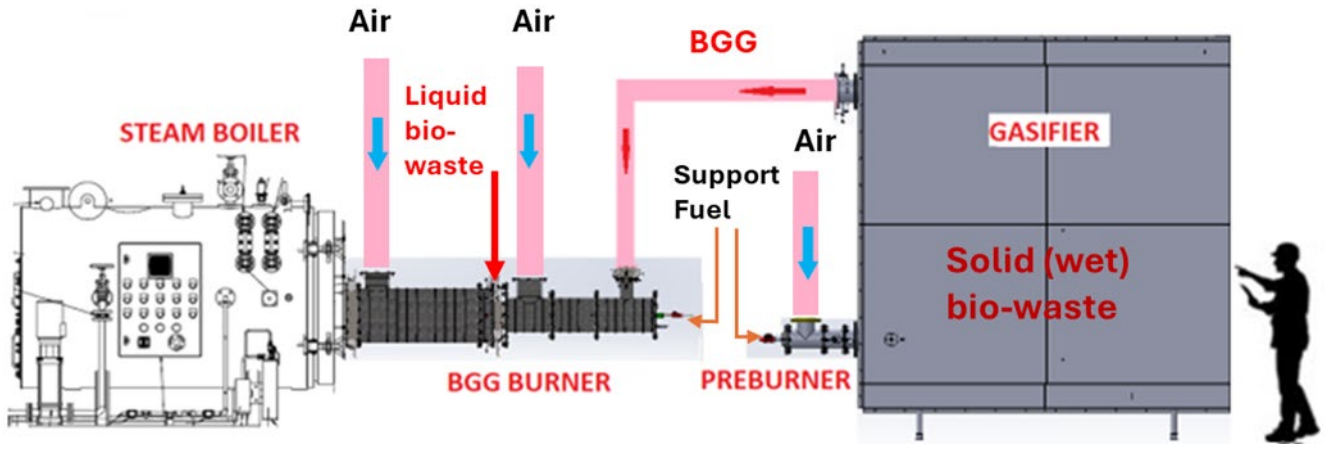
UK Government

Green Distilleries Project BATGASDW

Batch gasification of distillery waste biomass for renewable distillery fuel



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We would like to thank Ian Palmer of John Fergus, InchDairnie whisky distillery and the staff of Kingsbarns whisky distillery, for technical details of their distilleries and tours of the plants, to view the draff and pot ale waste disposal and the current steam boilers.

Contents

Executive Summary

The £10m Green Distilleries Competition, as part of the Department of Energy Security and Net Zero's £1bn Net Zero Innovation Portfolio, supports the government's approach for a clean, resilient recovery across the UK to support the creation of new jobs in the distillery sector, with an aim to support the development of the world's first green distillery. According to the Scottish Energy Hub in 2021, more than 4 Terawatt hours (TWh) are consumed by the 151 whisky distilleries, of which two thirds are currently connected to the natural gas grid, and the remaining 33% are operated using fuel oil. GD166 is one of the four demonstration projects successfully funded from 17 feasibility reports originally presented during phase 1 [R20]. The present was the only project looking at gasification of biowaste to produce a biomass gasification gas (BGG).

The BGG gas with NG assistance was shown to be able to gasify a mixed bio-waste with a large proportion of wet draff and achieve 49% decarbonisation using BGG. For dry draff with straw and wood an 85% decarbonisation was demonstrated. However, 100% decarbonisation could be achieved if the support gas for the BGG flame was hydrogen. Considerable work on hydrogen diffusion burners was undertaken as part of the project, as heating of the gasifier from cold start and the burning of low calorific BGG requires flame stability assistance at cold start, so the use of hydrogen for these cold start purposes resulted in a complete carbon neutral process. To decarbonise the third of distilleries heated by fuel oil, crude ethanol and glycerol [P2], which are currently being discarded during the automotive diesel manufacturing process, would be used. These low-cost biofuels should be used in their raw form, since purifying them comes as an unnecessary expense.

The objective of the work was to demonstrate that distillery solid draff and liquid pot ale (PA) could be used to generate useful energy, offsetting fossil fuel use and achieving some decarbonisation. Gasification of the wet waste draff was shown to be possible, but dry draff was preferable. If the energy to dry the draff was taken into account, there was little energy benefit of operating with dry draff. The other main distillery biowaste was pot ale, and this was also high in water content and the objective was to investigate ways to generate useful energy from PA. This was shown not to be useful for gasification. However, PA was shown to burn downstream of the BGG flame in an axial staged burner. PA could have the water vaporised and the heat released from the pot ale syrup (PAS). The PAS was sufficient to vaporise all the water in PA and the third distillery waste, spent lees wash (SLW).

Whisky industry waste biomass was reviewed, and it was shown that there was sufficient industry waste to fuel all the energy requirements of distilleries. However, for distillery wastes alone, there was insufficient wet draff, PA or SLW to operate the distillery without adding other waste biomass. Barley straw and wood were shown to be viable co-gasification biofuels. The waste bio-oil crude glycerol from biodiesel manufacture was investigated for gasification [P2] but was not effective. Its use in two stage combustion, injected at the same location as PA is recommended, and the second stage burner was designed to do this.

The project activities were undertaken at the Livingston Centre for Industrial Decarbonisation (LCID) in Scotland. This facility was built to deliver GD166. However, it is currently well-equipped to undertake combustion and gasification tests for decarbonisation purposes, aimed not only for the industrial sector but also the domestic heating market, whether using hydrogen or biofuels such as ethanol or glycerol.

Gasification power output from 400 kW - 2 MW was achieved, demonstrating that this approach to decarbonisation could be scaled up at no major extra cost. This corresponds to distillery production from 0.4 ML to 2 ML per year (continuous operation) using the average energy use of 30 MJ/L for distilleries. Both dry and wet draff achieve gasification, but the wet draff required more NG assistance (51%) for the combustion of BGG than the 15% NG assistance for dry draff. If low carbon hydrogen is used for heating the gasifier, then 100% decarbonisation is possible. Alternatively, the cost of hydrogen decarbonisation can be lowered by 49% using BGG to reduce the quantity and cost of hydrogen use and to achieve low-cost decarbonisation. A key feature of the results is that the gasifier load undergoes smouldering combustion if the air supply is cut off, once the preburner fuel is off. The gasifier can then supply heat simply by opening the air flow to the gasifier, with no use of fuel from the preburner cold start. The air shut down period was shown to be as long as a week if needed. For applications like distilleries, which require heat 24/7 but with periodic shutdowns, this can be achieved with this batch gasification approach. Thus, the gasifier would only need to cold star once per year after an annual maintenance shut down. Thus the flexibility of the gasification heat would be as good as using a NG burner that can be shut off when the heat is not needed. The gasifier only needs to shut the air off and no BGG fuel is delivered, but the gasifier remains hot.

Two quad-fuel (hydrogen/natural gas/diesel/ethanol) burners were developed for gasifier heating, and other two quint-fuel (BGG/hydrogen/natural gas/diesel/ethanol) burners were developed for burning the BGG released by the gasifier and providing the heat needed to run the distillery boiler. A route to distillery decarbonisation has been established.

Draff, pot ale and spent-lees-wash are waste disposal problems for distilleries and distilleries can pay farmers around £400,000 per year to dispose of these wastes. This work has shown that these wastes can be disposed of in a gasifier and a two-stage burner and the energy in the waste is sufficient to vaporise the water, eliminating the need for fossil fuels to dry these wastes. This makes their use practical and eliminates the cost of their disposal, representing a major advantage and cost-saving and demonstrating the viable use of biowaste to decarbonise whisky distilleries.

Nomenclature

Abbreviation	Meaning	Units
A/F	Air to fuel ratio by mass	kg/kg
AD	Anaerobic Digestion to produce biogas and biomethane	
BGG	Biomass Gasification Gas	
Biofuel	Solid (Biomass) or liquid (bio-oil) biowaste or energy crop	
BS	Barley Straw	
CFD	Computational Fluid Dynamics	
DD and WD	Dry Draff = WD – water and Wet Draff = DD + water	
DDGS	Dried Distillers Grains with Solubles = DD + PAS	
Ethanol	Crude ethanol that is mass produced to add to petrol after refining. The lower cost crude ethanol will be used for heat.	
FO	Fuel Oil	
GCV	Gross Calorific Value	MJ/kg
Glycerol	Crude glycerol a biowaste from the manufacture of biodiesel and is about 11% of the original vegetable oil.	
GHG	Greenhouse gases (mainly CO_2)	
GVA	Gross Value Added	
Kgw and Lw	Kg of water and litre of water	
LPA	Litre of pure alcohol produced (not whisky volume or bottles)	L
MLPA	Million litres of pure alcohol	ML
LCH	Low Carbon Hydrogen - <20 g CO_2/MJ H_2 with <5 g/MJ available. Grid electricity electrolysis LCH is not allowed due to the significant GHG with grid electricity.	g/MJ
MJ/LPA	MJ Energy consumed to produce one litre of pure alcohol	MJ/L
Mt	Million tonnes	10^9 kg
NG	Natural Gas	
PA	Pot Ale = PAS + water	
PAS	Pot Ale Syrup = PA - water	
PJ	Peta Joules. 1PJ=1x10^{15}J = 278 GWh	
SL	Spent Lees	
SLW	SL + vessel wash water	
SWA	Scotch Whisky Association	
Ø	Equivalence Ratio = (Stoichiometric A/F) / (Actual A/F)	Dimensionless
Ø < 1	Fuel Lean (burner conditions)	Dimensionless
Ø > 1	Fuel Rich (gasification conditions)	Dimensionless

Introduction and Background

Energy requirements and carbon emissions from whisky distilleries [P1, P10]

According to the Scottish Whisky's Economic Report [R1], in 2022 the whisky industry contributed £7.1 billion to the UK economy and provides £5.3 billion to the Scottish economy annually, with £6.2 billion of exports. It has 3% of the GVA for Scotland and supports over 66,000 jobs and invested £2 billion since 2018. It is also a significant consumer of energy and emitter of GHGs. Decarbonising UK's whisky industry is both an environmental necessity and a strategic economic opportunity. The present decarbonisation route using the production of BGG from solid and liquid biowaste from the Whisky industry, offers lower cost than the current use of NG and FO or of using 100% hydrogen, as well as >51% reduction of GHG emissions using whisky industry bio-waste including wet draff and pot ale (PA).

In 2022 the 151 Scottish whisky distilleries produced 792 MLPA. At an average energy input of 30 MJ/LPA [P1, P10], this means that the distilleries consumed 24 PJ, corresponding to about 10% of all energy consumption in Scotland (252 PJ in 2021 [R23]) and 1% of UK gas consumption [R7]. A substantial 95% of this energy is derived from fossil fuels, with natural gas (NG) accounting for 75% and Fuel Oil (FO) for 20% of the total consumption [R1]. The remaining 5% comes from electricity, which includes a mix of renewable and non-renewable sources. It is shown in the GHG section of this document that 30 MJ/LPA energy use converts to 1.9 kg CO_2/LPA. The Bunnalhabhain distillery on Islay [R1] reported a 1 kg CO_2/LPA saving by installing a biomass fired boiler using draff as part of the biomass fuel, with the rest being forest waste wood, saving up to 5,500 tonnes of carbon per year and 95% savings on fossil fuels. The aim of this project is to improve on this by using the energy in pot ale in addition to draff, to use the existing NG or FO steam boiler and to destroy all the liquid and solid waste from the distillery and so save the costs and environmental harm of their disposal.

One of the most compelling reasons for decarbonisation is the worldwide alignment with net-zero targets. As shown above the whisky industry has a pivotal role to play in meeting these targets.

Furthermore, there is growing consumer demand for sustainable products. According to a 2020 US consumer sentiment survey more than 60% of consumers prefer to purchase from brands committed to sustainability [R4], a trend particularly strong among younger demographics. By embracing renewable energy sources like biomass, wind, and low carbon hydrogen, the whisky industry can reduce its carbon footprint while also enhancing its brand appeal to a more environmentally conscious market.

Moreover, decarbonisation efforts could lead to significant cost savings in the long term. The Scotch Whisky Association (SWA) reports [R23] that some distilleries that have switched to renewable energy have reduced their energy costs by up to 20%, mainly using AD bio-methane plants, injecting gas into the grid and hence offsetting some of the gas used for heat

at the distillery. This not only makes the industry more resilient to volatile fossil fuel prices, but also increases its competitiveness globally.

This project uses zero cost distillery biowaste together with other low-cost biowaste from the rest of the whisky industry, including the barley farming straw waste and woodland wood waste, including logs and chips. It is shown that for wet draff as part of the bio-waste gasification load, 49% decarbonisation can be achieved, well in excess of that using AD plants, pot ale (PA) can also be burnt for heat in the two stage BGG/PA burner developed and demonstrated in this work. In 2019 242 kT of dry by products (Draff and PAS) were sent off-site AD plants where 1,503 TJ of bio-gas were produced and injected into the gas grid and received back from the grid by the distilleries. The present work measured the GCV of dry draff at 20.5 MJ/kg and PAS at 15 MJ/kg. The energy content of the draff and PAS was 4,797 TJ and thus the average thermal efficiency was 31.3%.

However, this did not include the energy for transport of the draff and PA to the AD plant and the grid energy cost for transporting the gas back to the distillery, which for the UK gas grid is 8% of the gas being pumped [R3]. Therefore, the real world thermal efficiency is approximately 20% in agreement with the study of Poschi et al. [R5] who found for farm agricultural waste the AD plant thermal efficiency varied between 5 and 35% taking into account the road transport energy, but assuming an AD plant 5 km away. They did not take into account the energy loss in the transport in the gas grid back to the source of biomass. Tashino et al. [R6] have measured the thermal efficiency of a bio-methane AD plant as 17.6%. The present work involves no draff and PA transport costs as the material is used on site in the distillery as it is produced and 49% thermal efficiency has been demonstrated for a bio-waste load that includes wet draff, with higher values possible using PA burning downstream of the BGG burner. For material such as barley straw, used in this work, AD plants are not suitable. Barley straw is one of the potential agricultural residues for distilleries from the same farms that provided barley for the malt use in distilleries.

This project was funded by the Green Distilleries Programme, which is an initiative by the UK government which is energy intensive as shown above. It is part of the broader effort to achieve the UK's net-zero targets by 2050.

Launched in 2020, the programme provided funding to support distilleries in developing and adopting innovative low-carbon technologies. This includes renewable energy sources such as hydrogen and bioenergy, electrification, and improvements in energy efficiency.

Whisky industry biowastes and energy recovery potential [P1, P10]

The Scottish whisky industry produces significant quantities of biowastes, including draff, pot ale, and spent lees wash (SLW), which offer potential as renewable energy sources. However, the high-water content in these wastes presents challenges for energy recovery. The energy potential of these biowastes and from the whole whisky manufacturing processes are reviewed here. The current energy use to manufacture 1 LPA has been reviewed and concluded to be

30 MJ/LPA [P1, P10] and the energy in the biowastes have been expressed in the same units so that the potential to offset fossil fuel energy can be determined. The results are shown in Table 1 for whisky manufacturing industry wastes.

Distillery biowastes.

The main biowastes generated by whisky distilleries include:

- Draff: The residual grain left after mashing.
- Pot Ale: The liquid residue from the first distillation.
- Spent Lees Wash (SLW): The liquid residue from the second distillation. Due to their high moisture levels, these wastes require substantial energy for drying before they can be used as fuel. The table below summarises the energy content of these and other relevant biowastes. This project shows that the wet waste can be dried as part of the gasification and staged BGG burner system, so that raw distillery waste can be used directly. This is the lowest cost option for utilising distillery biowaste.
- Dried Distillers Grains with Solubles (DDGS): Distillation byproduct, usually a mix of grains but mainly corn and rice. Dried wet distillers' grains (WDG) to a moisture content to 10-12%. Currently being used for the production of ethanol.
- Other biowastes are available in the whisky manufacturing process at the malthouse, in the maturation barrel processing and on the barley farm and these are also quantified in Table 1.

Table 1. Summary of whisky industry biowaste as potential energy resource per litre of pure alcohol produced (L in this table is LPA) [P1, P10]

Biowaste Source	Wet kg/L	Water kg/L	Dry kg/L	% water	GCV (dry) MJ/kg	Total Energy MJ/L	Energy for drying** MJ/L	Useful Energy MJ/L	% of Net Energy needs**
Distillery									
Draff	2.40	1.80	0.60	75%	20.50	12.30	4.64	7.66	25.5
Pot Ale	8.26	6.90	1.36	84%	19.00	25.84	17.80	8.04	26.8
Spent Lees Wash	3.00	2.97	0.03	99%	9.00	0.27	7.66	-7.39	-24.6
Malthouse									
Dark grains & rootlets	0.38	0.00	0.38		10.00	3.75	0.00	3.75	12.5
Husks	0.25	0.00	0.25		16.00	4.00	0.00	4.00	13.3
Farm									
Barley Straw	2.50	0.36	2.14	14%	17.00	36.38	0.93	35.45	118.2
Maturation									
barrel bio-char	0.06	0.00	0.06		30.00	1.89	0.00	1.89	6.3
Total	**16.8**	**12.0**	**4.8**			**84.4**	**31.0**	**53.4**	**178.0**

*Water evaporation energy from draff (used for all): 2.58 MJ/kg of water

**Total net Energy requirements per litre of pure alcohol: 30 MJ/LPA [P1, P10]

Review of Biowaste Potential to Replace NG or FO for Distillery Heat [P1, P10].

- **Draff**: Draff, with a dry weight of 0.6 kg/LPA and a GCV of 20.50 MJ/kg, offers a useful energy yield of 7.66 MJ/L after accounting for the energy required to dry it. This could meet 25.5% of the distillery's energy needs.
- **Pot Ale**: Although pot ale has a higher total energy content, its substantial water content results in a useful energy yield of 8.04 MJ/LPA, covering 26.8% of energy requirements.
- **Spent Lees Wash (SLW)**: SLW is problematic due to its extreme water content and low dry matter, resulting in a negative energy contribution after accounting for the energy needed to evaporate the water. It may be more economical to treat SLW as waste and send it to a treatment plant rather than attempting to use it as fuel.
- **Other Biowastes**: Dark grains, rootlets, and husks from the malthouse provide additional energy resources, though in smaller quantities. Barley straw, however, is highly advantageous with a low moisture content and a GCV of 17 MJ/kg, potentially covering over 100% of the distillery's energy needs if fully utilised.
- **Barrel Biochar**: Scraped char from barrels used in whisky maturation, though minor in volume, offers a high GCV of 30 MJ/kg and contributes to the energy balance with 1.89 MJ/LPA, covering 6.3% of energy needs.

The above energy contributions are based on 100% efficiency in driving out the water content and in releasing the remaining energy content of the materials. In practice these efficiencies are not achievable in the biowaste gasifier and BGG/PA staged burner used in this work, due to the need to heat the gasifier using NG and to add NG to the BGG Jet Mix burner to assist the flame stability of the BGG flame. An important aspect of this project was the practical demonstration of the feasibility and efficiencies of the gasification and associated combustion plant.

Supplementary Green Fuels

To achieve full decarbonisation and meet energy demands, it is necessary to supplement biowaste energy with additional green fuels. These include:

- **Glycerol**: A low-cost by-product of diesel/biodiesel production, glycerol can be used effectively in burner systems [P2], although it is more efficient in a staged burner setup due to its high viscosity and boiling point.
- **Low carbon Hydrogen**: Greed/blue hydrogen is an ideal zero-carbon fuel for distilleries, particularly for use during cold starts or when additional energy is needed beyond what biowastes can provide. It can be blended with other fuels to stabilise combustion and enhance efficiency.
- **Crude Ethanol**: Crude ethanol provides another renewable fuel option, particularly useful in dual-fuel burners. It offers a lower-cost, lower-carbon alternative to traditional fossil fuels.

Biomass Gasification and Versatile Burner Systems: The Optimal Approach

Given the variety of primary biowastes and the need for supplementary green fuels, a biomass gasification system combined with versatile and adaptable burner systems emerges as the best approach for distillery energy needs. Biomass gasification effectively converts diverse biowastes into a usable gas (BGG), which can then be burned efficiently using advanced burner systems capable of handling multiple fuel types.

The burners developed in this work were designed to operate on natural gas, hydrogen, fuel oil, ethanol, and BGG, without any major modification ensuring flexibility and resilience in fuel supply. This adaptability is crucial for optimising energy recovery, maximising decarbonisation, and reducing reliance on fossil fuels.

Distillery biowastes can provide a substantial energy source towards the distillery energy requirements. The use of wet draff and pot ale (as produced) has the theoretical potential of replacing over 49% of the distillery energy needs. This potential will be moderated by the efficiencies of the gasification and combustion processes utilised in extracting the available energy from these primary biowastes. Clearly, although substantial, these energy recoveries are insufficient (alone) to fully meet the energy demands of alcohol production. However, other biowastes in the total whisky production system are sufficient to provide the extra energy to decarbonise the distillation process. It will be shown in the results section of this report that to heat the gasifier from cold and to stabilise the BGG flame, a second more reactive fuel is required. For partial decarbonisation this could be NG or FO, but for complete decarbonisation low-carbon fuels such as glycerol, hydrogen, and crude ethanol will be required, and hydrogen was demonstrated in this work. Worldwide, hydrogen has become a strong growing economy and has a great potential towards decarbonisation. The existing UK natural gas grid could be repurposed, making it safe for hydrogen, as it is already happening in other countries such as Germany [R22]. However, in the meanwhile this fuel could be supplied from electrolysis using green or blue sources.

This approach not only enhances the energy efficiency of distilleries, but also significantly contributes to the industry’s decarbonisation efforts, and (as will be shown later) leads to significant cost reductions.

Project Objectives

The following broad project objectives led to the practical learnings and strategic adjustments made as the project progressed, ensuring that the solutions developed were both effective and aligned well with the needs and practices of the whisky industry.

1. **Maximise energy recovery from distillery biowastes**
   Develop and optimise gasification processes to efficiently convert primary distillery biowastes (draff, pot ale, and SLW) into usable energy, reducing reliance on fossil fuels and eliminating the need for costly waste disposal. Quantify the decarbonisation efficiency and financial savings from these processes.

2. **Integrate supplementary low-carbon fuels**
   Incorporate additional renewable energy sources, such as glycerol, low-carbon hydrogen, and crude ethanol, to enhance decarbonisation and provide a robust, flexible energy solution for distilleries.
3. **Develop versatile and adaptable burner systems**
   Design and implement burner systems capable of efficiently utilising a variety of fuels, including Biomass Gasification Gas (BGG), hydrogen, natural gas, fuel oil, and bio-oils, ensuring optimised combustion efficiency across different operational scenarios and future proofing the technology, as far as foreseeable.
4. **Achieve significant reduction in greenhouse gas emissions**
   Demonstrate and quantify the potential reduction in GHG emissions through the combined use of biomass gasification and versatile burner systems, aiming for 60-100% decarbonisation depending on the biowaste and fuel combinations used.
5. **Ensure system scalability and practical application**
   Design gasification and burner systems to be scalable and adaptable for distilleries of varying sizes, ensuring broad industry adoption and practical efficiency in real-world environments.
6. **Support economic viability and industry adoption**
   Focus on minimising operational costs and offering significant savings through reduced fossil fuel consumption and waste disposal costs, promoting widespread industry adoption.
7. **Contribute to the circular economy within the whisky industry**
   Promote the use of distillery by-products as energy sources, contributing to a circular economy that reduces waste and enhances sustainability within the whisky production process.
8. **Facilitate ongoing research and development**
   Encourage further research and development to refine gasification and burner systems, explore new biowaste resources, and enhance overall efficiency and effectiveness in decarbonisation strategies.

Overall Gasification and Combustion Plant Layout

The gasification and associated combustion plant developed as part of this project, for the decarbonisation of whisky distilleries, is shown in Figure 1. The plant can be connected to a steam boiler, or it can be used for direct firing of the distillation process.

The innovative features of this set-up are that this combined gasifier and burner system can handle both solid and liquid biowastes as produced (without drying or further processing) by the distilleries. The gasifier turns solid biowaste (draff, grains, husks, straw, wood etc.) into Biomass Gasification Gas (BGG), which is then burned in the first stage of a BGG burner. At the second stage, liquid biowaste from the whisky industry and elsewhere (pot ale, spent-lees, glycerol etc) can be injected and then air atomised, vapourised and burnt by the BGG burner hot combustion products.

Both the gasifier preburner and the BGG burner are assisted and stabilised in their processes, particularly from cold start, with auxiliary fuel burners designed to operate with various fuels,

including current fuels or potential low-carbon fuels or wastes from other processes such as natural gas, hydrogen, fuel oil, or ethanol, without any engineering modifications.

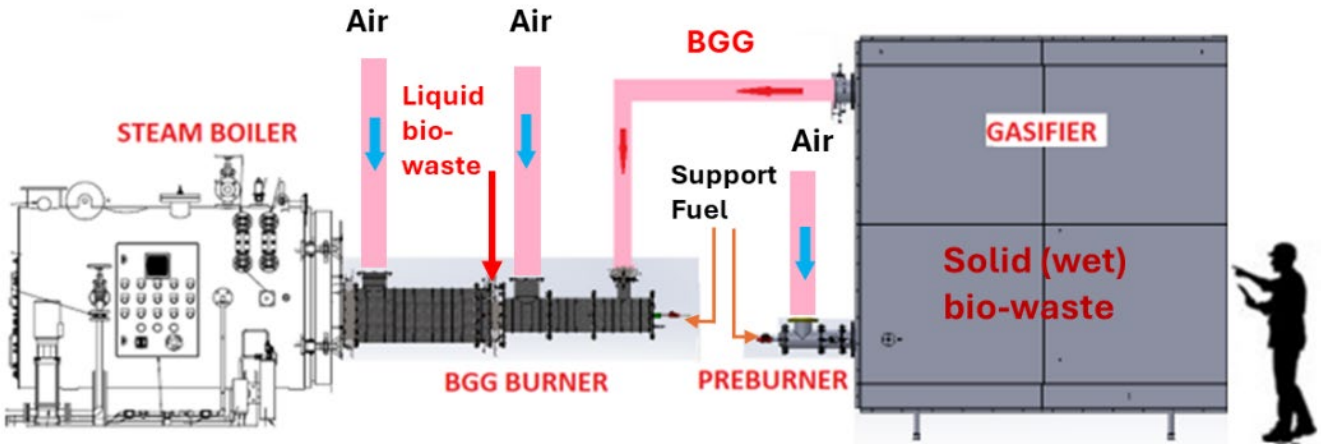

Figure 1. The overall gasification and combustion plant developed for the decarbonisation of whisky distilleries using both solid and liquid biowaste as produced.

For the demonstration gasification system developed for this project the biomass is added in batches, which is a cost-effective fuelling method. The current design is a scaled-up version of commercial log gasifiers which are usually available up to approximately 100 kW of thermal load.

Air gasification is used in this process, which involves reacting biomass (including whisky industry waste like draff and pot ale) and air at stoichiometries richer than an equivalence ratio of 2, which implies an environment where the amount of fuel is at least double the amount of usable oxygen (oxygen-deprived environment). This is enhanced by additional biomass sources like straw and waste wood, with air flow controlled to maintain a reactor temperature of 500 deg. C. Although air gasification produces a lower-calorific gas (BGG) containing about 50% nitrogen, it is a cost-effective method compared to more efficient oxygen gasifiers that produce higher-calorific gas without nitrogen.

To fully utilise all liquid and solid wastes from whisky production, this system employs air gasification of wet solid waste to generate BGG, which is then used in a two-stage burner to burn the liquid wastes, releasing additional heat. The resulting hot gases from this two stage BGG burner can be used for the distillery heating through a boiler or directly. This is a new and innovative approach to the utilisation of whisky industry waste.

Engineering Challenges and Solutions

The development and implementation of biomass gasification and burner systems for whisky distilleries presented several engineering challenges. These challenges were systematically addressed to ensure the successful operation, scalability, and decarbonisation of the systems.

Application to both direct fired and indirect (steam heated) distilleries

Challenge: Whisky distilleries use two primary heating methods: direct-fired systems, where burners heat an annulus around the distillation vessel, and indirect steam-heated systems, where burners heat a steam boiler and the distillation vessel is heated by steam. The challenge was to develop a decarbonisation solution compatible with both methods.

Solution: A versatile two-stage burner system was developed, capable of burning BGG in the first stage and bio-liquids such as pot ale and glycerol in the second stage. This burner design can be connected directly to the burner port of a direct-fired system or integrated with a steam boiler in an indirect system. The burner's cooling and air distribution features ensure stable and efficient BGG combustion, regardless of the application.

Replacement of natural gas (NG) or fuel oil (FO) with distillery biowastes.

Challenge: The goal was to replace NG or FO with BGG derived from distillery biowastes. However, the low calorific value of BGG, due to its high nitrogen content, and high water content of wet bio-waste, posed challenges for flame stability and energy output.

Solution: The burner systems were designed to be quint-fuel, capable of operating on BGG, NG, hydrogen, ethanol or biodiesel without any major modification required. During cold starts or when BGG alone could not sustain a stable flame, NG or hydrogen was used to support combustion. The design allowed for seamless transitions between fuels, ensuring consistent energy output and decarbonisation efficiency.

Requirement for dual fuel burners for preburner and BGG burner and the use of hydrogen or crude ethanol for 100% decarbonisation.

Challenge: The gasifier requires external heating during startup and to maintain optimal gasification temperatures. This heating must be compatible with multiple fuel types, including hydrogen for 100% decarbonisation.

The gasifier requires heating to a temperature where devolatilisation of the solid biofuel occurs. This is determined using thermogravimetric analysis (TGA), which heats the biomass in nitrogen and measures the weight loss as a function of temperature.

Figure 2 [P1, P10] illustrates the thermogravimetric analysis (TGA) of draff, highlighting how the material loses mass as it is heated. The wet draff in Figure 2 was raw draff with the water removed in the TGA. The dry draff was a sample dried by heating in a pan. The two samples are very similar but did come from the same batch.

Figure 2 shows that between 100 deg. C and 250 deg. C, 10% of the mass is converted into low boiling point gases. The most significant mass loss occurs between 250 deg. C and 350 deg. C, where 50% of the biomass is released as volatiles. By 550 deg. C, 80% of the draff's mass has been devolatilised, with further heating likely converting up to 90% of the mass into volatiles. This work showed that over 550 deg. C was achieved in most of the gasifier tests, but with lower wet draff peak temperatures at 450 deg. C , which would limit the devolatilization of the wet draff and hence the proportion of NG replaced by BGG.

The TGA demonstrates that draff can release a substantial amount of energy-rich volatiles at relatively low temperatures, which is crucial for efficient gasification. The figure underlines the importance of controlling the temperature during gasification to maximise energy recovery from the draff.

The TGA result for draff is compared with other biomasses, such as wheat straw and pine wood, in Figure 3 [P3]. This shows that most biomass release most of their volatiles between 250 and 400 deg. C. Figure 3 is normalised to the total volatile loss in nitrogen, whereas Figure 2 changes the nitrogen for air at 550 deg. C. and the weight loss is the char burn out. Figure 3 shows that 90-95% of the volatiles are released at temperatures close to 550 deg. C.

The comparison highlights that while draff has a lower volatile release temperature, it still efficiently contributes to gasification. The inclusion of other biomass materials like straw and wood can complement draff, enhancing the overall gasification process by extending the range of volatile release temperatures.

Solution: A grid cone preburner was developed, capable of burning NG, hydrogen, FO, or ethanol. The burner can operate across a wide range of conditions, from very lean mixtures to support low-temperature gasification, to rich mixtures for efficient energy production. The preburner's design ensures stable operation and allows for fuel flexibility, enabling decarbonisation through the use of hydrogen or ethanol when necessary. The preburner had to be capable of burning very lean to generate the temperatures in Figures 2 and 3. The burner had to heat the gasifier load and the gasifier walls and any refractory insulation. As the burner operated lean it also fed the gasifier with oxygen and gasification heat release could occur. It was found that once the gasifier outlet temperature was at 350 deg. C or higher (for tests where dry biomass wastes were used), the gasification became self-sustaining and the heat release from the volatile CO and hydrocarbons led to increased gasifier temperature and the preburner fuel could be switched off. The preburner air flow was left on and this determined the gasifier heat release (3MJ of heat release per kg of air supplied) and the gasifier temperature continued to increase until the volatile gases stopped being released, when the load was mainly char and ash.

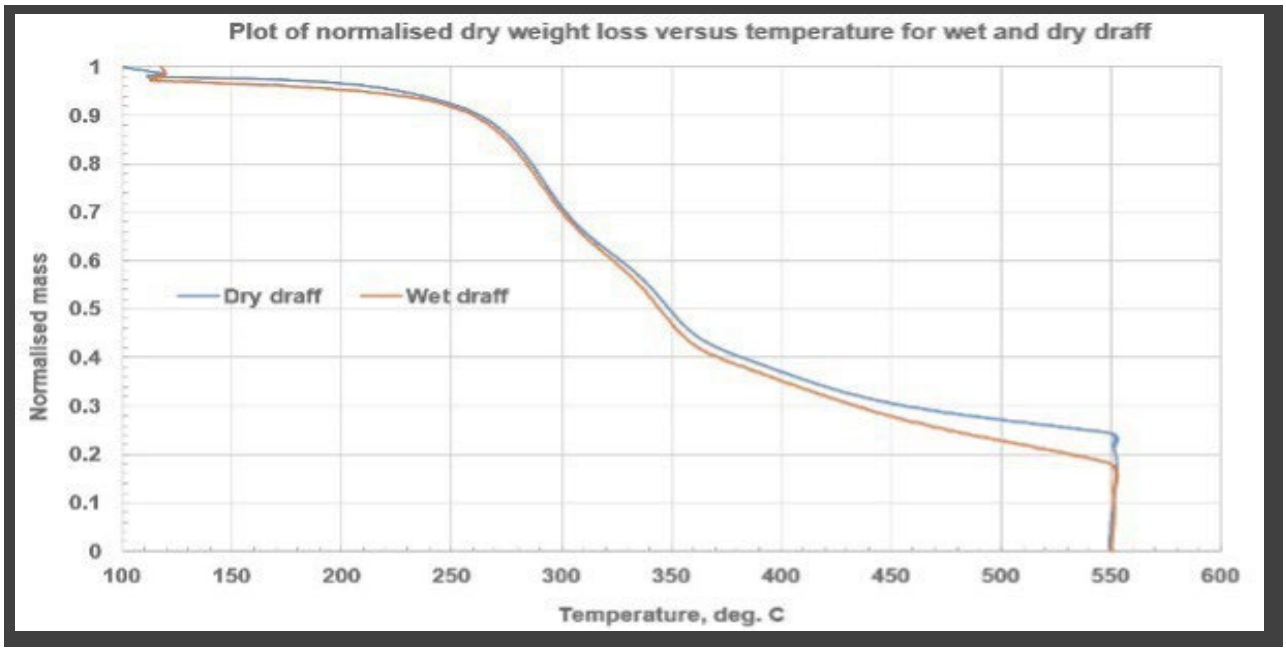

Figure 2. TGA of draff after all the water has been removed in the analysis. At 550 deg. C oxygen was introduced instead of nitrogen and this shows about 20% of fixed carbon and ash.

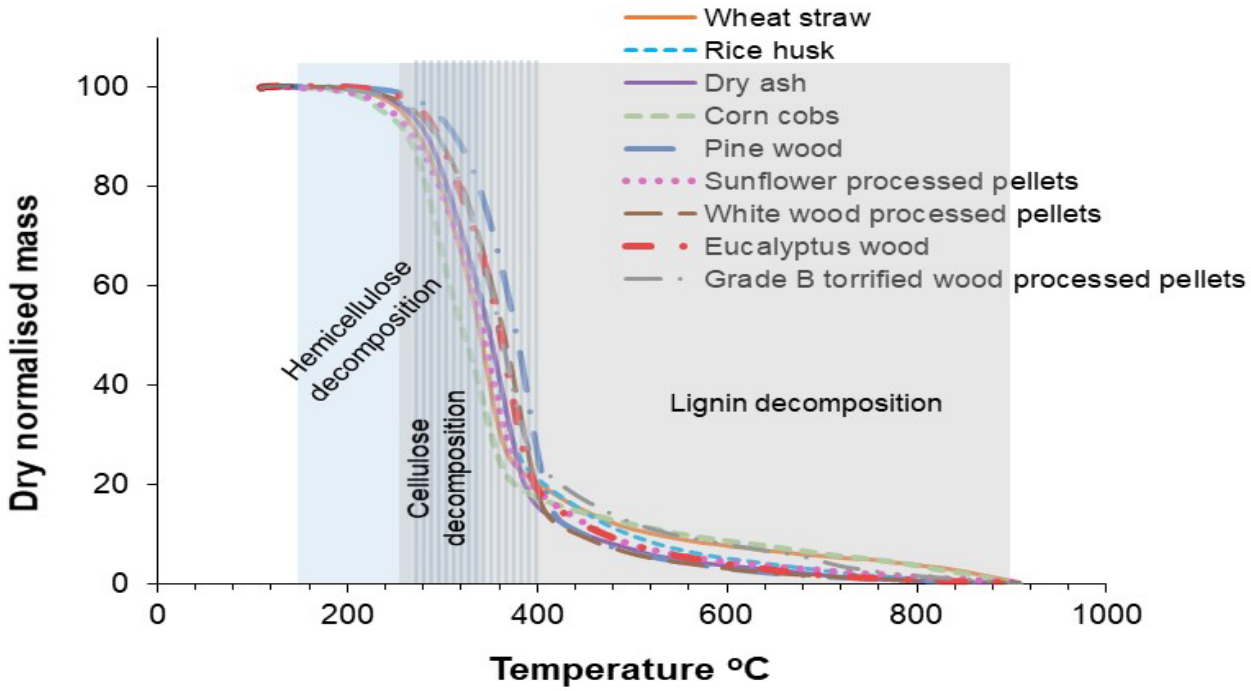

Figure 3. TGA of various biomass, including wheat straw and pine wood [R4].

In all the gasifier tests the preburner fuel was NG, but it was shown to be capable of operating on hydrogen so that a zero-carbon heat supply for a distillery could be demonstrated. For distilleries with FO operation the zero-carbon fuel was crude automotive ethanol and the preburner was designed for both gas and liquid fuel operation, with the liquid fuel air-atomised by the combustion air jets and the same fuel holes used for FO and ethanol. The burner was thus capable of operation on two gas fuels and two liquid fuels – a quad fuel burner.

The Grid Cone preburners [R8 – R10] were designed for quad fuel operation, and the Jet Mix BGG burner [R15] for quint-fuel combustion, with the gas holes used for NG and hydrogen and the liquid fuel holes used for fuel oil and ethanol. As electric cars take over from petrol and diesel vehicles, the existing manufacturers of crude ethanol for automotive use will have surplus supply and so its use for process heating will be a low-cost fuel source, as well as being a zero-carbon fuel.

The burners are designed to have all the combustion complete before the burnt gases enter the steam boiler or direct fired distillery. If a simple axial air flow burner configuration was used this would lead to a red-hot flame tube in the open, which would not be safe or a sensible design. The burners were designed with reverse flow air through an annulus around the burner tube and this both cooled the flame tube and heated the combustion air. Depending on the total burner power the air temperature entering the burner was in the range 200-300 deg. C. These high air temperatures assisted in the efficient combustion of the BGG gas and fuel oil. Figure 4 shows the BGG multifuel assisted burner in an axial staging arrangement with a downstream pot ale/glycerol burner.

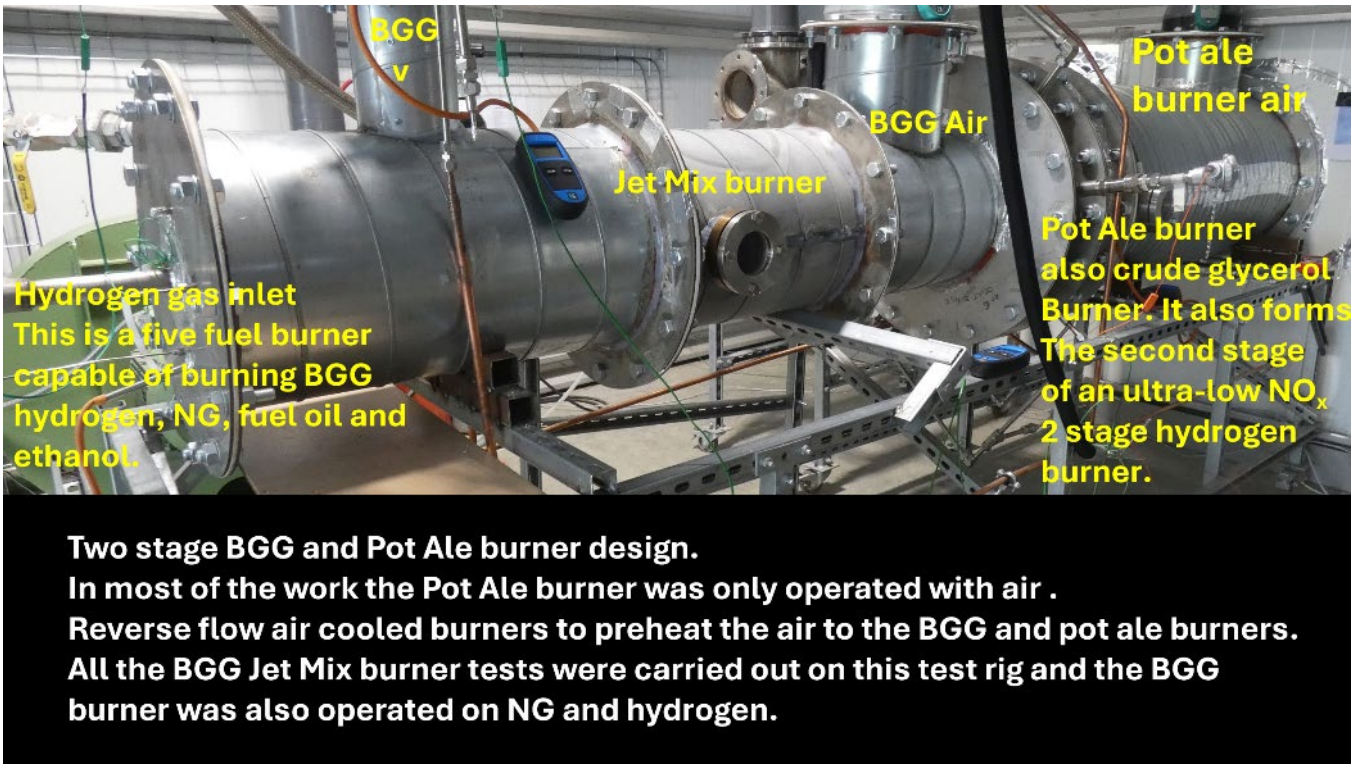

Figure 4. Reverse air flow cooled axially staged two stage burner

Batch Gasification and Biomass Gasification Gas (BGG)

Challenge: The gasifier needed to process wet draff directly from distillery vessel discharge, which presents challenges in maintaining consistent gasification temperatures and producing a stable BGG output.

Solution: A batch gasification system was chosen for its simplicity and cost-effectiveness. The principles are well known from log gasifiers in domestic applications and straw bale gasifiers for farms. The preburner heats the air by lean combustion and provides the oxygen for the gasification reactions and additional heat release (self-heating), in essentially very rich combustion conditions [P3]. This generates a low-calorific BGG [R8, R11] that contains CO, hydrocarbons, and inerts. The system was designed to be scalable, with a typical BGG output ranging from 400 kW to 2 MW, depending on the biomass load. The gasifier's performance was optimised by controlling air flow and gasifier temperature, ensuring consistent BGG production.

The efficiency of the process was determined by the reduction in the NG or hydrogen energy from that for 100% NG operation. The best result for dry draff was an 85% reduction in the NG use, including the NG used during the cold start of the gasifier. For wet draff it was 49% due to the energy required to vaporise the water.

The gasifier and linked BGG combustion system were designed as separate processes that could be optimised. The gasifier was initially sized to enable one batch of distillation at a distillery of 8 hours duration to be supplied with heat from the gasifier at 2 MW for 8 hours. The BGG gas from the gasifier was transported via an insulated connecting duct to the BGG burner.

Managing the high-water content in pot ale and glycerol

Challenge: Pot ale and glycerol, when added directly to the gasifier, created tar and other by-products that hindered efficient gasification rather than contributed to it. Additionally, their high-water content complicated their use as gasifier fuels.

Solution: Instead of direct gasification, pot ale and glycerol were used in a second-stage burner [R16 – R21], as shown in Figure 3, where they are injected and air-atomised into the hot exhaust gases from the BGG burner. This method allows the heat from the BGG combustion to vaporise the water in these liquids, enabling their efficient combustion and contributing to overall energy output without causing issues in the gasifier. In this work only PA was demonstrated to burn in the products of BGG combustion and the demonstration for glycerol will be done in the future.

The pot ale/glycerol injection system ensures that the high moisture content of such biowastes is effectively managed by utilising the heat from the gasification process. This approach enhances the overall energy efficiency of the system by integrating the energy contribution from pot ale into the BGG burner heat output, thereby avoiding the complications associated with direct gasification of high-moisture bio-liquids.

Quantification of the decarbonisation efficiency when using biowastes.

Challenge: Accurately measuring the reduction in fossil fuel use and the overall decarbonisation efficiency of the system was essential for evaluating its effectiveness.

Solution: Decarbonisation efficiency was determined by measuring the NG used during the process at the various stages (pre-burner and BGG burner) and using oxygen consumption calorimetry to calculate heat release of the NG and BGG fuels, and comparing with the NG required to produce the same heat release. 85% efficiency was met with dry draff after the preburner NG was switched off, while wet draff achieved 49%.

A feature of the two-stage burner design, which had not been expected, was that the BGG combustion efficiency in the BGG burner was about 90% and the 10% of BGG remaining burnt as a visible flame at the pot ale burner where additional air was added. This gave very efficient overall combustion of the BGG. The low calorific value of the BGG gas led to the flame blowing off in the BGG burner and stabilising on the PA burner in some of the tests, using the pot ale burner air supply for combustion, which also cooled the PA burner flame tube prior to combustion.

BGG leakages from the gasifier and thermal losses

Challenge: Spotting any leak point around the gasifier during operation, or any point in the transfer pipeline to the BGG burner that was not insulated and could result in a potential heat loss. BGG leakages and thermal losses are not only prejudicial for the efficiency of the gasification process, but also present a health hazard.

Solution: Identify weaknesses in selected materials and replace for design specifications to avoid future failures. Find proper seal/gasket that can withstand the gasifier operation conditions and could provide proper sealing during the batch process. Actively identify potential sources of thermal losses and solve accordingly.

Engineering Design Details

Gasifier design and gasifier heating

The gasifier was designed to operate for 8 hours at a 2 MW Biomass Gasification Gas (BGG) heat output, which corresponds to the heat required for one distillation batch in most distilleries. The issue of refuelling the gasifier for continuous use is acknowledged, with plans to address this in future work, following the successful demonstration of the gasification method for a single biomass batch.

Eight-hour operation at 2 MW is a total energy use of 57.6 GJ and using a typical biomass GCV of 15 MJ/kg, this would require a batch load of 3,840 kg. For a typical bulk density of solid biomass of 100 kg per cubic metre, the gasifier volume would be approximately 30 cubic meters. This gasifier was built by CBS and a high temperature refractory wall was installed by a commercial furnace wall installer. This large gasifier was designed with one wall having large opening doors to enable a forklift truck to load up a new gasifier load.

The BGG burner design assumed that 20% of the total air flow would pass through the gasifier to generate the BGG. As a result, the Jet Mix burner's fuel holes were designed for a large BGG flow volume. The preburner was intended for the combustion of natural gas, hydrogen, fuel oil, or ethanol in 20% of the total air flow, yielding a maximum preburner power of 0.4 MW. However, for the GD166 application, operation at 350 kW BGG energy was also included, which required a preburner capable of 70 kW (20% of 350 kW). The final design was a 100 kW preburner, which could operate at much lower powers for controlling the gasifier temperature.

Attempts to operate the gasifier with the 100 kW burner failed due to the high thermal energy requirements during cold starts. The gasifier, with an approximate 4-tonne load and a 300 mm-thick refractory wall, had a thermal mass that could not be heated to the required gasifier temperature with a 100 kW burner within a reasonable time frame; even after 10 hours of heating, the temperature had not reached 350 deg. C. Consequently, it was decided that the 0.4 MW preburner would be used for all tests. This burner, which shares the same housing as the 0.1 MW burner, differs only in the hole size of the flame stabiliser. It could be operated at 0.1 MW or lower by simply reducing the air flow.

Despite using a 0.4 MW preburner, cold start times remained lengthy, at around 2 hours. Additionally, when the gasifier reached 350 deg. C, gasification gases leaked from the furnace doors, posing safety risks for the operators. This prompted the construction of a new gasifier, which was installed inside the old gasifier and used the existing burner and exit connections, thus avoiding external modifications. The new gasifier features a bolted end wall to prevent leaks, as shown in Figure 5. An extract fan was fitted to the large gasifier enclosure to vent any leaked gases outside the building. The internal gasifier has mild steel walls with no refractory lining, reducing its thermal inertia. It is a cube measuring 1.22 m x 1.2 m x 2.66 m, with a volume of 6.4 cubic metres. This capacity allows for approximately 640 kg of biomass, containing 9,600 MJ of energy, sufficient for a 2 MW burner to operate for 1 hour and 18 minutes, which aligns with the BGG production timescales demonstrated. All subsequent gasifier operation results in this report refer to this smaller gasifier.

Figure 5 shows the 6.4 cubic metre gasifier with the end flange removed. The gasifier load rested on a floor supported by four load cells, with the supporting rods visible in Figure 5. This setup enabled the measurement of the gasifier's mass production of BGG gas, and heat release was determined assuming a typical biomass GCV of 15 MJ/kg. The gasifier preburner location is shown in Figure 5 on the rear wall at the bottom right, where it heated the gasifier load from the bottom, functioning as an updraught gasifier, with the BGG exit located at the top of the gasifier.

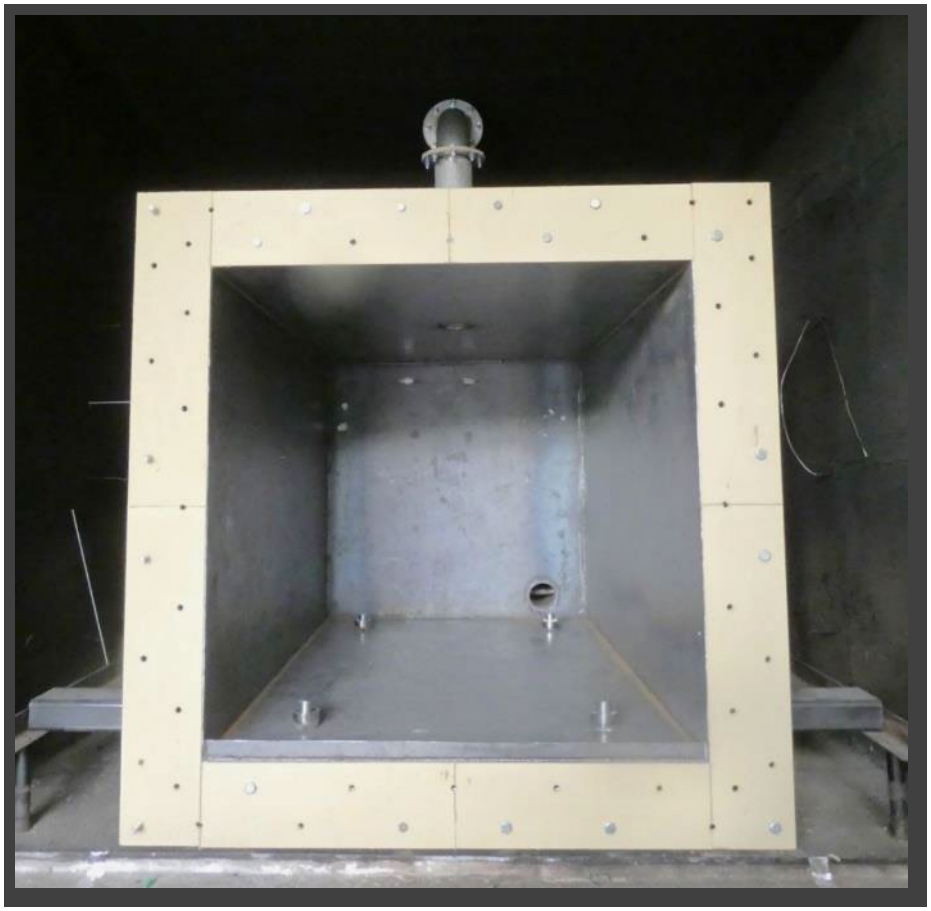

Figure 5. The 6.4 cubic metre gasifier with the end flange removed

Gasifier heater preburner design

The preburner has two purposes: to heat the gasifier load start the gasification reactions and to control the temperature of the gasifier. The gasifier must be externally heated under cold start and the Grid Cone burner has been developed for this, operating on NG, hydrogen, fuel oil and ethanol. This enables the technology to be used on sites currently using fuel oil as the main fuel. For 100% decarbonisation, the burner will operate on hydrogen or ethanol. The Grid Cone technology was based on previous work at the University of Leeds [R12, R13, R14]. It was developed for the present application on a burner test rig and shown to be operational on NG and hydrogen [P4]. As work at Leeds University had previously shown, the grid mix preburner could operate on fuel oil and could also operate with crude ethanol. The grid cone preburner is shown in Figure 6.

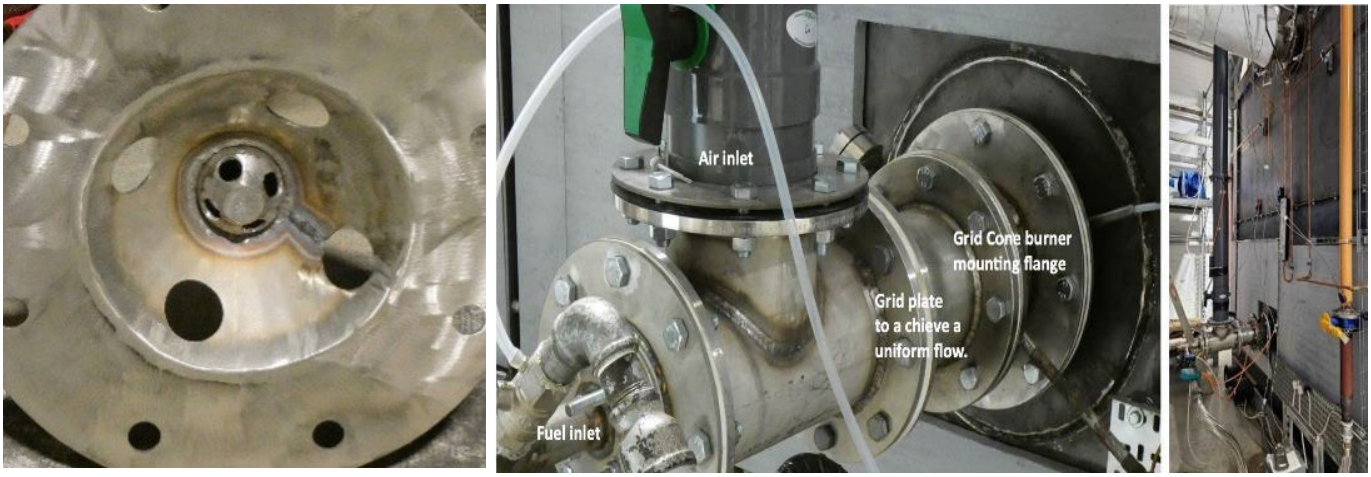

Figure 6. The 0.4 MW four air hole grid cone preburner used in all the gasification tests.

The central fuel injector for the Grid Cone burner is shown in Figure 6, with the large fuel hole diameter for NG and hydrogen operation. The liquid fuel injector was inside the gas fuel delivery tube with liquid fuel jets on the centreline of each gas fuel jet. The alignment of the fuel holes is offset from the air holes to give a better flame stability. The assembly of the preburner and its location in the gasifier furnace are also shown in Figure 6.

The Computational Fluid Dynamics (CFD) analysis predictions for the grid cone 0.4 MW burner operated with NG [P4] are shown in Figure 7. These were carried out using the modelling software ANSYS Fluent. This shows that the radial inward air jets for the 45 deg. cone angle flow onto the centreline and impinge on each other. The offset fuel jets create two rich regions: one in the cone head and one in the outer recirculation zone. This gives rich/lean combustion, which is a design technique for low NOx emissions, but in this work, it is the rich zone at the cone tip that makes the flame very stable and gives stable flames at any fuel flow so that the preburner power can be varied during the gasification period without any risk that the flame would blow out. At the equivalence ratio Ø=0.5 in Figure 7 the central rich zone is too rich to burn and all the heat release is in the outer recirculation zone. However, as the fuel flow was reduced combustion would occur in the central region, enabling very lean flames to be stabilised. The rich outer recirculation zone had some regions near stoichiometric and NOx formation was concentrated in this area.

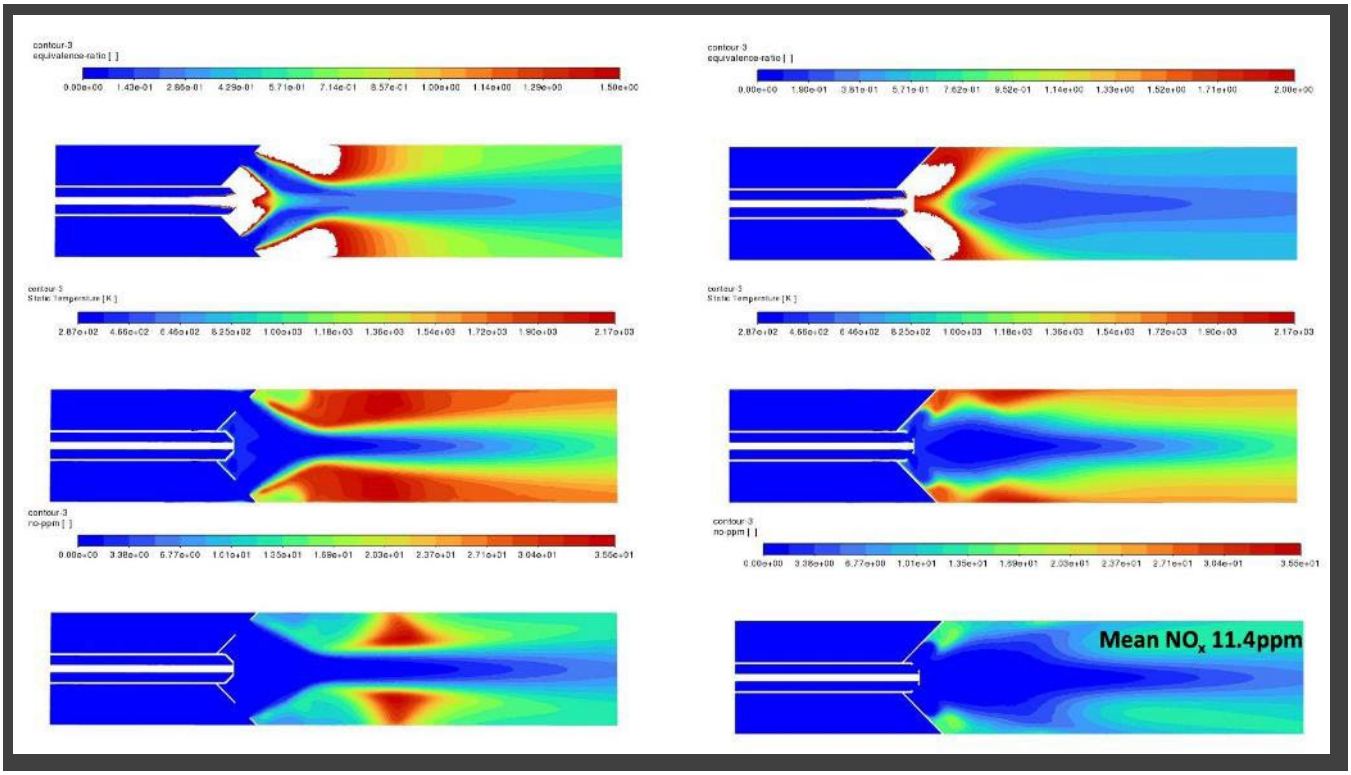

Figure 7. Ansys Fluent predictions of the 0.4 MW grid cone preburner operating on NG at Ø=0.5. View on the centreline of the air holes on LHS and between the air hole on RHS. 4 hole fuel injection aligned between the air hole [P4].

Figure 8 shows the 0.1 MW grid cone design operating at 70 kW on NG and hydrogen at Ø=0.5. The flame is clearly attached to the base of the flame stabiliser and fills the axial cross section of the burner tube. The NG flame is blue, and the hydrogen flame is orange and clearly visible. The hydrogen flames in the 0.4 MW version of the Grid Cone burner are shown in Figure 9 at 0.2 MW on the LHS and at 0.4 MW on the RHS. Again, the flame is clearly orange. For the 0.1 MW Grid Cone the hydrogen NOx emissions were 25% of those for NG [P4], showing that the oft repeated claim that hydrogen will increase NOx emissions is not true. The main reason for this is that hydrogen flames on burners designed for methane operation at Ø=0.95 will operate leaner at Ø=0.7 on hydrogen, which will have a lower temperature and NOx. Also, hydrogen has no hydrocarbon prompt NOx emissions.

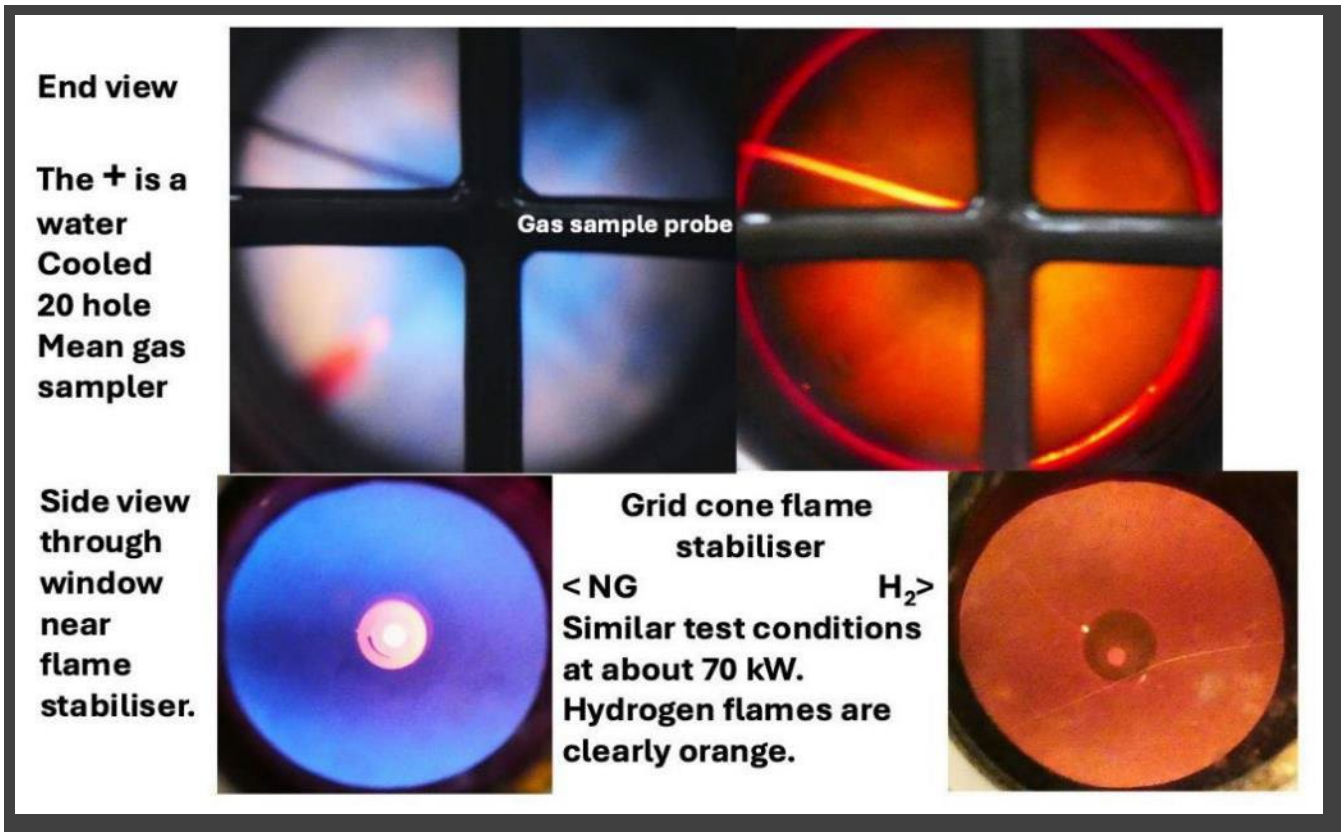

Figure 8. Comparison of the Grid Cone on NG and hydrogen for the 0.1 MW design [P4].

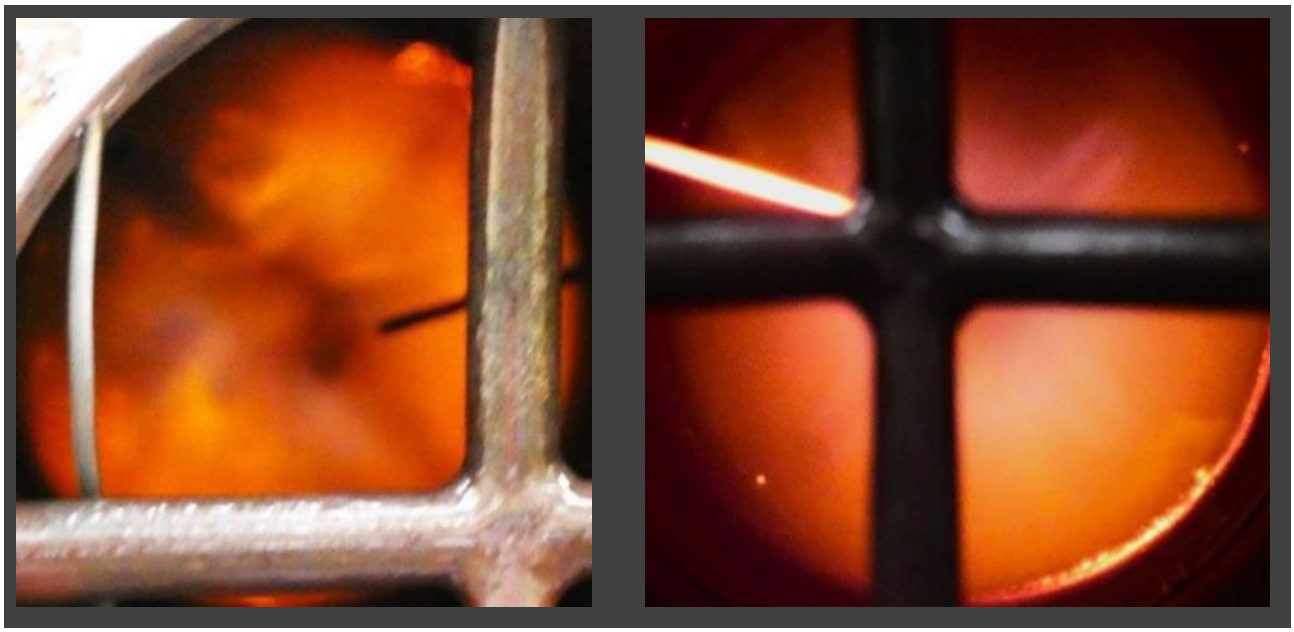

Figure 9. 0.4 MW grid cone operated on hydrogen at 200 kW (LHS) and 400kW (RHS).

BGG dual fuel burner design

The BGG low calorific value fuel needed to have a design capable of operation of a NG flame under very lean low flame temperature conditions, so that a low flame temperature low calorific value flame had a chance of being stable. Also, the burner had to be capable of accepting a very high volumetric and mass flow rate of BGG gas. The Jet Mix design, developed at Leeds University and shown in Figure 10, was chosen to have a good chance of being a suitable flame stabiliser for BGG gas. The BGG could be injected through the duct for the radial jet air holes. A central fuel injector, as shown in Figure 10, allowed the design to be operated on gaseous or liquid fuels (the gas fuel supply had a liquid fuel injection tube on the centre of the gas fuel delivery tube). The Jet Mix design could be operated with the radial BGG jets in line with the axial air jets or offset, as shown in Figure 10. It was found in the experimental work on the BGG flames that the flame was not very stable for offset jets but operated well with in line jets. This was because the BGG had no oxygen and could not burn until the axial air jets mixed with the radial jets, and this occurred faster with in line jets. All the gasification results were carried out with in line Jet Mix jets. This Jet Mix burner has also been operated on hydrogen [R15] and shown to have very low NOx characteristic at lean burning conditions, similar to the best hydrogen low NOx burners.

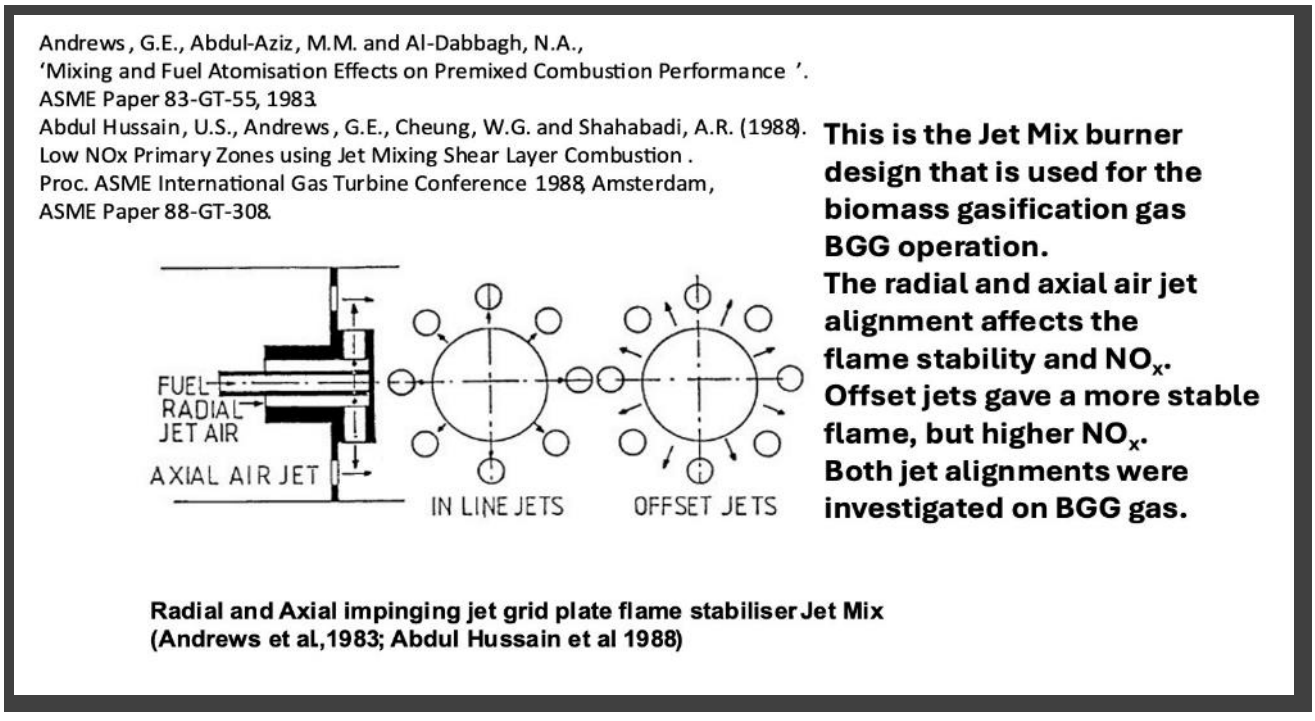

Figure 10. The Jet Mix BGG burner.

The Jet Mix burner was operated with NG injected through the central fuel injector and it was demonstrated that this burner could also operate well on hydrogen. Under cold start there is no BGG gas and as the gasifier warms up the NG or hydrogen flame burns the initial low concentration of BGG. As the BGG gas increases the NG or hydrogen support fuel is reduced, until the BGG flame is stable with no supporting NG or hydrogen. The operation of the BGG burner on NG, hydrogen and BGG is shown in Figure 11 for the exit plane view of the flame.

Figure 11. Jet Mix burner operating at 1 MW on NG (LHS), hydrogen (Middle) and BGG (RHS).

Two stage dual fuel combustion of BGG and liquid biowastes

The University of Leeds [R14 – R20] has developed different burner designs for axially stage combustion and the present work used the lean/lean staged burner approach. The principle of all these designs is that the fuel is injected in two places in the burner with an axial spacing between the two. The first fuel stage burns lean with its own fuel and air supply and the second stage burns in the products of combustion of the first stage. This is a form of internal burnt gas recirculation, which generates low NOx in the second stage. Hydrogen as the first stage fuel has been demonstrated [R21] as has liquid fuels as the second stage fuel [R20].

In the present work both the fuel and air were axially staged, as shown in Figure 4. The first stage fuel was the BGG burner which could have NG or hydrogen to support the BGG flame stability and this had an air supply that could be controlled to vary the air split between the two axial stages. At the end of the air-cooled BGG burner tube that was about 1m long, there was a water-cooled X probe to take a mean gas sample of the BGG exit gases. There was then a section that had wall injection of liquid fuels – pot ale or glycerol, with the combustion air used for air atomisation of the liquid fuels. This air was at 200 – 300 deg. C after cooling the second stage flame tube, which is shown in Figure 12.

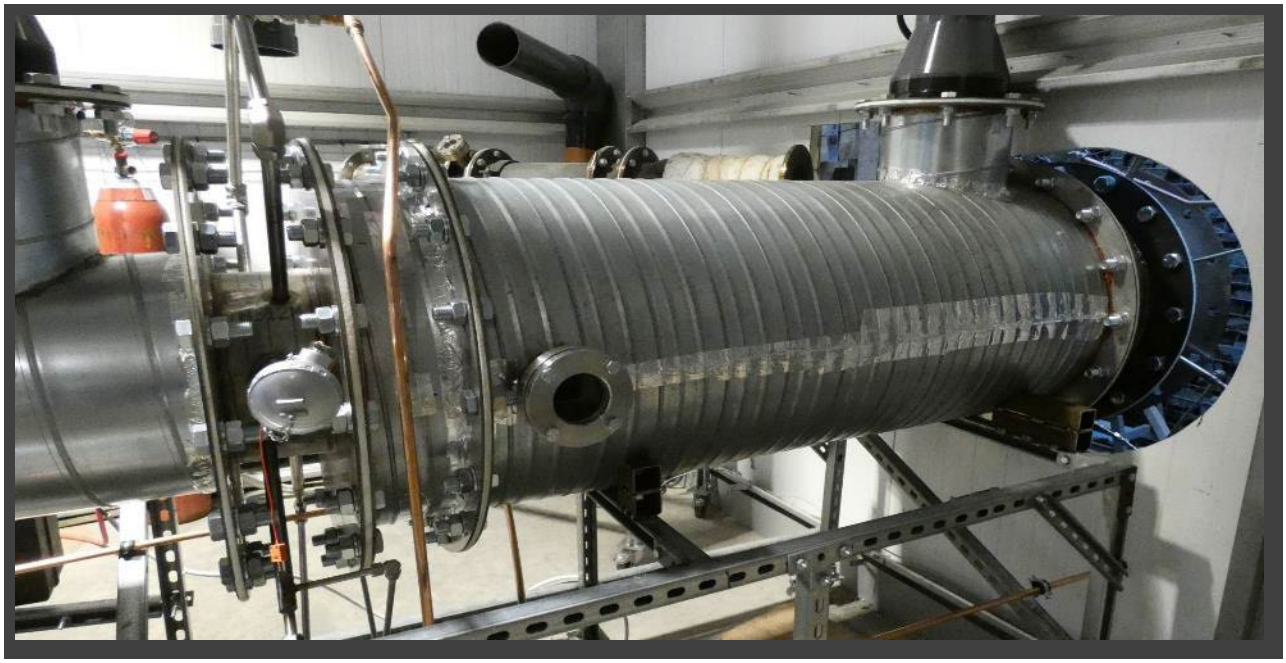

Figure 12. The second stage pot ale burner section, with its reverse flow air supply on the RHS.

Figure 12 shows the end of the BGG burner section with the water-cooled X gas sample probe and Type R mineral insulated flame temperature probe. The change in diameter of the flame tube from the BGG to the Pot Ale section can be seen in Figure 12, together with the second stage flame observation window just after the flame tube area change. The flame tube length was scaled from the BGG burner based on the burner diameter ratio. Figure 13 shows the wall cooling air slot (LHS) that feeds the wall injection pot ale fuel jets with surrounding air atomisation (RHS).

Figure 13. Pot Ale injection system.

The second stage air and fuel impinge into the hot BGG crossflow and the pot ale flame stabilises in the dump flow expansion, which is seen in the large flat metal area (LHS) and on the outlet of the pot ale injection stage (RHS).

The gasification test, with dry draff, wood and straw, discussed later, was tested with pot ale injection. This was a 650 kW BGG test and this is shown in Figure 14. The pot ale was injected from a 4 bar peristaltic pump with a design pot ale pressure loss of 1 bar. Figure 14 shows no atomisation of the pot ale jets that are laminar jets penetrating the BGG flame with no atomisation or combustion. At this condition the pot ale air pressure loss was 2 mb, far too low to have adequate atomisation, also the pot ale fuel injection pressure was well below 1 bar.

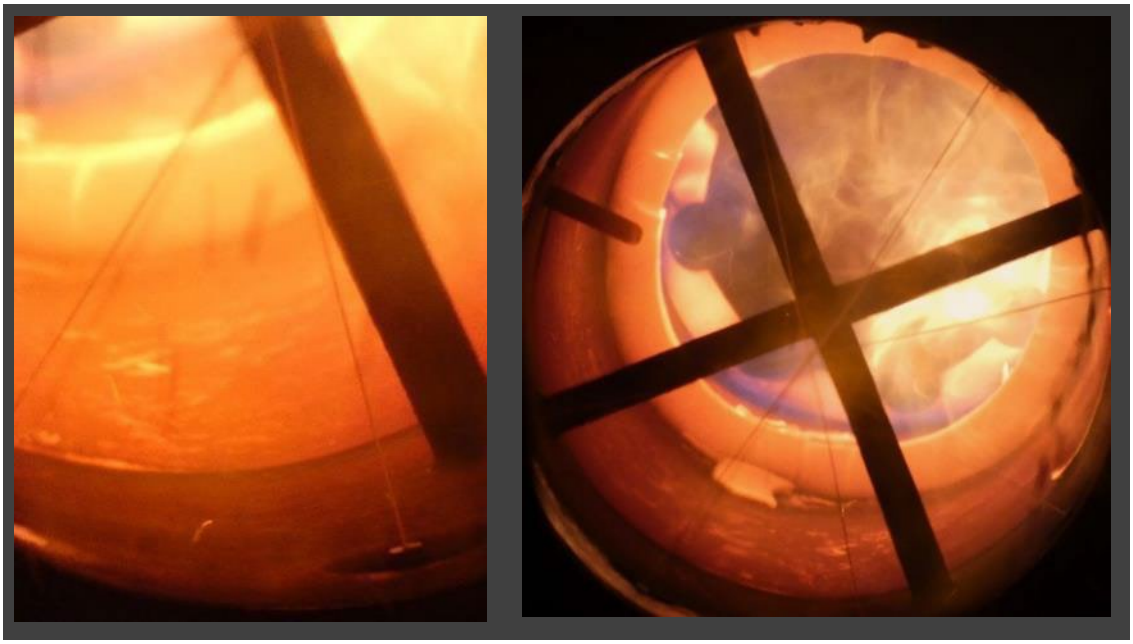

Figure 14. LHS shows PA Injection with atomisation of the PA.

Figure 15 shows a more successful pot ale test, with the upstream first stage BGG burner operating on NG at about 1.2 MW. The fuel injection pressure was 1 bar, and the air flow pressure loss was 1 mb. The LHS picture in Figure 15 shows a close-up view of one pot ale jet that is atomised and not a laminar jet as in Figure 14. The RHS picture in Figure 15 is a close-up view of the flame following a pot ale injection close to one of the pot ale injection holes and surrounding air jet. This is clear evidence that combustion of pot ale has been achieved. The aim of the pot ale injection is for the first stage combustion to evaporate the pot ale water, leaving the pot ale syrup to burn, with a net positive heat release. The pot ale burner heat release was determined from the difference in oxygen at the BGG outlet mean gas sampler probe and a downstream third X probe at the pot ale burner outlet. Determining this heat release was complicated by the addition of pot ale combustion air downstream of the BGG burner. The pot ale oxygen mass flow, based on the pot ale air injection pressure loss, was added to the oxygen mass flow at the exit of the BGG burner. A 25 kW heat release rate was achieved. This is 17% of the energy to evaporate the 87% water in the pot ale. When operating at 20 mb air pressure loss at the pot ale air injection (which is at the 2 MW design condition) more heat release should occur. This is a viable method for a distillery to incinerate its pot ale production, with no consumption of fossil fuels. A net release of energy to benefit the distillery energy balance is possible as shown earlier in this report.

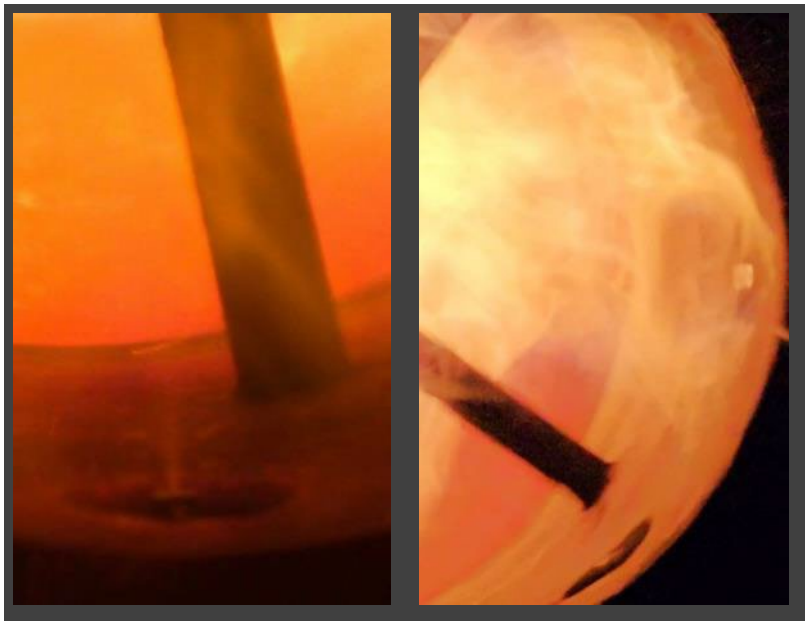

Figure 15. Pot ale injected into the BGG outlet gases when operating on NG, with a clear pot ale flame.

Results and Discussion

This section of the report provides an analysis of the experimental outcomes of various biomass gasification and combustion tests conducted as part of this study. These tests aimed to explore the potential of using distillery by-products, such as draff, pot ale, and barley straw, in gasification and burner systems designed for decarbonisation. The discussion evaluates the performance of these materials under different conditions, highlighting the technical challenges, energy recovery efficiency, and greenhouse gas reduction potential.

The tests were conducted with a focus on understanding the combustion characteristics of different biowastes, identifying optimal operating conditions, and determining the practical scalability of these solutions for industrial applications. Table 2 shows a summary of the tests and conditions reported in this work. The BGG outlet temperature corresponding to the concentrations in the Key Results column are included in Table 2, as is the peak temperature in the tests.

The design principles established in these tests demonstrate the ability to scale the gasifier size to match distillery batch operations. The current design, capable of producing a 2 MW BGG thermal output, can be adjusted to operate at lower power levels by reducing the air flow. However, it is recommended to modify the burners to maintain a 20 mb air pressure loss even at lower power settings and this only needs an air hole size change. In all the current work the power was varied by changing the air flow at the fixed burner size capable achieving 2MW

thermal power at 20mb air pressure loss. The burner could also be increased to 4 MW if the burner pressure loss at 80mb was acceptable.

Table 2: Summary of Biomass Gasification Tests (All the BGG powers are by oxygen consumption)

Test Description	**Materials Used**	**Conditions**	**Key Results**	**BGG Temp at the gas composition measurement**	**Peak Gasifier BGG outlet T**
TEST 1 Wood and Barley Straw Test. Material as Received with some water content. Both materials known to gasify easily.	228 kg wood logs, 167 kg barley straw **Total 395 kg** At the end of the test the weight remaining was 113 kg and 282 kg had been consumed in 3 hours 25 mins from PreB light up. An average power of 344 kW using an ave. GCV of 15 MJ/kg.	BGG burner on NG at 363 kW before PreB lit. Gasifier heated by PreB at 71 kW T = 160°C. after 22 mins. BGG energy with NG was 275 kW at T 565^{o}C Flame out if BGG NG turned off after 10 mins.	BGG composition with 78kW NG use. 7% CO 11% CH_4 9% CO 11% CH_4 8.2% CO 12.9% CH_4 1% ethylene 6.0% CO, 4.5% THC 3 hour 25 mins. BGG burn duration at 290 kW with 78 kW NG assistance. **73% decarbonisation** after PreB NG switched off. Flames at both the BGG burner and the second stage burner.	366^{o}C 435°C 616^{o}C 640^{o}C	**650^{o}C** After two hours 40 mins. with no preB NG and 78 kW BGG NG Max. BGG power at 650^{o}C **307 kW** **Max. Power** **With 78 kW NG assistance**
TEST 2 Addition of dry draff to Test 1 materials.	120 kg wood logs 40 kg barley straw 200 kg dry draff Total 360 kg.	Preburner at 230 kW for 2 hours to reach 440^{o}C when PreB fuel off. BGG flame operated with 100 kW	200 kg of dry draff was difficult to gasify the preburner was on for 2 hours. With PreB off BGG burner was at 650kW with 100 kW NG		440^{o}C After 2 hr with preB at 230 kW **470^{o}C**

	At end of test 56kg left. 304kg consumed in 3 hours. 422 kW ave.	NG assist for one hour. Flame out if NG turned off.	**85% decarbonisation after PreB NG off.** CO 2.4%, CH_4 1.4% Ethylene 0.16% CO 3.1%, CH_4 4.5%, ethylene 0.22%, ethane 0.18% Note: FTIR problem with very high water vapour, results not reliable.	440°C 470°C	After 1 hr with no PreB NG **650 kW** **Max.** **Power**
TEST 3 Wood, Barley Straw, Dry and Wet Draff	122 kg of logs, 74 kg of barley straw, 200 kg of DDGS, 221 kg wet draff (total load of 617 kg) 186 kg consumed in 3 hours from PreB ignition. 263 kW Ave	400 kW BGG With PreB NG off	12% CO, 12% CH_4. 8.5% CO, 9.3% CH_4 H_2O 30.5%, CO 1.2%, CH_4 0.05% - Unreliable. The peak conc. occurred prior to preburner shut down and were not sustained after preburner shutdown due to the high moisture content of wet draff . **49% decarbonisation with PreB NG off.**	218°C 437°C 454°C	251°C 47 mins from PreB Ign. 323^0C Just after PreB NG Off **467°C** 47 mins. After PreB NG Off **640 kW Max. Power**
TEST 4 Wood, Barley	165 kg of wood logs, 40 kg of barley straw,	Gasifier preheated,	8% CO,13% CH4, minimal hydrogen, sustained flame	318°C	**660°C**

Straw, DDGS, Glycerol Test	and 383 kg of DDGS, 90 kg glycerol; 678 kg total load	NG assistance	with minimal NG support. **24% decarbonisation** **Very poor due to large thermal inertia of the 678 kg load and glycerol did not vaporise adequately.**		5 hours after PreB ignition **2.1MW Max. Power**

Gasifier BGG Combustion Results

Wood and Barley Straw mass 400 kg – Gasification Test 1

In this test, the gasifier was loaded with 230 kg of wood logs and 170 kg of barley straw. A 71 kW preburner was used to heat the gasifier, raising the internal temperature to 160 deg. C within 45 minutes, at which point the outlet oxygen level was measured to be 1%.

This initial heating lasted 24 mins. after which the preburner was switched off while maintaining the air flow. After 8 minutes the exit temperature rose to 320 deg. C, and the composition of the BGG was measured at 9% carbon monoxide (CO) and 11% methane (CH4). This gas mixture was burned with 78 kW natural gas assistance. After 70 minutes of operation, the BGG composition was 8% CO, 13% CH_4, 1% ethylene, and 0.4% ethane, with no significant hydrogen detected. The majority of the heat release (90%) occurred at the BGG burner, with the remaining 10% at the axial staged burner, which was intended for pot ale burning but was useful in completing the BGG combustion.

After one hour operating with BGG with NG support, the NG was switched off, allowing for a pure BGG flame to be sustained for 15 mins., but then blew off. With 78 kW NG to the BGG burner, but no NG to the preburner the flame continued to burn for 3 hours 25 mins. at a combined BGG power of 290 kW, when there was a flame blow out. This is a 73% decarbonisation with BGG.

The BGG burner was then relit with a higher preburner air flow and continued to burn with the 78 kW NG BGG assistance until the gasifier ran out of volatile matter 90 mins later. The peak temperature of the gasifier outlet was 670^{o}C after 1 hour 20 mins. operation with 78 kW NG assistance. The average composition of the BGG during the sustained pure BGG flame (with preburner and BGG burner NG injection shut down) was 7.6% CO and 11.3% CH4 while the average BGG temperature in this period of rapid release of volatiles was 340 deg. C. This two-stage combustion process resulted in heat release at both the BGG burner and the PA burner, achieving a combined combustion efficiency greater than 99%. The BGG flame was a two-stage combustion process with heat release at both the BGG burner and the PA burner,

achieving a combined combustion efficiency greater than 99%. Flame photographs of the BGG flame with 78kW NG assistance are shown in Figure 16 Figure 18.

Figure 16 illustrates the BGG flames just after the NG was shut off to the BGG burner at 320ºC gasifier outlet temperature. Figure 17 shows the view of the BGG flame one hour after Figure 16 with 600ºC gasifier outlet temperature with the maximum 400 kW power output. The high hydrocarbon content from the gasifier gives the BGG flame its characteristic appearance.

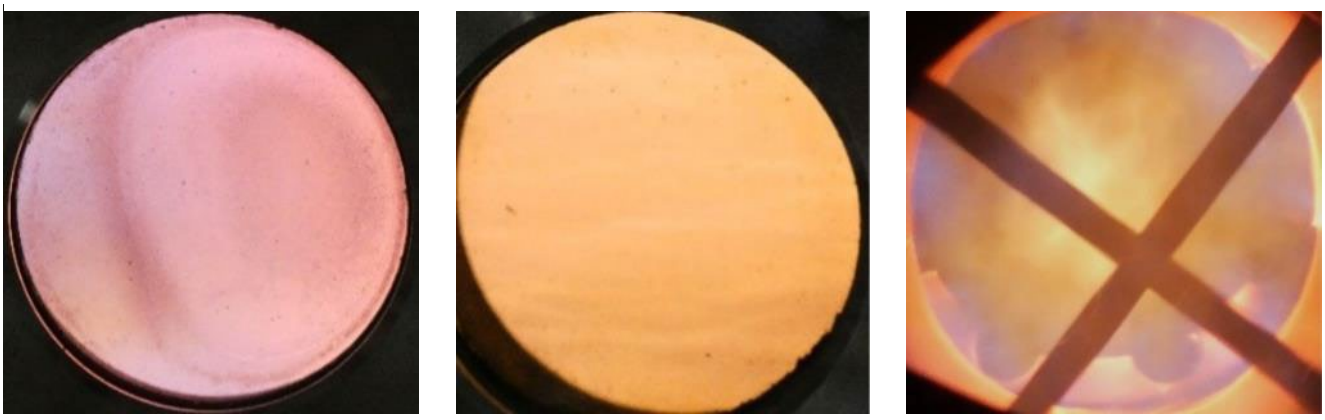

Figure 16. LHS- BGG flame close to BGG outlet; Middle – second stage flame ; RHS - Exit view of the BGG flame just after the NG was switched off. 320ºC gasifier outlet temperature.

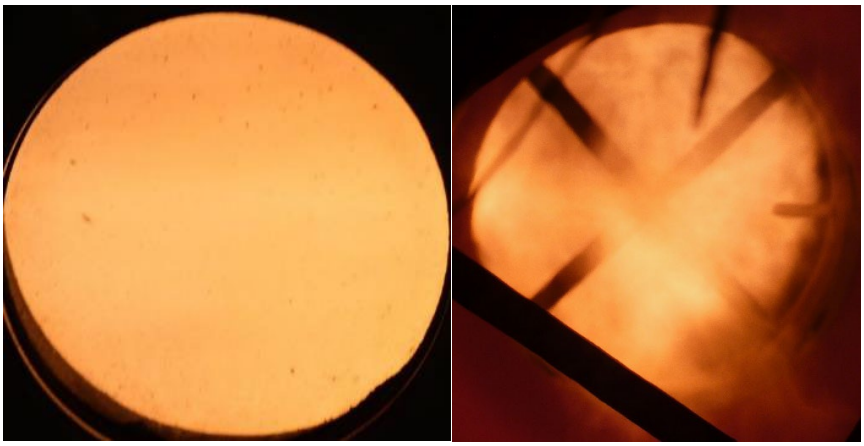

Figure 17. BGG burner flame operating on gasification gas alone at 400KW. LHS view is through the side window at the second stage PA burner. RHS view is from the end of the burner

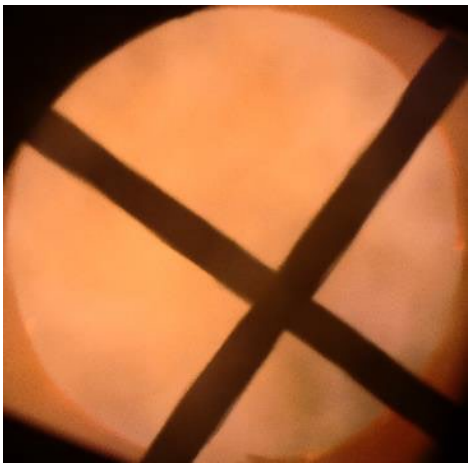

Figure 18. Flame one hour after Figure 17 with 400 kW continuous output with 78kW from NG

Figure 19 are the hot particles from the biomass undergoing gasification in the gasifier, further demonstrating the robust combustion process. This figure shows the BGG burner flame operating at approximately 800 kW, with a small amount of NG flow to support the BGG burner. The high hydrocarbon content from the gasifier gives the BGG flame its characteristic yellow appearance.

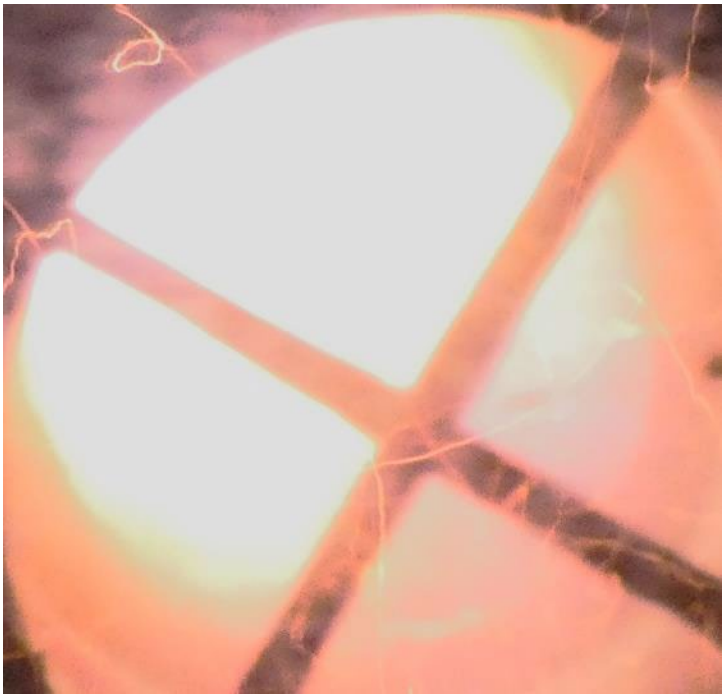

Figure 19. BGG burner flame operating on gasification gas alone at 800 kW. View is from the end of the burner.

Wood, Barley Straw, DDGS with mass of 360 kg – Gasification Test 2

In this gasifier test, a combination of 120 kg of logs of kiln dry wood, 40 kg of barley straw, 200 kg of DDGS, and 38 kg wet draff using a 230 kW pre-burner heater for 30 minutes to achieve self-heating gasification. With the preburner NG switched off there was enough BGG to generate 650 kW heat (by oxygen consumption calorimetry) with 100 kW of this from NG fuel

in the BGG burner. This was 85% of the energy from BGG or a NG cost and a carbon reduction of 85% with no preburner NG.

However, the 230 kW preburner operated for 30 minutes and used 0.414 GJ of heat. 550 kW of BGG was achieved for 2 hours 15mins, which is a heat generation of 4.455 GJ. The BGG burner had 100 kW of NG flowing to help stabilise the BGG flame, which is 0.810 GJ. So the total NG flow, including the pre-burner heat input was 1.224 GJ and the total heat used was 5.679 GJ so the BGG burner combustion of BGG displaced 78.4% of the NG used in the conventional NG heated steam boiler. This is the decarbonisation efficiency including the cold start, as the waste biomass are all renewable fuel on an annual basis. The final flame picture, in Figure 22, was taken 95 minutes after the gasifier was at 350 deg C and 1% oxygen. The gasifier temperature was 470 deg C. After this the BGG fuel was switched off and the BGG and second stage burner flame both went out. Thus, in this test some NG fuel was required to assist the BGG flame stability. This was not necessary for the wood/straw gasification in Test 1 and indicates the difficulty of gasifying draff. However, the proportion of the energy from BGG was high. Figures 20 and 21 depict the state of the flame at later times into the test.

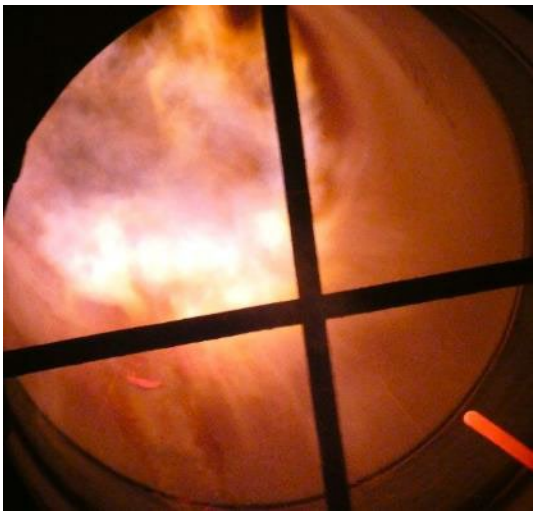

Figure 20. The BGG flame with the preburner fuel off but BGG NG on. Gasifier was at 350 deg C, and oxygen was 1%, which indicates gasification is active. 100 mins from the ignition of the preburner.

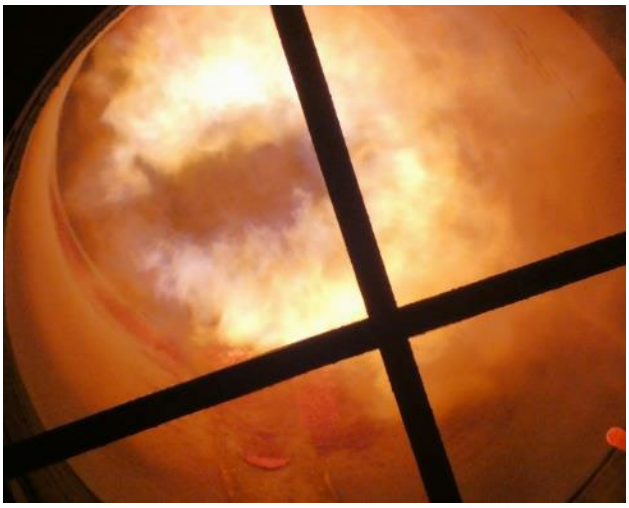

Figure 21. End flame view 45 mins after Figure 20 and 145 mins from the preburner ignition. The gasifier was at 500 deg C and the oxygen from the gasifier was 1.4%.

Figure 22. The BGG and PA flame view from the exit of the burner 30 min after Figure 21 and 95 mins since the gasifier was at 350 de C and 1% oxygen. 3 hours since the preburner was ignited. Gasifer outlet temperature was 548 deg C. BGG NG fuel was on all the time.

Wood, Barley Straw, Dry Draff and Wet Draff Total Mass 617 Kg (Total water content 36.5%). – Gasification Test 3.

In this gasifier test, a combination of 122 kg of logs, 74 kg of barley straw, 200 kg of DDGS, and 221 kg wet draff was used with the total water content amounting to 225 kg or 36.5% of the total load, 155 kg (75%) of this water was from the wet draff.

The gasifier was initially heated using a 69 kW (by oxygen consumption) preburner, which in 15 minutes achieved 333 kW heat release in the gasifier (by oxygen consumption) and achieved a temperature of 130ºC at the gasifier outlet. 40 kW of this heat release was used to evaporate water (assuming the weight loss was water evaporation). The rest was used to heat

the gasifier draff and the other waste biomass. The preburner was operated for a further 29 mins. (44 mins. in total) and the gasifier heat release at the end of this period was 282 kW and the outlet temperature was 273^{o}C.

The preburner NG fuel was switched off with the air left on. After a further 44 mins. (1 hour and 18 mins from lighting the preburner) the gasifier outlet temperature was 415^{o}C and there was 295 kW heat release in the gasifier (by oxygen consumption), which mainly heated the gasifier load. There was also an output of 49 kW in thermal heat in the BGG gas, that was sent via a thermally insulated pipe to the BGG burner as hot BGG gas, that aided the BGG flame stability. Although the transfer pipe from the gasifier to the BGG Jet Mix burner was insulated, there was a heat loss and the energy into the BGG burner was 31 kW, which will be assumed to add to the energy released from burning the CO and hydrocarbons in the BGG.

The hot BGG gas also contained CO and hydrocarbons, which released energy at the BGG burner when air was added. The BGG burner was operated on NG at 0.36MW with a high excess oxygen, before the gasifier preburner was lit, so that it would burn all the gases released from the gasifier as it warmed up. The oxygen would then decrease at the burner exit and the BGG heat release was calculated from this decrease in oxygen. For the situation just before the preburner was switched off at a gasifier outlet temperature of 251 deg C, the total BGG thermal output was 0.88MW and the BGG fuel released 0.47MW at the BGG burner, which is 54% of the total NG and BGG energy. The BGG flammable gas composition prior to switching off the preburner was 12% CO and 12% methane.

After the preburner fuel was switched off, with the air still flowing at the condition that the gasifier outlet temperature was 467 deg C, the total power produced by the combined NG and BGG by the BGG burner was 0.64MW with 0.30MW from the gasifier BGG, which is 47% of the NG energy replaced by BGG. If the 31kW if thermal input to the BGG burner from the gasifier is added to the heat release from the CO and hydrocarbons in BGG then the total heat release would be 0.66 MW and 0.32MW from the BGG and **the thermal efficiency increases to 49%.** The flame appearance at this condition is shown in Figure 23.

This test represents a significant milestone, providing the first proof that wet biowaste, specifically wet draff, can be effectively gasified with 49% of the NG to the burner replaced with zero carbon BGG. The results demonstrate the potential for wet draff to be used on-site in distilleries to generate substantial bioenergy through gasification. This is a much higher reduction in NG use than can be achieved by sending the distillery waste to an AD plant, which requires the draff to be dried and the conversion efficiency of AD plants is poor, as much of the energy in the waste remains in the solid waste from the AD plant. The best AD plant thermal efficiency is 30% [R5] and lower if the biogas is upgraded to be bio-methane suitable for injection into the grid [R6]. Distilleries that do this deduct the bio-methane from their NG use in a GHG audit. The present gasification approach is a much more energy efficient method of using the whisky industry waste to reduce NG or fuel oil consumption in the distillery.

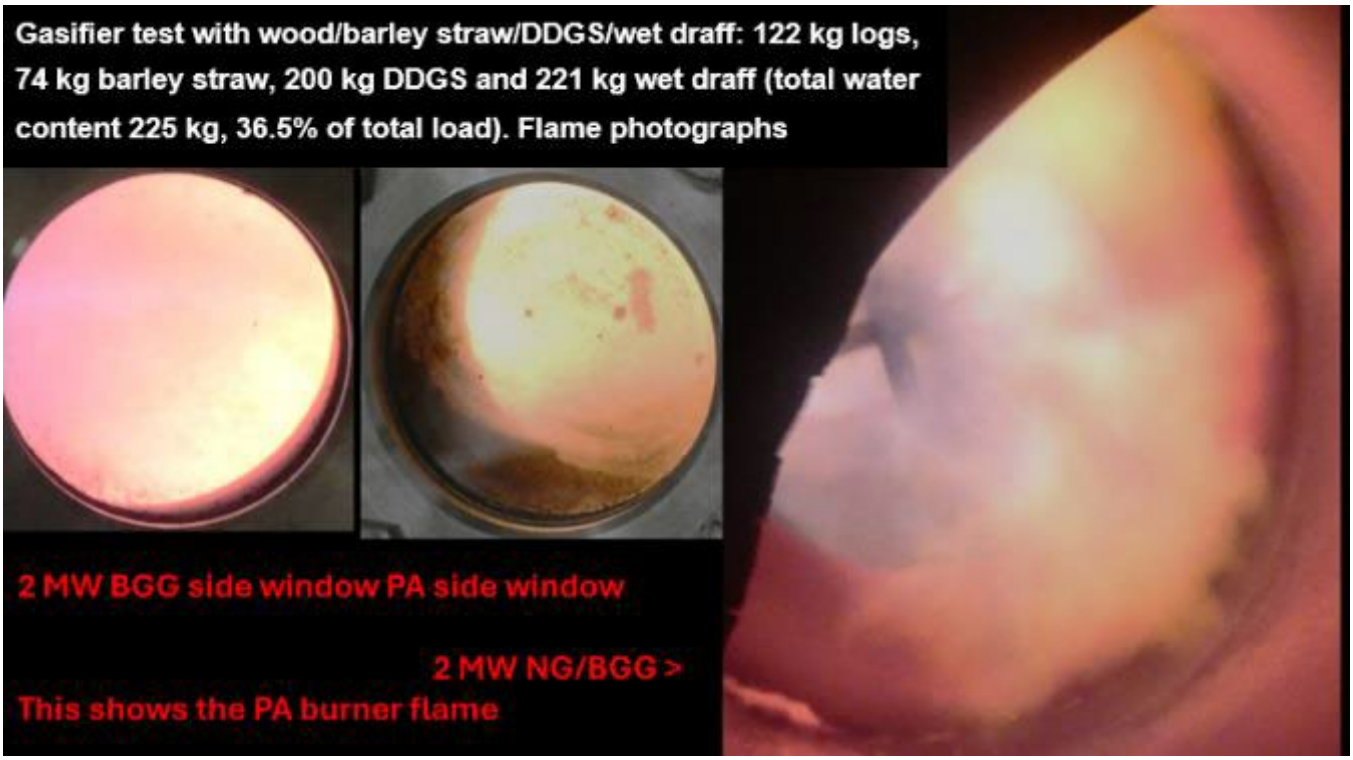

Figure 23. BGG flame photos at different locations for the test with wood, barley straw, DDGS and wet draff.

Wood, Barley Straw, Dry Draff and Glycerol – Gasification Test 4

165 kg wood, 40 kg barley straw, 383 kg dry draff, 90 kg of glycerol. Total load of 661 kg. Much greater load was used in this test than the load used in Test 1 to allow for longer operation at 2 MW.

The above batch gasifier load was arranged in layers and the new material in these tests was glycerol, a waste bio-oil from biodiesel manufacture. This was poured on top of the draff and the aim was to see if it acted as draff with a higher volatile content. It was quite difficult to stop the glycerol from flowing through the draff and dripping on the floor, a previous test had tried glycerol and pot ale together on the floor with draff and straw and this was ineffective, as most of it remained at the end of the test as a tarry material at the bottom of the vessel.

A feature of this test, which was not realised at the time, was that the back pressure of the preburner flow over the high load in the gasifier increased and this was taken as an increase in air flow. So although the test was intended to be 2 MW from the BGG, it was 500 kW BGG for one hour at the peak BGG production, with the rest being 1.1 MW of NG burning at the BGG burner and 0.4 MW at the preburner in the warm up stages. The test was very slow to heat the gasifier in spite of the high preburner power. At 40 minutes after lighting the preburner, the preburner outlet oxygen was 16.1%, the gasifier outlet temperature was 180 deg. C and 1% outlet oxygen. The PA burner outlet O_2 was 11.3%, but the heat release at the BGG and PA burners combined from the BGG was 0.525 MW and the preburner was still fired with NG at 0.4 MW. Overall, the BGG burner was operating at 2 MW but only 0.525 MW from the BGG. The BGG burner flame photographs are shown in Figures 24 and 25.

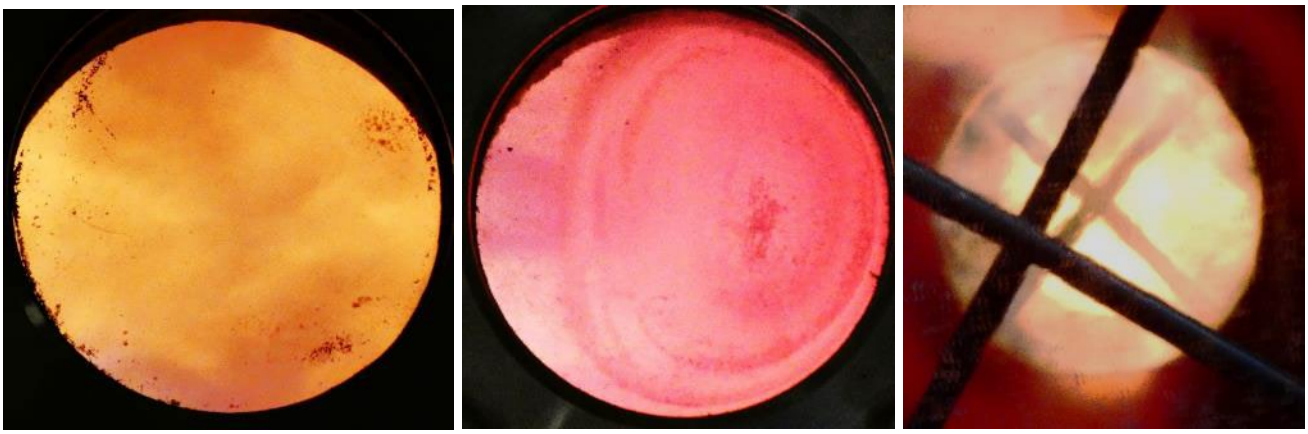

Figure 24. BGG flame photographs 40 mins from Preburner light up with 0.4 MW preburner and BGG with 1.1 MW of NG and 0.525 MW of BGG. Side window of the BGG burner on LHS, side window of the PA burner and end view of the flame on RHS.

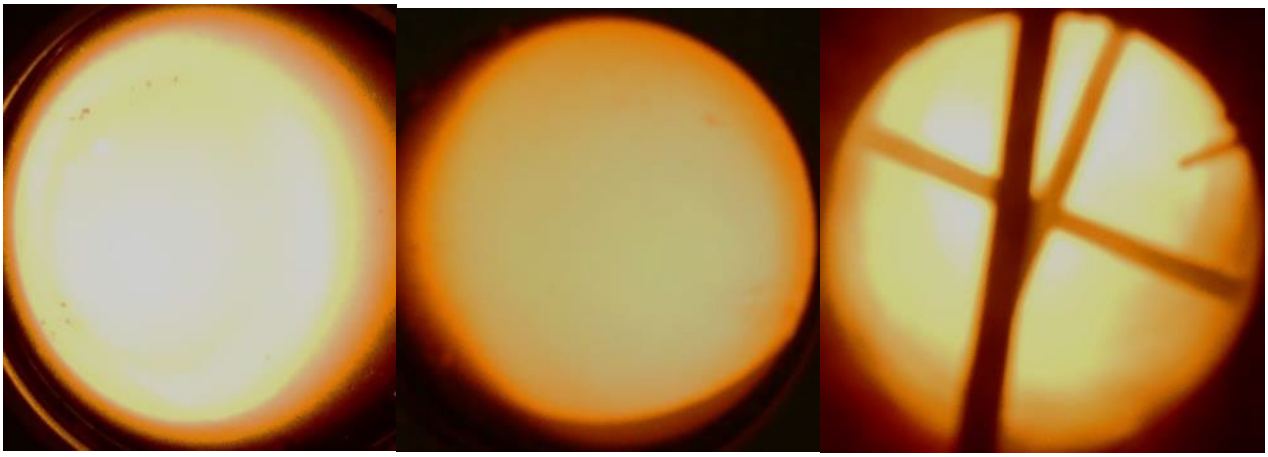

Figure 25. 2.1 MW flame with 24% of his power from the BGG fuel. View of the flame by the BGG burner side window on LHS, the PA burner side window in the middle and the view up the burner from the exhaust exit. The yellow flame is from the hydrocarbons in the BGG.

It took 2 hours 17mins from the preburner light up before the preburner fuel was shut off at 300 deg. C and 5.4% oxygen at the gasifier outlet. It then took a further 2 hours to reach 600 deg. C with a gasifier outlet oxygen of 9%. The was a completely different test to that undertaken above with no glycerol present. Just after the preburner fuel was shut off the BGG composition was: 7.7% CO, 7.9% methane, 3.8% ethylene, 0.4% ethane and 4.7% CO_2. This is similar to the BGG composition listed in the BGG section with higher ethylene than measured in previous tests, but the methane was lower. The flame was burning at the BGG burner and the PA burner. Flame pictures of this BGG flame are shown in Figure 25.

In these tests the BGG flame contributed 500 kW and was supported by a 1.6 MW NG BGG flow. The total thermal power was 2.1 MW with 24% from the BGG gas, much lower than in the previous results above. The gasifier was not operating in the same way as in previous tests as near 0% oxygen could not be achieved and the gasifier temperature rise was much slower, taking 4 hours to reach 600 deg. C. There were three changes from the previous test with dry draff: firstly, there was twice the load including twice the dry draff load; secondly, glycerol was

added and thirdly DDGS was used, which is a processed dry draff into an animal feed. The conclusion is that these changes deteriorated the evolution of BGG. Consequently, it is concluded that glycerol should not be used as a gasification fuel, but if desired should be used in the two-stage burner using the same injection method as for pot ale. Doubling the gasifier load was the reason for the slow warm-up and the rise in the back pressure and so all the problems in the test may not have been due to the glycerol. Also, as DDGS is not the raw dry draff, future work should only use raw dry draff.

Smouldering biowaste combustion for energy storage

The above tests were of long duration, 8 hours for the last test. To avoid operating through the night a method to shut the gasifier down was developed from a condition where the gasifier outlet temperature could be 600 deg. C. The procedure to do this was to shut off the air flow to the preburner and to close all the air intakes to the test facility, including stopping any air backflow from the PA burner exit. This was successful as the temperature of the gasifier fell, but not to extinction. Biomass contains organically bound oxygen and can undergo smouldering combustion and the gasifier went into a smouldering combustion mode when the preburner air was shut off. On the day after the wet draff test, 12 hours after the gasifier had been shut down, the weight loss overnight indicated an average 30 kW smouldering heat release. The preburner air was turned on and the gasifier produced BGG gas at 200 kW by oxygen consumption, with no NG assistance. Eight (8) days after shutting down the gasifier after the wet draff test, the gasifier was relit by letting in air. Peak BGG temperature of 326 deg. C was attained without a preburner NG flame.

This is an unexpected benefit of the process, as in the theorical application it was assumed that the gasifier output could not be controlled to shut down when the distillery was changing batches and using the BGG for heating water in other parts of the distillery was postulated. This is not necessary as the gasifier can be shut down from hot, smoulder for over a week, and be restarted without using NG for cold start. This is a major benefit for distillery operation, as the gasifier can supply heat simply by opening the air flow to the gasifier, with no cold start preburner fuel use. For applications, like distilleries, which require heat 24/7 but with periodic shutdowns, this can be achieved with this batch gasification approach. Thus, the gasifier would only need to cold start once per year after an annual maintenance shut down. Thus, the flexibility of the gasification heat would be as good as using a NG burner where the NG can be shut off when the heat is not needed. The gasifier only needs to shut the air off and no BGG fuel is delivered, but the gasifier remains hot. Thus, it is the thermal efficiency with the preburner off in this work that matters, as cold starts were a necessary feature of the present tests, but would not be necessary in a 24/7 heat application. This does assume that a method to refuel the gasifier can be developed and a method to refuel whilst shut down could be attractive for the batch gasifier operation as the draff could be transferred from one distillation batch directly into the gasifier, which would enable its heat to be retained. The pot ale could also be directly transferred to a supply tank for the PA fuel injection into the axial staged burner. Discussions with whisky distillery operators have shown that this capability would be

welcomed by the industry and would be a major advantage of the batch gasification route to decarbonisation for the industry.

Benefits

The various project benefits are detailed in Table 3. Some of these were discovered as the project progressed, and were additional gains added to the original proposal.

Table 3: Project benefits

Action	Benefit
Distillery waste disposal in the gasifier and second-stage BGG burner	No additional use of fossil fuels to dry the draff or pot ale since the energy in these fuels is enough to vaporise their moisture content No extra cost to distilleries for disposing their waste.
Constant and abundant supply of barley	The gasifier biomass can be delivered from the wider distillery industry or farms as barley straw. It is available in sufficient quantities and at low cost.
Fossil fuel displacement by BGG	The BGG displaces the use of NG or FO by 49% for wet draff and other whisky industry waste biomass, which reduces the carbon footprint leading to savings in energy bill and carbon credit. Pot ale injection downstream of the BGG burner will enhance decarbonisation.
BGG production by smouldering	When shutting down the air and fuel to the gasifier, the biomass leftover will smoulder but not burn, and when reigniting, this produces an immediate supply of BGG. This means that for 24/7 operation in distilleries there will be only one cold start between maintenance intervals and so normally the preburner will not be fuelled and

	the energy efficiency and GHG reduction is maximised.
Complete decarbonisation	If low C hydrogen was to be used as a primary fuel for the burners, the process would be decarbonised completely.
LCID	The Livingston Centre of Industrial Decarbonisation is well equipped to be used as a research facility for hydrogen combustion decarbonisation and for gasification for the industrial, commercial and domestic sectors.

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Lessons learnt and Barriers

The cold start thermal inertia of the initial 30 cubic meter gasifier with refractory walls was too high and the cold start use of NG was far too high, and the temperature rise too slow. A smaller lower capacity steel box was installed inside the larger gasifier and was more practical and achieved the gasification condition of 300 deg. C and 1% oxygen within 45 mins.

Once the gasifier was heated to about 350^{o}C and 1% oxygen in the outlet gases, then the preburner fuel could be switched off and the gasifier would be self-heating. The batch gasification load would smoulder if the preburner air was shut off and remain hot for up to a week, ready for a restart once air was introduced. Thus, the distillery heat demand could be met when required and switched off between distillation batches.

The thermal power could be varied using the air flow to the BGG burner. A 2 MW burner could be operated at any thermal output by reducing the air flow; 0.5 to 2 MW operation was demonstrated.

Wet draff and raw pot ale could be destroyed in the gasifier and burner, saving their disposal cost as well as extracting their energy.

Adding pot ale and/or glycerol to the gasifier was not recommended and these low-cost bio-oils should be used in the second stage PA burner.

The flammable gases in BGG were mainly CO and methane, with no significant hydrogen. Ethylene and ethane were the two other significant hydrocarbons in BGG. The operating temperature of the gasifier for any available bio-waste could be determined using TGA, as the gasifier operating temperature for CO and hydrocarbon release was the same as determined by TGA analysis.

Future Technical Work

Distillery wet draff should be the only distillery product that is used in future work in the gasifier. Wood and straw should be the main other biomass for providing energy of the operation of the distillery. Pelletised straw should be investigated as well as wood chips rather than logs, as these are easier to continuously add to the gasifier. It is necessary to carry out future work to demonstrate higher NG replacement efficiency than the 48% achieved in this work for the co-gasification of wet draff with other whisky industry waste biomass. Higher gasification efficiency for wet draff could be achieved by reducing the NG proportion of the BGG energy. Hydrogen as the support fuel would give a better performance as its better flame stability will enable lower hydrogen energy use.

Excess heat from the burner could be extracted and used to dry draff, but this will deteriorate the BGG flame stability and using hydrogen as the co-firing gas is considered the best approach, as this will enable full decarbonisation, as well as maximising the energy contribution from BGG.

The determination of the maximum loading in the gasifier, without deteriorating its performance on wet draff should be determined.

A method to add more biomass to the gasifier must be developed and continuous operation over many days should be demonstrated.

TGA of dry draff shows that although it had 88% of volatile matter (that form BGG hydrocarbons) the fixed carbon was 12% and this would form a char. To achieve a better overall conversion of energy in biowaste to energy in BGG the conditions to gasify char at the end of a gasification batch should be investigated.

Figure 1 shows that 20% of the biomass was non-volatile and the rest was char and ash. The ash from the gasifier should also be investigated as a potential fertiliser for farms, which would provide an additional income to the distillery as well as reducing costs for farmers. This has been shown to be viable for biomass combustion at the Bunnalhabhain distillery on Islay [R1].

More work on pot ale staged combustion is required to show that all the potential heat release from pot ale can be achieved. Glycerol needs to be demonstrated as a practical low-cost bio-oil for the staged burner, with heating of the glycerol using the hot cooling air and air- atomisation.

The firing of a steam boiler with the BGG and PA staged burner is still yet to be demonstrated on the 350 kW steam boiler at LCID. This is necessary to address the extra energy savings.

It is the intention to continue the development of the gasifier and burners and prepare the process for demonstration and commercialisation. However, this can only be possible with extra funding to cover the many tasks involved in upgrading the system. The facility of LCID continues to work as a decarbonisation centre for any project involving combustion of hydrogen and gasification of bio-wastes.

An assessment of the financial benefits of the gasification solution

The key benefit of this fuel switching proposal is that it could be implemented quickly as the biomass and bio-oils are available and low cost. For wet biomass 49% replacement of fossil fuel use for heat can be achieved and this is effectively 49% reduction in the GHG emissions. There would also be an energy cost reduction as the biowastes are free from the distillery and low cost for straw and crude glycerol. For complete decarbonisation the remaining heat would have to be supplied by hydrogen or ethanol. In the absence of hydrogen in the gas grid, either a hydrogen generation plant is built at the distillery or ethanol is used, sourced from the automotive ethanol for adding to petrol. The feasibility of onsite generation of hydrogen was part of other Green Distilleries projects.

This proposal enables a start to be made in 2025 on significant decarbonisation of distilleries. Even if NG is used for the gasifier heater, there will still be a substantial decarbonisation, as at least 49% of the steam boiler energy will come from the gasified wet bio-waste. This proposal is deliberately targeted at the use of biofuels and waste biofuel products, such as crude glycerol. The current industrial cost of NG is 0.71p/MJ compared with 0.6p/MJ for straw, 0.8 p/MJ for crude glycerol and 1.4p/MJ – 2.7p/MJ for hydrogen.

The main reactive biofuel that will be used, ethanol, has a current price of 2.6p/MJ. This is about the same cost as hydrogen and is unlikely to be used for decarbonisation unless the cost of hydrogen is well above 2.6p/MJ. Draff and PA are waste products from the distillery and PA currently costs the refinery to dispose of it. Wood chips are available at 0.7p/ MJ and wood pellets at 1.1 p/MJ (Perthshire Biofuels). It is clear that biomass sources can be obtained that are cost competitive with NG, with no subsidy for their use.

It is thus possible that fuel switching to gasified biomass could reduce energy costs as well as decarbonising the distillery industry. With the draff and PA waste being free, it is highly likely that the gasification route to decarbonisation will significantly reduce the operating costs of a distillery. However, the more reactive fuel for heating the gasifier will be a higher operating cost item, as for complete decarbonisation this has to be either bioethanol or hydrogen and both are a higher cost than NG or any of the biomass supplies. However, the gasifier was shown above for wet draff to displace 49% of NG and so the overall energy costs should be lower than current NG costs, even if hydrogen is used for 51% of the energy. In addition, the current expenditure on the disposal of PA and draff would not be necessary.

GHG savings

Scotland had the capacity to produce 845 MLPA in 2023 and in 2020 released 0.673 Mt of CO_2 [SWA] which is 0.8 kgCO_2/LPA. The SWA gave the total production in 2022 as 792 MLPA/year, which is 0.85 kgCO_2/LPA. The average energy used to produce alcohol is 30 MJ/LPA [P1, P10]. For NG as the fuel with a GCV of 50 MJ/kg this is 0.6 kg/L; for FO with a GCV of 43 MJ/kg this is 0.70 kg/LPA. There are about 2.8 kg of CO_2 produced per kg of NG burnt and 3.3 kg for FO. This gives the production of CO_2 per kg of fuel used in distilleries as 1.70 for NG and 2.3 for FO. The whisky industry is 2/3 NG and so the average production of CO_2 is 1.9 kg/LPA. For the 2022 production of 792 MLPA/year this gives a CO_2 production of 1.505 Mtonnes per year, which is much higher than the SWA estimate in 2020. The difference is likely to be the average energy used in MJ/LPA, which our review [P1, P10] shows was variable between distilleries.

If all the distilleries were fitted with the present BGG heating then the reduction in CO_2 for the use of wet biomass including draff would be 49% or 0.74 Mt of CO_2, leaving 0.77 Mt of CO_2 emitted, or 0.97 g/LPA. In addition, the burning of pot ale in the axially staged burner is shown in Table 1 to give a net energy release of 8.07 MJ/LPA which reduce the CO_2 emissions to 0.72 Mt CO_2. However, if SLW was also destroyed in the BGG burner flame then most of the PAS energy is used to vaporise water in SLW and there would be very little CO_2 benefit.

To achieve 100% decarbonisation, hydrogen or crude ethanol would have to be used for the remaining fossil fuel use. Ethanol is the simplest to use as this is available from automotive bioethanol manufacturers for addition to petrol in Europe. The decline in the use of petrol or diesel vehicle use, as electric vehicles start to dominate the market after 2035, will make automotive bioethanol readily available. This would then be a complete bioenergy solution to the decarbonisation of the whisky industry.

If a distillery wanted to use hydrogen to achieve net zero, then the BGG and bio-oils burner approach will effectively reduce the use and cost of hydrogen by 45% and by 79% if PA was burnt downstream of the BGG burner with SLW disposed of via water treatment plants. The distillery could, from local wind/solar power, generate its own hydrogen by electrolysis. Complete decarbonisation could be achieved using hydrogen preburners during cold start and hydrogen in the BGG burner to assist BGG flame stability.

The target in the Sixth Carbon Budget (CCC 2020) of 63% reduction from 2019 – 2035 could be met using the BGG approach, if all distilleries were decarbonised at 49% using wet biowaste, then only 14% reduction using hydrogen or ethanol would be required to meet the Sixth Carbon Budget target. The technology is then in place to achieve 100% decarbonisation once an increased supply of hydrogen or ethanol has been established.

Commercialisation

Business plan

We have shown that wet draff coupled with straw and wood can reduce NG or fuel oil consumption by 49% and higher if PA was burnt downstream of the BGG burner, based on 2 MW BGG burners, which are the size for 2 ML/year alcohol production distilleries. The alcohol production per year is about 800 ML and thus 400 2 ML distillery units could be required. It is estimated that the capital cost of these would be £1 million per 2 MW system or £400M.

Hydrogen or ethanol as zero carbon fuels only need to be used post 2035 and hydrogen in the gas network may be available by then. As the use of biowaste is cheaper than NG, decarbonisation with operational cost reduction can be achieved and this should ensure that the technology is in demand in the whisky industry. Further cost reductions arise because the cost of disposal of draff and pot ale has been eliminated.

There are 78 distilleries with a size below 2.5 ML per year and of these 33 are less than 0.5 ML per year. However, about 50% of whisky production is in the five largest distilleries in the 150 ML – 36 ML size range. There are 10 distilleries in the 10 – 25 ML range and 57 in the 2.6 ML to 8.5 ML range. However, as the amount of biowaste scales with the whisky production, there is no reason why the gasification approach cannot apply to all distilleries. We have established in this project that the technology can be scaled up or down from 400 kW to 2 MW and this shows that any scale of distillery could be designed for.

From the design stage of this project, it was considered that the best way to retrofit the gasification staged combustion decarbonisation technology would be to install a duplicate boiler to that used for NG, and build the current technology to operate that boiler. This then enables a switch over to biowaste steam with no interruption to whisky production. Also, this will leave the distillery with confidence that production can continue as the NG would be available as a backup.

However, this depends on a demonstration that we can move from the current batch gasifier demonstration facility at 2 MW to a practical continuously operated gasifier and PA burner. The fact that the burners can burn hydrogen or ethanol with no change for 100% decarbonisation, is a decision for individual distilleries as to when they want to implement that option. There is little equipment capital cost for moving to complete decarbonisation, apart from the hydrogen or ethanol supply infrastructure and higher fuel costs.

The big advantage of the biowaste approach is that a start on decarbonisation in distilleries can start in 2025 without having to wait for a hydrogen supply. Also, the design enables 100% decarbonisation using hydrogen or ethanol, to be achieved when these fuels are available, with no changes to the technology. Ethanol gives a route for any distillery to achieve zero carbon now, as the infrastructure to supply this for the automotive industry already exists. The transition to this technology, based on installing a new steam boiler, means that no loss in

production should occur as the two boilers could operate side by side until confidence in the reliability of the biowaste approach had been proved on a distillery site.

Roll out Potential

We anticipate that once the future technical work has been completed (testing of gasification and the axially-staged BGG and pot ale burner), this low-cost solution to decarbonise whisky distilleries will be ready to take orders from distilleries that wish to decarbonise using biofuel gasification from 2026. The product development could be then self-funding from sales.

The product also has applications in other areas such as BGG fuelling of diesels and micro-gas turbines for green power generation. Gasification of plastic waste for power or heat would also be possible. Farm waste would be suitable for gasification (solid waste, chicken manure) and for burning in the same way as pot ale (pig slurry). This would be of environmental benefit as we could decarbonise large commercial chicken and pig processing plants, where the biowaste is currently polluting nearby rivers from their run-off.

The preburner and BGG burner used in this system possess multi-fuel capabilities and can be scaled up at no major additional expense. The stabiliser technologies used in both burners have been previously demonstrated for ultra-low NOx gas turbine combustion. There is currently a need for manufacturing industries to swich from fossil fuels to green sources. Therefore, having combustion systems capable of burning several fuels not only generates significant economic benefits, but also allows for a much simpler and efficient transition to decarbonisation strategies.

Route to Market

The Livingston Centre for Industrial Decarbonisation (LCID) at CCEL, will be unique in demonstrating a gasification and hydrogen route to zero carbon for distilleries and for many other energy using industries. There are 151 (SWA) whisky distilleries currently operational, with more planned. LCID will showcase the technology of biowaste gasification and novel gas burners and show that the process involved can be moved out to individual distillery operations as a package.

We envisage, from existing discussions with the distillery industry, that the operating cost reduction of this biowaste and hydrogen route to decarbonisation will be welcomed by industry. Also, its application to FO-fired distilleries with ethanol as the low carbon fuel, will mean that all the distilleries can be decarbonised. In addition, the removal of draff and pot ale from the distillery with no fossil fuel use will result in an economic benefit.

Conversion of distilleries would have to take place at two 2 MW units per month which would decarbonise the whole industry by 2042. CCEL will lead this marketisation of this decarbonisation technology and CBS will manufacture the critical burner parts of the project.

We envisage that the simplest way to bring the technology to market is to install a duplicate steam boiler in a distillery which is modified to be fired using the axially staged BGG and pot ale burner. The steam output could be connected to the same point as the NG boiler and the NG boiler shut down. This would enable the NG burner boiler to always be available, should the gasification approach need to be shut down for ash cleaning or for any other problems.

This is a credible route to market, immediately reducing the distillery carbon footprint, which does not have to wait for hydrogen to be delivered through the Nat Gas grid.

The corporate contact base extends into the Japanese and US markets through current ownership structures in the distillery industry, and as we are seeing already, the keen worldwide interest in decarbonisation opening opportunities for Colorado/CBS in international markets. The SWA will be a valuable voice, sitting as it does between the distillery and the consumer, in publicly driving the route to Carbon Zero with pressure from its customers in the wholesale markets. Consumers want to know what the industry is doing about decarbonisation.

Intellectual Property

Regarding the Intellectual property (IP) of this project it encompasses various types of rights, including patents, copyrights, trademarks, and trade secrets.

Applying IP to a project involves identifying and protecting the unique aspects of the project that can provide a competitive advantage. For instance, in a research and development project similar in nature to this, securing patents for innovative technologies can prevent competitors from using the same inventions, thereby safeguarding the project's market position.

However, with a complex project like this it is important to ensure that any applied IP does not limit the end user/owner from further applications or have a patent granted that is too narrow to allow further development of the IP.

Several areas have been identified that are ‘novel’ and could have IP applied to them but at this time they are not being progressed until further trails and applications are set out by either dedicated research or end user requirements.

Conclusions

Whisky industry waste biomass was reviewed, and it was shown that there was sufficient waste to fuel all the energy requirements of distilleries. However, for distillery wastes only, there was insufficient wet draff, PA or SLW to operate the distillery without other waste biomass being added. Barley straw and wood were shown to be viable co-gasification biofuels. The low-cost waste bio-oil crude glycerol from biodiesel manufacture was investigated for gasification, but was not effective. Its use in two stage combustion, injected at the same location as PA, is recommended and the second stage burner was designed to do this.

For waste biomass to provide the main fuel for whisky, a range of biomass would be required, not just the biowaste from whisky distillation. It was concluded that a gasifier was the best

method to utilise a range of biomass and batch gasifiers of the type sold as log gasifiers were the basis of the technology. A system to give up to 2 MW thermal power from biomass gasification gas (BGG) was developed that separated the gasifier and BGG burner.

The flammable gases in BGG were CO and hydrocarbons, mainly methane. There was no significant hydrogen.

Considerable work on hydrogen burners was undertaken, as heating of the gasifier from cold start and the burning of low calorific BGG requires flame stability assistance during the cold start. The use of hydrogen for these cold start purposes gave zero carbon. Comparison with continuing to use natural gas or fuel oil in conjunction with the BGG gas was carried out for partial decarbonisation. For zero carbon from the 33% of distilleries heated by fuel oil, crude ethanol (automotive) would be used.

Gasification power output from 400 kW was achieved on a wood and straw biomass load, that achieved BGG combustion with 78 kW of NG at the BGG burner as fuel assistance to stabilise the290 kW BGG flame. This could fuel a 0.3 MLPA alcohol production for whisky, using 30 MJ/L for distillery energy needs. This result shows that the process developed would gasify dry biomass.

Both dry and wet draff achieve gasification, but the wet draff required more NG assistance (51%) for the combustion of BGG than the 15% NG assistance for dry draff due to the high moisture content of the wet draff. If low carbon hydrogen is used for heating the gasifier, then 100% decarbonisation is possible. Alternatively, the cost of hydrogen decarbonisation can be lowered by using BGG to reduce the quantity and cost of hydrogen use and to achieve low-cost decarbonisation.

The 49% decarbonisation efficiency for wet draff is superior to the <30% efficiency achieved in AD plants for dry bio-waste. Thus, this gasification approach offers greater cost savings and greater carbon reductions than the AD approach.

The other main distillery biowaste was pot ale and this was also high in water content and the objective was to investigate ways to generate useful energy from PA. This was shown not to be useful for gasification but was capable of burning downstream of the BGG flame in an axial staged burner. PA could have the water vaporised and the heat released from the pot ale syrup (PAS). The PAS was sufficient to vaporise all the water in PA and the third distillery waste, spent lees wash (SLW).

Quad-fuel and quint-fuel (BGG/hydrogen/natural gas/diesel/ethanol) burners were developed for gasifier heating and BGG fuel assisted combustion. Both also featuring scalable capabilities at no major configuration or expense.

Draff, Pot Ale and SLW are waste disposal problems for distilleries, and they can pay farmers around £400,000 per year to dispose of these wastes. This work has shown that these wastes can be disposed of in a gasifier together with a two-stage burner and the energy in the waste is sufficient to vaporise the water, so that there is no use of fossil fuels to dry these wastes and their use is thus practical and eliminates the cost of their disposal. This is a major advantage

and cost-saving feature of this demonstration of the use of biowaste to decarbonise whisky distilleries.

The work carried out using the Grid Cone burner for the preburner heating of the cold gasifier showed that the diffusion flames were orange, and the NOx were lower than for the same burner operated on NG. The NOx for both fuels was within the limits of the EU Medium Combustion Plant Directive. Thus, two errors of fact in the hydrogen literature have been demonstrated: hydrogen flames are NOT invisible, and the NOx emissions do NOT exceed the standards for NG operation.

A route to low-cost distillery decarbonisation has been established using gasification of biowaste and burning of pot ale and SLW in the combustion products of BGG combustion using a novel two stage burner design.

Dissemination

Key parts of the gasification and burner technology have already been published in the open literature as detailed below in Publications from the GD166 project. Most of these papers were presented at international conferences with the opportunity to discuss the results with others at the conferences.

We will use LCID to present training courses on the technology and to form groups of distilleries prepared to fund the transition from prototype to operating distilleries.

Publications from the GD166 project

[P1] Gordon E. Andrews , Herodotos N. Phylaktou, Hu Li, Mohammed Khan, J .Ramon Quiñonez Arce, Francis O. Olanrewaju, Jim Maxfield, Steve Smith, Richard Wakeman, Ian Bownes. “Whisky Distillery and Barley Biomass Waste Potential for Whisky Distillery Decarbonisation” Presented at: 2nd FERIA Conference, The European Conference on Fuel and Energy Research and its Applications, Monday - Wednesday, 4th - 6th September 2023,The Edge, The U. of Sheffield, UK.

[P2] José Ramón Quiñonez Arce, Gordon E. Andrews, James D. Maxfield, Herodotos N. Phylaktou, Steve B. Smith, Richard Wakeman. “Glycerol and glycerol/water gasification for the decarbonisation of industrial heat.” Chemical Engineering Transactions, 2023. Also, presented at the International Conference On Energy, Environment & Digital Transition (E2DT) that was held on 22-25 October 2023, in Palermo, Italy. E2DT is organised by AIDIC, The Italian Association of Chemical Engineering. Presented by Ramon Quinonez (CBS).

[P3] Francis O. Olanrewaju, Gordon E. Andrews, Herodotos N. Phylaktou, Hu Li, Steve Smith, Jim Maxfield, Richard Wakeman. “Renewable Energy from Whisky Distilleries By-products”. Chemical Engineering Transactions, 2023. Also, presented at the International Conference On Energy, Environment & Digital Transition (E2DT) that was held on 22-25 October 2023, in

Palermo, Italy. E2DT is organised by AIDIC, The Italian Association of Chemical Engineering. Presented by Francis Olanrewaju (CBS).

[P4] Gordon E. Andrews, J. Ramon Quiñonez Arce, Francis Olanrewaju, Ray Massey, Richard Wakeman, Steve Smith, Jason Poon and Herodotos N. Phylaktou. “Comparison of the NOx, emissions for a dual fuel hydrogen/natural gas industrial burner”. INFUB-14, Fourteenth Industrial Furnaces and Boilers Conference, Algarve, Portugal, 2 - 5 April 2024. Presented by Prof. Andrews.

[P5] Gordon E. Andrews, Herodotos N. Phylaktou, J. Ramon Quiñonez Arce, Jim Maxfield, Richard Wakeman, Steve Smith, “Myths and misinformation on the repurposing of natural gas grids for hydrogen”. Chemical Engineering Transactions, 2024. Also presented at the CISAP 11 - INTERNATIONAL CONFERENCE ON SAFETY & ENVIRONMENT IN PROCESS & POWER INDUSTRY, 15-18 September 2024, Naples, Italy.

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Appendices

A1 Summary of original GD166 Application Proposal Objectives and what was achieved during the project

Application Reference	Application Objective	Achievement
Q2a	Development Plan	LCID building completed to house the gasifier, the burner test facility and the analytical equipment. It is available for future work and demonstrations.
	Review of distillery energy and wastes	Completed and paper published in FUEL 2023. Energy required to operate a distillery is 30 MJ/L whisky. The distillery waste is insufficient to operation the distillery, but from farm to cooperage, there is sufficient waste biomass in the industry to operate distilleries. Wet waste is a problem but can be gasified. An additional 30 MJ/L of energy is required to dry the wet waste.
App. 1 Pot Ale	Release of energy from pot ale	Pot ale was shown to not be suitable as a gasifier load due to the high-water content. But the use of the two-stage burner with the pot ale injected in the second stage was demonstrated and 36 kW heat release from pot ale demonstrated. More work in this area is required.
Q2b App. 1	GHG reduction	GHG reduction is proportional to the reduction in NG use in the dual fuel BG/BGG burner. 49% NG reduction demonstrated for wet draff/dry draff/straw/wood (preburner NG heating was required to sustain gasification due to moisture content of wet draff).
Q2 Pot Ale	Method to release energy from wet PA	A two-stage BGG burner was designed, built and tested, with the second stage for burning PA in the products of combustion from the BGG first stage hot combustion products. This burner was also designed to operate with other waste bio-oils such as glycerol and the infrastructure to deliver metered crude glycerol to the burner was developed.
2.2 4.1 Q1a	Burner Development for multifuel applications including hydrogen	The grid cone preburner, the BGG burner and the PA burner were all designed and built and tested on NG and hydrogen. The burners were also designed for ethanol and fuel oil injection in the same burner housing. All three burners were successfully developed. The work on the preburner grid cone has been published. The two stage BGG/PA burner was externally air-cooled with the combustion air flow and temperatures of the air in the range 200 – 300^{o}C were demonstrated, which helps to stabilise the BGG flame. Also, this hot air was designed to heat crude glycerol to achieve adequate atomisation for the second stage PA burner to be capable of operation on difficult to burn waste bio-oils.
4.2 Q1b&c	Scalability from 0.35 to 2MW	The gasifier was operated on preburners and BGG burners designed for 2 MW heat output and scalability was demonstrated by operation at lower powers. Hydrogen tests from 50 kW to 1.5 MW successfully

		demonstrated. Combined NG and BGG operation 600 kW to 2 MW demonstrated.
4.2	Gasification with preburner operating	Demonstrated
Q1.b4	Preburner heating of the gasifier	500 – 700^{o}C achieved at the gasifier outlet
Q1B (D) &(H)	How the process works	TGA analysis of dry draff shows that 85% of the volatiles are released between 150^{o}C and 550^{o}C with significant volatile release at 350^{o}C. These temperatures were achieved in the gasifier. The FTIR analysis of the BGG gas showed that the composition of flammable components was CO and hydrocarbons, mainly methane. Hydrogen was not significant and the maximum hydrogen was between 0.2% and 1%. The BGG burner was mainly burning CO and hydrocarbons and had a yellow flame. The BGG burner was co-fuelled with NG to achieve a stable BGG flame. Operation of the burner on BGG only was demonstrated.
Gasifier results Test 1	Demonstration of wood/barley straw	Preburner 179 kW, 160^{o}C achieved and 1% O_2. Preburner NG switched off with air left on and gasifier heat release increased the BGG temperature to 320^{o}C. BGG burner combustion efficiency 90% with 99%+ after the second stage PA burner. BGG NG off and BGG only flame established. 616^{o}C BGG temperature.
Test 2	Addition of dry draff to Test 1 materials. 120 kg wood logs 40 kg barley straw 200 kg dry draff Total 360 kg. At end of test 56kg left. 304kg consumed in 3 hours. 422 kW average.	Preburner at 230 kW for 2 hours to reach 440^{o}C when PreBurner fuel off. BGG flame operated with 100 kW NG assist for one hour. Flame out if NG turned off. 200 kg of dry draff was difficult to gasify, the preburner was on for 2 hours. With PreBurner off BGG burner was at 650kW with 100 kW NG **85% decarbonisation after PreBurner NG off.** CO 2.4%, CH_4 1.4% Ethylene 0.16% CO 3.1%, CH_4 4.5%, ethylene 0.22%, ethane 0.18% Note: FTIR problem with very high water vapour, results not reliable.
Test 3	Wood/Barley straw/DDGS/WET draff 36.5% total water. Total load 617 kg.	231 kW preburner on NG and 323^{o}C achieved. Preburner NG off and air left on the BBG temperature increased to 470^{o}C. Combined NG and BGG gas output 1.95 MW with 45% from BGG. After shutting down the gasifier for 8 days, the smouldering load within was relit by just letting in air through the preburner without NG flame. By that time the wet draff had dried sufficiently so the smouldering biomass was relit by passing only air in from the preburner.
Test 4	Wood/Barley straw/DDGS/Glycerol	Although the test was intended to be 2 MW from the BGG, it was 500 kW BGG for one hour at the peak BGG production, with the rest being 1.1 MW of NG burning at the BGG burner and 0.4 MW at the preburner in the warm up stages. The test was very slow to heat the gasifier in spite of the high preburner power. At 40 minutes after lighting the preburner, the preburner outlet oxygen was 16.1%, the gasifier outlet temperature was 180 deg. C and 1% outlet oxygen. The PA burner outlet

		O_2 was 11.3%, but the heat release at the BGG and PA burners combined from the BGG was 0.525 MW and the preburner was still fired with NG at 0.4 MW.
5.4	Bio-oil use	The grid cone preburner and the BGG burner were designed to operate on liquid and gas fuels. Burners were manufactured for both. The two-stage burner was also designed for PA and any other bio-oil to be burnt in the products of BGG combustion.
5.8	Gasifier use when distillery is between batches	It was found that the gasifier could be shut down by shutting off the preburner air supply, the biomass was then under smouldering combustion. It could be restarted even after a week by letting in air through the preburner without switching on the preburner. Thus, the use for BGG gas when the distillery did not require it was not necessary. This is a significant practical operational advantage.
Q1BF	Engineering Design Other bio-oils	The grid cone preburner was designed for operation on ethanol and fuel oil, as was the BGG burner. The PA two-stage BGG/PA burner was designed to operation on crude glycerol, a low cost waste bio-oil, using the burner air preheat to heat the glycerol prior to atomisation.

A2 Drawing Register

1. LCID - Pipe Configuration
2. LCID – Plan View
3. LCID – Right View
4. LCID – Left View Pipes
5. LCID – Back View
6. Complete Assembly – 2MW-21-Partial
7. Burner Rig – 350KW- BGG – V5
8. PotAle – Burner
9. PreBurner – 2MW
10. PreBurner – Final – Gasifier
11. Gasifier – Outer Box Assembly
12. Gasifier – Outer Box – without Roof
13. New - Old Gasifier Assembly
14. New Gasifier – Exploded View

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