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# Renewable Waste-Derived Fuels for Glass and Ceramics Manufacturing: Feasibility Study

**Final Report**

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A report for

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# Executive Summary

Glass Futures (GF) were successful in obtaining funding from The Department for Business, Energy and Industrial Strategy (BEIS) under Phase 1 of the £55m Industrial Fuel Switching Competition; this is the second round of this programme (IFS-R2P1). The scope of this project was to investigate the feasibility of using low-grade, waste-derived biofuels to provide low-carbon energy solutions for the glass and ceramics sectors.

This work builds upon the previous BEIS Industrial Fuel Switching Round 1 Phase 3 project (IFS-R1P3, which ended in March 2022 [1]), in which GF undertook a series of studies, with input from industry and academia, to assess the combustion performance, emissions and ease of use of a range of biofuels, delivering a series of pilot-scale tests, techno-economic studies and laboratory characterisation of fuels. These fuels performed well in all tests. However, the IFS-R1P3 study identified that the higher-grade biofuels studied, such as biodiesel, were economically unattractive compared to natural gas and are also subject to stiff competition from the transport sector. Within this current IFS-R2P1 project, a further ten waste-derived biofuels were scoped out for possible use in glass furnaces and ceramics kilns. Flash point and viscosity were found to be the factors having the strongest influence on suitability, followed by calorific value and the availability of fuels in volumes appropriate to pilot scale testing. Four of the ten fuels were submitted for characterisation at Aston University. Confidentiality considerations mean that it is not possible to share specific details or names of these fuels and so they are referred to in this report as BF1, BF2, BF3 and BF4. Finally, due to late-stage supply chain issues, only three fuels (BF1-3) were put forward for combustion performance trials. These fuels were derived from cooking and waste oils.

In response to concerns over the sustainability of biofuels for use in major industrial processes, an evaluation of UK biomass resource for the glass sector was also successfully delivered. This sustainability study identified the leading biomass resources potentially available within given radii of key UK glass manufacturing sites and regions, indicating that there is more than sufficient biomass resource to meet the needs of the UK glass industry. Pathways for the conversion of the agricultural and industrial wastes into biodiesel, bioethanol and biokerosene have also been recommended. Optimal centralised locations for liquid biofuel production for glass furnaces, given the spatial availability of these biomass resources and the locations of leading UK glass manufacturing sites, were also suggested.

Routes for utilising waste heat from glass furnaces to improve the quality of the biofuels (for example by driving off excess water and other undesirable volatiles), or to power pyrolysis processes for the conversion of biomass into sustainable fuels, were also explored.

Much of the work within this project has focussed on the challenges that accompany the combustion of waste-derived biofuels, particularly the heavier fractions from biofuel production that are difficult to use, and which are normally considered as wastes. Methods of mitigating these issues have been identified, developed and successfully applied during trials on the Glass Futures Combustion Test Bed (CTB). These methods include:

- Tank heating, in-line heating and trim heating, recommended to manage the higher viscosity of these fuels,
- Modifications to the furnace control system to manage the batch-to-batch variability in calorific value to ensure a steady supply of energy into the furnace,

- Matching the fuel pump flowrate to calorific values (e.g. fuels with low calorific values required high volumetric flowrates to provide sufficient energy into the furnace),
- Regular cleaning of in-line filters. A clear intention of this work was to investigate the use of waste-derived biomaterials that had the potential to be used as fuels without further processing. As these lower-grade biofuels are not purified, some fuels might give rise to contaminants such as ash waste components and products of biofuel oxidation that could build up in the filters, impacting the pipeline pressure and fuel delivery to the furnace,
- Material compatibility checks and tests to prevent degradation of or damage to any of the parts of the fuel delivery system, e.g. seals, in the fuel skids.

Glass Futures' Combustion Test Bed facility is a scalable replica of an end-fired regenerative glass furnace, that can provide up to 350kW (thermal) energy to the main furnace chamber. The furnace is flexible in terms of combustion configurations and can also replicate ceramics kiln scenarios. The glass industry oil-firing set-up was used for the trials because, whilst the CTB facility has burners that can simulate ceramics industry firing with gases, the purchase of burners for oil firing of ceramics would be part of a Phase 2 project. The other aspects of the test conditions apply to both glass and ceramics industries; for example the furnace temperatures and furnace atmosphere. The trials identified that the heat energy transfer efficiencies of BF1 and BF3 fuels were higher, relative to natural gas, indicating these fuels are viable for use within industrial furnaces and kilns.

Engagement with industrial partners identified that the CAPEX investments required to transition to these fuels are expected to be relatively low, focussing mainly upon upgrades to fuel delivery systems rather than any major redesign of furnaces/kilns themselves.

The GF economic model was used to run a number of scenarios for the low-grade biofuels investigated taking into account fuel prices at the time of modelling (October 2022). This study identified that BF3 gave positive net present value (NPV) values for each year of fuel switching, indicating that, for the scenarios investigated, it could be economically viable for the glass and ceramics plants to switch to this fuel now that the technical feasibility has been demonstrated. This has been attributed to its low CO2e intensity and the fuel cost being only marginally greater than that of natural gas. Other advantages that are expected to make this fuel attractive include the increased heat transfer and lower flame temperatures that are predicted to lead to longer furnace life. BF3 is not currently known to be used within any foundation industries, such as glass, ceramics or steel manufacturing and so it will be put forward for industrial trials within glass and ceramics industries, contingent upon further funding.

The project identified the following knowledge gaps remain (which are proposed to be explored within the next phase of the work):

- The impact of the higher flame emissivity seen for most biofuels, compared to natural gas,
- The impact of batch-to-batch variability in waste-derived biofuel properties,
- Opportunities to reduce NOx emissions through flame optimisation and other strategies,
- Continued investigations into the compatibility of biofuels with CCUS capabilities,
- Further investigations to address perceived concerns around the sustainability of the chosen biofuels,
- The performance of biofuels when fired in an oxyfuel furnace.

Feedback from glass industry partners throughout the course of the project has been extremely positive, with many partners feeling confident about the potential opportunities that waste-derived fuels have for glass and ceramics manufacturing processes reaching net zero. Biofuels are increasingly being seen as a means to reduce carbon footprint until a suitable alternative technology is developed and then implemented in industry. The project identified a shortlist of the following five industrial sites willing to commit to industrial-scale waste-derived biofuel trials, each of which has secured top-level approval for participation in industrial trials within a proposed Phase 2 project, pending successful pilot-scale trials of the chosen fuels at GF's St Helens facility:

- O-I Glass, Alloa, Scotland,
- NSG Pilkington, St Helens, Merseyside,
- Encirc, Derrylin, Northern Ireland,
- Ardagh, Knottingley, West Yorkshire,
- DSF Refractories, Buxton, Derbyshire.

CAPEX and OPEX costs associated with such trials have been defined. Further sites did express an interest in undertaking industrial trials, however the limited budget within Phase 2 meant that only a selection of sites could be chosen.

## Background Context

In 2019 the UK became the first major economy to legislate a binding target to reach net zero emissions by 2050. To achieve this, all sectors of the economy need to review their operations, develop strategies and implement actions to reduce emissions from their activities. With industry representing nearly a quarter of UK emissions, the decarbonisation of industrial activities will be essential for meeting climate change targets. Decarbonisation will be achieved through a combination of: improving energy efficiency; updating practices; and greater utilisation of low-carbon energy technologies and fuels. In turn, the decarbonisation of industry will be an essential driver for reducing business energy costs, improving industrial productivity and competitiveness, and driving clean economic growth [2].

Historically (pre-1980s), most glass furnaces/ceramics kilns ran on heavy fuel oils but switched to natural gas partly due to ease of supply and tightening emissions targets. A transition back to liquid fuels is technically straight forward and could be implemented in a short time frame (<3-5 years), using established technologies and minimal changes to the furnace/kiln itself.

Glass Futures' previous fuel switching projects [1, 3] have demonstrated that the existing fuel-delivery and burner systems can deliver and atomise these fuels to enable stable combustion properties. In the present project, the viability of some low-cost biofuels has been investigated.

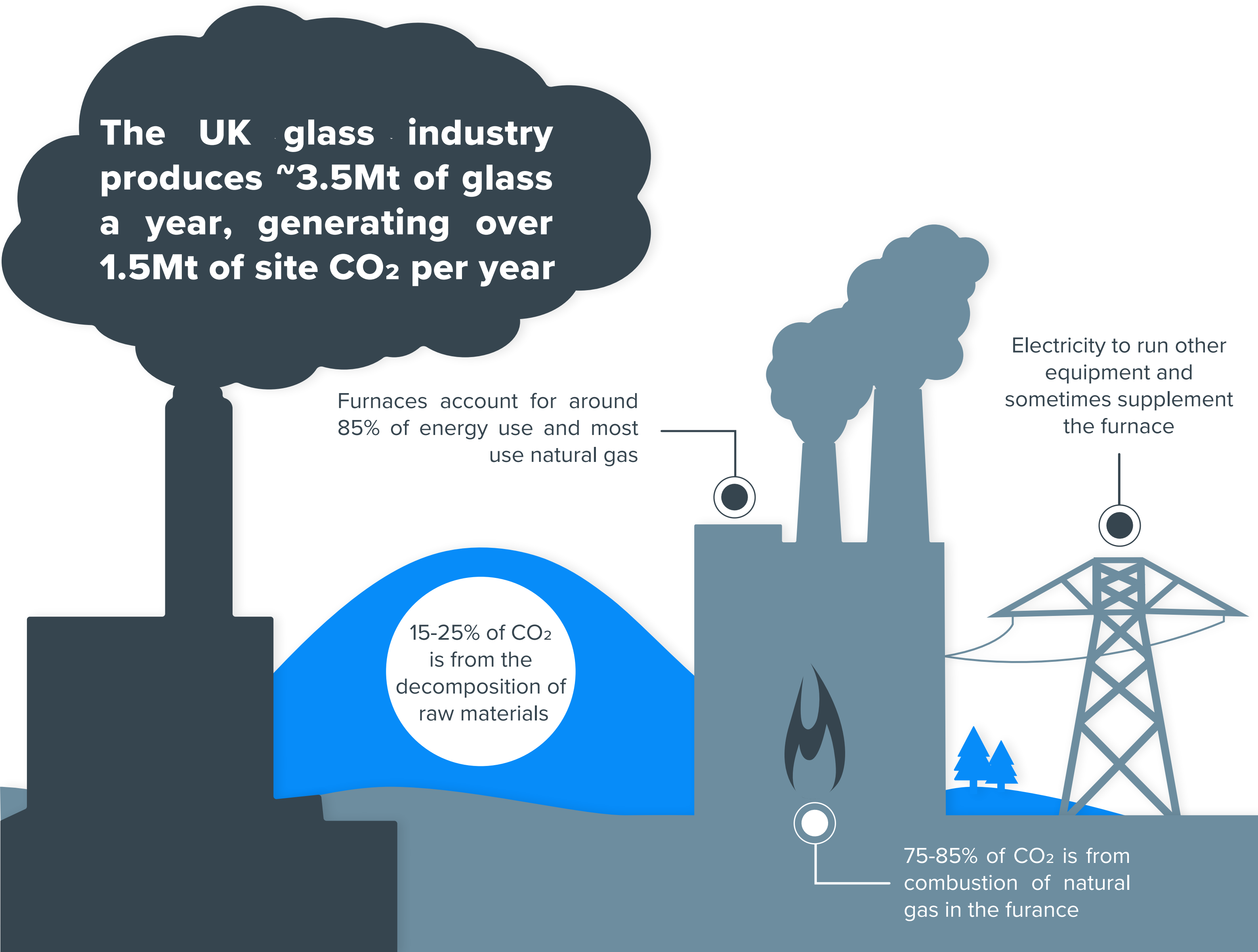
The manufacturing of glass is an energy intensive process, requiring high temperatures to melt the constituent raw materials and recycled glass and then refine the resulting glass melt to produce a high quality glass for forming into products. The UK glass industry produces ~3.5 Mt glass p.a., generating more than 1.5 MtCO2 p.a. of direct site emissions (Figure 1) [4]. Of these emissions, 75-85% are from combustion of fossil fuels (predominantly natural gas) and 15-25% are from decomposition of raw materials (such as limestone and sodium carbonate), depending on the recycled content [4]. Furnaces account for around 85% of energy used to manufacture the glass and predominantly use natural gas to generate the required heat. Some furnaces also use electric-boosting to provide additional thermal energy and to control glass flows within the furnace. Electricity is also used to run other site processing equipment, such as cooling systems and air compressors.

For the glass sector to decarbonise and contribute to the UK's net zero targets, alternative sources of low-carbon energy and/ fuels will be required to balance the significant demands of glass furnaces [4].

Glass Futures' previous Industrial Fuel Switching projects [1,3], which led to the successful demonstration of the use of biodiesel on a commercial glass container furnace, identified the following conclusions:

- The UK has ample biofuel capacity to supply the entire glass sector and this solution could be strengthened by potential later application of CCUS to mitigate process emissions and provide negative emissions for the sector.
- Higher-grade biofuels, such as biodiesel, were found economically unattractive compared to natural gas, thus likely to hinder their uptake. There is also likely to be stiff competition for such fuels from other sectors looking to decarbonise.
- Unpredictable variations in availability and price of different low-carbon fuels across the UK are likely to mean that no single low-carbon route will be suitable for the 21 largest glass manufacturing sites which account for 94% of the UK's glass output and associated carbon emissions and that a range of new low-carbon furnace scenarios (including biofuels, hydrogen and large-scale electric melting) should be investigated to decrease the risk that any one fuel scenario proves to be non-viable. This current BEIS Industrial Fuel Switching Round 2 Phase 1 (IFS-R2P1) project, 'Renewable Waste-derived fuels for Glass and Ceramics Manufacturing Feasibility Study' aims to build upon these findings through:

Figure 1: Carbon Output of UK Glass Industry, 2021 [4]



- Identifying lower cost waste-derived biofuels,
- Assessing routes to address issues with these fuels, such as variability in batch-to-batch quality and risks around contamination,
- Undertaking combustion trials to assess combustion performance and any associated issues (E.g. NOx),
- Developing a better understanding of the economic case for using such fuels and
- Building a case and identifying suitable sites for industrial trials of waste-derived biofuels.

# Introduction

## 3.1 Opportunities for Switching to Lower-grade Biofuels

Due to the nature of glass furnaces and ceramics kilns, fuel quality is less critical to product quality than other sectors, such as transport or domestic heating. This presents a special opportunity, since it means that these sectors should be more amenable than other industries to lower-grade, lower-cost fuels, which might be economically viable, when compared to natural gas.

The current project has addressed the challenges identified in the previous studies through investigating low-cost, waste-derived, fuel-sources that have the potential to provide a cost-effective route to achieve net zero in glass furnace and ceramics kiln processes as early as 2030.

Glass Futures, supported by NSG and Academic experts (Universities of Aston, Manchester, Leeds) have scoped out suitable waste-derived fuels (assessing availability, cost, sustainability and associated greenhouse gas (GHG) intensity). The three most attractive fuels have been benchmarked against natural gas and diesel on Glass Futures' 350kW multifuel Combustion Test Bed (CTB) rig to demonstrate feasibility.

## 3.2 Biofuels

The term 'biofuels' has been used to define any fuel derived from 100% renewable bio sources directly from virgin materials or wastes, excluding blends with fossil-based fuels. The attractiveness of these fuels could be further strengthened by potential later application of CCUS to mitigate process emissions and provide negative emissions for the sector [4]. This is a clear opportunity highlighted within the UK government's Biofuel Strategy [2] for various materials.

Glass Futures' fuel switching work has focused on investigations into the use of liquid biofuels as the use of "natural gas-type" fuels generated from bio sources, such as bio-methane, has already been demonstrated at industrial scale within the glass sector and shown to be compatible with existing glass furnaces. Fuels studied have ranged from those with similar physical characteristics and combustion performance to fossil fuels, already well known within the glass industry, to fuels which theoretically show potential for use in a glass furnace but will require further development in combustion systems to demonstrate viability and confidence that such fuels can be used safely without adversely impacting product quality or furnace infrastructure.

The supply-chains for waste-derived fuels are not currently very well established and there is a 'chicken-and-egg' scenario, whereby a demand needs to be created before an economically viable supply-chain will develop. Lack of confidence in future fuel availability creates a further barrier to glass/ceramics manufacturers' willingness to invest resources to develop these fuel technologies, and an additional reason as to why public sector funding is needed.

## 3.3 Project Objectives

The objectives of this project (Figure 2) were to:

(i) Scope out additional waste-derived fuels, assessing factors such as availability, cost, sustainability and associated GHG intensity and earmark blends of interest **(WP1)**

(ii) Identify methods to mitigate challenges associated with waste-derived fuels:

- Techniques to manage/mitigate batch-to-batch variability in fuel quality (e.g. optimising burner design) **(WP2)**
- Techniques to utilise waste-heat energy from the furnace/kiln to improve quality/consistency of fuels (e.g. drive off water content or drive pyrolysis processes) **(WP3)**

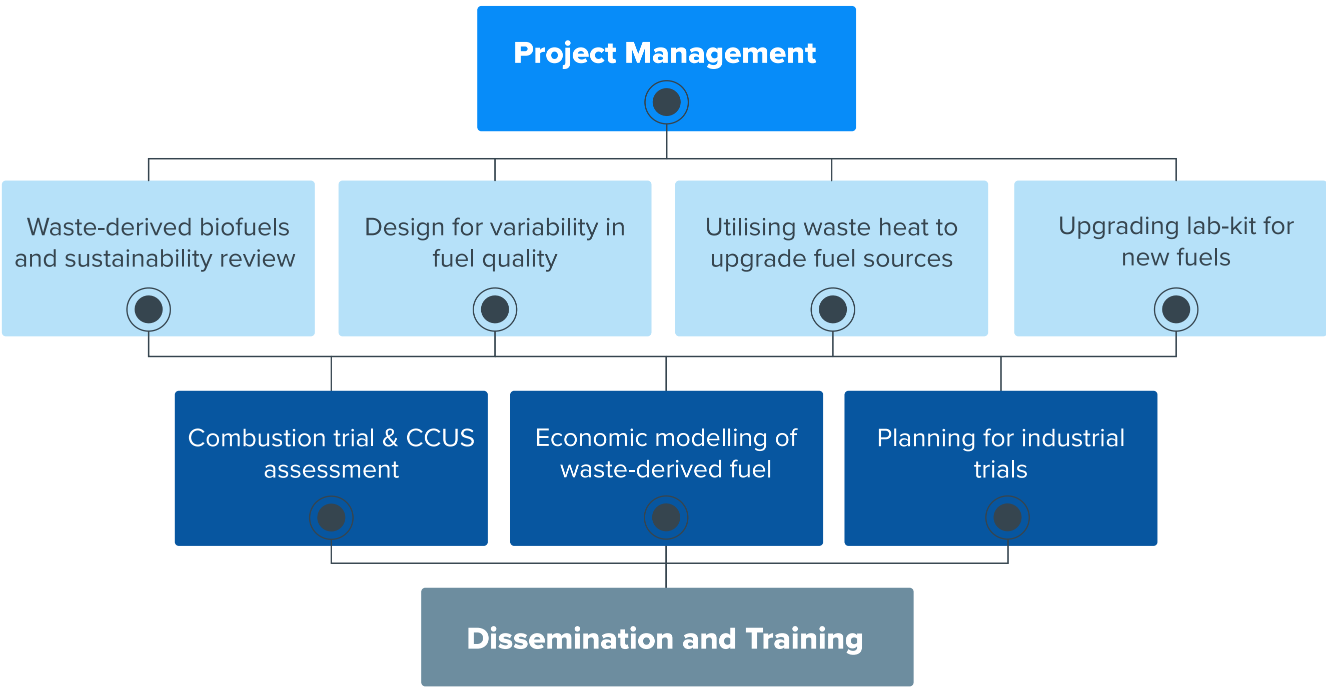
(iii) Upgrade Glass Futures' 350kW multi-fuel Combustion Test Bed (developed within IFS-R1P3) to benchmark fuels against natural gas and diesel, assessing combustion properties and compatibility with CCUS technologies. **(WP4, WP5)**

(iv) Evaluate the associated technical, economic and environmental aspects of waste-derived fuels, with the objective of securing sector-wide buy-in into future industrial-scale trials. **(WP6)**

(v) Prepare detailed plans to trial the most attractive fuels at commercial glass/ceramics plants, including an element of CCUS. **(WP7)** and finally,

(vi) Disseminate relevant findings in order to grow confidence and awareness across the glass/ceramic industries of the potential that waste-derived fuels plus CCUS technologies have for decarbonising manufacturing processes. **(WP8)**

Figure 2: Overview of Project Objectives



## 3.4 Technology Readiness Level at the Start of the Project

Given the range of fuels to be assessed and that several technology enablers were required to allow the use of these fuels, the TRL for this project at the start was as follows:

- It was known that a glass manufacturer had recently fired a pilot glass furnace using a high quality pyrolysis oil at TRL=7 (details of which cannot be shared due to being commercially sensitive).
- The combustion properties of other waste-derived fuels have only been assessed at lab-scale, TRL=3-4.

# Renewable Waste-derived Fuels

A clear intention of this work has been to find alternatives to the higher-grade biofuels (such as biodiesel), which are not currently economically attractive and instead focus on lower-cost biofuel feedstocks and by-products of biofuel production. The latter have included bottom fractions or unpurified products of biofuel production that are normally seen as wastes that are hard to reuse but have the potential to be used as fuels, without further processing.

The aim was to select three biofuels to put forward for combustion performance assessment in trials on the Combustion Test Bed with a view to assessing feasibility for industrial trials in a potential IFS Round 2 Phase 2 demonstration project. As part of the selection process, methods for mitigating the operational impact of batch-to-batch variations in fuel quality were developed. This included identification and measurement of the key fuel properties influencing operations and recommendations for upgrades to the equipment.

The sustainability of waste feedstocks has also been investigated, along with methods to improve the quality of biofuels using waste heat from the glass furnace, again with a view to incorporating the findings into a Phase 2 project.

## 4.1 Design for Variability in Fuel Quality

In order to ensure the stable operation of industrial glass furnaces, a constant energy input is critical. The batch-to-batch variability in the properties of waste-derived fuels is a potential barrier to their use in the volumes required for industrial-scale operations. To support glass manufacturers in taking up the opportunity to decarbonise furnace operations by using low-grade, low-cost biofuels, key fuel properties of interest were identified, together with laboratory analytical techniques for their characterisation.

The most important fuel properties for predicting combustion performance, safety and suitability for use in the glass industry are elemental composition (carbon, hydrogen, nitrogen, sulphur, nickel and vanadium), flash point, viscosity and calorific value.

In order to better understand the more specific properties and characteristics of waste-derived fuels, Glass Futures commissioned the Energy and Bioproducts Research Institute (EBRI) at Aston University (which has significant expertise in the areas of field of bioenergy, pyrolysis and catalysis, complemented by a wide range of specialist analytical equipment) to assess additional fuel properties recommended for consideration. Characteristics measured included the metals content, moisture and ash contents, acidity and presence of volatile fractions or noxious substances in the biofuels.

The following analytical tests were undertaken by the EBRI group:

- Carbon, Hydrogen, Nitrogen and Sulphur (CHNS),
- Flash point analysis,
- Dynamic viscosity analysis,
- Calorific value,
- Inductively coupled plasma - optical emission spectrometry (ICP-OES),
- Moisture and ash content,
- Water content analysis,
- Total acid number (TAN),
- Gas chromatography – mass spectrometry (GC-MS),
- Thermogravimetry and degradation control.

Atomisation of the liquid biofuels, facilitated by air, is used to enable combustion in the furnace, but requires the fuel viscosity to be sufficiently low when it reaches the burners. Viscosity is also critical for ensuring a consistent flow of fuel to the burners. Based on Glass Futures' previous studies, a target kinematic viscosity (dynamic viscosity divided by density) of 25 cSt was set.

As expected, the viscosity of all biofuels investigated decreases with increasing temperature. Given the significance of viscosity for successful combustion and concerns about the batch-to-batch variability of biofuels, viscosity tests were also carried out at the Glass Futures site prior to the CTB trials. In the example below (Figure 3), results indicate that the viscosity of a sample of a fuel BF4 could be reduced to the required 25 cSt if it were heated to 83°C.

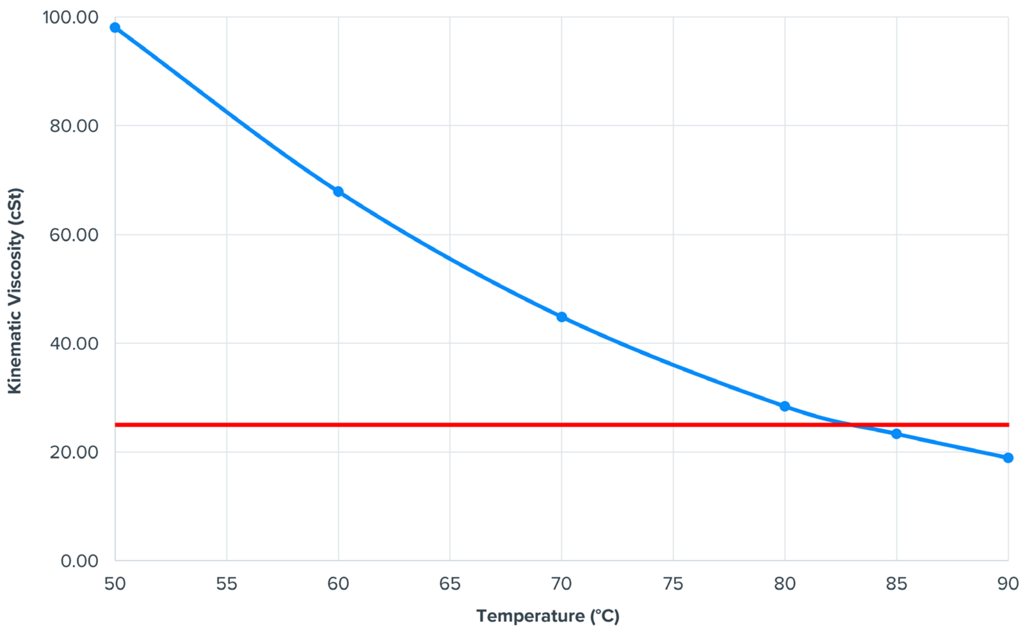



**Figure 3: Variation in Kinematic Viscosity of Fuel BF4 with Temperature (Red Line Indicates the Critical Value of 25 cSt Required to Achieve Atomisation of Fuel)**

Technical solutions identified as potential means of managing batch-to-batch variations in these fuel properties, especially viscosity and calorific value, included:

- Using a control system capable of calculating fuel flow from fuel properties such as net calorific value, density and stoichiometric air/fuel ratio,
- In-line heating,
- Blending of fuels,

- Flow control (oil and air) and
- Use of ATEX-rated equipment, which could maximise the flexibility of the system by extending the range of fuels that can investigated safely to include flammable materials.

## 4.2 Selection of Most Attractive Waste-derived Biofuels for Combustion Trials

The process of selecting lower-cost renewable waste-derived fuels for this study began by reviewing a list of roughly 80 different biofuels, generated as part of the IFS Round 1 Phase 2 study [3], compiled with input from experts at the University of Leeds, Guardian Glass, the Translational Energy Research Centre (University of Sheffield), Sheffield Hallam University, Global Combustion and Glass Futures. Fuels were assessed based on technical performance, as well as aspects including availability, sustainability and economic viability. After discussions with academics and industry experts, four waste-derived fuels were selected for the current project. These included heavy fractions, by-products of biofuel production and distillation processes, and pyrolysis oils. Samples of these were sourced and sent for laboratory characterisation.

A total of 13 different variations of fuel / fractions of these four fuels were analysed by Aston University using the tests outlined in Section 4.1; the results for the most promising nine of these variants have been summarised in Figure 4.

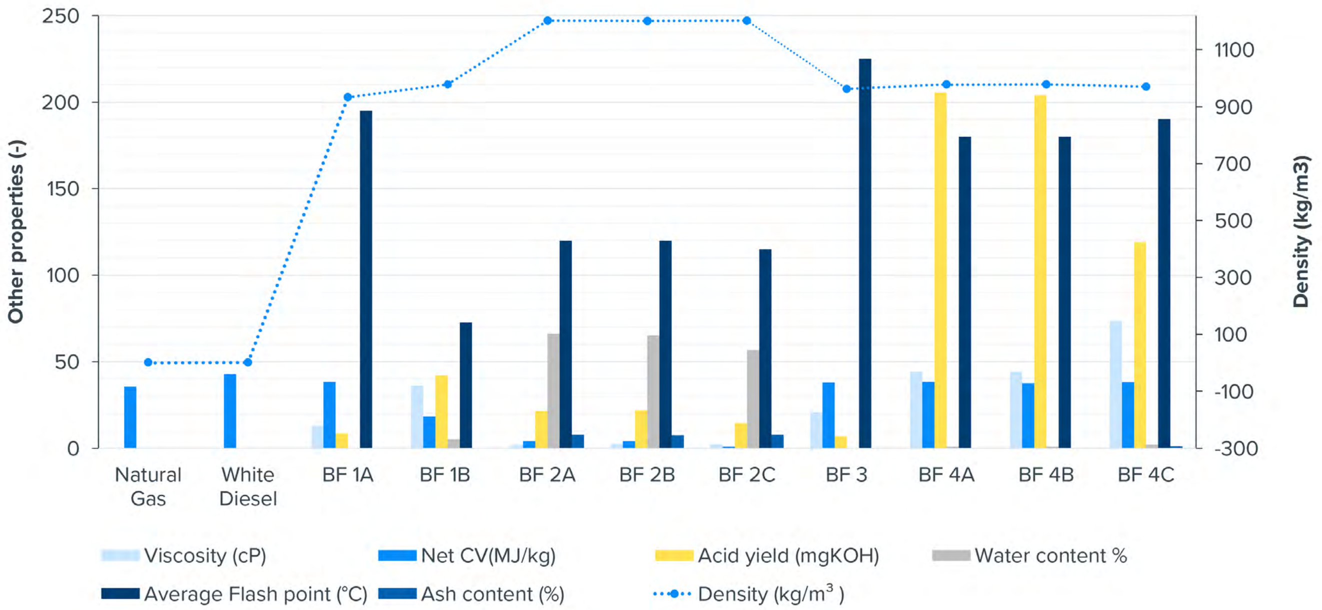



Figure 4: Results of Laboratory Analysis of Fuel Properties (Aston University)

In order to identify the most attractive fuels to put forward for combustion performance evaluation, the fuels were ranked based on these results and the outcome can be seen in Table 1. The most attractive fuels were found to be BF1 > BF3 >BF4 > BF2.

Due to the high acid yield for BF4, compatibility with the materials used for seals within the fuel delivery system was tested and confirmed before seeking to procure the fuel for the pilot trials. Unfortunately, at a late stage in the trial programme, it emerged that the supplier of this fuel did not have the equipment to supply BF4 in the relatively small quantities required for the CTB trials. Consequently, the final selection of fuels for the CTB trials was as follows: BF1, BF2 and BF3. BF4 remains a fuel of interest for future trials.

It should be noted that other criteria, such as availability in large volumes, unit costs and transportation costs, will also be important for industrial use.

Table 1: Ranking of Fuels Based on Key Properties

| Selection criteria + value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Fuel | Viscosity @ 75 °C | Density | Net CV | Acid value | Water content | Flash Point | Ash | Score |
| Aim / Preferred | 25 cSt | 700 – 900 | > 35 MJ/kg | < 50 | < 10 wt% | > 70 °C | ≈ 0 % | |
| | | kg/m3 | | | | | | |
| BF 1A | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 34 |
| BF 1B | 4 | 4 | 2 | 5 | 5 | 5 | 5 | 30 |
| BF 2A | 5 | 3 | 1 | 5 | 1 | 5 | 2 | 22 |
| BF 2B | 5 | 3 | 1 | 5 | 1 | 5 | 2 | 22 |
| BF 2C | 5 | 3 | 1 | 5 | 1 | 5 | 2 | 22 |
| BF 3 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 34 |
| BF 4A | 3 | 4 | 5 | 1 | 5 | 5 | 5 | 28 |
| BF 4B | 3 | 4 | 5 | 1 | 5 | 5 | 5 | 28 |
| BF 4C | 2 | 4 | 5 | 1 | 5 | 5 | 4 | 26 |

# Assessing Combustion Performance of Low-grade Biofuels

Trials of the selected biofuels on the Glass Futures' Combustion Test Bed formed the core of this feasibility study. To ensure compatibility with the fuels, the equipment was first upgraded, as outlined below.

The combustion performance of the renewable waste-derived fuels was benchmarked against natural gas. The primary objectives of this work were to:

1. Demonstrate that these fuels could be safely used within a glass furnace,
2. Establish procedures for comparing the energy efficiency of these fuels to natural gas,
3. Determine any impact on environmental emissions, especially NOx and
4. Provide a report to BEIS with recommendations regarding the potential use of low-carbon waste-derived fuels for the glass industry.

## 5.1 Upgrading Lab-kit for Compatibility with New Fuels

In order to prepare the Combustion Test Bed for the biofuel trials in WP5, various measures were required.

An upgrade for control system programming was tested and commissioned by the operations and control team in Glass Futures, with supervision of the Combustion Technical Lead, that provided additional control, especially for more highly viscous liquid fuels.

Due to the nature of some of the biofuels shortlisted for the trials, a material compatibility assessment was carried out to ensure that there would be no critical degradation or damage to any of the parts in the skid.

This consisted of a thorough chemical analysis of fuel samples, that was performed by Aston University, which was also corroborated by in-house testing of flash point and viscosity against temperature analyses.

To ensure an adequate flow from the fuel tanks to the burners, all of the fuel-delivery pipework was lagged, and trace heating was installed to maintain a consistent temperature of the fuel circulating towards the furnace.

Finally, and whilst in operation, the filters and lines in the fuel skid (Figure 5) were cleaned regularly to avoid any clogging of the pipework and damage to components, and to ensure that the flow setpoint for power input was achieved without any major difficulties.

A full HAZOP study of the CTB was carried out as part of the previous IFS-R1P3 project, based on the complete development of the design, where the intended design and operation of the system was understood, and several preliminary operating procedures had been produced. The study team comprised a broad representation of design and project engineers.

In the current project, the previous HAZOP study was reviewed in light of the shortlist of fuels (identified in WP1) and it was concluded that, given the nature of the fuels selected for the small-scale trials for this project, a new HAZOP study was not required. The fuels tested were of similar nature to those for which the fuel skid was originally designed and intended and so no new safety measures were required. The material compatibility study provided reassurance that the liquid fuels would not be detrimental to any of the fuel skid components.

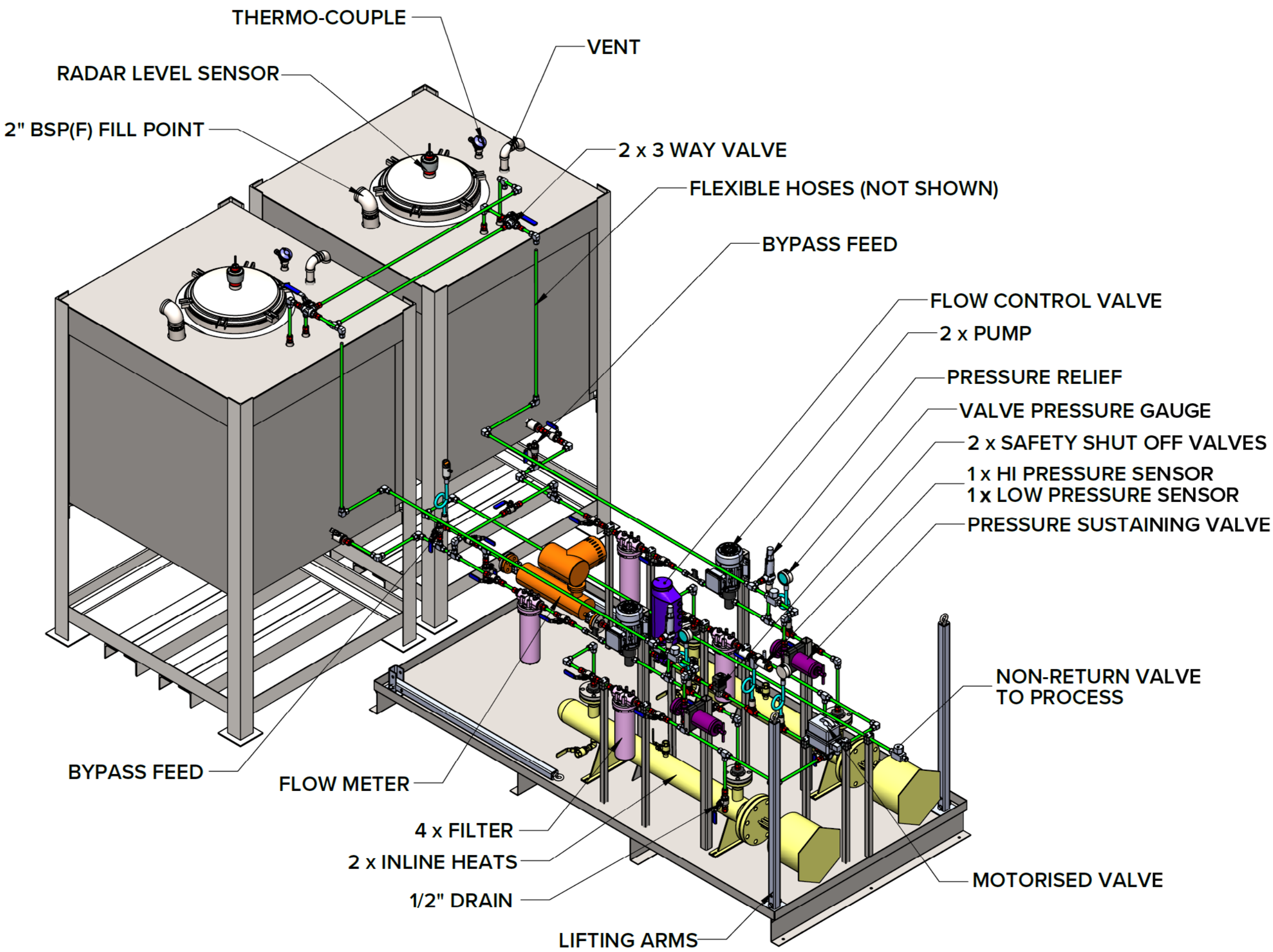



Figure 5: CAD model of Glass Futures Liquid Fuel Delivery System

## 5.2 Experiments on the Combustion Test Bed

### 5.2.1 Technical Description of the Combustion Test Bed

Glass Futures' Combustion Test Bed (CTB) consists of a scalable replica of an end-fired regenerative glass furnace in which the flame entry is located on one side of the back wall and the exhaust port is located on the other side of said wall (Figure 6). The CTB is capable of heating incoming air up to 1050°C to simulate the preheated air supplied into a typical regenerative glass furnace. The furnace is not designed to produce glass; instead, the thermal load of a glass melt is simulated by ten water-cooled pins covered with ceramic blankets to control the heat taken out from the combustion chamber. Previous work on burner developments using the CTB and CFD modelling have shown that results from the CTB can be correlated up to full-size furnaces.

The CTB can provide up to 350kW (thermal) energy to the main furnace chamber and operate on a range of gaseous or liquid fuels which require the appropriate burners to be selected. The CTB and fuel skids are also capable of supplying either two separately metred gas/liquid types or liquid-plus-gas depending on the burner types selected.

**Pictured (above) is a backwall with two underport burner lances, simulating an end-fired glass furnace and (below) an alternative backwall that uses a concentric baffle burner, simulating a steel reheating furnace/ soaking pit, or a ceramic batch kiln.**

Figure 5: Combustion Test Bed Backwalls Used at the Glass Futures Facility

Comparison of the efficiency of fuels is made by analysis of the thermal profile of the hot face refractories, exhaust gas composition and the amount of heat transferred to the water-cooled hearth.

The tests focussed on the glass industry firing set-up because, whilst the CTB facility has burners that can simulate ceramics industry firing with gases, purchase of the corresponding burners for oil firing would be part of a Phase 2 project. The other key features of the test conditions apply to both glass and ceramics industries; for example the furnace temperatures and furnace atmosphere.

The furnace is flexible in terms of combustion configurations and can replicate not only a glass furnace but also ceramic kiln or steel furnace scenarios, under a controlled environment by means of an interchangeable backwall and with the capability of using the hearth thermal load or not. In regard to firing cycles, the heat-up rate of the furnace can be done from ambient temperature, alternatively the electric preheater is able to heat up the incoming air at any temperature up to 1050°C.

The CTB is a highly instrumented furnace to ensure the characterisation of the combustion is thorough and complete (Figure 7). Thermocouples are positioned in the crown of the furnace, in the exhaust flue as well as at hearth level, which allow the monitoring and optimisation of the flame shape and length. Exhaust gas analysis is carried out by means of several gas analysers plus an oxygen probe. Additionally, there are many ports across the furnace to access the combustion chamber for in-gas analysis/suction pyrometry across any area in the chamber. Overall, the performance and material analysis are achieved by logging this extensive collection of data by means of the control system.

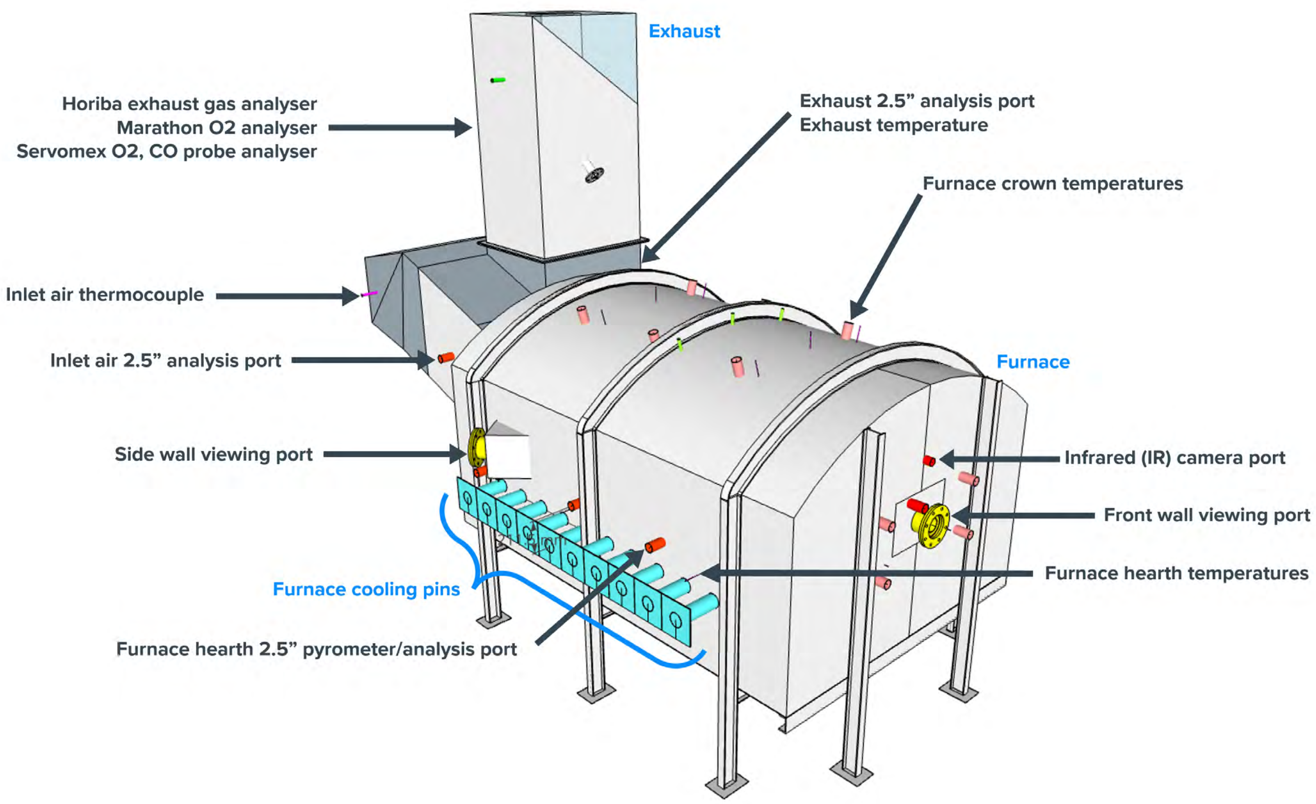



Figure 7: Schematic of CTB With Measuring Ports

### 5.2.2 Summary of Experimental Plan for Waste-Derived Biofuels on the CTB

Three biofuels were selected for the combustion trials on the CTB. A synthetic version of the fuel BF2 that was characterised by Aston University (Figure 4, Section 4.2) was used for the CTB trials for safety reasons because, depending on the batch, the flash point can drop below 60°C, making the fuel flammable. Two baseline trials using natural gas and white diesel were carried out to characterise and benchmark the performance of the biofuels against well-known fossil fuels. Two setpoints of thermal input power from the fuels, 280kW and 350kW, were investigated in terms of impact on heat flux to the hearth.

After the calorific value of the fuels was analysed, it was found that the calorific value of one of the biofuels (BF2), was very low compared to the typical values; therefore, a lower thermal input was selected to make it possible to perform the combustion analysis of this fuel. The main focus of the results is on the higher input power, where temperatures relevant to typical glass furnace operating temperatures (~1500°C) were reached and this excludes BF2. Table 2 shows the key experimental conditions. The data was extracted and averaged for the periods of time where these conditions were achieved and steady for longer than 1h.

| Input Power | Fuel flow | Oxygen % in exhaust | Crown temperatures |
|---|---|---|---|
| 280kW | Calculated in PLC using NCV of selected fuel | ~2% | Steady at circa 1400°C |
| 350kW | As above | ~2% | Steady at circa 1500°C |

Table 2: Target Experimental Conditions for Biofuels Trials

## 5.2.3 Key Experimental Results and Findings from Biofuel CTB Trials

The heat transfer to the hearth of the furnace provides a valuable insight into the energy efficiency of the fuel (Figure 8). All results were normalised with respect to natural gas. On average, the liquid fuels BF1 and BF3 showed higher heat transfer relative to natural gas due to the higher radiative properties of the flames.

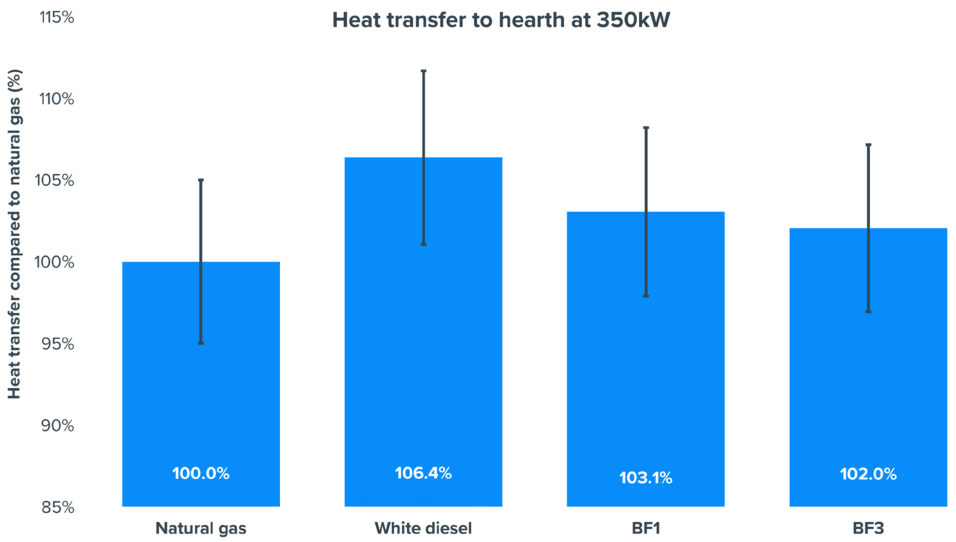



Figure 8: Heat Transfer to the Hearth of the CTB for 350k, Normalised with Respect to Natural Gas

Particular focus was given to minimising the NOx emissions, as this had previously been identified as a potential issue with the use of biofuels as alternative fuels for the glass sector. Additionally, adjustments to fuel flow and air/fuel ratio were made to ensure that combustion was completed within the combustion chamber, in order to minimise the amount of unburned fuel or combustibles (COe) exiting the chamber into the exhaust flue system. Oxygen levels in the exhaust flue gases were maintained at circa 2% by control of combustion air volumetric flow to replicate the combustion conditions in industrial glass furnaces.

Figure 9 shows that, as seen in the previous Industrial Fuel Switching project, NOx was higher for both the selected biofuels than for natural gas or diesel reference fuels. For this set of trials, the NOx was directly measured from the exhaust flue, providing straight post-combustion levels of the exhaust gases without any treatment. In this way, the measured gas levels will provide an insight as to what NOx reduction strategies will be required to tackle emissions and comply with UK regulations. Strategies for reducing NOx levels will be explored in the Phase 2 project. The low levels of carbon monoxide in Figure 9 are an indication of very good combustion during the trials.

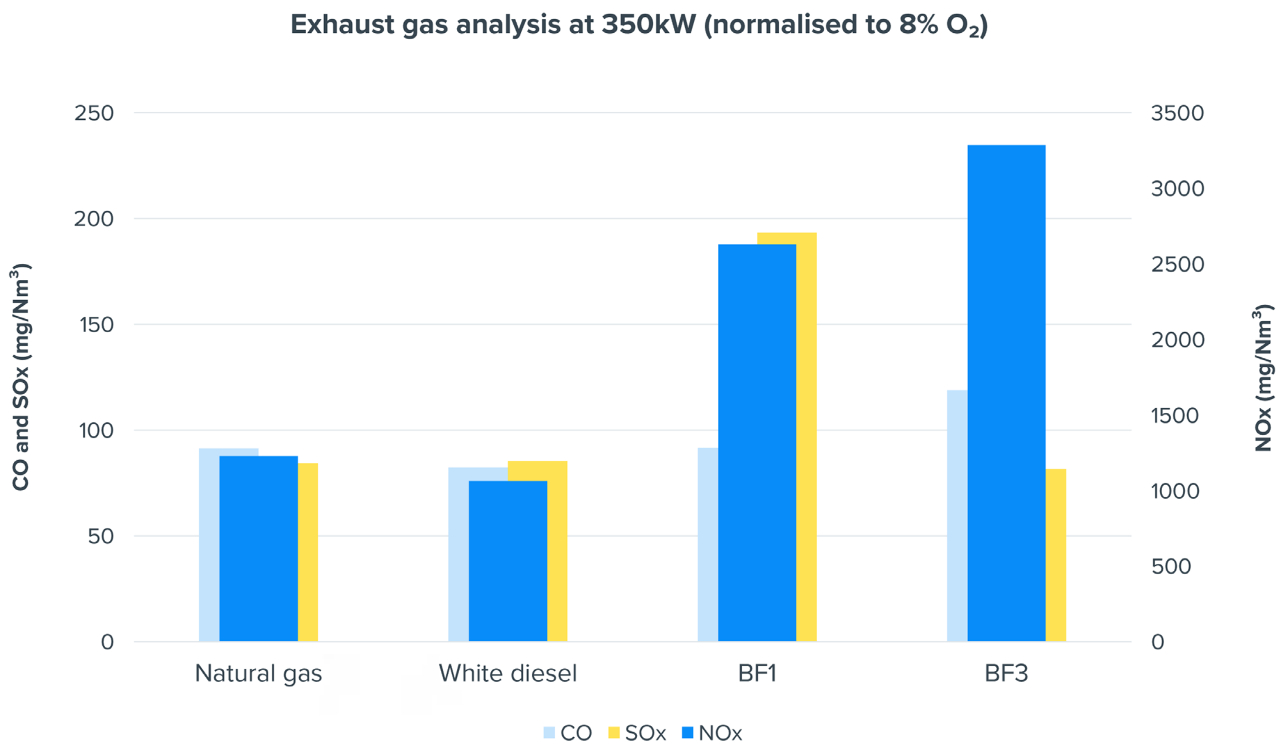



Figure 9: Exhaust Gas Emissions at 350kW

## 5.3 Routes to Optimised Combustion Performance of Biofuels

### 5.3.1 Conclusions and Recommendations from CTB trials

All the fuels tested in the current study showed good potential to substitute natural gas in order to enable the glass sector and other similar foundation industries to progress to net zero.

Although the potential of these biofuels for industrial scale is excellent, the following measures need to be considered when trialling these fuels on industrial furnaces/kilns (Figure 10):

1. The liquid fuel delivery system will potentially require several upgrades such as trace heating, heated tanks and in-line heaters to maintain the viscosity of the liquid at a level that is low enough to ensure the pumping system can deliver the fuel into the furnace at the targeted flow rate.
2. Due to the nature of these biofuels, a compatibility test of the materials in all the sealings in the oil system, end to end, should be assessed and upgraded if needed. The sealings will have to

withstand operation with heated and high acidity substances. Recommended sealing materials are Viton and PTFE.

3. Upgrades may also be required on the pipework, paying particular attention to material, joints and equipment in the lines such as flow or temperature transmitters, pressure transducers, etc.

In terms of combustion, the calorific value of the biofuel should be tested prior to any industrial trial so that burner configurations can be optimised, including fuel-flowrate setpoint and delivery pressure to ensure stable combustion within the furnace. Furthermore, once the fuel is introduced into the furnace, it is highly recommended that flame optimisation is carried out.

NOx levels produced by both BF1 and BF3 fuels were significantly higher than for the baseline fuels, therefore NOx control and/or mitigation measures will need to be investigated within future studies.

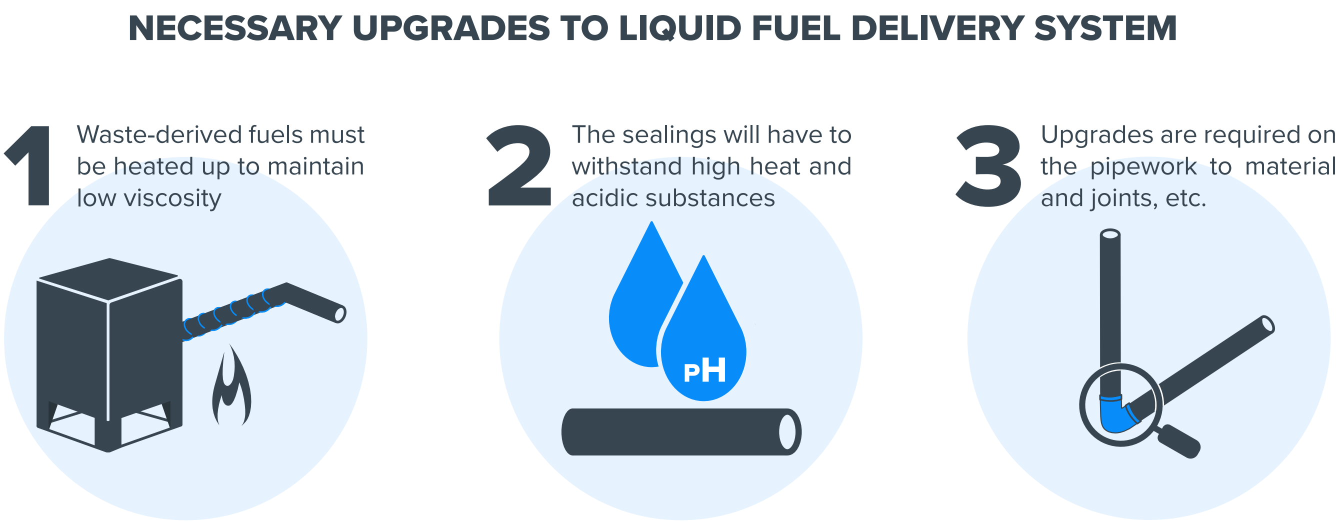



Figure 10: Upgrades to Liquid Fuel Delivery System that may be Needed to Facilitate Use of Some Waste-derived Biofuels

### 5.3.2 Best Performing Fuels Identified for Industrial Trials

This feasibility study concludes that all three biofuels assessed should be suitable for an industrial-scale trial, on the proviso that suitable NOx reduction measures are in place, capable of reducing NOx within regulatory levels if needed.

Although most of the fuels / fractions investigated had similar or slightly higher net calorific values (NCV) to natural gas, it was observed that the NCV for biofuel BF2 is considerably lower, therefore, posing potential challenges in terms of the volumes of fuel that might be required being incompatible with existing fuel delivery systems.

Finally, due to the temperatures to which the fuels must be heated, in order to generate the target viscosities needed for use, BF1 is recommended as the most convenient fuel for firing in a large-scale furnace.

## 5.4 Potential CO2 Emissions Reduction

Limited work has been undertaken into the GHG emissions factors for many bio-waste-derived fuels. Given GHG factors are dependent upon feedstock, location of waste-source to processing plants, variations in fuel quality and processing methods, adds further complications to calculations. Within IFS-R1P3 and IFS-R2P1, GF has undertaken extensive investigations to gather as much insight into these GHG reduction factors as possible such that most of the fuels are expected to have a GHG reduction factor of between 60-90% when compared to fossil fuels.

Literature indicates that there are routes to achieve net-negative emissions from processing biomass with techniques such as pyrolysis and gasification, e.g., Brown et al. [5], and CCUS technologies provide a route to achieving net-negative emissions.

As such, wide-scale uptake of these fuels across glass and ceramics sectors has the potential to reduce UK CO2 emissions by at least 1.76 MtCO2e/year corresponding to reductions in combustion CO2 emissions of 1.07 MtCO2e/year and 0.69 MtCO2e/year for the glass and ceramics sectors respectively. Thus, playing a vital role in helping the UK achieve Net Zero 2050 targets quickly. A switch to waste-derived biofuels requires low CAPEX investment compared to equivalent low-carbon fuels (e.g., hydrogen, electricity), especially for 'off-cluster' or 'dispersed' sites. There is also the potential to reduce UK CO2 emissions further through use of CCUS technologies, however the costs and space associated with such technologies will be investigated in future projects.

# Sustainability of Biofuel Feedstocks

Welfle et al. have previously shown that the volume of sustainable biomass feedstocks available within the UK is more than sufficient to supply the UK glass and ceramic industries [6]. In the current project, Welfle and his team were asked to identify the most sustainable sources in the regions of five UK glass manufacturing 'hubs' (each consisting of one or more glass plants) [7]. This was achieved using the Bioeconomy Sustainability Indicator Model (BSIM) that has been developed by Welfle et al. at the UK Supergen Bioenergy Hub (SBH) [7-10]. The model provides a flexible tool to map the performances of biomass resources, supply chains, technologies and/or whole value chains against 126 indicators of sustainability [6,9]. This includes the costs of moving the resource from source to site. In the course of developing the BSIM, a bioenergy literature database was established of 124,285 papers published between 2000 and 2018 [10].

The focus of the current research was to identify and quantify the opportunities and constraints of UK waste and residue biomass resources that may be mobilised to provide alternative low-carbon fuels for the glass and ceramics sectors, with the objective of:

- Identifying the key categories of UK biomass resource that may be available for the UK bioenergy sector;
- Identifying the regional biomass resource opportunities in the UK, highlighting the leading biomass resources potentially available within given radii of key UK glass manufacturing sites and regions;
- Identifying optimal centralised locations for liquid biofuel production for glass furnaces, given the spatial availability of UK biomass resources and the locations of leading UK glass manufacturing sites.

Analysis focused on three case studies developed through collaboration between the Manchester University team and Glass Futures, designed to highlight the types and quantities of biomass resource that may represent the leading opportunities for the glass and ceramics sectors in the regions where UK glass is manufactured:

- Single Site Case Study, focusing on a glass manufacturing site in Scotland, this case study analysed the biomass resource opportunities within 50km of the site.
- North West Glass Cluster, focusing on the large glass manufacturing sites within the North West region of England, this case study identifies the optimal location for a potential centralised biofuel production site that could provide liquid biofuels for all sites within the cluster. Analysis identified the biomass resource opportunities within 100km of a centralised North West facility.
- Humber Glass Cluster, focusing on the large glass manufacturing sites within the Humber region of England, this case study identified the optimal location for a potential centralised biofuel production site that could provide liquid biofuels for all sites within the cluster. Analysis identified the biomass resource opportunities within 100km of a centralised Humber facility.

Estimates of the productivity and location of the glass manufacturing sites studied are illustrated in Figure 11 and the waste biomass resources assessed are listed in Table 3. All models, including BSIM, assess the potential from animal wastes by focusing on the material generated whilst the animals are housed, e.g. chicken litter (housed all year round) or manure from cattle (housed periodically at certain times of year). These wastes are already routinely collected and managed.

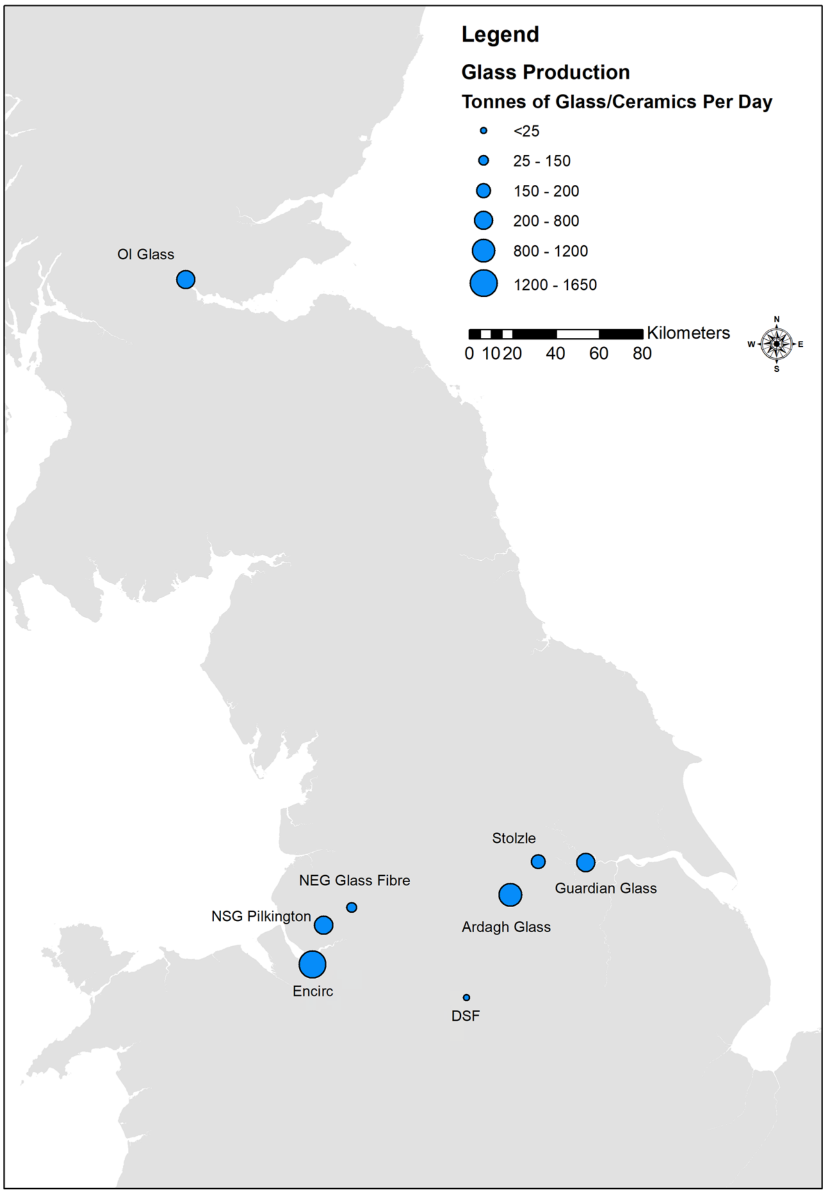



Figure 11: Location and Comparative Scale of the UK Glass Industry Sites Included in the Sustainability Study

| Biomass Category | Feedstock | | |
|---|---|---|---|
| Agricultural Crop Residues | • Potato Waste<br>• Sugar Beet Pulp<br>• Corn/ Maize Straw<br>• Winter Oat Straw | • Spring Wheat Straw<br>• Winter Wheat Straw<br>• Spring Barley Straw | • Winter Barley Straw<br>• Rapeseed Straw<br>• Pea Straw |
| Agricultural Animal Wastes | • Cattle Manure<br>• Horse Manure | • Pig Manure<br>• Sheep Manure | • Chicken Litter |
| Industry Wastes | • MSW (Paper, Wood, Food)<br>• Garden Waste<br>• Industry Paper | • Industry Card<br>• Industry Wood<br>• Industry Textiles | • Industry Food Waste<br>• Sewage Sludge<br>• Forestry Residues |

Table 3: UK Biomass Resources Assessed

Biomass resource modelling calculations were completed to identify the leading resource opportunities within the regions where the UK's glass manufacturing sites are concentrated. The research focused on the three case study sites outlined above and identified the following findings:

- At each Case Study site analysed, large quantities of biomass have been identified within a 50/100km radius of the site. The characteristics of biomass resource potentially available across the different regions of the UK vary. There are consistent potential opportunities from agriculture and industry activities. The specific categories of biomass and their availability depend on the spatial distribution of such activities and their focus.
- Based on the available resource and comparative energy demands of key manufacturing sites, the optimal location for a centralised biofuel production facility serving the glass sector in the North West of England is potentially near Helsby in Cheshire. The optimal location for a centralised facility serving the glass sector in the Humber region is potentially near Shafton in South Yorkshire.
- Animal wastes represent significant resource opportunity in each region analysed, particularly cattle manure. There are limited existing uses for this resource and ideally manure would be processed and converted to advanced fuels within close proximity of its source.
- Agricultural crop residues are a further leading resource opportunity available across the UK. By-product materials such as wastes from potato production/ processing and straws from core cereal crops such as wheat and barley are found to be consistently available in the regions where UK glass manufacturing is concentrated. There are existing uses for many crop residues particularly for wider agricultural activities, although research shows sustainable levels may be mobilised for bioenergy without adversely impacting existing activities.
- Residues from forestry sector activities such as mills are identified as a consistent biomass opportunity across each of the regions analysed, particularly Scotland and the North West of England. Large quantities of residue material are generated in the production of wooden products. These residues are already partly used by the bioenergy sector to produce pellet fuels etc.
- Waste materials that would otherwise be sent to landfill are found to be a potentially significant resource opportunity for the bioenergy sector where they can be mobilised. UK households and industry generating large quantities of wastes are managed through the waste hierarchy. Greater use of wood, paper, card and food materials that are currently sent to landfill could generate large quantities of energy/fuels and mitigate significant environmental impacts.

Potential biofuel production pathways from the UK biomass resources discussed have also been proposed and are summarised in Figure 12. The model used in the present work does not assess the processed cost of fuels derived from biomass. However, complementary models are available within the Supergen Bioenergy Hub that will specifically assess the techno-economics of bioenergy projects, including CAPEX, OPEX and what the energy cost will be.

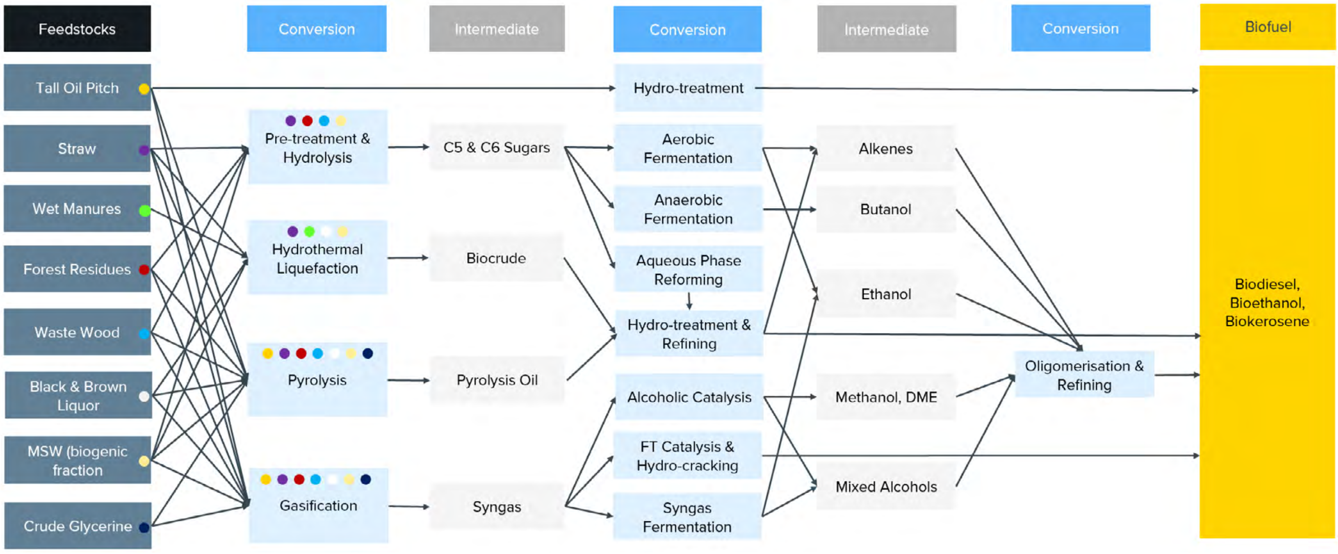



Figure 12: Potential Biofuel Production Pathways from UK Biomass Resources (Welfle et al. [11])

# Utilising Waste Heat to Upgrade Fuel Sources

Glass Futures has identified a number of low-grade bio-derived fuels that could be used as fuels in a glass furnace. However, many of these fuels are typically low-quality by-products and contain water and other undesirable volatiles that can reduce the net calorific value of the fuels and/or increase harmful emissions produced within the furnace/kiln.

A typical glass plant generates significant volumes of waste heat from the furnace, much of which is not generally utilised within most glass plants, especially the lower-grade heat energy, as outlined in the Sankey diagram shown in Figure 13.

A study was undertaken to assess whether some of this waste heat could be used to improve the quality of the biofuels identified within this project, or even to drive the process by which the biofuels are manufactured.

During these studies, a novel pyrolysis process developed by NSG was identified. Initially the plant was used to pyrolyse low quality wastes destined for landfill. It is envisaged that the NSG PEOL Pyrolysis Plant could be adapted to utilise waste heat from a glass furnace to pyrolyse bio-derived waste materials into high quality liquid and gaseous fuels suitable for firing a glass furnace. The following benefits and opportunities have been identified:

i) By supplying an integrated pyrolysis plant with waste material, the quantities of waste destined for landfill and the associated cost of waste disposal would be significantly reduced or even eliminated.

ii) By utilising surplus heat from a glass manufacturing furnace, the NSG PEOL technology offers a more energy efficient route to convert bio-derived wastes into valuable fuel, providing an alternative to the current use of fossil fuels.

iii) As a result, this technology offers an opportunity to generate low-cost fuel, as part of a circular economic solution.

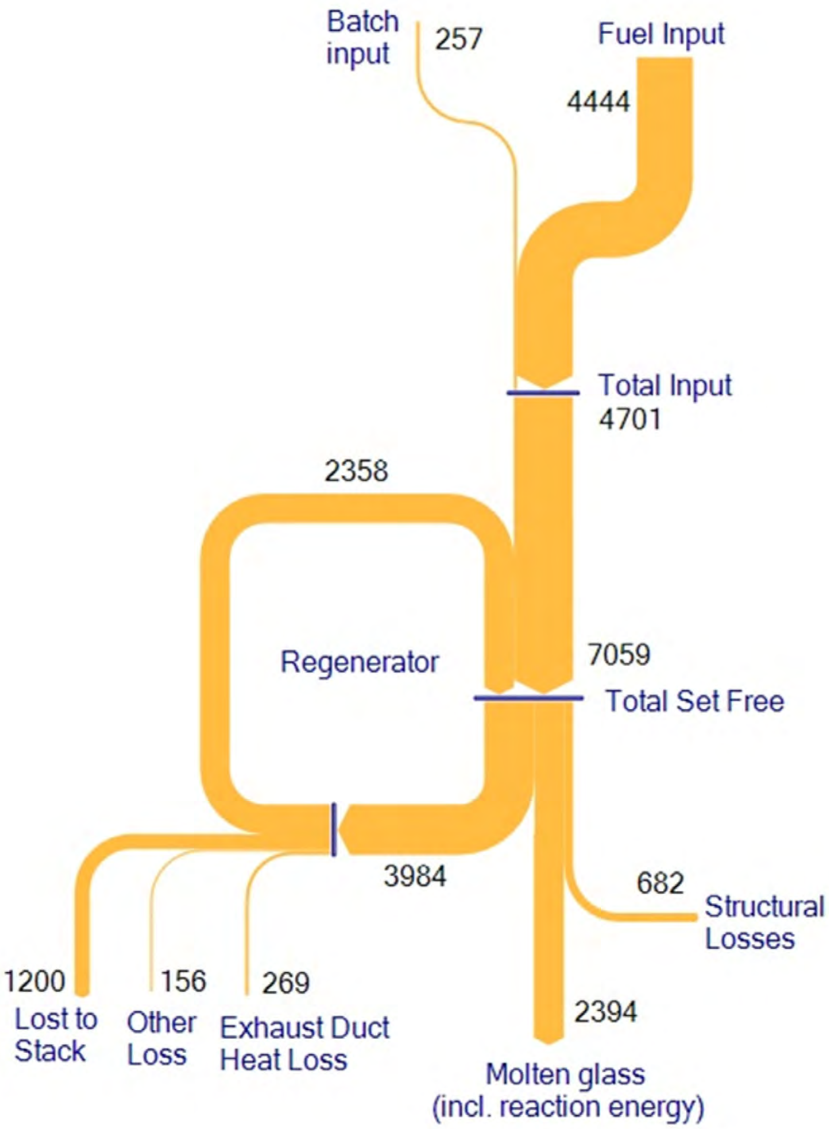



Figure 13: Sankey Diagram, Illustrating Waste Heat Generated from a Glass Furnace. Conditions: 500 t/day, 50% Cullet, Float Glass. Energy Units: MJ. [12]

vi) The NSG PEOL technology has the potential to process renewable biomass materials, initially blended with other low quality waste materials and potentially with a broader range of feedstocks and by-products, including those derived from biomass sources.

vii) A fuel produced from biomass materials will possess very low levels of embedded carbon and will consequently be a key enabler to support the progress towards net zero of glass manufacturing in the future, especially if it can be combined with CCUS technologies.

The next planned step is that NSG are seeking to collaborate with Glass Futures and its membership to undertake further pilot-scale trials to prove that NSG's patented technology is operational on a large scale, with a range of feedstocks and to demonstrate the ability of the technology to operate continuously. The new Glass Futures Pilot-scale 30 t/day R&D facility (Figure 14) offers an excellent venue to accelerate the development of this highly promising technology and will provide the potential to collaborate with a larger group of potential users.

Once continuous operation of the technology has been demonstrated and optimised for a range of feedstock materials, the project would seek to complete a detailed design of a 25 t/day industrial scale plant that could be installed on a commercial glass manufacturing plant. This would be accompanied by additional research to understand the logistics and supply of waste materials to glass manufacturing plants.

# Assessment of Potential of CCUS Technologies

The attractiveness of biofuels could be further strengthened by potential later application of Carbon capture (utilisation) and storage (CCUS) to mitigate process emissions and provide negative emissions for the sector [4]. This is a clear opportunity highlighted within the UK government's Biofuel Strategy [2] for various materials.

The previous IFS-R1P3 project identified a clear need for additional research to de-risk alternative technologies in the field of CCUS. CCUS is of interest to, but unlikely to be developed by, individual glass manufacturers because of the many technical barriers which have to be overcome. Therefore, Glass Futures, together with a number of organisations across their Membership (including glass manufacturers Encirc, NSG, Vidrala, Ardagh, Stoelzle Flacconage, O-I, Guardian; Universities of Sheffield, Leeds, Liverpool; plus Diageo, British Glass, Calumite and Magma Combustion), undertook an investigation into the various Carbon Capture (CC) technologies currently under development to identify the most suitable for use within the glass industry. The focus of the study was primarily on CC technologies which are at least at a technology readiness level of 4, ideally closer to 7, such that they are, or will be within the next 2-3 years, at a position to provide demonstrators to trial at the Glass Futures' St Helens Pilot line when it comes into operation in 2024.

This study aimed to address the following objectives:

1. Identify whether there are currently any CC technologies that are technically and economically viable for use, at scale, on glass furnaces, compared to other decarbonisation technologies,
2. If not, then identify and support the development of CC technologies that have the best chance of success for the glass sector, with the ambition of reducing the time before deployable CC technologies are widely available.

Figure 14: Glass Futures' Pilot-scale 30 t/day R&D Facility at St Helens

The study developed a list of criteria which was used to rank the more than 30 developers of CC technologies identified (see Table 4). The shortlist drawn up as a result can be seen in Table 5. Four case-study industrial plant scenarios, selected from a list of typical furnace target emissions produced by British Glass, were provided to each of these CC developers to help them provide estimates/modelling CAPEX/OPEX costs indications.

A questionnaire was developed to engage the various Developers and build a detailed understanding of the technical and economic viability of each technology. The methodology presented in the "New technology assessment framework" and "Technology Development Matrix (TDM)" by Baker et al. [13] was adopted and adapted.

The study concluded that, at this time, there is insufficient data available from CC developers to conduct meaningful Basic Economic Assessment and Techno-Economic Analysis and provide detailed information on the viability of all of the CC technologies for application in the glass industry. However, engagement with the shortlisted CC developers continues.

In a parallel project, funded under the BEIS Innovation 2.0 funding stream, a C-Capture solvent-assessment unit will be installed on the NSG float and GF pilot lines. This project aims to provide insights into ability to capture CO2 from commercial glass manufacturing furnaces. It is hoped that this unit could also be used within a separate follow-on project to investigate the compatibility of the C-Capture technology with furnaces firing biofuels.

Table 4: Summary of the Key Criteria to Enable the Working Group to Assess and Rank the Various Carbon Capture Technologies Identified

| Criteria | Key Considerations |
|---|---|
| CC Technology Type | What overarching field does the technology sit in? |
| Technology sub-sector | Which specific technology category does the technology sit in? |
| CC Providers | Who are the current leading CC technology developers in this field |
| Development Status/ TRL Level 2021 | What Technology readiness level is this technology at, for the glass industry and in other sectors? |
| Application / Scale | Has this technology been trialled at a pilot scale?<br>If so, what volumes of CO2 have been captured? |
| Active Discussions with any WG Members? | Do any of the Glass Futures CCUS Project Working Group have contact with these developers? |
| Features | Summary of any key features of the technology that would make them particularly suited to glass (or not) |
| CAPEX costs | Estimate of CAPEX costs |
| OPEX costs | Estimate of OPEX costs (per tonne CO2 captured), and how this might vary with scale |
| Footprint | What is the likely footprint (m2) of the CC technology required for a typical glass site? |

| | |
|---|---|
| Energy requirements | How much energy would be required to capture the CO2 (per tonne) and how might this vary with scale? |
| Flowrates and CO2 concentration | What range of CO2 in the exhaust gases does the CC system have the greatest efficiency?<br><br>What are the maximum gas flowrates that the system can cope with? |
| Size of the company | How big is the company developing this CC technology? |
| Track Record | What is the track record of the company developing this CC technology? |
| Location/Head Office | Where are the company headquarters based?<br><br>Do they have a UK footprint? |

Table 5: Provisional Shortlist of Carbon Capture Technology Developers to Engage in WP2

| Type | Technology Applied | Providers |
|---|---|---|
| Chemical Absorption (Liquid Solvent) | Traditional amine technology | Aker Solutions |
| | Patented “advanced” amine technology | MHI |
| | Patented “advanced” amine technology | Carbon Clean |
| | Patented CANSOLV CO2 Capture System, “advanced” amine technology | Shell |
| | Patented non amine | C-Capture |
| Solid Adsorption | Temperature / Pressure swing adsorption | Air Liquide (BB) |
| | Metal Organic Framework (MOF) materials | MOF Technologies |
| | | Promethean Particles |
| Mineralisation Processes | CO2 absorbed into waste to create new raw materials | Cambridge Carbon Capture |
| Microalgae/ Enzymes | CO2 absorbed by organisms | Swansea University |
| Molten Carbonate Fuel Cells | CO2 processed through fuel cell | ExxonMobil / Fuel Cell Energy |
| Oxyfuel Combustion | CO2 capture and compression | Air Products |
| Cryogenic | Cryogenic CC & pressurisation | CHART SES |
| Microalgae/ Enzymes | CO2 absorbed into wastes | Bechtel |

# Economic Modelling of Waste-derived Fuel Options for Glass and Ceramics Manufacturing

## 9.1 Background

Economic considerations present a major challenge to decarbonisation in the glass sector, in particular the high CAPEX of the equipment and the current high cost and low availability of low-carbon fuels compared to natural gas.

The G-FUSE (Glass Fuel Switching Economics) model was developed by Glass Futures and Element Energy within the BEIS-funded IFS-R1P3 project led by Glass Futures. The model calculates the cash flow of a glass manufacturing site over a multiyear period for scenarios with and without fuel switching, taking into account the impact of manufacturing processes and refurbishments or rebuilds of each of the site's furnaces on CAPEX spending, revenues, fuel and carbon costs. The model offers a scenario builder that allows sites to make an economic comparison of strategic scenarios, in particular for switching to low-carbon fuels (hydrogen, electricity, biofuel or a hybrid), based upon the year when the site switches to one of these fuels.

A typical model output will provide information on net present value (NPV – sum of net savings of fuel switching) and levelised cost of abatement (LCOA, £/tCO2 abated). The model takes into account a range of site-specific factors, such as:

- Number of furnaces,
- Number of production lines,
- Energy consumption,
- Maintenance schedules and
- Equipment age, etc.

## 9.2 Summary of Findings

For the current IFS-R2P1 biofuels project, this model was used to assess the scenarios of switching two glass plants and one ceramics site to a selection of biofuels. The counterfactual scenario was natural gas for the glass furnaces and industrial heating oil for the ceramics kiln. The biofuels modelled were: Used Cooking Oil Methyl Ester (UCOME) and BF3. UCOME is the form of biodiesel that was successfully trialled in two industrial glass furnaces (one container and one float glass furnace) in the previous IFS-R1P3 project and is selected here as the reference.

The model uses projections for the fuel prices, carbon prices and fuel carbon intensities. For natural gas prices, a modified version of a projection produced by BEIS (2020, high estimate [14]) was used. The modification was to take into account the high gas prices at the time of modelling (October 2022), with a gradual decrease back to the projected value by 2027. BEIS projections were used for natural gas carbon intensity (2020 [15]) and carbon costs (2021, high estimate, [16]). For UCOME, the price data used was for a standard biodiesel product (2020 [17]), and the carbon intensity data was taken from a report produced during the previous IFS project (In Perpetuum, [18]). The price data for BF3 was based on data supplied by the fuel supplier based on October 2022 prices.

An example of the results generated for one of the glass manufacturers studied is given in Figure 15. The Net Present Value (NPV) is shown for four scenarios at the site; both biofuels were modelled with non-furnace components, such as the lehrs, decorating lines etc., included or excluded. Generally, the impact of including/excluding the non-furnace components is smaller than the impact of the choice of biofuel. Due to the current natural gas prices, the NPV values are high initially before decreasing over the first 5 years. For BF3, the NPV is positive for all years of fuel-switching.

One of the key findings from this work is that any model of the economic impact of fuel-switching is highly sensitive to fuel costs. Although this project aimed to consider the current high natural gas prices, attempting to project price trends for any fuels with any degree of accuracy is extremely difficult. As such, the results presented in this report should be taken as illustrative only.

In general, BF3 was found to produce positive NPV values for each year of fuel-switching, due to its low CO2e intensity and cost compared to natural gas, and its low cost compared to UCOME. This fuel is not currently used in the foundation industries, and so it will be explored by Glass Futures for use in the glass and ceramics industries, contingent on a successful bid to the IFS R2P2 funding call.

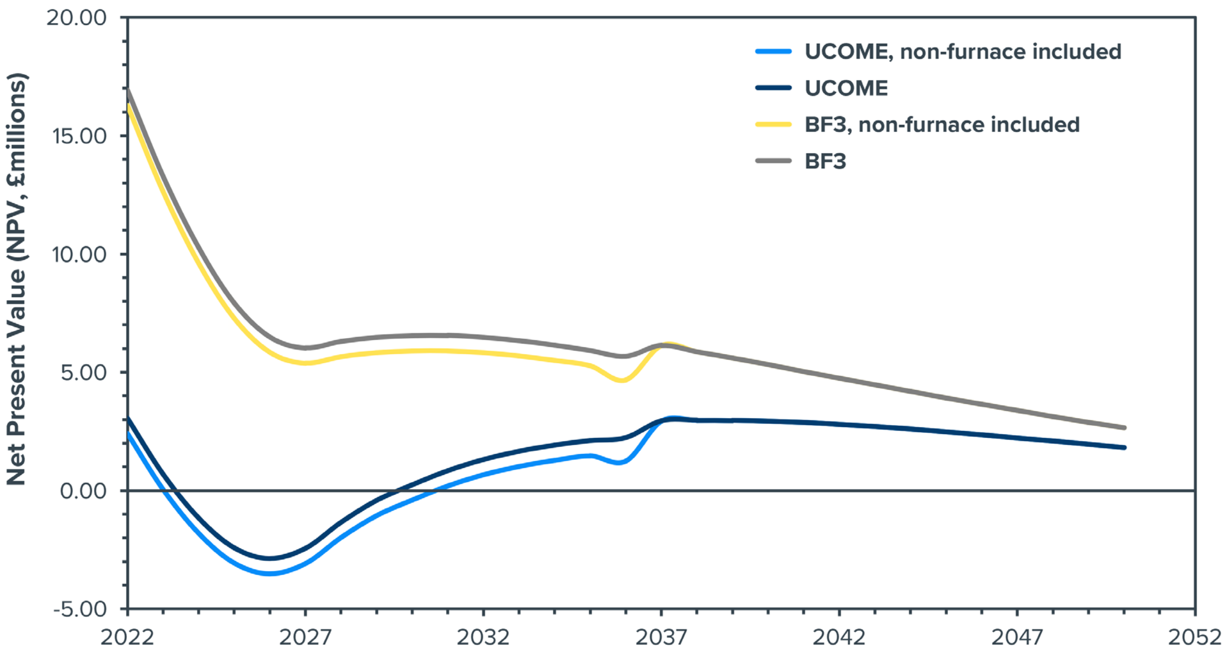



Figure 15: Net Present Values for One of the Glass Manufacturing Sites as a Function of Year of Fuel-Switching for Biodiesel (UCOME) and BF3

The G-FUSE model was adapted and run for a ceramics site. As the ceramics site investigated does not fall under the Emissions Trading Scheme (ETS), the NPV values are entirely a product of the difference in price between the three fuels: the currently used Industrial Heating Oil (IHO), UCOME and BF3. Providing the ceramics partner remains outside the scope of UK ETS, the primary economic factor will be fuel prices. This highlights the importance of developing low-cost sources of biofuels to drive uptake within the foundation industries.

## 9.3 Next Steps

There are several key pieces of work which Glass Futures is intending to carry out through a future project:

(i) Firstly, there is a need to develop a greater understanding of the economic factors around biofuels from wastes or feedstocks. The current project has identified several candidates for use in the industry and has analysed their technical properties. However, a more detailed understanding of available volumes and future pricing is essential for producing economic models with greater accuracy and applicability.

(ii) The cost of retrofitting furnaces/kilns to make them compatible with biofuel firing is another key requirement for accurate economic modelling. Depending upon existing facilities on site (e.g. oil-delivery systems, heated storage tanks, pumps, trace heating etc.) and the specific requirements of a chosen fuel (e.g. heating requirement, impacts on seals), the retrofitting costs could vary significantly from site to site, even for similar furnace designs.

(iii) Wider impacts of the fuel-switch should also be considered. For example, does the new fuel lead to an increase in heat transfer efficiency to the melt; will the abatement require the use of more ammonia and lime or need to be upgraded when combusting biofuels, etc.

(iv) The current G-FUSE model has been specifically designed for use in the glass industry. To more accurately model ceramic manufacturing sites, and those for other foundation industries, e.g. steel, there is a need to develop more bespoke models for these sectors.

## 9.4 Potential for Scale-up versus Counterfactual and Other Low-Carbon Alternatives

The work undertaken within this project has indicated that a range of biofuels can be used within existing glass furnaces and ceramics kilns with only minor changes to fuel delivery systems (for most of the biofuels identified). The potential for scale-up to other low-carbon alternatives, hydrogen and electricity, is discussed below.

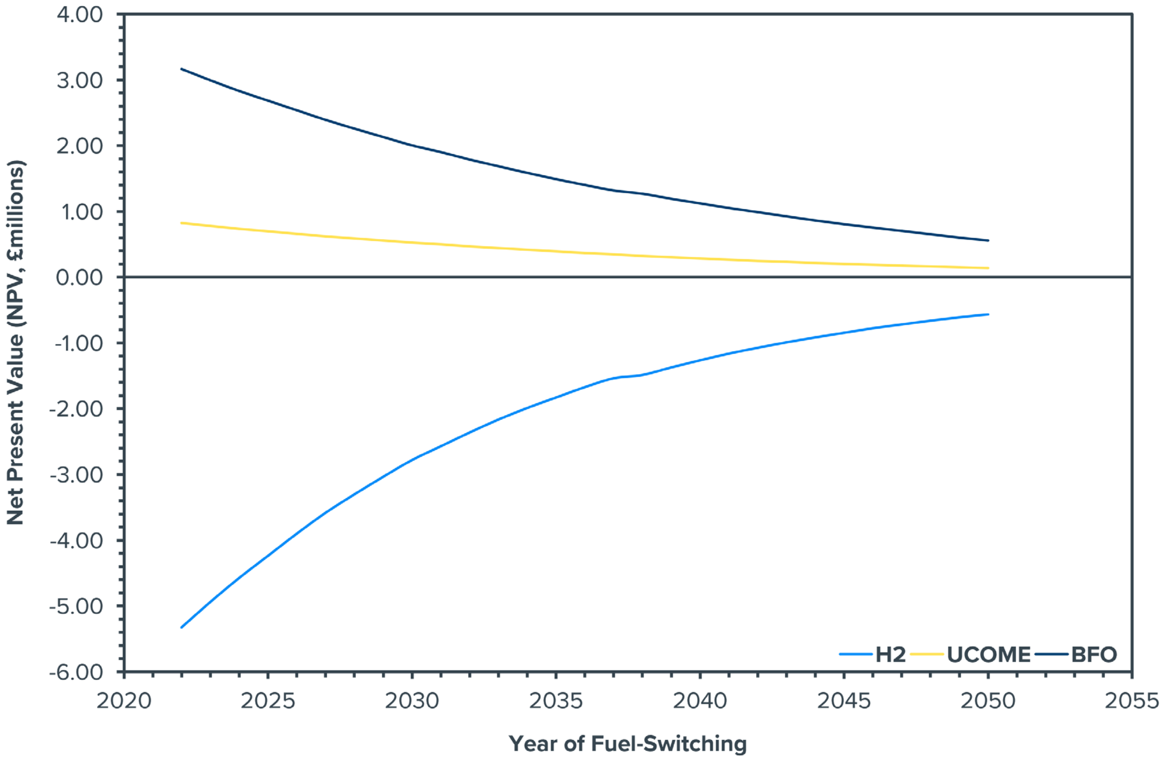



Figure 16: Predictions of the Economic Impact of a Ceramics Partner Switching to Biofuels and Hydrogen made Using the G-FUSE Model

The G-FUSE model has used the assumption that switching to hydrogen fuels will require a new furnace design, with new refractories that can cope with the higher moisture and more corrosive NaOH-containing atmosphere. In addition, the existing fuel lines and delivery systems may need to be upgraded.

Economic modelling using the G-FUSE model has been applied to fuel switching to both biofuels and hydrogen at a ceramics partner site (Figure 16). In the case of hydrogen, the counterfactual was natural gas. The positive Net Present Value (NPV) for biofuels indicates that fuel switching will save energy costs compared to the counterfactual of Industrial Heating Oil over the whole assessment period, whilst the negative NPV for hydrogen suggests the opposite compared to natural gas.

Electric melting is established for glass furnaces up to 300t/day, but not for larger furnaces, and not in float glass manufacturing. A switch to an electric furnace would require a complete furnace redesign and reconfiguration of the manufacturing site, plus investment in electric transformers and cabling. For most sites, the local electricity grid would also need to be upgraded.

# Phase 2 Industrial trials and Commercial Planning

## 10.1 Selection of Industrial Sites

One of the primary objectives of the current feasibility study was to develop a Phase 2 project for trials of waste-derived biofuels at commercial glass and ceramics manufacturing sites.

Several sites across Glass Futures' Membership were engaged to explore the possibility of industrial trials as part of an IFS Round 2 Phase 2 project. A questionnaire was circulated to the companies who responded (see Appendix 1); based upon the responses to the questionnaire and the availability of budget within the prospective project, the following sites were selected:

- O-I Glass, Alloa, Scotland,
- NSG Pilkington, St Helens, Merseyside,
- Encirc, Derrylin, Northern Ireland,
- Ardagh, Knottingley, West Yorkshire,
- DSF Refractories, Buxton, Derbyshire.

Other sites did express an interest in undertaking industrial trials, however the number of sites selected had to be limited in order to fit the budget available within Phase 2. The final selection was made on the basis of the range of products and CAPEX required.

## 10.2 Site Modifications Required for Phase 2 Demonstrations

It should be noted that all of the above sites had pre-existing liquid fuel delivery systems already installed, requiring only relatively minor modifications in order to run the preferred biofuels and so would minimise CAPEX, thereby maximising the duration of trials that could be undertaken within a Phase 2 project budget. The exact details of costs and nature of these modifications cannot be shared due to confidentiality considerations. However, the main types of upgrades can be summarised as follows:

- Fuel storage tanks,
- Heating system for storage tanks,
- Pipework lagging,
- Trace heating for pipework,
- Liquid fuel control skid,
- Modifications to control system,
- Oil burners and
- Pumps able to maintain fuel flowrates appropriate for calorific value of liquid fuel.

Additional costs may be incurred during the trials to mitigate against the following risks associated with waste-derived fuels, depending upon the specific fuel chosen for a given site and the design of equipment currently available on site:

- Lower flash point (mitigated through upgrading plant infrastructure to be ATEX rated),
- Increased risk of biofuels leaking through joints (e.g., compared to standard diesel), mitigated through careful checks during commissioning and replacement of any sub-standard pipework,
- Microbial build-up (if left stagnant or stored for prolonged periods of time), mitigated through flushing pipes with diesel or purging with compressed air, ensuring good flow/mixing of fuels, with scope to add anti-microbial agents if necessary,
- Contaminants in the fuels may pose additional toxicity risks and harmful emissions when combusted, but will be mitigated via standard abatement equipment and installation of filters in the pipework.

Established health and safety measures exist in other sectors to provide safe working environments for operators for all these risks, which can be applied in the glass/ceramics sectors with relative ease.

In addition to this, each biofuel will be screened by GF at the St Helens Pilot Facility using the CTB and/or the new 30t/day glass pilot line to identify and address any potential risks. The Glass Futures pilot facility will also provide opportunity to investigate the performance of biofuels when fired in an oxyfuel furnace.

## 10.3 Sustainability and Environmental Impacts

Activities within the Phase 2 project will be structured to develop a full understanding of opportunities and risks associated with the sustainability and environmental impacts of using waste-derived biofuels.

### 10.3.1 Sustainability

Whilst fuel suppliers will be selected based on their ability to provide guarantees of the sustainability of their fuels and feedstocks, GF will continue to work closely with Aston and Manchester Universities, to develop an independent understanding of the sustainability of any fuel trialled at an industrial level, covering all aspects of sustainability and which biofuels are compatible with UK ETS regulation.

Through enabling the glass and ceramics sectors to become a reliable customer of waste-derived fuels, this project can create a global demand for waste-streams that might otherwise end up in landfill or polluting rivers/oceans, so has potential, if undertaken appropriately, to help address various pollution challenges around the globe.

### 10.3.2 Environment

The project will look to understand and mitigate the following environmental risks associated with waste derived biofuels:

- Particulates emissions: GF will assess whether this is an issue and develop an understanding of routes to address any such issues, plus impact on CAPEX,
- NOx emissions: These could be an issue, depending upon the chemistry of the fuel, in which case, GF will look to identify and develop mitigation solutions. Primary techniques to reduce NOx from melting furnaces include combustion modifications such as: reduction of air/fuel ratio, reduction of combustion air temperature, staged combustion, flue-gas recirculation, oxy-fuel melting and use of low NOx burners such as the Auxiliary Injection System, developed by Global Combustion, assessed under the UKRI 'EcoLowNOx' project). Secondary techniques to reduce nitrogen oxides

include selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR).

- Compatibility with CCUS technologies: GF will engage with a broad range of carbon-capture technology demonstrators, sharing details of emissions from waste-derived biofuel combustion to help identify suitable CCUS technologies. GF will also look to utilise a solvent-assessment unit, developed by C-Capture (anticipated to be already installed on the GF pilot-facility as part of the CCUS Innovation 2.0 project), which can provide insights into the ability to capture CO2 from biofuels and therefore the potential for carbon-negative glass manufacturing.

## 10.4 Economic Considerations

The data collected from the proposed Phase 2 industrial trials will be used to improve the data and assumptions within GF's economic model (see Section 6) to provide glass and ceramics manufacturers with a more comprehensive understanding of the economic attractiveness of waste-derived biofuels.

GF will then look to engage other glass manufacturing plants across the UK, providing the opportunity to assess the economic viability of switching to such fuels for each glass site across the UK.

## 10.5 Assessment of Social Value

Discussions with major brands have revealed an increasing global demand for 'green'/'zero-carbon' glass and ceramics products, especially within the packaging and construction sectors. As such, the ability to supply low-carbon products has potential to create a significant competitive advantage over international competitors selling products manufactured using fossil fuels.

The UK glass industry employs 23,200 people, generating £3bn revenues, contributing £1.6bn GVA to the UK economy p/a [19]. The UK ceramics sector employs 17,500 people directly, with £1.6bn turnover and over £500m exports p.a. In laying the foundations for developing a quick and economically viable route to decarbonise, and as an enabler for the UK industry to supply premium 'low-carbon' products, this project will both safeguard existing jobs and create new jobs as growing demand for low-carbon products is likely to result in increased manufacturing output (Figure 17). The Phase 2 project would look to engage with organisations across the supply-chain (including multi-national brands) to develop an understanding of what this impact could be.

Given many glass and ceramics manufacturing sites are located in areas most in need of levelling up, this project offers both the motivation (i.e., new investment in manufacturing technologies) and means (through provision of bespoke training) to create highly-skilled jobs in these areas.

Further jobs are likely to be created through growth of the waste-derived biofuels sector due to increased demand from industry.

## 10.6 Route to Market

This IFS-R2P1 project has demonstrated that it should be possible to switch existing glass furnaces/ ceramics kilns from natural gas over to liquid biofuels with relatively low CAPEX, in short time frames, with low risk to product quality. For sites with pre-existing oil-back-up systems, costs to upgrade to biofuels could be in the region of £500k-£2m. However, the cost to switch larger sites with no pre-existing oil-systems could be as much as £5-7m. The proposed Phase 2 project would look to develop a more accurate understanding of these costs across each glass manufacturing site within the UK (where sites are willing to cooperate).

If the above assumptions prove accurate then, assuming suitable sustainable fuels can be identified and demonstrated at scale, the majority of UK glass and ceramics sites could be switched to low-carbon biofuels by 2030.

Biofuel supplier, Argent Energy, has confirmed that current UK volumes of the waste-derived biofuels they supplied for the CTB and large-scale trials, are sufficient to meet the needs for the planned Phase 2 trials and that they are able to increase the production volumes of such fuels to meet industry demand going forwards. Through the IFS-R2P1 project, GF was also able to begin developing partnerships with several other suppliers/producers of biofuels and waste products.

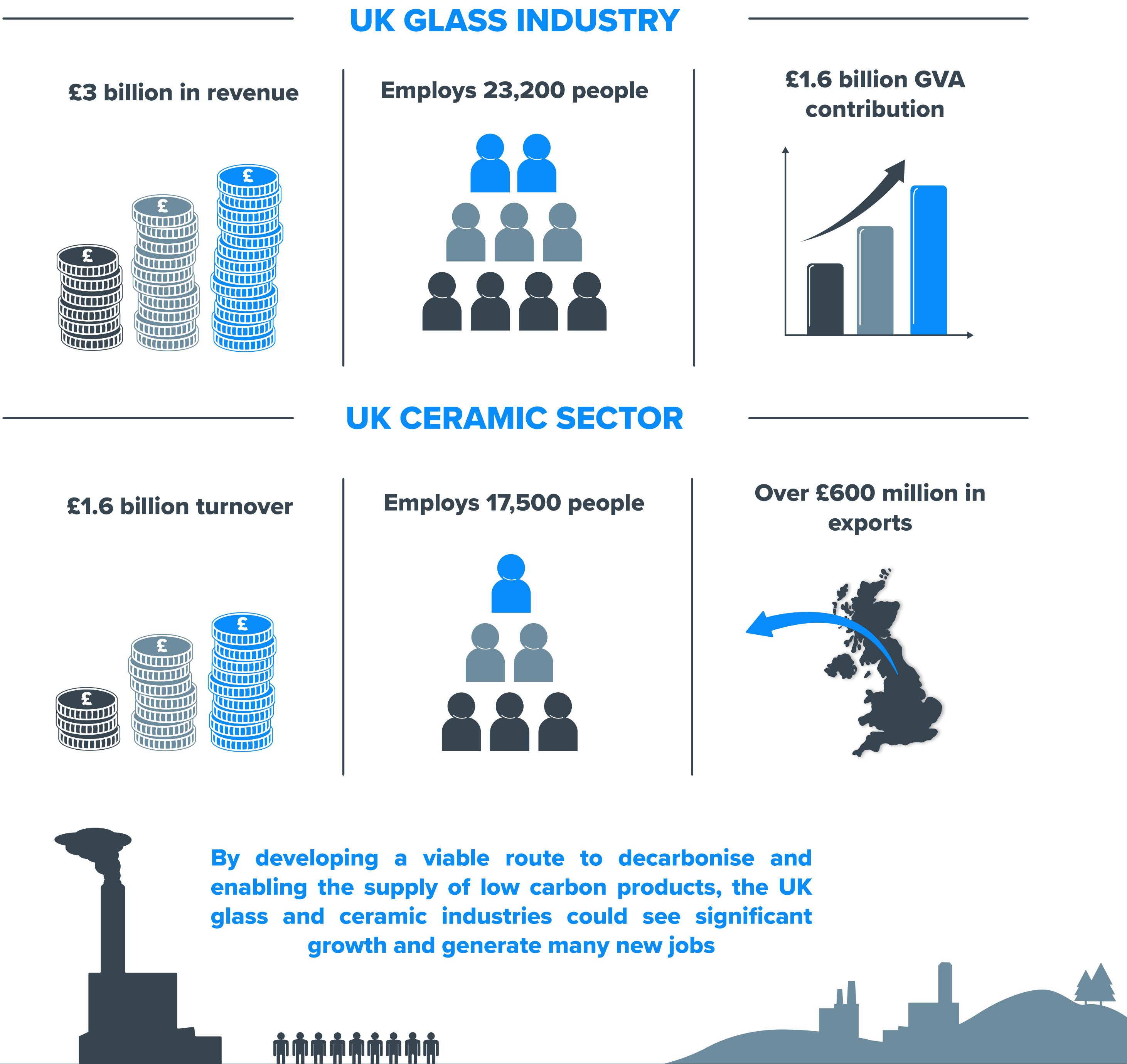



Figure 17: The Social Value of Developing a Viable Route to Decarbonise the UK Glass [19] and Ceramic [20] Industries.

# Conclusions and Recommendations

All of the objectives of the project have been met and a detailed plan for a Phase 2 project has been developed. Feedback from industry throughout the course of the project has been extremely positive, growing confidence and awareness across the glass and ceramics industries of the potential that waste-derived fuels plus CCUS technologies have for decarbonising manufacturing processes. A shortlist of five glass manufacturing sites that were willing to commit to industrial-scale waste-derived biofuel trials was drawn up. Each one has secured top-level approval for participation in industrial trials within a proposed Phase 2 project. CAPEX and OPEX costs associated with such trials have been defined. The sites are as follows:

- O-I Glass, Alloa, Scotland,
- NSG Pilkington, St Helens, Merseyside,
- Encirc, Derrylin, Northern Ireland,
- Ardagh, Knottingley, West Yorkshire,
- DSF Refractories, Buxton, Derbyshire.

The fuels will also be tested on the oxy-fuel furnace of the GF 30t/day pilot line at St Helens. Further sites did express an interest in undertaking industrial trials, however the limited budget within Phase 2 meant that only a selection of sites could be chosen.

This IFS-R2P1 project has developed an understanding to take a number of low-cost, waste-derived biofuels from TRL=4 up to TRL=7. Ten waste-derived fuels were scoped out (with respect to calorific value, viscosity, flash point, acidity, ash content and water content), three of which were put forward for combustion performance trials on the GF Combustion Test Bed facility. These trials showed that the BF1 and BF3 fuels demonstrated higher heat transfer efficiencies relative to natural gas.

The fuels identified and trialled are low-quality by-products and can contain water and other undesirable volatiles that reduce the net calorific value of the fuels and increase harmful emissions; routes to mitigate these challenges have been identified but further work is required to fully understand the most suitable mitigation strategies.

The following mitigation strategies were developed to overcome the challenges identified during the combustion trials:

- In-line Heating: Some biofuels are very viscous and need to be heated up to 90°C to reduce fuel viscosity to enable stable flow through the pipework and adequate atomisation within the burner. Additional heating may be needed to prevent fuels from solidifying, especially in colder climates.
- Regular cleaning of in-line filters: Low-grade biofuels were found to contain high levels of contaminants which will block filters installed in the pipework before the burners. As such a schedule for regular cleaning of the filters is recommended.
- Managing batch-to-batch variability: Batch to batch variability in biofuel quality can affect viscosity and the calorific value and energy supplied into the furnace, as such new control systems on fuel delivery systems will be required to manage this variability.
- Matching pump flowrate capability to calorific values: Some of the biofuels investigated had low calorific values and required very high volumetric flowrates to meet the energy demand of a furnace. As such, pumps and pipework may need upgrading to make certain biofuels viable candidates for use on some sites.
- Material compatibility: Some biofuels had potential to be slightly corrosive in nature or contained

solvents that could degrade certain materials, particularly seals and joints. Therefore, material compatibility checks and tests are recommended to prevent degradation of/damage to any of the parts.
- NOx: Opportunities to reduce NOx emissions through flame optimisation and other strategies currently being explored by Glass Futures will be advanced in a Phase 2 project, together with continued investigations into the compatibility of biofuels with CCUS capabilities.

Routes for utilising waste heat from the furnace to improve fuel quality were explored. The NSG 'PEOL' pyrolysis plant was identified as a promising technique for utilising waste heat from the glass furnace to process waste materials which might otherwise go to landfill, together with biomass, providing a low-energy route to convert such materials into valuable, sustainable, low-carbon fuels . Future work is planned to prove that NSG's patented technology is operational on a large scale and capable of running continuously, through collaboration between NSG and Glass Futures.

Economic modelling of the use of BF3, produced positive Net Present Value (NPV) values for each year of fuel switching, indicating that it could be economically attractive to switch to this fuel compared to natural gas. This has been attributed to a combination of its low CO2e intensity and low fuel cost compared to natural gas. BF3 is not currently used in the foundation industries, and so will be explored by Glass Futures within the proposed Phase 2 project.

A sustainability study, undertaken by Manchester University, identified the key categories of UK biomass resource that may be available for the UK bioenergy sector, highlighting the leading biomass resources potentially available within given radii of key UK glass manufacturing sites and regions. Leading resources included wastes from cattle, sheep, pig and chicken farming, potato wastes, wheat and barley straws, forestry industry residues, MSW and industry wastes. Waste wood together with food wastes also offered significant opportunities in the more densely populated areas. Optimal centralised locations for liquid biofuel production for glass furnaces, given the spatial availability of UK biomass resources and the locations of leading UK glass manufacturing sites were suggested.

Perceived concerns around sustainability will be investigated further. Even if the fuel being sourced is confirmed to be sustainable, proof will be needed that diverting it to the glass sector will not create a demand elsewhere that will be filled by non-sustainable fuels. As such GF will engage the Universities of Aston and Manchester in the proposed Phase 2 project to undertake an independent sustainability assessment of all biofuels submitted to industrial trials.

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- Encirc
- NSG

- O-I
- Ardagh
- Stoelzle
- Calumite
- Guardian Glass
- DSF Refractories
- The British Ceramics Confederation and their members
- The University of Manchester
- Aston University
- The University of Leeds
- The Supergen Bioenergy Hub (Home - Supergen (supergen-bioenergy.net))
- Argent Energy
- The BEIS Industrial Fuel Switching Team

# References

[1] Glass Futures (2022) Alternative Fuel Switching Technologies for the Glass Sector: Phase 3 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1119897/Phase_3_Alternative_Fuel_Switching_Technologies_for_the_Glass_Sector.pdf

[2] BEIS (2021). Biomass Policy Statement. Department for Business, Energy and Industrial Strategy. Biomass policy statement (publishing.service.gov.uk)

[3] Glass Futures (2019) Alternative Fuel Switching Technologies for the Glass Sector: Phase 2 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866364/Phase_2_-_Glass_Futures_-_Fuel_Switching_Tech_for_Glass_Sector.pdf

[4] British Glass (2021). Glass Sector Net Zero Strategy 2050. British Glass - Net Zero Strategy.pdf (britglass.org.uk)

[5] Brown, R.C. (2021) Role of Pyrolysis and Gasification in a Carbon Negative Economy'. Processes, https://www.mdpi.com/2227-9717/9/5/882

[6] Welfle A, et al. (2019). Establishing Viable Pathways for Increasing Biofuel Production from UK Wastes & Residues to meet Transport Energy Targets. Supergen Bioenergy Hub Report for the UK Department for Transport.

[7] Welfle, A. and Freer, M. (2022). UK Biomass Resource Availability for the Glass Sector: Exploring the Feasibility of Decarbonising the UK Glass Sector through Bioenergy. Supergen Bioenergy Hub. https://pure.manchester.ac.uk/ws/portalfiles/portal/234313457/SBH_Glass_Futures_Biomass_Resource_Feasibility_Report_FINAL.pdf

[8] BSIM Manual: Welfle, A., Röder, M. (2022). Bioeconomy Sustainability Indicator Model – Guidance Manual. UK Supergen Bioenergy Hub. http://www.research.manchester.ac.uk/portal/en/publications/bioeconomysustainability-indicator-model-bsim(42c62618-dd04-461c-9758-68f5dde4c883).html

[9] Welfle, A., Röder, M. (2022). Mapping the Sustainability of Bioenergy to Maximise Benefits, Mitigate Risks and Drive Progress toward the Sustainable Development Goals. https://research.manchester.ac.uk/en/publications/mapping-the-sustainability-of-bioenergy-to-maximise-benefits-miti

[10] Welfle, A., Thornley, P., Röder, M. (2020). A review of the role of bioenergy modelling in renewable energy research & policy development. https://research.manchester.ac.uk/en/publications/a-review-of-the-role-of-bioenergy-modelling-in-renewable-energy-r

[11] Welfle, A. and Freer, M. (2022). Biofuels Webinar, October 21, Hosted by Glass Futures.

[12] Griffin, P.W., Hammond, G.P. and McKenna, R.C. (2021). Industrial energy use and decarbonisation in the glass sector: A UK perspective. Advances in Applied Energy 3 100037. Industrial energy use and decarbonisation in the glass sector: A UK perspective - ScienceDirect

[13] Baker R., Alizadeh Sahraei O., Dal-Cin M.M. and Bensebaa, F. (2022) A Technology Development Matrix for Carbon Capture: Technology Status and R&D Gap Assessment. Front. Energy Res. https://doi.org/10.3389/fenrg.2022.908658

[14] BEIS (2019) Fossil Fuel Price Assumptions, Department for Business, Energy and Industrial Strategy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863717/beis-2019-fossil-fuel-price-assumptions.pdf.

[15] UK Government GHG Conversion Factors for Company Reporting, UK Departments for Business, Energy & Industrial Strategy and Environment, Food & Rural Affairs. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020.

[16] Valuation of greenhouse gas emissions: for policy appraisal and evaluation, UK Department for Business, Energy & Industrial Strategy, Published 2 September 2021. https://www.gov.uk/government/publications/valuing-greenhouse-gas-emissions-in-policy-appraisal/valuation-of-greenhouse-gas-emissions-for-policy-appraisal-and-evaluation.

[17] Neste, Biodiesel prices (SME & FAME). https://www.neste.com/investors/market-data/biodiesel-prices-sme-fame#ff7f386c.

[18] Isaac, D., Ireson, R., Li, H. (2022) Most suitable biofuels for the UK glass sector, economics and sustainability – A report for BEIS Industrial Fuel Switching Phase 3, 2022 [1].

[19] Ekosgen (2019) Glass Sector Mapping and Benchmarking Study for Sheffield Hallam University.

[20] British Ceramic Confederation (2022) Hydrogen for the Ceramics Sector, pub. BEIS, in press.

# Appendix

Scoping questionnaire that was circulated to all manufacturing sites interested in undertaking a biofuel trial:

Glass Futures

**GLASS FUTURES BIOFUELS TRIALS OPPORTUNITY: SITE EVALUATION QUESTIONNAIRE**

| No. | QUESTION |
|---|---|
| 1.1 | Do you have a furnace in mind for these trials? |
| 1.2 | If so, where is it based? |
| 1.3 | Is it regenerative/recuperative/oxy-fired? |
| 1.4 | How many burners does it have? |
| 1.5 | What is its tonnage? |
| 1.6 | How many manufacturing lines? |
| 1.7 | Who are the primary customers served by this line? |
| | |
| 2.1 | Is there an existing oil-fired system? |
| 2.2 | Are there storage tanks? |
| 2.3 | If so, how big are they? |
| 2.4 | Do you have a functioning capability to receive bulk tankers of oil? |
| 2.5 | Is there in-line/trace heating? |
| 2.6 | What condition are the above in? |
| 2.7 | Can you share pictures of these systems? |
| 2.8 | Is all pipework well-lagged? |
| 2.9 | How recently were the above installed/used? |
| 2.10 | What are the oil-firing pipework seals manufactured from? |
| 2.11 | Is the process control system functioning for the oil firing? |
| | |
| 3.1 | Do you have the internal engineering capability to plan and deliver oil firing system upgrades? |
| 3.2 | Would you have a period in mind for trials during 2023? |
| 3.3 | Are there any site specific issues we should be aware of? , e.g. an upcoming major shut-down? |
| | |
| | **FOR INFORMATION** |
| | |
| | All trials are expected to phase in over several days to ensure glass quality. |
| | Emissions testing and furnace setup support can be provided as part of these trials. |
| | During previous trials in green and flint glass no observable glass quality effects were encountered. |
| | If selected , GFL will build a detailed trial programme for the site looking at local factors. |

# Glossary

| Term | Meaning |
|---|---|
| ATEX | Appareils destinés à être utilisés en Atmosphères Explosives (Regulation for devices intended for use in explosive atmospheres) |
| BEIS | Department for Business, Energy, and Industrial Strategy |
| BF1 | Biofuel 1 |
| BF1-A | Biofuel 1 - Fraction A |
| BSIM | Bioeconomy Sustainability Indicator Model |
| CAPEX | Capital expenditure |
| CC | Carbon Capture |
| CCUS | Carbon capture (utilisation) and storage |
| CFD | Computational fluid dynamics |
| CO2 | Carbon dioxide |

| | |
|---|---|
| COe | Carbon Monoxide Equivalent |
| CO2e | Emissions from various greenhouse gases on the basis of their Global Warming Potential (GWP) by converting amounts of other gases to the equivalent amount of $CO_2$ |
| Container glass | Packaging glass for food and beverages storage |
| cSt | centi-Stokes; unit of viscosity |
| CTB | Combustion test bed |
| Cullet | Recycled glass |
| CV | Calorific Value |
| DSF | Derbyshire Silica Firebrick Company |
| EBRI | Energy and Bioproducts Research Institute at Aston University |
| ETS | Emissions Trading Scheme |
| EU | European Union |
| Float glass | Sheet of glass with uniform thickness and flat surface |
| GC-MS | Gas chromatography – mass spectrometry |
| GF | Glass Futures Ltd |
| G-FUSE | Glass Fuel Switching Economics model |
| GHG | Greenhouse gases |
| GVA | Gross Value Added |
| H2 | Hydrogen |
| HAZOP | Hazard and operability analysis |
| ICP-OES | Inductively coupled plasma - optical emission spectrometry |
| IFS | Industrial Fuel Switching Competition |
| IFS-R2P1 | Industrial Fuel Switching Competition, Funding Round 2, Phase 1 |
| IHO | Industrial heating oil |
| kg | Kilogram |
| km | Kilometres |
| kW | Kilowatt |
| Lehr | Oven used for annealing glassware |
| mgKOH/g | The amount of potassium hydroxide (KOH) base required to neutralise the acid in one gram of an oil sample |
| MJ | Megajoule |
| MSW | Municipal Solid Waste |
| Mt | Million tonnes |
| NaOH | Sodium Hydroxide |
| NCV | Net Calorific Value |
| NOx | Nitrogen oxides |
| NPV | Net present value |
| NSG | Nippon Sheet Glass |
| O2 | Oxygen |
| O-I | Owens-Illinois Glass |
| OPEX | Operational expenditure |
| p.a | Per annum |
| PLC | Programmable Logic Controller |

| | |
|---|---|
| PTFE | Polytetrafluoroethylene |
| R&D | Research and development |
| SBH | Supergen Bioenergy Hub |
| SOx | Sulphur oxides |
| t/day | Tonnes per day |
| TAN | Total Acid Number |
| TDM | Technology Development Matrix |
| TRL | Technology Readiness Level |
| UCOME | Used Cooking Oil Methyl Ester |
| UK | United Kingdom |
| WG | Working Group |
| WP | Work Package in project |
| wt% | Weight percent |
| £/tCO2 | Cost per tonne of CO2 |
| £bn | Billions of pounds |
| £m | Millions of pounds |
| °C | Degrees Centigrade |
| 2.5" | 2.5 inch diameter |

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SUSTAINABILITY | INNOVATION | COLLABORATION