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Project Amburn Phase 1

A consolidated summary report of the findings from a feasibility study into the viability of ammonia combustion as a low carbon solution for off-grid industrial heating.

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1 Introduction

1.1 Executive Summary

For industrial sites that are not connected to the natural gas grid, decarbonisation is a significant challenge. Currently, these sites receive trailer deliveries of oil, which is fed into steam boilers, to satisfy their process heating requirements. In the UK alone, 4.4 million tonnes per annum of oil is burned at such plants, equating to point source emissions of 14.1 $MtCO_2/y$.

In a net zero world, the trailer-delivered oil must be replaced by a zero-carbon fuel that can be stored and distributed inexpensively and combusted easily in a burner. Green ammonia, produced by reacting hydrogen with nitrogen separated from the air in the well-established Haber-Bosch process, is a promising alternative fuel for these applications. Ammonia requires only modest temperatures (-33^oC) or pressures (10 bar) to liquify, which increases its volumetric energy density to above the levels achieved by other e-fuels, such as liquid hydrogen. This enables ammonia to be distributed and stored inexpensively, using infrastructure that has been well established in the fertiliser sector.

Technical barriers in the combustion of ammonia have meant that ammonia boilers are not yet available on the market. Project Amburn Phase 1 has begun to remove these barriers, and has shown that ammonia fuelled boilers are technical possible, commercially attractive, and safe as an option to decarbonise off-grid industrial sites.

The Amburn Consortium is formed of the following organisations, who have jointly committed to investigating ammonia burner technology:

- **Flogas Britain Ltd** – Market leader in LPG solutions for off grid customers, aiming to replicate their success in oil to LPG fuel switching with a green ammonia solution. Consortium lead.
- **Enertek International Ltd** – Independent engineering research and development company specialising in combustion and fluid flow in heating equipment. The company brings vast experience in combustion system design and computation fluid dynamics (CFD).
- **Cardiff University** – World leading ammonia combustion research lab led by Prof. Agustin Valera-Medina. Cardiff University bring their own patent-pending ammonia burner design to the project, as well as lab testing capabilities and facilities.
- **Element Energy** – A low-carbon energy consultancy, part of the ERM Group, with a strong track record of initiating and supporting the delivery of innovative, first-of-a-kind technology demonstration projects. The company is supporting with the project management and leading the techno-economic analysis.

The group has undertaken a feasibility study as part of the Industrial Fuel Switching Competition Phase 1, which has shown promising results.

Key findings from Phase 1

The study showed that, from an economic perspective, ammonia-fuelled boilers have significant advantages over other low carbon solutions:

- Hydrogen struggles to compete with ammonia on a total cost of ownership basis, as it requires very low temperatures (-253^oC) or high pressures (>500 bar) to achieve reasonable volumetric energy density. This, along with the relative lack of hydrogen distribution infrastructure, causes storage and distribution costs to be exceedingly high, particularly for sites located in remote places and/or utilising >10 days of back-up storage, as is common for many off-grid sites.

- Biofuels may offer an attractive transitional solution for off-grid heating, however competition from higher value sectors such as aviation and plastics for a finite sustainable biomass resource, means that they likely do not offer a long-term, scalable solution.
- Direct electrification requires significant grid upgrades, which can be costly and has long lead times.
- Heat pumps are a viable alternative to ammonia-fuelled boilers, however, low coefficient of performance for high temperature operations (>150°C) makes them more suitable for low temperature applications, such as domestic heating.

As well as proving commercial viability, the study removed some of the technical barriers currently preventing ammonia burners from entering the market. The consortium developed an innovative design capable of addressing the two key challenges associated with ammonia combustion:

- **Low flame speed and flame stability:** Ammonia has a lower burning velocity than hydrocarbon fuels, which can lead to unreliable ignition and unstable combustion. The Amburn design mitigates this by integrating an ammonia cracker unit inside the combustion chamber. The ammonia cracker decomposes a fraction (5% by mass) of the ammonia to produce highly flammable hydrogen (and nitrogen). The resultant fuel mixture has a flame speed of a similar order to fossil fuels (e.g., propane). This was proven by laboratory tests at Cardiff University for a small-scale prototype system at 25 kW.
- **NOx emissions:** Ammonia combustion has the possibility of increased NOx emissions, primarily from the presence of nitrogen atoms in the ammonia molecule (‘fuel NOx’). Testing at Cardiff University’s laboratory suggested that NOx emissions are minimised when ammonia is burned rich. However, rich burning leads to ammonia slip, which both wastes fuel and is dangerous, as ammonia is toxic at very low concentrations. Therefore, the Amburn burner utilises a two-stage combustion process, whereby the bulk of the fuel is burned rich in Stage 1 (to minimise NOx). This is followed by a post-combustion zone where hot unburned ammonia traces reduce the remaining NO. The process is then followed by lean combustion stage (Stage 2), minimising any fuel residue in the exhaust gases.

Preparation for Phase 2

The group is now ready to demonstrate an industrial scale (1 MW) ammonia-fed steam boiler to prove the design works in an industrial setting.

- A conceptual design for a 1 MW system has been developed as part of Phase 1.
- A computational fluid dynamics (CFD) model has been created and calibrated with laboratory test results to aid with the detailed design.
- A comprehensive plan for the Phase 2 project has been drafted to mitigate risks and remove the remaining technical barriers identified in Phase 1.

The expectation is that Phase 2 will remove the remaining technical barriers in ammonia combustion technology, and take ammonia-fed steam boilers from TRL5 to TRL8 by deploying the system at a real customer site.

Moving from a lab-scale design to a full 1 MW can only be achieved through a constant testing and improvement cycle over the course of the 2-year project. Without this, the project risks making too many changes and scaling too fast without the correct checks and balances, leading to failure. Consequently, the Amburn Phase 2 project will be formed of two testing stages, followed by a final demonstration to achieve TRL8.

- **Stage 1: Detailed Design and Testing** – a MW prototype will be designed and tested at 200-500 kW at Cardiff University's test facility.
- **Stage 2: Optimisation and Deployment at a Real Industrial Site** – the system will be further improved based on the learnings from Stage 1 and be installed into a containerised steam boiler for demonstration at full rated power at a real customer site.

The planned demonstration will be ~4 weeks long, which is considered enough time to prove the system works in continuous operation.

1.2 Key Recommendations

The key recommendations of the study are listed below.

1. Develop a Phase 2 demonstration project that can address the remaining technical challenges associated with ammonia combustion.
    a. Produce a detailed design for the scaled 1 MW system.
    b. Undertake further testing of the 1 MW design to find the optimum operating conditions at industry scale.
    c. Develop a design more fit for commercialisation for the wider rollout. This includes the design of a fully automated control system, using industry standard components, and less of a reliance on 3D printed components.
    d. Investigate hydrogen embrittlement in the combustion chamber walls as a potential problem for retrofitted designs.
    e. Commission HAZOP studies for the demonstration areas to verify that ammonia is safe to use on the test site(s).
2. Monitor the technological progress of industrial heat pumps as the main competitor technology for ammonia boilers designs. In particular, monitor heat pumps that can attain high temperatures with minimal coefficient of performance losses without requiring high grade waste heat.
3. Commission a market analysis for larger scale industry and power, to understand the suitability of ammonia boilers for these applications.
4. Incorporate a spinout company that can design and fabricate the novel burner head for mass manufacture.

2 Project Background

2.1 Rationale for Ammonia-fed Boilers

Many industrial sites in the UK are not connected to the natural gas grid. These businesses instead prioritise proximity to feedstock and remoteness from residential housing in their siting plans. Examples of such industries include distilleries and cement operations.

To satisfy their process heating requirements, these plants operate steam boilers, fuelled by oil which is delivered by trailer. In the UK alone, 4.4 million tonnes per annum of oil is burned at such plants, equating to point source emissions of 14.1 $MtCO_2/y$. Flogas currently offers carbon reduction solutions to these consumers in the form of LPG or LNG, with LPG offering emissions saving benefits of ~20% compared to oil. However, full decarbonisation of these sites presents a significant and pressing challenge.

In a net zero world, the trailer-delivered oil must be replaced by a zero-carbon fuel that can be stored and distributed inexpensively and combusted easily in a burner. Hydrogen-fed boilers are a natural candidate for this; however, hydrogen requires very low temperatures ($-253^{o}C$) or high pressures (500-700 bar) to achieved reasonable volumetric energy density. In addition, the storage and distribution infrastructure is both costly and yet to be established. This makes the molecule expensive to transport long distances to remote sites. Furthermore, these sites often require up to 15 days' worth of back-up storage, which can be very expensive when using compressed hydrogen tanks, pricing the fuel out of consideration.

Green ammonia, produced by reacting hydrogen with nitrogen separated from the air in the well-established Haber-Bosch process, is a promising alternative fuel for these applications. Modest temperatures ($-33^{o}C$) or pressures (10 bar) are needed to liquify ammonia, which increases its volumetric energy density to above the levels achieved even by liquid hydrogen. In addition, transportation and storage infrastructure has already been deployed at scale in the fertiliser sector. Consequently, distribution and storage costs for ammonia are low. The International Energy Agency (IEA) Future of Hydrogen report (2020) suggests a trailer delivery cost of £717/kgH_2 for hydrogen and £62/kgH_2 equivalent for ammonia.

Although promising from an economic point of view, technical barriers in the combustion of ammonia has meant that ammonia boilers are not yet available on the market for these applications.

2.2 Challenges with Ammonia Combustion

There are two main challenges associated with ammonia combustion:

- **Low flame speed and flame stability:** Ammonia has a lower burning velocity than hydrocarbon fuels, which can lead to unreliable ignition and unstable combustion. This also causes ammonia flames to have an increased length, meaning a larger combustion chamber is needed for a given power.
- **NOx emissions:** Possibility for increased NOx emissions, primarily from the presence of nitrogen atoms in the ammonia molecule, but also changes in combustion temperature profile in the burner.

2.2.1 Low flame speed and stability

For all combustion processes, a high laminar burning velocity is required to achieve reliable and stable combustion. Ammonia's burning velocity is roughly one sixth that of incumbent hydrocarbon fuels (e.g., propane), see Table 2.1.

Fuel	Maximum laminar burning velocity [m/s]
Ammonia	0.07
Propane	0.47
Hydrogen	2.9

Table 2.1 - Comparison of maximum laminar burning velocity for selected fuels

The primary strategy observed in literature for increasing the burning velocity of ammonia is to co-burn with more flammable fuels, such as hydrogen (a 'combustion promoter'). This introduces complexity into the system as another fuel storage tank and distribution system is required, which in the case of hydrogen can be expensive, as outlined above.

Alternatively, ammonia could be 'cracked' prior to entry into the combustion chamber in an ammonia decomposition reaction, to generate the hydrogen (see Figure 2.1). However, cracking reactors are high CAPEX and require high temperatures with today's catalysts (800-900°C), which results in an efficiency penalty associated with heat losses.

$$4NH_3 \xrightarrow{+\Delta H\ (4.2\ kWh.kgH_2^{-1})} 2N_2 + 6H_2$$

Figure 2.1 - Ammonia cracking reaction

Research at Cardiff University suggests that a minimum flame velocity of 0.3 m/s will give similar performance and combustion characteristics to hydrocarbon fuels. Lab testing has shown that this can be achieved when co-burning ammonia with hydrogen at a volume fraction of ~30% (5% by mass). For other fuels (e.g., propane), the ratio of the combustion promoter by volume has been shown to be similar (see Laboratory Testing Section), however, the mass fraction is significantly higher (~25%).

2.2.2 NOx emissions

NOx's are a group of nitrogen-oxygen compounds including NO, N_2O and NO_2. They are formed from incomplete combustion in low concentrations (10's ppm), but if their concentrations increase to 100's ppm, they can be hazardous and have detrimental environmental effects (e.g., acid rain). N_2O, for example, is a greenhouse gas with 280 times global warming of potential (GWP) than CO_2.

NOx can be produced by three mechanisms:

- **Thermal NOx:** This NOx is enhanced at high temperatures (<1,300°C), as higher temperatures promote endothermic NOx reactions.
- **Fuel NOx:** This NOx is formed from nitrogen supplied in the fuel, and will increase for nitrogen-based fuels, such as ammonia.

- **Prompt NOx:** This NOx is formed from fuel being combusted in excess air, and NOx being generated from the resulting additional nitrogen presence.

In conventional combustion of natural gas and propane, thermal NOx is of largest concern, as high temperatures improve thermal efficiency, with an inherent trade off with thermal NOx production.

For ammonia combustion, the main increase in NOx emissions will be from fuel NOx, as the ammonia molecule is ~82% nitrogen by mass.

2.2.3 Industrial Fuel Switching Competition Phase 1

Phase 1 of the Amburn project aimed to remove these barriers and develop an ammonia burner design that can leverage this fuel's low distribution costs for off-grid heating applications. The consortium has received £242k in funding from the BEIS Industrial Fuel Switching Competition (IFSC) for a feasibility study investigating ammonia-fed steam boilers, to address these challenges.

2.3 Project Objectives

The primary aim of the Phase 1 project was to produce an ammonia steam boiler design of MW scale, based on existing steam boiler componentry where possible, with limited product emissions (NOx, unburnt ammonia etc), ready for rapid deployment and scale up within the decade.

Specific objectives of the project were to:

- Assess the business and safety case for ammonia fed boilers of three configurations identified prior to the project (pure ammonia fed, ammonia/hydrogen fuel mix, ammonia/propane fuel mix). Details of the configurations are given in the Techno-economic Analysis Section.
- Produce a CAD design for at least one of the configurations using a combination of desk-based study (e.g., CFD analysis), and experimentation.
- Take ammonia/propane/hydrogen-fed steam boilers from the stage of scientific research and experiment (TRL 4) to TRL 5 (representative model or prototype system is tested in a relevant environment).
- Plan for a Phase 2 demonstration that will construct the world's first 1-10 MW scale ammonia boiler system at one or more customer sites, proving that the developed design and associated ammonia supply chain is viable and safe. The consortium is targeting an ambitious TRL8 (technology is proven to work - actual technology completed and qualified through test and demonstration) by the end of Phase 2.

2.4 Project Team

The consortium is composed of the following partners, each with a specific role within the project.

Flogas Britain Limited

Flogas is the market leader in the distribution of LPG and LNG to off-mains industry throughout Britain, aiming to replicate their success in oil to LPG fuel switching with a green ammonia solution. Flogas, along with their parent company DCC, is now investigating potential market opportunities in renewable energy sources in order to meet its own carbon neutrality requirements, as well as meet the demand of their customers seeking carbon friendly options. Flogas is the project lead.

Enertek International Ltd

Enertek International Ltd is an independent engineering research and development company specialising in combustion and fluid flow in heating equipment. The company has played an instrumental part in hydrogen appliance development throughout BEIS' Hy4Heat programme and has significant knowledge and experience gained with hydrogen appliance testing to developing burners, which has been applied to the problem of combustion of ammonia. Enertek led the computation fluid dynamics (CFD) and MW scale ammonia burner design work.

Cardiff University

Cardiff University is one of the leading research-intensive universities in the UK. The university was ranked among the top five universities in the UK for research excellence and second for impact. The Institute of Energy at Cardiff delivers high-level extensive research activities with direct experience including ammonia combustion. Cardiff University provided its patent-pending ammonia burner design and ran experiments to determine the optimum operating conditions of ammonia/hydrogen/propane burner systems from a flame stability and emissions (NOx, etc.) perspective.

Element Energy

Element Energy is a low carbon and sustainability consultancy providing strategic advice, computational modelling, software development and engineering consultancy across the buildings, transport, and power sectors for a broad range of clients. With two decades' experience in the hydrogen sector, Element Energy has expertise in initiating and coordinating ambitious hydrogen/ammonia energy projects throughout the UK and Europe, including the FCH JU's major deployment projects for fuel cell cars and buses (H2ME, ZEFER, JIVE). Element Energy, part of the ERM Group since mid-2021, supported the coordination of the project and led the techno-economics analysis.

2.5 Work Packages and Structure

The overall scope of the project was broken down into 7 Work Packages:

- **WP1: Project management** – overall coordination of the project.
- **WP2: Techno-economics** – to compare the economic benefit of each ammonia boiler configuration against zero carbon counterfactuals.
- **WP3: Safety assessment** – to understand the health, safety and regulatory challenges associated with ammonia's toxicity at fuel switching sites.

Selection of boiler configuration and customer site, based on WP2 & WP3.

- **WP4: Burner design** – develop concept CAD design of 1 MW ammonia-fed boiler system, CFD modelling, and experimental testing (25 kW) of novel ammonia/hydrogen/propane burner to limit product NOx emissions.
- **WP5: Boiler system design** – develop preliminary design and costings of 1 MW ammonia-fed boiler system.
- **WP6: Trial planning** – preparation of a plan for on-site demonstration in Phase 2.
- **WP7: Dissemination** – knowledge sharing for the benefit of the wider sector.

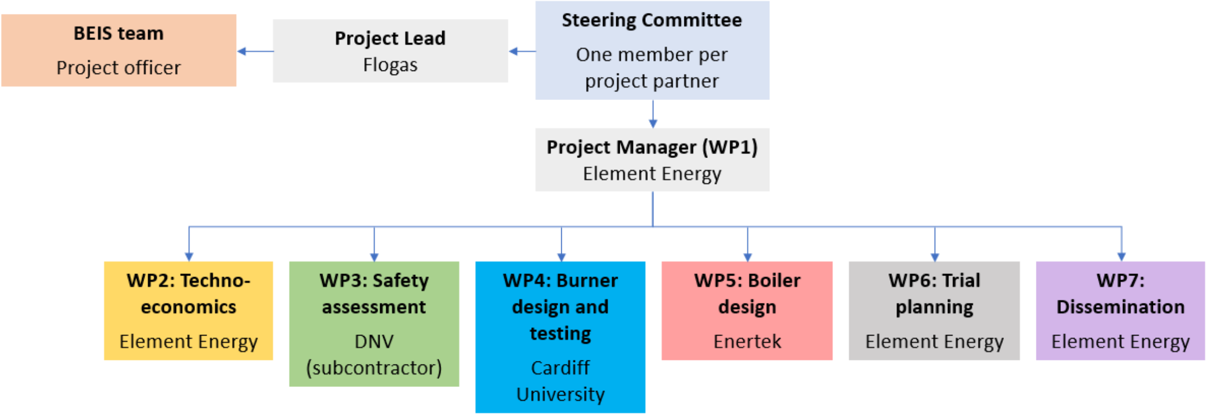


Figure 2.2 – Project Organogram

3 Key Findings

This section of the report summarises the objectives, activities, and key results and conclusions for each of the main work streams carried out in this feasibility study.

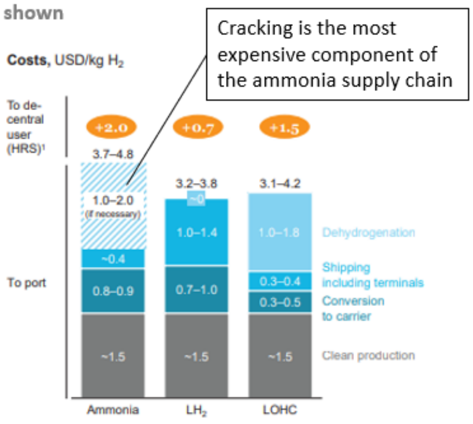
3.1 Techno-economic Analysis

The objective of the techno-economic analysis for Project Amburn was to assess the commercial feasibility of ammonia fuelled boilers, and to determine the most promising configuration of the three identified prior to the project to be taken to the design stage.

Ammonia fuelled boilers demonstrate early promise for the off-grid industrial sector for the following reasons:

- Many off-gas grid industrial sites currently take deliveries of liquid propane gas (LPG), which is stored and transported at similar conditions to ammonia (ammonia liquefies at -33°C and propane -42°C and ambient temperatures, or 8-10 bar at ambient temperatures in both cases). Delivery of ammonia presents an opportunity to reuse existing propane infrastructure with ammonia at low retrofitting costs.
- Liquid ammonia is a volumetrically dense energy vector compared to other carbon free alternatives such as hydrogen (compressed gas or liquid). This means trailer deliveries are reduced compared to other low carbon alternatives, minimising the logistics challenges for a switch to a low carbon fuels.

- Several studies have propose using ammonia as a vector for delivering hydrogen. This requires the cracking of ammonia to hydrogen at the end-use site. This is an energy intensive, high temperature catalytic process that increases costs and/or carbon emissions of the supply chain. Ammonia fuelled boilers remove the requirement for cracking, reducing costs and carbon emissions compared to ammonia used to deliver hydrogen.
- Many industrial users are located far from residential areas. This mitigates the toxicity risk posed by ammonia, by reducing the severity of possible leaks.
- The off-grid nature of these sites means that decarbonisation options available in larger hubs, such as pipeline delivery of hydrogen or electrification, may not be available. They therefore require an innovative solution to decarbonise their operations.



The Hydrogen Council: 2030 cost of large scale H_2 transport from Saudi Arabia to Rotterdam

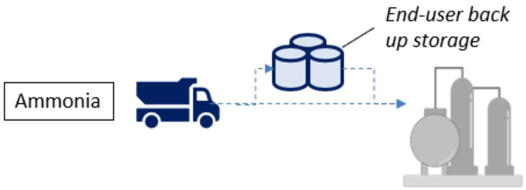
Ammonia, LOHC and Liquid H_2 – cost at port and cost to a decentralised refuelling station shown

Cracking is the most expensive component of the ammonia supply chain

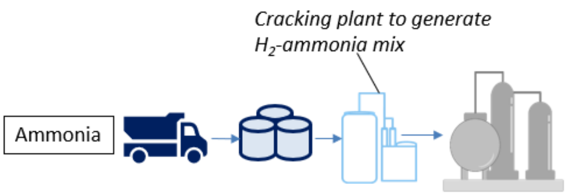
Three configurations of the delivery of ammonia to off-gas grid end users were assessed.

Configuration 1 (C1): 100% Ammonia combustion, consists of the delivery and burning of pure ammonia without a combustion promoter. This has the advantage of delivery of single fuel, with no additional steps require at the point of end use. The disadvantage is that boiler upgrades will be more costly due to the more challenging combustion properties of pure ammonia. The case where hydrogen is produced inside the combustion chamber via an integrated cracker is also considered here.

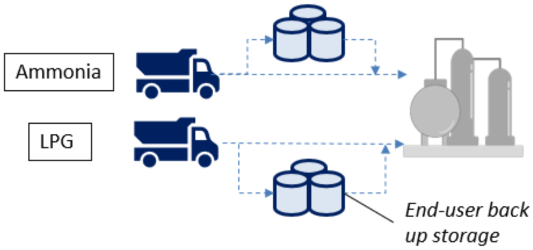
Boiler configuration 1: Off-gas grid industrial user set up



Configuration 2 (C2): Ammonia and hydrogen fuel mix, a small-scale cracker is installed upstream of the boiler system, to convert a small fraction of the delivered ammonia to hydrogen. This is to improve combustion performance of ammonia to offer close to propane combustion properties. This will help to minimise boiler upgrade requirements, if 100% ammonia proves technically challenging, or required upgrades are too costly.


Boiler configuration 2: Off-gas grid industrial user setup

Configuration 3 (C3): Ammonia and propane, consists of delivering both LPG and ammonia separately to separate fuel tanks, and co-burning both fuels together. This offers similar combustion properties to fossil-based systems, and so reduces boiler upgrade/redesign requirements. The drawback here is that two supply chains would need to be setup for the site (one for each fuel), and there would still be carbon emissions present.


Boiler configuration 3: Off-gas grid industrial user set up

Analysis of ammonia as a fuel was split into two parts:

1. Fuel cost analysis: Here, only the cost of delivering low carbon ammonia fuel was analysed. Two main scenarios were examined, for each of the three configurations:

- **Scenario 1:** Domestic production of low carbon ammonia. Here low carbon ammonia would be produced in the UK from low carbon hydrogen. Both use of green-electrolytic hydrogen, and blue-CCUS enabled hydrogen to produce green and blue ammonia respectively were analysed.
- **Scenario 2:** International import of green ammonia. Here, green ammonia would be produced abroad in areas with low-cost renewable power, and then shipped as ammonia to the UK before delivery to industrial off-gas grid users.

2. Total-cost-of-ownership (TCO) analysis: Here, the total cost of owning and operating an ammonia boiler for each of the three configurations was examined, including CAPEX increases associated with a combustion chamber redesign.

Sensitivities to identify key cost drivers, such proportion of secondary fuels, sources of hydrogen, and delivery distances were explored. This was to highlight use cases best suited to ammonia fuelled boilers from a commercial perspective.

The economics of ammonia delivery wre compared to counterfactual low carbon technologies. The following counterfactual were considered:

- Electrification (both heat pump and direct)
- Biofuels (biomethane and bioLPG)

- Hydrogen

Costs have been modelled for 2030, a viable timeframe for the commercialisation of ammonia-fuelled boilers. The scope of work analysed the costs of ammonia production, transportation, cracking to hydrogen, and use in boilers. Other components needed for the ammonia supply chain, such as low carbon hydrogen production, were not examined in detail in this project. Figure 3.2 shows the model boundary.

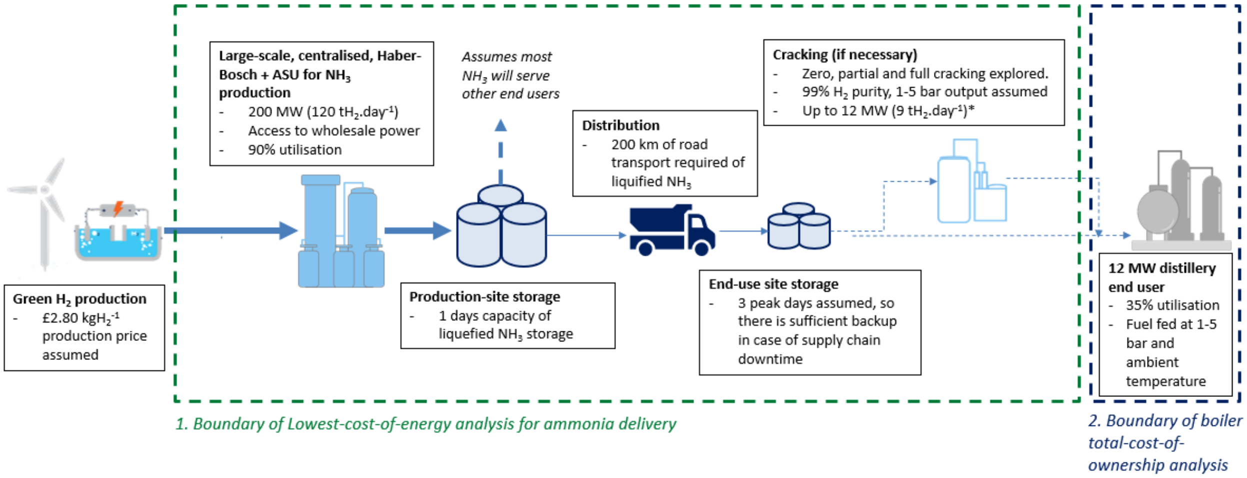


Figure 3.2 – Distribution chain to a 12 MW distillery from UK-based large-scale centralised production, showing boundaries of the first part of the technoeconomic analysis, lowest-cost-of-energy for delivered ammonia and second part, total cost of ownership (TCO) of ammonia fuelled boilers

Modelling assumptions

Hydrogen production costs have been taken from existing literature. Energy price assumptions, including gas and electricity have been taken from BEIS forecasts. Neither hydrogen nor energy cost assumptions reflect recent market volatilities since the Russian invasion of Ukraine. An increase in energy costs following this development will increase the cost of all technologies, but the exact impact is uncertain. A full breakdown of assumptions used for analysis is given in the supporting Final Techno-economic Analysis report.

3.1.1 Ammonia boiler configuration comparison - Lowest-cost-of-energy analysis

Figure 3.3 shows the estimated cost for delivering ammonia-based fuels to off-gas grid industrial users compared to LPG. In all cases, ammonia has a cost premium compared to conventional LPG operations, even with a carbon price of £0-50/tCO_2 and a high LPG price applied.

Boiler Configuration 3 offers the smallest cost increase, but as it is 23% propane by mass, offers more modest emissions savings. It should be noted that the high proportion of propane was required to give the fuel reasonable and stable combustion properties, i.e., a flame speed of ~0.3 m/s. This was confirmed by laboratory testing conducted by the University of Cardiff (see Laboratory Testing section). As a result, the Amburn partners consider ammonia/propane to be a possible transitional solution to abate some carbon emissions in the short term at a reasonably low cost. As it is not a long-term solution, it was chosen not to be the focus of the design phase. Instead, the partners aim is to construct a burner that can operate with ammonia/propane mixtures in the short term, whilst still having the functionality to operate on purely ammonia in the long-term. This will allow customers to transition smoothly to a low carbon fuel, whilst avoiding stranded assets.

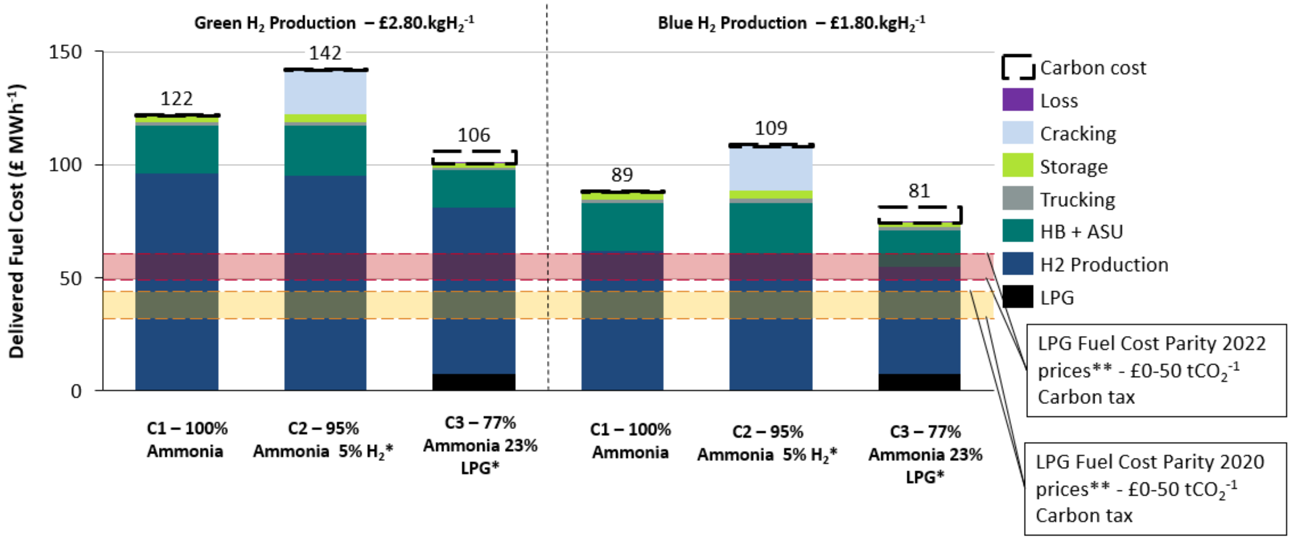


Figure 3.3: Delivered fuel cost for different ammonia boiler configurations, HB & ASY – Haber Bosch & Air Separation Unit (required equipment for ammonia production) *Blending % are by mass ** 2020 price is before any price spikes, 2022 includes price spikes during Spring 2022

Figure 3.3 shows that Boiler Configuration 1 is lower cost than Configuration 2, as it avoids any ammonia cracking requirement. Cracking cost increases are from two main factors:

- Expensive cracking equipment for the high temperature catalytic reaction to release hydrogen from the ammonia molecule.
- Supply chain inefficiencies introduced by the endothermic reaction, and the requirement to supply it with high temperature heat (900°C), some of which is lost to the environment. In the model, it is assumed that the end use site will not have other fuel supply available to provide this heat, and so a fraction of the cracked hydrogen output stream would be combusted for this purpose, which consumes a significant fraction of the fuel supplied.

To minimise fuel costs, cracking should therefore be minimised/avoided.

3.1.2 Total cost of ownership and comparison to counterfactual technologies

When comparing the total cost of ownership of the different configurations, the cost of fuel is the dominant component, as shown in Figure 3.4. The boiler CAPEX is minimal on a TCO basis at ~5%. This analysis assumes a 100% CAPEX increase to the system as a result of significant burner redesign to operate on ammonia. This is conservative assumption, the burner itself is only a small fraction of overall boiler cost, and so the actual total boiler CAPEX increase might be significantly lower. This means that any additional CAPEX for re-design, more advanced instrumentation, and controls, etc., will not significantly harm the economic case for ammonia boilers. The most significant driver is the price of the low carbon fuel. Figure 3.4 shows that generating a 5% blend of hydrogen from cracking upstream of the boiler (configuration 2) increases TCO by around 20%.

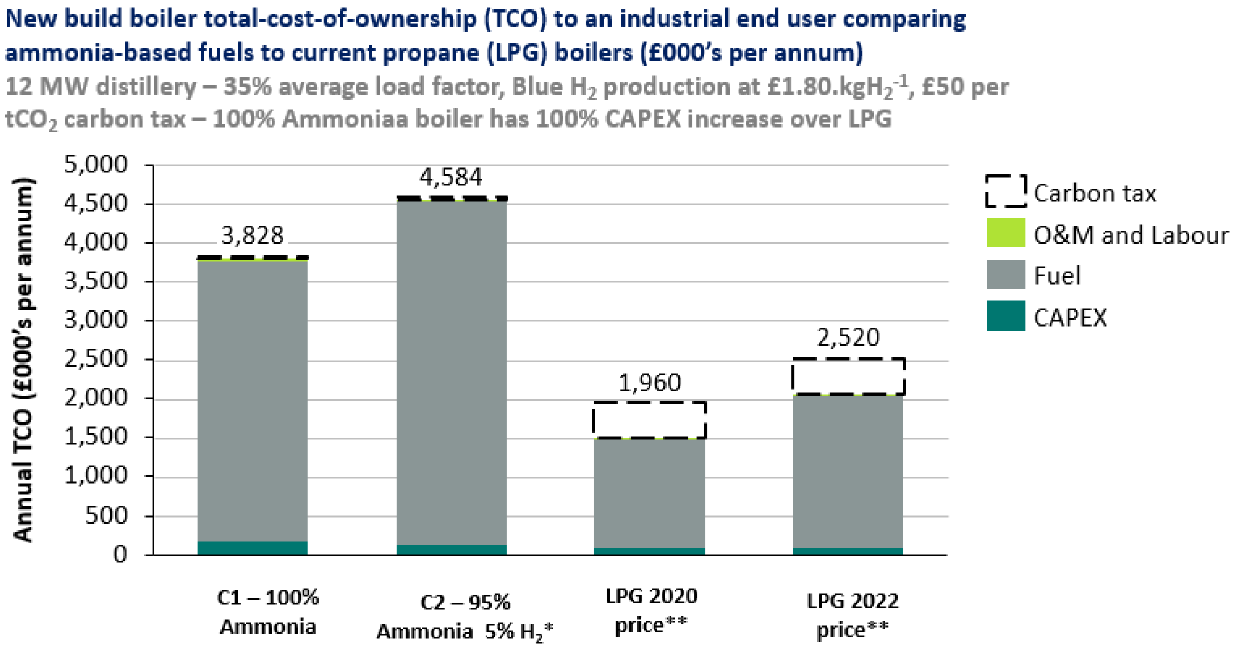


Figure 3.4: New build boiler total cost of ownership *% blend by mass **2020 price is before any price spikes, 2022 includes recent price spikes

Other low carbon counterfactual technologies were explored to assess the long-term commercial feasibility of ammonia fuelled boilers:

- **Hydrogen:** Delivery of both liquid and gaseous (350 bar) hydrogen via tube trailers was explored to feed a hydrogen boiler. It was assumed hydrogen pipelines would not be feasible, due to the size and location of off-gas grid industrial users.
- **Biofuels:** Delivery of bioLPG, which can be directly substituted into existing propane boilers. Additionally deliver of biomethane was explored via tube trailers.
- **Heat pumps:** Electrification via an industrial grade heat pump was explored, including costs of additional electrical cabling to install the system.
- **Direct electrification:** Direct electric heating was explored, including costs of additional electrical cabling to install the system.

Figure 3.5 shows a summary of the results for each counterfactual in three scenarios on a TCO basis:

- Central: Assumed base case for feedstock/fuel and electricity costs.
- Low: Lower fuel costs, coming from a higher availability of renewable power or low-cost bio-feedstocks. Lower ammonia boiler CAPEX assumed.
- High: Higher fuel costs, coming from lower availability of renewable power or low-cost bio feedstocks. A higher Ammonia boiler Capex is assumed.

Full assumptions for each scenario are provided in the accompanying Final Techno-economic Analysis report.

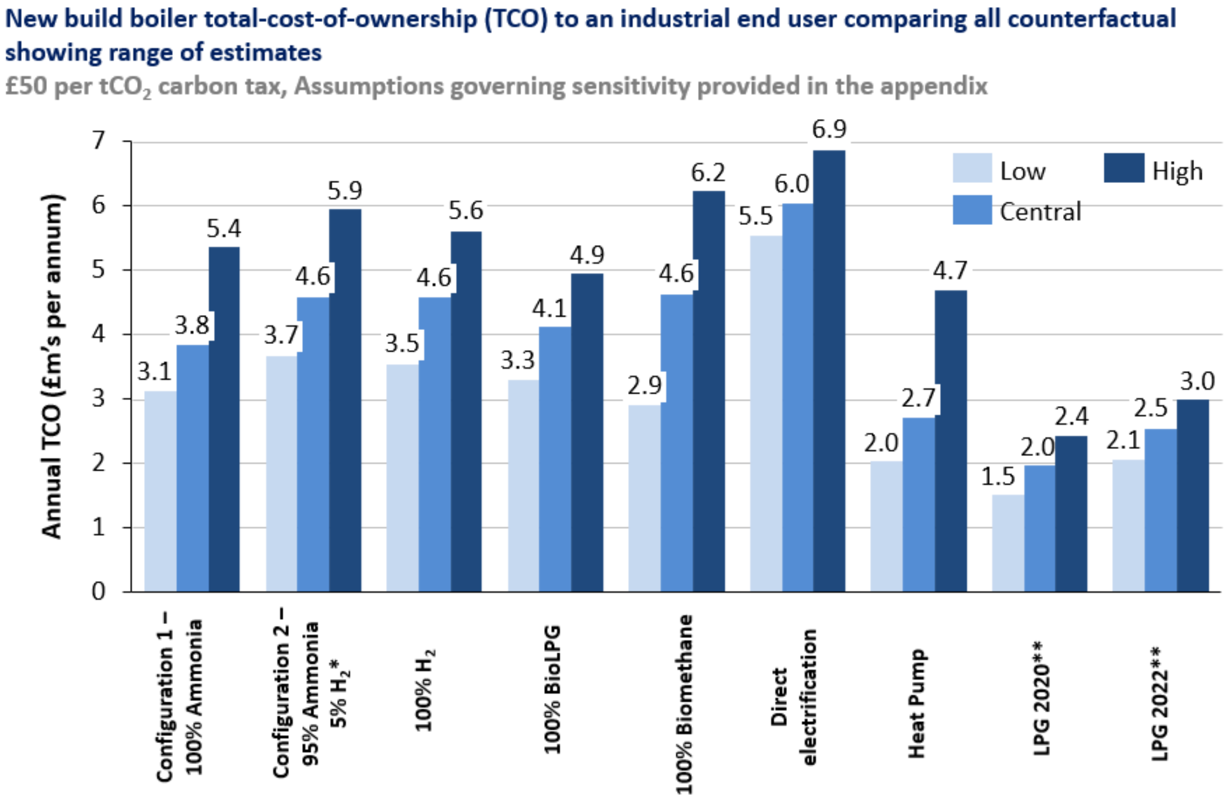


Figure 3.5: Comparison of all low carbon technologies, on a total-cost-of-ownership basis

Comparison with hydrogen

In Figure 3.5, delivery of hydrogen initially looks to be comparable in cost to ammonia. However, due to the low volumetric energy density of hydrogen in both liquid and compressed form, a hydrogen value chain would result in an increase in trailer delivery frequency for end users (Table 3.1).

Fuel	LPG	Ammonia	Compressed H_2	Liquid H_2
Storage/transport conditions	-42°C or 15-20 bar	15-20 bar	350 bar	-253°C
Trailer capacity (kg)	24,000 kg	26,600 kg	1,000 kg	4,000 kg
Trailer delivery rate – 3 MW Boiler (100% LF)	**0.25 per day**	**0.6 per day**	**2.3 per day**	**0.6 per day**
Trailer delivery rate – 12 MW Boiler 100% LF)	**1 per day**	**2.3 per day**	**9.4 per day**	**2.3 per day**

Table 3.1 - Comparison of hydrogen, ammonia, and propane tube trailer deliveries

Additionally, many of these off-grid industrial sites require large quantities of backup fuel (10-15 days) for resilience. If this quantity of storage is required, expensive storage infrastructure give a much larger cost increase for hydrogen over ammonia, as shown in Figure 3.6.

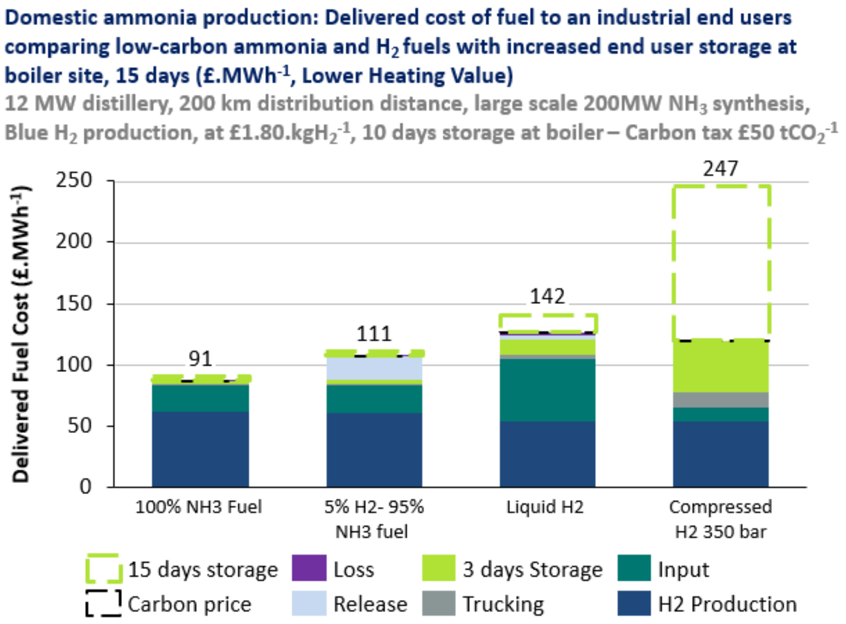


Figure 3.6: Comparison of ammonia and hydrogen delivery options with different levels of storage

Comparison with biofuels

BioLPG initially looks attractive due to the possibility of a direct fuel substitution with no equipment changes needed and could offer an interim solution. However, there is significant large demand for fossil LPG across many sectors, which must all be decarbonised to achieve net zero. The current primary source of bioLPG is as a by-product of HVO production, but with the current pipeline of European HVO plants, bioLPG supply will not be able to meet fossil-LPG consumption (Figure 3.7). As society transitions to net zero, this will create competition for the bioLPG supply which will drive up market prices. Without significant ramp up in supply this will not be a scalable zero emissions solution long term. Similarly, the cost of biomethane is highly sensitive to the cost of biomass feedstock used. If low-cost feedstocks are available, biomethane could be a promising option, but there will likely be high demand from other high value sectors in a net zero society (e.g., aviation and plastics), presenting equivalent scalability challenges.

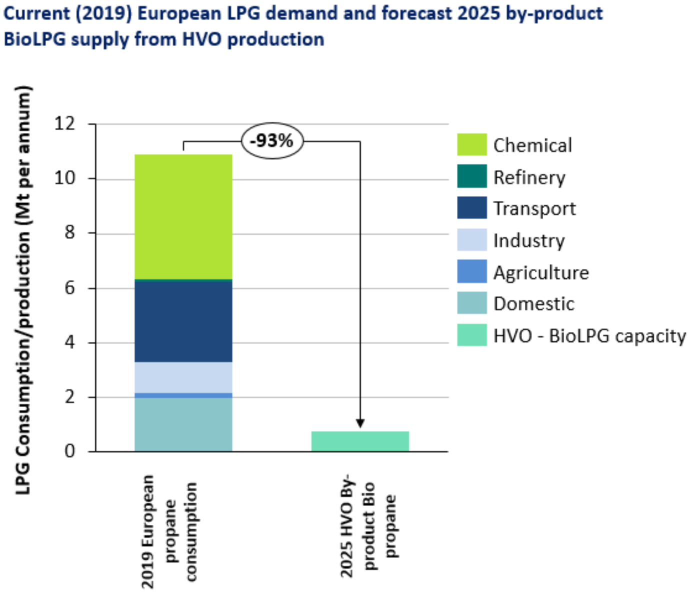


Figure 3.7: European LPG consumption, and project bioLPG supply from by-product HVO production

Comparison with direct electrification

In Figure 3.5, direct electrification is shown to be relatively expensive due to high grid electricity prices and additionally significant grid upgrades that could be required for large sites, which could increase both costs and timeframes for installations.

Comparison with heat pumps

If technically feasible, heat pumps offer the lowest cost decarbonisation option. Heat pumps are technically feasible today at temperatures of up to 150°C, and this may increase to 200 to 250°C with technology developments this decade. However, they are unlikely to be able to provide a technically viable solution for many industrial sites, which require higher-grade, heavy-duty heating. There are also other considerations, such as space constraints on existing heating system, and electrical grid upgrade requirements. Higher temperature industrial heat pumps also require an initial heat source, around 60-80°C to achieve 150-160°C temperatures, which could be provided by waste heat, but the possibility of this would have to be judged on a case-by-case basis. It is possible to generate 150-160°C temperatures from lower heat sources. But this will reduce the coefficient of performance and increase the cost of operation through an increase in electricity consumption, as shown in Figure 3.8.

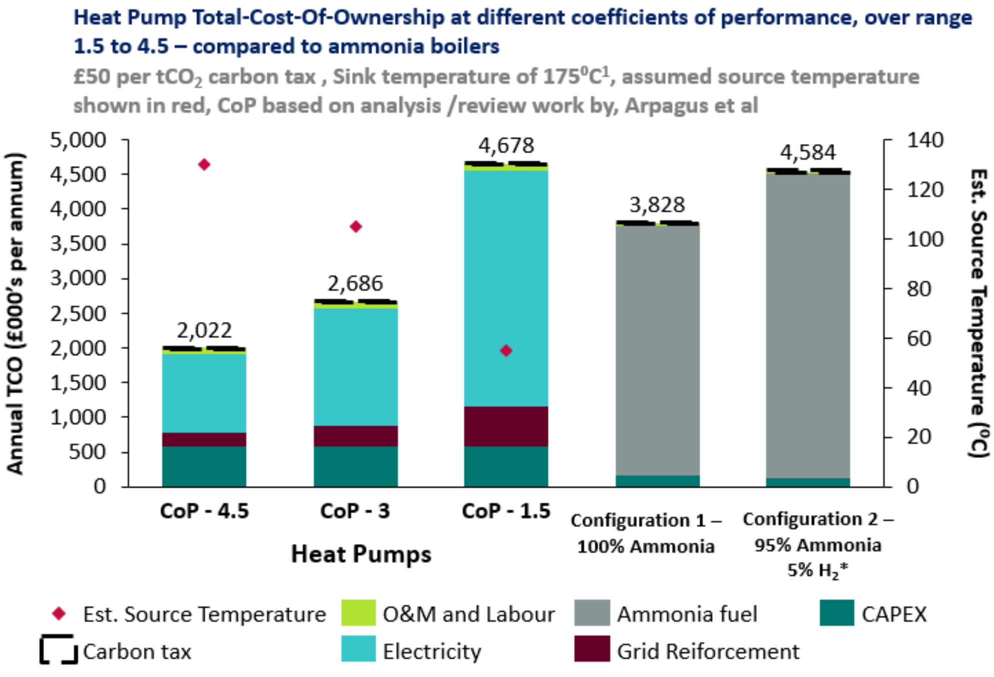


Figure 3.8: Impact of heat pump coefficient of performance on TCO, compared to ammonia-fuelled boilers

Grid constraints are also a concern for heat pumps and direct electrification. This presents itself in two ways:

- A higher penetration of intermittent renewable power will increase volatility and likelihood of electric supply-demand mismatches, causing strain to the grid.
- Electrification of other sectors including transport (through battery electric vehicles), domestic heating (via heat pumps), and other larger low temperature industrial applications will dramatically UK electrical demand, and place further strain on the grid.

In summary, heat pumps will likely not be able to deliver the quality of heat required for many industrial processes, however, where they do, they offer competition to ammonia-fed steam boilers.

3.1.3 Longer term future costs and import/export

The economic case for ammonia will be further improved by technological development in green hydrogen production (reducing the largest fuel cost component). Beyond 2030, electrolyser costs are forecast to continue to drop, and efficiencies are projected to improve. Meanwhile, other low carbon technologies will face further challenges beyond 2030, such as grid constraints (direct electrification and heat pumps) and competition for finite resources (biomass).

In addition, GW-scale green ammonia projects are being announced across the globe, scheduled to come online post-2025, in areas with strong renewable resource such as the Middle East, North Africa and Chile. Due to the low-cost renewable power in these regions' green hydrogen production (the largest cost component of green ammonia) will be less expensive. Bulk shipping of ammonia is also relatively low cost at scale, contributing an additional £8-12/MWh to the green ammonia cost (dependent on scale and distance). Therefore, if renewable power overseas is at least £8-12/MWh less expensive than domestic UK renewable power, the cost of green ammonia will be lower from imports, as shown in Figure 3.9.

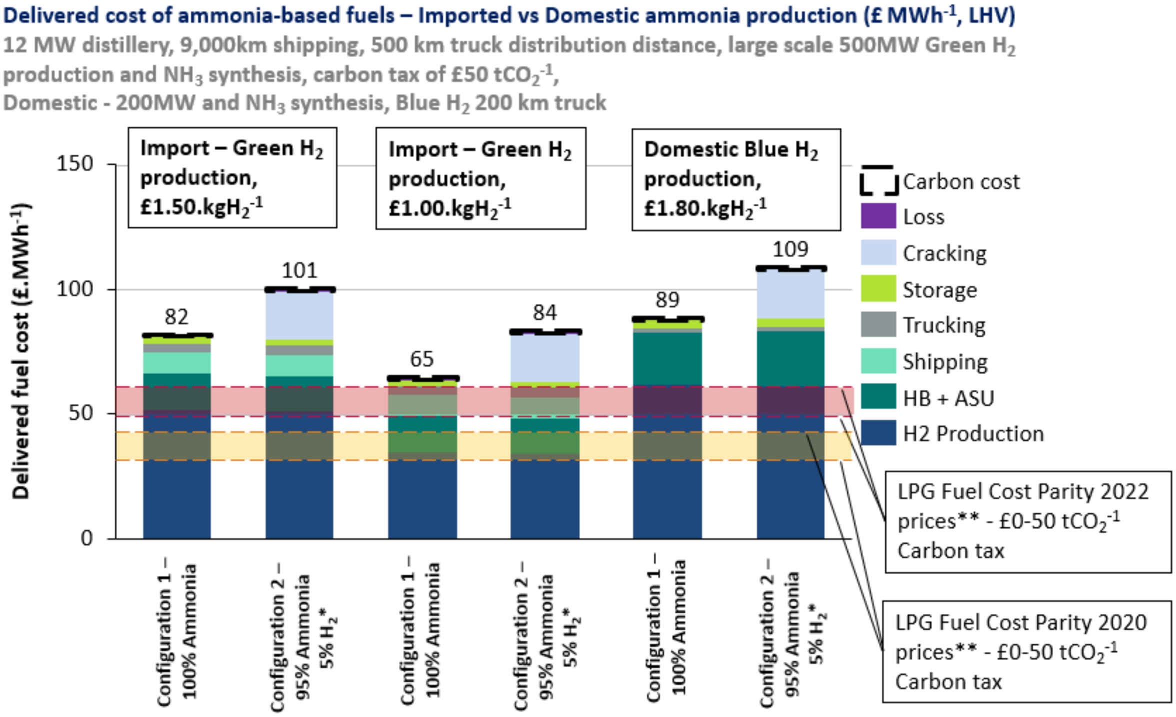


Figure 3.9: Comparison of domestic and overseas green ammonia production *Blending % are by mass ** 2020 price is before any price spikes, 2022 includes price spikes during Spring 2022

3.1.4 Conclusions and recommendations

Ammonia combustion can offer a scalable zero emissions solution for off-gas grid industrial customers. There are several key drivers, critical to minimising costs to end users:

- Minimizing any cracking to generate hydrogen. As the TCO to end users is dominated by the cost of fuel, developing a more sophisticated boiler capable of close to 100% ammonia combustion will likely be significantly less expensive (in the order of 20%), because it reduces the efficiency losses associated with losing a fraction of your fuel to power the cracking process.

- Minimising the cost of low carbon hydrogen used to produce ammonia. Hydrogen cost forecasting is challenging with current market volatilities, but blue hydrogen may offer an interim lower cost solution to green if gas prices resettle to pre-spike levels.
- Co-burning with LPG is not a viable long-term option to meet net-zero, but could serve as a low cost interim solution for sites looking to install an ammonia fuelled boiler to future proof against increasing carbon reduction targets, but not suffer high interim fuel costs as low carbon ammonia production scales up and comes down the cost curve.

Ammonia fuelled boilers demonstrate promise over many alternative low carbon technologies:

- Hydrogen systems cannot offer cost-effective backup storage in the order of 10-15 days, as is common in the target market (remote off-grid sites). Hydrogen also presents logistical challenges associated with high delivery frequency at the end-use site, because of poor volumetric energy density of delivery trailers. This adds additional cost and complexity to already challenging supply chains.
- Biomass used to derive biofuels will likely face increasing competition from other higher value sectors, driving their price to beyond green ammonia (which is a renewable resource). As boilers are fuel cost dominated, this will price them out of the market for off grid heating. Near-term ammonia-fuelled boilers may face challenges from bioLPG, but biofuels will struggle to offer a low-cost fully scalable solution in a net zero society.
- Direct electrification requires costly upgrades to grid infrastructure and can take significant time to install for permitting reasons.

Heat pumps are the strongest competitors to ammonia combustion for the intended application. For lighter duty heating applications at low temperatures (<150^{o}C), heat pumps can provide a viable a lower cost alternative to ammonia-fuelled boilers, if they are not restricted by space, or grid constraints. However, heat pumps at high temperatures (>150°C) either require waste heat sources at 60-80^{o}C to reach temperature (which may not be present at every site) or suffer from significant coefficient of performance drops. In addition, temperatures above 300°C are likely to remain out of reach, even after technological improvement is factored in.

High temperature off-gas grid industrial users therefore offer a relatively low risk market for ammonia-fuelled boiler technology. Given the limited options for off grid sites to decarbonise with a fully scalable solution, ammonia-fuelled boilers are a compelling option for these end users future low carbon heat needs.

3.2 Safety Assessment

The Amburn Consortium commissioned DNV to carry out a safety assessment to understand the health, safety and regulatory challenges associated with the hazards of ammonia, including its toxicity. The three ammonia configurations were assessed as part of the safety analysis.

The DNV scope of work for the Amburn Project was divided into the following tasks:

- Task 1. HSE screening/ranking exercise.
- Task 2. Hazard identification (HAZID) exercise.
- Task 3: Identification of regulatory risk.

In addition, other adhoc support was provided by DNV on the Amburn Project. These aspects were covered as part of Task 4 to support in the assessment of the design implications of the Amburn Project.

3.2.1 Task 1 - HSE screening/ranking exercise

The objective of Task 1 was to carry out a literature review to examine the hazardous properties of the three alternative fuel mixtures: pure ammonia, an ammonia/hydrogen mixture, and an ammonia/propane mixture and to carry out a risk ranking exercise to assist in the decision making between the different fuel mixes. The following characteristics and parameters were considered:

Characteristic	**Parameter**
Flammability	- Ease of ignition - Flammable range - Burning velocity
Explosivity	- Explosible concentration range - Max. explosion pressure - Max. pressure rise
Toxicity	- Acute toxicity thresholds - Emergency
Environmental	- Greenhouse gas contributions - Impact on flora and fauna
Material Implications	- Effects on pipework or storage materials
Transport	- Quantity - Design - Material - Accident
Storage	- Storage conditions - Separation distances - Boiling temperature

Table 3.2 - List of characteristics and parameters used for literature review

The risk ranking exercise was carried out using a simple ranking scoring system, with a score given to each parameter ranging between 0 to 3, where 3 is the most hazardous level.

There were several fuel characteristics explored in this task, with some more crucial than others, such as explosivity and toxicity.

Table 3.3 displays the risk ranking. It should be noted that the flammability and explosion characteristics have been combined and averaged.

Averaged Risk Ranking				
Characteristics	**Parameters**	**Ammonia**	**Hydrogen**	**Propane**
Flammability	Ease of ignition (minimum ignition energy)	1	3	2
	Flammable range (lower and upper flammable limits)			
	Burning Velocity			
Explosion characteristics	Explosible concentration range			
	Maximum rate of pressure rise and maximum pressure			
Toxicity characteristics	Acute toxicity thresholds such as STEL	3	0	1
	Emergency			
Environmental characteristics	Greenhouse gas contribution from combustion products	2	1	2
	Impact on flora and fauna of accidental release of fuel			
Material implications	Effects on pipework or storage materials.	3	2	1
Transport	Quantity	3	Not intended to transport or	1
	Design			
	Material			

	Accident		store hydrogen	

Table 3.3 - Averaged Risk Ranking

Overall, the literature review provided useful insight into each of the three pure fuels proposed to be used in the boiler redesign, looking at specific hazardous properties, environmental concerns along with identifying the challenges with transport and storage.

The risk ranking exercise provides a good visual summary of the risk characteristics, clearly capturing where each fuel component is the most hazardous and the areas of concern when looking at selecting an appropriate fuel mixture. It was identified that ammonia was the most toxic, scoring a 3. Hydrogen was identified as the most hazardous for its flammability and explosion characteristics, scoring 3.

3.2.2 Task 2 – HAZID exercise

The objective of Task 2 was to identify the associated hazards, potential consequences, and the measures in place to mitigate the potential major accident of the three boiler different configurations.

A total of 86 recommendations were raised during the HAZID (only the 78 non-site specific recommendations are shown below). The recommendations related to ensuring the precautions and safeguards were sufficient to either prevent the hazard occurring, or mitigate the severity of any consequence to an acceptable level, or to identify additional precautions or safeguards not sufficiently incorporated and outlined in the design to manage all the hazards.

Four sites were considered during the HAZID. Ardmore Distillery was used as the basis of the HAZID and then a 'HAZID by differences' was performed for the other three sites (Bladnoch Distillery, ABN Melmerby Food Manufacturing, and ABN Enstone Food Manufacturing). It was noted that various receptors were identified near the four sites. However, comparing all four sites, ABN Enstone was identified to be with the least number of receptors in close proximity.

For the three ammonia configurations, the following assumptions were made

1. For the first configuration, 100% Ammonia, fed directly in the boiler burner.
2. For the second configuration, the assumed process involves a 100% ammonia fed to a cracking unit heated by fuel which is assumed to be initially propane from existing supply, then by cracked hydrogen recycled to the cracker. The partially cracked ammonia is blended with hydrogen to give a 5% by mass hydrogen, 95% ammonia mix.
3. For the third configuration, 74% Propane 26% Ammonia by mass mixture as fuel in boiler burner. The assumption is that there will be a small number of ammonia storage pressure tanks on the site as well as separate propane storage tanks. Ammonia will be vaporised by dedicated ammonia vaporiser and piped to the boiler house where it will be blended a short distance upstream of the boiler burners. The HAZID assumes the location of the ammonia tanks will be in the vicinity of the existing propane tanks. Ammonia tank is operating pressure 4 to 5 barg and the vaporiser produces vapour for feeding the boiler at 0.75barg.

The HAZID was carried out by a multi-disciplinary, multi-stakeholder team who were familiar with the system being assessed. The team worked under the guidance of a chairman who was experienced in the use of the HAZID method. The HAZID study was prefaced by a short overview detailing the boundaries and design specifications of the system being assessed.

The key recommendations made during the HAZID study are presented in Table 3.4.

- Recommendations 1 to 46 are from HAZID of the 100% ammonia configurations and apply to all three configurations.
- Recommendations 47 to 60 are from the HAZID of the ammonia / propane mixture configuration.
- Recommendations 61 to 78 are from the HAZID of ammonia / hydrogen mixture configuration.
- Recommendations 50, 53, 56 and 58 are common to both the ammonia / propane mixture configuration and ammonia / hydrogen mixture configurations.

Recommendation
1. Review inspection period for tanks converted for ammonia use and confirm if it is appropriate for ammonia
2. Confirm if design code for tank and pipework is appropriate for ammonia
3. Develop site emergency plan to include actions in case of toxic ammonia release or spillage. After assessing risk of toxic release, if required, provide site toxic refuge and muster alarm
4. For site (distillery) already COMAH due to current inventory of dangerous substances, determine how presence of ammonia below threshold quantities may affect planning zones. If there are likely to be land-use planning consultation zones, use modelling to predict the extent of the zones in order to understand the implications.
5. Ensure that there is a site toxic refuge and muster alarm system in place.
6. If predictive work demonstrates a significant offsite risk from a toxic release, develop an offsite emergency plan.
7. After assessing risk of toxic release, provide ammonia gas detection at the ammonia storage.
8. Provide remotely operated shut-off valves on ammonia tank outlets
9. If predictive work demonstrates a significant offsite risk from a toxic release, develop an offsite emergency plan.
10. In boiler room, provide ammonia gas detection with audible and visual alarm and determine requirement for personal ammonia gas detectors.
11. Provide training, equipment, and people able to carry out emergency intervention using breathing apparatus.

Recommendation
12. Confirm if boiler flame out detection works with ammonia (Magic Eye)
13. Determine material of construction requirement for flue stack taking account of potential presence of ammonia/ammonia hydroxide as well as new combustion products with high NOx.
14. Determine type of connection to be used at ammonia road tanker offloading, as well as the method of leak prevention for this connection and confirm if pressure test is required.
15. If predictive work demonstrates a significant offsite risk from a toxic release, develop an offsite emergency plan.
16. Provide gas detection at ammonia tanker offloading point.
17. Ensure that there is a deadman's handle on the road tanker such that when released, it closes tanker outlet valve.
18. Determine requirement for fixed water curtain facility at the ammonia road tanker offloading bay to dilute and absorb released gas.
19. Determine safe method and location for ammonia pressure relief exhaust. Increase height for discharge if required, based on dispersion modelling.
20. Determine method for removing ammonia from one of the tanks including requirements for water absorber (scrubber) or vapour compressor for transfer to other storage.
21. Determine requirement for breathing apparatus equipment and training for maintenance technicians.
22. Ensure the use of personal gas detection when carrying out maintenance tasks.
23. Assess likely exposure of ammonia to tanker driver during ammonia delivery and reduce where possible including providing Respiratory Protective Equipment and Personal Protective Equipment.
24. Review structural supports of tanks taking account of density and fill level of ammonia, which may change the loading when compared to current loading.
25. Review requirements including environmental permitting for NOx or ammonia reduction and provide additional safeguards e.g., optimised combustion or post combustion treatment as required.
26. Due to additional toxicity of ammonia, seek advice whether additional security measures are needed on sites to prevent malicious damage leading to a release.

Recommendation
27. Review current emergency procedures for road tanker accidents and modify to take account of ammonia hazards.
28. Review safe systems of working including training for all technicians who will be working on ammonia. Maintenance inspection of ammonia systems will be new to technicians currently working on propane systems.
29. If fixed point ullage measurement is to be used, ensure modification of exhaust route for vapour release. Alternatively, provide different type of level instrument.
30. Review boiler operation parameters to prevent damage to the boiler tubes by ammonia combustion products temperature.
31. Pressure relief valve sizing to be reviewed when converting to different fuel.
32. Confirm likely maximum pressures in delivery road tankers. Assess the risk of exceeding safe pressures in the receiving storage tanks and ensure there are sufficient pressure safeguards.
33. Determine fill level limit for ammonia storage taking account of thermal expansion.
34. Review overfill protection on tanks and ensure sufficient integrity for ammonia use.
35. Carry out a review of all materials that come into contact with ammonia or ammonia mixtures (propane or hydrogen) (note presence of brass)
36. Review inspection frequency and type of inspection for ammonia tanks to prevent stress corrosion cracking.
37. Confirm suitability of existing PE supply pipeline for ammonia.
38. Determine material of construction requirement for flue stack taking account of potential presence of ammonia/ammonia hydroxide as well as new combustion products with high NOx.
39. Determine flue height requirement for safe dispersal of unburnt ammonia.
40. Confirm whether unburnt ammonia/NOx in combustion gases can cause damage to boiler internals.
41. Develop site emergency procedures which includes immediate action to prevent fires in area of ammonia tanks.
42. DSEAR Risk assessment should be carried out to determine requirements for ignition controls, including specifying type of Ex electrical equipment.

Recommendation
43. Determine risk of generation of static electrical charge caused by flowing ammonia within pipework.
44. Determine requirements for earth bonding, flowrate limits or other precautions against static accumulation.
45. Confirm whether boiler house fire detection is suitable for ammonia fires.
46. Determine flue height requirement for safe dispersal of unburnt ammonia.
47. Confirm if design code for tank and pipework is appropriate for ammonia & propane
48. Confirm that the current design code of pipework is appropriate for ammonia & propane.
49. Make provision of ammonia/propane gas detection - audible and visual alarm.
50. Provide Remotely Operated Shutoff Valves (ROSOVs) for Emergency Isolation
51. Make provision of ammonia/propane gas detection - audible and visual alarm.
52. Determine requirement for personal ammonia/propane gas detectors.
53. Ensure emergency intervention requiring breathing apparatus is provided with adequate resources, training, equipment and maintenance.
54. Confirm if flame out detection works with ammonia/propane mix (Magic Eye)
55. Review inspection period for tanks converted to ammonia use and confirm if it is appropriate for ammonia & propane.
56. Determine requirement for water curtain to dilute and absorb ammonia gas.
57. Ensure operational controls are in place to manage simultaneous arrival of tankers carrying ammonia and propane.
58. Determine method for detection of deviations in fuel mixtures and safeguards for preventing toxic emissions via the combustion gasses.
59. Review boiler operation parameters to prevent damage to the boiler tubes by ammonia/propane combustion products temperature.
60. Ensure the fire detection system can detect fires from ammonia/propane mix.

Recommendation
61. Confirm whether the pipework design code is suitable for ammonia & where appropriate, for ammonia/hydrogen mix.
62. Make provision of ammonia/hydrogen gas detection - audible and visual alarm.
63. Determine requirement for personal ammonia/hydrogen gas detectors.
64. Confirm if flame out detection works with ammonia/hydrogen mix (Magic Eye)
65. Determine safe operating method, possibility including purging to prevent air entry into cracker.
66. Review boiler operation parameters to prevent damage to the boiler tubes by ammonia/hydrogen combustion products temperature.
67. Provide protection to operators from high temperatures from the cracker.
68. Review materials of construction of the cracker and downstream of the cracker and ensure suitability for hydrogen at different temperature ranges.
69. Determine pressure and leak testing methods for hydrogen e.g., the use of helium tracer gas.
70. Consider providing additional temporary boiler during modification period.
71. Ensure fire detection is suitable for hydrogen, ammonia, and hydrogen/ammonia mix.
72. Ensure gas detection is suitable for hydrogen, ammonia, and hydrogen/ammonia mix.
73. Ensure that any building that has potential for hydrogen leak within it has a vent at its highest point to prevent accumulation of the hydrogen.
74. Ensure that on loss of power supply, the cracker will be shut down to a safe state.
75. Determine the need for inert gas purging when using hydrogen-based fuels.
76. Review safe systems of working including training for all technicians who will be working on ammonia/hydrogen and hydrogen systems.
77. Confirm that current tools and PPE used for propane work would be adequate for intervention on the hydrogen or ammonia/hydrogen systems. Refer to review carried out by HSE on tools and PPE for hydrogen use in gas distribution.
78. Determine control system requirement for the cracker

Table 3.4 - HAZID Recommendations

3.2.3 Task 3 - Regulatory risk

The objectives of Task 3 were to:

1. Identify the regulatory risk for a potential non-COMAH site and a lower- tier COMAH site; and
2. Carry out consequence modelling to assess the safety implications of the combustion of ammonia, ammonia/propane mixtures, and ammonia/hydrogen mixtures.

Regulatory Implications of Dangerous Substance Quantity Stored

The United Kingdom's Control of Major Accident Hazards (COMAH) Regulations 2015 purpose is to prevent major accidents involving dangerous substances and limit the consequences of any accidents which do occur to people and the environment. The regulations specify that any establishment having any dangerous substance specified in Schedule 1 of the COMAH Regulations, that is present at or above the qualifying quantity is subject to the regulations. The two thresholds for the qualifying quantities of dangerous substances have been set and are known as lower tier and upper tier.

For ammonia, propane and hydrogen, the qualifying quantities for lower and upper tier COMAH sites according to Schedule 1 of the COMAH Regulations are presented in Table 3.5. Any quantities stored at or above these qualifying quantities put a site into a lower tier or upper tier. Where quantities of dangerous substances stored are below the qualifying quantities, the site can be considered a non-COMAH site.

Dangerous Substance	Qualifying quantity for Lower Tier (in Tonnes)	Qualifying quantity for Upper Tier (in Tonnes)
Ammonia	50	200
Hydrogen	5	50
Propane	50	200

Table 3.5 - Qualifying Quantities of Dangerous Substances

The dangerous substance includes any form of the raw material, product, by-product, residue or intermediate. The mixtures of these substances are treated in the same way as the pure substance, so far as they remain in the concentration limits set according to their properties under the Classification, Labelling and Packaging (CLP) Regulation.

Flogas customers typically have 25 tonnes of LPG of onsite storage, meaning that these sites are usually non-COMAH sites. To remain non-COMAH sites, Flogas customers will be required to store the dangerous substances below the qualifying quantities, i.e., less than 50 tonnes of ammonia and 5 tonnes of hydrogen. It should be noted however, that the COMAH Regulations contain rules for aggregating sub-threshold quantities of dangerous substances in the same or similar generic categories. The aggregated quantities may lead to the installation qualifying under COMAH where it had not done so previously. This aspect of the COMAH regulations will need to be taken into consideration when storage of ammonia and hydrogen or ammonia and propane at the same site is being considered along with any other flammable or toxic substances.

Some Flogas customers are already lower tier COMAH sites, based on storage of other flammable substances as part of their operations (e.g., whisky). The qualifying quantity for a P5c flammable liquids dangerous substance (assumed to be the appropriate category for whisky) is 5,000 tonnes for lower tier and 50,000 tonnes for upper tier. Where these distilleries store less than the upper tier qualifying quantity of additional hazardous substances (i.e. less than 200 tonnes of ammonia or less than 50 tonnes of hydrogen or less than 200 tonnes of propane, threshold quantities which would cause the site to automatically qualify as upper tier), the aggregation rule should be applied to verify whether the site qualifies as an upper tier COMAH site. For example, a storage of 49,000 tonnes of whisky and 24 tonnes of ammonia, both less that their individual qualifying quantities for upper tier will be calculated as follows to understand if the site will remain within the lower tier or become an upper tier site:

$$49000 / 50000 + 24 / 200 = 0.98 + 0.12 = 1.1$$

As this result is greater than 1, COMAH will apply at upper tier.

Alongside the COMAH regulations, the Planning (Hazardous Substances) Regulations 2015, the Town and Country Planning (Hazardous Substances) (Scotland) Regulations 2015 or the Planning (Hazardous Substances) (Wales) Regulations 2015 will also apply if the stored quantities are at or above the thresholds in these regulations. Sites utilising ammonia as a fuel will need to obtain Hazardous Substances Consent in order to store these quantities of dangerous substances. The HSE is a consultee and advises the planning authority on land-use planning restrictions around the installation. The presence of ammonia may affect land-use planning restrictions for the site, as the Hazardous Substance Authority (usually the local planning authority) will need to consider whether the presence of a significant quantity of a hazardous substance is acceptable for the site.

For the lower tier COMAH site, a Major Accident Prevention Policy (MAPP) will need to be developed that details the major accident hazards and possible major accident scenarios in relation to the site, ensures these major accident hazards are clearly understood, and ensures that measures (including management system aspects) of prevention, protection and mitigation to limit the consequences of a major accident are adequate in preventing and mitigating the effects of major accidents involving dangerous substances which can cause serious harm to people and / or the environment. The overall objective of which will be to provide a high level of protection in a consistent and effective manner. The MAPP is an internal document but is likely to be requested for review by the COMAH Competent Authority (Health and Safety Executive & SEPA in Scotland, HSE and Environment Agency in England and Wales).

The regulator risk implications assessment indicated the following:

- To remain non-COMAH sites, the sites will require to store the dangerous substances below the qualifying quantities, i.e., less than 50 tonnes of ammonia, 50 tonnes for propane and 5 tonnes of hydrogen. However, COMAH regulations relating to rules for aggregating sub-threshold quantities of dangerous substances will need to be taken into consideration when storage of ammonia and hydrogen or ammonia and propane at the same site is being considered along with any other flammable or toxic substances.
- The sites will need to obtain Hazardous Substances Consent in order to store quantities of dangerous substances at or above the COMAH thresholds.
- For the lower tier COMAH site, a Major Accident Prevention Policy (MAPP) will need to be developed that details the major accident hazards and possible major accident scenarios in relation to the site, ensures these major accident hazards are clearly understood, and ensures

that measures (including management system aspects) of prevention, protection and mitigation to limit the consequences of a major accident are adequate in preventing and mitigating the effects of major accidents involving dangerous substances which can cause serious harm to people and / or the environment.

Consequence modelling

The consequence assessment carried out provides a generic consequence modelling results for ammonia, ammonia ammonia/hydrogen mixture and ammonia/propane mixture releases, solely for the purpose of providing typical hazard ranges.

The consequence modelling results presented have used assumptions and inputs from other previous Quantitative Risk Assessments that DNV has carried out. The fire and toxic effects consequence modelling are based on defined source terms, for which the derivation of representative release rates and other discharge parameters are key part of the analysis, while accounting for key safeguards such as isolation. The consequence modelling includes comparing assumptions around pressure depletion transients, rainout, dispersion from bunded pools, process and pipeline configuration and sizing etc. For toxic effects, the release duration assumption has been a key factor, as dose accumulates over time. Therefore, some comparison of Emergency Shutdown success and failure results have been presented.

The results of the consequence modelling are not shown in full here, however the key conclusions are summarised below.

- The most significant risk driver is the toxic effects of the ammonia, with flammability and ignition being a lower order risk.
- The toxic effect for releases of pure ammonia were the worst cases, reducing to about half the distance for mixtures of ammonia/propane mixtures modelled and further reduced ammonia/hydrogen mixtures modelled.
- Jet fires had the greatest effect distance of the hazards modelled for ammonia/hydrogen mixtures.
- Onsite and offsite receptors identified within the toxic effect distances/zones of release ammonia and ammonia mixtures of propane or hydrogen are likely to be impacted and there will be safety concerns associated with these impact zones.
- Other factors such as weather conditions and distances to identified receptors also influence these impact zones and the associated risk.

It was recommended that site specific assessment is carried out to further understand the risks from releases of ammonia, ammonia/propane, or ammonia/hydrogen mixtures to the Flogas chosen sites for Phase 2.

3.3 Configuration Selection

The results of the first two work packages culminated in the selection of a preferred ammonia boiler configuration to be taken to the design and testing stage.

The techno-economic analysis showed that boiler configuration 3 (ammonia/LPG) was of limited long-term value due to the high fraction of LPG required in the fuel mix to achieve acceptable flame speeds (23% by mass). This would lead to only modest CO_2 reductions. However, the analysis showed that it is by far the lowest cost ammonia-based fuel option, meaning it is an interesting transitional solution. The study also recommended minimizing the amount of cracking needed, to reduce fuel costs associated with losses in the cracking process.

The HAZID provided recommendations to mitigate the risks associated with an ammonia-fed steam boiler system. It showed that the most significant risks relate to ammonia's toxicity. Therefore, as ammonia is present in all fuel mixtures, the risk profile of each configuration is similar and acceptable, provided these recommendations are implemented. As a result, from a safety perspective, each configuration is viable as an option.

Cardiff University has been developing its own burner head design which was compatible with the recommendations of the studies. The patent-pending ammonia burner is integrated with an ammonia cracker located within the combustion chamber. This design has several important advantages, namely:

- Ammonia is the only fuel supplied and stored at the combustion site, except for the fuel required for the start-up of the burner (e.g., propane).
- Ammonia is mixed with hydrogen, acting as a combustion promoter. The hydrogen in the mixture greatly enhances the combustion properties and flame stability that are the main challenges for pure ammonia combustion.
- The hydrogen is obtained by cracking the ammonia molecules via an integrated ammonia cracker inside the combustion chamber. Heat losses from the cracker are therefore minimised, as the heat that would have been lost to the environment when cracking upstream of the boiler ends up inside the combustion chamber, heating the steam. Through this design, the thermal efficiency of the system as a whole is therefore much improved, and more in line with the pure ammonia configuration.
- Testing at Cardiff University's laboratory suggests that NOx emissions are minimised when ammonia is burned rich at an equivalence ratio (the ratio between the oxygen content in the oxidant supply and that required for complete stoichiometric combustion) of 1.2. Therefore, the system operates a two-stage combustion process, whereby the bulk of the fuel is burned rich in Stage 1 (to minimise NOx), followed by a post-combustion zone with hot unburned ammonia traces capable of reducing remaining NO. The process, known to produce large H_2 concentrations, will be followed by lean combustion in Stage 2 of the combustor, hence minimising any fuel residue in the flow gases.

Figure 3.10 shows a simple block flow diagram of the design.

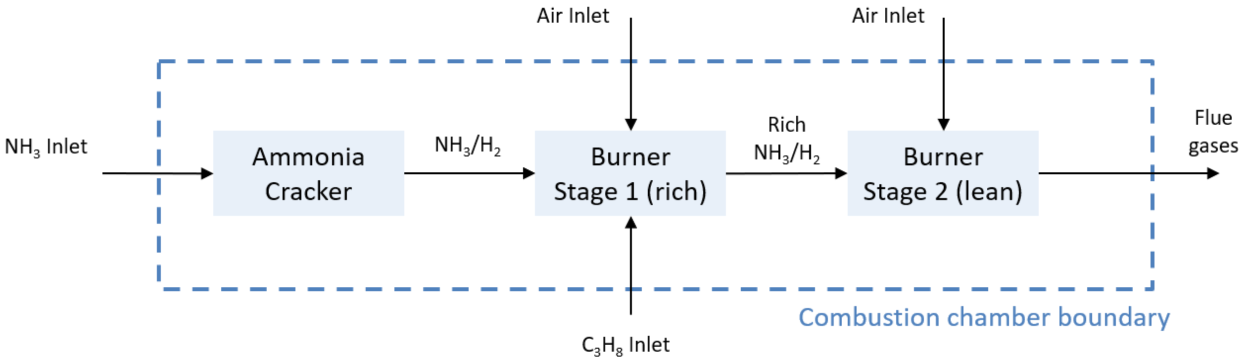


Figure 3.10 - Block flow diagram of design concept

The design is able to meet customer needs in the short and long term, as the burner can operate with tri-fuel capability ($NH_3/H_2/C_3H_8$), and run on a variety of different fuel ratios, including 100% LPG, with minimal efficiency loss. This means customers can operate in the short term with LPG and transition to ammonia/hydrogen mixtures to meet future net-zero targets.

3.4 Laboratory Testing

The objective of the laboratory testing within the study was to determine the stability zones for different propane/ammonia/hydrogen turbulent swirling flames, as well as understand the optimal operating conditions for various fuel blends with respect to NOx emissions.

Previous studies by Cardiff University [1] have examined stability maps of methane/ammonia/hydrogen ternary blends in an industrial scale swirl burner. However, mixing with propane had not been considered previously, despite it being a potential key aspect for the transition from propane to ammonia/hydrogen.

The lab scale burner at 25-50 kW, designed by Cardiff University, was tested at Cardiff University's ammonia testing facility to find the optimum operating conditions for various fuel blends as it relates to flame stability and NOx emissions.

3.4.1 Materials and methods

Fuel and air flows in the burner were supplied using dedicated Bronkhorst mass flow controllers (±0.5% within a range of 15-95% mass flow). Ternary blends stability zones were obtained with a constant hydrogen volume percentage of 10-50%, at 10% intervals. In addition, ammonia/propane and ammonia/hydrogen stability maps were also investigated. Experiments were conducted at atmospheric pressure (1.1 bara) and inlet temperature (288 K) with a constant fuel inlet thermal power of 10 kW. A Logitech C270 camera was used to monitor the flame stability at a distance of 5m.

A pair of LaVision CCD cameras were employed to obtain line-of-sight chemiluminescence traces of various species. The units were triggered simultaneously at a frequency of 10 Hz with constant gain. A range of optical (Edmund) filters were used for each species of interest, namely OH*, NH* and NH_2*. Exhaust emissions (NO, N_2O, NO_2, NH_3, CO, CO_2, O_2 and H_2O) were measured using a bespoke Emerson CT5100 Quantum Cascade Laser analyser.

3.4.2 Results and discussions

Stability Mapping

Figure 3.14 shows initial operability maps using propane/ammonia binary fuels. The figure shows a decrease in stability as the mole fraction of ammonia in the blend increases. The stable region remains somewhat constant up to $70_{vol.\%NH3}$, but further increase in ammonia mol fraction reduces the stable zone severely, as ammonia chemistry becomes dominant. It must be noted flashback was not observed in these binary blends as the flame speeds were not high enough to force flashback.

Figure 3.11 shows the stability map of propane/ammonia/10% hydrogen blends. Up to $20_{vol.\%}$ ammonia, the stable zone limits were similar to the binary propane/ammonia blends. But from $30\text{-}50_{vol.\%}$ ammonia, propane mole fraction decreases by a certain margin to allow hydrogen chemistry becoming dominant, and thus enhancing the stable zone region. As ammonia mole fractions increases beyond 50%, ammonia chemistry takes over and stability zone shrinks.

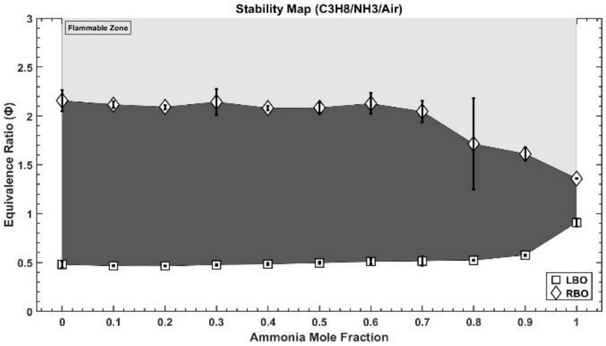


Figure 3.14 - Stability map of propane/ammonia flames.

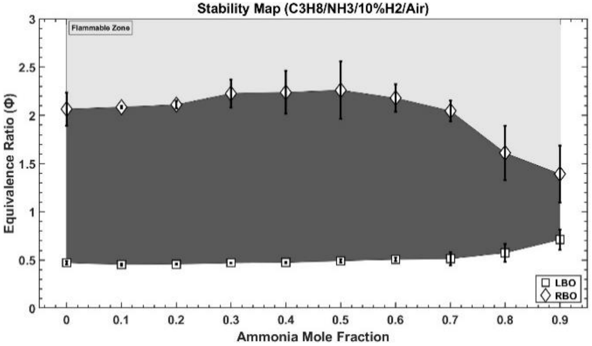


Figure 3.11 - Stability map of propane/ammonia/10% hydrogen flames.

Figure 3.13 and Figure 3.12 show the ternary operability limits with constant $30_{vol.\%}$ and $50_{vol.\%}$ H_2, respectively. With mole fraction of hydrogen ≥ 0.3, flashback phenomenon is observed as the flame speed increases substantially. For the $30_{vol.\%}$ hydrogen flames, the stability zone only widens when propane mole fraction drops below 30% and performs better than $10_{vol.\%}$ H_2 scenarios. Even though flashback was only observed for $70/30_{vol.\%}$ NH_3/H_2 blend in Figure 3.13 , flashbacks were observed for $50_{vol.\%}$ H_2 cases in wider cases ($X_{NH3} \geq 0.3$). For these cases, $X_{NH3} \geq 0.3$, wider blow off limits were also observed due to high hydrogen and low propane presence in the blends.

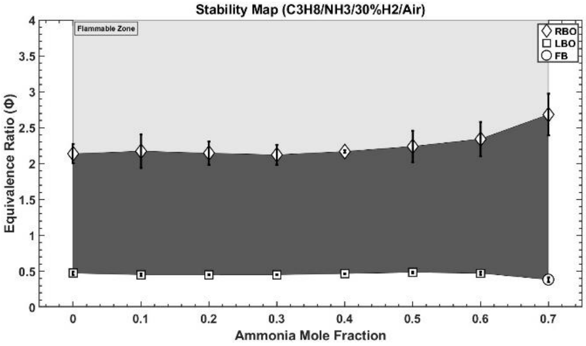


Figure 3.13 - Stability map of propane/ammonia/30% hydrogen flames

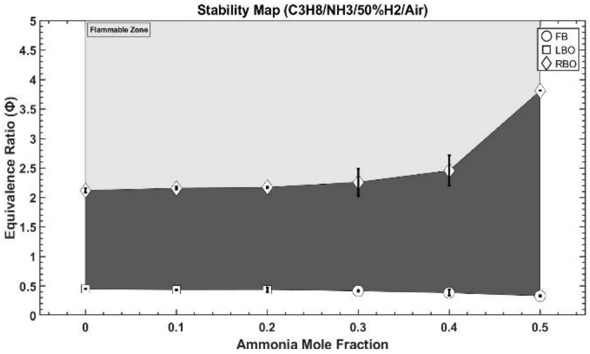


Figure 3.12 - Stability map of propane/ammonia/50% hydrogen flames.

Based on the results and analysis of the operability limits, 12 blends (Table 3.6) were chosen for further analysis. Experiments were carried out at four equivalence ratios (Φ = 0.6,0.8,1.0 and 1.2) for these blends. Chemiluminescence (OH^*, NH^*, C_2^*, NH_2^*) and exhaust emissions measurements (NO, NO_2, N_2O, NH_3, CO, CO_2, O_2 and H_2O) were taken at each point to identify possible suitable blends to achieve low emissions.

Blends	C_3H_8 (vol.%)	NH_3 (vol.%)	H_2 (vol.%)
1	90	10	0
2	80	15	5
3	70	20	10
4	60	25	15
5	50	30	20
6	40	35	25
7	30	40	30
8	20	45	35
9	10	50	40
10	0	55	45
11	0	60	40
12	0	70	30

Table 3.6 - Selected blends for further analysis

Chemiluminescence Analysis

Figure 3.15 shows the changes in radicals formation at stoichiometry for the selected blends shown in Table 3.6. Colourmaps are normalized to species dataset maximum to display the change in intensity of radical formations.

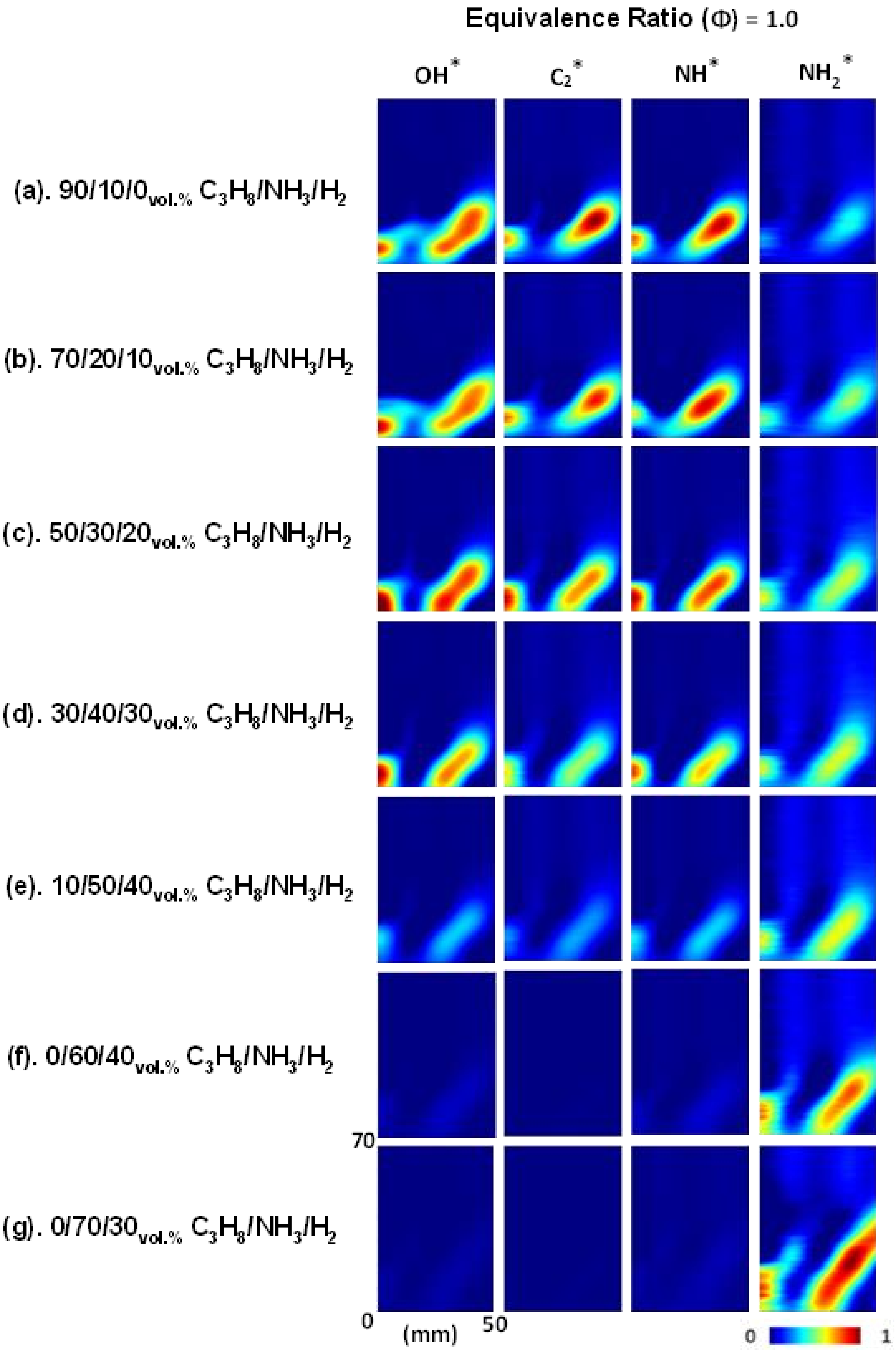


Figure 3.15 - Changes in radicals formation at stoichiometry for the selected blends.

At stoichiometry, intensities of OH*, C_2* and NH* decreases with increasing ammonia contents in the flames, whereas NH_2* follows the opposite trend. The flame thickness also increases with increasing ammonia content. Further analyses of OH* and NH_2* formations across difference equivalence ratio showed that OH* intensity peaks at $\Phi = 0.8$, while NH_2* intensity peaks at $\Phi = 1.2$. Also, OH* intensities were found to be peaking at $X_{NH3} = 0.45$ which can be attributed to increase in H_2 content in the blend with sufficient amount of propane present. These changes in radical formations control the emissions performances of these blends which will be analyzed in the following section.

Emissions Analysis

All the emissions data reported in this section are normalised to 15% O_2. Figure 3.18 and Figure 3.19 show the sampled NO and NO_2 emissions across different fuel blends and changing equivalence ratios, respectively. Both NO and NO_2 peaks at $\Phi = 0.8$ and $X_{NH3} = 0.45$, which coincided with maximum OH* production. This observation is in line with the findings from previous studies [1] [2]. OH reacts with NH to produce HNO through the reaction $OH + NH \leftrightarrow HNO + H$, which then reacts with OH, O and H radicals to produce NO. NO_2 is directly related to NO through the reactions $NO + HO_2 \leftrightarrow NO_2 + OH$ and $NO + O + M \leftrightarrow NO_2 + M$ and revert back to NO by reacting with H radical [3].

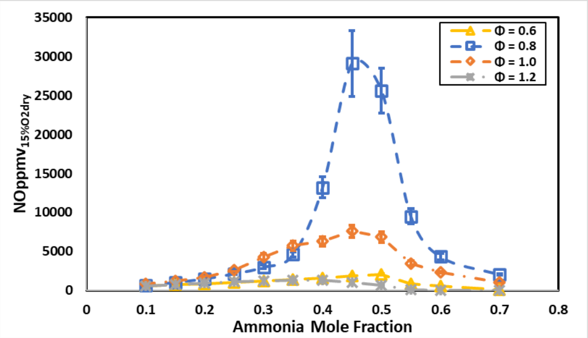


Figure 3.18 - Sampled NO emissions with changing blends and Φ.

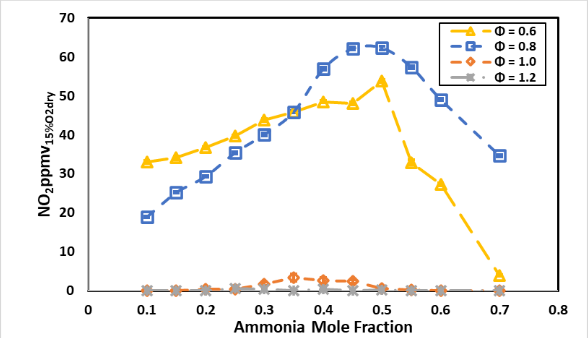


Figure 3.19 - Sampled NO2 emissions with changing blends and Φ

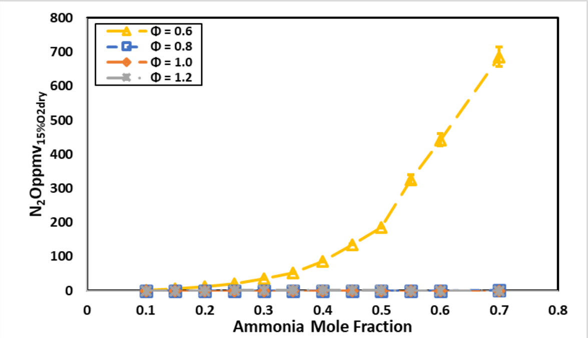


Figure 3.17 - Sampled N2O emissions with changing blends and Φ.

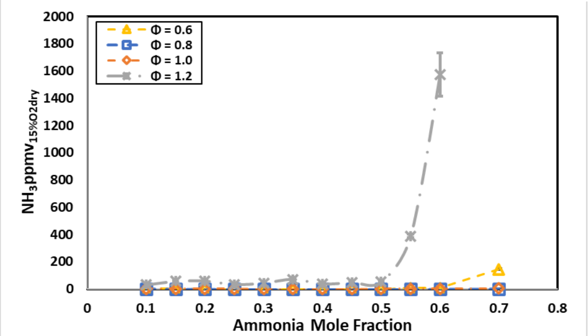


Figure 3.16 - Sampled NH3 emissions with changing blends and Φ.

Sampled N_2O and NH_3 emissions for different blends with changing Φ are shown in Figure 3.17 and Figure 3.16, respectively. N_2O is a greenhouse gas with 280 times global warming of potential (GWP) than CO_2. NH reacts with NO to produce N_2O in the flame but most of these N_2O reduce to N_2 through the reactions $N_2O + H \leftrightarrow N_2 + OH$ and $N_2O + M \leftrightarrow N_2 + O + M$. N_2O emissions is a concern at $\Phi = 0.6$ for the blends studied here due to low H radical production and low flame temperature as shown by recent studies [3]

[4] [5] [6] [7]. Unburnt ammonia emissions is a concern for the rich conditions but can be averted by the use of two-stage rich-quench-lean (RQL) burner system [8] [9] [10]. At Φ = 1.2, unburnt ammonia emissions increases significantly at $X_{NH3} > 0.5$. Below $50_{VOL.\%}$ NH_3 content in the fuel, high presence of propane ensures significant OH production which reduces ammonia through the reaction $NH_3 + OH \leftrightarrow NH_2 + H_2O$.

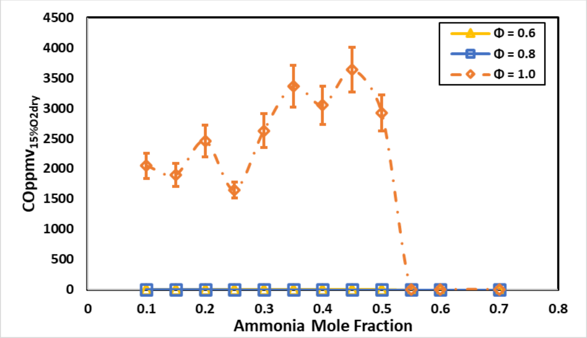


Figure 3.21 - Sampled CO emissions with changing blends and Φ.

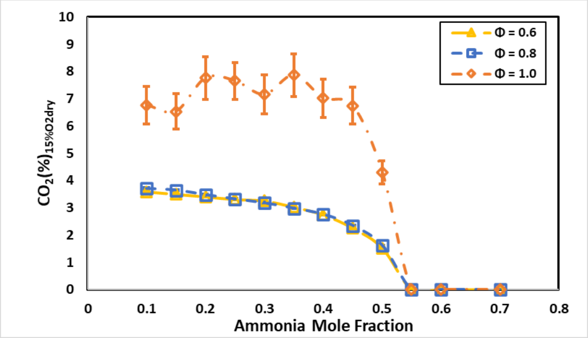


Figure 3.20 - Sampled CO2 emissions with changing blends and Φ.

No CO emissions were found at the lean conditions considered here but high amount of CO was observed at the stoichiometry and rich conditions (Figure 3.21) due to incomplete combustion of propane. CO_2 emissions decreases with increasing ammonia content in the fuel (Figure 3.20). CO_2 emissions at the lean conditions followed each other very closely.

From the above analysis, Φ = 0.6 can be considered for retrofitting in the current industrial combustion systems (Figure 3.22). NOx emissions were found to be low for $X_{NH3} \leq 0.3$ at Φ = 0.6. No nitrous oxide and carbon monoxide emissions were observed for these blends and CO_2 emissions were below 4% (Figure 3.21). These ternary blends can be considered for the existing combustion systems with selective catalytic reduction (SCR) system in place during the transition stage towards zero carbon fuels. However above $30_{VOL.\%}$ ammonia blends at Φ = 0.6, NO and NO_2 emissions increase significantly and thus limiting the use of these blends.

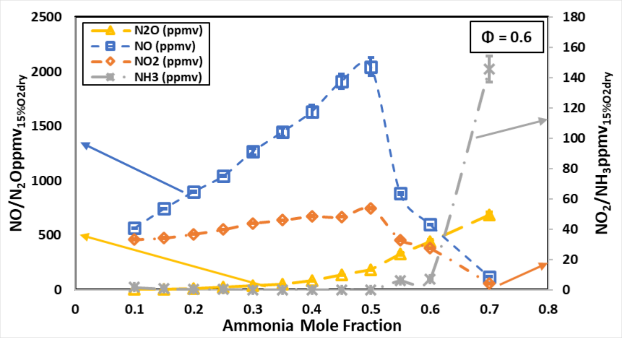


Figure 3.22 - Sampled NO, NO2, N2O and NH3 emissions with changing blends at Φ = 0.6.

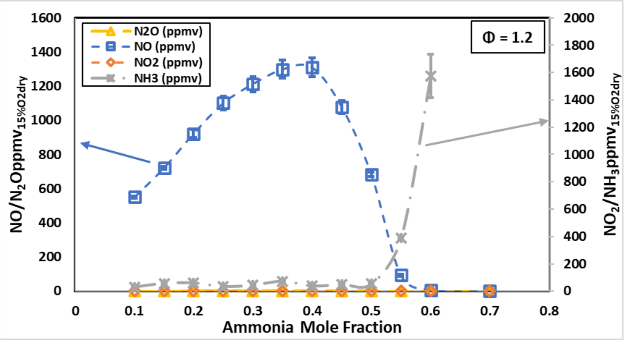


Figure 3.23 - Sampled NO, NO2, N2O and NH3 emissions with changing blends at Φ = 1.2.

With two-stage RQL burner in place, all these blends can be considered towards zero emissions. At Φ = 1.2, these blends showed high CO, CO_2, and NO emissions with high propane contents in the blends and high NH_3 emissions at $X_{NH3} > 0.5$ (Figure 3.23). However, during the 2nd lean stage with the presence of excess air and high H_2 content, these emissions will drop significantly [11] [12] [13]. Furthermore, transition towards ammonia/hydrogen blends will ensure absolute zero emissions.

Conclusions

The work conducted in this study examines the combustion characteristics of different fuel blends of propane/ammonia/hydrogen in air, using a newly designed premixed/stratified burner from Cardiff University that is currently under patent application.

One of the key challenges facing direct ammonia combustion is its low flammability, which is what has merited the examination of blending ammonia with other fuels such as propane and hydrogen in this study.

Increasing the hydrogen mole fraction in the fuel blend has been shown to widen the operability limits. This occurs when the other two fuel mole fractions (ammonia and propane) are in a certain range to allow hydrogen to take over the flame chemistry. For $X_{NH3} \geq 0.7$ and $X_{H2} \leq 0.2$, ammonia chemistry becomes dominant and shrinks the operability regions.

NO and NO_2 emissions peaked at Φ = 0.8 and $X_{NH3} = 0.45$ due to high presence of OH radicals. Significant amount of N_2O emissions were observed at Φ = 0.6 for $X_{NH3} > 0.3$ due to lower production of H radicals and low flame temperature. High unburnt ammonia emissions were observed for ammonia/hydrogen blends due to low production of OH radicals. Significant amount of CO emissions was observed at Φ ≥ 1.0 due to incomplete combustion of propane. Blends with $X_{NH3} \leq 0.3$ can be considered for retrofitting at the existing combustion system at low equivalence ratio (Φ = 0.6) with SCR in place. All these blends can be potentially used in two-stage RQL burner system without any SCR system at the transition stage towards zero emissions systems with ammonia/hydrogen blends. However, this requires a combustion chamber redesign to operate at rich conditions (the first stage of a RQL system).

3.5 CFD Simulations

As part of Amburn Phase 1, Enertek International, with support from Cardiff University, has produced a Computational Fluid Dynamics (CFD) model of the combustion taking place within the selected ammonia burner configuration. The results from the CFD model were compared with the experimental data obtained by Cardiff University in the laboratory testing, to verify the accuracy of the CFD model. The CFD model is planned to be used in Phase 2 to guide the burner design.

As was previously found in the literature review, the most promising conditions for low NOx ammonia combustion are:

a) an equivalence ratio of ~1.2 in the first (rich) stage of combustion and;

b) secondary air entrainment for lean combustion in the second stage.

As these conditions are expected to be used in Phase 2, these conditions are modelled in the CFD simulations. It should be noted that only the first stage of combustion was modelled in the simulations presented here.

The CFD simulation results are presented in Figure 3.24.

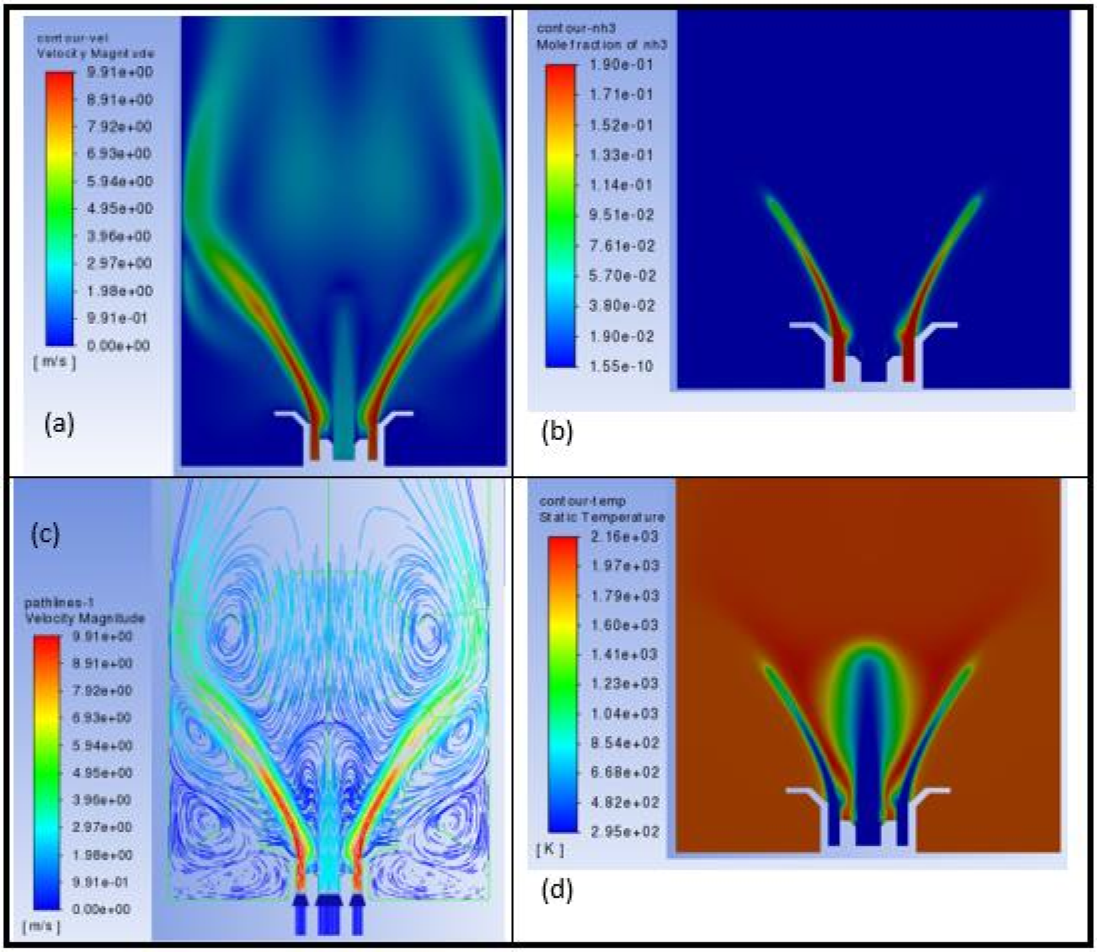


Figure 3.24 - 2D CFD predictions, a – contours of velocity magnitude, b – contours of mole fraction of ammonia, c – flow path-lines coloured by velocity magnitude, d – contours of temperature

It can be seen in Figure 3.24, most clearly in section b, that a “V” shape flame was predicted from the CFD model. This is the typical flame shape desired in a swirl burner.

The predicted mole fractions of the intermittent species of the combustion reaction (OH, NH and NH_2) are depicted on the left-hand side of Figure 3.25.

These intermittent species are expected to predominantly appear in the region of the flame front, which allows to use them as an indication of the flame shape. The experimental chemiluminescence images of these species are presented on the right hand side of Figure 3.25 for comparison purposes.

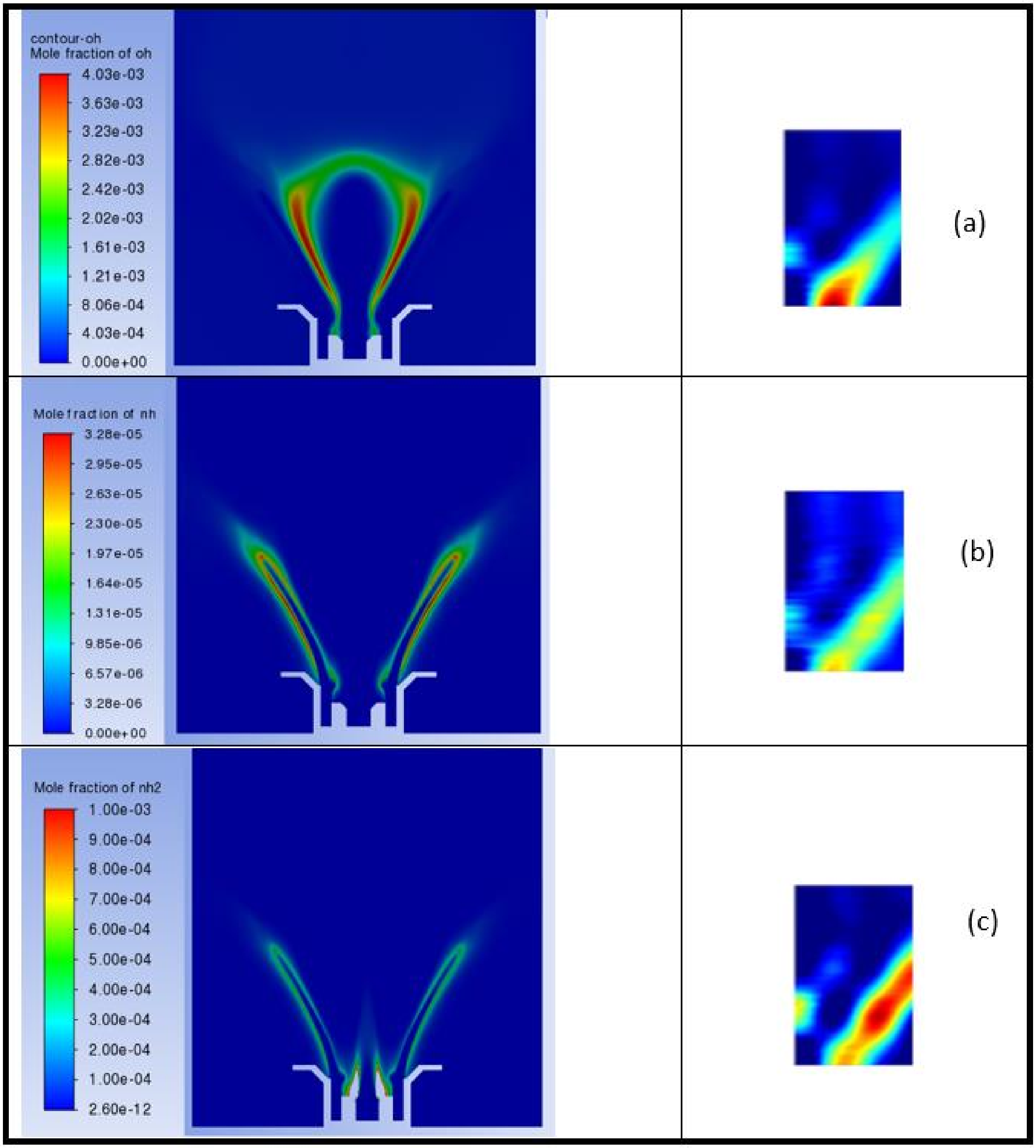


Figure 3.25 - Predominant locations of the intermittent reaction species, left hand side – 2D CFD predictions, right hand side - chemiluminescence experimental images by Cardiff University, a – OH*, b – NH*, c – NH2*

The emissions predicted by means of the CFD model described in this section are presented in Table 3.7.

	NH_3	NO	NO_2	N_2O	H_2
CFD Prediction	1.007	135	0.000606	0.00326	54,286

Measurement	>2000	<2	<1	<3	

Table 3.7 - Predicted and measured emissions in ppmv

3.6 Phase 2 Planning

3.6.1 Objectives of Phase 2

The primary aim of Amburn Phase 2 is to demonstrate the 1 MW ammonia-fed burner design at a real customer site. The project will prove the technical viability of ammonia-fed steam boilers as a low carbon alternative to the oil and propane-based incumbent found in many small to medium sized off-grid industrial sites. The project is therefore envisaged to support the UK’s net-zero target of 2050 by offering a credible decarbonisation solution to these hard-to-abate sites.

The long-term aim of the project partners is to commercialise this novel technology after the demonstration.

Over the course of the Phase 2 project, the consortium will:

- Conduct a comprehensive Front End Engineering Design (FEED) of a 1 MW ammonia-fed boiler system, to be tested and optimised throughout Phase 2.
- Perform testing on the prototype design to allow for a simple, optimised, and safe system to be taken to a real customer site, with minimal efficiency losses and low costs.
- Install the boiler solution at a customer site for demonstration.
- Develop ammonia-fed steam boilers to TRL8.
- Develop a commercialisation roadmap with key industry stakeholders, such as burner manufacturers and ammonia suppliers, to be executed after project close. This will include considerations on how best to modify the prototype design for mass manufacture.

The objective of the Phase 2 planning is to prepare for a demonstration, considering all the technical challenges and uncertainties associated with a project of this size and level of innovation.

3.6.2 Conceptual design of 1 MW burner

In preparation for a demonstration in Phase 2, Cardiff University’s lab scale design concept was scaled to 1 MW by Enertek International. A concept CAD design of the 1MW ammonia burner, fitted to a combustion chamber was developed. Its intended principle of operation is identical to the small-scale ammonia burner tested in the laboratory. However, its dimensions and construction details were adjusted to make them more suitable for the intended heat input and fabrication methods applicable to this scale.

3.6.3 Scope

The Phase 1 design is believed to be viable from a technical and commercial perspective by the project partners. However, some technical challenges remain:

- **Detailed design:** The 1 MW design is currently at concept phase.
- **Optimal operation:** As no testing has been done for the scaled system, uncertainty remains over the optimum operating conditions.
- **Automated control:** The lab scale testing done in Phase 1 and prior used manual control systems. A fully automated control system, using industry standard components, has not yet been developed.

- **Hydrogen embrittlement:** Hydrogen embrittlement was identified as a potential problem in the combustion chamber when using certain materials. Cardiff University currently has a BEng student investigating hydrogen embrittlement for a variety of industry standard materials (to be completed in June/July 2023).
- **Simplified system:** Currently, the group plans to 3D print components for the burner head and use sophisticated mass flow controllers and flow meters. A design more fit for commercialisation must be developed before the wider rollout.

To address these challenges and demonstrate the system at 1 MW scale, the Amburn Phase 2 project is envisaged in two stages.

Stage 1: Detailed Design and Testing

A MW scale prototype combustion chamber will be constructed at Cardiff University's test facility. The prototype will be manually controlled to allow the project partners to assess the system's optimal operating conditions. This testing has already been done at the lab-scale by Cardiff University, but will be repeated for the specific geometries and operational environment at the larger scale. Due to the nature of the facilities at Cardiff University (in a built-up area with large student population), it is intended to run the system at 200-500 kW, hence limiting H&S issues to manageable levels at this complex.

In the first stage of testing and development, the project team intends to use a manual control system, together with a combustion chamber test facility. Mass flow meters are intended to be coupled with automatic control valves linked to PC software, in order to manually adjust flow rates of the fuels from the control panel in the PC.

Propane is intended to be supplied for the start-up and eventually be replaced by ammonia. The bulk of the ammonia fuel will be introduced slowly into the flame to allow the testing personnel to shut down operation with limited ammonia present, in the event of a malfunction during start-up. Hydrogen will be produced in the integrated cracker within the combustion chamber. The cracked gas (a hydrogen and nitrogen mixture) will either be directly supplied to the burner or separated by molecular sieves to its constituents, in order to supply the hydrogen combustion promoter to the burner.

A gas analyser will monitor the composition of the flue gas, which in theory should contain only N_2 and H_2O. Sensors will be installed to detect the presence of hazardous gases (e.g., ammonia slip), which may potentially appear either in the test room air or in the flue gas. These detecting devices are intended to be connected to automatic shut-off valves as well as to audible and visual alarms. This is to automatically close the supply of the fuel, to terminate production of the detected hazardous gases and to alarm the staff in the test room to initiate their evacuation until the hazardous substances dissipate to the surrounding air and safe atmosphere in the test room is restored.

Further to the safety precautions described above, it is planned to use a chimney in order to disperse hazardous gases which may potentially appear in the flu gas and to avoid potentially harmful concentrations of these gases on the ground. All tests will occur during the afternoon and evening times, to ensure minimum student presence in proximity to the test facility.

Stage 1 may also include additional hydrogen embrittlement tests on industry standard combustion chamber wall materials (e.g., carbon steel). This will be dependent on the result of the BEng project at Cardiff University. If the embrittlement problem is significant, the project partners intend to coat the combustion chamber walls with TBC to mitigate the issue. The Amburn partners are currently in dialogue with a coating specialist on the possibility of applying their coating process to resolve this issue.

Stage 2: Optimisation and Deployment at a Real Industrial Site

Taking the learnings from Stage 1, a simplified design with an automated control system will be developed. This design will be more appropriate for commercialisation, removing some of the more expensive manual control systems and precise delivery equipment. The simplified combustion system will then be installed into an ‘off-the-shelf’ containerised steam boiler and air delivery system. This ‘demonstrator unit’ will be delivered to the customer site for demonstration, after further testing at 1 MW to validate its technical performance and safety.

The consortium is currently engaging with potential customers to select the most suitable site for Stage 2 demonstration. This will be based on criteria including: safety (site far removed from residential areas), willingness to be involved in the project, and boiler system size (1 MW targeted). So far, the consortium has received 5 letters of support from customers, who have offered 13 sites for potential demonstration.

The details of the control system are not clear at this stage, therefore neither the schematic diagram nor further description of this system is given in this document.

3.6.4 Work Packages

The overall scope of the proposed project is broken down into 12 Work Packages (WPs).

Nº	WP Title	Partners Involved (lead in bold)	Description
1	Project Management	**Flogas** Element Energy	Overall coordination of the project.
2	Safety & HAZOP	**Safety contractor**	Detailed HAZOP study for the selected site to mitigate safety risks identified in Phase 1 HAZID. This includes the further development of health and safety procedures, building on Phase 1.
3	CFD Simulations	**Enertek**	Improvement to Phase 1 CFD model to enhance its accuracy. The CFD simulations will be used to guide the ammonia burner detailed design process.
4	Preparation of Test Facility	**Cardiff University** Enertek Flogas Safety contractor	Procurement and installation of 1 MW combustion chamber for testing at Cardiff University's test facility. This includes the installation of safety equipment identified in Phase 1 (e.g., alarms), as well as procurement of ammonia fuel and storage equipment. This includes coating the combustion chamber with TBC to reduce hydrogen embrittlement, depending on the results of Cardiff University's preliminary material testing.
5	Detailed Design of 1 MW Burner	**Cardiff University** Enertek Burner manufacturer	Detailed design, fabrication, and installation of the 1 MW Stage 1 ammonia burner concept, including integrated cracker. The burner head will nominally be fabricated using components produced using Cardiff's 3D printer, however, off-the-shelf components will also be considered where possible, to reduce burner costs.
6	Stage 1 Combustion Testing	**Cardiff University** Enertek	Operational mapping to find the optimum conditions of the 1 MW design. Nominally, this testing will be done at 200-500 kW at Cardiff's test facility. At this stage, manual control systems will be used.
7	Development of Automated Control System	**Burner manufacturer** **Enertek** Cardiff University	Based on learnings from the testing, an automated control system is developed (based on off-the-shelf systems) that is inexpensive, safe, and easy to use for the customer. A propane-based control system will be procured as a basis.

8	Procurement of Steam Boiler and Installation of Simplified Burner	**Enertek** Cardiff University Burner manufacturer Safety contractor	Procurement of ‘off-the-shelf’ 1 MW steam boiler, ideally identical to the one used at the customer site. The new burner design will be installed into the steam boiler, which will be containerised for deployment at the customer site.
9	Stage 2 Testing	**Enertek** Cardiff University Burner manufacturer Safety contractor	Final testing to ensure the containerised solution operates at the required standard and is safe to use.
10	Demonstration at Customer Site	**Flogas** Enertek Cardiff University	Transferal of the container to the customer site. This includes upskilling of the site’s staff to use the system and operate safely. Lastly, this includes the demonstration task at the site.
11	Commercialisation Roadmap	**Flogas** All partners	All project partners will develop a roadmap to commercialisation of the technology, with close collaboration with ammonia suppliers.
12	Dissemination	**Element Energy** Flogas	Knowledge sharing for the benefit of the wider sector via channels identified in Phase 1 (press releases, events, Ammonia Symposium, etc.).

3.6.5 Timeline

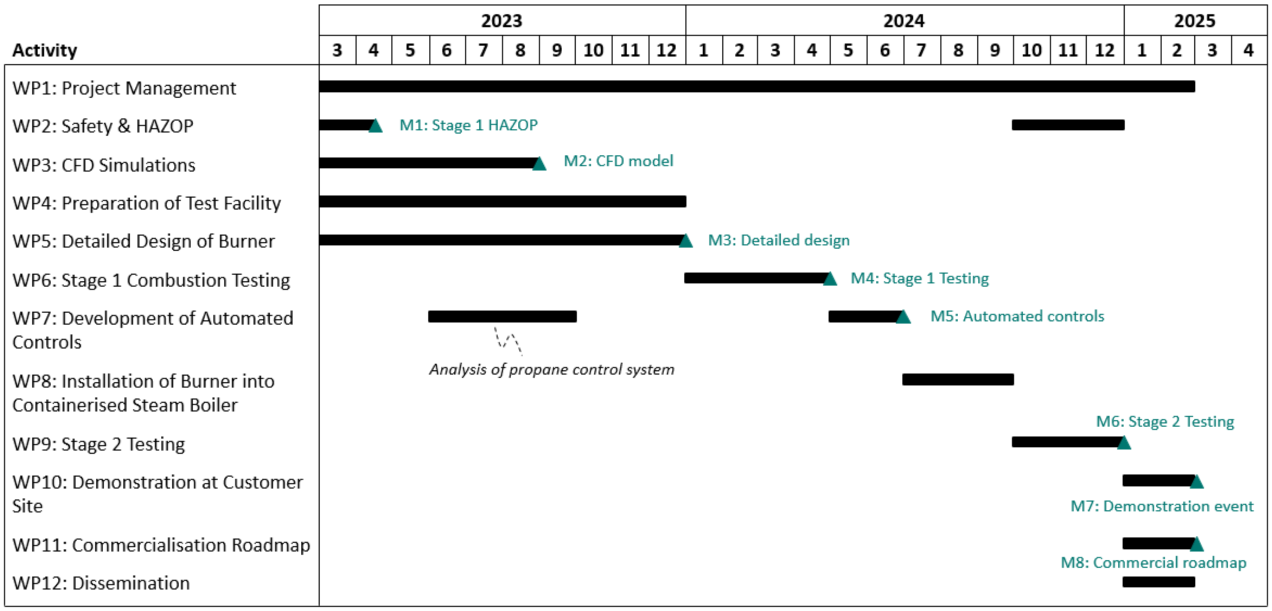


Figure 3.26 - Gantt chart for Amburn Phase 2

3.6.6 Partner roles

Organisation	**Role**
Flogas	The Flogas team will be responsible for overall project management, customer interaction, installation of the ammonia storage and delivery systems, and fuel supply logistics.
Enertek International	Enertek will support with the burner design in Stage 1 using CFD simulations, and co-develop the simplified Stage 2 design and control system with the burner manufacturer.
Cardiff University	Cardiff University will lead the detailed design and testing of the burner and integrated cracker system in Stage 1, and support with the design of the demonstrator unit in Stage 2 with combustion fundamentals expertise. Cardiff University will also fabricate the burner head using 3D printed components whilst also evaluating the reduction in costs of the system.
Element Energy	Element Energy will support with the project management and dissemination activities. The team will also support with the development of a roadmap to commercialisation and build a rollout strategy for ammonia boilers beyond the demonstration phase.
Burner manufacturer	The burner manufacturer will co-lead the development of an automated combustion system in Stage 2. They will also fabricate/procure components in Stages 1 & 2, where necessary.
Safety contractor	Responsible for a full HAZOP of the chosen customer site, as well as development of safety procedures and protocols at the test sites. The safety contractor will also be responsible for upskilling customer personnel to use the systems safely.

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