



Department for
Energy Security
& Net Zero

WhiskHy

Green Distilleries Competition
Phase 2 (Demonstration)

September 2024



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Please note that this public version of the report has had some confidential and commercially sensitive information removed from the Government commissioned version. As a result, there may be some omitted Figure or Table Numbers throughout the report.

Executive Summary

In November 2021, Supercritical and Suntory Global Spirits published their feasibility study that evaluated the impact potential of Supercritical's technology on Ardmore Distillery. You can find this study [here](#). In 2022, the WhiskHy project team was awarded £2,944,778.29 by the Department of Energy Security and Net Zero through Phase 2 of the Green Distilleries Competition which was funded through the £1 billion Net Zero Innovation Portfolio. The goal was to demonstrate whisky distillation through direct firing of hydrogen to a Suntory Global Spirits copper still and to demonstrate and test Supercritical's next generation green hydrogen technology at a multi-cell level out of the lab. The project completed in 2024 successfully achieving the project goals.

Supercritical and The Manufacturing Technology Centre demonstrated that its manufacturing methods can scale from lab to module scale cell sizes and in the process developed automated methods for production which positions the company well for scale-up of manufacture. These cells were built into Supercritical's V1 module, a module designed to demonstrate scalability and for flexibility of testing, with each cell individually powered and with the ability to change cells. Tests on Supercritical's technology yielded world-leading performance at operating conditions only achievable with Supercritical's novel design. The company filed its second patent under the project, protecting an advanced membraneless methodology for achieving ultra-high efficiency and high product purity at 220 bara.

Teesside 1, Supercritical's demonstration rig with a capacity of 3kg/d, was designed, built and operated in Teesside, one of major hubs for hydrogen in the UK. The design process addressed many of the challenges associated with scaling a technology with inherent hazards including hydrogen, oxygen, temperature, pressure and electricity. Through rigorous hazard studies, the team has developed a blueprint for future scaling efforts and Teesside 1 offers Supercritical the ability to conduct extended duration module testing going forward, a crucial capability for commercialisation.

Demonstration showed that in scaling from Supercritical's lab scale architecture to TS1, 95% of ideal performance was achieved, a fantastic outcome for a first-of-a-kind test. Supercritical successfully tested multiple cells simultaneously in their V1 module architecture and showed that >99% purity is achievable demonstrating minimal gas crossover with their membraneless design.

Suntory Global Spirits successfully combusted hydrogen beneath a copper still and produced hydrogen direct fired whisky – a global first. Despite challenges with commodity fuel and raw material prices due to tumultuous geopolitical events that occurred throughout the project, Suntory Global Spirits navigated these challenges by leveraging its global footprint and business-wide ambition to advance decarbonising technology throughout its assets. Trials were run at Yamazaki, with heat profiles, NOx and product quality assessed. It was found that NOx levels were higher with hydrogen, but with already established techniques for NOx reduction like recirculation of flue gases, it is anticipated that this is not a major risk to

commercial deployment. With a goal of maintaining or even improving on product quality, preliminary assessments of spirits show no notable differences to a methane fired control batch of spirit. The hydrogen fired and methane fired spirit control are now maturing at Glen Garioch distillery in Aberdeenshire.

The WhiskHy partnership was incredibly successful in attracting interest via its dissemination. With over 30 engagements, the team shared findings, initiated debate and ignited the sector.

The positive outcomes of the project have culminated in the signing of a Memorandum of Understanding between Supercritical and Suntory Global Spirits to further advance the WhiskHy approach. The ambition is to take this technology to Auchentoshan Distillery to conduct longer term operational trials, achieving TRL 7, injecting green hydrogen into the distillery's natural gas feed, an approach possible due to Auchentoshan's boiler burner being capable of accepting up to 20% hydrogen and a move that will further Suntory Global Spirits' operational understanding of electrolyzers.

Project Outline, Aims and Objectives

Supercritical is developing the world's first high pressure, ultra-efficient electrolyser for the production of hydrogen and oxygen from water, with zero emissions.

WhiskHy (pronounced Whisky) saw Supercritical's technology advance from single cell scale to a multicell module which was demonstrated and tested. Distillery partner, Suntory Global Spirits, trialled 100% hydrogen fuel delivery to supply heat at the point of combustion to a still at one of their distilleries. Plans were prepared for pilot deployment of Supercritical's technology at one of Suntory Global Spirits' Scottish distilleries where the green hydrogen will decarbonise the existing steam boiler.

WhiskHy will demonstrate the lowest cost route to a zero-carbon distillery reliant only on its local natural resources. The demonstration will be the first of its kind, paving the way for distilleries and other industries across the UK and the world.

Hydrogen Production

State of the art

Greater than 95% of the world's 95 Mt hydrogen production in 2022 was produced from fossil fuels¹. The leading method of producing hydrogen is via a process called steam methane reforming (SMR), where CH₄ is broken down into H₂ and CO₂. On a mass basis, 11x more CO₂ is produced than H₂ in this process. The hydrogen produced through this process is often described as grey Hydrogen and is considered the incumbent process today.

¹ [IEA Global Hydrogen Review 2023](#)

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Numerous approaches to producing hydrogen with no or few CO₂ emissions have been explored and developed. Leading amongst these methods are 'green hydrogen' production methods which follow a water electrolysis route; splitting water into hydrogen and oxygen using electricity. Another approach is known as 'blue hydrogen' production, which follows a similar approach to steam methane reforming but rather than emitting the CO₂, the CO₂ is captured for storage or utilisation.

Green hydrogen methods that are commercialising can be typically segmented as follows:

Alkaline Electrolysis: Utilises a liquid alkaline solution (usually potassium hydroxide) for electrolysis, the most mature, known for its low temperature operation and lower cost but slower response times operating at pressures up to 30 bar.

PEM (Proton Exchange Membrane) Electrolysis: Uses a solid PFAS membrane electrolyte for hydrogen production with quicker response times, also operating at lower temperatures and pressures up to 30 bar and requiring precious metals as catalysts.

SOEC (Solid Oxide Electrolysis Cell): High-temperature electrolysis using a solid oxide electrolyte to produce hydrogen with typically higher efficiency than lower temperature electrolyzers but constrained to much lower operating pressures (often near atmospheric), considered well suited for coupling with heat sources but less mature and more expensive.

AEM (Anion Exchange Membrane) Electrolysis: A developing technology that combines low-cost alkaline chemistry with the membrane-based advantages of PEM, aiming for lower-cost, higher-efficiency hydrogen production without precious metals, but operating at lower pressures (sub 10 bar).

Each type of green hydrogen technology has differing pros and cons and each is still finding its place in the market. Moreover, novel technologies are coming to the market, considered 'next generation' electrolyzers, which are showing promise and addressing some of the big challenges faced in achieving fossil competitive green hydrogen prices.

Fundamentals of Supercritical's Technology

Supercritical has developed a next generation electrolysis technology which operates at intermediate temperatures and high pressures. The novel design employed is designed to sustain these more challenging conditions whilst eradicating supply chain risks like PFAS chemicals, iridium and hydrogen compressors.

The intermediate temperature of operation (300-400 °C) enables high electrical efficiencies and requires the complete removal of polymers which do not survive at these temperatures. Supercritical's patent pending design achieves these high electrical efficiencies, whilst separating the product hydrogen and oxygen safely without the need for a membrane. Membranes are relied upon by incumbent technology to separate hydrogen and oxygen products, but they are fundamentally fragile and are the first point of failure in the technology, being a major risk to longer term operation. By removing this, Supercritical's technology is expected to last longer in operation than market leaders today. By operating at 230bar, the

technology produces high pressure hydrogen natively in the electrolyser and delivers it to the downstream processes without any gas compressors required up to 220bar. This higher pressure delivery removes, cost, risk and complexity introduced by hydrogen gas compressors and is optimal for delivery to high pressure vessels for long term storage and ideal for the largest industrial and chemical users of hydrogen today, which all require hydrogen at high pressures.

Supercritical has demonstrated that, through the application of pressure and temperature, superior electrical efficiencies can be achieved in the conversion of water to hydrogen via electrolysis.

The efficiency of electrolysis is a function of resistances, called overpotentials, within the cell. These can be divided into three categories:

- **Activation overpotential** - represents the charge transfer limitations of the system representing the electrochemical kinetic behaviour. Activation losses occur at low operating current densities and can be deduced from the Butler-Volmer equation.
- **Ohmic overpotential** - occurs due to the resistances of the components of the electrolysis cell. In traditional electrolysers, the resistance of the membrane, which is a measure of the membrane conductivity, dominates the ohmic losses.
- **Concentration overpotential** - is dictated by the access of reactant to the electrode surface. At low pressures, formation of product bubbles has a significant effect here and becomes increasingly limiting at high current densities when a prominent amount of hydrogen and oxygen gases are formed.

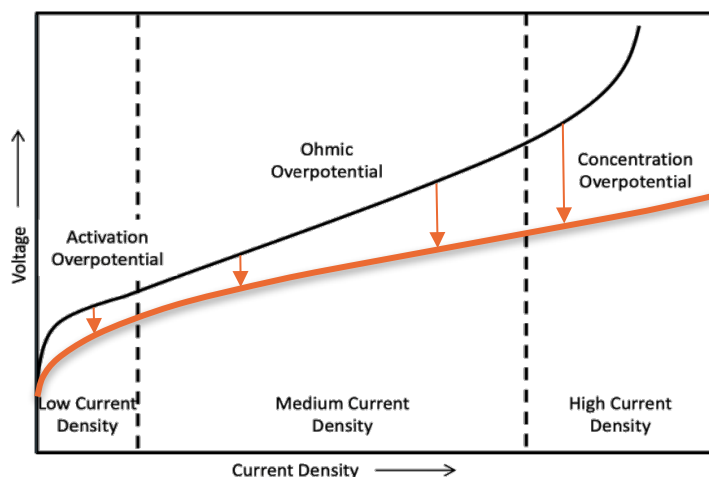


Figure 1 - Overpotential regions of a polarisation curve. Operating at Supercritical's conditions can help reduce these overpotentials at all current densities relative to low temperature electrolysis

Supercritical's approach to water electrolysis offers step-change differentiating benefits:

- Operating at higher temperatures has the potential to replace some of the electricity required for electrolysis with thermal energy, thereby **lowering the activation overpotentials**.

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- Higher temperature operation also **increases catalytic activity** by reducing the activation overpotentials.
- The specific conductivity of water rises as its density increases. Increasing the operating pressure therefore increases the conductance of water with an electrolyte, **reducing the ohmic resistance** and enabling significantly lower electrolyte concentrations.
- The negligible bubble formation at the electrodes means that no insulating layer is formed between catalyst and water, further reducing the concentration losses.
- Pumping the feedwater and conducting the electrolysis at pressure, so that the product gases are produced at pressure using **10x less energy than downstream pressurisation of the hydrogen gas**.

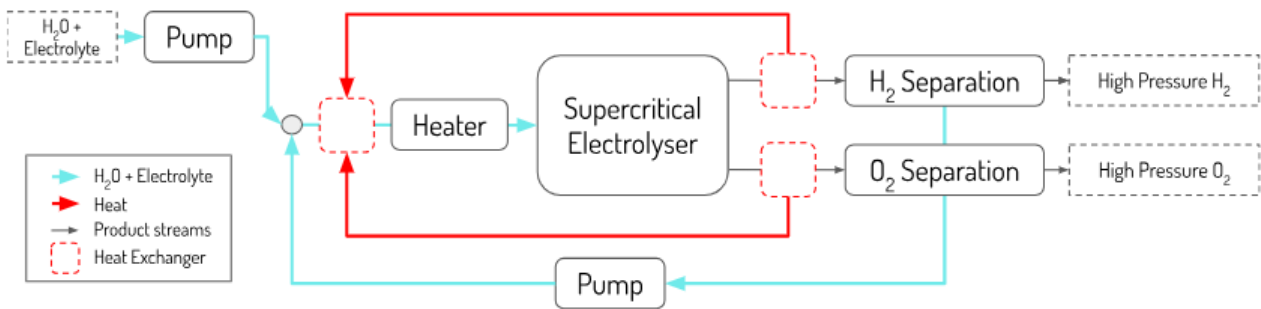
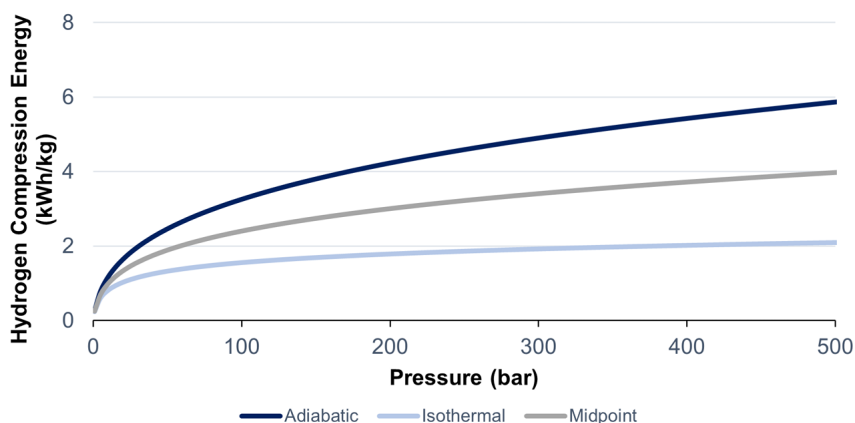


Figure 2 – Block Flow Diagram of the Supercritical system

At a system level, as represented in the block flow diagram in Figure 2 the re-allocation of compression energy to the pumping of liquid water instead of compressing hydrogen gas, offers a further step change improvement in efficiency in the production of high-pressure hydrogen. HM Gov's Hydrogen Transport and Storage Cost Report demonstrates that compression of hydrogen to 200 bar requires between 2-4 kWh/kgH₂ (Figure 3) whereas pumping water required to produce hydrogen is an order of magnitude lower than this.



2

Figure 3 – Energy required to compress Hydrogen. Source: Hydrogen Transport and Storage Cost Report

Distilleries typically do not require hydrogen at pressures greater than a few hundred millibar at the point of use. This is because distilleries' primary use of fuel is to raise heat through

² [Hydrogen Transport and Storage Cost Report](#), Dec 2023

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combustion at a burner head beneath a copper still (direct firing) or in a steam boiler. Though to facilitate supply of green fuel to facilities that operate 24/7, hydrogen must be stored to manage the levels of intermittency of renewables.

In the WhiskHy Phase 1 feasibility study published in 2022³, the team modelled the intermittency of wind and how that dictated both the incremental size of the electrolyser (to be able to take advantage of excess wind and top-up hydrogen storage tanks) and the size of the hydrogen storage to fully decarbonise the distillery whilst ensuring a zero impact in terms of supply of energy considering its 24/7 operation. The optimal increase in electrolyser size in the model was 52% and storage enough for 2.5 days of operation for the Ardmore Distillery scenario. Storing hydrogen at 200bar requires 189x less volume than storing hydrogen at atmospheric pressure and so for any site or supplier considering green hydrogen for 24/7 operations, storage at pressure is an essential requirement.

Heat Generation (Hydrogen Utilisation)

Suntory Global Spirits has a long-term ambition to achieve Net Zero Operations across its Value Chain by 2040 – this is part of their global [Proof Positive](#) strategy. In parallel to their environmental ambitions, Suntory Global Spirits is also focused on producing spirits of the highest quality. Combining these two (often competing) ambitions was the underlying Suntory Global Spirits objective of this hydrogen trial.

As part of Suntory Global Spirits' quality enhancement roadmap for Scotch Whisky, their strongly held belief is that some of the more traditional production techniques, specifically including direct firing of stills, result in a greater complexity and depth of character in the new make spirit. Direct firing of stills significantly increases the contact temperature differential between the energy source and the fluid being boiled when compared with indirect (steam) heated distillation. It is this elevated temperature differential (often >1,000°C Vs. ~40°C for steam) that promotes increased caramelisation and copper interactions (Maillard reactions) that Suntory Global Spirits believe drives that enhancement of character depth and flavour creation.

Once this spirit matures, the enhanced depth and elevated character of the original spirit produced is retained through into the final product. A testament to this ambition is the recently refurbished Glen Garioch Distillery where a direct fired Wash Still has been re-introduced – one of the first 'traditional direct fired stills' to be installed in Scotland for many years.

Many of Scotland's Distilleries, including (now) Suntory Global Spirits owned facilities, have been moving away from more traditional production methods for several decades. The motivation for these changes varies, some of these drivers and reasons are outlined below;

- Driving production volume (shorter fermentations, higher gravity mashing, commercially produced malted barley).

³ [WhiskHy – Feasibility Study, Phase 1](#), Nov 2021

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- Cost avoidance/energy efficiency (higher gravity mashing, MVR/TVR, indirect heating).
- Health and safety improvements (manual handling, DSEAR regulations, indirect heating).

Focusing on the industry wide adoption of indirect heating in recent decades, replacing many legacy direct fired processes, there are many benefits and reasons for this industry level shift. Indirect heating e.g. the use of steam generating plant combined with steam/ condensate distribution pipework and localised heating pans/coils/exchangers has resulted in achieving many improvements versus legacy direct fired equipment, such as:

- Generally improved overall energy efficiency – it is broadly accepted that steam heating, when combined with good condensate recovery and operational control, is more energy efficient than individually directly firing equipment – around 10% more energy required per litre of spirit produced when direct firing compared with indirect heating.
- (DSEAR) Removal of furnaces and possible ignition sources from Still houses – this supports the deployment of COMAH, DSEAR and ATEX improvements.
- Easier decarbonisation – a centralised steam generation system can have multiple fuel sources, for example many distilleries have recently moved to Biomass Boilers in-place of fuel oil boilers in order to decarbonise their distillery heat source.

As outlined above, the benefits of moving to indirect fired distillation align more naturally with progress against environmental aspects e.g. energy efficiency/carbon reduction when compared with more typical & traditional direct fired distillation installations. Additionally, unlike centralised steam generation, the fuel options for direct firing are limited to gaseous fuel types in order to comply with current H&S regulations, making this production technique even more difficult to decarbonise.

With Suntory Global Spirits' ambitions of combining quality enhancement and decarbonisation, the concept of using Hydrogen as the fuel in a direct fired still was theorised as a result of the Green Distilleries Fund Phase 1 project. This Phase 2 project aimed to prove that hydrogen could be used as a fuel within an existing direct fired spirit production facility (fuel switching), safely and without negative impact to spirit quality. If the concept of using hydrogen as a fuel within direct firing was proven, this would ultimately unlock the potential of this as a decarbonisation approach for this traditional production technique and could be deployed across industry as hydrogen availability improves and a 'green hydrogen supply chain' develops.

Roles and contributions of each project partner

Supercritical

Supercritical is at the forefront of the clean energy revolution, with a mission to dramatically reduce the cost of green hydrogen and address the most challenging 20% of global emissions. Established in 2020 in London, their vision is to catalyse a sustainable future where renewable energy solutions, like their pioneering electrolyser technology, are mainstream and financially viable without subsidies. As the creators of the world's first high-pressure, ultra-efficient electrolyser, they will deliver hydrogen and oxygen at pressures exceeding 220 bar, achieving full system efficiencies up to 42kWh/kgH₂ with 99% purity. Their innovative approach not only curtails operational costs but also surmounts formidable industry challenges, forging a path towards a zero-emission future. By offering scalable, PFAS-free, membrane-free, and iridium-free solutions, Supercritical aims to lower hydrogen production costs to under £1/kgH₂ within this decade, driving the shift from grey to green energy across industries.

Supercritical was the lead partner in the WhiskHy project and lead partner on the hydrogen production work stream. They are the principal technology developer within the project. This work stream included all efforts with respect to the supercritical cell, module and system development, resulting in first hydrogen from the resultant out of lab demonstrator in Teesside.

Suntory Global Spirits⁴

Suntory Global Spirits' key role as WhiskHy's distillery partner is delivering valuable insight into the whisky production process and market requirements.

Suntory Global Spirits is committed to a decarbonisation journey for their global premium spirits business as communicated in their recently announced, 'Proof Positive' sustainability vision, which commits it's Scottish Malt Whisky distilleries to achieving a 50% reduction in Greenhouse Gas emissions by 2030 and to achieving net-zero carbon emissions by 2040.

Suntory Global Spirits is committed to maintaining, and in some cases re-introducing, traditional production processes where they strongly believe that these methods protect and enhance the unique spirit quality and character of Scotch Whisky. In this quest, Suntory Global Spirits is strongly supported by parent company, Suntory Holdings in Japan, who also share these ideals and who invest heavily in R&D to develop novel methods to achieve traditional practices in a sustainable way.

⁴ At project beginning, Suntory Global Spirits was named Beam Suntory. In April 2024, the leader in premium spirits rebranded. Throughout this report, the distillery partner will be referred to by their new brand.

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Suntory Global Spirits firmly believes that WhiskHy can achieve the twin goals of re-introducing traditional production methods whilst also achieving the environmental sustainability goals and we believe that we have the knowledge and expertise within our business to help deliver this project.



Alistair Longwell, Head of Distillation & Environment

Senior Leader within Suntory Global Spirits with operational responsibility for the distilleries within the Scotch estate and overall ownership of developing and delivering the Proof Positive environmental strategy.

Acting as Principal Suntory Global Spirits sponsor on this project, Al acted as key conduit between Supercritical, Suntory Global Spirits and Suntory colleagues based at Yamazaki Distillery. Al represented Suntory Global Spirits at key Project WhiskHy steering committee meetings between the project partners.



Alistair Leckenby, Environmental & Sustainability Manager UK&I

Manager within Suntory Global Spirits responsible for developing and delivering opportunities to support Proof Positive ambitions.

Alistair supported the technical ideation and development of the trial project from the proposed Glen Garioch Distillery trial through to the actual trial delivered at Suntory's Yamazaki Distillery. Supported two visits to Japan, firstly to engage with local consultants, engineers and suppliers and a subsequent final visit to observe the trial itself.

The MTC

The Manufacturing Technology Centre, a member of the High Value Manufacturing Catapult is WhiskHy's manufacturing partner bringing a huge breadth of manufacturing expertise and resources to the manufacturing processes of Supercritical's core components.

The Manufacturing Technology Centre (MTC) was established to prove innovative manufacturing processes and technologies in an agile environment in partnership with industry, academia and other institutions.

Housing some of the most advanced manufacturing equipment in the world, creating a high-quality environment for the development and demonstration of new technologies on an

industrial scale, the MTC provides a unique opportunity for manufacturers to develop new and innovative processes and technologies.

The MTC, as a pioneer of advanced manufacturing methods and a lead centre for processing within the UK High-Value Manufacturing Catapult, supported the WhiskHy project with its best-in-class facilities and expertise. In addition, the MTC provided expert insight into potential alternative manufacturing techniques, design, build and integration, high integrity fabrication, advanced tooling and fixturing, non-conventional machining, robotics and autonomous systems, design and simulation and manufacturing informatics.

Their team of experts, supported by their state-of-the-art facility on material characterisation, non-destructive testing and metrology, enabled the delivery of high quality, volume manufacturable components throughout the project as developments advance.

Allocation of Budget and Responsibilities across Partners

The allocation of responsibilities and budget across the three partners was as follows:

Table 1 – Summary of preliminary budget and responsibilities of WhiskHy project partners

Partner	Responsibilities	Total Spend	% of spend
Suntory Global Spirits	Enable the direct firing trial to validate the H2 utilisation objectives.	£287,167	9.75%
The MTC	Progress the cell design concept validation and manufacturer selection to enable demonstrator level scaling.	£296,181	10.06%
Supercritical	Development of cell, module and demonstrator to validate H2 Production objectives.	£2,361,430	80.19%

As part of the MTC's modus operandi, scale production of components was assigned to industrial partners once processes were validated. These costs were paid directly by Supercritical, resulting in the budget allocation for MTC being reassigned to Supercritical in agreement with the Consortium Steering Committee and DESNZ. The final allocation of funds was £234,999 (7.98%) to MTC, £262,194 (8.9%) to Suntory Global Spirits and £2,447,577 (83.12%) to Supercritical.

Description of activities/work packages/milestones and final results

H2 Production

Materials

Performance, durability and cost are essential to any competitive product. Incumbent electrolyzers fall short of market expectations on cost and durability due to inherent challenges faced by the materials within their systems. Supercritical aims to achieve a >80,000h lifetime for its modules and optimal material selection is essential to this. Operating safely for extended durations in a high pressure and intermediate temperature is challenging for materials of construction due to high rates of corrosion among traditional construction materials.

The need for research and development in this field was evident due to the lack of knowledge of materials corrosion at such novel operating conditions. Parallels can be drawn with similar systems: supercritical water oxidation / gasification technologies and nuclear fission pressurised water reactors represent similar operating environments but are without Supercritical's proprietary electrolyte and reaction products hydrogen and oxygen. Existing literature in this space was evaluated and Supercritical commissioned collaborative materials studies with leading materials experts.

Cell and Module Design

Advancing Cell Fundamentals

The Supercritical cell is the heart of the technology making high pressure, ultra-efficient water electrolysis a reality and it is the central pillar to Supercritical's IP portfolio.

To harness the benefits of temperature and pressure a new electrolyser design that is able to tolerate said conditions was required. Traditional polymer membranes would disintegrate, and ceramics would crack, gaskets would blow, and bipolar plates would buckle.

Macroporosity

Following trials on off-the-shelf components and preliminary modelling results, Supercritical conducted a technology study and prioritised a proprietary method as a manufacturing process potentially capable of achieving the design intent.

This specific area of focus was supported by the extensive experience capability of our partner, the Manufacturing Technology Centre (MTC). After a series of trials led by the MTC on flat plates, Supercritical demonstrated that it is possible to achieve the porosity desired. This learning was translated to enhanced geometry, where the apparatus needed to be configured to unique and specific set up parameters.

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The development was successful and yielded a good penetration and porosity, however it left a significant amount of material on the surface which would have a negative impact on the fluid dynamics around the cells and the integrity of any passivation layer could be compromised.

In an effort to try and remove the material from the surface, several methods were investigated and an effective process selected and advanced.

Tuning Microporosity

Increasing the surface area of the electrode configuration is key to generating high amounts of oxygen and hydrogen for a given applied potential. The catalyst is designed to be deposited at the desired active site, held in place and set following a sequence of processes that leave a combined high surface area, tortuosity and electrochemical activity.

Extensive development work and analytical techniques combined with in-situ testing is providing Supercritical with an unparalleled understanding of morphology and performance in the high pressure, intermediate temperature operating conditions.

The macroporosity method has been optimised through a combination of different metallic catalyst compounds, cleaning methods, deposition methods and curing approaches.

Scaling Cell for Deployment

The MTC's role as a catapult centre is to prove capability and enhance opportunities for the British manufacturing centre. Following extensive parameter development on the downselected methods for manufacture, the MTC supported Supercritical in identifying suppliers of manufacturing technology who will enable the production of these components to scale quickly.

Supercritical now works with suppliers across the UK to create its electrode assemblies at small production volumes for both its lab scale cell and demonstrator scale designs. As volumes increase, Supercritical intends to establish in-house manufacturing capacity using the technologies that have been advanced during this project, sourcing the manufacturing equipment from their existing partners.

The importance of developing a robust supply chain to support the scale up this technology cannot be under stated given the forecast demand for clean hydrogen globally expected to be up to 580+ million tonnes of hydrogen by 2050⁵. Already leveraging the UK's widespread capabilities in advanced manufacturing already and having established 16 direct jobs at Supercritical, the technology has incredible potential to enhance the UK's position as a producer and exporter of highly valuable clean technology as well as creating thousands of jobs in clean technology and manufacturing.

Module

The WhiskHy project propelled Supercritical's technology out of a lab environment and facilitated the design, build and testing of what became known as Supercritical's V1 module. The first physical prototype would demonstrate the linear scalability of multiple cells. It would

⁵ [Global Energy Perspective 2023: Hydrogen outlook](#), Jan 2024

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be a test bed for larger scale demonstrator cells and would provide crucial learning to Supercritical in its pathway to commercial deployment. The V1 module would act as an array of cells connected using manifolds to have a single aqueous electrolyte inlet, an O₂ rich outlet and an H₂ rich outlet. Some of the key features for shortlisting a prototype design were:

- Low contained volume to minimise stored energy
- Traditionally manufactured design
- Cells replaceability to allow for testing of different cell designs
- Even distribution of the flow between cells

Designed not for commercial exploitation, but for maximum learning and ease of re-build, the V1 module has the capability for cell-by-cell replacement as well as separate power supply to each cell.

After a series of improvements, the final V1 module design had an optimised electrical set up, the module would also be 33% shorter.

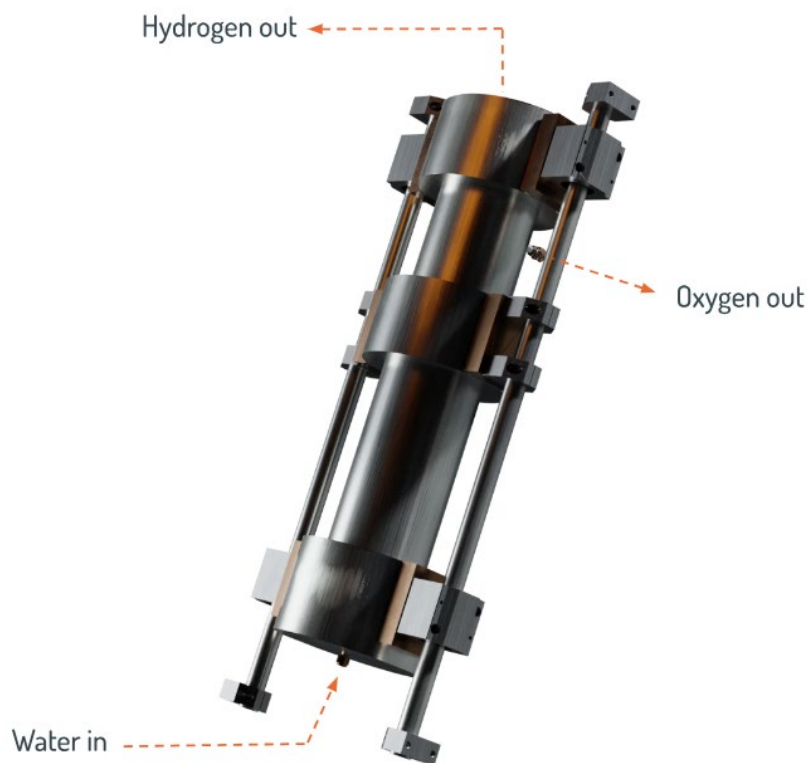


Figure 7 – Module Design

Supercritical has worked with third parties to manufacture this first V1 module. Each manifold went through dimensional quality inspection of the target tolerances, and Non-Destructive-testing of the welds. The final verification test was the hydrostatic and leak test which took each manifold to 400 bar.

Teesside 1

Supercritical's technology will be scaled linearly by multiplying the number of cells. Cells will be grouped in modules and those modules will be deployed as arrays in systems. The balance of plant of these systems will be scaled to the module array's production rate and costs will scale more akin to the 0.6 rule of scaling, enabling significant cost benefits at larger system scales.

Teesside 1 (TS1) sought to address a number of key known unknowns that Supercritical's design team had identified, in addition to fundamentally demonstrating the scalability of the core electrolyser technology and the system that supports it. TS1 offers a heavily instrumented, data heavy test capability that has capacity for testing Supercritical's early module versions and for testing equipment like heat exchangers and separators as well as control systems with more rigour. With greater scale comes inherently greater hazards and the approach to risk mitigation changes.

By operating at such fundamentally different operating conditions to any other electrolyser manufacturer on the market, it became apparent that existing literature and information was lacking versus established operating conditions. For example, vapour liquid equilibria data for hydrogen and water, or oxygen and water mixtures at 220 bara are virtually non-existent and heat capacities of these mixtures are not tabulated or referenceable within typical thermophysical property databases of process modelling software. As Supercritical is pioneering innovation in this space, this understanding was going to have to be developed.

TS1 is a test bed that will enable an improved understanding of

- Operability
- Electrolyser module performance
- Equipment capability
- Instrument capability
- System control
- Product specification / purity
- Effluent product / purity
- Heat exchange
- Separator efficiency / operating conditions
- Heat losses
- Corrosion
- Lifetime

An external site needed to be considered for TS1, due to the limitations of the current Supercritical laboratory premises, including:

- Space available
- Availability and reliability of required utilities

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- Constraints on the installation of additional protective equipment to ensure a suitably high level of safety.

Design requirements for Test Stand 1 were developed by Supercritical based on the outputs from SET cell testing, single cell testing and multi-physics simulation. It was important for Supercritical to work with an engineering partner to allow the design of Test Stand 1 to be delivered in a suitably short timescale.

Teesside was selected as the optimal location for locating this demonstrator given the engineering capabilities in the area for the design, build and operation of TS1. The location offered Supercritical ease of access to trusted partners, specialist facilities and customised, flexible premises to meet the needs of a technology developer like Supercritical. By leasing a test bay at Wilton Centre, design, build and testing teams were co-located, enabling better collaboration and communication between teams throughout the project.

Basis for TS1 Design

Design of TS1 revolves around the V1 module. TS1 is capable of delivering electrolyte to the module at 230 barg and a range of temperatures from 250 - 410°C.

The capacity of TS1 was defined to be forward looking, allowing us to test performance from existing Gen 2 single cells at a small scale, up to a 6kW module. TS1 will become an integral asset in Supercritical's test capability as it progresses with development, testing new cell iterations and module designs beyond this phase of the WhiskHy project.

As the process for producing high pressure hydrogen from water under supercritical conditions is developed, it was imperative that safety of personnel, the environment and assets was considered at every stage. A formal system popularly used by Imperial Chemical Industries (ICI) was used to review technical safety appropriately at each stage of the project. A Basis of Safety has been established, identifying the hazards and worst-case consequences of the process incidents. It also notes the safeguards that have been employed to prevent, protect and mitigate against these consequences.

The major hazards identified in the test stand operation are the flammability and explosivity of hydrogen, particularly in the event of oxygen presence in the headspace of any of the separators downstream of the electrolyser. Given the first-of-a-kind nature of the test rig, TS1's purpose is to demonstrate the electrolyser and system's capability to ensure a hazardous environment like this does not occur at any frequency considered to be unacceptable. Prior to this being established for a commercial product, increased prudence and diligence regarding the safe operation of the rig is warranted and has been deployed.

The effect of temperature and pressure on the hydrogen explosion limits are presented in Figure 8 and Figure 9 respectively. Hence a primary focus was to prevent the formation of flammable atmospheres. Controls are put in place to trip the system if the monitored compositions on the gas outlet vents are higher than 50% of the Lower Flammability Limit (LFL)/ Limiting Oxygen Concentration (LOC).

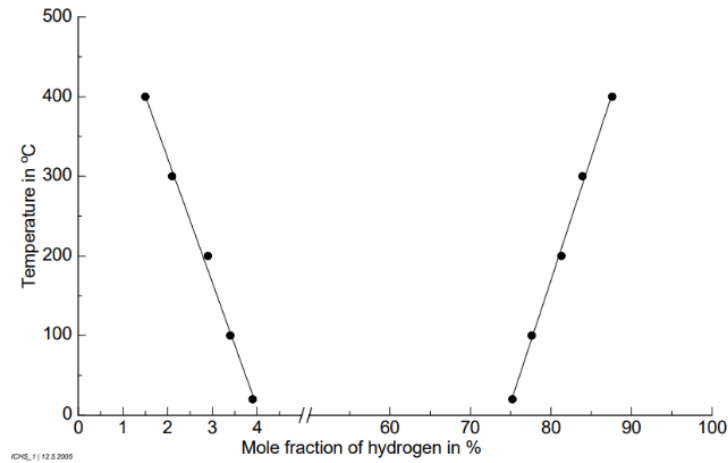


Figure 8 - Effect of temperature on hydrogen explosion limits⁶.

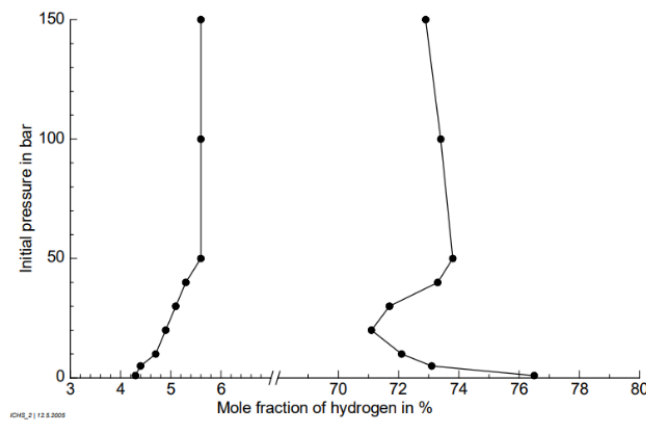


Figure 9 - Effect of pressure on hydrogen explosion limits.

Furthermore, to control the effects of any potential explosion, it was decided to house TS1 within a pre-existing blast bay, which can withstand 1 kg TNT equivalent energy output (see Figure 10). The rig is remotely operated with local extraction and a trip function on extract failure included in the control system. The use of nitrogen within the system for purge purposes necessitated the provision of an oxygen depletion alarm system to prevent asphyxiation of personnel.

Safe Operations

The major hazard identified with the process was explosion risk due to potential crossover of hydrogen and oxygen and the buildup of a flammable atmosphere in the separator headspace. Note that it was appropriate to take these measures as the electrolyser had never been operated at this scale before, therefore measures to protect against undesired crossover, a mitigated risk in lab operations, were taken. To mitigate against any flammable atmosphere created which could lead to deflagration and detonation, an analysis was performed to determine the energy release on separator vessel rupture. This governed the separator volumes used for the test stand, based on the predicted rise in pressure in the worst-case

⁶ Figure 8 and Figure 9: Explosion Characteristics of Hydrogen-Air and Hydrogen-Oxygen Mixtures at Elevated Pressures" by V. Schroeder and K. Holtappels, 2005

deflagration and detonation scenarios. The limited separator volume ensures that the maximum energy released in the worst-case failure scenario remains below the limits of which the blast bay is rated.



Figure 10 - Blast bay at Wilton Centre before TS1 was installed.

In the worst-case explosion scenario, a secondary hazard to be mitigated is the conversion of the explosion energy into kinetic energy to vessel fragments. Hence, an analysis was carried out to establish whether the reinforced concrete walls and mild steel cover plates in the Wilton blast bays are likely to be sufficiently thick to resist penetration by the generated projectiles. The calculations of the minimum required thickness for reinforced concrete and mild steel were performed using the HSE guidance on Pressure Test Safety. Based on the results, it was agreed that during the recombination and electrolysis trials, the separators should be run at low pressures as a safeguard. A blast curtain has also been installed outside of the blast bay door as an additional layer of protection to safeguard against any risk to personnel outside the blast bay (see Figure 11).



Figure 11 - Blast bay curtain being installed outside Bay 9 door.

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Supercritical prioritises safety above all else, in development and in future commercial deployments. Several layers of protection have been designed and put in place to ensure that the scenarios which could lead to a potential injury or fatality are prevented from taking place. These include the minimisation of hazardous material volumes and concentrations, the operation of the test stand in the blast bay and the exclusion of personnel from the area while the rig is in operation (at high temperatures and pressures). Access to the bay was also controlled throughout operations with a lock out tag out procedure.

An assessment of the adequacy of these protection measures to mitigate the hazards identified during the HAZOP was carried out using a fault tree order of magnitude assessment. The assessment concluded that the total combined risk of fatality during the Phase 1 operation is within the CPI standard combined target frequency of 1×10^{-6} / year. Based on this result, there was no requirement for additional safeguards for operations.

Thermophysical Properties for Process Design

Standard simulation software options for process design (e.g. HYSYS, UniSim, Proll, ProMax) struggle to model fluid mixtures that include supercritical water. Based on a comparison of Equations of State available (including from these simulation tools), the highest accuracy data currently available is from NIST. However, the vapour liquid equilibria data available for hydrogen or oxygen in water, and water in hydrogen or oxygen, at elevated pressures is limited. Where it is available, the literature presents a broad range of measured values, due to differences in experimental procedures and measurement methodologies used. Design of TS1 was progressed based on conservative values from literature; however, TS1 has the capability of gas injection to facilitate controlled trials at and around these operating conditions which will allow for these assumptions to be validated against gas and liquid phase VLE data.

Heat Exchanger Design

Heat exchanger design to cool supercritical water is less well established than more common gas or liquid phases. Commercial heat exchanger design software is not able to accurately model the transition of water through the critical region. The challenge is further compounded when dealing with dissolved oxygen or hydrogen, which comes out of solution as the supercritical electrolyte fluid is cooled.

This is a significant drawback to conventional design tools, as the largest contribution to cooling duty is required as the fluid cools below the critical temperature (between 380°C and 360°C), due to the inflection point in the temperature-enthalpy curve observed at the module operating conditions as shown in Figure 12.

Figure 12 - Enthalpy of water as a function of temperature at 230 barg

Supercritical worked closely with the technical development director at the cooler supplier to ensure that: custom fluid properties based on NIST data could be used for the heat exchanger design in order to avoid a pseudo-phase change occurring along the exchanger length, and

that materials could be sourced and welded to construct and qualify the heat exchangers to a suitable design specification.

While significant work has been performed to appropriately design the heat exchangers for supercritical operation, this performance and behaviour will be validated through operation of TS1 and will help to further understand and model heat exchange behaviour and properties of supercritical electrolyte for future system design.

Control

Due to the rig being concealed inside a blast bay and the high-risk factor with hydrogen, alarms and trips are configured on the major temperature, pressure, flow, level and product outlet purity signals in order to give the operator a high level of confidence whilst the rig is in operation. The majority of the control system was designed using hardwired relay logic as recommended by Supercritical's design partner.

The output signals from the instruments in the rig such as temperatures, pressures, flows, levels and concentrations are recorded on a SCADA (Supervisory Control and Data Acquisition) software. This will allow operating personnel and the Supercritical team in London to view the system behaviour locally and remotely. The SCADA records data of the rig which can be saved and used to analyse process performance and inform future design decisions.

The current control panel design is sufficient for the scope of TS1 however there are disadvantages with continuing with a hardwired relay logic control system such as limited functionality, scalability, and flexibility. It is not simple to make changes to relay logic easily without rewiring or adding/removing components and it can only carry out simple logic operations. It also takes up more space and consumes more power if more control loops are to be added. For commercial operation and to be advanced in the near future, the intent is to move to fully automated control with PLC for each module and DCS for overall system control. The control philosophy will be refined for large scale deployments in preparation for full system design demonstrating that Supercritical's green hydrogen production system is inherently safe and operable against commercial expectations.

TS1 Mechanical Build

A modular rig design comprising three structural steel welded frames facilitated manual handling of the frame, keeping individual frames to a weight that could be moved using hand winches as well as a forklift. This allowed the initial rig assembly to be made in a nearby workshop, with more space and greater access to machine tools, and then a straightforward transport for reassembly within the blast bay. This also offers Supercritical the option to relocate the rig more easily to a customer facility such as one of Suntory Global Spirits' Scottish distilleries.

Equipment & Quality Assurance

To ensure that the high-pressure vessels, heat exchangers, and module components were delivered to the required level of quality, and in compliance with the applicable pressure equipment legislation, Supercritical worked together with the manufacturers, visiting the factories and staying in regular contact with the designers and quality teams. The pressure

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equipment was supplied UKCA marked, with appropriate Non-Destructive Testing, pressure and leak testing, in line with ASME BPVC, and for the module, UK PD500 standards.

The scale of TS1 meant that tubing with compression fittings, rather than a fully welded piping approach was appropriate. Achieving the required level of gas-tight high-pressure performance for operation with hydrogen with these fittings required working closely with suppliers. Testing campaigns were made to our requirements, to ensure certification to the requisite level of performance. A successful fitting test is shown in Figure 13 where the tube has failed ahead of the fitting.

The tubing, meanwhile, was procured to ASTM standards. Through engagement with the suppliers of our compression fittings and tubing it was discovered that applying tighter geometric tolerance requirements for our tubing gave the best results for our materials. All tubing was specified to meet the

requirements given by the fitting suppliers, in line with ASME B31.3.

Test - Electrolyser and system testing

TS1 was designed to demonstrate the scalability of Supercritical's technology. Design for the rig as well as operating procedures were influenced by trials conducted at lab scale. A 'perfect' result would be if TS1 performed equivalently to the parameters that it was scaled against. Active area (cm²), for example, is a physical feature that if scaled by 5x, would result in a theoretical 5x higher current given that a cell's performance at a given voltage (V) is measured as a current density (A/cm²). Critical parameters for electrolyser system operation extend beyond the cell, however, and the team examined elements from flow control through to gas purity.

Electrode testing at lab scale has developed over time and research conducted by the Supercritical team has permitted the down-selection of materials, physical features and operating conditions. Given the operating space (high pressures and intermediate temperatures) is so minimally explored, the learning rate has been fast and the development of newer and improved features has followed.

The initial phase of testing was focused on validating that the mechanical build and control system implementation delivered a system that met the target operating conditions. This was followed by first electrolysis trials on Supercritical's larger cells and V1 module. It represented the first opportunity to operate and understand the behaviour of a system which operated with all equipment and components running at high pressure. Lab test operations minimise operational risk by minimising higher pressures and temperatures to the electrolyser only. Commercial systems will operate >200 bar pressure to deliver high pressure hydrogen product that meets the needs of consumers in the largest industrial sectors that use hydrogen today and for storage for fuel switching users.

Testing also acted as an introduction for the operational teams, enabling them to develop, experience and finesse the operating protocols for start-up, operation, shutdown and other activities related to the plant management (e.g. waste management and electrolyte make-up). It provided an essential opportunity to understand how to control key aspects of the plant, such as ramping temperature in a controlled manner, as well as understanding in practice how the SCADA system could offer the greatest value to operators.

Heat Management

The process fluid in TS1 is heated via electric heaters in the feed and electrolyser. Temperature loss will be minimised by design and through the application of insulation. Temperature control and management of heat is a critical element of system design with poor decisions capable of de-valuing efficiency gains achieved in the electrolyser. During testing, a number of positive outcomes regarding the thermal performance of the system were observed.

The responsiveness of the system to changes in set points was assessed. Ensuring close following of the intended ramp rate ensures that material stresses are kept to the designed minimum and demonstrates the appropriate sizing and specification of the equipment down-selected. Trials were run without insulation and with insulation. Responsiveness to control and performance of insulation was assessed.

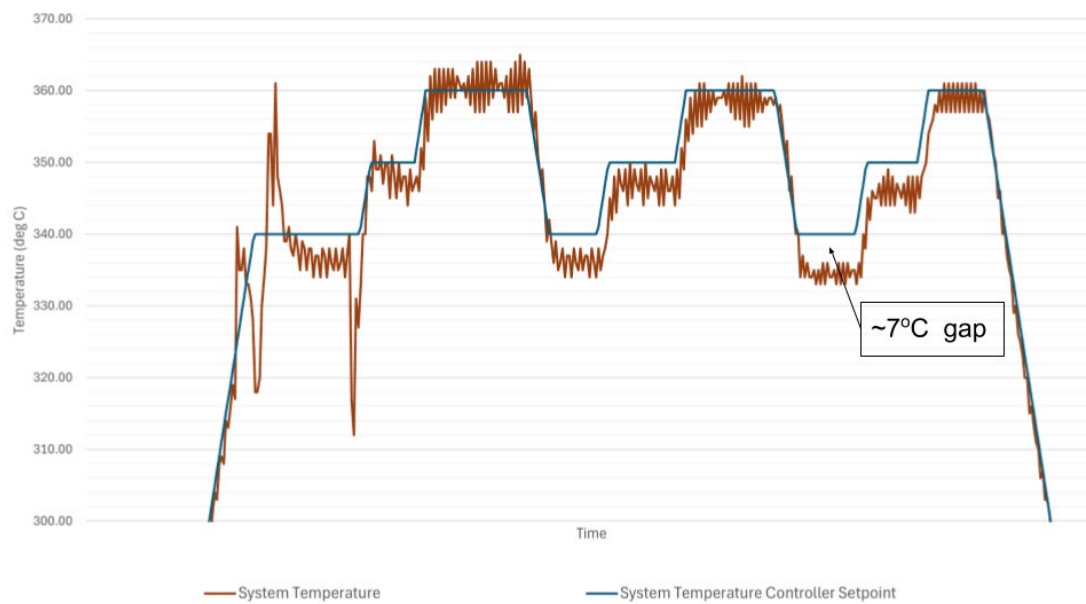


Figure 15 - System temperature ramp control on TS1 when insulated

The application of insulation proved highly effective in reducing temperature losses and allowing good control of the system during ramp up to desired operating temperatures and during stable operation (see Figure 15). Though it is noted that the remaining gap is an area for further optimisation in future designs.

Complementing this, it was observed that the heat losses from the module in actual operation were lower than originally predicted, based on thermal modelling. The thermal model was originally developed to establish a suitable design for maintaining supercritical conditions in the cell.

Figure 17 - Predicted vs Actual temperatures across the electrolyser

As can be seen in Figure 17, at the module inlet, subcritical and supercritical conditions were successfully achieved without insulation, and temperature losses through the module were lower than anticipated. Going forward the applied duty and insulation will be modified to optimise for efficiency, taking these learnings into account. It is noted that the simulation's exact conditions varied from the actual conditions of the room and that additional runs would be valuable to align the thermal models to actual performance. The additional insight will allow us to improve our models and better predict heat losses for future module designs, enabling better heat optimisation. Furthermore, it will permit more accurate interpretations of larger scale systems in model format, allowing commercial customers to better predict plant economics and justify technology adoption.

System commissioning and issue resolution

With all first of a kind designs, there is an expectation that there will be challenges found during commissioning and operations that were not foreseeable during the design and engineering

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phase. As part of the Phase 1 preparation and commissioning, a number of these challenges were overcome and addressed. The team were also subjected to issues that were less related to the novelty of the plant, but instead unanticipated logistical hurdles such as having to design and install an alternative dedicated supply of high-pressure nitrogen (as a result of the failure of Wilton Centre HP Nitrogen utility supply) and having to retrim valves that were not delivered as specified.

Flow control

The electrolyser separates the flow into two streams – an oxygen rich and a hydrogen rich stream. In Supercritical's design, controlling flow is a requirement to achieve the desired operating profile. At lab scale, the control of the system and operating conditions is well understood and a known operating range is defined to achieve both optimal performance and product purity. Going to TS1, with a larger cell design, multiple cells in parallel and a balance of plant at a scale larger than ever demonstrated before, this control needed to be re-established, taking initial guidance from lab parameters.



Figure 18 - Using lab parameterisation to define target operating range for TS1 (Right: lab, Left: TS1)

Significant collaborative effort involving the process design, build, control and operational teams enabled the necessary balance between the accuracy of the control and the pressure difference required to manage flow distribution. Through the mapping of the system's performance across a range of operating conditions, the team now has a clear view of the resultant impact of key variables and has defined the acceptable range for operation in addition to procedures for start-up of the rig to facilitate the targeted range being achieved.

V1 Module Performance

The cells deployed into the V1 module for this first ever test were of a Gen2 design. The Gen2 design has run through a number of iterations throughout the WhiskHy project and the resultant performance has shown to have clear dependencies on the aforementioned microporosity, microporosity and other design parameters. Moreover, the performance of an individual cell can be influenced by physical parameters relating the hardware such as the quality of the macro/micro porosity, and the current distribution across the cell; the conditions surrounding it such as the local temperature, the flow rate and its distribution, and time variables such as the time the cells have been permitted to condition. A number of datasets

demonstrating a range of data generated during lab trials of different variants is shown in Figure 19, each cell is held at constant voltage and set of operating conditions.

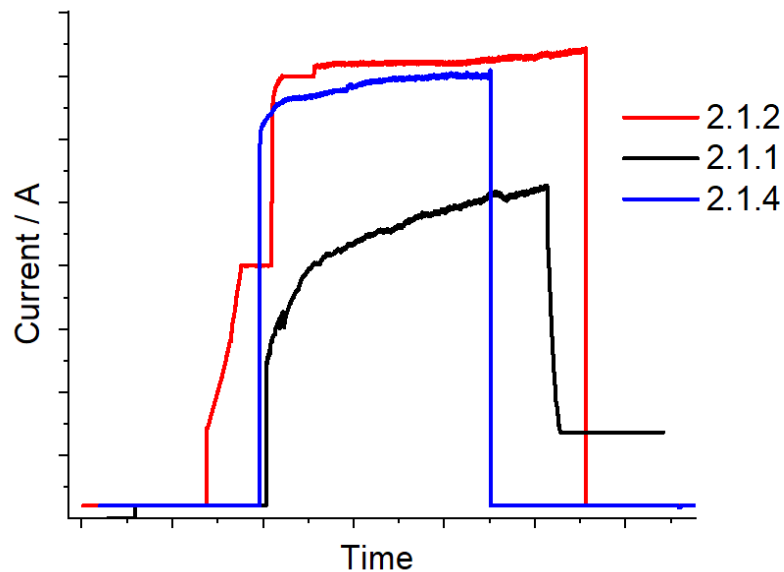


Figure 19 - Lab Gen2 test data

It can be observed that the stabilising of the cell's performance takes some time. The stabilisation of the cell's performance requires some time, primarily because the cells are not yet fully conditioned. Conditioning involves several mechanisms, including electrochemical reduction of the cathode, oxidation of the anode, and restructuring of the electrode's surface morphology and crystallinity. Additionally, extended testing duration and exposure to elevated temperatures help to optimise the electrodes' performance over time.

Relative to lab testing, there were 6 cells in simultaneous operation in V1 and the V1 cells had a 3.75x larger geometric surface area relative to lab tests. The cells were initially started up individually to test performance before then being tested at a range of different temperatures as can be seen in Figure 20.

Figure 20 - TS1 test data, cell by cell at 3 different temperatures

The cells show good equivalency for a first test with results showing a range of -8% to +4% at the middle temperature and -7.5% to +15.6% around the mean performance at the higher temperature. Results also show clear improved performance over time, demonstrating that these cells are not yet at their peak operating point at these given conditions. There are numerous factors at play influencing performance. Gaining greater consistency in the electrode hardware through isolation of manufacturing tolerances, improving control of operating conditions through improved design and control, and in testing for longer durations, the team will better determine the resultant commercial performance of this V1. The preliminary testing achieved during the WhiskHy project provides an excellent footing to build on.

The cell specification selected for the V1 module was the 2.1.1 specification. When comparing V1's absolute performance relative to that of the range of lab data that has been gathered across all 2.1 variants, the V1 Cell performance is between 2.4 (vs 2.1.2 variant) and 3.7 (vs 2.1.1 variant) times that of the lab performance (see Figure 21). The active area of the V1 cells is 3.72x that of the lab cells, an ideal / perfect scaling would result in a 3.72x output on performance. In this case, the V1 cells performed 3.52x of the lab, 95% of the ideal operating point. This is a very positive initial finding demonstrating that at the higher end of the range, there is a close-to-linear relationship between the geometric surface area and performance between lab and TS1 scale - a very encouraging outcome. This will be further demonstrated with different cell architectures.

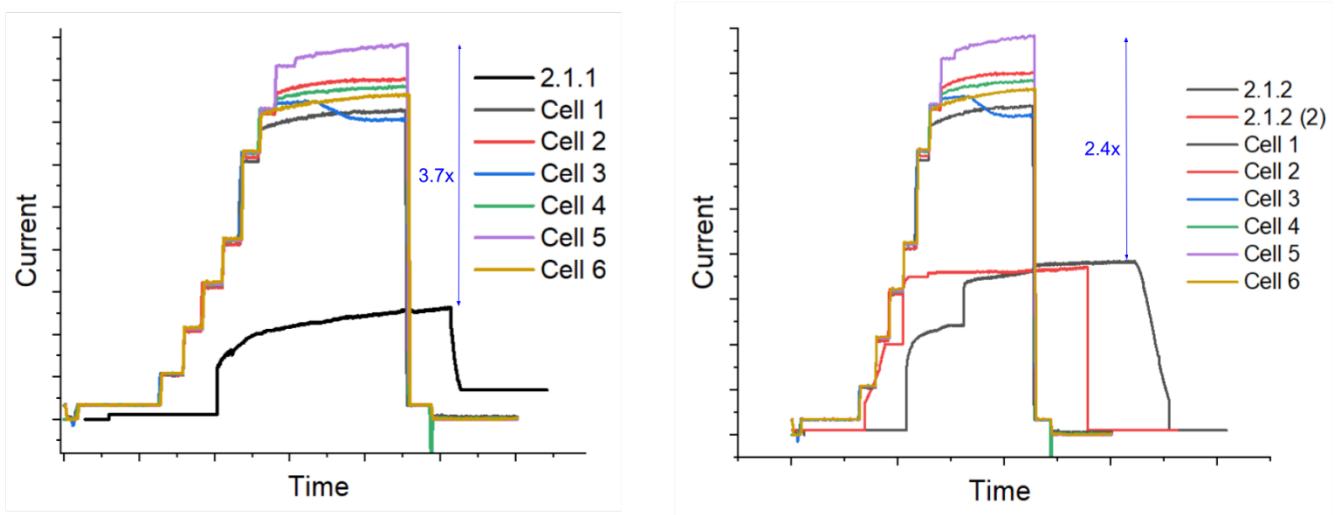


Figure 21 - Comparison of lab cell performance to module cell performance on an absolute basis

Seeing this same information in a different format, considering the performance on a per cm² basis, the near equivalency of some cells and the delta of others is more clearly observed with performance very comparable to 2.1.1 but acknowledging that 2.1.2 achieved a current density 1.7x that of the module, though the cell architectures were fundamentally different so this was to be expected.

Figure 22 - Comparison of lab cell performance to module cell performance on a /cm² basis

The findings provide great insight into the scalability of results in the lab, offering new routes to understanding the potential commercial impacts of changes at lab scale. TS1 provides a proven means of validating those models. Going forward, TS1 can and will be adapted to test new iterations of cell designs that show promise in a lab environment and it will also house new iterations of Supercritical's module designs.

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Separator design and operation

Another key aspect of the system is the safe design and operation of the separators. The separators enable the separation of the produced gases at 220bar from the 2 phase flow coming out of the electrolyser. Risk was mitigated through composition control and management of gases and gas headspace volume. The headspace, managed by control of the liquid level in the separators was dependent on a significant number of factors ranging from the sensitivity of the instrumentation, the flow of the inlet fluids entering the vessel, the accuracy of control of the output valves, and the impact of pressure on the separator behaviour.

Following preliminary hurdles, during operation, level control remained a challenge. Figure 23 shows the set point vs process value and the control action of the level control valve - LICA403 (the level indicator). FIZA 101 shows the liquid flow out of the electrolyser. The observed level in the separator did not track closely with the setpoint of the level in the separator.

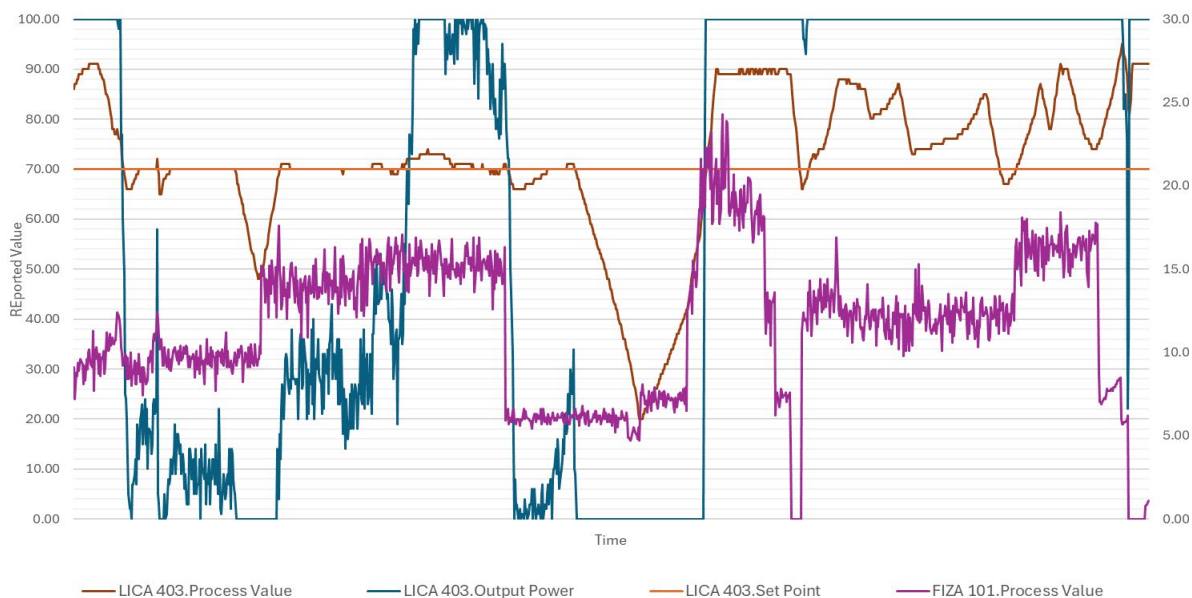


Figure 23 - Plots demonstrating challenging level control during initial testing

The engineering team implemented various changes to the system and found that in the second phase of testing, the level control was much improved (see Figure 24).

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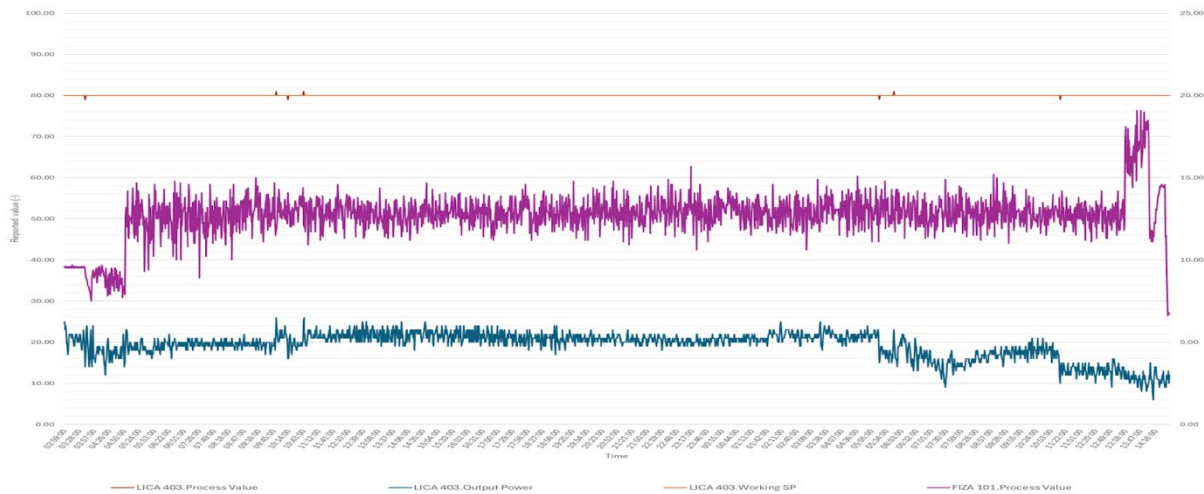


Figure 24 - Plots showing improved level control during later stage testing

Subsequent level control has proven far more effective, with minimal variance between the setpoint and observed separator levels. Further testing at high pressure operation is recommended and planned.

With one of the main functions of TS1 being able to monitor the product gases produced, the Supercritical team designed a supplementary knock-out system to minimise the risk of any liquid carry-over into the gas lines and downstream sampling equipment. This helped to ensure moisture and gas analysis equipment were protected.

TS1 was designed to take both liquid effluent samples and gas samples from the separator with the gas being measured by gas chromatography with the purpose of monitoring hydrogen and oxygen content of the streams. The liquid effluent was sent to a secondary site for analysis.

As can be seen from Figure 25, gas purity, monitored during cell conditioning and during operation at T1, T2 and T3, preliminary tests demonstrate that gas crossover is well controlled and in line with early lab scale testing. The gas chromatograph was calibrated with hydrogen, oxygen and nitrogen calibration gases to ensure accurate measurements of the produced gases as well as the diluent nitrogen. However, in post-analysis, it was found that the local supply of nitrogen contained traces of helium. This was not communicated on the specification of nitrogen supply and made the determination of some samples inconclusive. The peak for helium is very close to that of hydrogen in a gas chromatogram. The cathode gas results for cell 2 and 3 conditioning and 6 cell operation at T3 were unfortunately not readable. Supercritical will run many more electrolyser trials and will recalibrate and modify the gas chromatography methods to account for this additional gas component and mitigate this risk going forward.

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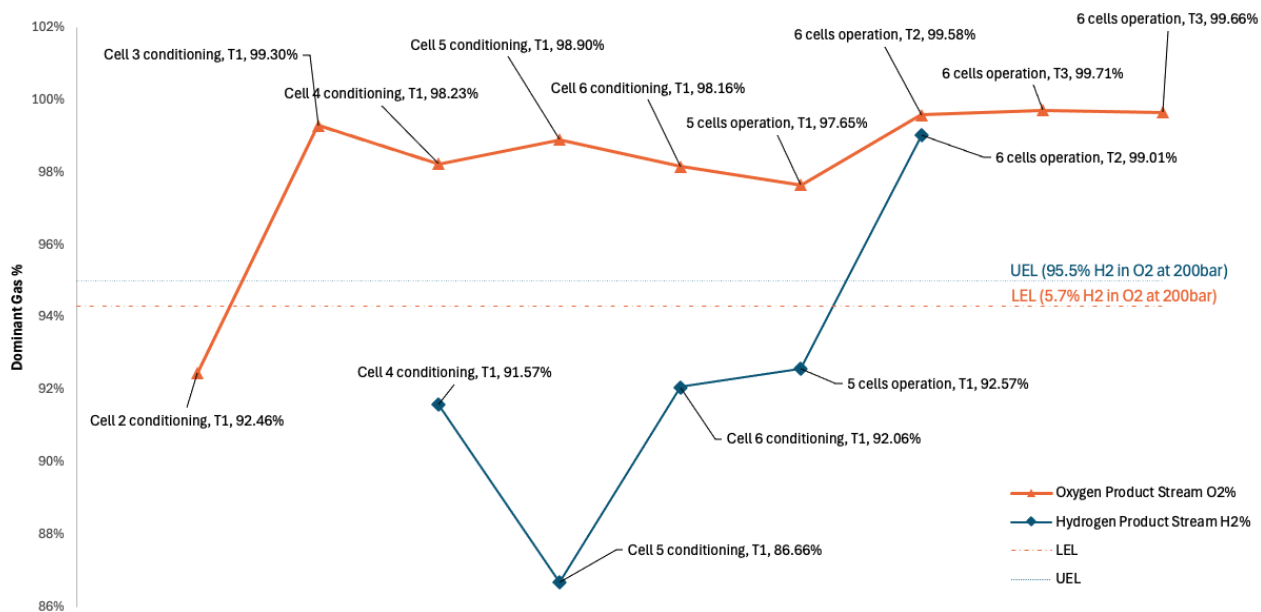


Figure 25 - Product gas purity measurements over time

As a membraneless electrolyser, demonstrating purity at desired operating conditions is crucial to commercialisation. As can be seen from Figure 25, as expected during conditioning, oxygen:hydrogen ratios were still stabilising and had not achieved the designed safe operating point of >98% in both product streams. Oxygen purity stabilised more quickly than the hydrogen purity, but positively, the hydrogen purity achieved the desired composition as operation at T2 was underway. This operating point and T3 are of most interest to Supercritical as it is at these higher temperatures where electrolyser performance was also at its best.

This data shows that Supercritical's technology can safely deliver hydrogen and oxygen from its high pressure electrolyser on its multi-cell V1 module. This is a huge milestone and achievement and will advise future commercial module designs.

H2 Utilisation

Direct firing hydrogen

Direct Firing Planning

WhiskHy aimed to demonstrate fuel switching (from Methane to Hydrogen) in the application of Direct Fired Distillation for Spirit Production (Whisky). The aim of this trial was to temporarily retrofit a hydrogen supply onto an existing production asset to demonstrate that hydrogen could be efficiently, and safely, used as fuel for this traditional spirit production technique.

Glen Garioch trial – UK H2 supply

The initial intention was for this trial to be completed at Suntory Global Spirits' Glen Garioch Distillery in Oldmeldrum, using the recently re-introduced direct fired Wash Still (21,500L). However, on developing this project, it was quickly identified that the cost for the volume of hydrogen required to supply a distillation run was substantially higher than the budget awarded. Additionally, the requirements of the Green Distillery Competition are that the project

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must be 100% funded by the fund without private subsidy, therefore, completing this trial at Glen Garioch was not possible using the available hydrogen suppliers at that time. The summary of these budget costs are as follows:

Table 2 – Direct firing trial optioneering

	Value
Original Budget	£270k
	Based on Supplier 1 quotation for compressed H2 provided 05/2021
Supplier 1 supply of compressed H2	£408k
Supplier 2 supply of liquid H2 (supplier subsequently revoked proposal)	£210k
	Note this needs to consider a more complex implementation, incurring implementation costs that would result in budget being exceeded)

Suntory Global Spirits investigated alternative options for this trial across its Global estate of distilleries and identified the Yamazaki Pilot Distillery as a potential alternative location.

Yamazaki Pilot Plant

The Yamazaki Pilot distillery, located near Kyoto, is an industrial scale production facility with an existing 2,000L direct fired wash still of similar technology to that deployed in the UK.

Additionally, all malted barley processed at the Pilot Distillery is sourced from UK Maltsters as are the liquid yeasts used, and therefore, the production is at suitable scale and of identical feedstock to Scotch Whisky production. Any observations from the trial at Yamazaki are expected to be repeatable in Scotland. Due to the small size of the wash still (2,000L vs 21,500L) the amount, and therefore cost, of hydrogen required was significantly lower than the option at Glen Garioch. The below table is the comparison used to conclude that the project should be progressed at Yamazaki Pilot Distillery.

Table 3 - Comparison of trial location options

	Baseline - Glen Garioch Distillery Direct Firing (as per application)	Option 1 - Alternative Fuel Source, Glen Garioch Distillery Direct Firing	Option 2 – Direct Firing at Yamazaki plant in Japan.
Delivery Partner	Suntory Global Spirits UK Ltd	Suntory Global Spirits UK Ltd	Suntory Spirits Ltd (Subcontractor to Beam Suntory UK Ltd)
Duration	~1 week	~1 week	~1 week
Description	Beam Suntory to manage 10-18 distillation wash distillation	Beam Suntory to manage 10-18 distillation wash distillations back-to-back	Beam Suntory to manage at least 3 wash distillation runs back-to-back at their Japanese plant.
Output	After a number of years 57,700 fully matured bottles of whisky.	(no change)	Processes and samples to enable decisions about hydrogen transition to be carried across the BS estate
Deliverables for WP7	1)H2 direct fired Spirit produced	(no change)	(no change)

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Milestones that track progress through the project:	2) Spirit Analysis report 1) Direct Firing detailed plan 2) Direct fire with H2 completed 3) Spirit in warehouse casks 4) Spirit Maturity report	(no change)	(no change)
Cost / Budget for WP7 as a whole	Projected cost: £408k	Projected cost: £210k	Projected cost: £210k
Fuel to be used	Bottled pressurised hydrogen transported by road (requiring over 5% of Supplier 1's UK hydrogen trailer fleet).	ISO container capable of holding 2.7 tonnes of liquid hydrogen.	Bottled pressurised hydrogen. Smaller scale of plant enables ~10% of hydrogen to be used.
Timing	Original target date planned for August 2022, deemed no longer feasible	Original target date planned for Dec 2022, deemed no longer feasible	Original target date planned for late 2022, actual delivered date Jan 2024
Engineering Risks	None	Vaporisation of liquid hydrogen being explored with engineering firms	None
Other Issues or Comments	Costs currency exclude additional kit to reduce pressure from 10 Bar to millibar pressure needed for burners. Actual number of Wash distillations reduced to ~5	Quantity of hydrogen on site requires hazardous substances licence. Cost very high-level and risk of increase. The most complex approach **Supplier 2 revoked this offer**	Testing at Yamazaki is a well-worn route for validating transformational change, and was used previously to justify Glen Garioch's transition to direct firing (a £6M investment in UK asset to improve quality and efficiency)

A single Yamazaki trial distillery direct-fire wash distillation will require ~650 kWh, as against a single Glen Garioch distillery direct-fire wash distillation which would require ~7,000 kWh. Therefore, the hydrogen required for this trial will be 10% of what would have been required in Scotland and the plant allowed for a more robust demonstration trial, which can be delivered within the confines of the Project's financial structure.

This was presented to DESNZ and the Yamazaki Pilot Distillery plan was approved as a suitable alternative that would allow the project to progress and remain within the timescales and fund allocation. With the plan for the new make spirit produced at Yamazaki using Hydrogen to be sent to Scotland for casking and maturation where it would be periodically sampled to determine if there has been any influence on the maturation profile as a result of being produced using hydrogen direct firing.

Direct Firing Design

Working closely with the local Japanese Suntory Engineering Team, Suntory Global Spirits and Supercritical supported the design discussions and options for introducing a temporary

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hydrogen supply on the Yamazaki site. This also included supporting discussion with local authorities and suppliers. Ahead of the trial at Yamazaki, the team achieved the following:

- Pre-trial NO_x Emissions testing, with Tokyo Gas, using the same burner design as per Yamazaki's existing equipment, fired on Hydrogen gas using Tokyo Gas emissions testing facility.
- All equipment (pipework, gas handling systems, safety/control systems) installed to local regulatory standards and commissioned ahead of the trial started on 18th January 2024.
- Site received temporary relaxation on NO_x emissions (i.e. no upper limit for 3 wash runs) for the duration of the trial – this was agreed with the local fire department.
- Contracts and supply arrangements for hydrogen supply agreed.

Pre-trial NO_x results

During the planning of the project, NO_x emissions were identified as a potential compliance issue for this trial, and any future industrial fuel switch to Hydrogen. The regulatory requirements in Japan have fixed values for NO_x stack emissions, similar to the EU's Medium Combustion Plant Directive (MCPD). The emissions limit at the Yamazaki Pilot Distillery is 120ppm NO_x.

The trial was conducted at Tokyo Gas' emission testing facility, in Tokyo, and used the same burner supplier/design as that of the existing installed burner at Yamazaki Pilot distillery. In consultation with the burner manufacturer, multiple variations of their Low NO_x burner heads were used.

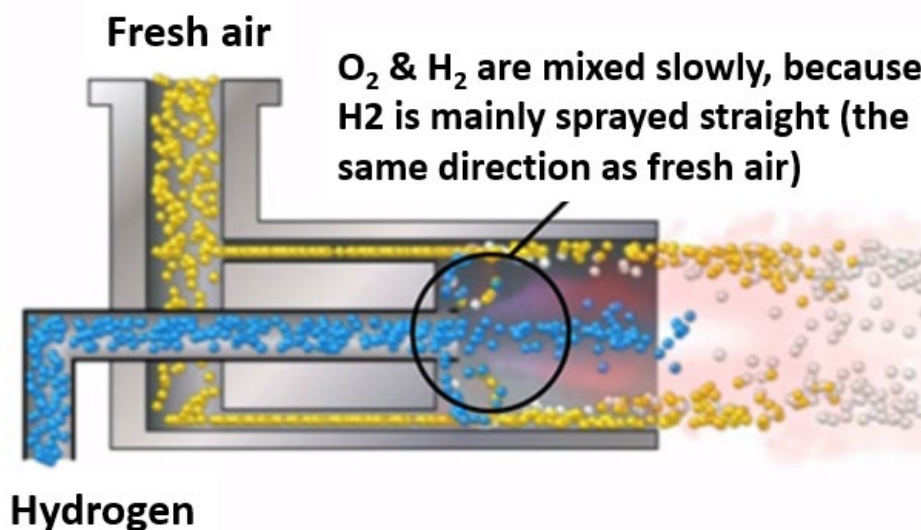


Figure 26 – Low NO_x Burner design

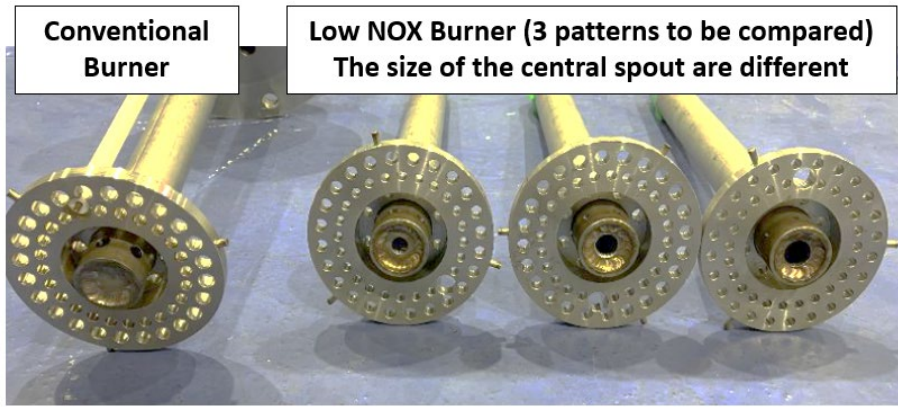


Figure 27 - Burner design schematic and burner head designs

The NOx trial used all 4 burner head arrangements and ranged through 100% natural gas to 100% hydrogen, with blended mixtures of 90/10% and 50/50% (Natural Gas/Hydrogen) also tested. The NOx content (at 6% excess oxygen) was recorded for each fuel scenario, and each burner head. The results are displayed in the below graph.



Figure 28 – NOx trial results

As can be seen, the results from the NOx trial only resulted in a single exceedance of the regulatory 120ppm NOx value and this was when firing 100% hydrogen using the conventional burner nozzle. All other scenarios and mixtures returned lower than 120ppm NOx. The results also show that as hydrogen content increases, the NOx levels recorded also increase. Interestingly though, an unexpected correlation in these results was that when the rate of firing increased i.e. furnace temperature increased, the NOx emissions slightly decreased in each scenario (800°C to 1,100°C).

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The output of this assessment was shared with the local authorities and regulatory bodies in Japan. It was on the strength of these results that Suntory obtained a temporary derogation for NOx emissions at Yamazaki for the duration of the direct firing trial on site.

Back-fire protection

There is typically a requirement for backfire protection devices to be installed on 100% hydrogen burners due to the increased flammability range of hydrogen and the increased speed at which it burns when compared with most commercially available natural gases. This is only required where the hydrogen is ignited by the burner.

This was a challenge for the project as the space required to install the backfire protection device did not exist within the existing pilot plant layout. The solution was to instead introduce hydrogen at 10% then 100% (hence the trial conditions for NOx) into the flame that was already ignited. This was achieved by integrating a split gas supply manifold and the existing burner's control system.



Figure 29 - Hydrogen Burner control system

Direct-fire

Yamazaki trial distillery is gas direct-fired (similar to Glen Garioch) and we can therefore assess quality of hydrogen direct-fire spirit against gas direct-fire spirit, similar to what we would be looking to achieve at Glen Garioch.

Therefore, due to the common raw materials used (Scottish malted barley and UK-sourced Distilling Yeast), and the similar whisky making processes utilised, the new make spirit obtained from the Yamazaki trial distillery will be very similar in style to that which would be produced at Glen Garioch and will therefore be able to reflect any impacts on the new make spirit arising from the use of hydrogen as a direct firing fuel source.

H2 Demand

A single Yamazaki trial distillery direct-fire wash distillation will require ~650 kWh, as against a single Glen Garioch distillery direct-fire wash distillation which would require ~7,000 kWh.

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Therefore, the H2 required for this trial will be 10% of what we would require in Scotland and will allow for a more robust demonstration trial, which can be delivered within the confines of the Project financial structure.

Trial at Yamazaki: 18th - 22nd January 2024

The WhiskHy team successfully ran 3x back-to-back Wash Distillations using hydrogen gas to fuel the direct fired furnace at Yamazaki. This trial was completed successfully without any issue; either H&S or measured production performance. The below is the sequence of this operation:

- Wash Still brought up to Temperature for 2 hours (not distilling).
- Fuel switch - Hydrogen automatically switches on.
- Run on hydrogen for 87 minutes of the 140-minute distillation cycle (circa 65% of Wash distillation).
- Switch back to methane for furnace cool down (not distilling).

The Low Wines were then distilled into Spirit using the steam heated Spirit Still. The spirit has been isolated and circa 280L at 63.5% ABV was shipped to Scotland for casking, maturation and ongoing quality assessment to determine if H2 direct fired has had any effect on the maturation process.

The H2 direct fired spirit will mature beside a cask of normal Yamazaki Pilot Plant product (methane direct fired spirit) as a control at Glen Garioch Distillery.

Analysis of Produced Spirit

The new make spirit produced during the trial distillation has been assessed by Suntory Global Spirits using their normal approach for quality assessment.

Organoleptic assessment, using the experience and skills of their Master Blender and Blenders to compare trial spirit against baseline methane direct fired spirit.

Gas Chromatography (GC), using chemical analysis of the spirits to measure key indicators of character and quality against baseline methane produced spirit.

[Organoleptic Results](#)

The Suntory Global Spirits Spirit Quality team have confirmed that no significant differences were found between the control samples and the Hydrogen samples assessed: there were 7 positive results (detectable differences) over 22 overall results, which is not enough to be statistically different.

Below is the profiling difference between the 2 samples, which clearly shows the consistency between both distillation methods.

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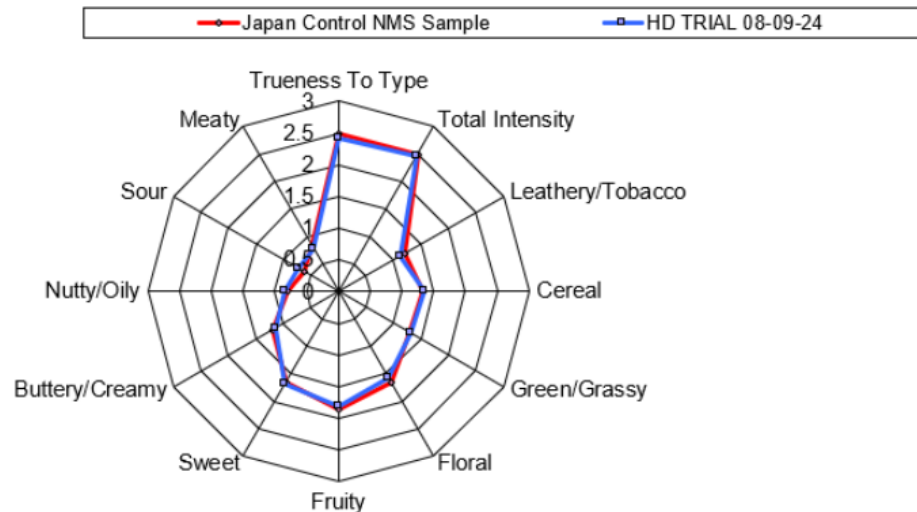


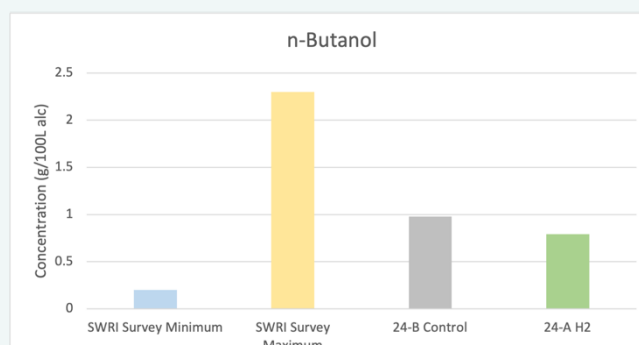
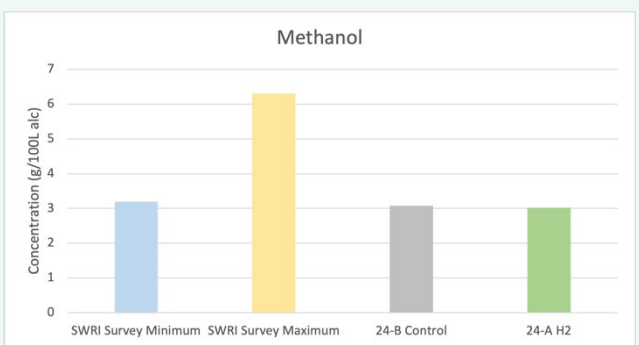
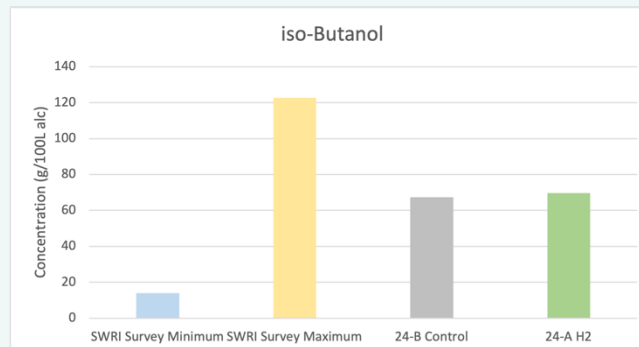
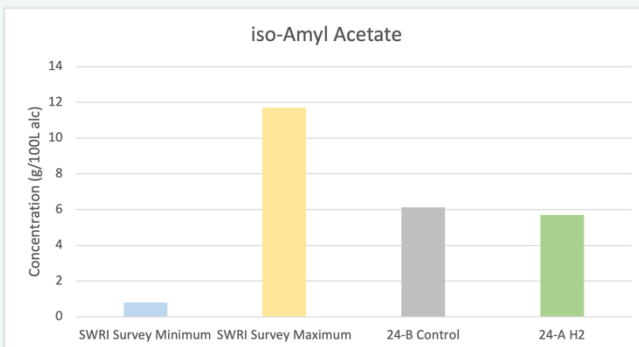
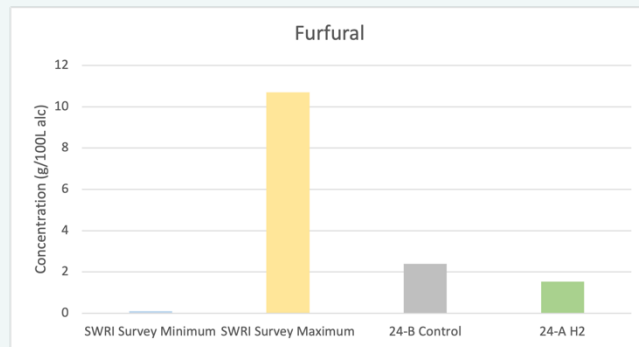
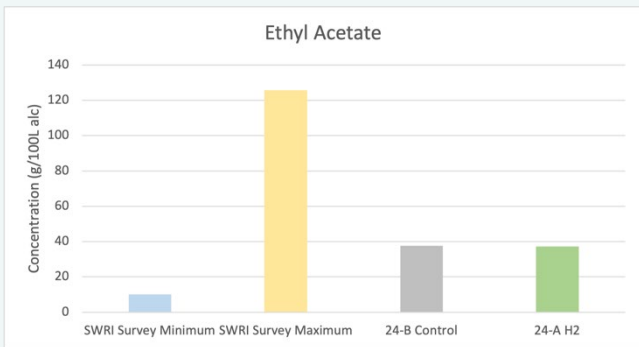
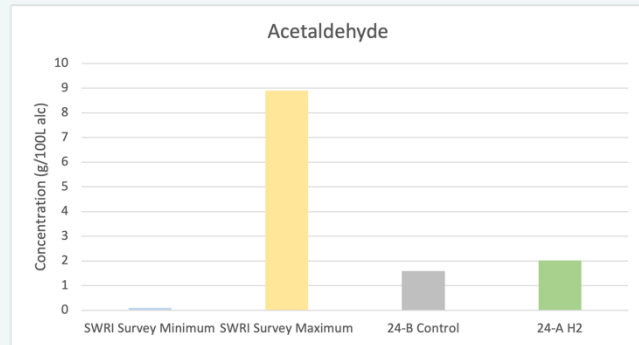
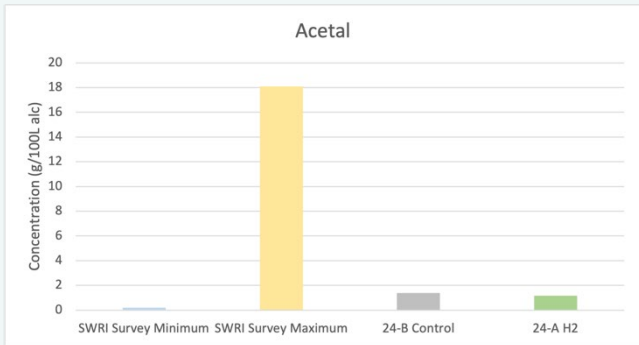
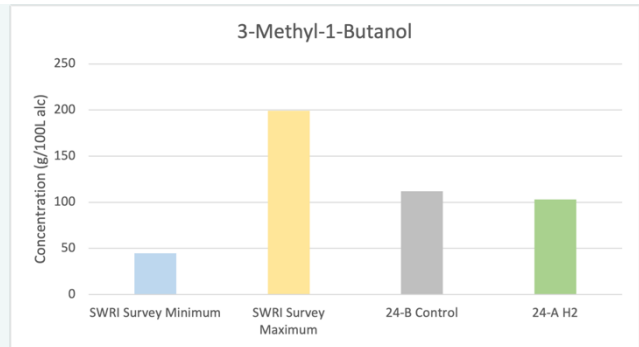
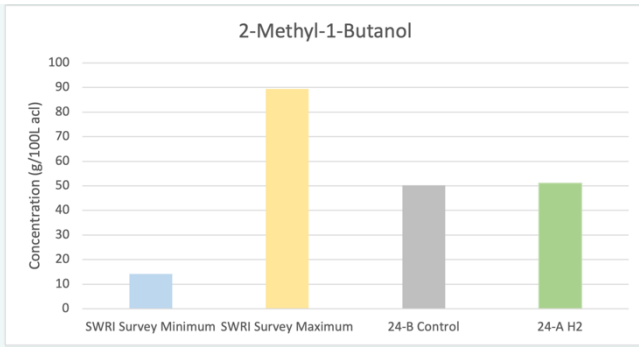
Figure 30 – Organoleptic Spider Diagram

Gas Chromatography Results

The results from the GC analysis of the reference (methane direct fire) and hydrogen trial NMS (New Make Spirit) liquids confirmed that there was little variation between the samples 24-B Control and 24-A H2.

For completeness, the results (Figure 28) were also referenced against the range of results from the latest SWRI (Scotch Whisky Research Institute) NMS survey, which includes representative samples from across the full malt distilling industry) to show that they are well within expectations for Scotch Whisky.

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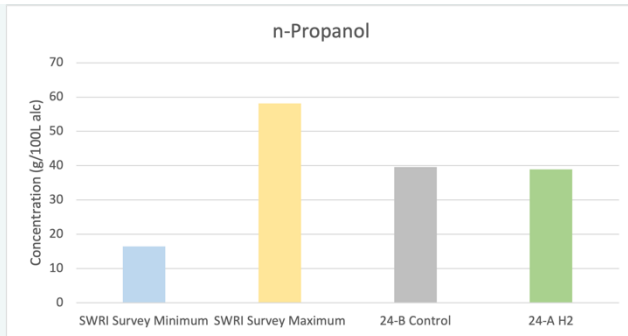


Figure 31 - GC Analysis results for different components comparing H2 sample (24-A H2), methane control (24-B Control) and SWRI NMS Survey minimum and maximum

Table 4 – Sensory descriptors to chemical comparison

Chemicals	Sensory Descriptors				
2 methyl-1-butanol	Fruity, banana, tropical fruits	Sweet	Solventy Alcoholic	Alcoholic	
3 methyl-1-butanol	Pungent	Solventy	Fruity	Medicinal	
Acetal	Fruity, apple, pear	Sweet	Solventy	Estery	
Acetadehyde	Pungent	Fruity, green apple	Alcoholic		
Ethyl acetate	Fruity, pear, banana, pineapple	Sweet, ripe fruits			
Furfural	Almondy	Toast like	Caramely	Woody	
iso amyl acetate	Ripe banana	Fruity	Solvent-like	Artificial	
iso-butanol	Alcoholic	Solventy	Sweet	Fruity	Floral
methanol	Alcoholic	Astringent	Sharp	chemical	
n-Butanol	Alcoholic	Sweet	Solventy	Fruity	
n-Propanol	Alcoholic	Sharp	Solventy		

Noting Furfural slightly decreased with the H2, but the variation is so small that it is not considered as significant.

Table 4 above shows the specific sensory characteristics of the chemicals in that analysis, this confirms the lack of difference observed between the 2 sensory profiles established earlier (control vs H2): the process is not affected by the H2 heating system; the sensory profile is not affected either.

Maturation

To determine if the hydrogen fired spirit has had any impact on maturation profile, circa 280L of Hydrogen fired spirit and 280 litres of methane fired spirit (control) have been shipped from Japan to Scotland. This spirit has been filled into identical casks and is now maturing at Glen Garioch Distillery, the original intended location of this demonstration trial.

The spirit will be assessed at regular intervals to determine if there are any notable differences between the H₂ and Methane control spirits over the next few years.

Electrolysis on a whisky distillery

Liquid co-products and waste streams

During feasibility, it was predicted that it could be possible to use the distillery liquid co-products and waste streams as a feedstock for the electrolyser, minimising additional freshwater withdrawals.

Liquid co-products and waste streams from distilleries can present different chemical composition, depending on the feedstock used to produce whisky, the operational conditions, and the sampling point (e.g., spent lee sample, pot ale sample, final effluent sample etc). In general, raw streams from a distillery can contain different types of carbohydrates (e.g., starch, sucrose, glucose etc), proteins (e.g., from the feedstock and yeast cells), oil, fat and grease, phenolic compounds, intermediate compound from carbohydrate decomposition (e.g., 5-HMF), fatty acids, lignin, cellulose, melanoidins, alcohols and/or others. In addition, not only the type but also the quantity of each compound is particular to each distillery company.

A high-level breakdown of the malt distillation process is presented in Figure 29.

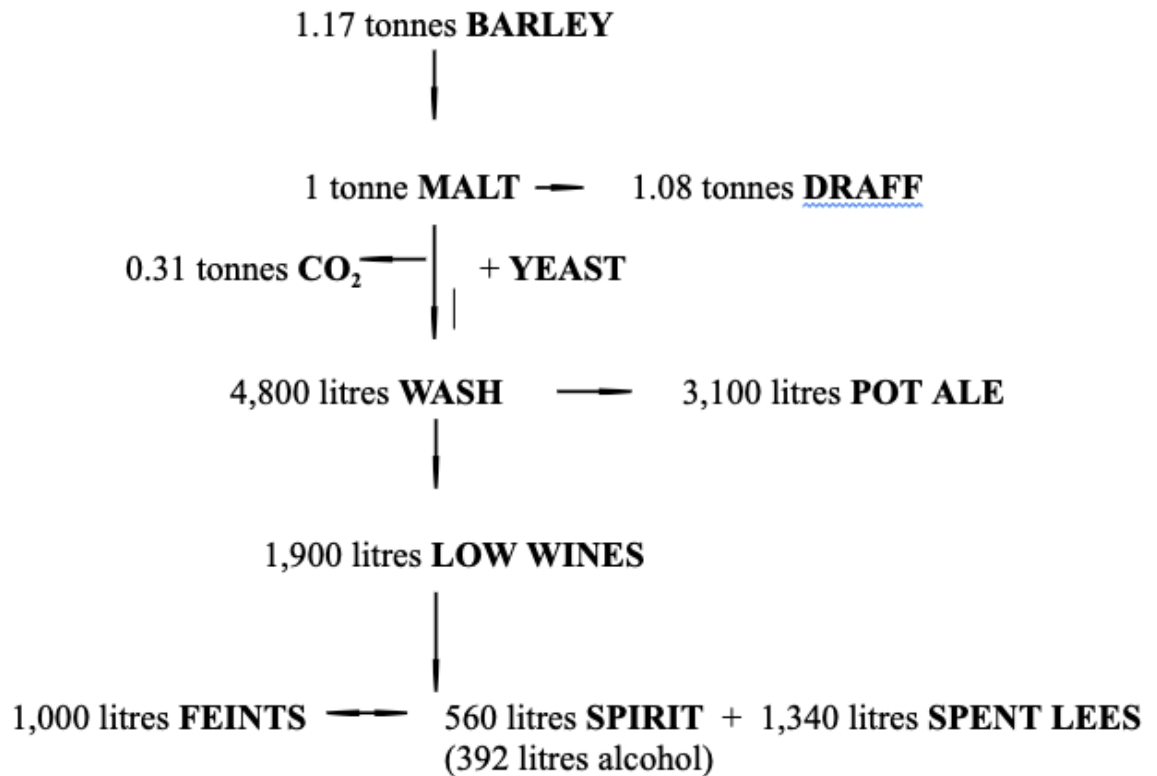


Figure 32 – Generic spirit and by-products from 1 tonne of malt

Definitions:

DRAFF – grain residue after the malted barley has been mashed and the extractable sugar removed

WASH – Distillers Beer generated from fermenting the sugary liquid extracted from the Mash (called Wort) with yeast (strength of Wash ~8.5% abv)

POT ALE – The residue left after the first distillation of the WASH (beer) which includes about 4% solids (proteins, unfermented sugars, yeast etc.)

LOW WINES – The alcohol collected from the first distillation of the WASH (beer) which is typically about ~ 25% abv

FEINTS – the initial alcohol collected (high alcohols known as ‘Heads’) and final alcohol collected (low alcohols known as ‘Tails’) from the second distillation of the LOW WINES

SPIRIT – the middle runnings of alcohol after the Heads and before the Tails (known as the ‘Spirit Cut’ or ‘Heart’) from the second distillation of the LOW WINES

SPENT LEES - The residue left after the second distillation of the Low Wines which includes no beneficial material and has to be treated or disposed of

During the project, liquid co-products and waste stream samples were analysed from the following locations across a full week of operations:

- Pot Ale
- Spent Lees
- Raw Foul Condensate (from pot ale evaporator)
- Raw ETP Influent
- DAF Effluent
- MBR (final) Effluent

Analysis was undertaken of the following parameters to establish the liquid co-products and waste stream components and implications for the electrolysis activity;

Table 5 – Components analysed as part of the liquid co-products and waste stream analysis

Analysis	Commentary
COD	Chemical Oxygen Demand (COD) measures the reactivity (oxidation) of the carbon compounds present in the samples
TOC	Total Organic Carbon (TOC) is the measurement of the amount of carbon in the sample; carbon can be converted to gases or deposit in the reactor in supercritical water.
Conductivity	This has a direct relationship with the number of dissolved metals/substances in the sample.
Total Nitrogen-N Total Sulphur-S	Gases containing nitrogen and sulphur can be produced in supercritical water.
Alkalinity	carbonates may reduce corrosion and can precipitate as particles in supercritical water.
Silicon as SiO₂	silicon may be present in the feedstock/grains used to produce whisky and end up going to the waste streams
Chloride	
Metal Analysis	For the following components: Silver, Aluminium, Arsenic, Barium, Calcium, Cadmium, Cobalt, Chromium, Copper, Iron, Mercury, Potassium, Lithium, Magnesium, Manganese, Molybdenum, Sodium, Nickel, Phosphorous, Lead, Strontium, Titanium, Zinc

As a result of the analysis the following conclusions could be drawn:

The COD and TOC of Raw Pot Ale was an order of magnitude greater than all other samples and two orders of magnitude greater than the MBR (final) effluent.

Total Organic Carbon (TOC) is the measurement of the amount of carbon in the sample and Chemical Oxygen Demand (COD) measures the reactivity (oxidation) of the carbon compounds present in the samples.

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There was significant variability in composition depending on the operations being undertaken. The following graph shows the significant variation in the Raw Pot Ale COD/TOC ratios over a week's worth of samples.

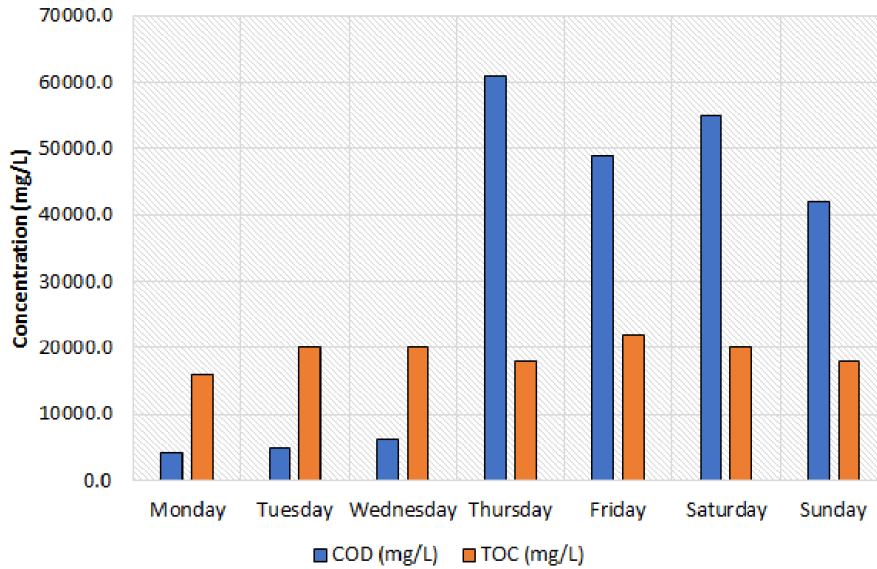


Figure 33 - COD and TOC of Raw Pot Ale samples

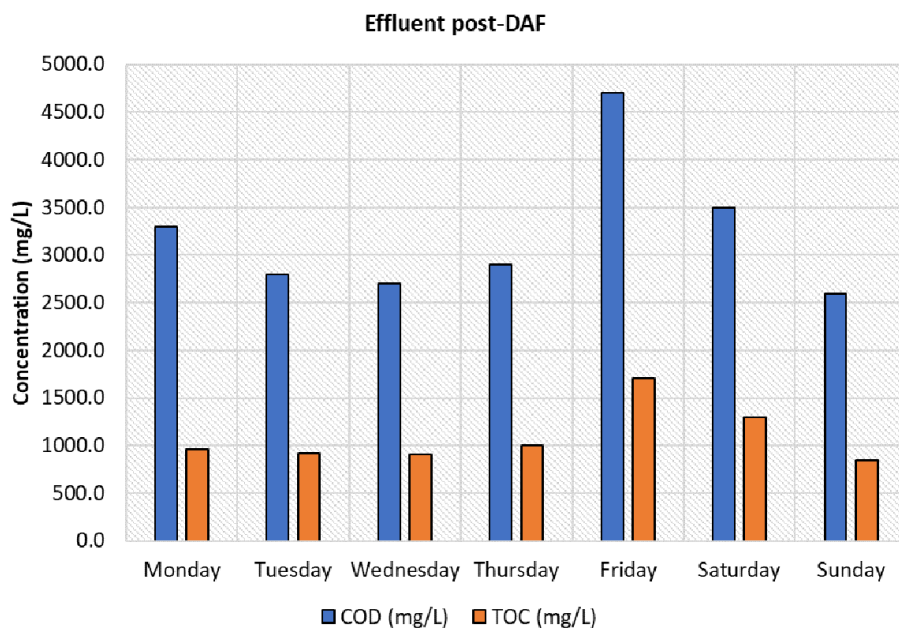


Figure 34 - COD and TOC of Effluent post-DAF samples

In a wastewater treatment system, an influent (raw wastewater) will normally present high COD/TOC ratio. In industrial wastewater, the COD/TOC ratio may vary from 0.60 to 6.65, the lower the ratio the higher the amount of nonbiodegradable organic compounds. After a wastewater treatment system, the effluent may present predominantly recalcitrant organic compounds, which result in a low COD/TOC ratio.

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Analysis is required to understand the impact of Macronutrient and Trace elements, though Calcium (Ca), Magnesium (Mg), Phosphorus (P), Potassium (K), Sodium (Na), and Sulphur (S) were the predominant metals identified in all the samples. Metal elements in a distillery industry may come from the feedstock (e.g., the type of water used, barley and/or other types of grains), the distillery equipment, the equipment and facilities cleaning process and/or the effluent treatment system used to treat the streams. These elements can promote a catalytic effect in supercritical water and form metal particles and precipitate on or cause solid buildup in the reactor.

Anionic compound impacts need to be assessed further. Chloride and nitrogen compounds were seen throughout the samples. The impact of chlorides on durability and precipitates (such as NaCl) as well as the potential for Nitrogen-based gases (e.g., NO, NO₂, N₂) would have to be factored into the reactor conditions used.

To effectively utilise the distillery liquid co-products and waste streams without it being detrimental to plant durability or the purity of the outputs of the electrolyser, the temperature, pressure and hydraulic retention needs to be adapted to provide the optimal reaction conditions to maximise the conversion into gas products.

Moreover, the most appropriate use of the distillery's liquid co-products and waste streams must be determined. For example, the Raw Pot Ale, due to its higher organic content, is currently sent to animal feed post evaporation. The least 'useful' streams today are the Spent Lees and the Raw Foul Condensate which have reasonable organic content and could offer a sustainable source of water for electrolysis, subject to management of the macronutrients and chloride ions.

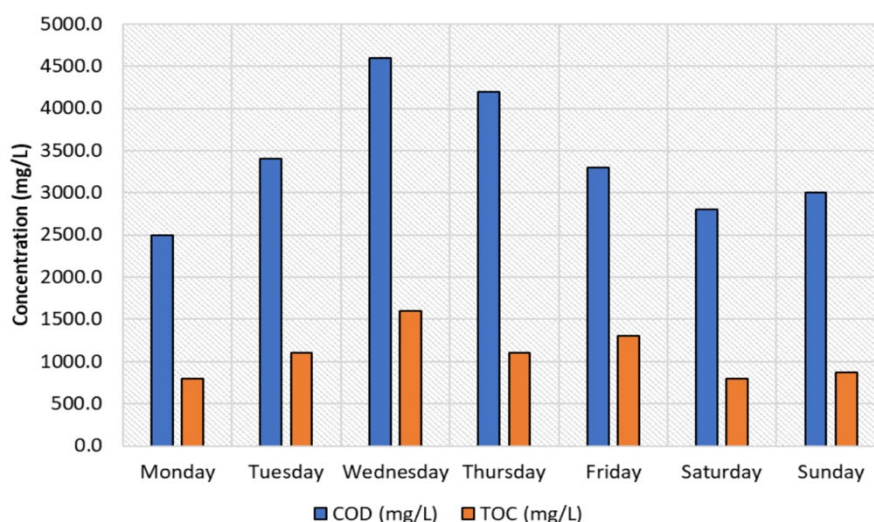


Figure 35 - COD and TOC of Raw Spent Lees samples

Table 6 - Raw Spent Lee samples macronutrient elements results

	Total Ca (mg/l)	Total Mg (mg/l)	Total P (mg/l)	Total K (mg/l)	Total Na (mg/l)	Total S (mg/l)
Monday	44	11	4.5	12	38	10
Tuesday	2.6	6.5	29	31	1.6	10
Wednesday	3.5	12	41	59	1.9	10
Thursday	66	31	120	190	50	10
Friday	6.2	11	32	54	3.9	10
Saturday	2.3	3.1	8.2	14	1.7	10
Sunday	2.6	2.9	8.1	13	0.77	10

Table 7 - Raw Spent Lees Parameter Results

	COD/TOC	Conductivity (mS/cm)	Alkalinity (mg/l)	Chloride (mg/l)	Nitrogen-N Total (mg/L)
Monday	3.13	221	10	9.90	8
Tuesday	3.09	210	10	13	37
Wednesday	2.88	365	10	16	73
Thursday	3.82	151	10	7.9	20
Friday	2.54	371	20	17	71
Saturday	3.50	162	20	5	16
Sunday	3.45	151	20	8	16

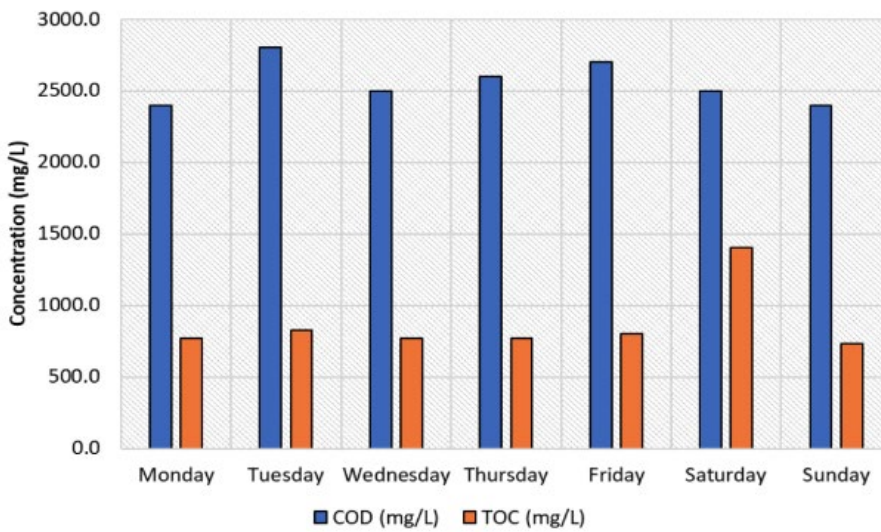


Figure 36 - COD and TOC of Raw Foul Condensate samples

Table 8 - Raw Foul Condensate samples macronutrient elements results

	Total Ca (mg/l)	Total Mg (mg/l)	Total P (mg/l)	Total K (mg/l)	Total Na (mg/l)	Total S (mg/l)
Monday	0.26	0.08	0.41	0.42	0.24	10
Tuesday	0.52	0.14	0.34	0.43	0.59	10
Wednesday	0.16	0.02	0.22	0.08	0.07	10
Thursday	1.3	2.3	6.8	11	0.67	10
Friday	0.5	0.04	0.15	0.08	0.07	10
Saturday	0.62	0.06	0.23	0.11	0.07	10
Sunday	0.41	0.04	0.16	0.1	0.07	10

Table 9 - Raw Foul Condensate Parameter Results

	COD/TOC	Conductivity (mS/cm)	Alkalinity (mg/l)	Chloride (mg/l)	Nitrogen-N Total (mg/L)
Monday	3.12	161	10	2.7	4
Tuesday	3.37	162	10	3.2	4.1
Wednesday	3.25	171	10	2.4	3.1
Thursday	3.38	153	10	2.2	3.4
Friday	3.38	172	20	2.9	3.7
Saturday	1.79	744	20	19	51
Sunday	3.29	150	20	1.5	2.4

The analysis of the liquid co-products and waste streams has clarified the actions involved with utilising the byproduct of whisky production in preference to freshwater withdrawals. It has also helped clarify the opportunity to pursue hydrogen derivatives from the electrolysis of organic compounds, which is being actively considered and evaluated outside of the scope of the project.

By-product utilisation

Oxygen, a by-product of water electrolysis for hydrogen production, can find application in a working distillery environment. Different distilleries use oxygen in different ways, but considering a future state where oxygen is potentially available to use with no extra cost due to on-site green hydrogen production, the application of oxygen may increase.

The two most probable use cases for oxygen within a distillery would be in effluent treatment of oxy-fuel combustion.

Today, many distilleries use aerobic digestion as an effective way of reducing the BOD and COD levels in its effluent to ensure that it is suitable to be released to the environment. Oxygen could be used to accelerate this process relative to using air.

Oxy-fuel combustion could be considered to provide a greater efficiency within the boiler / still and to reduce NO_x emissions. With oxy-fuel combustion, there is just fuel and oxygen. In the case of hydrogen combustion, the only by-product would be water. There are technologies under development that are focused on utilising these co-products from electrolysis to improve the overall efficiency of renewable electrons through to heat. This cannot typically be done with systems designed to run on air as flame temperatures under oxycombustion can be

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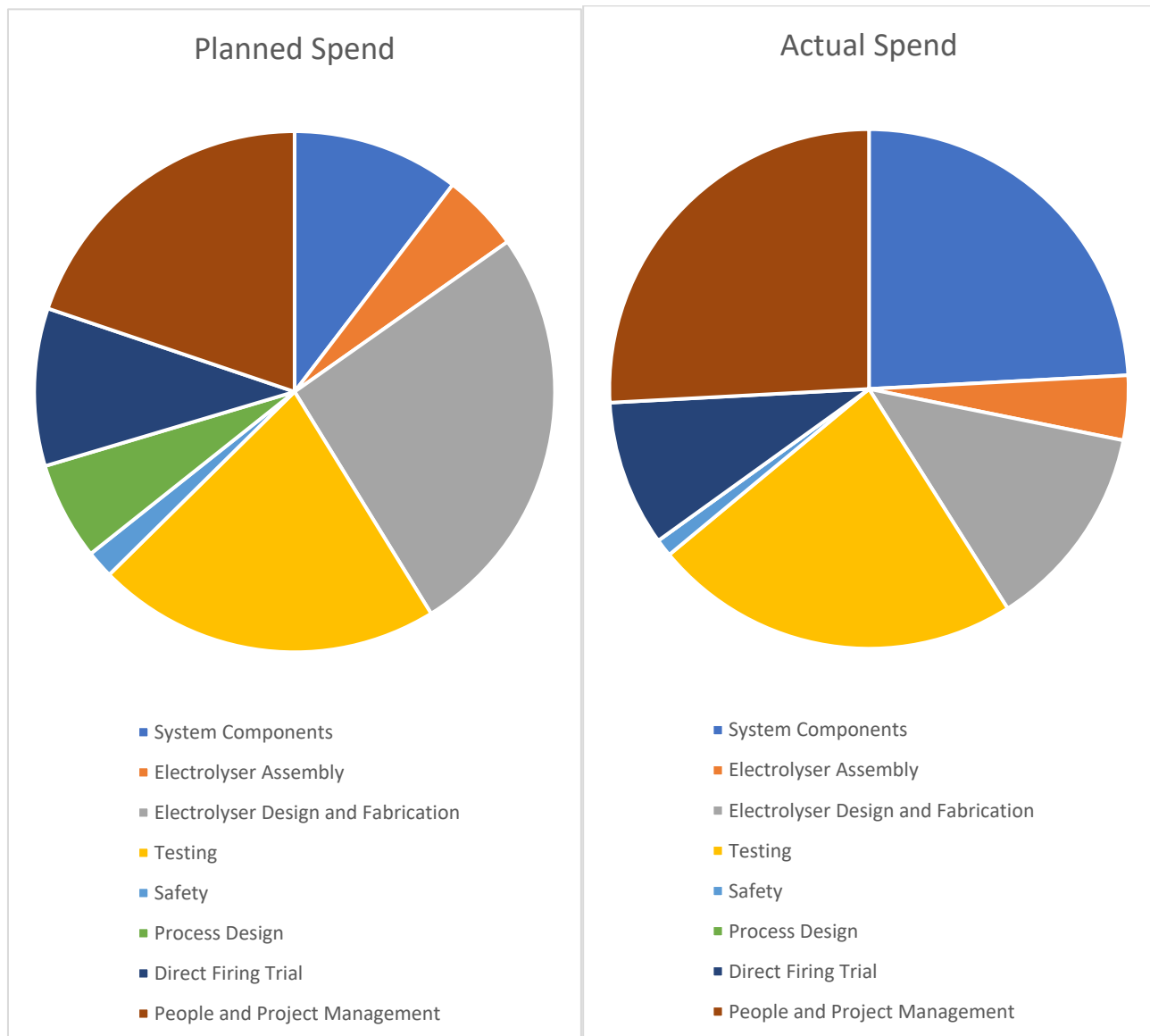
significantly higher than combustion under air (approximately 1000°C hotter with hydrogen) which introduces material challenges.

Oxygen can also be considered for use in some smaller demand scenarios, for example to improve early stages of fermentation and accelerated maturation. Yeast requires oxygen to grow and multiply. Controlled oxygenation can support a quicker development at earlier stages before transitioning to an anaerobic state for alcohol production.

It should also be noted that the use of pure oxygen must be managed carefully in operational environments, especially those with flammable and explosive material such as alcohols or dust. With higher concentrations of oxygen, the risk of ignition, fire and explosion is greater and a full hazard analysis must be conducted before considering its use to mitigate and manage the gas very carefully.

Financial summary

The project was delivered within budget with the desired outcomes achieved. The below charts demonstrate the change in spend profile from planned to actual following the completion of the project. The headline titles are indicative of the contents and the detail of each spend category was shared directly with DESNZ. Total planned spend was £2,944,778. Total actual spend was £2,944,770.



The planned spend was budgeted over the course of Phase 1 during 2021 and the project was awarded in 2022. Significant negative variances from planned spend through to actual were System Components (£405k) and People and Project Management (£177k). Positive variances were Electrolyser Design and Fabrication (-£386k) and Process Design (-£179k).

These variances can be explained with a combination of macro scale events and internal project management decisions throughout the course of the project.

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System Components were subjected to significant cost increases largely due to the Russia-Ukraine conflict. The conflict, which began in February 2022 pushed natural gas and nickel prices up. The price of nickel also saw a record rise due to nickel market dynamics following the initial rise.

Other cost variances were the result of project alterations during the project lifetime. For example, 'Process Design' as a specific work package was removed and efforts were split out between People and Project Management. Moreover, a significant amount of 'Electrolyser Design and Fabrication' costs were re-allocated to 'System Components' to account for the market change in the supply chain.

Over the project delivery period, the project team worked closely with government to appropriately tackle both large macro market challenges as well as more project specific challenges with optioneering and re-planning to ensure that the end outcomes were achieved despite the specific originally drafted plan being challenged.

Benefits and Dissemination activities

H2 Production Benefits

- Supercritical's technology can operate at unparalleled system efficiencies as low as 42 kWh/kgH₂ for the delivery of 220bara hydrogen at >99% purity, offering a route to the lowest cost of pressurised green hydrogen
- The electrolyser operates at such high electrical efficiencies due to its operating conditions and unique membraneless design, minimising waste, minimising cost
 - Intermediate temperatures improve the kinetics
 - Membraneless design minimises ohmic resistances in the cell
 - High pressures remove bubbles
- Other electrolyser's inefficiencies become Supercritical's efficiencies - Supercritical benefits from the heat generated through electrical inefficiencies, minimising waste, minimising cost
- High current densities can be achieved by exploiting the bubble-less nature and high mass transport rates of the high-pressure fluids, minimising footprint, material requirements and CapEx and maximising output
- Supercritical delivers both hydrogen and oxygen across the battery limit at 220 bara - reducing the need for expensive and higher risk compressors, minimising capital cost and increasing uptime (note oxygen can be let down and vented safely if not required)
- Operates with zero scope 1, and scope 2 emissions when exclusively supplied with renewable power
- Operating conditions drive materials of construction towards high performance nickel alloys for the electrolyser, this can result in a higher capital cost per unit mass of material needed, however this is offset by excellent anticipated in-life durability, high current densities (minimising size of unit) and high recovery of materials at end of life, resulting in a leading levelised cost of pressurised hydrogen
- Unparalleled in life reconditioning capability and end-of-life recycling capabilities - given its no membrane, no PFAS (forever chemicals), all metal design, the Supercritical electrolyser can be almost entirely recycled ensuring minimal negative effect on the environment in addition to its zero-carbon operation capability, putting the environment first, optimising material utilisation and minimising cost

H2 Utilisation Benefits

Zero emission hydrogen direct firing offers a unique opportunity to revive traditional practices that were once core to crafting Scotland's world-renowned spirit. Over recent decades, the method of delivering heat in a distillery has become increasingly standardised with steam heating delivering reliable, consistent heat to the process. Until the 1950s / 1960s, most of the whisky was produced by direct coal firing.

As distilleries were modernised, this practice was largely replaced with indirect steam heating and with the introduction of the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) in late 2002, the direct firing practice has been all but removed, with the exception of a handful of compliant, pressurised gas direct-fired stills.

This direct flame against the copper stills meant that the still and spirit saw a wide variety of temperatures creating conditions that cannot be produced with steam heating. It is a part of the process that is thought by many to offer a unique character and flavour to the finished product.

Hard to abate sectors like the whisky sectors and others that use fossil fuels for heat today will struggle to decarbonise through electricity alone. The sector

- wants high grade energy on demand
- has highly variable energy demands requiring high energy supply flexibility
- is made up of large energy consumers
- has 24/7 operations, therefore seasonal variations in supply cannot be tolerated
- needs the system response time to be directly comparable to existing systems
- ideally needs energy bills to be the same as their fossil fuel-based energy
- benefits from high pressure hydrogen to minimise storage space on-site

Supercritical's technology has the potential to deliver green hydrogen at fossil-competitive prices at scale, whilst meeting the needs of industrial heat users like whisky distilleries.

Dissemination

Past

Over the course of the project, all partners have been highly vocal about the project, shared the benefits and disseminated findings as they have become available. Media used has extended from social posts to newsletters and press releases, supported with imagery and videos and complemented by blogs. Conferences have been attended in the whisky and drinks sector as well as in the energy and hydrogen space and the manufacturing environment, with each partner disseminating their findings to their respective sectors. Below are a few memorable events that the WhiskHy team have driven throughout the project.

STEM Outreach

Supercritical's engineers went out to Ellen Wilkinson School for Girls to talk to students about the choices in education that got them to where they are today and what they are doing on a daily basis to help enable green hydrogen at scale.



Institute of Brewing and Distilling Lifelong Learning Day

Alistair Leckenby and Luke Tan presented to the IBD's passionate lifelong learning group to share findings from WhiskHy and learn more about how the industry is driving to be more sustainable.



HazardEx Live 2024

Titilola Oliyide, Senior Process Safety Engineer, presents Supercritical's process at HazardEx Live 2024. A Process Safety and Hazards event where experts convene to share learnings.

TS1 Ministerial Visit

The Minister for Energy Efficiency and Green Finance, Lord Callanan, visited Supercritical's Teesside facility in late 2023. A promotional video and press release were released following the visit.



Planned

In late 2024, following project completion, Suntory Global Spirits will host a formal casking ceremony for the world's first direct hydrogen fired hydrogen whisky. Ministers from the Department of Energy Security and Net Zero and national and industry press will be invited to attend along with the project partners. The gathering will be a celebration of British technology and perseverance towards decarbonisation of hard to abate sectors. The partners will share their findings, and the hydrogen fired whisky will take pride of place at the Glen Garioch distillery next to King Charles' royal cask for all to see during future tours of Glen Garioch, where Suntory Global Spirit's direct fired and hydrogen firsts in innovation will be a permanent fixture of the historical tour.

Lessons learnt and barriers

Project Lessons Learnt

- Raw material price fluctuation can have significant consequences on project delivery capability. The natural gas price and nickel price soared to 3 times the price that the project was budgeted at (difference between 2021 and 2022). The way that projects are budgeted (without contingency) does not leave scope for variation in material costs.
- Geopolitical instability can have long reaching consequences. When Russia invaded Ukraine in 2022, supply of nickel and of metal products was heavily disrupted, forcing lead times to dramatically increase.
- Estimates on project delivery for novel systems, whether in process engineering design, mechanical design, mechanical build, control / electrical design and build are regularly underestimated. The novelty and complexity in the unknown extends delivery times and puts pressure on project timelines.
- A 'one stop shop' in engineering for design through to operation has its pros and cons.
 - Pros: there is continuity of knowledge within the core team, it can be more cost effective as there is less 're-learning', it can be faster, it is 'easier' to go back to check things from previous stages of a project.

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- Cons: it opens the risk of phase creep – starting the next phase prematurely has a tendency to produce poorer paperwork and outputs if not managed well, it can result in poor performance due to lack of competition.

The lesson learnt is that if one opts to seek the 'one stop shop' approach for the pros, then the project needs to be closely managed to avoid the cons, ensuring that the partner is held accountable for the phased deliveries and that mechanisms are in-place to ensure this.

- Determination and out-of-the box thinking from project partners and flexibility from the funding body can yield fantastic results when challenges to project delivery are met. The direct firing trial re-assessment following supply chain and geo-political challenges is a case study of how to remain focused on the outcomes, and to maintain a degree of flexibility in the journey to achieve those outcomes.

H2 Production Lessons Learnt

- Efficiency scales. Supercritical's scaling and testing of the 2.1.1 variant of their electrode architecture whilst achieving up to 95% of lab scale testing demonstrates the potential of their novel technology at larger commercial scales.
- Safe gas compositions can be achieved out-of-lab. Achieving safe hydrogen and oxygen compositions in early testing on the multi-cell V1 module is a fantastic earlier indicator of the scalability of Supercritical's membraneless technology.
- Stacking membraneless cells is viable. The operation of multiple cells simultaneously whilst maintaining performance and minimising gas cross over is a testament to the ability for this cell architecture to stack – a key feature required of electrochemical technologies at scale.
- Heat is key. Heat plays a significant role in Supercritical's electrolyser's ability to achieve the efficiencies that it does. Mismanagement of the heat in the system can discount that benefit significantly. Testing has shown that through testing, heat retention is even better than was previously modelled.
- Manufacturing of larger componentry has proven successful whilst maintaining a route to scale production. By selecting established manufacturing techniques from other industries, Supercritical has de-risked the supply chain that incumbent electrolyser technologies face and has a clear route to scalability. Lesson is to think about commercialisation from day one and try not to stack novelty (i.e. don't use an invention in manufacturing to build an inventive design).
- When taking novel technology out of a lab environment for the first time, there are regularly more questions than there are answers. The approach to process design is deliberately holistic and seeks to design from well-defined criteria. The Hazard Study process is rightly designed to identify and quantify all potential hazards. When designing a system that has not been operated at the scales proposed, and with a new reactor design, the process of design can be long. Supercritical and its partners spent significantly more time than originally anticipated. The result is a very safe, well-designed rig. The test results are extremely positive and form a brilliant foundation for future testing. The lesson learnt is not to take a different approach, but to respect the time it takes to do things right and plan for that.

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- Change is more challenging the bigger you get. As a start-up, operating predominantly in the lab before this project, Supercritical was used to operating in an extremely nimble way. Implementing new ideas very quickly. As you get bigger, the hazards are greater and systems are more complex. More people are involved and change control and formalisation of decisions is ever-more important. Make as many decisions as you can at the smallest scale you can to save time and costs.

H2 Utilisation Lessons Learnt

Lessons Learned at Glen Garioch

- The current UK supply chain for Hydrogen as a fuel source is limited in capacity and extremely expensive when comparing £/kWh to natural gas.
- The equipment requirements for demonstrating hydrogen as a fuel in the UK are significant in cost and complexity.

Lessons Learned at Yamazaki

- The ability to supply hydrogen for smaller applications (for this trial) were much more straightforward as this utilised cylinder/Multi-Cylinder-Packages, as opposed to tube trailers or liquid storage.
- The NO_x levels recorded during the trial ranged from 200-230ppm, which is above the allowable emissions rate at Yamazaki (although this was pre-approved for the trial). Any future retrofit of H₂ into existing equipment may need to consider NO_x abatement for more permanent fuel switching.
- The principle of using hydrogen as a fuel for direct firing has been proven to technically work well without H&S concern. With more time, and more hydrogen, it would be beneficial to see if adjustments to burner settings could be leveraged to maximise Maillard reactions (i.e. drive furnace temperature higher).

Project Impact and Follow on/route to commercialisation

TS1 Deployment - Auchentoshan

Auchentoshan Distillery

Auchentoshan new make spirit is the highest strength distillate produced by any Single Malt distillery in Scotland, due to its triple distillation process. Because they distil away many of the heavier congeners in the liquid, strong notes of fruit and citrus come through. It also makes the spirit more prone to the epic woodiness that comes from the casks in maturation. This makes Auchentoshan the smoothest, most delicate tasting Single Malt Scotch whisky.

Auchentoshan heats its three stills with steam, which is raised by burning natural gas sourced from the grid. As part of Suntory Global Spirit's ambitions to be carbon neutral by 2040, they have been exploring the option of full decarbonisation of Auchentoshan with green hydrogen.

Phase 3 – Deployment at Auchentoshan

It is proposed that TS1 is re-located and moved from its current location in Teesside, to Auchentoshan Distillery. The hydrogen produced by TS1 will be supplied via a new manifold to facilitate injection of the hydrogen into the main fuel supply line to the distillery's burner. This will provide a dual fuel supply to the burner in a composition that is to be determined. It is assumed that for the purpose of this phase, oxygen will not be a useful product and oxygen will be safely vented. It will be essential to ensure that sufficient fuel is supplied to the burner at all times to minimise disruption to distilling operations. A strategy to ensure this will be developed.

There will be minimal planned changes to the design of the hydrogen plant (electrolyser system), with the majority of changes expected to be those along its battery limit, tying into the feedstock, utilities, receiving equipment and waste stream disposal sites. TS1 has an upper capacity of up to 3 kgH₂/day. The WhiskHy team must ensure that design basis equivalence can be largely achieved and ensure that any changes are captured by difference to the existing, with relevant amends and hazard studies conducted as appropriate. Assessment of the risks of siting TS1, its ancillary equipment and any new equipment to facilitate the injection of hydrogen into the gas will be conducted.

The goal will be to run 5x 1000h trials over the course of a 12-month trial period.

Operating Philosophy

The plant will operate against a set of pre-defined operating protocols. Existing protocols exist for TS1, and these will form the basis of those to be used at Auchentoshan, with relevant amends being made as required. Given the trial nature of the facility, it is anticipated that these tests will be run in weeks or months blocks. Whilst running, it is assumed that the hydrogen plant will operate 100% of the time uninterrupted, with certain parameters being changed to evaluate the consequences in the system. Flow to the downstream steam boiler will be managed by a hydrogen delivery manifold. The manifold will mix the hydrogen with the existing natural gas fuel and will control the flow of natural gas to ensure that sufficient fuel is delivered to the burner.

Auchentoshan has recently installed a new boiler. The manufacturer of the burner installed claims that the burner is hydrogen capable up to 20% in natural gas feed. For 100% hydrogen burning, a new burner would be required however the boiler could continue to be used.

TS1 has been designed for operation by trained operators. For safety reasons, and to restrict lone working, during operation 2 operators will be required at all times when operational.

Plant Layout

The electrolyser module and associated balance of plant equipment will be contained in a pre-fabricated blast enclosure. The control room will be containerised and the feed electrolyte and any associated utilities will be co-located but likely outside of the enclosure.

General layout and tie-in points to supply utilities, product streams and waste locations for any waste product are to be determined.

Suitable locations for the electrolysers deployment include two neighbouring fields by the facility (which are owned by Suntory Global Spirits) and the boiler house.



Figure 37 - Potential sites for TS1 trial deployment 1 & 2 are fields owned by SGS. 3 is the boiler house.

Requirements from Insurer

A requirement for the trial to go ahead for Suntory Global Spirits is to ensure that adequate insurance is in place and to qualify that their insurer is comfortable with the potential risk of the installation. The following represents a preliminary list of requirements to satisfy the insurer for this proposed 3rd Phase of WhiskHy:

- Process description (summary of) and how this will be integrated at Auchentoshan
- Management of Change analysis done by Suntory Global Spirits including the risk analysis
- Safety concept regarding the solution
- Material / piping design
- Process safety interlocks to detect hazardous deviations: over-pressure, low or high temperature, power supply, H₂-O₂ gas cross-over, etc.
- DSEAR compliance
- Pressure relief and venting system
- Fire (flame detectors) and H₂ gas detection provisions
- Ventilation vs maximum H₂ leakage rate if installed indoor
- Automatic emergency shutdown actions triggered when:
 - The ventilation system is not properly functioning
 - A fire detector or a hydrogen detector is triggered
 - High H₂-O₂ gas cross-over is detected in the H₂ stream
 - An operational deviation occurs in the process

The list of requirements is considered achievable by the WhiskHy team with some additional work and modifications to the system ahead of transferring the equipment to Auchentoshan. The WhiskHy project looks forward to the opportunity to facilitate this.

Memorandum of Understanding

Supercritical and Suntory Global Spirits remain committed to accelerating the decarbonisation of the distillery sector and have signed a Memorandum of Understanding to further this ambition to commercialise the technology. The partners agree to continue to pursue opportunities to further advance and test Supercritical's electrolyser technology and to continue to support each other in understanding around hydrogen technology and industrial requirements. The two will continue to share their story far and wide and encourage the industry to embrace new ways of decarbonising as they have done throughout their partnership to date.

This publication is available from: www.gov.uk/government/publications/green-distilleries-competition

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