual offtake is 5%

Table 13: Storage requirements for each off-taker.

Off-taker	Storage Requirements*	Method	Pressure	Notes
1. Cement	a) 1 week's supply at cement site – an alternative fuel for strategic purposes b) 1t (~4hrs) - for flexibility	Depends on site fuel cost Storage tank or multiple tanks	A low-pressure supply only is required	The strategic storage requirement is large and gaseous storage is probably not an option, possibilities are: • Back up fuel, possibly natural gas • Ammonia • eFuel The flexibility store requirement is to give time for fuel switch over and to allow for short periods when the H2 supply is lost for technical (unplanned) or commercial reasons (planned). Although the supply pressure to the cement plant is relatively low (20-30bar), for economic reasons (size of storage tanks) storage pressure could be at a higher pressure which would necessitate a compressor at the cement site.
2. Asphalt or other distributed off - taker	2t at H2 production site	Storage tank or multiple tanks	250 to 500bar	• Pressure to match tanker distribution pressure • The volume to be optimised commercially based on demand and to reflect market flexibility (electrical price)
3. Asphalt	2t at each asphalt site	H2 Trailers	250 to 500bar	• Having storage at the asphalt site enables optimal operation of the plant, avoids having two mobile trailers on site with the associated twin decant system • It is assumed that parked trailers would form the optimal storage arrangement at the site but this could be static tanks depending on commercial optimisation
4. Transport	1t	Storage tank or multiple tanks	250 to 500bar	• The storage pressure would be matched to the requirements of the hydrogen fuelling station which may include a small compressor consistent with filling requirements for transport offtakers
5. Nuclear Station	0.5t on nuclear site	Storage tank or H2 trailer	250 to 500bar	• Nuclear stations in the UK typically use H2 trailers parked up in a H2 compound to provide hydrogen supplies to meet the station needs, the current trailers typically operate at 200bar max.

*The total H2 storage mass on the H2 production and storage site is assumed to be up to 6 tonnes (excluding storage at the cement, asphalt and nuclear site), this is made up of 3 ts of dedicated storage, 2 ts of trailer storage during filling and H2 present within the system (pipework, vessels and compressors)
*The lower tier COMAH limit for H2 is 5 tonnes (t)

Table 14 Other considerations for NEH facility scale up.

Concern	Challenges and Recommendations
Water Supply	Demand: ~50,000 litres/hour. Challenges: Securing a reliable source, managing heat loss, and cooling needs. **Recommendations**: Explore multiple water sources, invest in efficient technologies, and develop climate change mitigation strategies.
Nitrogen Supply	Options: Scale up on-site production or purchase additional nitrogen bottles. Benefits of Scaling: Continuous supply, potential cost savings. Benefits of Bottles: Simplified system, lower maintenance. **Recommendations**: Assess long-term needs, conduct cost analysis, and consider associated risks.
Electric Supply	Grid Connection: Likely needed; could strain the reactor site system. Direct Connection to Nuclear Plant: Challenging and easier on new build reactors. Demands impact efficiency and nuclear safety. Infrastructure: Requires transformers, switchgears, cabling. Ownership: NPS owns grid breakers and switchgear on site., off-site supply will be provided through discussion with the grid. Concerns: Legal implications, hydrogen plant as parasite load, metering needs. **Recommendations**: Understand site-specific details for NPS equipment connection requirements. Be aware of the legal implications of a Licence Exempt Network and the responsibilities of a Distribution Exempt holder. Address concerns about the hydrogen plant as a parasite load and its impact on post-trip cooling supplies. Ensure metering compliance with the balancing and settling code for any connections.
Air Supply	Increased air supply is essential. Redundancy and diversity in air compression needed. **Recommendations**: Implement redundant and diverse air compression systems. Establish rigorous maintenance and monitoring schedules. Design air reservoirs to provide a buffer during supply interruptions.
Site Licence Conditions	LC2: Minimise penetrations; build a trench designed for future expansion. LC7: Ensure effective incident management. LC11: Adjust emergency plans for higher hydrogen storage. LC26: Review control and supervision strategies. LC27: Review safety mechanisms and devices. LC36: Ensure changes don't affect organisational capability. **Recommendations**: Reduce penetrations through the site boundary. Implement robust incident management procedures. Update emergency plans to reflect increased hydrogen storage. Confirm no significant increase in risks in control and supervision. Maintain organisational capability despite new equipment.
Emergency Response Procedures	Fire Suppression: Evaluate systems for hydrogen fires. Ensure sufficient and reliable access. Coordinate to avoid conflicts. Maintain clear routes for emergencies. **Recommendation**: Choose effective fire suppression systems for hydrogen. Plan for adequate water storage and access. Align emergency plans to prevent interference. Keep emergency access and egress routes unobstructed.
Security	Proximity to nuclear site requires meticulous security planning. Increased hydrogen storage impacts security. Potential for unauthorised access via raised structures. **Recommendations**: Maintain a minimum 5-meter sterile zone from the NPS fence. Assess and mitigate the impact of larger hydrogen storage tanks. Address physical security, cybersecurity, and regulatory compliance. Evaluate byproducts and waste for potential hazards. Ensure effective communication and collaboration between sites.
Safety Case	Moderate and manageable adjustments needed and approach, process, and structure remain the same. Claims, arguments, and evidence are similar. Greater impact on steam and electrical systems. Increased utility demand affects nuclear safety. **Recommendations**: Assess maximum steam output at all power levels. Evaluate electrical supply during all power levels. Ensure systems handle all fire and explosion scenarios. Confirm no impact on existing routes. Ensure hydrogen facility does not compromise nuclear plant security. Assess waste management capacity for increased volumes.

Concern	Challenges and Recommendations
Economies of Scale	Higher initial costs are offset by faster recovery through increased revenue. **Recommendation:** Leverage discounts on electrolysers and other equipment for supplies above 100MW.
Planning Requirements	Navigate complex regulations; separate planning applications needed for multistage scale up. Address complexities during construction; maintain safe distances. **Recommendation**: Complete assessments and adopt a phased construction program. Coordinate effective communication between hydrogen and nuclear plants. Develop detailed planning and risk assessment strategies and maintain clear communication channels to ensure seamless integration.

REFERENCES

Reference number	Reference title	Owner	Source
Reference 1	History of Nuclear Enabled Hydrogen	UKNNL	For access to these References, please contact EDF
Reference 2	Demand Based Modelling Summary	UKNNL	
Reference 3	Details about Solid Oxide Electrolysers	EDF	
Reference 4	Health and safety considerations	EDF	
Reference 5	Approach to ensuring site licence compliance	EDF	
Reference 6	Regulations and Standards	EDF	
Reference 7	24MW FEED – vendor packages, intermediate loop, safety design basis, applicable codes and standards	EDF	
Reference 8	Additional Assessments (safety distance, assessment of explosion hazard, heat loss, full HAZOP, full Control Philosophy)	EDF	
Reference 9	Safety Case Structure and Fault Schedule	EDF	
Reference 10	Further technical details on 96MW scale-up	EDF	
Reference 11	Hartlepool Heat Hub BEIS Phase A Pre-FEED Report Deliverable 1 – Issue 001 February 2023 HHH-BEISA-301-001]	EDF	
Reference 12	Heat Loss Calculations	EDF	
Reference 13	NEH Requirements Summary	EDF	
Reference 14	NEH 24MWe Design Study	EDF	
Reference 15	Project Delivery Schedule	EDF	
Reference 16	Demand Based Modelling Full Report	UKNNL	

Reference 1 – History of Nuclear Enabled Hydrogen

Japan and China are both engaged in projects with High Temperature Gas Reactor (HTGR) designs. Initial experimental tests in both countries have generated small amounts of hydrogen. The electrolysers used in Shandong and those planned for the larger scale-up project in China are not explicitly specified. In Japan, Japan Atomic Energy Agency (JAEA) operates a closed-loop Sulphur-Iodine (S-I) cycle, achieving continuous operation for 150 hours, producing 100 litres of hydrogen per hour. Approximately equal to 0.24 kg/day. The UK is progressing two Advanced Modular Reactor (AMR) designs both with the aim of hydrogen production.

In the US, the Department of Energy (DOE) is actively promoting the advancement and refinement of clean hydrogen production in the future. They are allocating funding for the establishment of 6 to 10 regional clean hydrogen hubs throughout the United States. Notably, at least one of these hubs will specifically concentrate on clean hydrogen production facilitated by nuclear energy.

Furthermore, additional financial backing is allocated to support clean hydrogen production through tax credits. These credits have the potential to provide up to $3 per kilogram for low-carbon hydrogen. The overarching goal of these efforts aligns with the DOE's 'Hydrogen Shot' mission, which aims to achieve an 80% reduction in the cost of clean hydrogen, bringing it down to $1 per kilogram within a decade.

For the three projects currently producing hydrogen, the hydrogen is used on site. In the case of constellation energy (nine-mile point), it is stated the hydrogen is "more than enough to meet the plant's operational hydrogen use". Apart from one steel production project in Sweden there appears to be no other fixed use for the hydrogen currently produced by the test sites.

Close monitoring of these projects is crucial to identifying successes and challenges in deploying hydrogen production using energy from Nuclear Power Stations (NPSs). As these projects progress to commercial scales, it becomes imperative to address challenges like electrolyser scale up, meeting regulatory requirements, hydrogen transportation and storage, further developing hydrogen demand, surveying water supply, and engaging stakeholders and the public. Given that most projects are in early stages or planning phases, specifics such as electrolyser type and size remain subject to change in the coming years.

Reference 2 - Demand based modelling

The aim of the UKNNL demand-based modelling work is to provide an example case study of the capability UKNNL has to support analysis of the feasibility of using nuclear power to generate hydrogen.

In this study, Heysham 2 is assumed to run continuously while Heidelberg's asphalt plant at Criggion operates Monday to Friday in an 8-5 dayshift pattern, with no operation over the weekend. Two scenarios are considered, and they are differentiated in their hydrogen production and storage profiles:

1. Hydrogen production is continuous at a moderate level as this is most efficient use of electricity, but will require more hydrogen storage.
2. Hydrogen production is halted over the weekend and ramped up to a higher level than in scenario 1 to account for this during the week. This scenario is less energy efficient but also requires less storage of hydrogen at the Criggion site.

Key outputs

1. The hydrogen storage capacity needed.
2. Profiles for where energy is used from Heysham.
3. A series of rules of thumb to guide future analysis of such systems.

This work has led to the below rules of thumb for future consideration:

- 1 MWhe equivalent (i.e. the amount of electricity production given up to produce hydrogen) would result in ~26 kg of hydrogen gas.
- On standby mode, electricity from the NPS can be used to keep the electrolyser cells warm. This will reduce the efficiency of the NPS to generate electricity slightly, and that is accounted for in this work – typically ~5% of the electrical demand of a running Solid Oxide Steam Electrolyser (SOSE) stack is needed to maintain temperature in standby mode.
- Storage of hydrogen at scale is an active area of research – most has focused on a scale suitable for hydrogen powered vehicles rather than supporting industrial applications. Assuming storage in a similar manner to vehicles, i.e. compression, this would result in a loss of 2-3 kWh/kg hydrogen in energy due to compression needed (in these application hydrogen is typically stored at 250-700 bar)[38]. Typical trailers would store 225-250 kg per trailer with on-site storage potentially being larger at 500-1000 kg depending on the vendor.
- Other storage/transport mechanisms are available, such as liquid hydrogen, metallic hydride storage etc and which is most economical and best suits the safety considerations will need to be decided on a case by case basis; these are unlikely to be economic at the scales considered in this current work.

[38] *M. Gardiner, Energy requirements for hydrogen gas compression and liquifaction as related to vehicle storage needs, DOE Hydorgen and Fuel Cells Program Record #9013: US DOE, 2009.*

Reference 3 – Details about Solid Oxide Electrolysers

Overview of Solid Oxide Cell Electrolyser

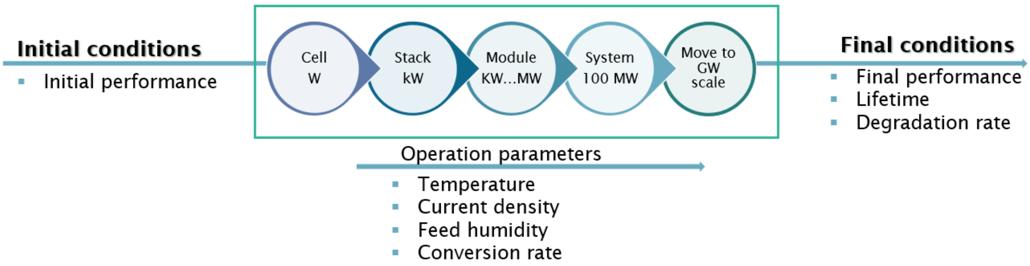


Figure 34 Scaling-up from a single cell to a MW range and beyond.

An electrolyser is made of modules in the 100 KW range that are multiplied to achieve the MW range and beyond. The modules are made of stacks in the kW range and each stack contains several cells corresponding to its power (Figure 34).

The cell is the core of the electrochemical process, and for SOEL, three architectures are currently considered that covers an operating temperature range from 550 °C to 850 °C. as follows:

- Metal supported cells (MSC) operate below 600 °C where a metal sheet is the substrate on which electrodes and electrolyte are screen-printed.
- Fuel electrode (cathode) supported cells (CSC) operate between 750 °C to 800 °C and use the fuel electrode as a substrate on which the electrolyte and the oxygen electrode are screen-printed.
- Electrolyte supported cell (ESC) with an operation temperature from 755 °C to 855 °C has the electrolyte as substrate and the fuel and oxygen electrodes are screen-printed and sintered on each side of the electrolyte.

Overview of Solid Oxide Cell Electrolyser technology development

Currently, higher operating temperatures are limited by the melting point of the glass sealing used at 860 °C. The controlled parameters are the operating temperature, current density, feed parameters and steam conversion. The key parameters of importance such as durability, performance and degradation rate are continuously optimized to reduce the production and operating cost and to extend the lifetime.

Technological advancements are centered on the industrialization of cell manufacturing processes, automation of stack and module production, and the development of media and power supply systems for multi-MW applications. Research institutes and industries collaborate within flagship programmes and projects to address the challenges associated with scaling up the technology. Figure Industries and research institutes involved in the development of SOEC (Excluding Asia to ease the reporting and understanding). displays the international players as well as the industries related to ESC or CSC. It should be noted that the Asian players are not considered, as development of the technology in Japan, Korea or China is currently not visible.

- The world's first multi-MW system with a 2.6MW nominal power based on 12 modules is built and integrated in Neste's renewable products refinery in Rotterdam (i.e. EU project MultiPLHY).
- Ceres Power (Bosch GmbH and Linde AG) deployed a 1MW demonstrator in Bangalore at Shells R&D centre.
- Topsoe A/S is considering an installation of a 5GW capacity electrolyser in Germany and in the US. Topsoe is a unique company which made available commercially the eCOs product (i.e. on-site production of CO via CO_2 electrolysis).
- Bloom Energy has installed a 4MW system at a NASA research facility in California that is producing more than 2.4 metric tons of hydrogen per day.

Coupling a NPS with a high temperature electrolyser has been studied by multiple research agencies and industry bodies, including National Nuclear Laboratory (NNL), International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA) and the Idaho

National Laboratory (INL). However, no demonstration has yet taken place worldwide on a nuclear site. Preliminary studies were undertaken to define the electrolyser heat and steam requirements, and suitable extraction points to couple it to the secondary steam circuit of a NPS.

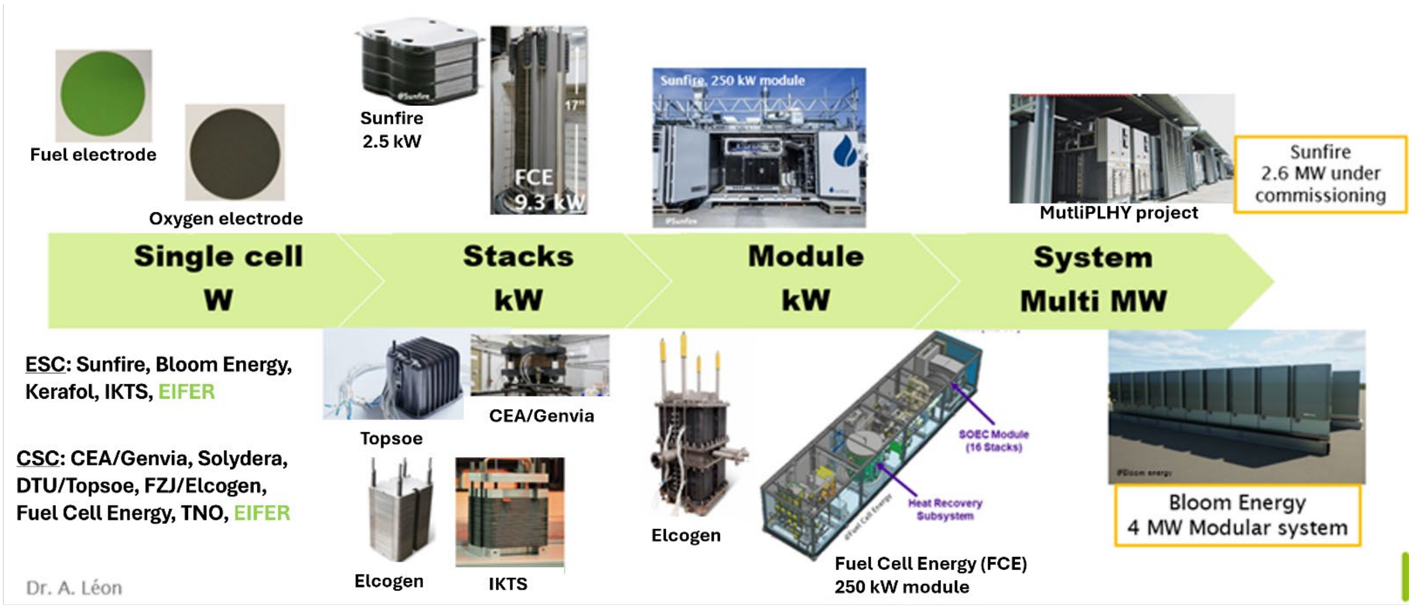


Figure 35 Industries and research institutes involved in the development of SOEC (Excluding Asia to ease the reporting and understanding).

Future technology development required for scale up

The advantage of this technology is the possibility to operate at the thermoneutral voltage that is c. 1.29 V at 800 °C. At this point, the heat released by the cell (i.e. inherent Joule effect) equals the heat demand for the electrolysis reaction to proceed. This potential adds on the efficiency of the technology and allows for different operating strategies:

- Operate at higher current density (i.e. increases the hydrogen production rate and lowers the capital cost)
- Compensate degradation and extend lifetime by continuously increasing temperature (i.e. operate as long as possible at thermoneutral voltage)
- Operate in dynamic mode by performing ON/OFF switching between the thermoneutral point (current ON) and the open circuit voltage (current OFF) (i.e. increase the steam conversion).

These operation options have been made possible, and recently demonstrated, thanks to advances in cell manufacturing. Optimizing the electrodes, electrolyte, and intermediate layers help minimize several detrimental degradation processes, including electrode delamination, ohmic loss, and contamination. For example, ohmic degradation in electrolyte supported cell has been reduced by decreasing the electrolyte thickness from 90 to 40 µm. The state of the art is an ESC cell operated for 6,000 hours at -1.2 A/cm2 at 850 °C with a degradation rate of 4 mV/kh. Similarly, the stack and modules are optimized to enhance their lifespan, reduce their footprint, and simplify operation and maintenance.

FuelCell Energy – case study

Key Features

FuelCell Energy (FCE) designs and manufactures both power generation and hydrogen generation solutions based on its proprietary solid oxide (SO) cell, stack and system technology. FCE’s SO technology is designed and manufactured in its Calgary, Alberta, Canada facility, and represents over twenty years of continuous SO technology development.

Key features of FCE’s SO technology for high-temperature electrolysis include:

- Fuel electrode supported cell design with thin electrolyte layer (5 – 10 micron) resulting in:
    - High cell efficiency
    - Superior dynamic responsiveness to modulate stack operating output
    - Moderate operating temperature of 750 °C, allowing for use of more common materials of construction and manufacturing processes (e.g. stamped stainless steel interconnects)
    - Compact stack architecture with annular cell design resulting in:
        - Isothermal cell conditions through counterflow of reactants
        - High energy density with low mass and volume per unit of output
- System design approach: FCE designs and supplies a complete system from water and AC power input to 99% hydrogen output, ensuring a high-level of quality and performance in operation and a streamlined site design, procurement and installation process
- High electrical efficiency using steam electrolysis: stack efficiency of 34.5 kWh/kg and system efficiency of 44 kWh/kg (based on deionized water input, AC power input, and 99% hydrogen output at near atmospheric pressure)
- Heat integration option: able to use external source of heat (for instance from a NPS) to further reduce electrical consumption to 40 kWh/kg
- Low water use: system water usage of 9.5 litres/kg of hydrogen output through recovery of water in hydrogen outlet stream
- Commonly available materials: no platinum group metals, and abundant rare-earth metal (yttrium)

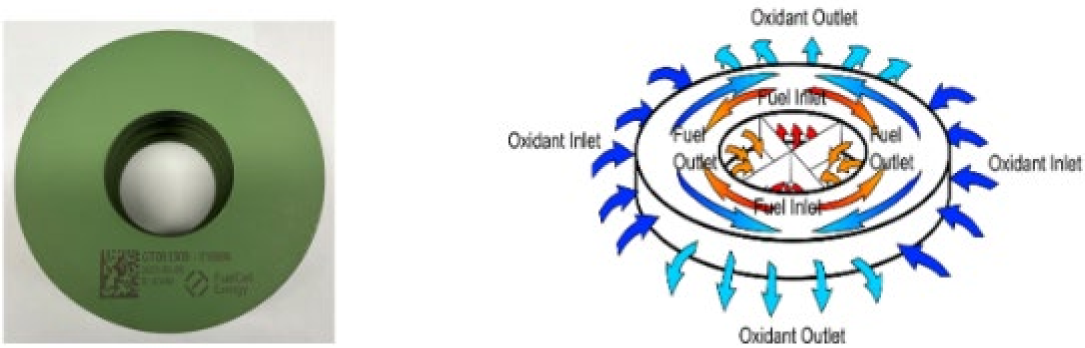


Figure 36 FuelCell Energy's solid oxide annular cell design.

Technology Verification Status

FCE's solid oxide cell and stack technology has been fully validated in electrolyser mode through extensive testing both inhouse and by Idaho National Laboratory. Test plans have explored dynamic response, full up/down ramping capability, and robustness to thermal cycles. The leading stack test article has passed 12,500 hours of operation with little performance degradation. Each commercial stack is tested after build and conditioning to assure in-specification performance in the field.

Figure 38 FCE's commercial stack in production test stand.

Figure 37 FCE's 150 kg/day SOEC system prototype.

FCE has successfully designed, built and tested a 150 kg/day (250 kW) electrolyser system under a U.S. Department of Energy funded program. This comprehensive system is functionally comparable to FCE's commercial product under development, operating with cold water and utility AC power as the inputs and generating dry product hydrogen with high efficiency. The system has successfully operated at full rated hydrogen output at FCE's Danbury, Connecticut headquarters. As of March 2025, the system has been delivered to Idaho National Laboratory (INL) and is in the final stages of commissioning before undergoing extended duration operation, including testing of heat integration with a simulated nuclear plant-supplied source of steam to demonstrate maximum system efficiency.

Reference 4 - Health and safety considerations (DSEAR, CDM)

The designer has a duty to follow the Construction Design and Management (CDM) Regulations 2015. A Designer's Risk Register shall be developed as part of the design process. The Designer's Risk Register shall identify potential hazards and risks from construction through to decommissioning. Any residual risks not designed out shall be highlighted to interested parties, through the register or as notes on design drawings.

All temporary access and support structures necessary to execute the work at site will be provided by suitable supplier. This will include the routine inspection and certification of all such temporary structures.

HAZID/ HAZOP

During the design process a series of hazard studies will be carried out.

Risk Assessments and Underlying Documentation

The following Project Risk Assessments should be developed / updated in support of the project.

Core Documents

- Nuclear Safety Case(s)
- COMAH Major Accident Prevention Policy (MAPP)

Underlying Risk Assessments

- Civils / Ground assessment of location where that asset will be located
- Identification of Major Accident Hazard Scenarios & Assessment thereof (e.g. Blast, dispersion etc) - needs to integrate with COMAH MAPP.
- Environment Risk Assessment (e.g. Civil Defence, Operational, and Industrial Framework (CDOIF)) & Permitting - needs to integrate with COMAH MAPP.
- Hazard & Operability Studies (HAZOP's) - To include identification and assessment of any Layers of Protection / Mitigation (e.g. via LOPA study)
- DSEAR Assessment (HSE L138). To Include Hazardous Area Classification & Review of potential ignition sources to IEC 1127-1 (International Electrotechnical Commission)
- Lightning. Assessment to BS EN/ IEC 62305. Needs to consider asset protection, ignition & effects of Lightning Electromagnetic Pulses (LEMP).
- Workplace Transport risk assessment- in support of increased hydrogen movements
- Cyber Risk Assessment - In support of remote access to control systems
- Emergency Response / Fire Assessment

Vendor Packages

Equipment supplied by key vendors (e.g. electrolyser, compressor, tube trailers etc.) to be supported by UK-CA [EU-CE] Marking (or equivalent) and should include underlying documentation to include:

- Evidence supporting identification of, and compliance with, all pertinent legislation and relevant good practice (RGP) standards & guidance.
- Underlying hazard identification & risk assessments (e.g. Blast, Dispersion, Hazardous Area Classification, CDM Designer Risk Assessments etc)
- Operation & Maintenance Manuals - Detailing all Safety / Protection / Mitigation Functions and any maintenance and testing requirements.

CDM

The project must align to the requirements of the UK Construction (Design and Management) Regulations 2015. This requires that all the safety, health and environmental hazards should be identified; and associated risks assessed. Risk assessments must consider the lifespan of the asset including construction, commissioning, operation, maintenance and decommissioning.

Where it is not possible to eliminate risks, the measures taken to reduce / control them (i.e. Safety Functions) should be implemented using relevant good practice standards and guidance.

Safety functions implemented to protect against, mitigate risk must be:

- Realised such that they are independent of the system operational functions so far as is reasonably practicable.
- Supported by maintenance & test procedures (e.g. proof tests).
- Clearly signposted in documentation (e.g. operation and maintenance manuals) and on the asset itself.

Control of Major Accident Hazards

Project to align with the pertinent requirements of Control of Major Accident Hazards Regulations.

Pertinent risk assessments will be developed/modified in support of the underlying requirements of COMAH (and other) legislation. These include, but are not limited to:

- Civils / Ground assessment of location where that asset will be located
- Identification of any Major Accident Hazard Scenarios & Assessment thereof (e.g. Blast, dispersion etc.)
- Environment Risk Assessment (e.g. CDOIF) & Permitting
- Hazard & Operability Studies - To include identification and assessment of any Layers of Protection / Mitigation (e.g. via LOPA study)
- DSEAR Assessment (HSE L138). To Include Hazardous Area Classification & Review of potential ignition sources to IEC 1127-1
- Lightning. Assessment to IEC-62305. Needs to consider asset protection, ignition & effects of Lightning Electromagnetic Pulses.
- Workplace Transport risk assessment- in support of increased hydrogen movements
- Cyber Risk Assessment - In support of remote access to control systems
- Emergency Response / Fire Assessment

Safety Functions and Layers of Protection

Through the process of hazard identification and risk assessment (e.g. HAZOP, LOPA etc) the project should clearly identify all Safety Functions, Loss of Protection's (LoP's) and Loss of Mitigation's (LoM's).

The integrity of these functions will be quantified and resulting systems / equipment designed, signposted, operated and maintained based on RGP.

NOTE: All safety functions, LoP's and LoM's to be implemented to be independent of operational functions so far as is reasonably practicable.

- Assessment. To include HAZOP, LOPA and Safety Integrity Level (SIL) assessment (if required)
- Design, Operation & Maintenance of pertinent layers of Protection / Mitigation to underlying Relevant Good Practice standards & Guidance.
- Process / Mechanical.
    - HSE HSG51/140 Safe Use and handling of flammable liquids
    - HSE HSG143 Designing and operating safe chemical reaction processes

- HSE HSG244 Remotely operated shutoff valves (ROSOVs) for emergency isolation of hazardous substances: Guidance on good practice
    - BS EN 13445 Unfired Pressure Vessels
    - BS EN 14015 Specification for the design and manufacture of site built, vertical, cylindrical, flat bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperatures and above,
    - American Society of Mechanical Engineers (ASME) B31.3 Process piping
- Electrical.
    - HSE HSG85 Electricity ay work – safe working practices
    - HSE HSG230 Keeping electrical switchgear safe
- Control. Functional Safety
    - IEC 61508:2010 **Functional safety of electrical/electronic/programmable electronic safety-related systems - Parts 1 to 7**
    - IEC 61511 **Functional safety - Safety instrumented systems for the process industry sector**
    - IEC 62061**Safety of machinery - Functional safety of safety-related control systems**
    - HSE OG46 **Management of instrumented systems providing safety functions of low / undefined safety integrity**
    - HSE OG 7 **Operator Response within Instrumented Safety Functions in the Chemical, Oil & Gas, and Specialist Industries**
    - HSE OG54 **Proof Testing of Safety Instrumented Systems in the Onshore Chemical / Specialist Industry**
- Control. Alarms
    - EEMUA-191EEMUA Publication 191 Alarm systems - a guide to design, management and procurement
    - IEC-62682**Management of alarm systems for the process industries**
- Control. Instrumentation BS-6739 **Instrumentation in process control systems: installation design and practice. Code of practice.**
- Fire. BS 5908-1:2012 **Fire and explosion precautions at premises handling flammable gases, liquids and dusts - Code of practice for precautions against fire and explosion in chemical plants, chemical storage and similar premises**

DSEAR and Prevention of Ignition

Project to align with requirements of DSEAR and include:

- DSEAR Assessment (HSE L138). To Include Hazardous Area Classification (IEC-60079-10-1:2020 **Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres**)
- Review of potential ignition sources in all zoned areas (IEC 1127-1:2019 **Explosive atmospheres. Explosion prevention and protection - Basic concepts and methodology**)
- Design, operation, and maintenance/test of resulting equipment / systems to pertinent Relevant Good Practice. For example:
    - Mechanical (ISO-80079 Explosive atmospheres includes explosion venting devices and flame arresters)
    - Electrical / Instrumentation (IEC-60079 Series e.g. **Explosive atmospheres - Equipment with Separation Elements or combined Levels of Protection**)
    - Lightning – to also include the potential effects of LEMP on critical safety systems, LoP's and LoM's
        - IEC 62305 Series Protection Against Lightning
        - HSE OG44 Lightning protection at onshore hazardous installations
    - Static (PD IEC/TS 60079-32-1) Explosive atmospheres: Electrostatic hazards, guidance
    - Radio Frequency Ignition (PD IEC/TS 60079-32-1) Explosive atmospheres: Electrostatic hazards, guidance

- Gas Detection (IEC-60079-29) Explosive atmospheres: Gas detectors – Performance requirements for detectors of flammable gases
- Fire Detection & Alarm (BS-5839) Fire Detection and Alarm Systems for Buildings

Intermediate loop

Two potential options have been considered for the heat transfer from the NPS to the SOEC electrolyser package. First approach is to connect the NPS steam to a heat exchanger which then suppliers the heat to a second heat exchanger on the hydrogen production facility. Second approach removes the second heat exchanger on the hydrogen facility and provides heat directly to the SOEC package from the nuclear side heat exchanger. A simple illustration of the two options is shown in the figure below.

If the intermediate loop is removed, then the process water (ultra-low conductivity) from the hydrogen plant would be piped to a heat exchanger inside the NPS licence boundary where it is turned to steam and then returned back to the hydrogen plant. Steam from the nuclear plant must remain inside the NPS licence boundary and therefore this steam may not be moved to a heat exchanger inside the electrolyser boundary.

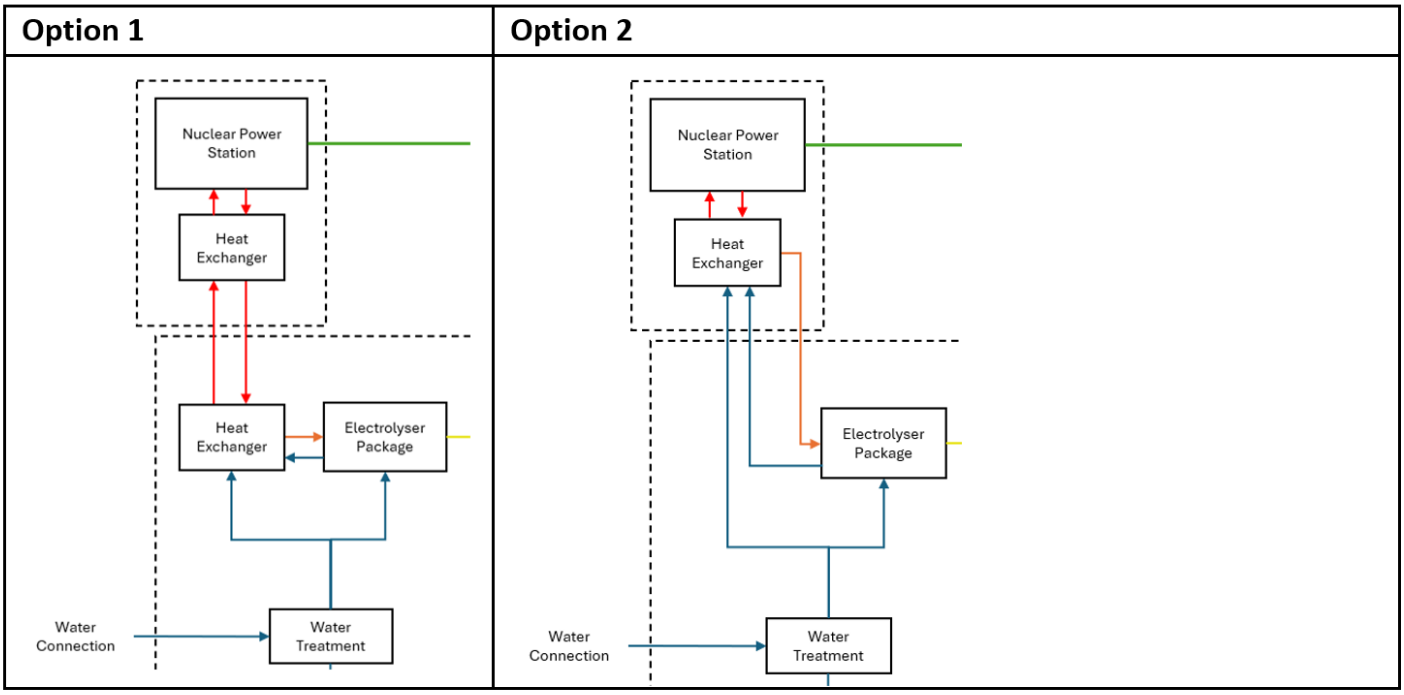


Figure 39 Options with and without intermediate loop conditions.

Safety Design Basis

- The process is non-classified in terms of nuclear significance
- The design will ensure no interaction with nuclear safety classified equipment and appropriate measure will be designed to protect nuclear significant plant from faults
- Nuclear safety takes the upmost priority over the operation of the NEH Facility
- Hazard Identification (HAZID) and Hazard and Operability (HAZOP) studies will be taking place throughout all stages of the design process
- A Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) risk assessment and Hazardous Area Classification to be carried out during detailed design to manage the risk of unwanted ignition
- Fire risk assessments will be conducted during detailed design to underpin the fire management strategy

- Layers of Protection Analysis (LOPA) to be carried out through detailed design
- As Low As Reasonably Practicable (ALARP) principles have been employed throughout the design process
- EDF procedures and policies will be complied with in terms of security and tanker routing through site
- The intent of the NEH Facility design is to have no impact on nuclear significant plant; any measures required to assure this claim will be assessed and implemented as part of the detailed design phase

Cost

Removal of the intermediate loop would remove one heat exchanger and a condensate pump from the design which could reduce CAPEX. However, to maintain the stringent water quality required by the SOEC the 100-500m of pipework to/from the NPS must be stainless steel (304 grade) instead of carbon steel (A106) which comes at an increased cost.

Concept level modelling suggests that removal of the intermediate loop leads to increased cost because the reduction in cost due to removal of the heat exchanger is less than the increase in cost from switching from carbon steel to stainless. High level modelling results are shown in the figure below. This shows the relative cost of the heating system (CAPEX for heat exchangers, pipework, condensate pumps) for both the 100m and 500m option. Hence, it would be preferred to keep the intermediate loop (option 1).

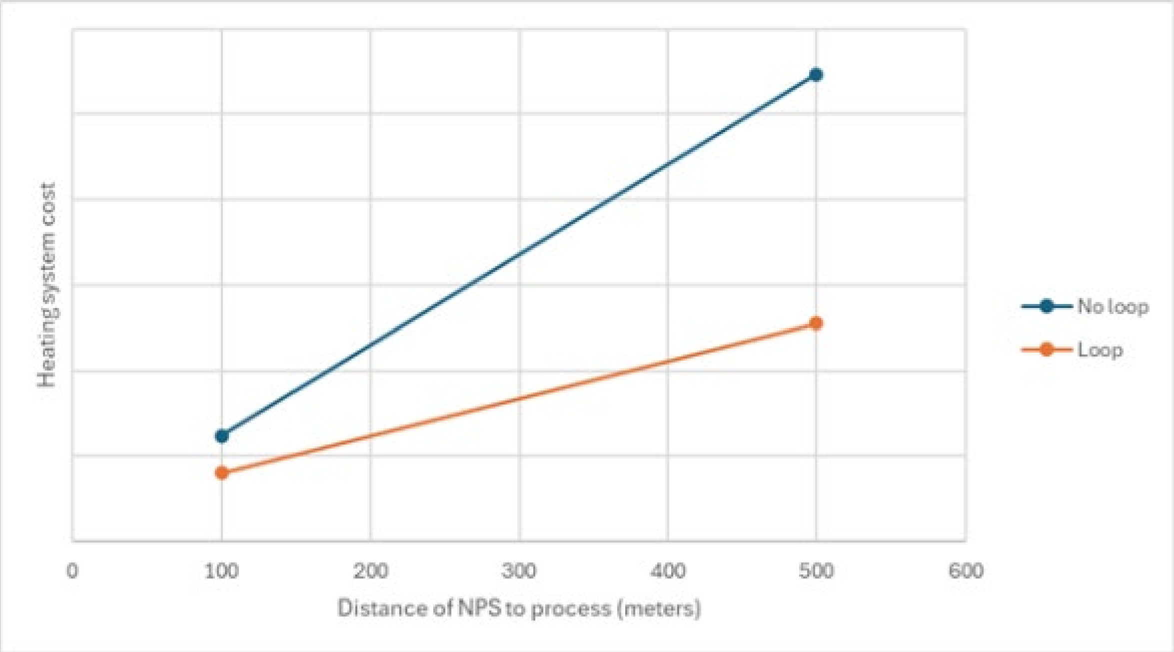


Figure 40 Comparison of heating system cost vs distance from a NPS.

Environmental review

This section provides a guidance on what environmental aspects project developers and planners need to consider for an environmental license/permit to install a water electrolyser for hydrogen production adjacent to a NPS.

For a license to install a water electrolyser near a nuclear site, it is essential to engage with the Environment Agency (EA), the primary regulatory body in England for such projects. However, for projects located outside England, it is crucial to identifying corresponding regulatory body for environmental assessments and permits (Natural Resources Wales (NRW) and Scottish Environmental Protection Agency (SEPA)).

The EA is responsible for issuing environmental permits and ensuring compliance with regulations related to air, water and land pollution, flood risk and land drainage in England. Any new installations will require an environmental permit even if located adjacent to or within the boundary of an existing nuclear site. The permit application must detail the emissions (including non-polluting substances like oxygen) and potential environmental impacts (e.g. on protected species/areas). The installation of hydrogen plant will be considered a new source of emissions and resource usage, thus falling under the EA's jurisdiction.

While hydrogen production via electrolysis is considered a clean process, it still involves emissions and resource usage that must be evaluated.

Air quality emissions:

- Oxygen venting – water electrolysis process produces oxygen as one of the products, which is typically vented into the atmosphere (whereas more valuable product, hydrogen, is captured). Even though oxygen is non-polluting, large releases still qualify as an emission under environmental regulations and must be included in the permit.
- Hydrogen leakage – accidental hydrogen releases, though unintended, must be anticipated. Even small quantities of hydrogen leakage into the atmosphere could pose risks and need to be documented as emissions.

Water use and wastewater:

- Water sourcing – the electrolyser will require a consistent source of demineralised water, which may be sourced from the nuclear facility. Developers must assess the sustainability of this water supply and its impact on local resources.
- Wastewater discharge – electrolysis may generate minimal wastewater, but the quality and quantity are essential, and potential impact on nearby water bodies and aquatic ecosystem must be assessed.

Ecological impact:

- Protected species - developer must evaluate the potential for the project to disturb or harm protected species. Impacts on wildlife, including breeding birds, should be part of the assessment.
- Habitat disturbance – construction and operation may lead to disturbance in local ecosystems. A Habitat Regulations Assessment (HRA) may be required to evaluate these impacts as advised by EA.

Additionally, when installing an electrolyser near a nuclear site, climate change must be a factor in the environmental assessment. The project developer must consider the environmental changes that climate change will bring, and ensure adapting the installations design and resilience accordingly. In this context water availability and usage are particularly important. Rising global temperatures and changes in weather patterns can lead to more frequent droughts and water shortages. This is particularly relevant if the water electrolysers located in areas prone to water stress, or if water-intensive industries are concentrated near the nuclear facility. Assessing the sustainability of the water source is important to ensure that the electrolyser's operation does not exacerbate local water scarcity or conflicts with other water users. As a mitigation strategy, developers should explore the possibility of water recycling within the electrolyser system and using alternative water sources such as treated wastewater or desalinated seawater if feasible – that could reduce reliance on freshwater resources.

Extreme weather conditions review

The co-location of a hydrogen production plant with a NPS presents unique opportunities. However, it also introduces complexity in terms of safety, especially when considering extreme weather conditions. This part of the report reviews the potential impacts of extreme weather events on the co-located facility and explores the possibility of applying nuclear safety regulations to the hydrogen production plant.

Temperature extremes such as heatwaves and cold spells could affect both Nuclear Power plant and the hydrogen production systems. Hydrogen storage tanks and pipelines may be subject to thermal expansion, increasing the risk of leaks or equipment failure. Freezing temperatures would also bring undesirable outcomes of mechanical failures of hydrogen pipelines.

Nuclear facilities are designed to withstand significant **flooding events**, but water electrolysers might not have the same level of resilience, which might result in leaks and pose explosion risk. Proper flood defence mechanisms should be in place and the developer of the hydrogen plant might consider following the nuclear station flood resilience standards. There is also a challenge on the location of the facility, and the flooding mechanisms, i.e. pluvial, fluvial, coastal and/or compound.

Winds, tornadoes and extratropical storms can also pose a significant risk to above-ground hydrogen production infrastructure. NPSs can typically withstand such conditions, but hydrogen infrastructure might require addition reinforcements. Especially that hydrogen is a highly buoyant gas, and for this reason, hydrogen production plants are designed to be open to the atmosphere.

Additionally, **seismic** activity could damage both plants, causing leaks and equipment failure. Earthquake-resistant design and automatic shutdown systems should be considered by developers.

Hydrogen production sites developers might consider applying safety measures similar to those in nuclear regulations, given their proximity and shared infrastructure. The subject of extreme weather conditions in relation to NPSs in the UK is primarily regulated by the Office for Nuclear Regulation (ONR) and secondarily by the Environment Agency (if in England). In September 2020, the Expert Panel on Natural Hazard provided updates for 3 items, among there was a draft paper and a review document on Extreme Weather Events in the UK which are part of a wider research programme. The report provides guidance to support assessments of extreme weather conditions hazard studies for nuclear sites in the UK including an overview of the challenging area of climate change and how it should be incorporated. The report provides useful information in the following areas:

- Overview of the UK climate and weather
- Data sources for meteorological hazard analysis
- Use of statistical methods in analysis of meteorological hazards analysis
- Climate models and UK climate change projections
- Analysis of flooding, wind, and other hazards such as heat waves, fog, lightening and space weather.

While nuclear regulations are stringent due to radiological risks, hydrogen plant normally would follow chemical industry standards. However, co-location of nuclear site and hydrogen site may necessitate adopting some nuclear safety principles to ensure comprehensive risk management.

Recommendations:

- Implement robust structural and safety systems for extreme weather and climate change.
- Apply nuclear-level safety standards to hydrogen production facility
- Develop coordinated emergency response plans to manage risks across both facilities

Overarching Strategy and Principles Submission

The overarching strategy paper is intended to present the fundamental principles for the design and operation of the hydrogen facility. Taking this approach allows the risk from the design to be defined and plans for reasonably practicable mitigations to be put in place. The aim is to demonstrate the risk is ALARP and allow the nuclear licensee to show the risks to the reactor plant are adequately managed early on; before physical work on the plant begins. Principles and claims for the project will cover the whole project lifecycle, examples are given below:

1. The credible plant faults and hazards that affect the design and operation of the hydrogen facility have been identified.
2. The hydrogen facility has been designed to minimise the risks from its construction and operation.
3. The manufacturing and procurement of the components for the hydrogen facility will be to the relevant standards and approved procedures.
4. Construction and installation of the hydrogen facility will be controlled to approved methods.
5. Commissioning of the hydrogen facility will be carried out to approved methods.
6. Long term operation of the hydrogen generation facility is adequately controlled.
7. The overall risks from the construction and operation of the hydrogen facility are ALARP.

The Strategy and Principles Submission should identify the Safety Functional Requirements and set out the basis for the design of the facility.

This submission will also describe how the modifications on the reactor site will be tied into the secondary circuit and any other services that are provided by the reactor site to the hydrogen facility. The principles for modifying the site boundary will also be addressed e.g., protection of the site security boundary where the steam supply passes through it. The Strategy and Principles submission will also present the strategy for gradually updating the safety case over a series of Stage Submissions allowing the risk to be controlled and understood throughout the project.

Stage Submission 1: System Design and ALARP Justification

This Stage Submission will provide an overarching case to demonstrate the design has met with the relevant regulations and standards and that it is safe to construct and operate. Stage Submission 1 will substantiate that the design is sound by presenting a detailed design substantiation report for the facility. The overall aim is to show that the risks to the reactor site have been shown to be consistent with the ALARP principle and that construction of the facility can proceed as the risks are being controlled.

Stage Submission 2: Construction

This Stage Submission will justify the safe construction and installation of the plant equipment onto the supporting civil structures. This submission will be purely covering the work required to get the equipment into its installed position and connected. It will justify any invasive groundwork for the selected location and demonstration that the civil work to construct plinths or support structures can be safely achieved and will be suitable to support the plant equipment. The submission will also cover any enabling work for the construction of the plant e.g., provision of services to the location in a safe state ready for connection. This submission will cover work on and off the nuclear reactor site and include the arrangements for any changes to the reactor site security boundary. This submission will need to confirm the requirements for electrical power supplies for construction and the arrangements for the final facility. Where supplies are taken from the reactor site a safety case will be required to justify the change to the electrical systems.

Stage Submission 3: Commissioning

Stage submission 3 will justify taking the plant from a construction site into a period of testing and commissioning. This submission will cover making the services/systems live, initial testing, e.g. mechanical, electrical and Control and Instrumentation testing, all the way through to subsystem testing and the final commissioning of the hydrogen generation plant. Commissioning will also cover the risks of exporting the hydrogen to the storage vessels and road transport depending on the customers being served. The aim of the submission is to confirm the plant has met the original design intent and is safe to handover and operate i.e., the risks up to this point have been adequately managed.

During commissioning the risk to the reactor site will have increased as there is the possibility something could go wrong and result in a fire or explosion that affects the reactor site. This submission will therefore present the communication arrangements and emergency arrangements should anything go wrong and potentially affect the reactor site.

Stage Submission 4: Operation

Stage submission 4 is required to take the plant from a commissioning state into long term operation. The submission will define the approach for handing over the plant and addressing any outstanding issues that affect safe operation of the plant. The submission will also justify the operations documentation to allow control and operation of the plant long term. As the plant will be generating, storing, and handling hydrogen the proposal will update the risk position for exporting greater quantities of hydrogen and present the long-term emergency arrangements for operating the facility.

Stage submission 4 will also introduce the requirements for maintenance of the structures, systems and components and arrangements for addressing shortfalls that affect the risk on the reactor site.

Final Report

Once work is complete and the hydrogen generation plant has entered operation the final report will confirm that the hydrogen generation facility and the final safety case have met the original principles and that risks from continued operation have been shown to be As Low As Reasonably Practicable. The final report will be presented as a safety submission and is intended to go through the same approval stages as the original Strategy and Principles submission to confirm that the hydrogen generation project has been safely delivered, and an appropriate safety case is in place that maintains the risks throughout its lifecycle.

This section summarises the findings from two HAZOP workshops on the concept design for Hydrogen production facilities. The first HAZOP for the Bay Hydrogen Hub (BHH) was conducted over four days in November 2023, involving representatives from

Jacobs, EDF, FuelCell Energy (FCE), Hanson (now known as Heidelberg Materials), and the United Kingdom National Nuclear Laboratory (UKNNL). The second HAZOP for the Hydrogen Hub Project was held over two days in September and October 2024 at EDF Javelin House, Gloucester, with attendees from Amentum/Jacobs, EDF, FCE, UKNNL, and Alfa Laval. Both studies assessed normal operation, hot standby, startup, and shutdown modes, identifying cause and consequence pairs for potential faults using guidewords and dividing the system design into nodes.

HAZOP STUDY 1 Bay Hydrogen Hub:

The first HAZOP study focused on the concept design for the Front-End Engineering Design Study, using steam from nuclear reactors to generate hydrogen via SOEC technology. The hydrogen is then compressed and stored in multiple element gas container (MEGC) trailers for road transport. The study aimed to identify hazards and operability aspects for detailed design, covering the entire system from steam supply to hydrogen export. The design concept was for a 1MW electrolyser. See below the Nodes studied.

The scoping work identified that hazards would differ across each operating mode of the plant. However, it was determined that there was no significant difference in hazards between mode 3 (startup) and mode 4 (shutdown), therefore both modes can be considered simultaneously for nodes 1 (Steam supply electrolyser) and 2 (Compression and intermediate storage). It was also determined that little benefit would be gained from considering separate operating modes for node 3 (Hydrogen export trailers), therefore node 3 considered potential hazards arising from any operating mode. See below key findings from each Node.

NODE 1 Inputs and outputs of the electrolyser

Table 15 HAZOP study: Inputs and outputs of the electrolyser, Node 1.

Category	Concern	Recommendation
Flow (Normal Operation)	Loss of feedwater flow Blockage of air feed High feedwater flow High hydrogen flow Low feedwater flow Low steam flow Low air flow Water treatment system (WTS) component failure Other gases	Assess buffer requirements and place low temperature alarms to address loss of feedwater flow Evaluate impact and corrective measures for blockage of air feed Consider overpressure scenarios and protect potential leak/release routes for high feedwater flow Implement gas detection systems and automated trips for high hydrogen flow Place filters in Water Treatment System to prevent low feedwater flow Confirm steam sources to compensate for low steam flow Evaluate higher concentration in outlet stream for low air flow Review water treatment system (WTS) design to prevent component failure Consider impact of non-air gases at SOEC inlet
Flow (Hot Standby)	Loss of flow Loss of feedwater Loss of hydrogen High hydrogen flow	Determine buffer storage and redundancy requirements for loss of feedwater Investigate pressure increase and determine redundancy for hydrogen vent design for hydrogen release Include pressure relief, venting arrangements, and dispersion assessment for high hydrogen flow release scenarios.
Flow (Startup and Shutdown)	Loss of steam Air feed blockage	Use electrical heaters to cope with loss of steam Implement alarms and trip systems to address air blockage
Pressure (Normal Operation)	High pressure Vacuum	Implement pressure relief to address high pressure Prevent low/vacuum pressure through operational procedures.
Temperature (Normal Operation)	High temperature (water, oxygen, steam)	Identify safeguards for excess superheat and consider upstream pressure/temperature regulation failure to address high steam temperature
Composition (Normal Operation)	Feedwater composition (ice formation, reduced quality) Steam contamination	Use conductivity sensors to detect reduced water quality and consult site chemistry team for dosing to address steam contamination
Composition (Startup and Shutdown)	Condensate in steam supply lines	Insert low point drains to address condensate formation
Utilities (Normal Operation)	Loss of power	Review power requirements and ensure backup UPS power supply to address loss of power

Category	Concern	Recommendation
Utilities (Hot Standby)	Insufficient process heating	Implement automatic trip to emergency shutdown to address insufficient process heating
Utilities (Startup and Shutdown)	Bottled hydrogen/nitrogen supply unavailable for purge or discharging at greater flow rate	Consider redundancy, interlocks, and safety measures, and monitor and detect leaks to address unavailability or greater discharge rate of bottled hydrogen/nitrogen supply
Control of Ignition (Normal Operation)	Static build-up in flammable atmosphere	Design to appropriate ATEX rating and manage ignition sources to address static build-up
Fire (Normal Operation)	Hydrogen fire and explosion risk	Assess fire and ignition risks, review site fire plan, and limit flammable materials to address hydrogen fire and explosion risk
Seismic (Normal Operation)	Seismic robustness	Ensure plant can fail to a safe state during and after seismic events to address seismic robustness.

NODE 2 Compression and intermediate storage

Table 16 HAZOP study: Compression and intermediate storage, Node 2.

Category	Concern	Recommendation
Flow (Normal Operation)	Loss of hydrogen flow Loss of nitrogen flow Hydrogen high flow Low hydrogen flow Low nitrogen flow Hydrogen reverse flow Hydrogen misdirected flow	Review control and safety functions for no flow scenario Review control system and limit switches for nitrogen flow Implement hydrogen detection measures and controls for compressor Examine nitrogen flow rate balances and include flow instrumentation Include check valves, pressure relief, isolation, and venting for reverse flow Include detectors for leaks and apply DSEAR.
Flow (Hot Standby)	Hydrogen reverse flow	Consider design requirements to withstand reverse flow
Flow (Startup and Shutdown)	No flow Misdirected flow	Consider operational sequencing and safety functions for no flow Design to prevent reverse flow from product vent
Pressure (Normal Operation)	Hydrogen overpressure Less pressure	Review design pressures of pipework and connections Use filters to prevent plant damage
Pressure (Startup and Shutdown)	Hydrogen overpressure, vacuum	Implement operational sequencing and design pressure ratings Define safe startup conditions and protect against low pressures
Temperature (Normal Operation)	High temperature and pressure Low temperature	Examine material properties of metal pipework Include monitoring for failed heat exchanger Use glycol mix to prevent freezing
Temperature (Startup and Shutdown)	High temperature	Examine rapid expansion of hydrogen and design pressure relief valves accordingly
Composition (Normal Operation)	Increased moisture, oil ingress	Review hydrogen end product requirements Review technologies to eliminate contamination
Composition (Hot Standby)	No flow/depressurization	Integrate condensate management and drainage
Composition (Startup and Shutdown)	Ingress of oxygen	Consider nitrogen purging requirements to ensure safe startup
Utilities (Normal Operation)	Loss of power	Evaluate impact of power loss and ensure fail-safe positions
Fire (Normal Operation)	Oil leak from compressors	Conduct risk assessment on lubricants Consider non-flammable lubricants
Maintain (Hot Standby)	Increased maintenance burden	Reduce operator intervention with automated trips and remotely operated valves

Category	Concern	Recommendation
Maintain (Startup and Shutdown)	High frequency of startup/shutdown	Evaluate system's ability to endure high frequency of thermal cycles

NODE 3 Hydrogen export trailers

Table 17 HAZOP study: Hydrogen export trailers, Node 3.

Category	Concern	Recommendation
Flow	Less flow of hydrogen Air in process lines Misdirected flow	Review pressure ratings of pipework and fittings Consider pressure relief valves on tube trailers Monitor air in process lines continuously and shut down if high oxygen levels are detected Apply DSEAR requirements and ignition control Consider automatic plant responses for leaks or open connections Insert block and bleed valves to prevent high-pressure hydrogen into nitrogen purge inlet.
Pressure	Less pressure	Introduce alarms/trips to prevent re-pressurisation if internal linings detach; provide remote indication from tube trailer.
Temperature	High temperature Low temperature	Include high temperature trips/alarms to protect against reduced pressure rating; manage pressure differential during filling to minimise Joule-Thomson effect; address low ambient temperature with process heat
Utilities	Loss of power and lighting	Ensure power provision for prismatic valve emergency buttons and trailer control lighting; implement emergency lighting for filling station

HAZOP STUDY 2 – Hydrogen Hub Project

The second HAZOP study evaluated the design changes for a larger hydrogen production plant located outside the NPS boundary. Heat is transferred via an intermediate loop containing Heat Transfer Fluid (HTF), avoiding direct connection to the NPS's steam systems. The study focused on the impact of this intermediate loop on the design.

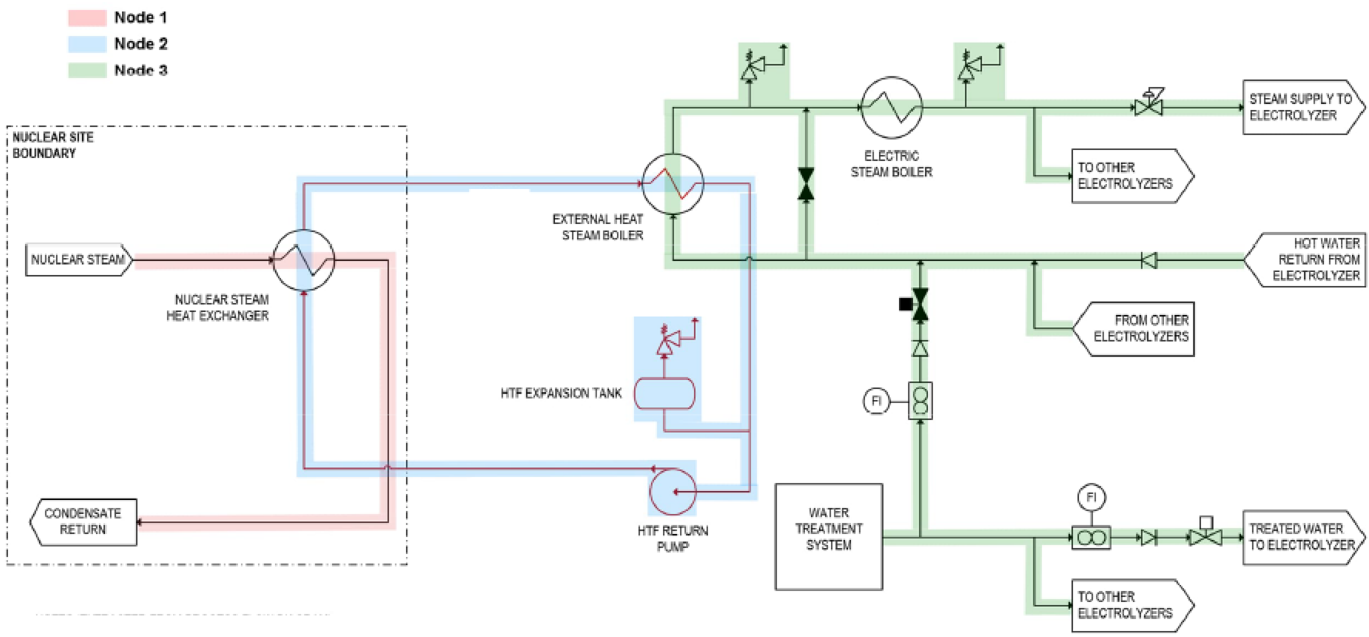


Figure 41 Overview of the nodes considered in the HAZOP study.

NODE 1 Steam side of Nuclear Steam Heat Exchanger

Table 18 HAZOP study: Steam side of nuclear steam heat exchanger, Node 1.

Category	Concern	Recommendation
Flow	Loss of flow (upstream blockage/steam supply unavailable, downstream blockage) More flow Misdirected flow	Consider design of electric steam boiler to handle abrupt changes in steam conditions for upstream blockage Use gasket-less HX for downstream blockage Ensure correct sizing of system pipework and add condensate return system for more flow Evaluate strainer requirements to prevent damage/blockage to HX internals Examine suitable pipe routing and safe location of HX to prevent misdirected flow
Pressure	Lower pressure (leakage or condensate drop-out, startup and shutdown transient)	Analyse plant response to loss of HX pressure differential or absolute steam pressure drop Activate differential pressure instrumentation to prevent HTF ingress to steam side
Composition	Boiler tube leak (contamination to steam circuit)	Consider minimum action levels to respond to increased radioactivity Investigate potential impacts and review approach for handling contamination
Seismic	Seismic robustness	Ensure design is seismically robust to prevent loss of containment and steam release

NODE 2 Intermediate loop between the Nuclear Steam Heat Exchanger and External Heat Steam boiler

Table 19 HAZOP study: Intermediate loop, Node 2.

Category	Concern	Recommendation
Flow	No flow Reverse flow Nuclear steam HX tube leak Misdirected flow	Evaluate strainer requirements for no flow, manage reverse flow with robust maintenance, non-return valves, and design to prevent negative pressure Add detection for steam ingress into HTF and explore isolation options for nuclear steam HX tube leak Implement automatic cut-off of HTF pump and bunding/secondary containment for misdirected flow
Temperature	Low temperature	Apply insulation, trace heating, and local heating loop around HTF pump for startup
Control	Ingress of radioactive contamination	Consider moving HTF loop components within NPS site boundary for control by NPS personnel
Seismic	Seismic robustness	Ensure system meets appropriate seismic standards

NODE 3 Feed to the electrolyser

Table 20 HAZOP study: Feed to the electrolyser, Node 3.

Category	Concern	Recommendation
Flow	Trace amounts of hydrogen in feed water Overpressure/fail open of pressure relief valve Partial/gross pipe leak	Identify safeguards and consequences for trace hydrogen in condensate Construct relief routes for safe steam venting and bunding/drainage for hot water release Ensure adequate pipework inspection and maintenance to prevent leaks
Pressure	Low pressure (external heater in/out of service)	Evaluate pressure differential maintenance across External Heat Steam Boiler to prevent HTF ingress Assess impact of HTF ingress in electrolyser
Utilities	Loss of power or instrumentation air supply	Review requirements for back-up electrical supplies to ensure safe plant shutdown
Maintain	Boiler out of service for maintenance	Consider duty/standby requirements for maintenance and plant availability
Fire	Possible hydrogen release	Design to minimize ignition sources and hot surfaces Investigate fire detection and suppression requirements
Seismic	Seismic robustness	Perform risk assessment on potential steam release scenarios

Detailed information about HAZOP assessment, including different modes of operation, utilities, ignition, fires, seismic and other, can be found in Reference 5 (Approach to Ensuring Nuclear Site License Compliance).

Reference 5 - Approach to ensuring nuclear site licence compliance

The Nuclear Site Licence is a legal document and is uniquely numbered for each Nuclear Installation. The ONR grant a licence once they are satisfied the arrangements to construct and operate the site are adequate and the risk is being appropriately managed. The licence conditions that are likely to be affected by the hydrogen generation plant have been discussed above. This section addresses the likely arrangements for maintaining site licence compliance.

All Nuclear Site Licensees will have arrangements in place to maintain compliance with the Nuclear Site Licence Conditions, their arrangements will cover all 36 licence conditions and where the arrangements are affected the impact on the operating nuclear reactor must be assessed. The Licensee must provide the ONR with the appropriate documentation that outlines their intentions and how compliance with the site licence will be maintained. Where there are changes to the nuclear safety related plant and equipment and the arrangements relate to nuclear safety a safety justification will be developed and assessed by the ONR. The assessment will need to be carried out before work commences and where there is an impact on safety the ONR may need to approve the justification before work can commence.

For nuclear safety, the Nuclear Installations Act 1965 (NIA65) and, the nuclear site licence and attached Licence Conditions issued under it, provide the principal legal basis for regulation by ONR of safety on nuclear licensed sites (ONR publication NS-PER-GD-001 Nuclear Safety Permissioning).

The ONR's approach to permissioning is that it should be proportionate to the risk /hazard associated with the proposed. activities. Permissioning is undertaken using two approaches:

- Primary powers: the six powers specified in the licence conditions (specification, approval, consent, direction, agreement and notification;

  and/or

- Derived powers: hold points where a defined point in a proposed activity, change or stage in a project beyond which the licensee shall not proceed until the hold point is released by the ONR.

These powers can be used separately or in combination with each other to ensure the necessary regulatory control over a given project.

Primary Powers

Licence Conditions include powers which are used to intervene and control the licensee's arrangements and activities to ensure safety. Section 4 of the Nuclear Installation Act 65 "Attachment of conditions to the licences" allows six primary powers which include specification, approval, consent, direction, agreement and notification. They are explicit in the wording of the 36 licence conditions and are legally binding. These primary powers provide the basis for the permissioning regime used by the ONR. Where hold points are specified using these powers, they will be released using a primary powers Consent Licence Instrument which is accompanied by a supporting letter (NS-PER-GD-001).

Derived Powers

Derived powers are used where the ONR requires regulatory control, but primary powers may not be necessary. Control and oversight are achieved by flexible permissioning via powers provided from the licensee's arrangements for LC compliance to the ONR. These are termed derived powers.

Derived powers typically control operations using arrangements made under LC 19 to 22, 35 and 36. They may include implementing a particular proposal, undertaking an activity or progressing from one stage to the next in a project. Construction, installation and commissioning are examples of where permission of these phases in a project lifecycle require regulatory oversight and control.

Adopting this stage wise approach means early judgements are available on whether the risks have been reduced so far as is reasonably practicable when safety is impacted. Derived powers allow flexibility and allow proportionate regulatory control and encourage the licensee to adapt their processes and encourage self-regulation. The ONR and licence holder will exert control using hold points which are removed by positive confirmation using a Licence Instrument (NS-PER-GD-001).

Licence Instruments

Each nuclear site licensee will have their own bespoke arrangements for compliance with the site licence, therefore the derived powers will differ. The licensee will request permission to undertake a change to the safety case that affects nuclear safety, the ONR will grant permission using one of the derived power Licence Instruments (LI). Derived power LIs will generally be used on issues that are of greater nuclear safety significance (NS-PER-GD-001). Use of a particular derived power will be based on the activity to be carried out and its nuclear safety significance. The types of Licence Instruments are described in NS-PER-GD-001 and can take the following forms:

Agreement – ONR will provide agreement to a specified on-site activity to take place once the safety case has completed the assessment process.

Acknowledgement – this allows the ONR to acknowledge receipt of the licensee's proposal to implement a specified activity and by implication the Licensee can proceed.

Specification – use of a specification enables the ONR to identify a hold point within a proposal and the agreed requirements for its release to control the safety risks.

Notification – notifications are used where the ONR wishes to either: confirm no formal action is required by the Licensee, or to confirm that the ONR will assess the Licensee's proposal in the interests of safety. In the latter case the licensee's requirements will need to include arrangements that the on-site activity does not commence until the ONR indicates it is content.

Development of a hydrogen generation facility will be covered by Licence Conditions 19, 20, 21 and 22 and demonstration of compliance will likely require use of licence instruments at multiple points in the project. The individual Licence Conditions and the potential approach for compliance are discussed further in the next two sections.

Licence Conditions That Control Introduction Of New Plant

Construction of a hydrogen generation facility alongside a NPS will impact the site safety case and care must be taken to ensure site licence compliance is maintained at all times during the project. Work that affects nuclear safety on or off the site will be covered by the following licence conditions.

Licence Condition 19 - Construction or installation of new plant.

As the Licensee will be constructing and installing new equipment that may affect safety on the licensed site there must be adequate arrangements to control the construction and installation of the plant equipment. For example, it must be shown that installing the Nuclear Heat Exchanger and associated equipment on the reactor site can be done safely. The Licensee's existing arrangements for compliance will control the design and construction and ensure that changes to the nuclear reactor systems will be agreed via appropriately categorised safety submissions before work starts to justify the design.

Construction of the off-site equipment is unlikely to present a risk to the nuclear reactor as the plant will be constructed away from the site boundary. The scope of work will be typical construction activities that are low risk e.g., civil works, construction and installation of process plant equipment, installation of services etc. The safety justification for construction will cover these activities to confirm they can be safety carried out without presenting on site risks.

Where modifications are required to existing plant, they will be controlled through the arrangements for Licence Condition 22, in practice the changes will both be presented as safety cases. Progression will be stage wise to control the risk, with hold-points to ensure that the project progresses in a safe manner and manages the risk to the nuclear reactor.

Where the ONR specifies the arrangements will be submitted for approval the nuclear site licensee will be required to submit the safety justification for assessment. Once ONR has approved the safety proposal no changes should be made to the arrangements unless the ONR approves the change.

Licence Condition 20 - Modification to design of plant under construction.

Where equipment is being constructed and installed on a reactor site there is likely to be the requirement for modifications to the plant during construction as the design is realised. Where these modifications could affect nuclear safety related equipment the impact on the safety case must be controlled.

For the hydrogen generation facility this will also extend to the equipment off site as well as there could be an increase in risk from changes to the design. These will be captured under this licence condition and LC 22.

Where changes to the design are necessary the modification must be shown to maintain the safety functional requirements and the original design principles or modify them as appropriate. Modification to the safety case will be controlled by using the existing Licensee processes for modification of safety cases. The modification will be subject to the appropriate approvals and oversight to demonstrate they will not undermine nuclear safety.

Licence Condition 21 – Commissioning.

The requirements for commissioning new equipment on the nuclear reactor site need to be appropriately controlled to ensure that the design principles have been achieved, and the risk is minimised as far as reasonably practicable. There are specific requirements within LC 21 to control the use of suitably qualified and experienced personnel, production of adequate records of commissioning and introduction of controls for long term operation.

The arrangements for safely commissioning the plant and confirming it can be operated safely will be controlled using the licensee's safety case modifications process. The licensee may be required to submit these arrangements as specified by the ONR for their approval. Once approved there should be no alteration to the arrangements unless the ONR has approved the change.

Licence Condition 22 - Modification or experiment on existing plant.

Where existing safety related equipment is impacted or requires modification an appropriate safety justification will be required. This will be managed according to the existing arrangements the Licensee has in place for modifying nuclear safety claimed equipment on the nuclear reactor site. The existing arrangements will already have been shown to be adequate to control all modifications to safety on the licensed site and will have been agreed with the ONR.

Justification for the impact of the hydrogen generation facility on the nuclear reactor site will be covered under these arrangements as the risk to the nuclear reactor will have changed as the equipment for the hydrogen generation plant is installed and then commissioned and operated. The existing processes for modifying safety cases will be used to adequately assess the changes to the nuclear reactor safety case. The risk will be controlled in a stage wise manner with the Overarching Strategy and Principles submission setting out the initial standards, and the staged submissions presenting the arrangements to demonstrate the risk is ALARP for each stage within the project e.g., System Design and ALARP. Further details are provided in the next section.

The conditions within LC22 give the ONR the power to regulate modifications to the safety case and ensure work cannot commence until the licensee had adequately demonstrated the proposed work is safe. Under this licence condition the ONR can also halt work or intervene at any point in the interest of safety. Where these powers are used work must not recommence without the consent of the ONR.

Strategy To Control Site Licence Compliance

It is predicted that the ONR will issue LIs at strategic points throughout the project that will confirm the proposed changes have been assessed and permission has been granted to carry out the agreed scope of work. Within the LI strategy the regulator may specify that the licensee must not progress beyond certain points in the scope of work unless the consent of the ONR has been given. Where compliance with the Licence Conditions cannot be demonstrated or is challenged work will not be allowed unless a safety case can be made that satisfies the ONR. This can occur at any time in the project's lifecycle.

The following paragraphs outline one potential approach to regulation.

Overarching Strategy and Principles Submission

As described in section 7 (Safety Case Strategy) the licensee will develop a safety submission that sets out the principles for developing the safety case for the hydrogen facility and the safety justifications that control the changes to the nuclear safety case. As there are going to be changes to the on-site systems and an increase in risk from the hydrogen facility it is anticipated that the ONR will assess the safety justification and once satisfied confirm by an AGREEMENT LI that the project can be safely delivered and that the design, on-site and off-site activities can begin. At this point the Licensee and ONR are likely to agree the hold points during the project and the requirements to release them.

Stage Submission 1: System Design and ALARP Justification

As the design progresses and the final design basis has been confirmed it will be possible to set down the impact on the nuclear reactor site and how this will be managed. A vital part of this is the ALARP justification that will show the risks to the nuclear reactor site have been reduced so far as is reasonably practicable. This stage will require a mature design and a clear understanding of how the design then feeds into the later stages of the project.

At this stage in the project the ONR may wish to maintain an awareness of the design and its impact on the nuclear licensed site. Under these circumstances the ONR may choose to use the powers of notification. Using a NOTIFICATION allows the ONR to be flexible in assessing the proposals and either confirming no formal action is required or setting out further conditions for assessment of the arrangements and any requirements to provide further information or to take certain actions before work can continue.

Stage Submission 2: Construction

Construction of the hydrogen facility will be relatively low risk for the nuclear site. On site work to excavate, lay foundations then install mechanical, electrical and C&I equipment will be controlled using existing licensee procedures. Construction and installation off site will be controlled by similar arrangements to ensure the hydrogen generation facility meets the regulations for this type of plant. The ONR may chose not to formally assess this stage if there is sufficient confidence the risk is low, and it is covered by existing regulations to ensure safety of the system and the nuclear site.

One area that may require ONR oversight is the modifications to the site boundary to allow the services to pass to the hydrogen facility. The proposal will introduce a potential nuclear security risk and potential associated safety risks whilst the modifications are carried out. The ONR may choose to use a SPECIFICATION to introduce a hold point for this part of the proposal if deemed appropriate.

Stage Submission 3: Commissioning

Once the hydrogen generation facility has been constructed and is ready to start commissioning there is a significant increase in risk to the nuclear reactor. Commissioning signals the start of hydrogen generation, its intermediate storage, low-pressure compression, use of bulk storage and high-pressure compression to fill transport trailers. Throughout the testing and commissioning of the plant it is necessary to show that the risks are controlled and that there are appropriate emergency arrangements to cover the reasonably foreseeable things that could go wrong. The on-site commissioning arrangements will be controlled by the Licensee's existing arrangements to ensure that the plant is operated safely, and the emergency arrangements are in place.

Off-site arrangements will be expected to follow the relevant good practice for commissioning these types of facilities and it is recommended a similar approach to controlling the plant on the nuclear site is adopted so that the risks can be managed and reduced as they arise.

Where there is new plant being commissioned that increases the nuclear safety risk the ONR will ensure they are satisfied before work can commence. The exact nature of the oversight will need to be confirmed but could take the form of formal AGREEMENT to the proposed work, via the commissioning safety proposal, or SPECIFICATION of an appropriate hold point that would be released once the commissioning proposal has been assessed and the ONR are content appropriate arrangements are in place.

Stage Submission 4: Long Term Operation

Arrangements for long term operation will be developed as part of the commissioning of the plant. Stage submission 4 will then introduce the long-term arrangements and update the operational services documents, emergency arrangements and other requirements for long term operation. At this point the risk will not be changing significantly from the commissioning stage and the proposal will introduce the arrangements for steady state operation and maintaining the risk ALARP.

As the risk is not changing significantly the ONR may choose to ACKNOWLEDGE the safety proposal for this stage or make use of the NOTIFICATION powers if the regulator wishes to see further detail of the arrangements before it will allow long term production of hydrogen.

Final Report

Preparation of the final report will be in accordance with the Licensee's arrangements for preparation and approval of these documents. It will be subject to the same approvals as the original Overarching Strategy and Principles Proposal and provides positive confirmation that the original design and safety case principles have been achieved and that the risk is ALARP now the system has entered its normal operational state. The final report will provide sufficient confidence that the longer-term risk will be appropriately managed and where any changes to the original intent have been made, they have been adequately justified. The Final Report will be submitted to the Licensee's Nuclear Safety Committee and presented to the ONR for ACKNOWLEDGEMENT or AGREEMENT as appropriate and informed by the risk on the ongoing operation of the nuclear reactor site.

Presented to the ONR for ACKNOWLEDGEMENT or AGREEMENT as appropriate and informed by the risk on the ongoing operation of the nuclear reactor site.

Reference 6 – Regulations and standards

Permitting Process

Due to the inherent risks linked to both nuclear and hydrogen installations, the permitting process for a combined site includes several key regulatory bodies and a multi-stage application and approval process.

Broadly speaking, the Office for Nuclear Regulation (ONR) oversees the licensing and regulation of nuclear installations in the UK, including those combined with a hydrogen production plant. Some other relevant UK authorities that play a central role include the Health and Safety Executive (HSE), the respective environmental agency (EA for England, NRW for Wales and SEPA for Scotland, depending on the location), and the relevant Local Planning Authority (LPA).

The legal framework for the permitting process is based on the Health and Safety at Work Act (HSWA), the Energy Act, and the Nuclear Installation Act (NIA)

Throughout the process, several types of documents will need to be created and submitted or archived. In the following subchapters, the specific roles of the different agencies will be described, along with relevant procedural and administrative information.

ONR

The Office for Nuclear Regulation (ONR) plays a critical role in overseeing all stages of a nuclear project, from its earliest feasibility studies to decommissioning. Its responsibilities include managing site and construction licence applications and preparing and authorising safety cases. The ONR also ensures compliance through regular inspections, safety audits, and incident reporting.

Throughout the project, numerous documents must be submitted to the ONR:

- Pre-Construction and Pre-Operational Safety Reports (PCSR & POSR) detailing design, safety systems, risk assessments, mitigation measures, operational safety, and commissioning.
- Site Licence Application, including site layouts, safety management systems, and foundational plans.
- Justification Document outlining benefits vs. risks and alternative options.
- Detailed Design Submissions with engineering drawings, material specifications, and safety functions.
- Construction Documents, such as quality assurance plans, safety cases, and security plans.

Additional required documents may include emergency arrangements, event and incident reports, maintenance and inspection records, and annual audits.

The ONR remains deeply involved throughout all phases of the project to ensure adherence to safety and operational standards.

EA

The environment agencies (Environmental Agency (EA), Natural Resources Wales (NRW) and Scottish Environment Protection Agency (SEPA)) are responsible for overseeing key environmental aspects of the project from the earliest feasibility stages through construction, commissioning, operation, and decommissioning. Its responsibilities include creating Environmental Impact Assessments (EIA), issuing permits for hydrogen production emissions and effluent discharges, approving commissioning plans for nuclear and hydrogen production, and conducting routine inspections and environmental monitoring to ensure compliance.

Throughout the project, the EA requires several key documents, including:

- Environmental Impact Assessment (EIA): Evaluates impacts on air, water, soil, fauna, and local communities.
- Habitats Regulations Assessment (HRA): Included in the EIA if protected areas could be impacted.
- Environmental Permit Applications: Cover Radioactive Substances Regulation (RSR), Water Discharge Activity, Waste Management, and other permits.
- Land Contamination Assessment: Assesses and mitigates risks to soil.

- Operational Environmental Management Plan: Outlines procedures for managing environmental risks.
- Diverse Reports: Includes annual environmental reports, incident reports, audits, and compliance documents.

HSE

The Health and Safety Executive (HSE) plays a vital role in regulating workplace health, safety, and welfare, focusing primarily on the commissioning and operational phases of the project. Its responsibilities include ensuring compliance with the Control of Major Accident Hazards (COMAH) regulations through safety reports, risk assessments, and emergency planning. The HSE also reviews Hydrogen Safety Cases and Operational Safety Cases to ensure the safe operation of both nuclear and hydrogen facilities, while conducting regular safety audits and monitoring incident reports.

Key documents required by the HSE include:

- Hazard Identification (HAZID): Evaluates potential risks to workers and the public across all aspects of the site.
- COMAH Report: Provides detailed site descriptions, inventories of hazardous substances, and emergency plans.
- Detailed Risk Assessments: Identifies hazards, evaluates risks, and outlines mitigation measures.
- Occupational Health and Safety Risk Assessment: Addresses health and safety measures specific to the site.
- Health and Safety Management Plan (HSMP): Includes roles, responsibilities, protocols, and training requirements.
- Various Reports: Covers incidents, accidents, workplace monitoring, maintenance, inspections, and audits.
- Safety Training and Competency Records: Tracks training programs and qualifications of personnel.
- Human Factors Integration Plan: Ensures human factors are considered in safety protocols and system design.

LPA

The Local Planning Authority (LPA) plays a key role in managing local land use planning and must be engaged from the earliest stages of site selection to assess the feasibility of the project. The LPA oversees obtaining a Development Consent Order (DCO) for large-scale infrastructure projects, reviewing planning applications that include various technical studies (e.g., Environmental Impact Assessment, traffic impact, visual impact), and managing potential Public Inquiries as part of the DCO process.

Key documents required by the LPA include:

- Pre-application Consultation Documents: Outlines the proposed project and site location, aiming to gather feedback before submitting a formal application.
- Formal Planning Application: Seeks consent for the development of the nuclear site.
- Environmental Impact Assessment (EIA) & Operational Environmental Management Plan (OEMP): Covers the project's environmental impacts and operational mitigation measures.
- Additional Assessments (as applicable): Includes transport, noise impact, heritage and archaeological impact, air quality, and biodiversity assessments.
- Construction Environmental Management Plan: Outlines measures to manage environmental impacts during construction.
- Public Consultation and Engagement Reports: Documents feedback and engagement with the community.

Methodologies and principles

ALARP

ALARP is a risk management philosophy requiring that risks are reduced to a level where further reduction would be grossly disproportionate to the benefits gained. This principle ensures that risks are managed systematically and responsibly in alignment with good practice.

Key Concepts of ALARP:

- Risk Reduction: Hazards are identified, and appropriate control measures—such as safety technologies, procedures, or operational measures—are implemented to reduce risks.
- Reasonable Practicability: Measures are applied until the cost, effort, or complexity of additional risk reduction becomes disproportionate to the benefit gained, ensuring gross disproportionality is avoided.
- Continuous Improvement: ALARP is not static and requires regular reassessments of risks and controls to ensure improvements are adopted when new technologies or methods emerge.
- Good Practice and Learning from Experience: Adherence to established good practice and incorporating lessons learned are vital for achieving and maintaining ALARP compliance.

Claims, Arguments, Evidence

In the nuclear sector, the Claims, Arguments, and Evidence (CAE) approach is used to underpin risk management and ensures compliance with the ALARP principle by providing transparent and robust reasoning.

CAE stands for:

- Claims: The key safety statements or conclusions being demonstrated (e.g., a system is safe under defined conditions).
- Arguments: The logical reasoning or rationale that connects the claims to the evidence, explaining why the claims hold true.
- Evidence: Data, studies, analysis, and real-world examples that substantiate the arguments, proving the claims are valid.

The following sub-claims help to support the CAE golden thread:

1. Hazard Identification and Understanding: All potential risks, both nuclear and non-nuclear, are identified and thoroughly understood.
2. Hazard Prevention and Management: Risks are systematically prevented or mitigated, unmitigated consequences are determined, and controls are shown to reduce risks to ALARP.
3. Operational and Engineering Controls: All essential measures are defined, implemented, and maintained to uphold safety and reduce risks.

Safety Case Development under the Golden Thread incorporates the following stages:

1. Hazard Identification: Understanding all risks associated with the site or system.
2. Hazard Assessment and Control Measures: Evaluating risks and identifying safety measures to address them effectively.
3. Substantiation of Safety Measures: Providing evidence that controls are sufficient, effective, and reliable.
4. Implementation and Maintenance: Ensuring controls are in place, operational, and regularly assessed.

This framework ensures that claims, arguments, and evidence are consistently and transparently linked across all phases of the facility's lifecycle, maintaining safety and adhering to ALARP principles.

If you have any questions or would like to know more about EDF in the UK, email **rdoperations@edfenergy.com** or visit **edfenergy.com**