BEIS Green Distilleries Competition - Phase 1 Report

Lead Applicant: Supercritical Solutions Ltd

Project partners: Beam Suntory, Xodus Group, Centre for Process Innovation, DNV.

www.supercritical.solutions

Glossary

Abbreviation	Explanation
BEIS	Department for Business, Energy and Industrial Strategy
CCL	Climate Change Levy
CFD	Computational Fluid Dynamics – AKA computer modelling
CfD	'Contracts for Difference'
CO_2	Carbon dioxide
COMAH	Control of Major Accident Hazards
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
Electrolyser	Equipment to separate water into Oxygen and Hydrogen using electricity
ENVID	Environment Identification
EPC	Engineering, Procurement and Construction
EV	Electric Vehicle
FEED	Front End Engineering Design
GHG	Greenhouse Gas
H_2	Hydrogen
HAZOP	Hazard Operability Study
kWh	kilowatt hour
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
NG	Natural Gas
NOx	Nitrogen oxides
NPL	National Physical Laboratory
O_2	Oxygen
PEM	Polymer Electrolyte Membrane
SOEC	Solid Oxide Electrolyser Cell
TC	Test Cycle - a number of tests and iterations within a fixed scope of testing environment or set of boundaries
TRL	Technology Readiness Level
Whisky	In this report is a (40% abv) product for consumption
WP	Work Package

Executive summary

Whisky production is an energy intensive, often remote, 24/7 operation which is heavily dependent on regular truck deliveries of non-renewable fossil fuel for combustion to produce heat. Switching from Liquified Petroleum Gas (LPG) to hydrogen would reduce CO_2e by 615 g per litre of whisky. The proposed pilot would produce 164,100 bottles (70 cl) of zero CO_2 whisky per year reducing annual CO_2e from the distillery by 71 tonnes.

Producing, storing and consuming hydrogen on-site has the potential to be cost neutral with LPG by the end of the decade and cost neutral with natural gas in the UK by 2040, both possibly earlier if carbon taxes are increased above current plans. Producing the hydrogen on-site (or in close proximity) has the benefit of removing the challenging step of transporting the light gas to the distilleries, providing greater independence and lower costs of consumed fuel.

The technology advancement and pilot deployment of the world's first supercritical electrolyser at a 50 kW system at Ardmore distillery is predicted to cost a total of circa £3.6M over 3 years. The investment will accelerate this UK based low-cost hydrogen production technology to Technology Readiness Level (TRL) 5 accelerating affordable decarbonisation in response to the government's policy to achieve Net Zero by 2050, in line with the Prime Minister's Ten Point Plan.

Hydrogen is a carbon-free fuel, which burns at a slightly higher temperature than fossil gases in air and an additional 600 °C in oxygen. The compatibility with existing fossil gases offers a seamless transition for heat response and temperatures. For the reference distillery, there were no technical barriers for the combustion of hydrogen in the existing LPG combustion boiler. The existing boiler can accommodate between 0 - 100% hydrogen with minimal modifications. This dual fuel approach minimises distillery modification costs and enables a gradual transition to hydrogen with a proportional CO_2e reduction to zero.

Electrolysers require at least 9 litres of water for every kg of hydrogen produced. However, through the feasibility study, Supercritical believes that it will be possible to use the distillery wastewater as a feedstock for the electrolyser requiring no addition to the freshwater withdrawals.

With directly connected local renewable energy and on-site hydrogen production, Supercritical addresses the intermittent nature of renewable energy to ensure supply to the 24/7 distillery demand. Supercritical supplies 200 bar hydrogen and stores it in high pressure storage tanks, which inturn feed the boiler, without any need for a hydrogen compressor. Cost and safety considerations regarding hydrogen storage are site dependent but could be a deciding factor in technology choice.

Zero emission whisky could promote the distillery sector not only within the UK but also abroad, acting as a flagship product of Supercritical's green hydrogen technology decarbonising a hard-to-abate sector.

1 Overview of the project

Rising greenhouse gas (GHG) emissions and global warming represent the biggest challenge that the world has ever faced. To counteract the risks that climate change poses, emissions must be reduced to zero and, by some estimations, turn negative. The UK government has set a target of Net Zero by 2050 and the Scottish government aims to exceed that by achieving Net Zero by 2045. In 2018, the whisky industry alone accounted for 1.3% of Scotland's territorial GHG emissions (Scottish Government, 2018).

The Scotch Whisky Association has set itself the ambitious goal of Net Zero Operations for the sector by 2040, to which Beam Suntory is aligned. Cost effective solutions to deliver against these targets are required.

Project WhiskHy will demonstrate the use of low-cost green hydrogen to decarbonise the 19th largest distillery in Scotland, Ardmore (nameplate capacity of 5.5M litres of spirit per annum) (see Figure 1). The deployment of Supercritical's UK developed electrolyser technology will be a world first. It will utilise wastewater from Ardmore Distillery and in the full solution, locally sourced renewable power. Hydrogen will be generated on-site and this will augment the distillery's existing LPG boiler via a dedicated hydrogen line.

Distilleries in Scotland are often located in remote areas, away from gas and electricity grids and so are reliant on delivered fossil fuel as an energy source. The use of LPG at Ardmore as a fuel source has achieved around 25% decarbonisation compared to more traditional heavy fuel oil but will never offer a zero GHG solution. Scotland, benefitting from abundant renewable resources (wave, tidal, offshore wind and onshore wind), could lead in the deployment of decentralised on-site green hydrogen production using water electrolysers. The use of hydrogen fuel as a replacement for LPG is an attractive option for decarbonising the distillery sector. However, due to electrolyser costs and efficiencies, the near-term cost difference of fuels remains a major barrier to fuel switching.

At commercial scale, it is anticipated that Supercritical's electrolyser will perform at >85% electrical efficiency, but at lower temperatures than Solid Oxide Electrolyser Cell (SOEC) and whilst delivering a high-pressure product suitable for direct storage. This will be achieved with a proprietary membrane-less design that allows the electrolyser to exploit the beneficial properties of water at supercritical conditions (>375 ^{o}C and >221 bar).

The objectives of this Feasibility Study;

- Deliver an implementation plan for a Phase 2 pilot study of a 50 kW Supercritical electrolyser at Ardmore Distillery, including a site plan, environmental impact assessment, technology risk assessment, system concept study, test and validation plan and costed development plan for Phase 2.
- Deliver a technology feasibility assessment that will look at the distinct properties of the technology and its ability to integrate with and decarbonise Ardmore Distillery and consider its applicability on a more macro scale at other distilleries and across other industries in the UK and outside of the UK, including a detailed route to market assessment.

Figure 1. Photograph of Ardmore Distillery, Eastern Highlands, Scotland.

2 Experimental / Modelling Results and Conclusions

2.1 Modelling Full Decarbonisation of Ardmore Distillery

As part of the feasibility study, Supercritical and partner Xodus, modelled the energy flows and requirements to switch from the existing fuel source of LPG to locally generated renewable energy from an existing wind turbine in close vicinity of the distillery (see Figure 2). The objective of the model was to assess the levels of 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.

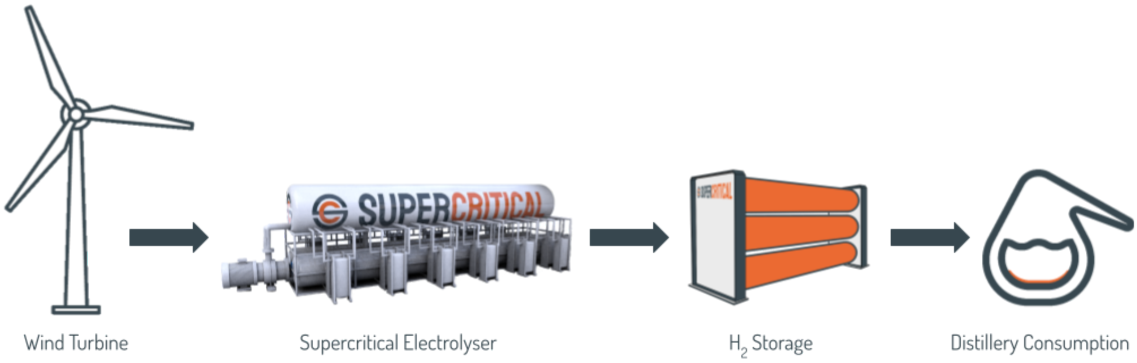

Figure 2. Diagram illustrating energy flow at a distillery.

2.2 Wind

At the reference location, a model was developed by using a full year's energy generated at an hourly granularity (Renewables Ninja - MERRA-2). The net capacity factor for the location was 45% over the year. The longest single period of insufficient wind versus the distillery nominal demand was 230 hours (therefore requiring hydrogen storage)[1]. The model balanced the depreciated cost of H_2 storage capex against the benefits of storing hydrogen and assumed that any electrical shortfall would be met with grid supplied electricity (at green industrial rates). On pure economic terms the optimal H_2 storage capacity from this model was **2.9 days** of distillery demand, which resulted in **1,289 hours** in the year (14.7%) where the H_2 storage capacity was exhausted and backup grid electricity was used.

After a period of low wind and the H_2 storage being exhausted, there needs to be sufficient energy from wind to both meet the distillery demand and top-up the H_2 Storage. To enable this, a larger electrolyser will be required. The model balanced the incremental capex for the electrolyser, against the available 'curtailed wind' and therefore its economic effectiveness (note that this is all one model and H_2 storage capacity is also a factor). The optimal increase in electrolyser size in the model was **52%.**

2.3 Solar and Wind

It would be possible to use both solar and wind in parallel, as a renewable energy source, where typically solar is more productive when wind is less so (spring/summer), resulting in fewer hours throughout the year where the H_2 storage is depleted (see Figure 3).

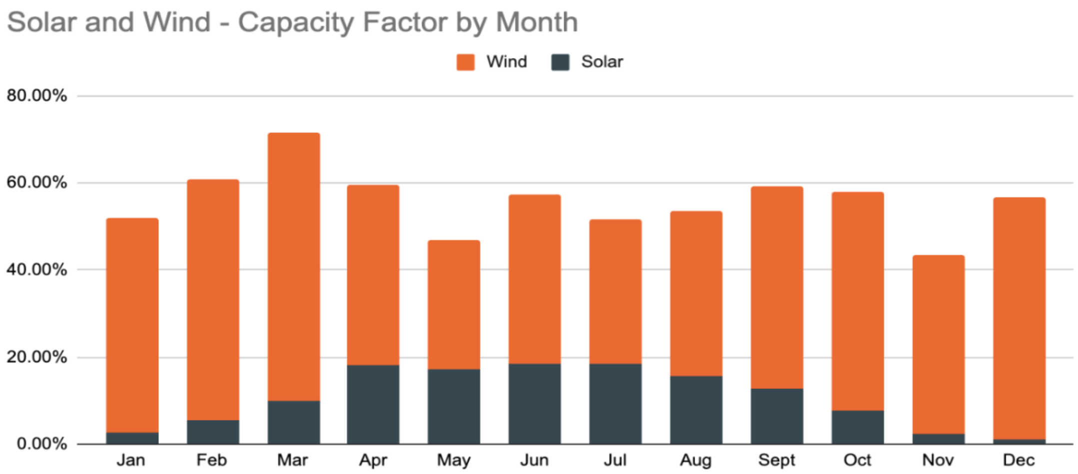

Figure 3. Graph illustrating complimentary capacity factor for wind and solar.

Initial (non-optimised) modelling suggests that keeping the total renewable energy delivered (i.e. accounting for capacity factor) the same as the wind only model will reduce storage requirements. Replacing some wind turbines with a solar array, angled for optimal summer generation, with a wind capacity factor of 45% and solar capacity factor of 11% (Renewables Ninja - MERRA-2). The hydrogen storage requirements can be reduced to 2.5 days and the resulting grid demands reduced to 12.2% of the annual hours (6.98% of the electricity consumed by the solution).

For this model it is assumed that a sufficiently scaled back up grid connection can be installed, and the grid is able to deliver 100% of the demand. Alternative solutions such as

[1] Supercritical assumptions: The high-level analysis was based on an assumed LCOE from directly connected renewable farm via private wire. The hourly data models the level of intermittency and resulting electrolyser and hydrogen storage sizing for the cost model. Wind speed source (MERRA-2 2019 data), turbine capacity (2 MW), turbine type (Vestas V90/2000), 100 m hub height, and indicative generation output (Renewables Ninja tool). The data from a single turbine was used and multiplied to meet full capacity, with assumed linear scaling. The capacity factor was higher than the general expectation for onshore wind in the range of 25-30%. Full location solution would need to be engineered and tendered.

increased renewable systems, or alternatives to compressed gas storage could also be considered.

The 52% larger electrolyser, the 2.5 days of H_2 storage and the 6.98% grid rate electricity were all factored into the cost per kWh of hydrogen calculations.

3 Description of the Demonstration Project

WhiskHy Phase 2 will see Supercritical's proprietary novel water electrolyser enable fuel switching to zero emission sources in the distillery industry. The ultra-efficient electrolyser will deliver a pathway to the lowest cost of production of H_2 and will bring a step change in the technology's development, progressing it from TRL4 to TRL5. The H_2 delivery system to Ardmore's existing boiler can be achieved with a retrofit to the burners enabling co-injection of between 0% and 100% hydrogen, reducing the LPG load. For the distillery, it marks the first step towards enabling a transition to 100% green H_2, expected to be achievable and cost competitive with the existing LPG fuel source by 2029.

The project progresses two key early-stage objectives:

1) Core technology development;
2) In-field demonstration in heavy industry energy systems.

It will provide Supercritical with a model for rapid deployment and decarbonisation in the whisky sector and act as a live case study for further project development in Supercritical's other key sectors.

4 Design of Demonstration

4.1 Overview of Process

The basic process for the demonstrator is shown below (see Figure 4):

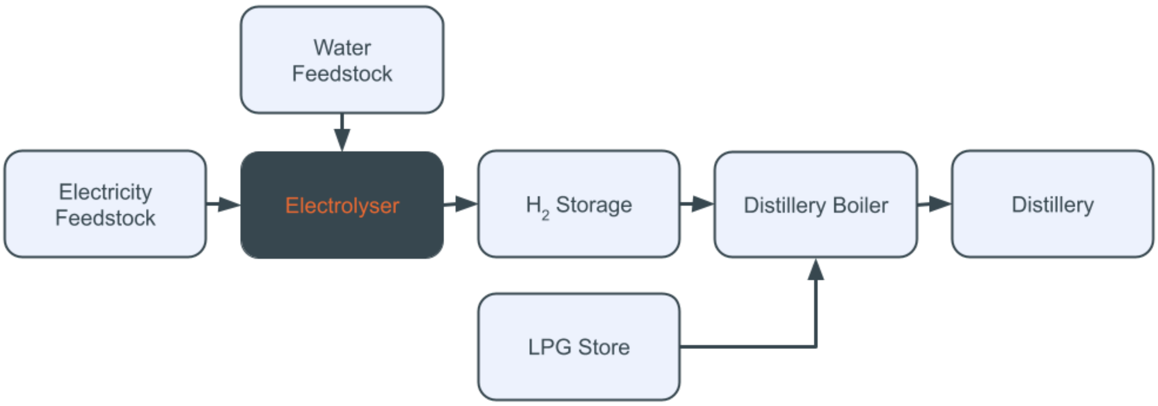

Figure 4. Diagram illustrating the basic process for the Phase 2 demonstrator.

To minimise both cost and timescales for the Pilot, a grid connection at the distillery (green electricity tariff) will be used.

Existing distillery 'wastewater', is believed to require minimal treatment and would not increase the overall freshwater consumption of the distillery and is proposed to be used as the water feedstock. There is believed to be more than sufficient volume at the site for both pilot and full-scale operation.

In addition to the electrolyser, there would be minimal hydrogen storage installed to act as a buffer between the production and combustion processes. This will be stored at the output pressure of the electrolyser (up to 230 bar) and ‘let down’ via regulator to the combustion boiler. For the pilot, the produced oxygen would be vented, however on-site uses for the oxygen will continue to be explored, potentially utilised in the on-site organic wastewater treatment (either as a gas or sodium hydroxide/oxygen/water mix).

The distillery combustion boiler will require minimal modifications to accommodate the hydrogen feed, in addition to the LPG currently used on-site. The boiler control systems will require minor updates to reduce LPG feed based on the temperature sensors, therefore adjusting to the delivered hydrogen feed automatically.

No modifications or behaviour changes to how the distillery operates are required nor will there be any effects to the whisky product quality.

4.2 Technology Development

A core priority of Supercritical is to optimise the balance of catalyst activity, operational lifetime and the cost of the materials and components of the system. Such an ambition will involve exploring the electrolyte to maximise conductivity while minimising the corrosive environment, assessing a range of alloys and/or coatings for both catalyst and reactor housing and developing facile catalyst production methods that can be affordably scaled for mass production.

The existing cell will be physically enlarged and electrochemically optimised, while in parallel, a multi-cell module arrangement will be designed and tested. It is anticipated that the design and test cycle will require at least three iterations before baselining the pilot demonstration specification. Design reviews with a multifunctional team to consider safety, performance, cost and manufacturability will take place prior to each iteration where at least 10 minor variations in component design will be built and tested.

The above will be supported by Computational Fluid Dynamics (CFD) modelling, building on the existing model created through a partnership between Supercritical and The National Physical Laboratory (NPL) which has enabled modifications to the design and exploration of theories based on lab test data. Outside of the core electrolyser reactor development, the supporting system will need to evolve including detailed design of the sub-systems.

4.3 System Design Including Sub-Systems

Reviewing the wider system and the equipment involved, the novel electrolyser is supported by well-established equipment that is regularly used in industry, minimising overall system risk and complexity.

Whilst optimising performance, safety is of paramount importance. High temperature and high-pressure conditions with hydrogen and oxygen present potential hazardous scenarios which need to be mitigated. Iterative design, material and system control reviews and tests to reduce these risks have been scheduled, taking into consideration safety, performance, durability and cost. To that end, Supercritical is in in-depth discussions to lead development in partnership with specialists for critical aspects of the technology to expedite the optimisation and build of the 50 kW electrolyser.

Equipment for the wider system such as heat exchangers, pumps and vessels will be sourced externally rather than developed. Leading UK suppliers have been identified and indicative prices have been sought for later stage system integration. The full system will be amalgamated with a detailed concept study and Front End Engineering Design (FEED) study led by our Engineering, Procurement and Construction (EPC) partner, a company who have successfully completed multiple pilot hydrogen systems in recent years.

4.4 Site Plan

The site plan focused on investigating potential locations for the pilot system and to consider the layout and the risks associated with the electrolyser, hydrogen storage (~16 kg worth of hydrogen production) and the piping route of each. For the pilot plant, hydrogen is being fed into the boiler to demonstrate hydrogen as a replacement for the LPG fuel stock used to generate steam for heating the stills. Hydrogen will not be physically blended with the LPG fuel for the pilot project, instead it will use separate burner heads. Two sites have been identified as possible locations for the pilot system;

1. The outside area west of the boiler house
2. The forklift truck building, east of the bio plant

Given that the technical equipment footprints are still in development, only the total footprints have been assessed. Both sites have a range of advantages, disadvantages, risks and unknowns. Based on the assessment, Site 1 is the preferred option due to the following reasons:

a) Total system is located outside (inherently safer);
b) Likely the lower cost and the simplest option (less piping, less risk of IIC T1 ex-rating equipment upgrades needed);
c) Furthest away from warehouses (large hazardous ethanol inventories);
d) Safest pipe routing option.

There are several system requirements that are yet to be specified and site constraints that may change or rule out the site location(s) suggested.

The key criteria that may influence the site selection and layout in subsequent project stages are as follows:

i) Pilot system size (final equipment footprints and system hydrogen inventory);
ii) On-site storage (requirement, final inventory);
iii) On-site IIC requirements (current equipment status, scale of upgrades required);
iv) Ardmore Hazardous Area Classification and mitigations (Zone classification and required protection methods);
v) HAZID and any interactions with the current Ardmore COMAH case and Hazardous Area Classification.

4.5 Validation Overview

The test and validation plan will be driven by the standards and methodologies selected during the detailed design and incorporated into an evolving plan. Once a definitive list of technical standards and criteria have been agreed, the relevant design and testing criteria can be integrated into the plan, however until that level of detail has been agreed, it is not possible to define what the testing will physically look like.

5 Benefits and Barriers

5.1 Environmental Assessment

5.1.1 Greenhouse Gas Emissions Assessment

The feasibility study investigated the potential carbon savings brought about by an increased use of hydrogen in the fuel mix in the UK distillery sector, as well as environmental and social impacts for the pilot and full-scale system.

The 50 kW hydrogen pilot scale system is expected to deliver approximately 1% reduction in CO_2e emissions from the distillery, which would enable the production of 164,100 bottles (70 cl) of whisky per year with zero carbon emissions from the distillery. The emission reduction based on the percentage of hydrogen in the LPG fuel mix is shown in Figure 5. The calculations were based on the following assumptions:

- Existing LPG use in the distillery: 4,800 litres of LPG per batch
- Average number of batches per year: 968
- Energy content of hydrogen vs LPG: 33.3 kWh/kg vs 12.6 kWh/kg (**LHV**)
- The UK Gov GHG Conversion Factor for LPG: 1.55537 kg CO_2e / litre (BEIS, 2021)
- Annual whisky production on-site: 4,700,000 litres of spirit

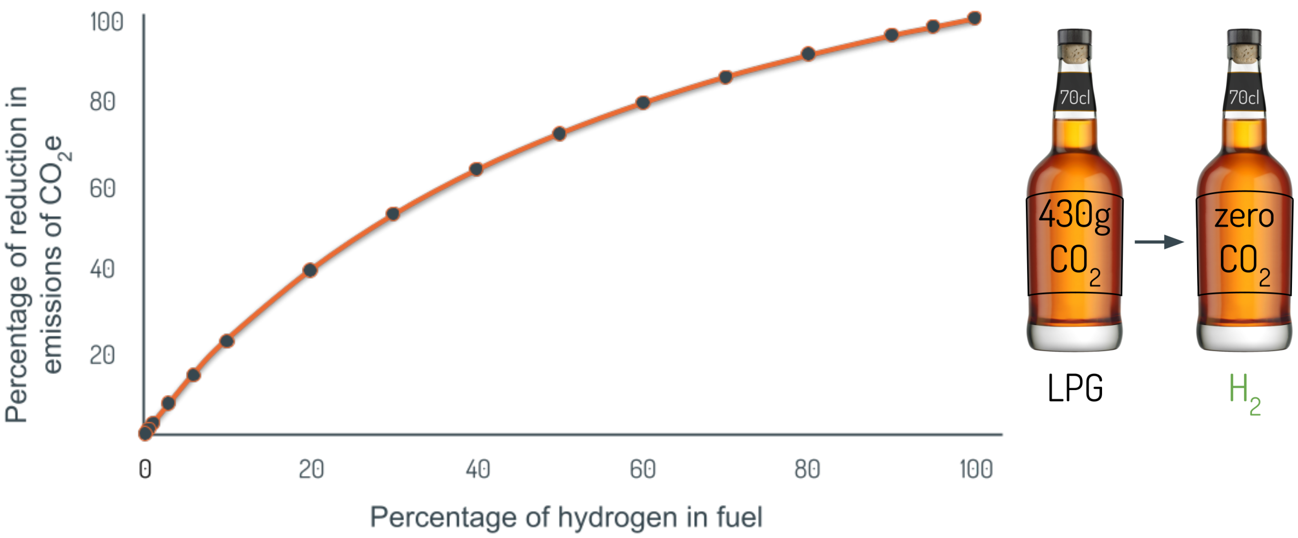

Figure 5. a) Percentage reduction in CO_2e with an increase in percentage of hydrogen in the fuel mix (based on mass). b) CO_2e from a bottle of whisky using LPG and 100% green H_2.

Based on the assumptions stated above, the existing carbon footprint of the distillery from the LPG use is 7,223 tonnes of CO_2e per year (using **1 kg of green hydrogen would abate 7.07 kg of CO_2e**). If the hydrogen system was scaled up to completely replace the LPG system, all 7,223 tonnes of CO_2e would be abated. To estimate the CO_2e abatement potential of the Supercritical electrolyser, this estimation was scaled up across the UK whisky distillery sector (data was available only for the Scottish whisky distilleries).

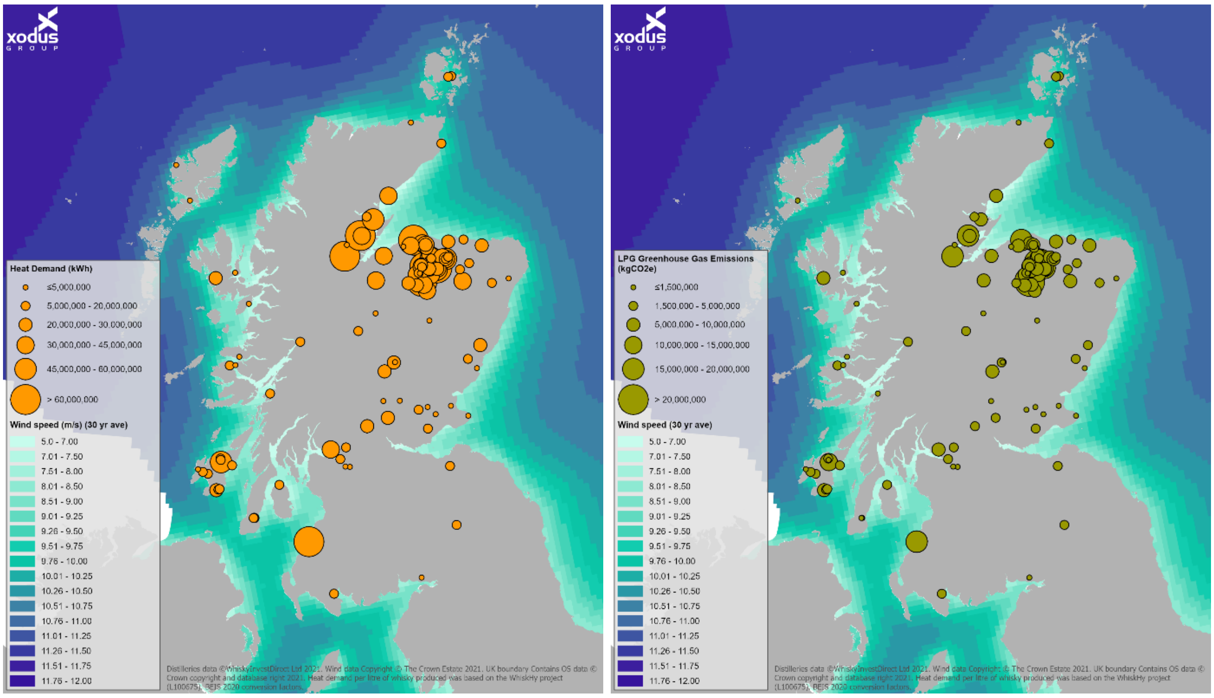

Figure 6. (Left): Heat demand (kWh) across the Scottish whisky distillery sector and average wind speed (m/s); (Right) CO_2e footprint from LPG across the Scottish whisky distillery sector and average wind speed (m/s)

Figure 6 shows the distribution of the whisky distilleries across Scotland and their corresponding heat demand and CO_2e footprints. The results are based on their maximum whisky production capacity per year (Whisky Invest Direct, 2020), and the Ardmore results per litre of whisky produced: heat demand (7.24 kWh/litre of spirit) and CO_2e footprint per litre bottle (615 g of CO_2e / litre of whisky). Based on these assumptions, the heat demand of the Scottish distillery sector was assessed to have a total emission footprint of 606,011 tonnes of CO_2e, equivalent to approximately 1.5% of Scotland's territorial GHG emissions in 2018 (Scottish Government, 2018). It should be highlighted that the CO_2e footprints assume the use of LPG[2].

Figure 6 also shows offshore wind resources in Scotland to outline which distilleries are most suitable to use offshore wind generation to supply the electrolyser system with renewable electricity.

5.1.2 Impact Assessment

An environmental aspects identification (ENVID) workshop was conducted with experts from Xodus. The objective of the ENVID was to identify the actual and / or potential environmental aspects associated with the installation and operation of the electrolyser, both at pilot and full scale. The scope of the ENVID covered six topic areas:

1. Discharges to water
2. Physical presence
3. Atmospheric emissions
4. Waste
5. Resources
6. Accidental events

[2] The actual CO_2e footprint would be approximately 14% lower for distilleries using natural gas and 25% higher for distilleries using fuel oil due to different CO_2e conversion factors. It should also be noted that these estimates are based on the maximum production capacity of distilleries, rather than actual production. The results are therefore only indicative as the high-level assessment did not consider what fuels are used within individual distilleries, nor what their current actual whisky production outputs are.

Within each topic area a list of potential environmental hazards was considered. It should also be highlighted that the hazards may differ for other distilleries based on their site and location.

It was concluded that the pilot project would have minimal impacts on the key areas as it is expected to be fabricated off site, transported to site within a container, and installed within the existing site layout. It is unlikely that there would be any changes to the current distilling process as limited hydrogen is going to be used at the pilot scale. It is therefore unlikely that the pilot plant would trigger a major amendment to the site environmental permit. However, in the next phase of this project the regulator should be engaged, and this assumption confirmed.

5.2 Customer Value Proposition

The Supercritical system is competing for a market dominated by fossil fuels and therefore the customer expects any new system to behave and cost like their existing systems, namely the customer:

- Wants high grade energy on demand
- Is a large energy consumer
- Operations are 24/7, therefore seasonal variations in supply can NOT 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
- High pressure hydrogen to minimise storage space on-site

The Supercritical electrolyser can achieve these factors in addition to:

- Zero carbon emission in the production of hydrogen and in its combustion/use, saving **615 g of CO_2e** per litre of whisky production (based on replacement of LPG as a heating fuel).
- Local generation and storage of energy in hydrogen, removes the need for tanker deliveries of fossil fuels (note, some customers will be on the natural gas grid), improving reliability of supply and reducing the CO_2e emissions from transportation of fuels (quantification is out of scope of this study).
- Local energy storage in the solution minimises drawing electricity from the grid, when renewables are not delivering the required demand.

In addition, regarding whisky quality, zero emission H_2 direct firing offers a unique opportunity to revive age-old practices that were once so core to 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 more efficient indirect steam heating and with the introduction of the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) in late 2002, this 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's a part of the process thought by many to offer a character and flavour that cannot be replicated without it.

5.3 Cost Comparison

Supercritical believes that exceeding 90% electrical efficiency in the electrolyser is possible (the theoretical maximum with water feedstock, is 100%). At 88% efficiency, to produce the same amount of hydrogen a Polymer Electrolyte Membrane (PEM) or Alkaline electrolyser will need to be 40% larger (on a kW basis) and will use at least 15% more renewable electricity.

The Supercritical system has a projected energy generation cost as low as 4.8 pence per kWh (£1.59 /kg of H_2) if produced, stored, and consumed at the customers location from directly connected renewable electricity (assumed £26/MWh), which is comparable to today's fossil hydrogen generation price (at point of consumption) but with zero emissions, saving 10 kg of CO_2e per kg of H_2 produced.

Based on projected capex per kW for the electrolyser and with known UK Climate Change Levy (CCL), we expect hydrogen produced with Supercritical electrolyser, to be **comparative in UK cost per kWh of LPG and heavy fuel oil**, **by 2029** and 48% cheaper by 2040. The UK benefits from the low costs for natural gas and therefore the **UK cost parity per kWh for Natural Gas is predicted around 2040.** These dates will be accelerated if the UK government increases CCL above the current planned levels (or incremental Carbon Taxes) and/or introduces incentives such as Hydrogen 'Contracts for Difference' (which transformed the offshore wind industry).[3]

Co-locating demand, storage, and consumption eliminates energy transport costs and energy losses. Transporting hydrogen is a challenge and represents low 'yields per vehicle', increasing any transportation costs compared to existing fossil fuels. Hydrogen pipeline or non-gaseous transportation could improve transport economics.

The WhiskHy project will prove that cost competitive green hydrogen can be achieved through on-site production and can displace existing fuels in a staged approach, without affecting the high quality of the whisky produced. For heat, existing burners and boilers can be upgraded for a minimal cost for dual fuel capability and over time phased to 100% hydrogen.

The normal expected operating life of a boiler in this industry is 30-40 years when well looked after, with burners requiring replacement every 15 years. Considering this cycle, it would be pertinent that the next boiler replacement for any given distillery be built to be hydrogen ready to meet net zero goals.

5.4 Process Risks

The major process risks associated with the process have been grouped into two main categories: 1) pressure and temperature and 2) flammability and explosion. In order to mitigate these risks, a comprehensive approach to safety and risk is proposed. Together with CPI, Supercritical will hold design reviews prior to each test iteration in which a full safety assessment will be undertaken. As the project progresses through pre-FEED into FEED, the select EPC contractor will be engaged to expand on the functions of the assessment team as we fulfil Hazard Studies 1 and 2. As we approach detailed design for the wider system, the EPC contractor will lead the HAZID / HAZOP and follow through with all risk management through to commission.

[3] Assuming fossil fuel cost increases of 3% per year, BEIS growth assumptions and prices and full application of known Climate Change Levy, without discounts. Representative only and actual costs will vary.

5.5 Process Scale-up Against a Counterfactual

Supercritical's electrolyser technology will scale in a similar modular manner to existing electrolyser technologies like alkaline electrolysers. Alkaline electrolysers are considered as a counterfactual for comparison as they are the only electrolyser technology to have reached full commercialisation and are being deployed and funded at scale today. With the cost for renewables dramatically dropping in the last few years this has enabled >35 GW of electrolyser capacity announced for deployment globally before 2030 (UK Hydrogen and Fuel Cell Association, 2021).

Numerous parallels can be drawn against Supercritical's technology and traditional alkaline electrolysers. Supercritical's proprietary design uses an alkaline electrolyte but differs in operating conditions. According to Schmidt et al (2017), between 1956 and 2014, the learning rate for alkaline electrolysers was 18±6%. A significant amount of the learning achieved, and capabilities demonstrated through alkaline electrolysis commercialisation will benefit a much faster rate of deployment of Supercritical's technology. Pairing that with the wider macro environment that is creating demand for large scale electrolysis, it is predicted that a commercial product could be developed by as early as late 2024.

Each module will be optimised for performance, durability and cost, and will be deployed in arrays to scale to required capacity. With these modular electrolyser units, economies of scale in the electrolyser componentry and module manufacture can be achieved by standardising across all markets. When considering ever larger sites, cost benefits through optimal sizing and procurement of supporting equipment will enable cost downs on a system level. The power system, regardless of the site and power source that it is connected to, will be directly comparable to those of existing alkaline electrolysers and therefore already overcome as a technical barrier.

With so many like-for-like comparisons in scaling the technology, it is pertinent to consider the differences: high temperature and high pressure, and the architecture enabling production and separation through proprietary flow driven cells, for which commercial comparators are readily available. There is wide precedent for temperature and pressure management. Supercritical water reactors are becoming increasingly common due to the beneficial properties of the fluid. Design and safety considerations can and will be taken from these references. An industrially comparable process operating at high pressure, high temperature and with an exothermic reaction being conducted with hydrogen present is found in ammonia synthesis via the Haber-Bosch process, a process that has been operated at world scales for over 100 years.

The design and manufacturing process for the grouping of cells into modules was developed to enable ease of build and service. Though the lifetime of operation is expected to be enhanced compared to alkaline due to the lack of a traditional diaphragm, it is anticipated that maintenance will be an increasingly important cost consideration for electrolyser operators. Supercritical's design allows module repair and individual cell replacements reducing lifetime costs and extending system life.

6 Development Plan

To further develop the design of the new fuel switching solution, there are two distinct sections, the first focused on the advancement of the core technology and the second building a pilot scale system for installation at the reference distillery (see Figure 7).

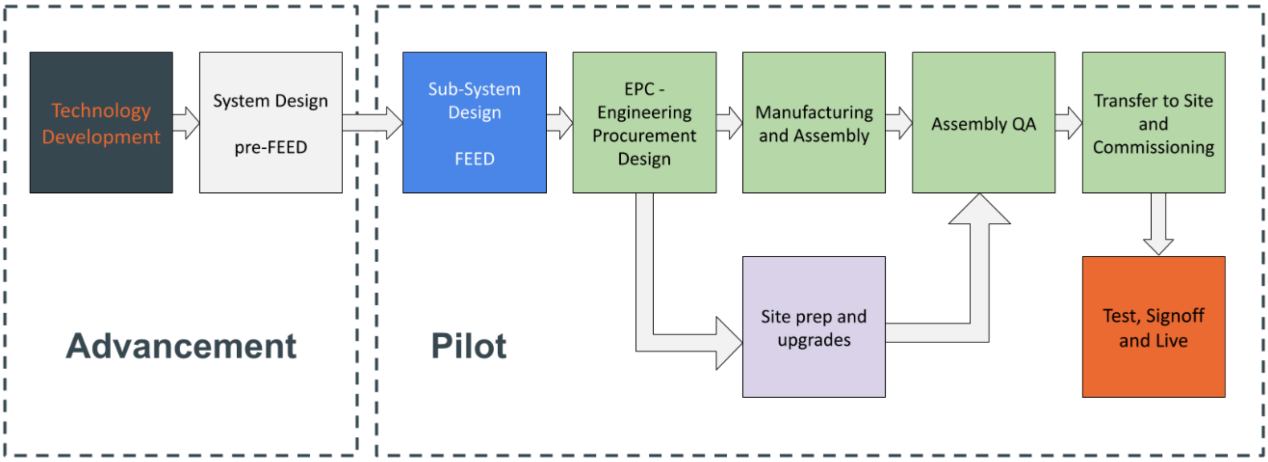

Figure 7. Block flow diagram of the development plan.

6.1 Advancement

The novel development is the electrolyser, currently being tested at cell level in the lab with component optimisation underway. Supercritical will work with multiple centres of excellence in material characterisation and electrochemistry to determine the optimal make-up of the system. The results developed through this research will directly feed into design reviews led by Supercritical's core technical team. Testing of cell and module variants will take place at Supercritical's test facility with design reviews taking consultation from all component suppliers and system stakeholders to ensure manufacturability and operability respectively.

The project cost for this advancement is estimated to be **£1.9million**, with ~53% for subcontractors, ~27% for materials and ~20% Labour costs. >90% of the cost is optimisation of the electrolyser cell, increasing its physical size and performance and developing and testing the multi-cell module.

Milestone Dates:

- Project Start (GD155 Phase 2) - Start July 2021
- Preliminary electrolyser spec defined - Start Oct 2021
- Updated electrolyser specification (post TC2) - Start Feb 2022
- Updated electrolyser specification (post TC3) - Start June 2022
- Pilot electrolyser specification defined (post TC4) - Mid Sept 2022
- Pilot electrolyser 'system full specification' - Mid Dec 2022

Following test cycle 4, it is anticipated that the electrolyser module's operating parameters will be confirmed against previous estimations enabling confirmation of the sizing of the supporting system. CPI will be consulted throughout the Technology Development stages to ensure the pre-FEED Concept Study is progressed without delaying any critical path activities.

6.2 Pilot System Deployed at Reference Distillery

With the 'system full specification' from the Advancement section, an EPC will be engaged. The EPC contractor will progress process safety, mechanical engineering, electrical control and instrument engineering and plant design before completing detailed design and procurement. In parallel, the pilot electrolyser will be built by Supercritical according to the specification defined post TC4 for integration into the resultant skid-mounted pilot facility.

Whilst the procurement and construction are ongoing, specifications and schedules will be supplied for site and civil work to get underway in preparation for the delivered pilot. Upon completion of the build, the demonstrator will be certified for mechanical completion enabling off-line and on-line commissioning to begin.

The existing civil infrastructure will be able to support the demonstrator due to the relative sizes of the existing facility and the pilot. Relevant bodies and regulators will be consulted to confirm this through the early stages of the project to ensure absolute compliance given the changes being proposed. COMAH, DSEAR and ATEX compliance are of highest importance given the nature of the pilot proposed.

External to the electrolyser skid package is the boiler burner retrofit to be carried out by Dunphy Combustion. This burner package will tie into the pilot once off-line commissioning is complete. It may be necessary for the burner retrofit to happen significantly in advance of the electrolyser package, during an existing planned plant shutdown, to minimise distillery downtime.

The skid will be built off-site and transferred to the distillery for integration. As a result of this, the transfer of the system by road will be taken into consideration during the FEED and EPC phases to ensure transit and delivery is feasible. The EPC contractor will manage the transfer and deployment on-site, with Supercritical overseeing the work.

Once re-commissioned on-site, Supercritical will work with Dunphy Combustion and Beam Suntory to begin hydrogen injection into the boiler. For a trial period, green tariff grid electricity will be supplied to the system and hydrogen production and control will be monitored, with hydrogen being stored on a half day basis. With the hydrogen available, as a separate test, hydrogen injection will take place to test the boiler's control system reaction for turn down of LPG supply. If successful on both tasks, an extension of the trial will be monitored with full time operation and hydrogen supply to the boiler.

The project cost for the Pilot is estimated to be **£1.7million**, ~53% for Materials, ~28% for subcontractors, and ~19% Labour costs.

Milestones Dates:

- Project Start - Start Jan 2023
- Detailed Design, Procurement, Construction complete - Start Sept 2023
- Installation at site and commissioning - Start Dec 2023
- Live - Start March 2024

6.3 Business Plan

Supercritical incorporated in June 2020 and has experienced full-time staff who are dedicated to creating products that make a positive difference by decarbonising hard to abate industrial sectors. The founders are committed to commercialising the technology, creating multiple products to address the varied industrial customer segments.

A successful small-scale Pilot at a customer location will progress the technology to TRL5. Supercritical will seek additional private funding as Supercritical builds private investor confidence at higher TRLs, building on BEIS early support.

In order to become commercially viable, Supercritical must improve system costs through economies of scale. This can only be achieved through application of the technology and investment in Research and Development (R&D). We will actively seek additional government funding and partners for further installations, an order of magnitude larger than the initial pilot. The customer/partner will benefit from the hydrogen / oxygen produced and provide an upfront contribution to the costs.

Early-stage technologies can make the cost of finance prohibitively high for smaller developers and can prevent innovative technologies that might otherwise be successful, from ever making it to market. We intend to partner with established suppliers to benefit from their lower cost of capital to deliver larger and larger solutions.

Long term, the development of green hydrogen for use in decarbonisation has the potential to create high quality jobs (often in remote, rural areas), significantly contribute to HM Government's own decarbonisation targets, and has global export potential.

7 Rollout Potential

The largest energy usage at distilleries is thermal heating during the distillation process. Presently, the predominant thermal sources of energy are NG, Fuel Oil and LPG. 98% of Scottish distilleries use steam boiler heat systems for distillation (only Glenfiddich, Glenfarclas and Spingbank currently employ direct firing). LPG, NG and Fuel Oil can be partially replaced by green H_2 via a relatively straightforward and affordable steam boiler retrofit, which has the advantage of supporting H_2 / fossil fuel mixes, accommodating a phased approach to displacing fossil fuels by H_2. Heat demand per distillery varies hugely from 0.2 GWh to >60 GWh per annum, for smaller distilleries and large top 5 distilleries, respectively. With development, tidal and off- and on-shore wind can provide sufficient renewable electricity to power the H_2 production required for a distillery wide industry fuel switch to 100% green H_2.

With confidence in the demand, the scale-up feasibility of the Supercritical electrolyser into multi-module array solutions that are large enough to deliver the required amounts of hydrogen was considered.

This work included a supply chain analysis to ensure that all the required components and services are readily available to design, build, operate and decommission the Supercritical electrolyser scaled-up system, and enable its rollout potential. Xodus had previously developed a green hydrogen supply chain database, as part of the Offshore Wind to Green Hydrogen Opportunity Assessment (Scottish Government, 2020). This captured the Scottish supply chain capability and identified Scotland-based companies that are already operating, or planning to operate, within the green hydrogen sector. The established database was used as a baseline and expanded upon as part of the WhiskHy feasibility study.

The assessment concluded that approximately 90% of the supply chain can be sourced from the UK, as it can take advantage of operating many elements of parallel sectors, most notably, the oil and gas and renewables sectors. It is due to this overlap that the current strengths of the hydrogen supply chain are in the areas of project development, manufacture and operations & maintenance where these capabilities can be transferred from companies with experience in similar industries.

The areas that require support and development are predominantly in supply chain areas bespoke to the manufacture and installation of hydrogen systems. The potential challenge of this is related to the demand aspect where without demand, and especially with the backdrop of COVID-19, suppliers will need support or at least greater certainty if they are to invest in hydrogen related products and services.

The UK market is the ideal place to launch green hydrogen projects and benefit from what the projects will bring such as job creation and clean technology exports. Suppliers will need to be engaged early in the transition to better understand the specialist skillset required for hydrogen. Supercritical have endeavoured to engage with UK based companies to deliver this project. With a large rollout potential, due to the size of energy demand and relative ease of H_2 use and fuel switching, distilleries will be a key initial market for H_2 production companies, including Supercritical.

8 Route to Market Assessment

8.1 Route to Market

Key enablers for a commercial product:

- The technology fully deployed at a customer site at scale;
- Durability/reliability data available;
- Validation of costs.

The journey to deliver the above will occur through the application of the tacit knowledge and know-how that comes through application, aka learning by doing, specifically in manageable steps building to a full-sized deployment.

8.2 Steps to Commercialisation

Activity to date

The first benchtop prototype was a single pass, single cell (key component) design that validated the concept, conducted electrolysis and produced hydrogen and oxygen products. Experimentation and data gathering has continued in the characterisation of materials and performance of the cell at different operating conditions in the world's first continuous Supercritical electrolyser.

The next step in the design evolution of the single cell is the more powerful multi-cell arrangement.

With our partner at the world leading NPL Electrochemistry Group, Supercritical have created a computational fluid dynamics model of the single cell design operating above the critical point of water. This has enabled Supercritical to progress design at a faster pace than an experimental-only approach would permit.

Next steps in core Research and Development

Supercritical will continue the core electrolyser development as explained in Sections 4.2 and 6.1. With patent pending on the cell, additional innovation and invention in the multi-cell module will be developed, strengthening Supercritical's IP portfolio. However, the reactor does not operate in isolation and relies on a system and balance of plant. Through project WhiskHy, CPI has developed the process flow and specified requirements in the heat recovery system, optimising the flowsheet for maximum system efficiency. The remaining equipment items offer a low development risk, as this is the application of knowledge rather than research, these tasks will still need to be diligently completed.

Progress to TRL5

The first small scale pilot solution will be the next milestone in the commercialisation of electrolyser. Functioning in real world conditions with hydrogen being consumed to produce heat at the distillery. The size of the electrolyser is of less consequence compared to the completeness of the solution and the learning opportunity that this represents. For clarity, at this stage the amount of hydrogen produced is not material in the total distillery needs of a large top 20 distillery but will nonetheless decarbonise a percentage of the operations whilst active. Direct customer feedback and troubleshooting in a live environment is crucial to product development, enabling improvements to be made on the following iterations. Success at this point would represent progression to TRL5.

Progress to TRL6/7

The next stage would be a 10x larger electrolyser, enough to produce ~1.6million bottles (70 cl) of zero emission whisky a year, replacing the small-scale pilot, with any issues and challenges addressed. At this stage, with approximately 10% of the distillery's energy demand being met, it is anticipated that the system would offer more advanced renewable connectivity and complexity control and operations, enabling deployment for a longer trial period. Success at this point would represent progression to TRL6/7.

Barriers and Risks

The biggest risk to the business and the commercialisation of the technology is funding through the early pre-revenue higher risk stages, where this early TRL stage is perceived as considerable risk by private investors but confidence would build with government financial assistance, we were able to progress to a higher TRL.

Scaling

The biggest technical challenge is in the scaling of the technology. We need to increase the cell power density, design an effective multi-cell module arrangement and a multi-module array solution, all while reducing the cost per kW and maintaining durability. The optimisation of the entire solution will be required to prevent the 'balance of plant' from eroding the significant efficiency gains in electrolysis. Funding will enable Supercritical to hire additional development team members and perform the identified work to solve these problems.

Credibility

At a later stage of the business, we will be faced with the challenge of credibility, not in the technology or the management team but in the lack of track record demonstrating ability to deliver on multi million-pound contracts. Therefore, we are partnering at an early stage with companies that already have this reputation and could form more meaningful partnerships to service large contracts together.

Hydrogen Storage size

Hydrogen is an incredibly light gas and while that gives it an amazing energy density by mass (33.3 kWh/kg LHV), that story reverses when you look at the volumetric energy density, where under ambient pressure hydrogen is 0.0899 kg per cubic meter (m^3). The Supercritical system delivers pressurised hydrogen at upto 200 bar (3,336 psi), where the density increases to ~17 kg/m^3. Manufactured vessels to store large quantities of compressed hydrogen, however, start to require substantial amounts of space and metal in their construction. Storing 1 tonne (2205 lbs) of compressed hydrogen at 200 bar (3,336 psi) would require ~58 m^3 or 58k litres (2k feet^3, 15k US gallons), which is a tank 2 m x 14 m in size, which is possible and cost effective. However, for a large distillery, 1 tonne is only 4 hours' worth of fuel at 100% operation. This is a hydrogen ecosystem problem for larger industrial users, with the centralised or distributed production model and not unique to Supercritical. Alternative methods such as liquid hydrogen, liquid organic hydrogen carriers, ammonia and solid-state options are available or in development and the applicability of each method will likely be site dependent and must be considered for any permanent installation.

Renewable energy systems

For a distributed model of hydrogen production, the most cost-effective method is to directly connect renewables to the electrolyser. The technology (wind or solar etc.) is at an enabling price point today however the 'amount' that will need to be installed in locations may not always gain strong public support. A 100% hydrogen powered large distillery would require around six 2 MW wind turbines. This is a challenge that all renewable energy solutions will have to address.

Benefits for other sectors

Cost effective production of hydrogen is a perfect decarbonising fuel for the foundation industries, which produce 75% of all the material in the UK's economy and vital for the manufacturing and construction sectors. They are worth £52Bn annually but emit 50 million tonnes of CO_2 per year, 10% of the total UK CO_2. They use an equivalent of 12 million tonnes of oil (oil equivalent fossil fuel) each year (excluding electricity), equivalent to ~12k tonnes of hydrogen a day (KTN, 2021).

UK road freight is 13 million tonnes of CO_2 opportunity or 6697 tonnes of hydrogen each day (ONS, 2020). The main competition for decarbonisation in this sector is battery Electric Vehicles (EVs), with the trip distance and fuelling time being the differentiator between the two EV technologies.

Cost effective hydrogen with zero emissions in its production, would also be a welcome alternative to the fossil hydrogen used in the chemical feedstock sector, which globally currently consumes 70million tonnes of fossil hydrogen and emits 700 million tonnes of CO_2 in its production.

9 Dissemination

Upon being awarded Phase 1 funding, Supercritical and WhiskHy subcontractors issued a press release explaining the project's goals and objectives. This was shared via LinkedIn and re-shared by our subcontractors. In addition, BEIS issued a press release announcing some of the winners which was distributed by mainstream media such as the BBC.

Over the course of Phase 2, this first of a kind hydrogen solution will act as a means of demonstration and education for multiple stakeholders.

On a technical stage, as a world first for electrolysis, Supercritical will use hydrogen and renewable energy platforms such as the Renewable Energy Association and the UK Hydrogen and Fuel Cell association to disseminate technical information, benefits and lessons learnt from the pilot.

In the world of distilling, novel approaches to decarbonisation are being sought. Supercritical are actively engaged with Ardmore Distillery (see Figure 8) and will share detailed findings through the larger Beam Suntory group, the third largest distilling group in the world. In addition, if successful, findings will be presented to members of the Scottish Whisky Association.

Given the novelty of the proposal and associated infrastructure implications for the local communities to reach a net zero status, local councils have been engaged. Aberdeenshire is a vast council and is consequently split into 6 areas for management where decisions are made by local Councillors. Ardmore sits in the Marr area. The project has been introduced at both a county level and area level. This open communication will continue throughout the project to maximise dissemination through the council's extensive network.

Lastly, at a national and international level, findings will be shared with BEIS directly and disseminated to the leading national institutes for energy and clean technology such as InnovateUK, OGTC and the Offshore Renewable Energy and Energy Systems Catapults. With these organisations, opportunities to further deploy the technology will be explored.

Figure 8. Photograph of Ardmore Distillery, Eastern Highlands, Scotland.

10 Conclusions

- Switching to zero emission hydrogen as a fuel from LPG would reduce CO_2e by 615 g per litre of whisky and save on truck fuel deliveries. The proposed pilot would produce 164,100 bottles of zero CO_2 whisky per year (70 cl).
- The use of distillery wastewater as the electrolyser feedstock will be tested and prioritised if feasible, meaning valuable freshwater is not depleted for the on-site production of hydrogen.
- Producing, storing and consuming hydrogen on-site has the potential to be cost neutral with LPG by the end of the decade and cost neutral with natural gas in the UK by 2040.
- Zero emission hydrogen direct firing offers a unique opportunity to revive age-old practices that were once so core to the perceived quality of Scotland's world-renowned spirit.
- For the reference distillery, there were no technical barriers identified for the combustion of hydrogen in the existing fossil gas combustion boiler, with the existing boiler able to accommodate between 0 - 100% hydrogen with minimal modifications. This dual fuel approach minimises distillery modification costs and enables a gradual transition to hydrogen with a proportional CO_2e reduction to zero.
- Findings for hydrogen use in steam boilers are likely to transfer to multiple industries, enabled by low cost hydrogen produced via Supercritical's methodology.
- Renewable generation from wind augmented with solar, complement each other well and mitigate some of the intermittency challenges. Social concerns around increased renewable energy installations will need to be addressed.
- Storage of hydrogen on-site, topping up with curtailed renewables is cost effective but with limits of the total amount stored due to the size and cost of pressurised hydrogen containers.
- The alkaline purge water from the electrolyser can potentially be utilised in the on-site organic wastewater treatment plant to neutralise the input water to the membrane bioreactor.
- Zero emission whisky could promote the distillery sector not only within the UK but also abroad, acting as a flagship product of the green hydrogen technology decarbonising a 'hard-to-abate' sector.

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