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Alternative Fuel Switching Technologies for the Glass Sector: Phase 3

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Glass Futures™

A report for

Department for Business, Energy & Industrial Strategy

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1. Executive Summary

The Department of Business, Energy and Industrial Strategy (BEIS) contracted Glass Futures under the Industrial Fuel Switching Competition Phase 3 (IFS-P3) to answer some of the fundamental questions on low carbon energy within the UK Glass sector. Glass Futures designed a series of studies with a large consortium of industry, academia and non-governmental organisations (NGOs) to advance all alternative fuel technology options for the glass industry. This programme of work proved highly successful in delivering large scale industrial demonstrations within operating commercial glass manufacturing sites as well as a series of pilot scale tests and techno-economic studies.

Of the tests, experiments, modelling and scenarios performed and evaluated, a number of key results and insights were returned:

- Industrial scale demonstrations of bio-fuels providing 100% of the energy input for extended trial periods showed carbon savings of circa 70-80% of CO_2 vs natural gas, proving that the technical feasibility to decarbonise the glass manufacturing process exists today in both float and container glass sectors. However, due to economic factors the market is unable to justify such a change
- Results from the large lab-scale experiments on less commercially available and technically unproven options (including biofuels and hydrogen) were highly positive, indicating that significant future investigation is warranted and that options to decarbonise the glass industry will not be restricted to a single solution. This gives the glass industry the opportunity to both decarbonise and respond to market factors in the drive to net zero by 2050 or sooner
- A complex landscape exists around the many fuel switching solutions, and a number of key technical questions still remain regarding the long term impacts of fuel switching choices. There are limited opportunities to change furnaces during production campaigns which last for up to 20 years. Major changes to furnace design can only be executed between such campaigns and will incur significant costs

From this programme of work, it is clear that there must be additional research to de-risk alternative technologies to enable the transition required. This is particularly true for technologies such as Carbon Capture (Utilisation) and Storage (CCUS) which is of interest to, but unlikely to be developed, by individual glass manufacturers because of the many technical barriers which have to be overcome.

The uncertainty in long term energy policy and prices may affect the investments made by both domestic and international companies. New assets installed are likely to be based on incremental improvements to existing designs rather than revolutionary changes.

This project has positively demonstrated that some fuel switching options exist today and, with the correct economic factors, could be taken up sooner than expected. In particular, the use of biofuels to decarbonise a part of the current fuel mix could yield beneficial carbon emission and economic outcomes. Furthermore, the BEIS IFS programme has attracted critical global acclaim within the glass manufacturing sector and has directly supported the growth of Glass Futures as a leading combustion research institution within the foundation industries.

The key outputs of this report provide the platform to begin to discuss the strategic approach that must be taken by policymakers to enable the uptake of key fuel switching solutions. Whilst some barriers are technical and others economic, the key highlight of this work is that by investing more into industrial demonstrations of low carbon fuels there is an opportunity to bring low carbon products to market sooner than later. This is evident from the two ground-breaking industrial trials on container and float glass plants that had a genuine carbon reducing impact within the glass supply chain in 2021 and 2022, and as such should be taken as a blueprint for future approaches to innovation in decarbonisation.

It is difficult to provide detailed strategies for the various sub sectors, but a hybrid approach looks attractive and could provide organisations with the flexibility to use low carbon fuels on an ongoing basis as part of their energy mix, or use significantly higher amounts to produce high value products for specific markets.

2. Background

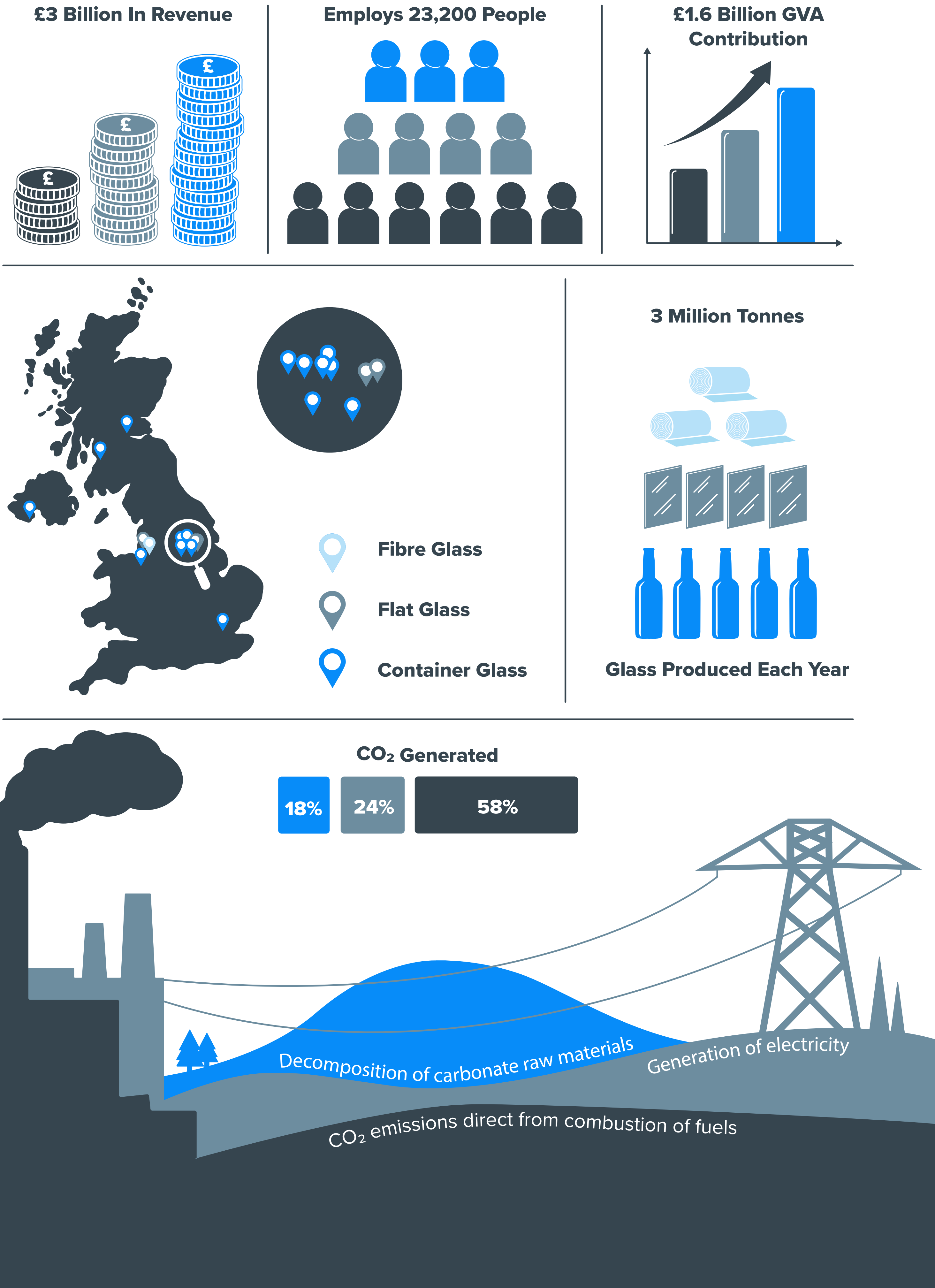
The UK glass industry produces ~3.5 Mt glass p.a., generating more than 1.5 $MtCO_2$ p.a. Of these emissions, 75-85% are from combustion of fuel and 15-25% are from raw materials, depending on the recycled content [British Glass, 2021] (Figure 1). The industry is committed to reduce emissions to net zero by 2050, as such there is a pressing need to identify suitable routes to decarbonise the glass melting process.

Glass Futures was funded under the BEIS Industrial Fuel Switching Competition Phase 2 (IFS-P2), the study undertook a series of literature reviews, industry engagement workshops, 1 to 1 meetings with industry and supply chain organisations, SWOT analysis and economic modelling. The study identified that:

- A range of low-carbon scenarios should be investigated to decrease the risk that any one fuel scenario proves to be non-viable and to avoid technology lock-in
- There are a range of requirements and challenges experienced across the various subsectors of the glass industry (e.g. float, container, fibre), such that different sectors are likely to experience unique challenges with certain fuel types and technologies
- Unpredictable variations in availability and affordability 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. For example, hydrogen supply may be localised; local grid capacity for electricity supply may be limited in some areas

In response to the findings from IFS-P2, the follow-on IFS-P3 project was undertaken to evaluate a wide range of potential technical options and likely economic impacts of such and to focus on executing some of the world's first industrial scale demonstrations of low-carbon fuels.

Figure 1: Overview of the UK Glass Industry



3. Introduction

3.1 Industrial Fuel Switching Scenarios

The IFS-P3 project assessed a range of low carbon fuels likely to be of interest to the glass industry based on a range of factors including health and safety, economic viability, thermal efficiency, effect on batch melting, glass quality and emissions (especially NO_x). Much of the engineering and equipment required to supply these fuels is readily available but likely to require significant capital investment and/or modification for use in the glass industry. Further work to study the effects of different fuels on furnace design and construction will be required to move this work beyond TRL 4.

3.1.1 Hydrogen

It is generally accepted that hydrogen will be available within the UK for both domestic and industrial heating. The most likely short term provision of hydrogen will be via the existing natural gas network at a level of 20% hydrogen by volume. Some areas of the UK may also benefit from the generation of hydrogen to supply industrial "hubs" with up to 95% hydrogen via dedicated pipelines.

The actual source of the hydrogen (grey, green or blue) will not affect the technical issues, but will significantly affect the economic feasibility of using this fuel.

The use of hydrogen in the glass industry presents some unique challenges and will require more research and development work to understand the effects of hydrogen combustion (due to high water content atmosphere above the melt) on the glass melting and forming processes, glass quality, emissions (particularly NO_x) and refractory corrosion. The solutions to these questions may be different across the various subsectors (float, container, etc).

Pilot scale (300kW) combustion tests:

These tests were carried out on the Glass Futures' Combustion Test Bed (CTB) rig which has demonstrated that results found are scalable up to the large "end-fired" furnaces common within the glass container sector.

The IFS-P3 project investigated how hydrogen fuels may perform in a glass furnace by benchmarking combustion characteristics compared to natural gas in both of the following well-established combustion types common within the glass industry:

- Hydrogen and air, representative of "regenerative" and "recuperative" furnaces
- Hydrogen and (near pure) oxygen, representative of "oxy" furnaces

A desk study of a hydrogen forehearth: Assessing the impacts of natural gas and hydrogen blending of direct replacement of typical natural gas fired forehearths and its impacts on safety, technical performance and economics.

Site hydrogen use engineering study: Looking in depth at the installed infrastructure on a major glass manufacturing site to understand the safety, economic, and technical concerns that could arise from the conversion of a full manufacturing site to the use of 100% or blended hydrogen.

3.1.2 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 [British Glass, 2021]. This is a clear opportunity highlighted within the UK government's Biofuel Strategy [Biomass Policy Statement, 2021] for a number of materials.

The IFS-P3 project was limited to the investigation of the use of liquid biofuels. The generation of "natural gas-type" fuels from bio sources is unlikely to require any changes to current asset design, engineering or operations.

The choice of liquid biofuels was a critical step in the IFS-P3 project and required a comprehensive screening of bio-options for the pilot scale (300kW) tests. Over 60 biofuel candidates were considered and ranked against seven relevant criteria (Figure 2) to determine the potential for current and /or future use within the glass industry. The fuels chosen for testing on the CTB ranged from those similar to fossil fuels, already well known within the glass industry, to fuels which theoretically show potential use but will require further development in combustion systems.

Large scale industrial demonstrations: The key aspect of the programme's biofuels work hinged upon two industrial scale demonstrations of 100% biofuel energy for extended trial periods covering several days of commercial (float and container) glass production. These trials showed CO_2 reductions of between 70-80% when compared to natural gas, proving that the technical feasibility to decarbonise the glass manufacturing process exists today in both float and container glass sectors. The high cost of these alternative biofuels is the primary reason for these fuels not being used currently within the glass industry. These findings were identified in the Glass Futures Economic Model, but the underlying reasons and potential changes in UK Government Policy are outside the scope of this IFS-P3 work.

3.1.3 Electric Melting

Some glass manufacturers have applied increasing amounts of electric "boost" (so-called "super-boosting") to larger furnaces (>300 tonnes per day output (Tpd) container: >650Tpd float), but these have generally supplied 20-40% of melting energy. The application of higher proportions of "boost" to existing furnace designs is unlikely to be beneficial, as was seen in some computational fluid dynamics CFD work carried out in this project.

It is well known that the energy efficiency of electric melting is significantly greater than that of natural gas, but this is offset by the significantly different cost of these fuels per unit of energy supplied. The monetary efficiency of natural gas is significantly higher. This is only one aspect of the economic barriers to switching to higher electricity use. All-electric melting will require significant changes to furnace design and operation and carries high investment costs and risks. Plant layout, electrical infrastructure and the supply of electricity to the plant may also present barriers to the use of high levels of electric melting depending on local conditions.

Uncertainties exist around the scope/cost of upgrading the supply to each site in the UK to facilitate full-electric melting, the size of CAPEX investment required in new furnace designs and potential changes to plant layout.

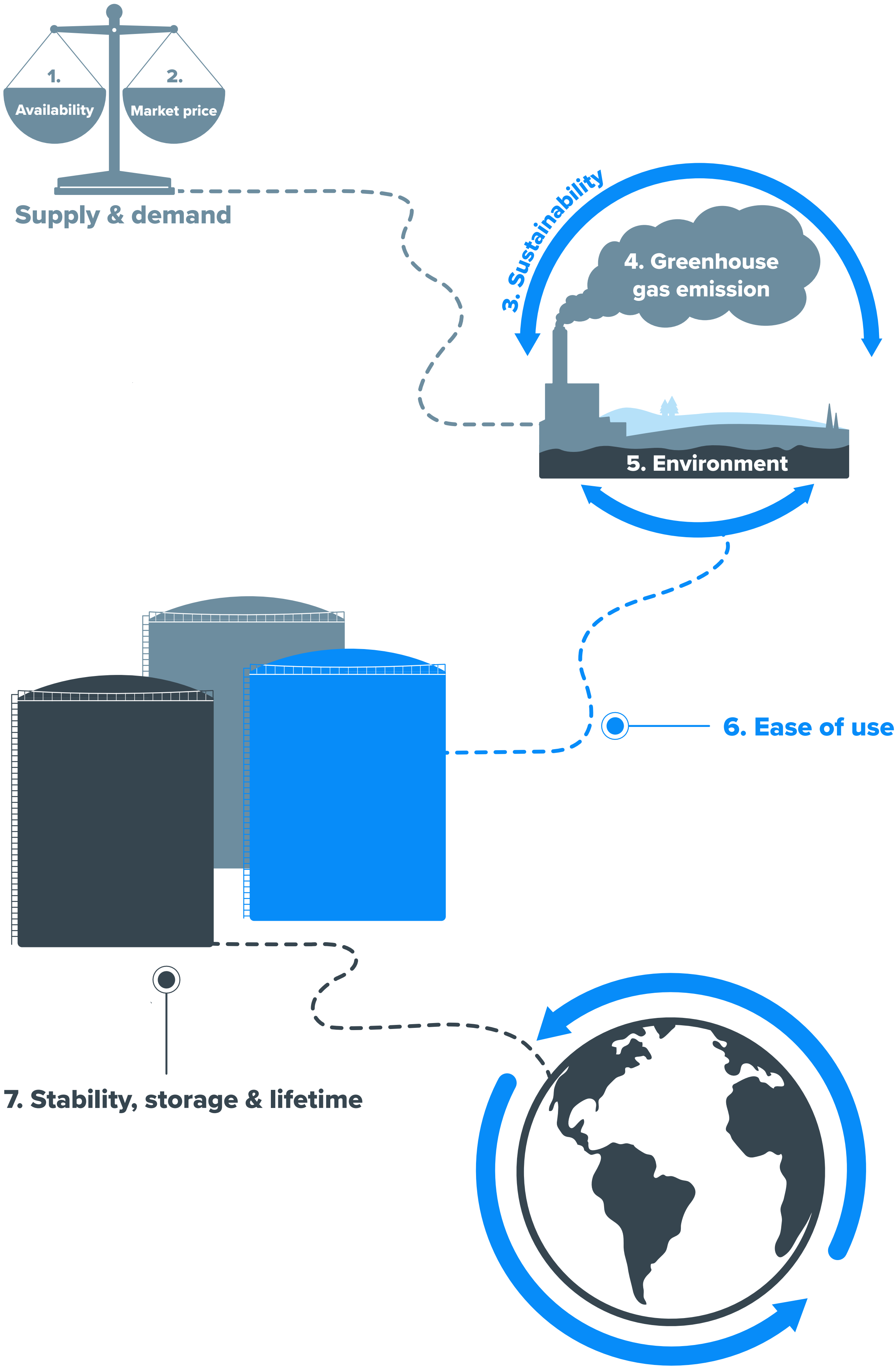


Figure 2: Overview of fuel investigation and ranking criteria

The following studies were undertaken to provide some additional insight into the application of higher electricity use:

UK electricity network impact: High-level assessment and modelling was performed to explore the feasibility and cost associated with upgrading UK sites to enable 100% electric melting. This modelling looked at the grid connection costs, potential electricity network reinforcement costs, and the possibility of flexibility in electricity usage to take advantage of Demand Side Response opportunities to reduce fuel/ connection costs.

Scoping of typical flue gas composition: This desk study looked to assess CO_2 emissions from all electric melters and their applicability to Carbon Capture (Utilisation) and Storage (CCUS).

3.1.4 Hybrid Scenarios including Economic Modelling

Findings from the above studies were combined with site audits for most major UK glass production facilities to develop further detail on the economic and hybrid fuel scenarios that are likely to be the most attractive to the UK glass industry when considering the technical and economic feasibility of combinations of low carbon fuels.

Economic modelling to build an understanding of the costs of fuel switching in the sector: Sites were individually modelled from present day to 2100 to develop some of the likely scenarios and costings for individual sites to switch to low carbon fuels. In particular, emphasis was placed on scenarios involving conversion to low carbon fuels prior to 2035 that were likely to ensure a realistic approach to scenario mapping.

Modelling of large-scale "super-boosting" melting: A modelling exercise to understand the implications of retrofitting a significant amount of electrical boost to currently installed furnaces was carried out, highlighting some of the limits of adding additional melting capacity to the currently installed furnaces across the UK.

Dynamic fuel-switching capacity: During site visits, the infrastructure and control systems of plants were assessed to understand the opportunity to switch fuels dynamically. Conversations were also held with several manufacturers to assess their approach towards full switching vs hybrid switching scenarios, highlighting the opportunities to make use of low carbon fuels as a transition fuel as opposed to a complete instantaneous replacement.

3.2 Overview of Additional Work

As part of the programme several other activities were undertaken:

- **Emissions data** from Combustion Test Bed (CTB) trials was used to identify different challenges for different CCUS technologies at scale.
- **Review of industry roadmaps** to build a more detailed understanding of what work has been previously undertaken into alternative, low carbon fuels for the glass sector.
- **Dissemination** at a number of conferences (regional, national, and international) as well as with glass manufacturers and other relevant adjacent sectors to enhance knowledge sharing.

3.3 An increasing interest in Industrial Fuel Switching

The unexpected emergence of COVID-19 in the UK in early 2020 caused a huge amount of disruption to global supply chains and industrial confidence, especially through the first 12 months of the IFS-P3 programme. This was fuelled by a highly volatile consumer market which left large scale industrial installations looking at reduced demand and fears of jobs losses. However, as the global economy rebounded the impacts of pent up consumer demand on international supply chains had significantly increased the cost of natural gas. In late 2021, with planned UK government investment in hydrogen infrastructure and a highly successful January biofuel trial at Encirc Derrylin (Northern Ireland), Glass Futures received a large amount of interest from across the foundation industries in the work being carried out.

Despite an early 2022 market rebound, events in Ukraine and the impacts of global sanctions/ commitments to move away from Russian fossil-based energy have caused a frenetic interest in industrial fuel switching. The cost of energy and alternatives to natural gas is likely the number one priority for directors, shareholders and operators of glass manufacturing sites around the world, particularly within Europe.

Given one of the key drivers for long-term investments is based around certainty in costs and prices, the context of this work becomes vital. One thing seems certain, in the current world of industrial fuel switching, **industry is genuinely looking to move as soon as possible**, both for cost and long-term security. If sustainable fuels can be made economically competitive, the industry will not need to be pushed to switch, it will transition willingly to ensure future energy security.

4. Body of Work

4.1 Laboratory Scale Glass Melting Experiments

4.1.1 Objectives of Study and Experimental Design

At the outset of the study, a primary industrial concern was that combustion atmospheres (particularly those with a high water vapour content) might have a negative impact on glass foaming (both generation and stability). The impact of glass foaming in full scale manufacturing can compromise glass chemistry, quality and efficiency, controlling foaming characteristics of melts is therefore vitally important to the commercial glass manufacturing process.

Two laboratory experiments were performed to study foam generation and foam stability.

- **HTMOS-EGA (High Temperature Melting Observation System with Evolved Gas Analysis) trials** in which glass batches were melted at a defined heating rate in a controlled atmosphere from room temperature up to melting temperature. During heating, the melting, fining and foaming processes of the batch and glass melt were video recorded together with measurement of the released gases as a function of time and temperature (Figure 3).
- **Foam stability trials** in which glass batches were heated to a target temperature then the presence of foam was monitored (video recorded) for a defined period of time. After this time variations in the atmosphere were made whilst monitoring the impact of the atmosphere composition in foam thickness.

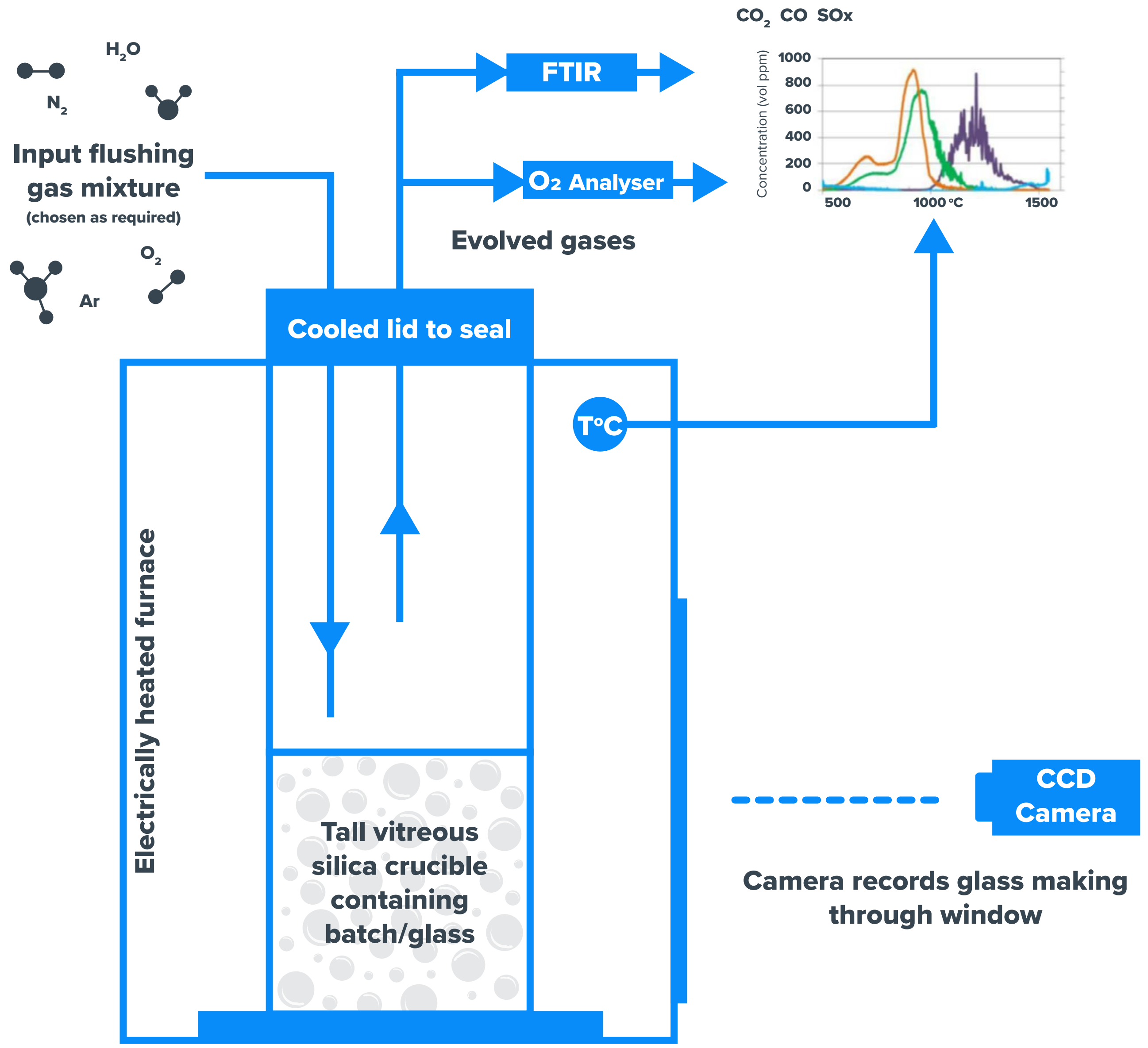


Figure 3: Schematics of HTMOS-EGA setup

4.1.2 Conclusions and Next Steps

The experiments support the hypothesis that water presence in the furnace atmosphere may affect the production process. The HTMOS-EGA results suggest that secondary foaming is likely to be increased under hydrogen combustion, and that modifications to sodium sulphate levels and/or reducing agents in the batch may be necessary to limit the extent of both primary and secondary foaming.

The key challenge with these experiments is that the laboratory scale results we see are often not replicated in full scale production, therefore commercial manufacturers need to see further evidence to have confidence in the experimental results.

Consequently, further investigation is required to assess the effects of hydrogen on industrial-scale glass furnaces, for which the Glass Futures St Helens pilot plant, due to be commissioned in 2023, will be an excellent opportunity to answer these questions without putting any commercial production at risk.

4.2 Oxy-hydrogen Combustion Trials

4.2.1 Objectives of Study and Experimental Design

The combustion of fuel (typically natural gas) using oxygen instead of air is well known within the glass industry, especially within the container sector. The burners used for “oxy-firing” are very different from those used in the more commonly found “gas and air” furnaces. The characteristics of hydrogen were therefore expected to require the development of specific burner designs, especially of oxy-hydrogen combustion.

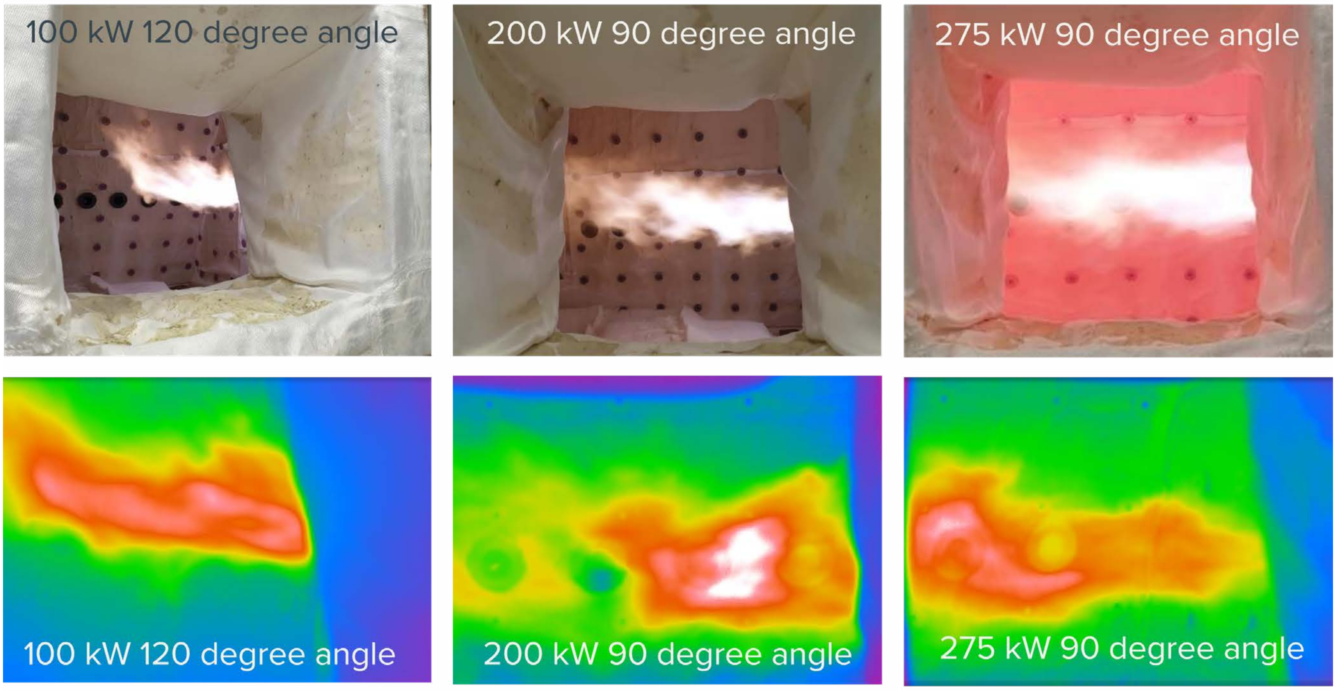


Figure 4: Oxygen - hydrogen combustion at three energy levels

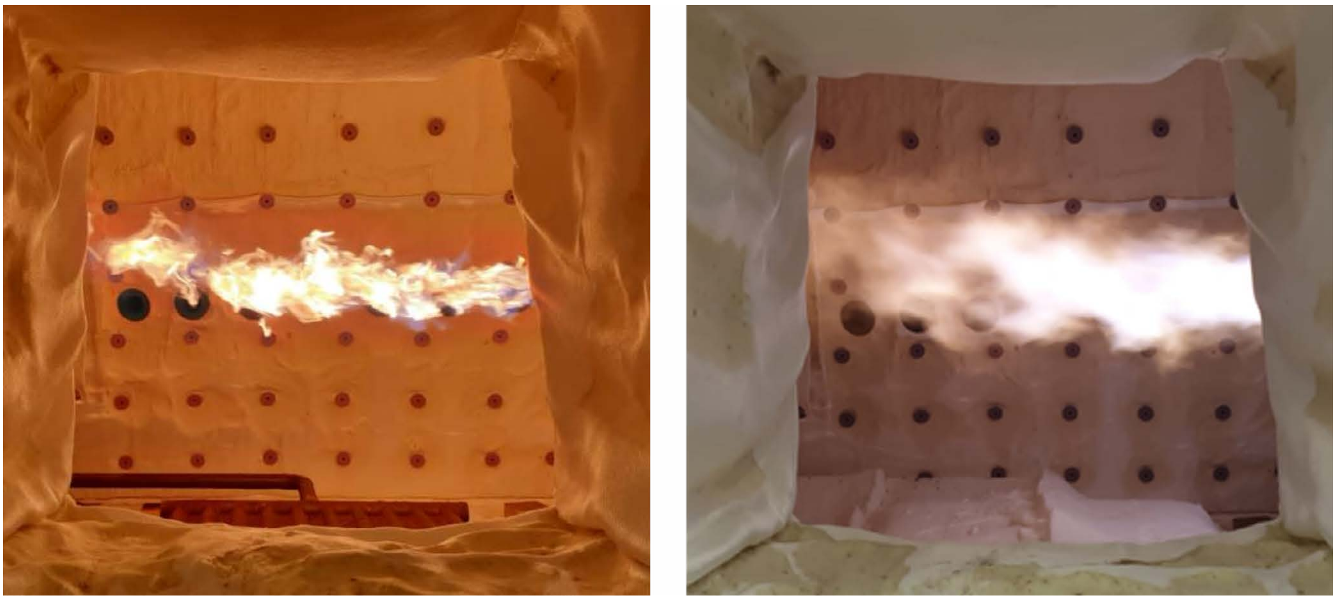


Figure 5: Natural gas flame (left) and hydrogen flame (right) at 200 kW

During March 2021, Glass Futures commissioned a series of oxy-hydrogen combustion studies utilising

275 kW burners (provided by Linde and Flammatec) under development for commercial applications to assess how the emissivity of the hydrogen flame can be optimised compared to pure natural gas, including optimisation of the hydrogen:natural gas ratio, burner design, and use of additives.

To investigate if the radiative heat transfer could be improved by adding a carbon-containing component to hydrogen; propane, methane and CO_2 were added to hydrogen while keeping the thermal input and the air-fuel ratio constant.

4.2.2 Conclusions and Next Steps

Preliminary tests performed revealed that the heat distribution and heat transfer of the burners can potentially be improved by changing the nozzle position within the burner block. In order to tackle unwanted NO_x formation, management of furnace pressure and hydrogen purity could significantly reduce the potential for NO_x formation.

The results show that both burners have similar heat transfer to the cooling floors. Generally, no large differences between the NO_x emission of the two burners in development was observed.

The tests and measurements performed in this study showed that both of the “pipe-in-pipe” burners were likely to be effective for oxy-hydrogen combustion on an industrial scale.

The use of oxy-hydrogen combustion at scale is seen as a route to transitioning to combustion with low carbon fuels. Glass Futures is well positioned to fulfil this testing at the end of 2023 by utilising its St Helens pilot plant currently under construction to develop burners to achieve more desirable flame shape and heat transfer characteristics.

4.3 Combustion Test Bed (CTB) Trials

4.3.1 Objectives of Study and Experimental Design

One of the key parts of the project was a set of Combustion Test Bed (CTB) trials which took place on a Glass Futures developed 350kW furnace. The following fuels were investigated:

- Natural gas (NG), used as the gaseous baseline
- Red diesel, used as the liquid baseline
- Used Cooking Oil Methyl Ester (UCOME, pure)
- Used Cooking Oil (UCO, pure)
- Rapeseed Oil (RSO, pure)
- Hydrogenated Vegetable Oil (HVO, pure)
- Hydrogen (Both 100% hydrogen and a 20/80 vol/vol ratio of hydrogen/natural gas)

The aim of the trials was to investigate different performance aspects to characterise the fuels and determine their potential use as low carbon fuels for glass melting.

4.3.1.1 CTB rig design and instrumentation

The CTB is based on the design of an end-fired regenerative container glass furnace and is capable of heating incoming air up to 1050°C to simulate preheated air. This air preheat is similar to that found in real furnaces. This furnace is not designed to produce glass but instead the hearth comprises a series of

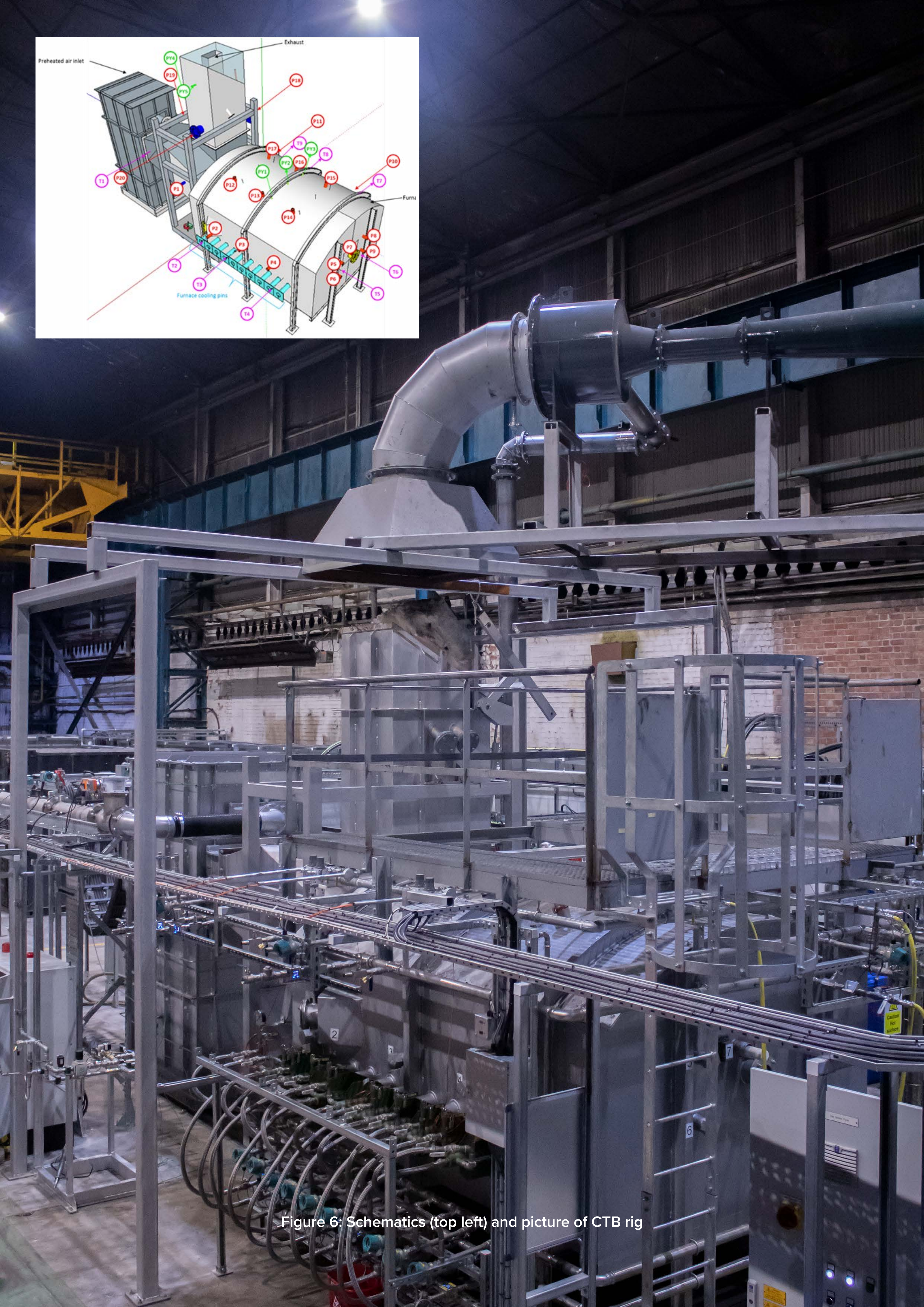


Figure 6: Schematics (top left) and picture of CTB rig

the water-cooled pins under a refractory wool blanket. Heat flux is calculated by measuring water flow and temperature rise through each pin and facilitates comparison of heat flux and flux profile along the hearth to be able to compare different combustion characteristics such as fuel type, air/fuel ratio, burner settings, etc.

Key combustion aspects of the fuels were monitored and recorded and a current picture of the furnace inc. schematics showing test ports is visible in Figure 6.

4.3.1.2 HAZOP study and learnings

A Hazard and Operability (HAZOP) study was carried out prior to the operation of the CTB. During this study a number of key learnings were gained, such as the safe approaches for identifying ATEX (abbreviation referring to the two European Directives which control explosive atmospheres) classifications when looking at low pressure hydrogen systems. Importantly: It is uncommon for gas systems used within the glass industry to be ATEX rated and as such, learnings from this activity have allowed Glass Futures to feedback key design considerations for hydrogen systems in industrial settings.

4.3.1.3 Experimental plan

Glass Futures selected natural gas and red diesel to provide baseline data. Energy input (based on net calorific value) was set at 250kW which resulted in CTB combustion chamber temperatures similar to those found in real furnaces (~ 1450'C). Air/fuel ratio was controlled to achieve 1.5% oxygen (1.5% O_2 vol% "wet") in the exhaust gas port. Glass Futures then planned a programme of works to test these alternative low carbon fuels as listed in section 4.3.1 to test against the baseline data.

4.3.2 Conclusions and Next Steps

The heat transfer to the hearth was calculated from measurements of water flow and temperature rise to each pin. These results, shown in Figure 7, were normalised to show natural gas (NG) at 100% and serve as a useful screening tool. The performance of the natural gas with hydrogen blend (80/20 vol%) proved to be better than that of natural gas, showing the blend that the UK Government is planning to inject in the national grid could have a positive impact on heat transfer. There are however several other factors to consider that were not tested including the long-term impact on refractories, impact on batch chemistry, glass quality and furnace atmosphere, etc.

As expected, the liquid based fuels showed good performance, with heat transfer 8-10% higher than natural gas, on average. If the economics of using these biofuels could be improved they might provide a good route towards lower carbon glassmaking without significantly affecting current operational practices and allow time for the development of other decarbonising technologies.

Hydrogen showed the best performance in terms of heat transfer to the hearth; Glass Futures believe this is due to water being highly thermally radiative and thus imparting more heat into the cooling pins. As the CTB experiments were a combustion test these early indications are positive however, further work is needed on the effects of hydrogen combustion on the glass melting process and on refractories.

One key issue found during the trials is the fact that the NO_x levels produced by the majority of these fuels are quite high, therefore NO_x control and/or mitigation will have to be investigated and implemented.

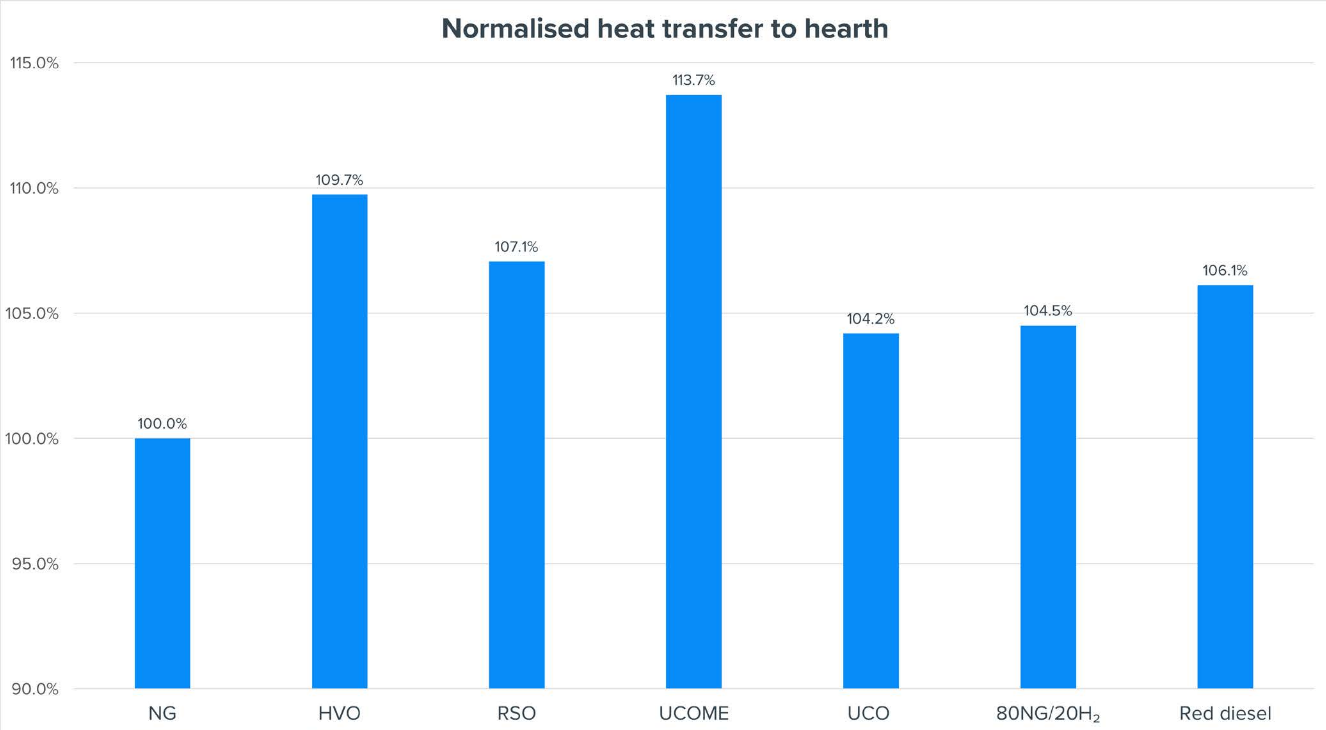


Figure 7: Normalised heat transfer to the CTB hearth for each fuel

Previous work on burner developments using the CTB and CFD modelling have been proven to be scalable up to full-size furnaces. All the fuels tested in the current programme showed good potential to substitute natural gas in order to enable the decarbonisation of the glass sector and other similar foundation industries. Next recommended steps are to investigate the performance of lower-grade low carbon fuels and simulate different combustion scenarios such as the ceramic or the steel configurations as a screening exercise as well as investigate the effects of these fuels on other aspects such as furnace atmosphere, impact on refractories, glass chemistry, etc.

4.4 Hydrogen Combustion in Industrial Forehearths (Desk Study)

A forehearth is a refractory channel and superstructure arrangement which allows for controlled heating and/or cooling of the glass leaving the furnace to achieve the target glass temperature required by the forming process. There are significantly more (~80) forehearths in the UK than there are furnaces (~20). Combustion conditions in forehearths are significantly different from those found in the main furnace.

Almost all of these forehearths currently utilise **premixed** natural gas and air combustion whereby this mixture moves through circa 10m of pipeline before coming to the combustion chamber. These systems contain no UV flame detection due to operating temperatures of circa 1200°C (above auto-ignition temperatures) and contain no flashback arrestors due to the long standing history of utilising this method safely in installations all around the world. **On this basis, the introduction of this gas blend could potentially make every single installed container manufacturing line an explosion hazard, representing a major risk.**

The use of a 20% hydrogen blend within the natural gas grid represents a huge risk to the industry, potentially rendering up to £90m of capital equipment redundant. In the event of a hydrogen blend being introduced into the gas main network that created an unsafe condition for these firing systems, a conservative estimate of the rectification cost to industry is outlined in Figure 8.

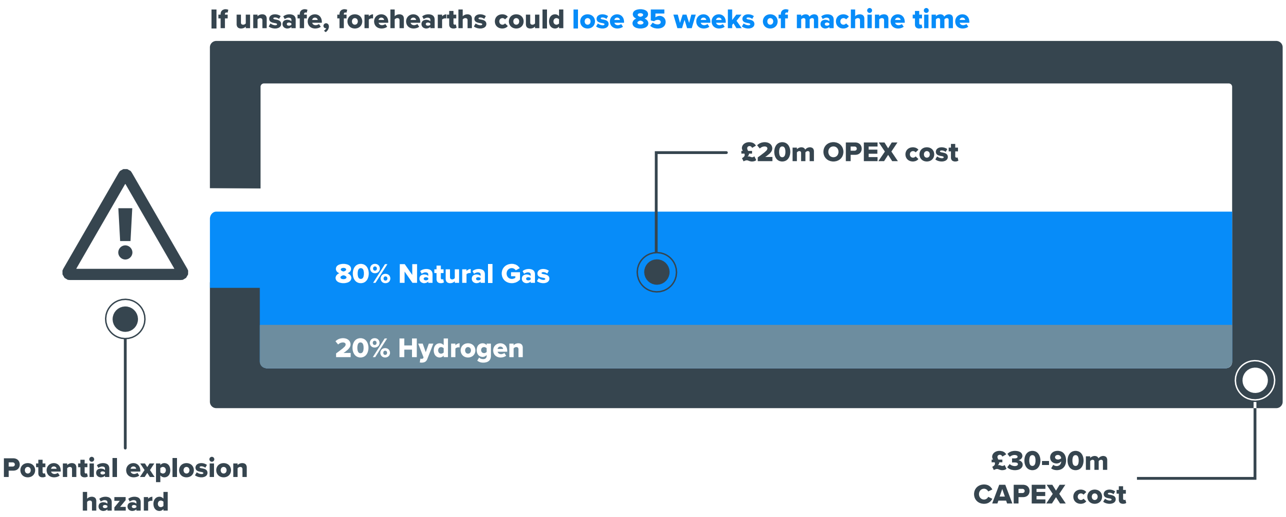


Figure 8: The impact that a hydrogen blend would have on the industrial glass sector if the blend is unsafe for use in forehearths

In addition to its financial considerations, a 20% hydrogen blend could also cause supply chain disruptions if this is done outside of planned maintenance times. For example, if the industry is forced to accommodate a blended mixture outside of planned downtime with all plants needing to carry out works at the same time, there would be a significant drop in supply of glass containers within the UK.

Glass Futures has estimated that if all sites were forced to make a simultaneous transition to a 20% hydrogen blend, UK glass output would reduce by 2% with the associated 85 weeks of lost machine time.

If all UK sites had to upgrade their combustion systems simultaneously, there could potentially be huge delays caused by equipment supply issues which may take plants offline for significantly more downtime than is currently estimated. This is due to the long lead times and relatively small supply chain able to provide the specialist equipment used.

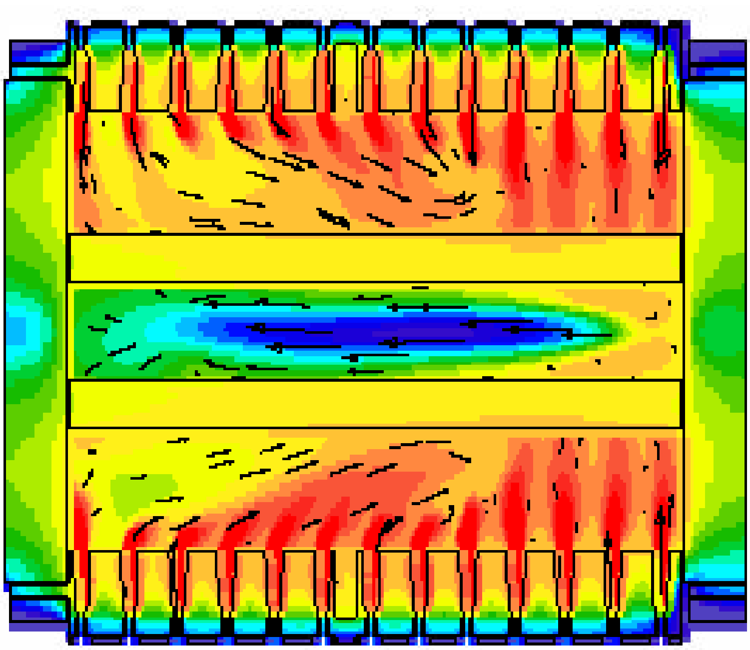


Figure 9: Modelling of glass forehearth combustion conditions

Figure 10: Glass Futures staff present during biofuel firing tests at Encirc, Derrylin, Northern Ireland

4.5 Industrial-scale Biofuel Trials

4.5.1 Introduction

Biofuels were identified within the industry as a good alternative fuel to trial at a large industrial scale during the IFS3 programme; in particular, their relative ease of use and availability made them attractive

In that context, the concept was to prove this fuel type on a container furnace initially, then moving to a float glass furnace (moving up in scale and risk profile through the programme). During both trials, Glass Futures supported sites with technical advice, procurement support and dissemination to enable a successful trial and to ensure that learnings could be shared across industry.

Whilst there were some nuanced differences between the programmes, both industrial trials carried out largely followed the same principles and objectives:

- Furnace throughput (pull rate) would be maintained throughout the trial
- The amount and distribution of electric boosting would be kept constant unless glass quality deteriorated
- The total (net) energy input from natural gas and/or biofuel would be maintained
- The transition to biofuel would be via changing out natural gas burners for "oil" burners in a controlled fashion
- Subject to continuing normal furnace operational and glass quality targets, the trial would continue for a reasonable time to enable good quality results to be obtained
    - Normal operating parameters tracked were mainly superstructure and glass temperatures, NO_x and SO_x
    - Glass quality parameters focused on defect counts (mainly "seeds' - small bubbles) and glass colour (e.g., dominant wavelength)

4.5.2 Container Glass plant: Encirc, Derrylin, Northern Ireland

4.5.2.1 Purpose and Objectives

Sourcing, storing and equipment modifications provided some key learnings (which were subsequently shared with NSG Pilkington) and were useful for the float glass trial. Sampling and testing procedures were established to ensure the fuel met specifications for consistency, heating value and to monitor potential contaminants.

Several upgrades, checks and adjustments were performed to the existing oil installation prior to the testing:

- The existing heavy fuel oil (HFO) storage tanks and heating system were upgraded to store the full trial fuel supply required
- Fuel supply lines, control systems and burner equipment used for HFO had to be upgraded or replaced to accommodate the differences in characteristics of the biofuel compared to the HFO
- Stack testing was carried out before and during the trial to ensure compliance
- A derogation from the local authority was secured prior to the trial in case of any deviation in stack

emissions during the trial
- The fuel supply system (from storage tanks to the burners) was upgraded as necessary to provide consistent leak-free operation. Specialised burners were installed to accommodate the biofuel
- The control system was reviewed and modified to enable switching from natural gas to biofuel
- Trial execution had a few minor challenges around fuel transport to the furnaces

4.5.2.2 Results and Findings

The trial achieved all the goals set beforehand with the trial totalling in excess of 2 weeks of full operations melting over 300 tonnes per day of glass for the duration of the trial:

- All operations were safely carried out in accordance with Encirc's established operating procedures with no safety issues recorded.
- CO_2 from fuel was decreased by up to 80% compared to using natural gas[1].
- Output and glass quality were maintained.
- Stack emissions were within normal levels

4.5.3 Float Glass Plant: NSG Pilkington, St Helens

4.5.2.3 Purpose and Objectives

Following successful trials at Encirc, the next logical step to demonstrate industrial applicability of biofuels was to demonstrate a long-term trial on a glass site manufacturing float glass. Proving this technology on a float glass furnace means that all aspects of the glass manufacturing process, including the largest scale, have successfully demonstrated the use of biofuels at a TRL 9 level.

Figure 11: biofuel firing picture taken with endoscopic water-cooled furnace camera at NSG Pilkington, St Helens

1 The Derrylin site conducts its operations under the UK ETS system, and as such calculates and accounts for its GHG emissions.

Given that at the beginning of the process this had never been performed, to achieve demonstration on this scale and within this time frame shows the ability for the industry to adopt this option in a short time period.

A similar approach was taken utilising the learnings from the Encirc Derrylin Trial. Procurement proved to be troublesome (due to rising and uncertain energy costs) and the trial required some infrastructure upgrades and some maintenance of older equipment on site, but proved to be very similar to the Encirc trial in terms of the overall challenges and planning required for the site.

4.5.2.4 Results and Findings

Flame length remained acceptable throughout the trial and heat release across the furnace width appeared similar to standard oil. The crown temperatures were largely steady during the trial apart from the first few hours during which the oil flow rates were increased due to the lower fuel CV.

The biofuel trial continued for over 3 days in total, melting in excess of 600Tpd of glass before the trial was considered complete, during which the glass quality remained steady with only a small increase in fine bubbles seen related to the initial loss in temperature.

4.5.3 Conclusions and Next Steps

Using biofuels is likely to be an attractive option for most glassmakers provided the cost per tonne of good glass produced does not increase significantly. It is therefore plausible to switch from natural gas to biofuels as it has been shown to have no deleterious effects on glass quality or throughput. In particular, there appears to be no major changes to furnace design or (mainly refractory) materials used and it may only need minimal changes to batch composition (mainly refining agents).

This trial also showed the wide applicability of biofuel across a smaller container furnace and a large scale float furnace proving that as a drop-in fuel, there is a wide range of opportunities available to glass makers today.

For most glass manufacturers, whilst this is a new fuel group, the technology and engineering required for conversion is readily available. However, more investigations are needed to identify the effect of variations in fuel composition and properties. This is especially true if fuel blends or fuels are sourced from different sites/suppliers, and in particular, the effects of any potential contaminants on:

- Glass quality (especially colour)
- Refractory wear
- Stack emissions

Overall, the interest and positive results of these trials show good promise for the use of biofuels within the glass industry. The main barrier to the adoption of biofuels is likely to be due to economic rather than technical considerations. While not in the scope of this study, the impacts of supply and demand in competition with other sector must be considered.

4.6 Furnace Modelling and Super-boosting

Computational Fluid Dynamics (CFD) models are widely used within the glass industry to support operational improvement and facilitate furnace design. The Encirc container furnace which undertook the biofuel trial was modelled using an industry-standard CFD model for biofuel, increased electric boosting and “super-boosting” and the results were compared to the standard natural gas/electric boost “standard” operations.

The CFD models for “standard” natural gas and biofuel operation were in good agreement with actual practice. The results for increasing the amount of melting energy provided by electric boost suggests that there is a limit to how much energy can be supplied directly to the melt before the required convection currents are lost. Loss of this mechanism of transferring energy throughout the melt is likely to have serious effects on glass quality.

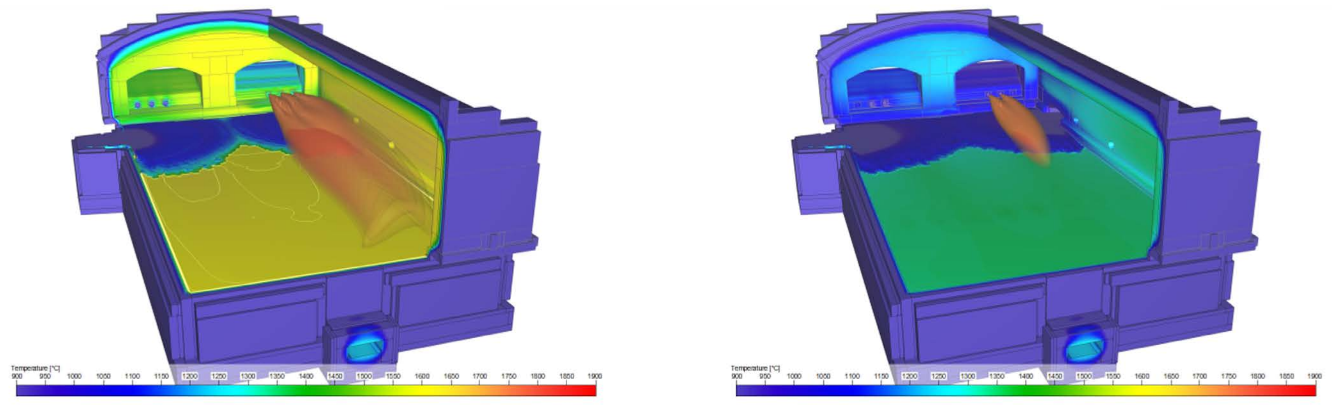


Figure 12: CFD results for super-boosted furnace (right) vs standard furnace (left)

Increasing the proportion of electric melting and decreasing “top fire” decreases the efficiency of the regenerator (heat recovery) system. **It is likely that the amount of additional heating from electric boost in this type of (container glass) furnace will be limited to 20-40%.** While this is a high percentage compared to other high temperature industrial heat, this further electric heating will require significant changes to furnace operation and a move towards “hybrid” melting is considered to be a plausible route to the use of low carbon fuels as an interim step (e.g., oxy-firing, restriction of regenerators and/or addition of recuperators).

Using high levels of electric melting (above 40%) will require redesign and replacement of the furnace and is highly unlikely to be achievable on existing furnaces.

4.7 Use of hydrogen on industrial sites

The potential risks involved in using hydrogen at commercial-scale were reviewed to provide a greater understanding of the issues involved to integrate hydrogen into the industrial processes.

Hydrogen leaks are difficult to detect and could increase the risk of explosions so it is important to carry out a full risk assessment and to implement ATEX ratings as appropriate to ensure the safety of personnel and plant. Additionally, the potential for hydrogen to damage metal pipework through hydrogen embrittlement is a further concern if the delivery of the hydrogen is at high pressure, as this means that existing pipework used for natural gas might need replacing which will increase costs of deployment.

4.7.1 Hydrogen delivery to site

The selection of hydrogen delivery by pressurised container or pipeline will depend on the location of the site and volume of gas required. The generation of hydrogen on site by electrolysis is possible, but depends on the availability and cost of electricity. This option may be attractive if the direct use of electricity in the furnace is restricted. Supply by pipelines may not be possible so some sites may require hydrogen to be delivered in containers, even though that is more expensive.

The UK Government's strategy of putting hydrogen into the natural gas mains grid will also have an impact on hydrogen distribution and use. By 2030 it is predicted that the hydrogen pipeline network will be tens of kilometres in length and serve multiple end use applications [UK Hydrogen Strategy, 2021].

4.7.2 Site considerations

Each site must be evaluated based on a number of factors including the potential challenges to upgrading specific parts of the glass furnace/utilities, various health/safety measures, and upgrade costs. The focus of the analysis will be the impact of three key parameters (furnace, forehearths and boiler system) on the above criteria.

4.7.3 Indirect costs and concerns

Non-monetary costs include the time taken for a hydrogen project and the number of staff required to work on the project. Whether existing staff need to be taken out of regular production to support this work or additional contractors need to be hired will also have an impact. With the possible changes to the zoning, health and safety, various specific procedures and even working culture, additional training will be required to work on the sites when hydrogen is incorporated. The increased safety concerns of the site may also require more rigorous maintenance processes which could have an impact on production schedules if it is necessary to stop production. If on-site hydrogen storage is required, then the additional space required for this will need to be considered on the site as well as the impact it will have to existing facilities and operation.

4.7.4 Conclusion

The CAPEX costs and return on investment (ROI) for plant and equipment to use a range of hydrogen/natural gas mixes (up to 100% hydrogen) can be estimated subject to the usual caveats. The major unknown in doing this is the unpredictability of hydrogen and natural gas costs. UK Government policies will shape the decision making process and long term commitments will enable glass manufacturers to invest with greater confidence.

4.8 Fuels Sustainability Assessment

4.8.1 Alternative Fuels Potential

Work was conducted to evaluate the sustainability of alternative fuels potentially used in the glass manufacturing industry. This provided a high level review of some of the impacts of these fuels on the environment (air, water, land) and their resource use (water use, supply chains).

The report produced a graph of anticipated carbon intensity of these alternative fuels when compared to the natural gas baseline case (Figure 13). Although the UK's Net Zero commitments are expected to decrease the carbon intensity of both electricity and hydrogen from grid electrolysis, the exact rate of decarbonisation is not clear, but the figure gives an estimate based on the current best available data.

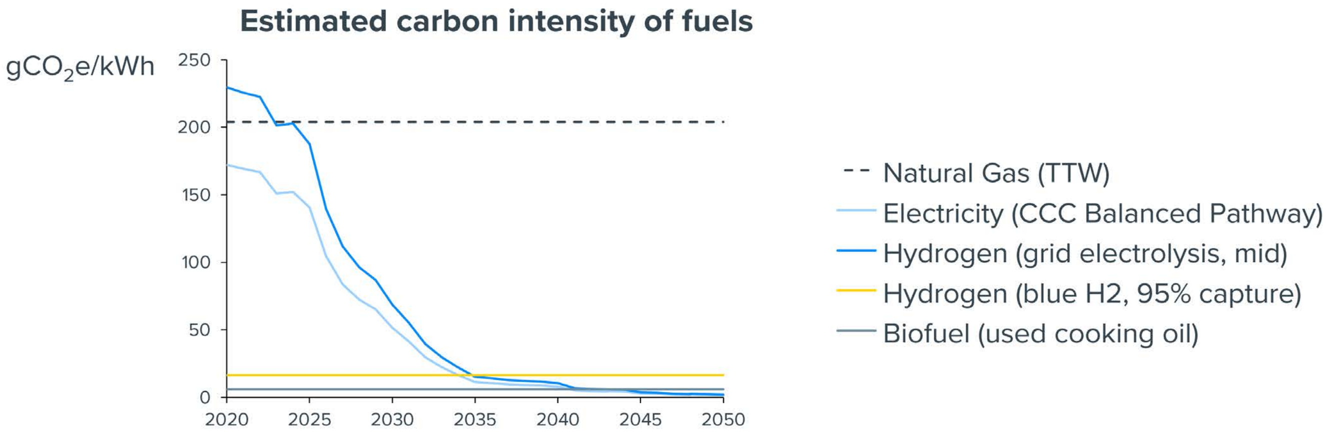


Figure 13: Estimated carbon intensities of selected fuel options (note that the efficiency of each fuel for the use in the glass manufacturing industry is different). TTW signifies tank-to-wheel, or where the energy is absorbed to the point of discharge

4.8.2 Fuels Availability

Within a typical supply and demand cycle, the UK glass sector could potentially have a large impact on UK biofuel use and production if it were to become an active consumer, bringing on-line a large demand in a short period of time. As such the fuels are considered as available, but not readily for a total switch to biofuels.

The UK consumed 2,535 million litres of liquid biofuels for transport in 2019 and 1,268 million litres in 2020 [Department for Transport (DfT), 2021]. In all future scenarios highlighted by the DfT, there will be a drop in the demand of biofuels due to increased electrification of motor vehicles. The declining long term use of bio-oils represents an opportunity for the glass industry to generate a fresh market demand where the current transport market is reduced.

Based on current operations, and an overall furnace gas consumption of circa 5.2TWh/y, the UK industry switch to 100% to biofuels would use in the region of 600 million litres of liquid fuels. Biofuels are seen as a strategically important opportunity for the glass sector, but this is not considered as a "fix-all" solution.

4.9 CCUS investigations

4.9.1 Summary of Glass Industry Emissions

The glass manufacturing process emits CO_2 from the combustion of fossil fuels and the decomposition of certain raw materials within the glass batch. Figure 14 provides an indication of the typical composition (included expected CO_2 content) from a range of glass furnace scenarios.

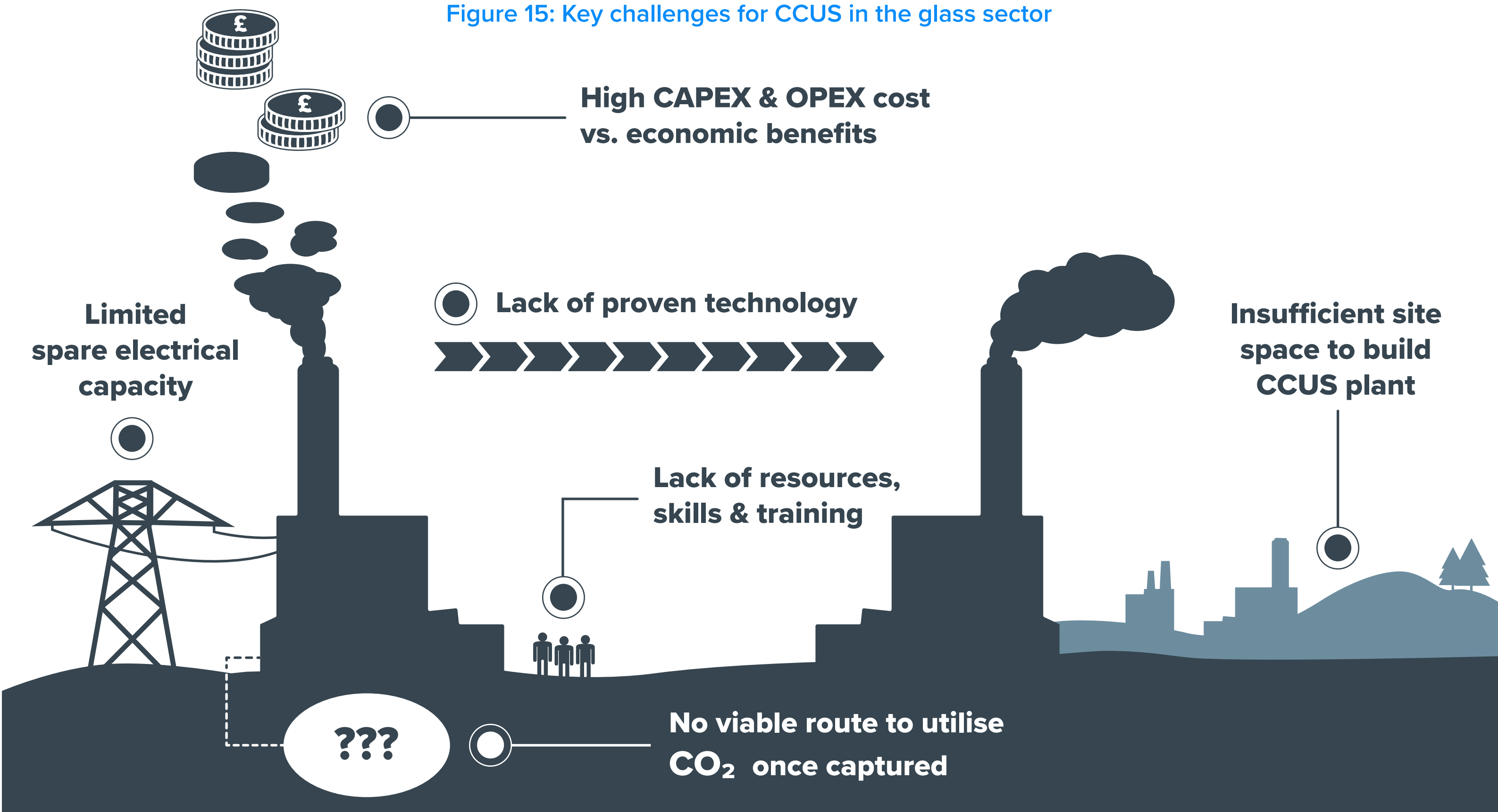
	Float		Container					
	Regenerative		Regenerative		Oxy-fuel	Hybrid (80/20)	All electric
Fuel	Natural gas	Hydrogen	Natural gas		Natural Gas	Electricity / Natural Gas	Electricity
Pull rate (tonnes/day)	700	700	800	350	350	350	540
Abatement	EP SCR	EP SCR	EP SCR	BF	BF	BF	BF
Cullet (%)	30	30	50	50	50	50	50
Flue gas temp	325	325	325	180	180	180	
Vol flow at duct conditions (m^3/h)	226889	178602	175542	90771	41915	6282	dependent on extraction and filter
Water vapour (%)	8.9	32.6	8.9	6.1	11.9	11.9	
CO_2 (% of wet gas)	6.6 – 12.0	2.4	6.7 – tbc	4.5	8.7	24.2	
Oxygen %	10.9	8.1	10.9	14.1	17.2	17.2	very low
NO_x at duct (mg/m^3)	201	286	253	223	278	278	-
SO_x at duct (mg/m^3)	144	204	158	139	261	1741	very low
Dust at duct (mg/m^3)	6	8	6	6	21	139	very low
HCL at duct (mg/m^3)	7	10	6	6	10	70	very low
HF at duct (mg/m^3)	1	2	2	1	0	2	very low
CO_2 (t/d)	323	91	253	116	104	43	50

Figure 14: Typical composition (including expected CO_2 content) from a range of glass furnace scenarios. (Courtesy of M Pudner, British Glass)

4.9.2 Challenges Deploying Carbon Capture Technologies on Glass Furnaces

Although there is a wide range of carbon capture technologies available, some of which have been assessed for the glass sector, no large-scale carbon capture trials have been successfully undertaken on a glass furnace. This is due to the challenging nature of the furnace flue gases.

Figure 15: Key challenges for CCUS in the glass sector



No carbon capture technology was identified during this study which could extract CO_2 gases from glass furnace exhaust streams without experiencing significant degradation over a short time frame.

The barriers shown in Figure 15 must also be overcome if the glass industry is to adopt CCUS.

The glass industry is not incentivised to develop its own CCUS technology as it is likely to be complex and costly, especially while other routes to decarbonizing have not been explored.

4.9.3 Glass Industry Interest in CCUS

Glass Futures engaged several glass manufacturers across the industry to gauge interest in CCUS technologies. The overwhelming response was that the industry sees CCUS as an important option to consider for decarbonising their operations, but felt overwhelmed with the number of different technologies and suppliers and did not have the resources internally to build a sufficient understanding to enable them to identify the most suitable technologies to invest their limited R&D into.

As a result of these discussions, Glass Futures initiated a cross-sector, through-supply-chain research project, including involvement from BEIS, to produce a detailed summary of CCUS technologies and providers, and assess technical and economic feasibility with the intention of shortlisting the most suitable CCUS technologies. The project is supported by a number of organisations across a wide variety of supply chains and academic connections. The comprehensive and diverse nature of these supporting partners, including Encirc, Vidrala, O-I, Ardagh, and Stoelzle (container glass), as well as Guardian Glass LLC and NSG Pilkington (float glass), indicates the industry's desire to understand and develop CCUS within each sector.

Glass Futures are also engaging with glass manufacturers and CCUS developers to design the 30 tonnes per day, oxy-boosted pilot plant in St Helens to trial a range of different CCUS systems once the plant is operational in 2023/4.

In light of the successful biofuel trials undertaken within this project, there is also growing interest within the glass sector to explore whether the use of CCUS technologies on a furnace fuelled by biofuels could enable carbon-negative glass manufacturing, which could help offset process emissions from raw materials and Scope 3 emissions from supply-chains.

4.10 Network Implications of Electric Melting

Element Energy and Glass Futures assessed the impact and costs of the electrification of the electrical infrastructure connected to UK glass melting sites, as well as the broad economic impact of electric melting on the UK power network, in order to evaluate the impact of electrification of the UK glass industry at a high level.

Of the estimated 21 glass melting sites in the UK (including glass wool), only one hosts a fully electric furnace (glass wool). Full UK electrification of the sector would increase electricity requirements but reduce overall energy demands (Figure 16), due to the greater efficiency of the electric-based processes.

The report found that the overall costs for each site could be disaggregated into individual components which could be broken down broadly into 3 categories: connection costs, reinforcement costs and, connection agreement costs. High and low costs were estimated based on the required additional capacity of a glass melting site, and a rough rule of thumb was produced for how the costs typically depend on the additional installed capacity (Figure 17).

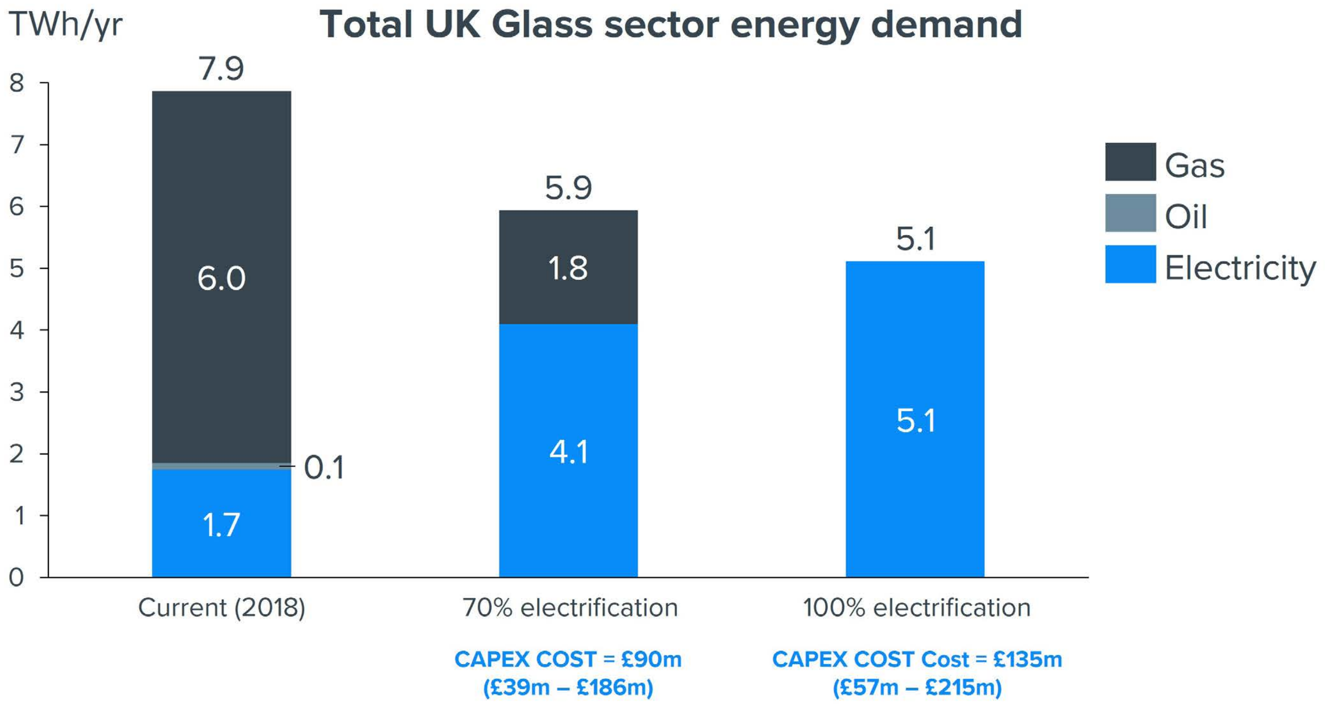


Figure 16: Current and potential annual energy demand in the UK glass sector (TWh/yr), as well as approximate expected CAPEX costs per scenario (and their potential range)

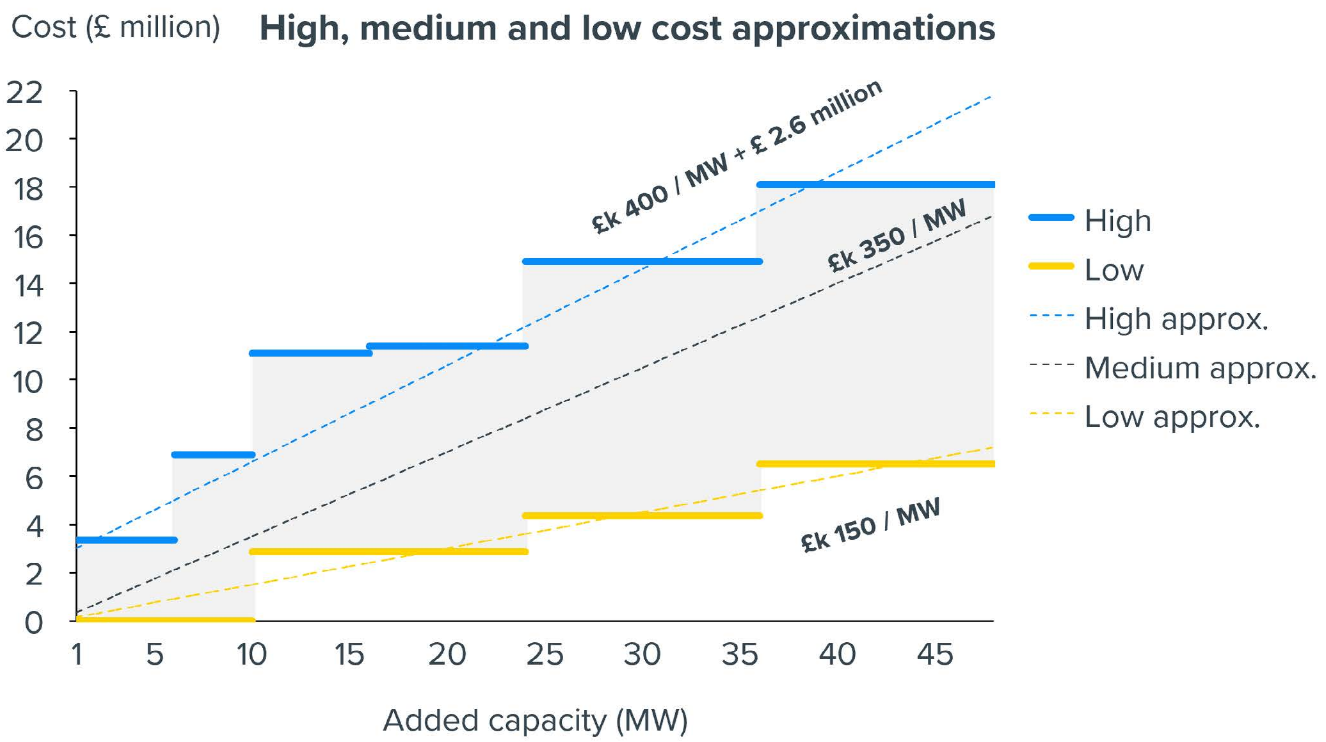


Figure 17: High, medium, and low cost approximations for installing additional electrical capacity to industrial sites based on added capacity (MW)

The average cost of a connection upgrade was found to be in the region of £350,000 per MW of added capacity with the majority of UK furnaces between 6MW and 28MW of energy demand. Although the costs of upgrades at individual sites were found to depend primarily on the amount of additional electrical capacity required by the site, a number of site-specific factors also need to be appraised through a full design analysis, giving rise to a big variance in cost.

4.11 Economic Modelling

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. Glass Futures has helped to develop a model which can be used to evaluate the economic impact of fuel switching at a particular glass manufacturing site. The model calculates the cash flow of the site over a multiyear period for scenarios with and without fuel switching, and represents the impact of manufacturing processes and overhauls of each of the site's furnaces on CAPEX spending, revenues, fuel and carbon costs.

The model has been developed for use by individual sites in different glass subsectors, including flat glass, container glass, glass wool, and continuous fibre. It allows sites to make an economic comparison of strategic choices, in particular the choice of low carbon fuel (hydrogen, electricity, biofuel or a hybrid) and the year when the site switches 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, £/tCO_2 abated) (Figure 18). Furthermore, users can explore the impact on annual cash flows for both furnace and non-furnace equipment and a variety of cost categories (Figure 19).

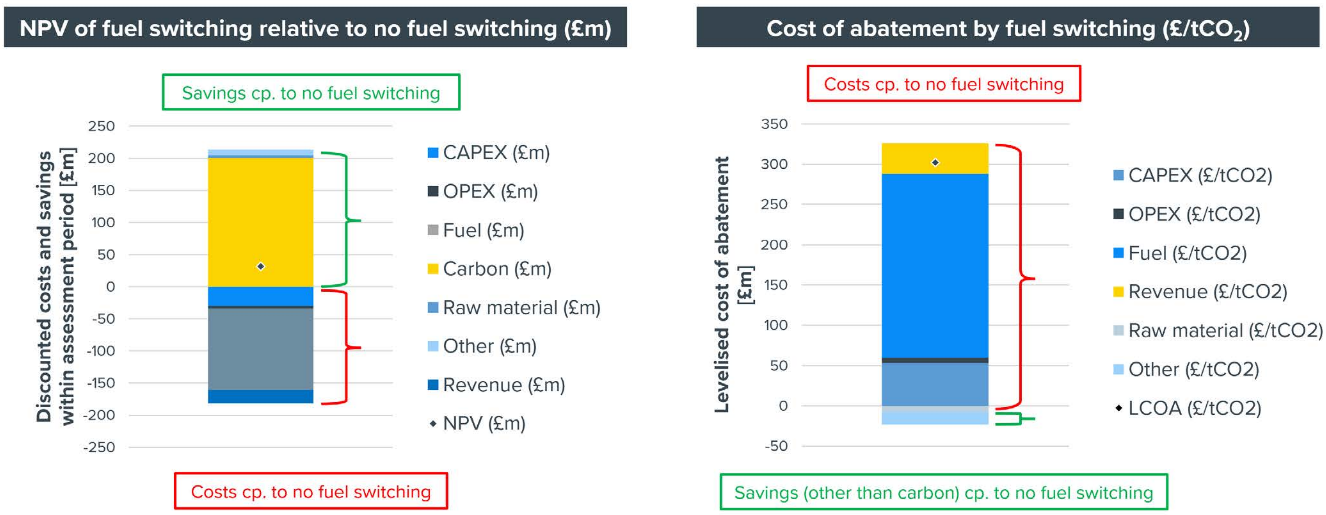


Figure 18: Typical model output showing NPV (left) and LCOA (right) of a customised fuel switching scenario for a particular glass site (illustrative example)

The model can be used to improve the understanding of fuel switching impacts based on a highly customisable scenario builder, and provides a high-level screening opportunity for glass sites at the beginning of their decarbonisation journeys. The studies show that glass decarbonisation costs will primarily originate from the higher price of low-carbon fuels when compared to relatively cheaper natural gas, with the benefits of fuel switching largely derived from the carbon savings and policy support available. The wide range of potential future fuel prices creates significant uncertainty around the optimal choice of low carbon fuel. Furthermore, the work has shown that there is not a standard solution applicable to every glass site – optimal choices e.g. on fuel and year of fuel switching will depend heavily on site location and set up.

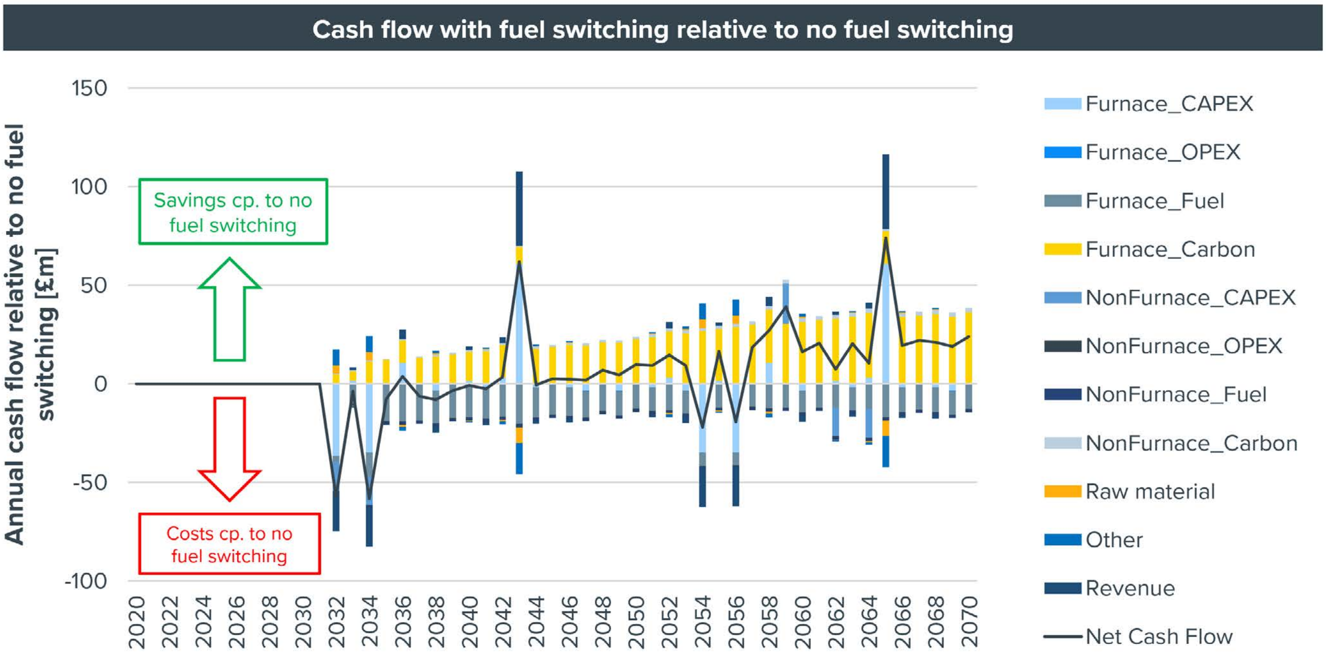


Figure 19: Annual cash flows when fuel switching relative to no fuel switching (illustrative example)

4.11.1 Engagement with Industry

Given early indications that each individual site within the UK would have a different approach to fuel switching, a number of plants were initially engaged to utilise the commercial scale biofuel trial preparations as a foundation for advanced discussions on fuel switching.

With support from the British Glass Manufacturers Confederation, all UK glass container, flat and fibre manufacturing sites were invited to an engagement session, which resulted in visits to 7 sites and online meetings with 3 others to collect information in relation to each manufacturing unit within the UK.

Around 60% of UK sites engaged directly, with a number of others choosing to only issue publicly available information due to commercial confidentiality policies of their parent organisations. Given the similarities with the manufacturing operations of these sites, a number of assumptions were made from public information, which gave Glass Futures a high degree of confidence in the outcomes.

4.11.1.1 Results and Findings

This selection resulted in an accurate database of the UK's furnaces. A low carbon fuels transition scenario was selected for each site based on collected data and assumptions on the possible costs and decision making processes that may be applied to selected years of fuel switching.

4.11.1.2 Scenario mapping a UK solution

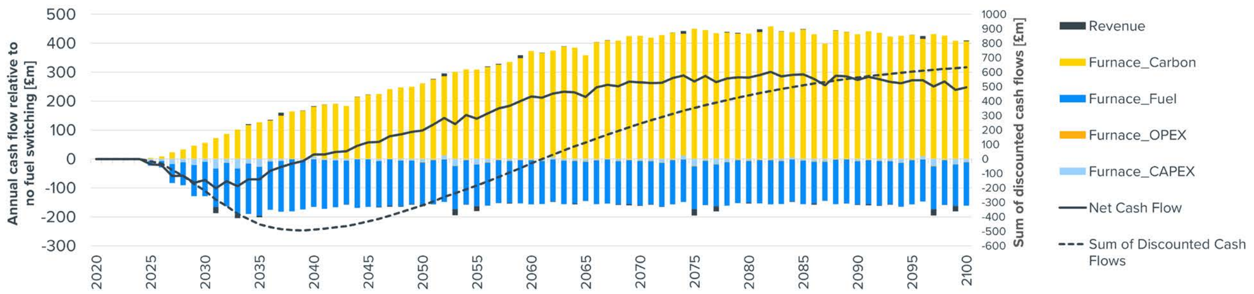
Assuming all furnaces switch between now and 2035 to low carbon options, given the early adoption, this looks at the following profile of switching on a plant by plant basis e.g. a whole site switches all furnaces to the listed low carbon fuel at or before 2035 where furnaces that are electrically boosted continue with the same level of electrical boosting:

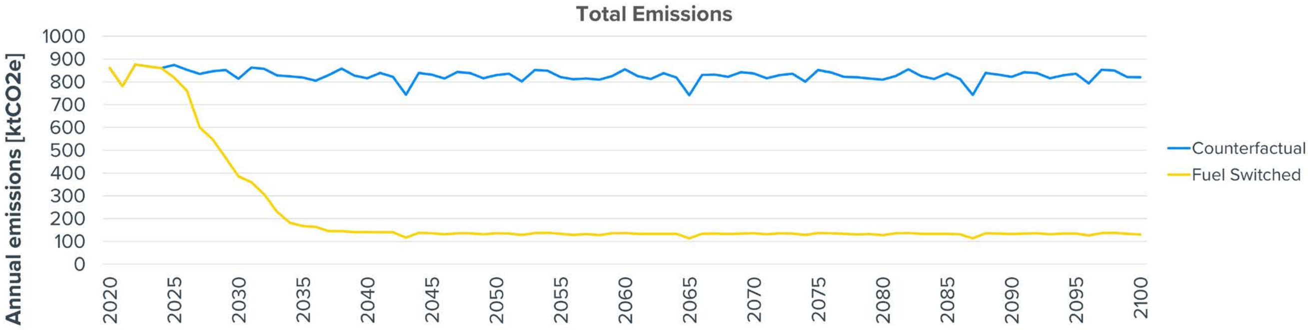
Biofuels	60%
Hydrogen	30%
All-Electric	10%

This resulted in a total investment requirement (CAPEX and OPEX) of circa £500m, **in addition to current CAPEX and OPEX commitments by 2040** (when the costs of carbon vs the costs of fuel begin to show a positive payback) before being fully repaid by circa 2060 and leading to a longer term positive NPV, this cross over point is significant as it represents the "break even" point.

This profile has been selected as an aggressive route to low carbon manufacturing as it represents industry and public policymakers working together to find economically attractive solutions that allow the current furnaces that are running to be retrofitted as low carbon, as opposed to new capital equipment which is much less attractive to industry.

It should be noted: All associated costs used energy prices in mid-2021 – so significantly lower than we see at the time of writing this report, this is significant as with lower energy prices the return on investment was already circa 30 years.





Figures 20 & 21: Estimated carbon emissions of a UK wide fuel switching scenario before 2035

4.11.2 Conclusions and Next Steps

This model does not show an industry achieving net zero carbon, as this is not possible from fuel switching alone. Two important factors are highlighted:

- The current model only allows for a single fuel-switch, which may not be accurate for some manufacturers. A multi-stage switch, such as NG -> Biofuel -> electricity could lead to lower emissions when the carbon intensity of the national electrical grid is lower later in the century
- The model does not include any on-plant CCUS or waste heat recovery (WHR) technologies,

which are likely to contribute significantly to net-zero for the industry (CCUS is included in the carbon intensity of blue hydrogen)

The key issue currently faced is that without intervention, the economically attractive option is to fuel switch as far into the future as possible under current emissions regulations. This is a major issue, however, given proof of concept of a number of different technical solutions, it is viable for the UK sector to switch sooner than 2035 but this will require major economic drivers beyond those which currently exist within the market.

The British Glass Net Zero strategy looks towards a higher uptake of all electric melting by 2050 (British Glass, 2021). On the face of it this seems like an attractive option in the long term however, the Glass Futures research carried out for IFS-P3 shows this is not likely. More research and development into new technologies will be required especially for large (>300Tpd) container and float (>650Tpd) furnaces.

The most likely case is that these furnaces will continue to burn liquid or gaseous fuels to melt glass. If a new technology base is not found by 2040, these furnaces are likely to be replaced with a similar footprint and output as the currently existing regenerative models with incremental improvements to achieve higher furnace efficiencies.

5. Dissemination and Industry Engagement

5.1 Dissemination Activities

External interest in this project has been vast, providing over 90 press and media opportunities, and garnering wider engagement from industry partners across the global glass sector (including Europe, India, Australia, USA and Japan). The project also facilitated the involvement of multiple major brands. In particular, HEINEKEN and Diageo supported the dissemination and publicity activities by providing widespread exposure to a global audience.

This culminated in the opportunity to exhibit at the United Nations 2021 Climate Change Conference, COP26, in Glasgow. Out of thousands of applications, Glass Futures secured an important opportunity to display four bottles (Figure 22) produced during the biofuel trials that were undertaken by Encirc at their Derrylin plant as part of this project (see section 4.5).

Glass Futures has also held a number of workshops to disseminate project findings from the hydrogen combustion trials, hydrogen glass melting and carbon capture technologies. In addition, Glass Futures has presented at eight international conferences to engage industry by covering fuel-switching, glass melting and CCUS technologies.

Ultimately, the vital dissemination activities performed in this project have worked to generate further interest, public knowledge and potential future opportunities to continue to advance decarbonisation efforts in the glass industry.

5.2 Industry Roadmapping Exercise

A review of existing industry roadmaps from across the globe was conducted to build a more detailed understanding of what work has been previously undertaken into alternative, low carbon fuels for the glass sector, as well as to identify their key enablers and challenges.

The review highlighted that many roadmaps identified low-carbon fuels as a key enabler to decarbonise the glass sector, however, none of the roadmaps contained any significant detail in terms of the technologies or solutions that need to be explored to deliver low carbon fuel switching. Similarly, little technical work has been reported publicly into the technical and economic feasibility of low carbon fuels.

5.3 Engagement with Other Sectors

The successful delivery of this project, coupled with the development and commissioning of the multi-fuel Combustion Test Bed, has enabled Glass Futures to secure funding to undertake research and development work with other foundation industry sectors in the following areas:

- Development of new combustion technologies to reduce NO_x emissions in the glass and steel sectors
- Experimental programmes to explore the feasibility of hydrogen and biofuels to fuel ceramic kilns
- Engagement with Cement and Steel sectors to explore CCUS technologies

Glass Futures is also in discussions with a number of other ceramics and steel manufacturers to explore how the CTB can be used to provide product validation in a hydrogen fired furnace/kiln. This ties in perfectly with the £15m Transforming Foundation Industries (TFI) funding that has been secured to build a unique open-access glass manufacturing pilot line and provides a suite of additional benefits by co-locating heavy industry decarbonisation work.

Given the complex intertwined relationships of global supply chains, all of this work has the added

Figure 22: Diageo Black & White Scotch whisky bottles and HEINEKEN beer bottles, displayed against equivalent bottles that are 90% lower carbon at COP 26, demonstrating how glass quality can be maintained when manufacturing with significantly lower carbon fuels

advantage for the glass sector of helping its supply chain to decarbonise. This is important work as a decarbonised glass sector will rely upon other materials from other industries and often other continents, to become truly net-zero carbon.

6. Conclusions and Recommendations

6.1 Conclusions

This extensive study of the options available to the glass industry within the UK have identified that there are several different key aspects that determine each manufacturing site's decision-making process.

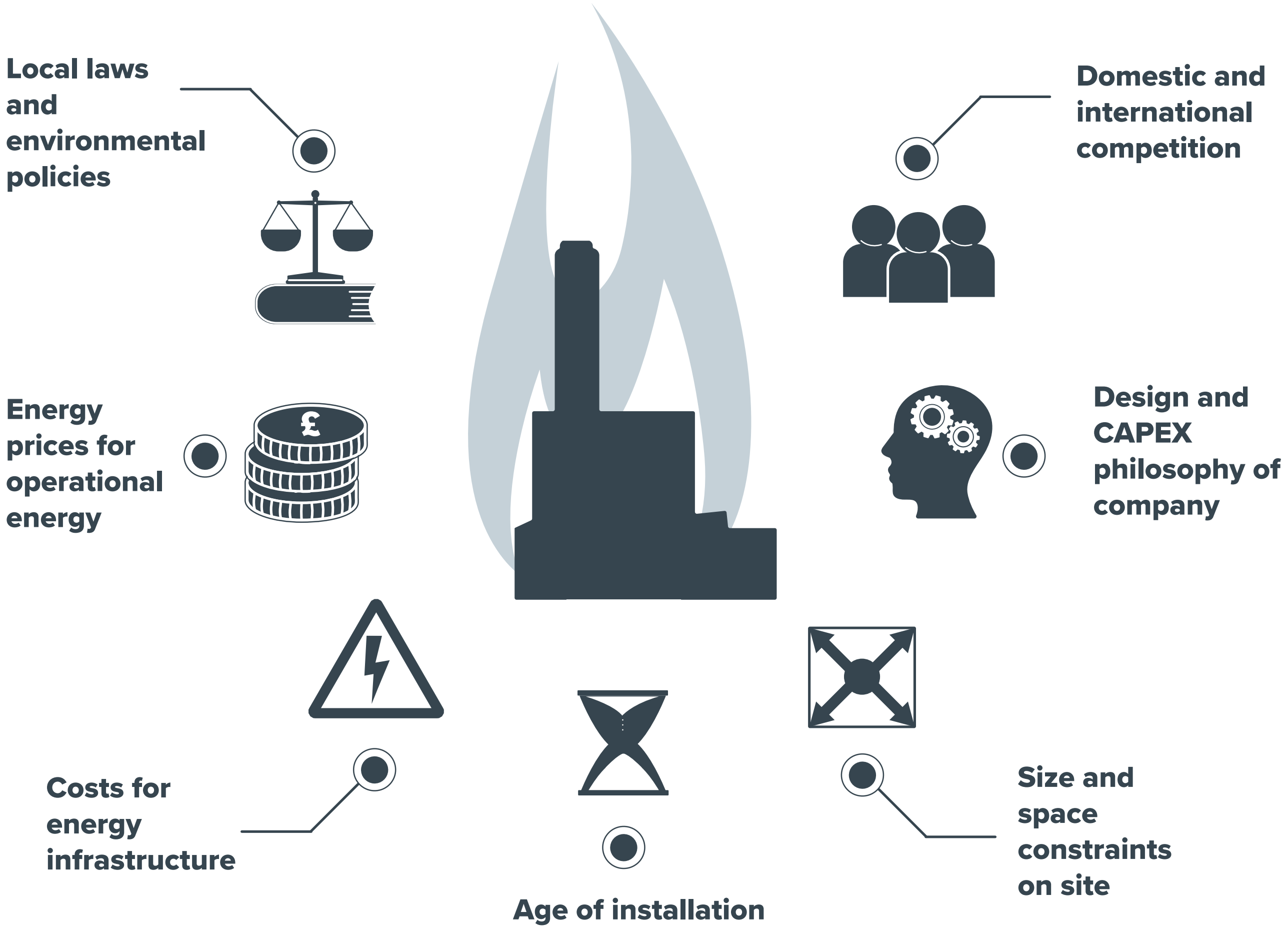


Figure 23: Key considerations for fuel switching within the glass industry

Glass manufacturers will choose economically attractive options and we can clearly see that **continued innovation funding** is critical to supporting short term developments. Furthermore, **a mechanism which enables low carbon fuels to become economically attractive** is vital to maintaining a sustainable long term change.

The Glass Industry, driven by a sense of consumer pressure, moving with the times and attracting the workforce of the next generation, **wants to make these changes.** Furthermore, **the market is both willing and able to explore ways to make this switch viable without government support.**

While there is no "silver bullet", options do exist to allow fuel switching within industry to proceed sooner rather than later. **All fuels which were investigated in this report are potentially viable given additional investment and demonstration at scale.** However, the cost of switching is not just the fuel vs carbon OPEX, but also the risk factor for changing, the CAPEX cost and the impact on society. In particular where commodity products are being manufactured, all additional costs would go directly to the consumer, thus driving inflation and other macroeconomic trends. **These additional costs must be well understood before implementing any wide scale changes.** This becomes vital when considering the differential between a plant's abilities to adopt new fuel types and any preference for an individual fuel which could impact a particular process or plant more or less than its competitors.

In particular, where there is a large premium associated with fuel switching, **the industry is looking at innovative ways to attract a new classification of premium, low carbon products within which the cost of low carbon fuels is afforded as an increase in the baseline cost of the products.** This will be a key trend going forward and will allow market pressures to enable some fuel switching well before 2030.

The international attraction for this programme cannot be understated, especially considering that the Glass Industry operates multi-nationally. This UK programme has garnered attention on every glassmaking continent as people look to research organisations to support their sustainability journeys. Both this UK Government investment and Glass Futures' unique approach to collaboration of the programme has been directly praised for its unique approach to procuring a decarbonisation solution in a manner that both supports innovation and industry in an equitable, market-led fashion.

The overwhelming amount of interest and future work preparation is beginning to ensure continuity regarding decarbonisation within the glass sector. Given this heightened interest, the driving forces behind industrial fuel switching are more compelling than ever to support decision makers committing to changes sooner rather than later. These factors should be used to the advantage of governments and policy makers given how resistant to change entire systems are during times of calm.

6.2 Recommendations

All classifications of fuel switching require some work and the supply chain itself must be engaged to support a timely transition.

There is a key risk with global supply chains that if the rate of transition cannot be supported, then even with enough investment, and a suitably poised industry, that a transition cannot occur due to material, equipment and skills shortages.

We are proud of progressing both hydrogen and biofuel melting along the TRL level rapidly over the past 2 years whilst adding to our knowledge of electric melting.

We have uncovered some critical activities that must be carried out when it comes to low carbon melting mechanisms.

For hydrogen, the impacts of full scale melting on glass and refractories must be understood before any major investments can be made. Extended trials on the St Helens pilot line must be carried out to offer improved understanding in manufacturing conditions.

For biofuels, there are a number of waste based biofuels that warrant significant investigation given the potentially economically attractive profile of bio-wastes as a direct fuel source which should be investigated and trialled.

For electric melting, very large scale hybrids are important to demonstrate operating with oxy-firing, especially where the oxy-firing element is with a low carbon fuel.

7. Next Steps: The Route(s) to Decarbonisation

7.1 Next Steps for the UK Glass Sector

The glass sector is at a crossroads as it has begun to move and investigate alternative fuels quicker than previously expected. The success of our large scale biofuel trials will continue to drive interest and investigation in these types of fuels. As such, the work carried out over the last two years is the beginning of a journey of change for the industry.

Collaboration is the way forward, as public and private institutions begin to invest large quantities of funding to try and ensure their domestic markets do not fall behind the progress curve.

In the UK this push is coordinated by British Glass, who support the UK glass industry to achieve long term decarbonisation targets. By working with policymakers, technology institutions, academics and NGOs, the UK glass sector has an opportunity to create a valuable societal contribution in coalition with the UK Government; one that commits to leading the way on sustainability and innovation. This has potential to generate a profitable UK export market for knowledge and leadership when discussing sustainability strategy and technologies to enable deep decarbonisation.

7.1.1 Next Steps for Glass Futures within the Global Glass Industry

This programme has allowed Glass Futures to attract international attention both from the global glass sector and, based on the cross-sector nature of the work, across other similar energy intensive industries. This attention is focussed around the large scale aspect of the pilot trials carried out but also around the UKRI Transforming Foundation Industries investment of £15m into our globally unique, open access innovation centre in St.Helens which will offer a uniquely large demonstration platform to continue to answer the above questions that remain about industrial fuel switching.

With the plant due to open in 2023, the timing of UK investments places the country on the precipice of an internationally growing interest in this research. In particular, approaching the issue from an industry (not academic) lens provides a unique perspective. This ultimately yields nuanced solutions, as decarbonisation challenges to the glass industry are both economic and technical.

7.1.2 CCUS in the Glass Sector

This project has highlighted that the glass industry is keen to pursue R&D into CCUS technologies and it is hoped that the outcome of the Glass Futures Membership project, currently underway, will provide CCUS developers an opportunity to engage the glass sector as well as a platform to trial their technologies. This will enable the glass sector to identify any suitable CCUS technologies to support while further developing and de-risking them, and creating a deeper understanding of CCUS economics.

After extensive consultation with a number of carbon capture technology developers, Glass Futures believes that the following development time-frame could be achieved with sufficient support from government and industry:

Figure 24: CCUS timelines within the Glass Sector

7.2 Government Policies

The world finds itself at a crossroads. Significant investment is required, with the key question being how to best invest. The global market follows trends and profitability above all else, ensuring that products can be manufactured in a way that makes business sustainable as well as the carbon intensity of manufacturing. With regards to long term cost certainty, policymakers should be aware of the following key aspects:

Although there are premium products in both container and float sectors, these are essentially commodity markets.

Governments and their policies will determine which decarbonising technologies will be adopted and which industries will survive. In particular it is important to ensure the following:

- Governments must be aware of the fact that energy pricing has a huge impact on fuel switching choices
- Governments must be aware of regional differences in the cost of infrastructure, which differs widely depending on site and location
- Governments must maintain a level playing field whilst incentivising the behaviour that it wants to support

Given the resource intense nature of research and development, it is obvious following Glass Futures recent work that there is both a significant cost and reward to be gained from effective investment into low-carbon technologies:

- Continued investment in R&D is vital, sustainability is the biggest opportunity of our decade for businesses to find a “good solution”
- Funding for late stage (TRL 7-8) demonstration work is vital and companies are willing to work together more than historically within this area

- Promoting global cross-sector collaboration is a great opportunity for the UK government as the world looks to low carbon solutions

It is important to note that, regardless of other investments made, there is a significant need within the UK's foundation industry sectors to ensure that the people as well as the industry is ready:

- Investment in the workforce and skills of the industry is vital given the changing nature of some of the associated risks and new skills required.
- Attracting people into heavy industries is vitally important to ensure the sustainability needs of the future are met.

References

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- British Glass, 2021. Glass sector Net zero strategy 2050. British Glass.
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- HM Government, 2021. UK Hydrogen Strategy. Department of Business, Energy and Industrial Strategy.
- Renewable Fuel Statistics 2020 Final Report [Department for Transport, 2021]

A more detailed list of references can be available upon request. Other pieces of work which Glass Futures has produced but are not in the public domain include':

Report Reference	Report
GFL-001-SGED-001	Report: List of most suitable bio-oils, economics and sustainability
GFL-001-SGED-002	Report: Performance of biofuel benchmarked against diesel: Heat transfer and emissions
GFL-001-SGED-003	Report: Performance of lower-grade bio-oils benchmarked against diesel: Heat transfer and emissions
GFL-001-SGDD-001	Report: Performance of Biodiesel compared to Natural Gas and Diesel in container furnace (Encirc)
GFL-001-SGDD-003	Report: Performance of Biodiesel compared to Natural Gas and Diesel in float furnace (NSG)
GFL-001-SGFD-001	Report: Fuel-mix for optimum emissivity defined
GFL-001-SGFD-002	Report: Optimum H2/O2/NG atmosphere conditions for glass melting
GFL-001-SGFD-003	Report: Performance of H2 benchmarked against Diesel: Heat transfer and emissions
GFL-001-SGGD-001	Report: Optimum H2 combustion conditions defined: Glass melting, final glass properties, emissions
GFL-001-SGGD-002	Report: Performance of H2 benchmarked against NG: Glass melting, final glass properties, emissions
GFL-001-SGGD-003	Report: Feasibility of H2 forehearth defined
GFL-001-SGGD-004	Simulation: H2 furnace models designed
	Report: Optimum parameters defined from simulations and validated against lab tests
GFL-001-SGGD-005	Report: Findings from engineering study and Economic assessment for full-sale H2 trial

GFL-001-SGID-001	Report: Map of current capacity & electricity needs identified for 100% electric melting across all UK sites
GFL-001-SGHD-001	Computer Model: Large-scale superboosted furnaces
	Report: Preferred designs and parameters for large-scale electric melting
GFL-001-SGHD-002	Report: Most promising Hybrid fuel scenarios identified
GFL-001-SGID-002	Report: Economic model of fuel-switching options

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Glossary of Terms

Term	Meaning	Term	Meaning
ATEX	Appareils destinés à être utilisés en Atmosphères Explosives (Regulation for devices intended for use in explosive atmospheres)	IFS-P3	Industrial Fuel Switching Competition Phase III
BEIS	Department for Business, Energy, and Industrial Strategy	kg	Kilogram
CAPEX	Capital expenditure	IHO	Industrial heating oil
CC(U)S	Carbon capture (utilisation) and storage	kW	Kilowatt
C3H8	Propane	LCOA	Levelised cost of abatement
CH4	Methane	MJ	Megajoule
Container glass	Packaging glass for food and beverages storage	MW	Megawatt
CFD	Computational fluid dynamics	MWh	Megawatt-hour
CO2	Carbon dioxide	NG	Natural gas
CVD	Chemical vapour deposition	NOX	Nitrogen oxides
CTB	Combustion test bed	NPV	Net present value
Cullet	Recycled glass	OPEX	Operational expenditure

EU	European Union	p.a	Per annum
Float glass	Sheet of glass with uniform thickness and flat surface	R&D	Research and development
Forehearth	Forward extension of the hearth of a glass furnace	RSO	Rapeseed Oil
GFL	Glass Futures Ltd	SOX	Sulphur oxides
GHG	Greenhouse gases	TDP	Thermal design power
GWh	Gigawatt-hour	TRL	Technology readiness level
HAZOP	Hazard and operability analysis	t/d	Tonnes per day
HFO	Heavy fuel oil	TWh	Terawatt hour
HVO	Hydrotreated Vegetable Oil	UCO	Used Cooking Oil
HTMOS-EGA	High temperature melting observation system with evolved gas analysis	UCOME	Used cooking Oil Methyl Ester
H2	Hydrogen	UK	United Kingdom
IFS	Industrial Fuel Switching Competition	£m	Millions of pounds