BEIS Industrial Fuel Switching Phase 2

Alternative Fuel Switching Technologies for the Glass Sector

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Final Report

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1 Executive Summary

1.1 Introduction: Why the UK needs the glass industry to switch to low carbon fuels

The UK glass sector employs 23,200 people, generates £3bn revenues and contributes £1.6bn GVA to the UK economy (Ekosgen, 2019). The sector also makes a significant contribution to many other sectors and to addressing the challenges facing society. Innovations in the glass sector have the potential to benefit everyone - through improved energy efficiency in construction, through improved ways of generating green energy, through demonstrating the circular economy in action through the use of recycled materials, and across many sectors through the development of novel applications benefiting medicine, agriculture, transport and advanced manufacturing.

The core glass manufacturing industry produces around 3 million tonnes (Mt) of glass per annum, generating more than 2 million tonnes of CO_2. Of these emissions, 58% are emitted directly from combustion of fuel, 24% come from primary generation of electricity used on site and 18% are released from the decomposition of carbonate raw materials. (British Glass 2014). Whilst the sector has made progress by halving emissions in the last 50 years, there is a need to urgently accelerate efforts to increase energy efficiency and reduce CO_2 emissions to meet the UK's 2050 carbon commitments.

As many furnaces due to be installed in the coming years will be expected to run for up to 20 years, new low carbon fuel technologies need to be proven technically and economically within the next 10 years if the glass sector is to fully decarbonise by 2050.

To address this need, Glass Futures Ltd. (GFL) successfully applied for and secured a £300k grant under the *BEIS Industrial Fuel Switching Competition Phase 2* to run the feasibility study entitled 'Alternative Fuel Switching Technologies for the Glass Sector' (which ran from April 2019 to October 2019).

A significant amount of data and feedback has been gathered during this study; the following report provides a summary of the key findings, conclusions and recommendations.

1.2 Why more than one solution is required

There are significant differences in infrastructure across the UK glass sector in relation to furnace design, age and specific application. All these factors will influence the most suitable route to decarbonise a given site. There is also uncertainty over availability and economics of fuels across the UK and this is likely to vary from region to region. As such, it is unlikely that one fuel scenario will be able to address the decarbonisation needs of the entire UK glass sector.

Therefore, to effectively decarbonise the entire sector as fast as possible, it is recommended that the following four fuel-scenarios need to be investigated and developed by the Glass Sector in order to maximise the chances of successfully decarbonising manufacturing process by 2050:

- Biofuels
- Hydrogen
- 100% electric melting
- Hybrid-fuel scenarios

There is a strong argument to add biomethane to this list; although this fuel is considered out of scope for the current competition and has not been investigated in this current study, biomethane does offer potential to decarbonise glass making and so it is recommended that it be included in future studies.

1.3 Technical opportunities

Given the glass sector's commitment to decarbonise, the UK's industrial strategy to support that decarbonisation ambition and the existing research expertise within the UK in combustion technologies, there is a significant opportunity for the UK glass sector supply chain to bring new technical concepts to market and become a world leader in the decarbonisation of a heavy industry. These new supply chains and processes could also provide knock-on benefits to other sectors, such as Steel, Cement, Ceramics, Waste management and Energy generation.

Through industry engagement activities and literature reviews, this Phase 2 study has identified that there is a great deal of interest in fuel switching within the glass sector but that are also significant gaps in knowledge and technical barriers that need to be addressed for this to be realised. The study also identified that the UK has both the industrial appetite, the necessary research excellence as well as government backing to address these challenges. The technical developments and capabilities required to decarbonise the UK glass sector therefore represent an area of opportunity for UK based businesses and research organisations to become global leaders in this field.

1.4 Timescales and findings

The study highlighted the significant impact that the economics of fuel switching will have upon uptake timescales. All of the four proposed solutions investigated have the potential to enable full decarbonisation of heat required for glass melting across the UK glass industry before 2050. However, to fulfil this timescale large scale demonstrations must occur within a relatively short time frame (<10 years) to allow industry to make the business cases and engage new supply chains to bring these decarbonised solutions can be brought on-line within 10-20 years. Given the 15-20 year life expectancy for glass furnaces, these timescales are essential if the industry is to decarbonise by 2050.

Although an economic study was undertaken, the high level of uncertainty in fuel costs resulted in a conclusion that any of the options could be the most economically feasible option in the future. It is important this this is reflected in the decarbonisation roadmap for the glass sector which currently shows a heavy reliance on electrification.

There is significant concern across the industry that without significant investment now, the ability for the industry to carry out the research it needs will be difficult. This is due to the capitally intensive nature of the glass sector and its requirement to run uninterrupted 24 hours a day 365 days a year which as a process, does not lend itself well to disruptive demonstrations. The glass industry has limited R&D funds available, much of which is already committed to product development rather than process development. Given the magnitude of research and investment required, there is a need for a united approach across all sectors of the glass industry with significant government backing.

2 Introduction

2.1 Remit of Glass Futures

Glass Futures is a not-for-profit company, created as a core entity to develop two UK-based "catapult-like" centres of excellence in glass comprising R&D, innovation, technology incubation and implementation, training and up-skilling. It brings together the global glass industry and academia. Led by some of the world's largest glass manufacturers, supply chain partners and leading UK university research groups, its aim is to create two centres of excellence:

- A unique multi-fuelled 'Hot' glass pilot facility in St Helen's, Merseyside
- A high-tech 'cold' glass research centre based at the University of Leeds

These centres will be supported by a series of smaller research hubs across UK academic and industry research groups with the aim of strengthening and aligning existing industrial and academic expertise within the "Northern Powerhouse" region. The ultimate ambition is to create a globally recognised UK-based hub in glass technology and manufacturing with the capability to drive significant improvements in productivity and sustainability within the UK glass industry, providing the platform to drive the sector towards net-zero CO_2 emissions by 2050.

2.2 Background

The UK Government has committed to reduce net carbon dioxide emissions to zero by 2050. National efforts to meet these emissions reduction targets could potentially result in conversion to a hydrogen gas grid, or alternatively could see localised decommissioning of the gas grid and a move towards electrification and decentralised energy supply.

It is estimated that 90% of UK industry relies on energy supplied from the gas grid either directly for their industrial processes or indirectly in the day-to-day business. Whilst the glass sector has made progress by halving emissions in the last 50 years and its products contribute to energy savings in other sectors (e.g. glazing and insulation, wind turbines, aerospace), there is a need to urgently accelerate efforts to increase energy efficiency and reduce CO_2 emissions to meet the UK's 2050 carbon commitments.

The BEIS Glass Industry Decarbonisation and Energy Efficiency Roadmap to 2050, identified 100% electric melting as the preferred route to decarbonise the industry. However, findings from subsequent industrial engagement activities have identified other technologies that can now be considered as real alternative routes to decarbonisation, such as biofuels and hydrogen, that were not highlighted on the original industry roadmap. This Phase 2 study therefore looked to build upon the original findings to increase understanding those different options and explore how to facilitate wide-scale adoption of all low-carbon fuel scenarios across the glass sector.

2.3 BEIS Industrial Fuel Switching competition remit

BEIS have stated that the aim of the Industrial Fuel Switching Competition is to identify and demonstrate solutions which will enable fuel switching in industry from fossil fuels to less carbon intensive fuels. Fuels in scope include electrification, hydrogen and biomass (whilst biomethane is a lower carbon fuel, it is not in scope for this competition). The Competition was split into three phases: Phase 1 was a market engagement and assessment study into fuel switching in the UK, Phase 2 is feasibility study into a fuel switching solutions (of which this report relates), and Phase 3 will fund demonstration of these solutions.

In Phase 1, the market engagement and assessment study conducted by Element Energy considered the viable energy sources for industrial fuel switching, the industrial processes compatible with fuel switching, and the potential solutions to achieve these switches; the complete report will be available at: www.gov.uk/guidance/funding-for-low-carbon-industry

BEIS' stated aim of Phase 2 was to identify and test the processes and technologies required for industries in the UK to switch to low carbon fuels, providing funding for the consortium to demonstrate the feasibility of their proposed technology or approach.

2.4 Scope of Study

In preparation for the Phase 2 bid, Glass Futures undertook a detailed review of the original glass industry decarbonisation roadmap, alongside discussions with a number of industrial and academic partners.

These discussions highlighted that, due to differences between manufacturing requirements of subsectors (float, container and glass fibre), capital refurbishment time tables and predicted future variations in availability and affordability of different fuels across the UK (e.g. hydrogen supply may be localised; local grid capacity for electricity supply limited) no single low-carbon fuel scenario is likely to be suitable for all glass manufacturing processes. It was therefore agreed that the scope of the Phase 2 study should cover the following four low-carbon fuel scenarios:

- Biofuels (with potential for subsequent addition of carbon capture utilisation and storage (CCUS))
- Hydrogen
- 100% large-scale electric melting
- Hybrid fuel scenarios (i.e. combinations of the above with/without natural gas)

There is a strong argument to add biomethane to this list, however this fuel is considered out of scope and has not been investigated in this current study.

2.5 Approach

Led by Glass Futures and project managed by Glass Technology Services Ltd. (GTS), the Phase 2 study consisted of five work packages (see Figure 1 below) and was supported by project partners representing glass manufacturers (Encirc, NSG Pilkington), furnace designers (F.I.C, Tecoglas), control systems supplier (Siemens), research groups (Sheffield Hallam University, University of Leeds) and The Society for Glass Technology. Further support was provided by Element Energy, In Perpetuum, CelSian and the University of Sheffield.

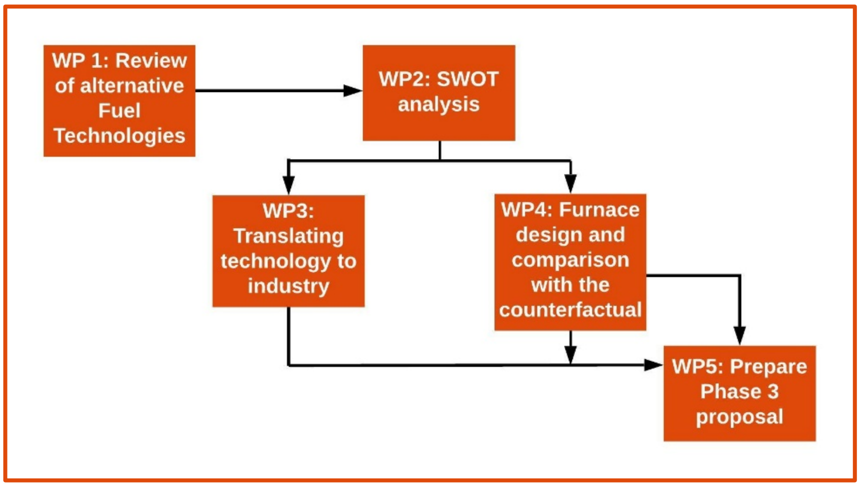

Figure 1 *Inter-relationship of work packages within Phase 2 study*

The Phase 2 study aimed to determine technical and economic feasibility for each of the above four fuel scenarios along with the potential to decarbonise the glass furnace heating process whilst meeting regulatory requirements.

2.5.1 Literature reviews

GTS, Element Energy, UoL and SHU undertook detailed literature reviews into each fuel scenario to build a foundational understanding of the current state-of-art in each field. Due to the substantial nature of this study, these will be published as a separate report, hopefully in the form of a published academic paper.

2.5.2 Industry and supply chain engagement workshops and SWOT analysis

Three workshops were held (April, July, September), to which academic and industrial partners were invited. In addition to this, two further workshops were held to explore the strengths, weaknesses, opportunities and threats to each of the four fuel scenarios. The findings are presented in Section 5.

2.5.3 Direct Industry Engagement

In addition to the workshops, numerous one-to-one meetings were held with industry organisations, including meetings and/or e-mail correspondence with all major UK glass manufacturers and several supply chain partners, many of whom were invited to join the Phase 3 project. These meetings provided valuable insights into the current views of the glass sector and the scope to implement new low carbon fuel technologies.

2.5.4 Energy networks and suppliers

In order to build a more detailed understanding of current supply network capabilities, discussions were held with various suppliers of energy and gases, including BOC, Cadent and Northern Power Grid.

2.5.5 Engagement with wider glass community and other research groups

The Project team also engaged the research groups working in the field of glass technology and alternative combustion technologies. This provided insights into related research programmes being undertaken across the wider glass sector, ensuring Glass Futures activities will complement these research programmes (and not duplicate work). It also provided valuable opportunities to build partnerships that will lay the foundations for future collaborative research programmes. The following groups were directly engaged within the Phase 2 study:

- University of Sheffield, PACT
- DNV-GL
- CelSian
- Glass Trend
- British Glass
- IPGR
- Supergen
- Progressive Energy

2.5.6 Economic modelling

A high-level economic review of each fuel switch scenario was modelled by Element Energy to build a more thorough understanding of the potential life-time costs for each fuel scenario. The findings are presented in Section 6.

3 Current state of art

3.1 Overview of glass manufacturing

Glass is produced from sands and other minerals that are melted at very high temperatures to form a material that has found application in a range of sectors e.g. construction, packaging, pharmaceuticals, automotive, fibre optics and other specialist applications in both nuclear and oil and gas to name a few.

Around 60% of all UK glass production is classed as ‘hollow glass’ that is glass packaging containers, used within the food and drink sector. A further 30% of glass output is flat glass, largely used by the construction and automotive sectors. The final 10% of glass manufacture consists of fibreglass and speciality glasses (lighting, oven hobs, optical, medical and scientific uses). The total value of all glass sectors to the UK economy is estimated to be over £1.3 billion[1]

The vast majority of glass produced (>95%) can be recycled; the recycled glass (also known as cullet) is added back into the furnace as a raw material to help decrease the energy consumption of the process and reduce the need for raw materials. It has been estimated that every tonne of recycled glass used in glass manufacture saves approximately 320kWh[2] of natural gas. In addition to the CO_2 savings from the reduction in fuel use, there is a CO_2 saving associated with the reduction in use of carbonate raw materials. For every tonne of cullet used it is estimated that 250kg less CO_2 is emitted compared with using virgin raw materials[3]

A range of processes can be used to produce glass articles from molten glass into its final form and shape, including drawing, blowing, pressing and floating. The physical and chemical properties of glass vary depending on the formulation of the material; however, the methods used to shape and form the glass as it cools will also have a significant impact on the final physical properties of the glass. The glass manufacturing process starts with the batch preparation. Sand, limestone/dolomite, soda ash and minor additives are weighed and mixed according to the glass formulation; the resulting mix of raw materials is referred to as the ‘batch’. This glass batch usually includes a percentage of cullet and this mix is then conveyed to a batch storage bin where the blend is held before being fed to the melting furnace.

The batch blend is charged to the melting furnace that operates at temperatures ranging from 1550 – 1600 °C. In this stage the materials should go through melting, refining, homogenising and thermal conditioning before leaving the furnace. Melting starts when the batch is charged into the furnace and should optimally be completed in the first half of the melting chamber. Several factors affect the rate at which the material is melted such as the temperature in the chamber, the grain size of the batch materials, the amount of cullet in the mixture and the homogeneity of the batch. As the molten glass goes through the furnace it reaches the second half of the chamber where the refining (or fining) process removes gas bubbles formed during melting of the raw materials. The homogenising of the molten glass occurs throughout the furnace and is intended to eliminate variations in its properties such as refractive index, density or coefficient of expansion. It typically takes 24 hours for the glass to go through a container furnace, however it can take up to 2-3 times longer for the glass to travel through a float furnace, due to the more stringent quality requirements on appearance. Figure 2 provides an example of the various steps used in the manufacture of float glass.

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[1] Prodcom sales figures, 2015, Office of National Statistics
[2] Case Number 2003-03-082, Glass Technology Services, 2004
[3] Carbon Trust, 2005

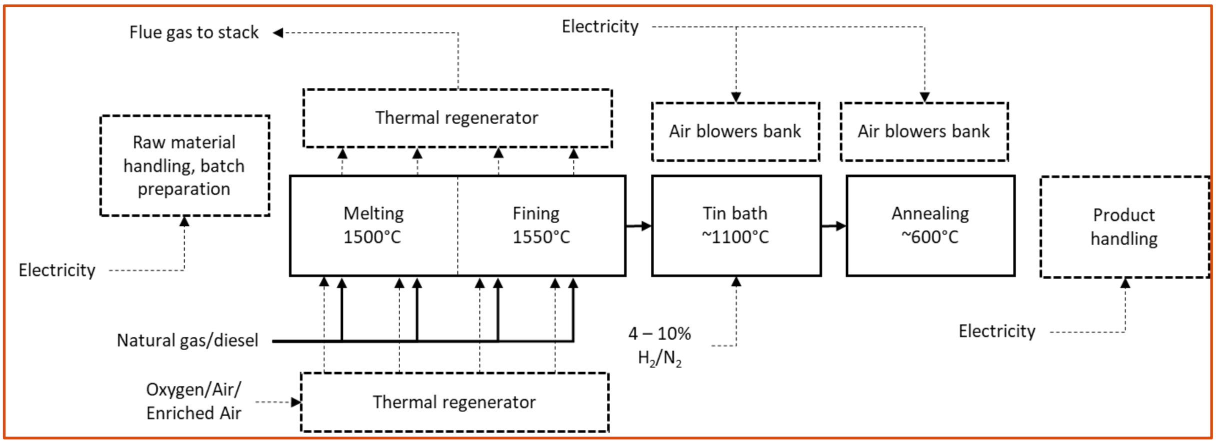


Figure 2 *Manufacturing process of float glass*[4]

There are several glass melting furnace designs most of which are distant relatives of the 1860's Siemens regenerative furnace designs with natural gas as the primary fuel source. Some historic context is important within the glassmaking industry as the early designs all used coal as the primary fuel source. Through developments the primary fuel source across the UK switched to heavy fuel oil which in turn switched to natural gas due primarily to economics.

Throughout the course of these changes the core design principles of the glass making furnace have changed very little due to the relatively high efficiency offered by the regenerative furnace design. Alternative recuperative designs are less efficient at a large-scale and as such do not see widespread use across the large-scale commercial glass making sector.

In the UK most furnaces are of the Siemens regenerative type, which can be either side-port or end-port and operate with natural gas as the primary fuel source, however, many current UK furnaces have the capability to fire diesel, primarily to provide energy security for the large capital assets. The combustion of natural gas is attained with air and in some cases enriched air or oxy-combustion are utilised. The fuel is received in the facilities from the natural gas grid and its pressure is regulated to ca. 1 Bar relative pressure. Combustion air is preheated on the hot side of the thermal regenerator of the furnace to around 1200°C, which our study has highlighted is almost unique to the glass sector. Combustion temperatures are in excess of 2000°C and the flue gases leave the furnace chamber at circa 1400°C where the waste heat is recovered on the cold side of the thermal regenerator, this process reverses every 20-30 minutes and as such the heat from the exhaust gases is mechanically stored and recovered in highly specialised refractories.

After the melting stage the glass is cooled to around 1100°C and sent to the forming stage; this step is specific and individual to each type of glass product. For float glass as an example, the molten glass flows over a tin bath on which the glass sheets are formed and drawn away from the furnace. For glass containers, the glass is sheared into 'gobs' of glass which are fed into an Individual Section forming machine. For glass fibres, the glass is fed into a platinum bushing from which the fine fibres are pulled.

3.2 Energy consumption and emissions

Glass manufacture is an energy–intensive process, primarily due to the large amount of energy required to melt and refine the glass, with an annual consumption of 9 TWh[5]. The most common

[4] Figure credit: University of Leeds

furnace types across the UK are fuelled with natural gas with some additional electrical boost. Table 1 shows the statistics on energy consumption in the manufacture of glass in the UK per type of energy source. It can be seen that the highest share of energy consumption corresponds to natural gas, totalising 517 ktoe, which represents 76.5% of the total energy consumption by this industry. No less important is the consumption of electricity totalling 150 ktoe and is mainly used in the process for handling of raw materials and products and to provide the energy to fans and blowers for glass cooling.

Many glass plants in the UK use an electrical boost system, where electrical energy is delivered through a molybdenum electrode fully submerged in the glass melt. This accounts for a relatively small percentage of energy delivered to the melts as opposed to natural gas. Electric boost is used to:

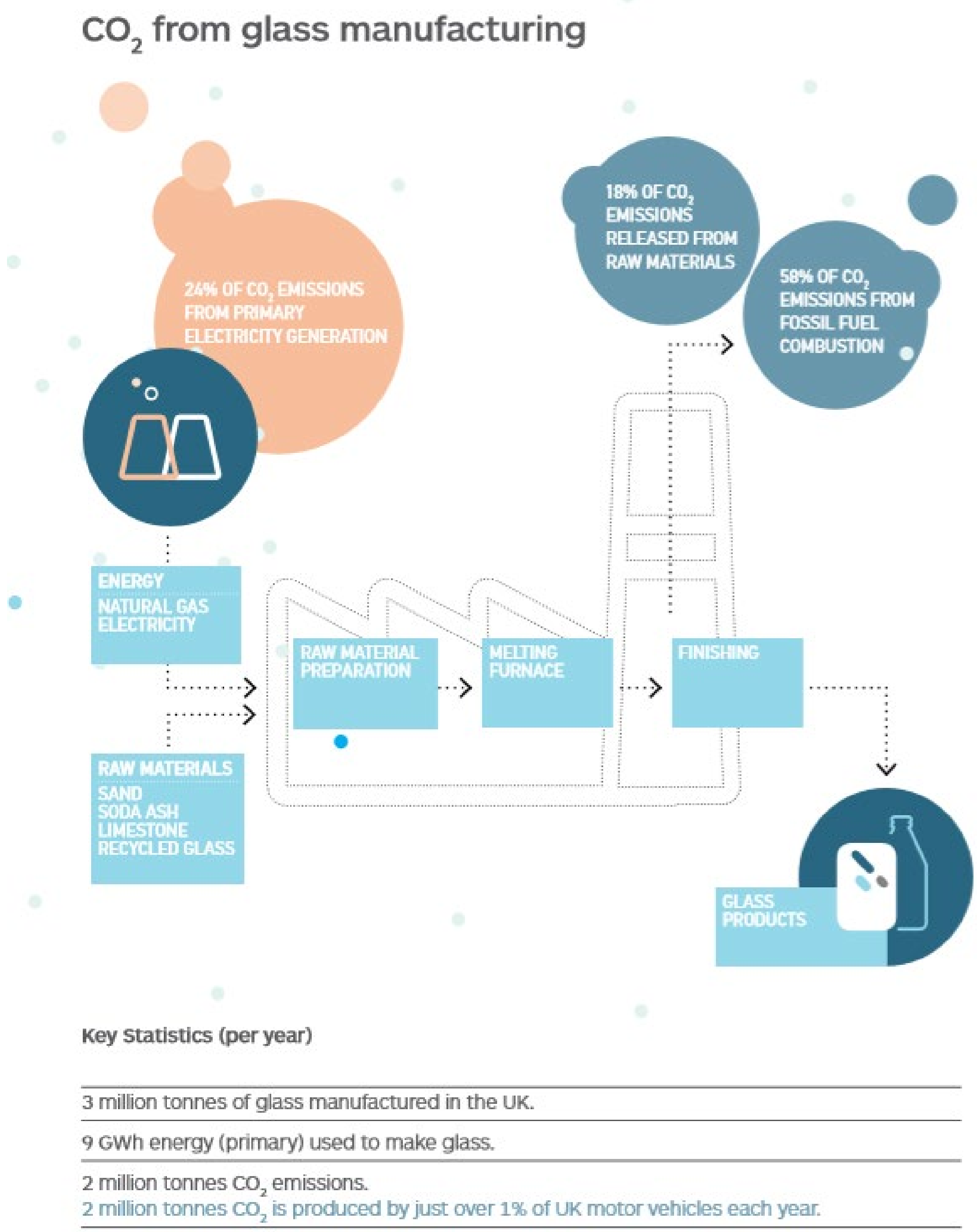
- Provide additional pull giving flexibility of operation and on-the-run expansion. This includes melting both dark glasses like amber and green (where the majority of the radiative heat from the natural gas flame is absorbed close to the surface) but also Flint/Clear.
- Improve glass quality, depending on specific quality issues, not all quality issues can be fixed.
- Reduce emissions from furnace (through reducing the natural gas requirements)
- Energy substitution (e.g. if cheap electricity is available at certain times of the day/year)
- Provide a back-up heating system, for example adding boost to enable maintenance of pull whilst organising a regenerator repair to assist furnace breathing.

	Gas oil	Fuel oil	Natural gas	Electricity	Total
Manufacture of flat glass	-	58.2	1709.6	186.1	1965.5
Shaping and processing of flat glass	11.6	0.0	69.8	383.8	465.2
Manufacture of hollow glass	11.6	23.3	3140.1	802.5	3965.8
Manufacture of glass fibres	0.0	0.0	721.1	267.5	988.6
Manufacture and processing of other glass, including technical glassware	-	0.0	372.2	104.7	476.8

Table 1: *Energy consumption in the UK Glass Industry in 2018 in thousands of tonnes of oil equivalent (GWh)*[6].

[5] British Glass. *A Clear Future: UK Glass Manufacturing Sector Decarbonisation Roadmap to 2050.* [Online]. 2014. [Accessed 10 June 2019]. Available from: https://www.britglass.org.uk
[6] UK Department of Business Energy & Industrial Strategy. *Energy Consumption in the UK: 2018 update.* [Online]. 2019. [Accessed 10 July 2019]. Available from: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

British Glass estimated the total emissions in 2012 to be 2 million of tonne of CO_2[7], most of which come from the melting process, representing approximately 70%. Other sources of emissions are the degradation of raw materials (CO_2 is released from soda ash, dolomite and limestone) and the electricity used for e.g. compressors, cooling fans, drives and downstream processing equipment. Figure 3 provides a high level summary of the main sources of CO_2 emissions.



TWh

***Figure 3** Overview of glass process and original of CO_2 emissions (British Glass, 2014)*

[7] British Glass. *A Clear Future: UK Glass Manufacturing Sector Decarbonisation Roadmap to 2050.* [Online]. 014. [Accessed 10 June 2019]. Available from: https://www.britglass.org.uk

3.3 Diesel and fuel oils

While the delivery method for fuel oils into the combustion chamber is very similar to natural gas, there are a few distinct differences between fuels, and these typically come in the form of on-site storage and a higher cost per kWh.

While no UK manufacturer regularly fires using fuel-oil anymore, the use of stored diesel is still prevalent across a number of UK Glass manufacturing sites to ensure that operators can maintain the value of their primary capital asset (furnace) in the event of an emergency with the gas delivery network.

3.4 Oxyfuel furnaces

An oxyfuel furnace fires pure oxygen into the furnace along with the natural gas (i.e. with no ambient air) and so are noticeably more thermally efficient than furnaces that use ambient air. Although the flame is hotter, no nitrogen is fed into the furnace and so NO_x levels will be very low. Most oxyfuel furnaces are used within specialist and specific applications which are generally under the following situations:

- Melting of speciality or high temperature glasses (Borosilicate for instance)
- Where an economic source of oxygen exists
- To aid an old furnace to meet its campaign requirements

The technical aspects of oxyfuel firing are well understood and has some distinct benefits but comes at a reasonable cost for either on site oxygen manufacture or regular deliveries of liquid oxygen. It is also notable that due to the energy demand of producing oxygen there is generally low CO2 reductions from the use of oxy-fuel furnaces.

3.5 Praxair, Optimelt

Across Europe there are a number of designs utilising waste heat as a method to produce syngas. While these are relatively new to the market, there are only two commercial furnaces in the EU operating with this technology. The Optimelt system has a number of benefits, including significant improvements in fuel efficiency, however it is still seen as a technology that requires a significant capital investment. It should also be noted that although the Praxair system is more efficient than standard furnaces, it is reliant on a natural gas fuel supply and so is not a low carbon option.

4 Overview of most attractive Low carbon Fuel Switching technologies

The following section provides a brief overview of each of the fuel scenario investigated within the Phase 2 study.

4.1 Biofuels

Biofuels are fuels derived from biomass. If combined with carbon capture technologies, biofuels offer a route to net-negative CO_2 emissions (BECCS) from glass manufacturing processes.

Biofuels typically burn with a more radiant flame, have lower CV content per kg and can contain higher moisture content than natural gas or hydrogen fuels, and therefore are expected to have a higher heat transfer from the flame into the glass melt. Burning at a lower flame temperature, biofuels are also likely to emit lower NO_x levels.

4.1.1 Biodiesel

The most common back-up fuel used by UK glass production sites is fossil gas oil, also known as diesel. With an equivalent specification, biodiesel from 100% renewable sources (i.e. no blending with conventional diesel) would provide a low-risk switch. Although most conventional diesel used in transport and industrial heating applications contains approximately 7% biodiesel blended into the fossil-fuel derived diesel oil (and so the industry has used fuels with low-levels of biodiesel), the glass industry has not yet explored the performance of pure, 100% biodiesel fuel, and how it compares to conventional diesel, and so such a transition is currently deemed as high risk. Figure 5 provides an outline of a typical process for producing biodiesel.

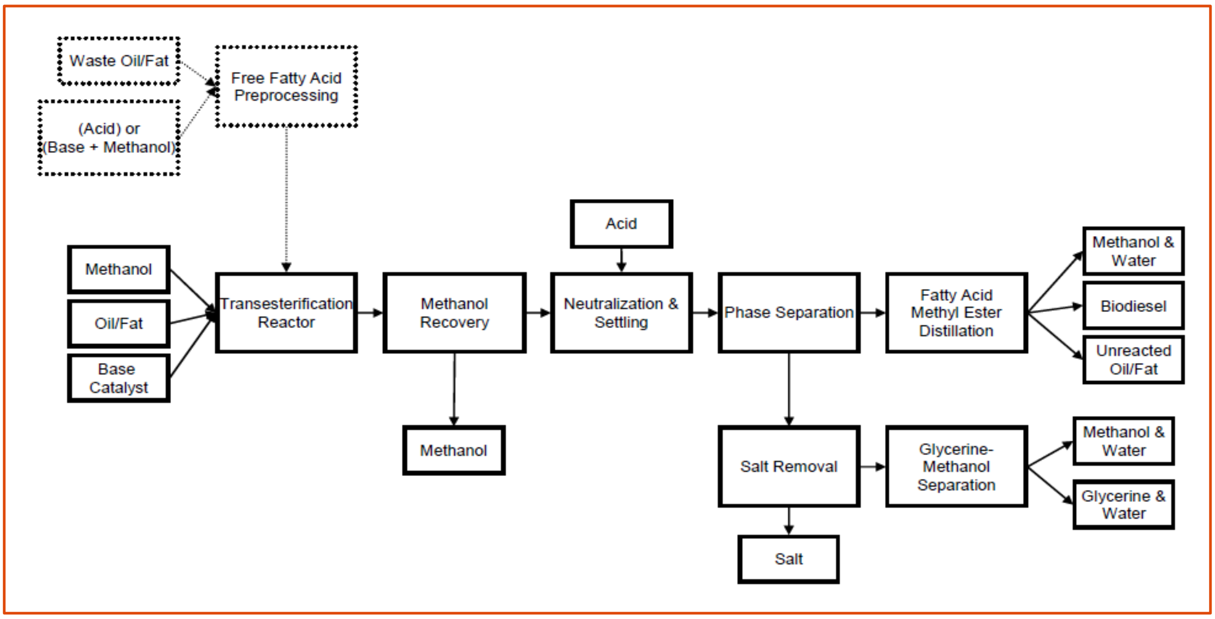


***Figure 5** Manufacturing process of a typical base-catalysed process for producing biodiesel; in this case the pre-processing of Waste Oil is shown in the dotted outline at the top left of the diagram*[8]

[8] Image courtesy Inperpetuum Partners LLP

4.1.2 Lower grade bio-based fuels

Lower-grade bio-derived fuels (e.g. pyrolysis of carbon-based bio-wastes) may provide a lower-cost fuel solution than biodiesel, which may even be economically competitive with natural gas. As such, the UK glass industry may have some real options for utilising demonstrably sustainable liquid fuels in the short, medium and longer term.

There is some conflict between UK policies for heat, power and transport with regards to use of crops from land and this shows some room for consideration. There are various sustainability schemes that can be adopted to demonstrate compliance with suitable sustainability standards, although sustainability is something that would need investigating further, both in terms of available volumes of such carbon-based wastes and the potential knock-on impact on other sectors which might have to switch to non-sustainable fuels and feedstocks if the glass sector puts pressure on the supply of sustainable sources of biomass or carbon-based waste streams.

4.1.3 Availability of biofuels

UK volumes of biodiesel are largely focused on the use of wastes and residues from various sources:

- Food supply chains: specifically cooking oil turned into used cooking oil methyl ester (UCOME). There is also the potential use of animal fat or tallow that can be turned into a biodiesel known as tallow methyl ester (TME). Finally, there are a range of greases and fats collected from domestic sources via the sewers through fat traps in the sewers and from waste-water cleaning operations. These are also known as UCOME biodiesel fuels. Similar feedstocks can also be used to make HVO fuels.

- Oil bearing crops like oil seed rape or palm oil as well as starch crops such as wheat or maize can be converted into traditional biofuels and hydro-treated vegetable oil (HVO). However, due to fuel versus food debates and concerns over sustainability (e.g. over links to deforestation), legislators do not consider these types of feedstocks as sustainable fossil fuel replacements at this time.

- Waste and residue plastics and tyres from various supply chains could be converted into fuels. Such conversions may be appropriate if the fuel supply route turned out to be economically competitive in the long run compared to comparative fuels. Although, unless the wastes were derived from renewable sources, such fuels would need to be used in conjunction with CCUS technology to be classed as a low-carbon source.

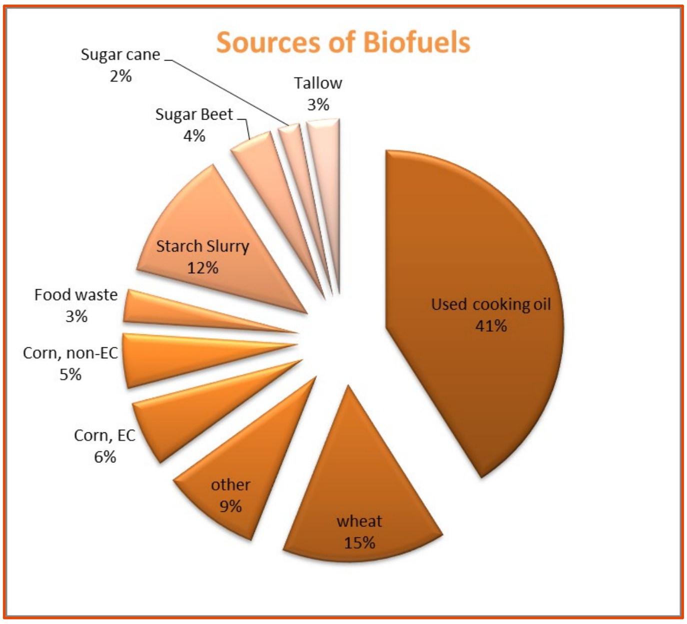


Figure 6.1 *sources of Biofuels used in the UK*[9]

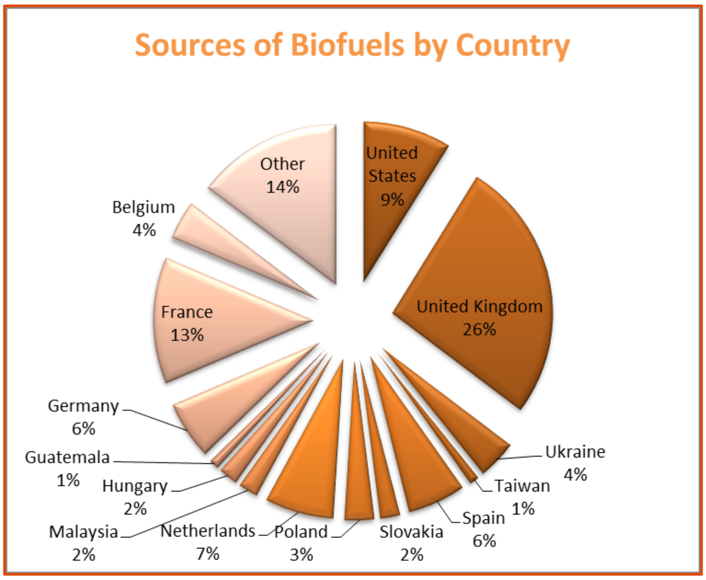


Figure 6.2 *sources of Biofuels used in the UK by country*[10]

[9] Source: DfT (covering period 15th April 2016 – 14th April 2017)
[10] Source: DfT (covering period 15th April 2016 – 14th April 2017)

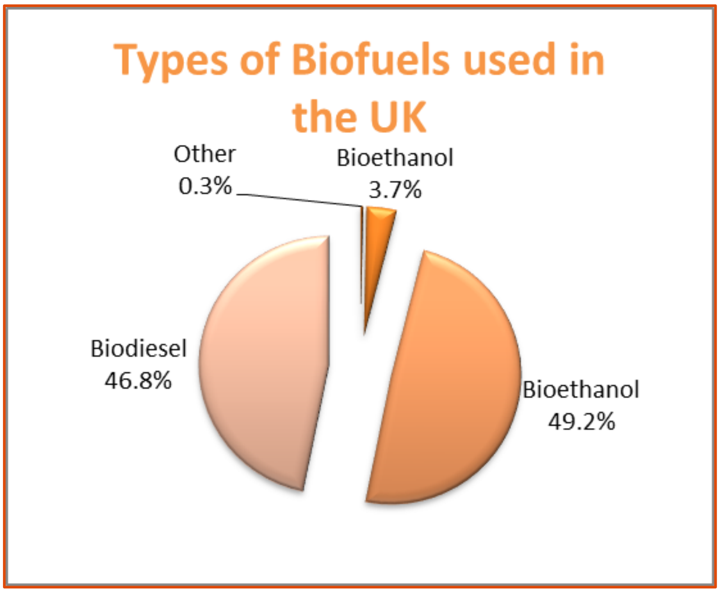


Figure 6.3 *Types of Biofuel used in the UK*[11]

Our study estimated that the current UK glass sector would require annual volumes of 400 million litres of biodiesel. Current biodiesel supply in the UK is at around 804 million litres[12], however the production of biodiesel has been stagnating in previous years mainly because of the level of supply being limited by the Renewable Transport Fuel Obligation (RTFO); the lack of policy or market incentives has led to loss of confidence from investors which has resulted in facilities operating below installed capacity. Investigations by Inperpetuum identified that many biodiesel facilities are running below maximum capacity due to the decline in numbers of diesel vehicles and that demand is falling by approximately 300,000 litres year on year.

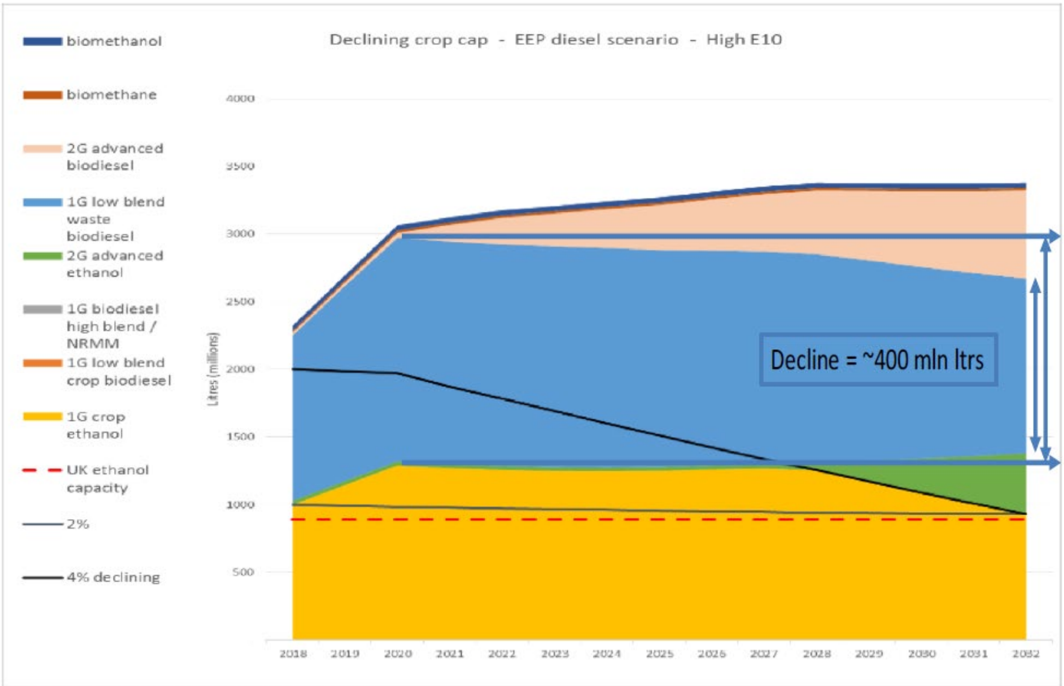
Therefore, the consensus between producers and studies is that there is scope to create sufficient feedstock accessibility to meet a foreseeable uplift in supplying 100% of the fuel needs for the glass sector, however, this may be affected if competing industries emerge. E4tech reported the availability of feedstock will become more constrained in the period to 2030, and consequently, the long-term deployment of biofuels plants in the UK would need to rely more on feedstock imports or switching feedstock use from power to biofuel applications. However, in the short term, through conversations with the CEO for Global Biofuels at Greenergy, the Director of Corporate Affairs at Argent Energy and the Commercial Director at Mabanaft Ltd, it was identified that if the UK Glass Industry market needed volumes of vegetable oil or waste derived biodiesel, then they would all want to be supplying this finished product and would be able to source the needed feedstocks.

There is a very low fuel duty payable on biodiesel used in industrial heating. Due to legislators and policy influencers pushing markets away from food / feed crops for use in biodiesel, it is our view that waste feedstock biodiesel, such as tallow and used cooking oil (UCO), should be preferred to reduce the CO_2 impact of the fossil derived product. The use of tallow and UCO in the production of biodiesel is now commonplace within the UK with the two largest producers being Argent Energy, using tallow / UCO and Greenergy, using UCO.

Due to increases in demand in recent years, within the UK and EU, the feedstock and the finished Biodiesel are starting to be imported on a more regular basis and the volumes growing

[12] DfT: Renewable Fuel Statistics 2019 First Provisional Report

dramatically, showing that if the market for this type of product exists the global market will supply. Biodiesel producers, traders and blenders have seen growth in demand, but expect biodiesel demand to fall in line with Department for Transport forecasts as diesel demand falls in the UK and across Europe. This is in line with forecasted increase in adoption of electric vehicles within the passenger car fleet and potential shift to bio methane use for heavy goods vehicles. Below is the view of the UK Department for Transport (the blue box is the biodiesel that we suggest using in UK Glass Industry):



Department for Transport (DfT) data

Figure 7 *potential decline in future biodiesel use*

Biodiesel trades as a commodity and has shown over many years how it can be affected by policy levers in different geographies. Biodiesel price has however fallen relative to crude oil over recent years despite strong growth in demand. This is understood to be due to increase in availability of feedstocks from wastes that has expanded to include large levels of imports to the European Union.

4.1.4 Potential for reducing CO_2 emissions

The potential CO_2 emissions reductions for fuel switching within the Glass industry are shown in Figure 8 below, which gives an estimation of the relative CO_2 emissions savings associated with switching from natural gas to heating oil and biodiesel, as well as from heating oil to biodiesel. The chart indicates that a move from main natural gas to fossil derived heating oil would result in an increase in CO_2 emissions by 42%. However, a move from natural gas to biodiesel would see a 91% reduction in CO_2 emissions.

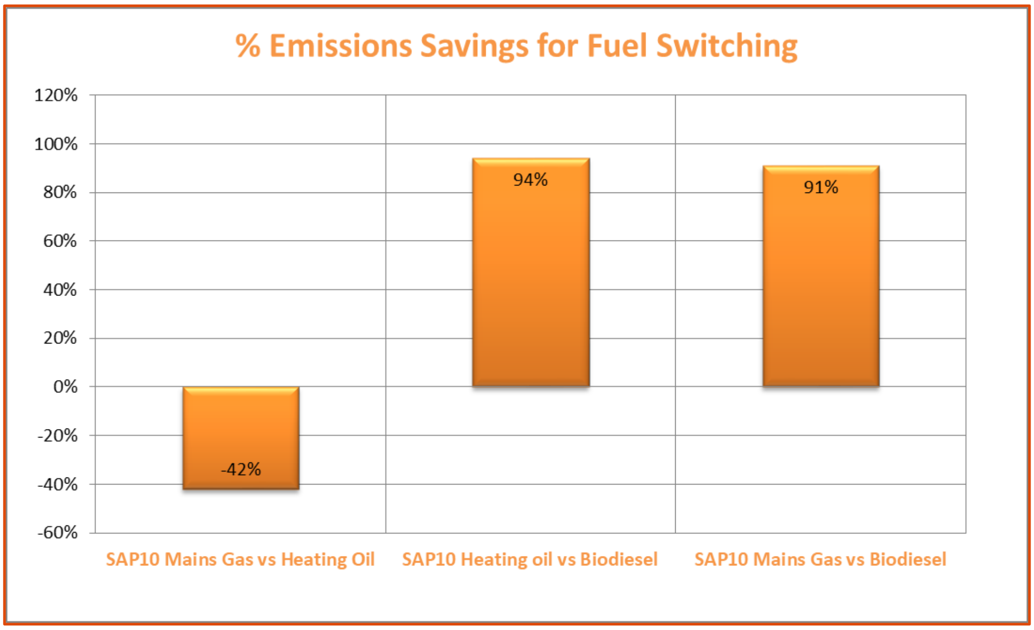


Figure 8 *Comparison of net CO_2 content of natural gas, heating oil and biodiesel fuels*

4.2 Hydrogen

A number of groups in the UK are exploring the possibility of converting the natural gas network to 100% hydrogen as a route to decarbonise both industrial and domestic energy applications. If a 'decarbonised' hydrogen supply could be delivered directly to site through existing natural gas pipelines, it could provide an ideal opportunity to decarbonise the glass manufacturing process.

4.2.1 Applicability of hydrogen fuel for glass melting

The substitution of natural gas with hydrogen to fire the glass furnace is subjected to the feasibility of hydrogen to provide the radiative heat transfer required by the melting process. At atmospheric conditions hydrogen has a gross calorific value of 12.1 MJ/m^3 and a relative density of 0.0696, which is equivalent to a Wobbe Number of 45.88 MJ/m^3. Natural gas used in the UK must currently have a Wobbe Number in the range 47.20 – 51.41 MJ/m^3; therefore, to achieve the same heat release a slightly higher hydrogen mass flowrate is required.

The substitution of methane by hydrogen has barely been investigated by the glass manufacturers due to the poor radiative properties of the hydrogen flame and combustion products. The literature reviews undertaken by academic partners UoL, SHU and UoS only identified one reference to investigations on glass melting with hydrogen.

Although there is minimal evidence of the application of hydrogen in glass furnaces, there are a number of research groups developing hydrogen burners that are suitable for glass furnaces (e.g. the Flamatec division of Glass Service). Andrews et al.[13] addressed the use of pure hydrogen using a rapidly mixed jet burner design and demonstrated the feasibility of operating a combustor with low NO_x emissions. They showed that to achieve the desired level of NO_x in the

[13] Andrews, G.E., Altaher, M.A. and Li, H. Hydrogen Combustion at High Combustor Airflow Using an Impinging Jet Flame Stabiliser with No Flashback and Low NOx. In: *ASME Turbo Expo 2012: Turbine Technical Conference and Exposition*, 2013, pp.1479-1489.

exhaust, very lean mixtures are required. In addition, the flame stability attained with hydrogen was shown to be higher than that of both, direct and premixed propane. They showed that NO_x emissions lower than 25 ppm are achievable with hydrogen up to temperatures of 1600 K. However, these temperature levels are lower than the typical melting temperatures in glass furnaces.

It has also been speculated that alternative solutions to enhance the radiative properties of hydrogen in the glass melting furnace might be the use of hydrogen/natural gas or hydrogen/biogas co-firing schemes or the injection of other additives that increase the luminosity of the flame, without damaging the glass quality or the furnace integrity.

4.2.2 Availability of Hydrogen fuels

If a fuel switching scenario with hydrogen as fuel is technically feasible from the process standpoint, the question remains on how to produce it. According to the report of the Energy Research Partnership (ERP) on the potential role of hydrogen, the UK production is about 26.9 TWh/yr, with half coming as a by-product from the industry, and being used onsite or sold as chemical feedstock[14].

The two main routes within the UK to produce low carbon hydrogen on a large scale are steam methane reformation (SMR) and electrolysis of water using renewable electricity.

The demand of hydrogen as a fuel can be met at the early stages of the transition using SMR, typically referred to as 'blue' hydrogen. Currently, 48% of the production of hydrogen is attained via SMR as it is a mature and reliable technology, with a lower cost in comparison to electrolysis[15]. In order to contribute to glass decarbonisation, hydrogen production needs to be low or zero carbon; most of the modern steam reformers can achieve high efficiency levels that reduce the CO_2 emissions, however, further reduction will only be achieved by the integration of CO_2 capture and storage/utilisation in the process scheme.

The addition of a CCS unit to the SMR process increases the CAPEX and OPEX of the facility, the International Energy Agency (IEA)[16], investigated the economics of deploying CCS in a SMR based hydrogen plant and concluded that the addition of CO_2 capture would increase the plant cost by 18% to 79%.

Hydrogen produced using renewable sources is referred to as 'green' hydrogen. The obvious choices are to produce hydrogen either centrally or distributed by means of wind or solar energy and electrolysis, or to produce it through steam reforming of bio-sources.

The production of hydrogen via wind energy represents a more likely scenario than the use of solar energy. In 2018, the solar energy installed capacity was 13 GW, which represented a share of 3.9% of the total electricity generation in the UK, compared to 7.9GW installed wind power. However, the support from the UK government to solar power projects has waned since 2016 when it announced the suspension to subsidies for renewable energy projects and wind capacity is increasing at more than twice the rate of solar. As such the case for wind energy is a better one.

[14] Energy Research Partnership. *Potential Role of Hydrogen in the UK Energy System.* [Online]. 2016. [Accessed 10 June 2019].
[15] Energy Research Partnership. *Potential Role of Hydrogen in the UK Energy System.* [Online]. 2016. [Accessed 10 June 2019].
[16] International Energy Agency. *Techno-Economic evaluation of SMR based standalone (Merchant) Hydrogen Plant with CSS.* [Online]. 2017. [Accessed 10 October 2019]. Available from: https://ieaghg.org/exco_docs/2017-02.pdf

Several questions remain with respect to the use of solar or wind energy in the production of hydrogen. The applicability of this option depends on the availability of a surplus of low-price electricity to reduce the OPEX of electrolysers. This surplus, however, depends on certain parameters like the seasonal weather or the design characteristics of the wind turbines (e.g. height of the hub). Although it is expected that the CAPEX of electrolysers will decrease with time, the uncertainty of the availability of electricity surplus would lead to scenarios where electrolysers operate with low load factors or at reduced efficiencies which would create capital burden and, possibly heat management or safety issues[17].

If projects such as HyNet and H21 North of England are successful, the UK glass industry would have access to 100% supply of low-carbon hydrogen (i.e. hydrogen with no or very low net CO_2 emissions associated with its production) to site through existing natural gas pipelines. Therefore, the UK glass industry needs to be ready to respond to this scenario.

4.3 100% Large-scale electric melting

Electric melting is well established and significantly more efficient than equivalent heating technologies that rely on combustion and would offer an ideal route to decarbonise glass melting at the point where 100% 'green' electricity is available. Existing all-electric melting is considerably more energy efficient than comparable sized fossil fuel fired furnaces so developing larger units is very desirable for fuel efficiency and decarbonisation.

The largest commercial electric furnaces available have a capacity of upwards of 300t/day; significant further developments in furnace design are required if this is to provide a low carbon replacement for new furnaces that can have a capacity of up to 900t/day. CFD modelling has demonstrated that large all-electric furnaces are possible but not with conventional vertical melting. Horizontal electrical melting looks promising but demonstrating it is essential before it will be adopted. The additional advantage of the all-electric horizontal melter is that it utilises an almost identical footprint as existing furnaces.

The technical feasibility of 100% electric furnaces is promising, however there are significant economic barriers to its uptake. The greatest concerns relate to the future economic viability of using electricity, primarily due to the higher cost of electricity compared to other fuels in the UK, but also due to the CAPEX costs associated with upgrading site infrastructure. The challenges and costs associated with upgrading the electricity supply to site are also significant and represent a major challenge for the UK glass sector.

4.4 Flexible hybrid fuelled furnace

As discussed in Section 3, many glass furnaces have the ability to use electric boost, to complement the natural gas firing. It was identified that this concept could be extended to include furnace designs powered by a range of different fuels (e.g. the ability to switch from 100% natural gas to 100% electric to 100% hydrogen or biofuels, and any combination in between). This could offer greater protection against fluctuations in fuel prices or supply disruptions, whilst facilitating the transition from natural gas towards new low-carbon fuels.

A flexible-hybrid design also offers the advantage in future to allow for more dynamic fuel switching; for example, a furnace could dynamically switch from electric to biofuels in order to support future smart load balancing networks (effectively acting as a dynamic battery come power plant).

[17] Energy Research Partnership. *Potential Role of Hydrogen in the UK Energy System.* [Online]. 2016. [Accessed 10 June 2019].

5 Key Challenges and Opportunities

5.1 Biofuels

Our study did not identify any references to trials of biofuels within the glass sector beyond small lab-scale experiments.

Adhering to the same standard as conventional diesel-fuel, biodiesel should be compatible with existing glass furnace infrastructure with minimum additional CAPEX investment required (with the caveat that port design will need to be changed). Although changes to port design and burner assemblies would be required to convert from natural gas to biodiesel in order to achieve optimum fuel efficiency, the time and costs associated with this are minimal compared to hydrogen.

As discussed in Section 4, it should be possible for the UK biofuel sector to up-scale production in order to supply the entire glass sector, if needed. Biodiesel therefore offers a low-risk route to decarbonise UK glass manufacturing with minimal changes to current infrastructure and relatively low risk to production. The emissivity of the combustion flame from biodiesel (and also other bio-oils) is also well aligned to that required for good transfer of heat to the glass melt (diesel is up to 5% more efficient than natural gas[18] and also likely to be more efficient than hydrogen (although this is yet to be confirmed)). A further benefit is that a fuel-oil burns at a lower temperature than natural gas (similar is expected for biodiesel and bio-oils), so should theoretically reduce NO_x emissions however, again, a lack of any data in this area highlights the need to carry out further testing. The main barriers to implementation are a lack of data to demonstrate that 100% biodiesel will not adversely impact furnace infrastructure, nor glass melting.

Historically, glass furnaces have been operated on much lower grade fuels than diesel (such as heavy fuel oils and even coal dust). Whilst investigating biofuels, the current study identified a whole series of low-grade oils from sources such as the pyrolysis of carbon-based wastes such as tyres and plastics, that could be used in a glass furnace (although such products are currently manufactured from fossil-fuel sources they do at least reduce the demand on extraction of virgin fossil fuels, and in the future such products may well be manufactured from renewable sources). However, the performance of these fuels when combusted in a glass furnace is much less well known and so industrial trials would be much riskier than biodiesel.

It is therefore recommended that a series of lab-studies should be undertaken to understand the performance of such fuels. In parallel, industrial trials of biodiesel would provide a lower risk route to build confidence in using biofuels within the glass sector, thus offering a stepping-stone to the use of these lower-grade bio-oils (e.g. derived from waste) which have potential to be economically competitive with natural gas.

One of the main challenges with biofuels is that the combustion process will require careful control so as not to leave unburnt carbon (which could create a reducing atmosphere affecting the redox state of the glass chemistry and colour as well as emissions), although it should be noted that the glass industry has a great deal of experience at managing such challenges.

Sustainability is also a potential issue with biofuels and can be difficult to demonstrate when feedstocks are imported from outside the EU. Even if the chosen biofuel is from a sustainable source, care must be taken to ensure that the glass industry does not create a deficit within another sector that then needs to be met through creation of additional non-sustainable biomass

[18] [Industry data, British Glass, Glass BREF Section 4.8]

sources (e.g. the cooking oil used to make biodiesel is often used in animal feeds in parts of Asia and so removing large volumes of cooking oil from the supply chain may result in a greater demand for non-sustainable palm oil). This issue will need to be assessed in any future studies that explore the use of biofuels within the glass sector.

Compared to large-sale electric melting, biofuels offer a lower cost route to decarbonise existing glass furnaces, with significantly less investment required into new infrastructure (furnace and supply-side) and therefore should be easier and faster to implement. Switching the glass industry to biofuels would also reduce competition low carbon electricity capacity to decarbonise other sectors (e.g. transport). CCUS may be more challenging for biofuels than for electric melting (where the only emissions are the release of CO_2 and other gases from the decomposition of the carbonate-based raw materials), as the volumes of CO_2 and other gases will be greater, however the greater volumes of gases may offer economies of scale and if CCUS can be applied, biofuels offer a carbon-negative glass-melting process.

The following table provides a summary of the main considerations that need to be considered by a glass manufacturer looking to switch to biofuels.

Biofuels		
Factor	**Impact of alternative energy source**	**Scalability potential & mitigation measures**
Impact on H&S	All biofuels should be safer to handle than natural gas and comparable to diesel, with lower risk of explosion compared to natural gas. Current infrastructure and practices across the UK glass sector are well equipped to handle liquid biofuels and no changes to existing H&S processes should be required. Some investigations into H&S impacts of contaminants will be required, which may raise additional H&S measures (e.g. biohazard risks if fuels are derived from animals).	Biofuels could easily be adopted across industry in a short timeframe given current infrastructure, with minimal additional H&S training required. All sites handle diesel for transport so current systems are well equipped to handle large biofuel volumes.
Impact on regulatory measures/ Environment	Emissions from biofuels should be similar to those of a diesel-oil powered furnace, possibly containing additional components such as alkalis and chlorine which may require more sophisticated abatement systems. Although comparison with diesel suggests it should meet regulatory measures, biodiesel is as-yet unproven at scale and so there is a risk of unseen regulatory issues arising. The literature review indicates that overall SO_x and NO_x emissions are expected to be lower. The Phase 3 project will provide quantitative analysis of emissions to	Based upon the levels of emissions measured the current UK abatement infrastructure should be able to deal with emissions from biofuels and so minimal additional abatement equipment will be required. Most sites have back-up diesel tanks which may require minor modifications to cope with biofuels; additional fuel tanks may also be required if running 100% biofuels, but this should be relatively low cost and quick to implement. Current infrastructure for managing diesel spillages should be more than adequate to eliminate risk of biodiesel escaping into local watercourses.

	build on this knowledge. Biodiesel may have greater impact on local ecosystems if escaped into watercourses (e.g. higher biological oxygen demand).	
Fuel Delivery Logistics	There would be increased road-traffic by a small amount to sites that already employ large amounts of site traffic e.g. • Largest plants (1600t/day across 2 furnaces) have up to 54 haulage movements/day • Fuel is an additional 5-6 tankers per day • A 10% increase in site traffic for an overall net decrease of 91% CO_2 emissions from fuel(increase in transport CO2 not considered during this study) Delivery may be more difficult in plants in urbanised areas, though this is not seen as a significant issue. The GF-P2 feasibility study showed the availability of biodiesel for the UK glass industry is good, with additional work to estimate the availability of suitable low-grade bio-oils to be done before low-grade bio-oil/mass rollout could occur. The location of the glass industry relative to areas of biodiesel production are very well placed to ensure consistent and reliable deliveries. Mains gas as a backup would also be used to ensure continued production in the event of a fuel logistics issue.	
Production Disruption	Given data from past firing setups with diesel we expect biofuels to increase furnace efficiency by up to 5%, which would give installed UK capital infrastructure a productivity boost if successful. Switching from natural gas may cause short-term disruption (e.g. impact on glass colour) whilst operators adjust to the new fuel technologies, but this is likely to be minimised through a phased switch over (e.g. switching one burner port at a time).	
Relation to state of the art	The performance of biodiesel is expected to be similar to diesel type fuels already in use as a backup and therefore swap-over is expected to be a lower operational risk than switching to other fuel sources. However, other biogenic materials are unknown and therefore require further study and development.	
Barriers to implementation	The main barrier will be cost (mainly fuel cost) and the inherent risk associated with trialling a new fuel as the first mover. Minor infrastructure and training would be required at some sites across the UK, so this investment is unlikely to be a barrier. The impact of impurities within the fuel on furnace infrastructure are unknown. For example, much research will be required to see the effect of the biofuel on the regenerator refractories as depending on source of biofuel we may be putting new compounds down the regenerator much like Vanadium from heavy fuel oil.	
Driving factors for adoption	Development of low-grade 2nd generation bio-oils could provide a lower cost bio-oil in the short term (pre 2030) with only minor capital infrastructure costs for uptake. The ability to become carbon negative if applied with CCUS (BECCS) is highly attractive. A number of new innovative technologies exist within the use of waste heat from furnaces to drive new symbiotic processes, especially the pyrolysis of wastes into biofuels.	

	As all large-scale glass furnaces in the UK use natural gas and most have diesel back-up systems, there is significant potential for rapid replication across all sectors of the glass industry
Commercial	Biodiesel (~6.5p/kWh) is currently more than twice as expensive as natural gas (2.3p/kWh), so is unlikely to compete without carbon costs considered. Lower grade bio-oils (e.g. from wastes) could be lower cost than biodiesel. Lower cost bio-oils might compete with natural gas + carbon over a 30 year lifetime for a furnace constructed in 2024 or 2025 if available at low cost <5p/kWh and efficiency is same as diesel. Cost of delivery will impact economics, unless fuel can be made on-site from a local source/waste stream. There is a significant question around the competition within the future bio-oils sector and the impact this may have on price.

Table 13 *Overview of bio-based fuels suitability for the glass industry*

5.2 Hydrogen

Low-carbon hydrogen offers a potentially lower fuel cost than electricity, however further economic modelling is required to understand how the future costs might compare to biofuels.

One of the greatest barriers to the adoption of hydrogen melting are the many technical unknowns associated with the process and lack of process data even at lab-scale. Although it is anticipated that it should be possible to convert the furnace design used with current natural gas furnaces to a pure hydrogen fuel with relatively minimal disruption (at least with minimal changes to the furnace footprint and geometry), a plant will still need to make significant investment in infrastructure, from new H&S measures and training to new furnace designs with new advanced refractories. It is likely that an oxyfuel generation plant or supply pipeline would also be required (to avoid high NO_x), which would further add to the CAPEX and OPEX due to the electricity required. However, despite this, the lower cost of hydrogen compared to natural gas + carbon may well off-set this over the life of the furnace.

A further advantage is that hydrogen could be delivered through existing natural gas pipelines, maintaining the existing methods of fuel delivery (albeit potentially with some pipework replacement) and reducing cost of delivery to site (significant advantages over biofuels and electricity). However, the need for ATEX approved zones and stainless-steel pipework will be challenging and costly to implement on existing glass plants and operators will need to be educated on the H&S risks associated with using hydrogen fuels.

Whilst a transition to 100% hydrogen is likely to be very technically challenging, our findings highlighted that, in the short term, it is likely that hydrogen will be blended into the natural gas grid at reduced levels (e.g. starting at 10%, increasing to 20-30% hydrogen by volume). As such, furnace modelling indicated that a ‘hydrogen + natural gas’ fuel-mix (up to 50% hydrogen by volume) would operate under conditions much closer to that of an existing furnace (such that it might even be possible to use such a mix with minor modifications to existing infrastructure), which could provide a short-term measure to reduce carbon emissions without significant disruption to sites or furnace changes.

Assuming a scenario whereby an oxyfuel configuration is employed, the need for further CCUS on-site will be minimal, especially if carbon-emissions from raw materials can be eliminated (e.g. through increased use of recycled glass combined with use of non-carbonate raw materials).

The following table provides a summary of the main considerations that need to be considered by a glass manufacturer looking to switch to hydrogen melting.

Hydrogen Melting		
Factor	**Impact of alternative energy source**	**Scalability potential & mitigation measures**
Impact on H&S	Current conventional H&S systems in place *should* be sufficient to handle hydrogen however significant training of operators and site-engineers will be required to ensure safe practice is adhered to and so that clear practices are in place in the event of problems. New H&S equipment will be required for use of hydrogen e.g. ATEX rated and enclosed fuel skids; this is expected to require significant changes to site infrastructure depending on the fuel delivery methods employed. Hotter flames and higher volumes of gas throughput may also require additional H&S measures. Pipework may also have to be upgraded to stainless steel and more frequent checks employed, given the greater liability of hydrogen to leak.	To use pure hydrogen, industry will require a comprehensive change in site H&S systems and infrastructure for the entire industry. If this is part of a nationwide push, this will reduce the impact as change adoption strategies can be shared across industries. Our feasibility study has shown a very small proportion of the industry is used to ATEX/DSEAR regs which will put extra workload in a rapid adoption scenario.
Impact on regulatory measures/ Environment	Hydrogen burns at a higher temperature; if N_2 is present then greater volumes of NO_x will be present *[GWI, Glass Trend, 2018];* even if an oxyfuel process is used some NO_x will be generated (as N_2 still leaks into the furnace). Enhanced evaporation of volatile species as a result of higher furnace operating temperatures may add to emissions handling costs. None of the above factors lead to any regulatory problems or challenges that the industry is not already addressing. As such the risk of hydrogen combustion leading to issues in meeting regulatory compliance is very low.	Existing NO_x handling technologies should be able to cope with any additional NO_x produced, although may need to be upgraded/expanded. The GF-P2 feasibility study identified that work to explore how concentrations of volatiles vary with combustion conditions in a lab-environment is essential before any large-scale trials can be carried out. There are many unknown factors surrounding the emissions expected when pure hydrogen combustion is used to melt glass. As such small-scale industrial demonstration is necessary to inform the industry of the effects of hydrogen combustion in large scale industrial settings.
Fuel Delivery Logistics	Any hydrogen delivered via new or old gas grid infrastructure would work well for the industry given its use of natural gas. On-site production of hydrogen through	

	electrolysers is not seen as viable for the Glass industry as all-electric would be a more efficient fuel delivery method to the glass melt. For tanker based deliveries (~8 required/day for a 10 MW furnace) Large scale hydrogen storage on site is seen as a risk for long term deployment, and the energy density of hydrogen means it is less suitable for tanker-based deliveries, so it would be preferable to be delivered through gas grid network infrastructure.
Production Disruption	Switch over to hydrogen would require a major change in capital infrastructure above an 80/20% natural gas/ hydrogen blend. The effect of pure hydrogen combustion has not been carried out in relation to glass and is highlighted by our feasibility study as a major area of research. Pure hydrogen combustion chemistry needs to be studied across a number of glass types due to the unknown effects of a very high moisture content in the combustion gases. Work with Dartington glass identified issues when melting lead oxide glasses due to the formation of lead crystals, some other effects may exist that are as yet unknown for more mainstream soda lime silica/boron glasses. If combustion is steady and able to fulfil environmental obligations then theoretically furnace throughput could be maintained, the longer-term impacts on capital equipment, especially refractories needs to be studied further.
Relation to state of the art	Implementation of full-scale pure hydrogen firing is at a low TRL with many hurdles to overcome across the board before it sees major uptake in industry. Rapid widespread adoption is not expected, as deployment of hydrogen technology is likely to be a phased approach by region, meaning some glass manufacturers may not have access to hydrogen until significantly later than other sites.
Barriers to implementation	Lots of work needs to be carried out to assess the full range of implications for large scale adoption of hydrogen in the glass sector and reassure a risk-averse industry. Large changes to site safety infrastructure could impose a large CAPEX cost to change fuel sources, and if hydrogen is not cost competitive with other fuel sources the industry will move to the most economical option.
Driving factors for adoption	Hydrogen is seen as a good option to utilise grid assets to remove carbon emissions from the melting process, if there is not major CAPEX investment required then uptake could be over a medium timescale and part of wider (industrial cluster) decarbonisation plans for appropriate regions.
Commercial	hydrogen could become lower cost than natural gas, if carbon costs included) by 2042-45. In this scenario the process could be lower cost. However, CAPEX costs could be higher due to requirement of new furnace designs and H&S infrastructure. Due to the large number of unknowns and lack of suitable furnace designs it is not possible to quantify this gap currently.

***Table 14** Overview of hydrogen fuel suitability for the glass industry*

5.3 100% Electric melting

Electric furnaces typically operate with a 'cold-top' whereby raw materials (or batch) are fed into the furnace from the top (where the temperature can be as low as 50-100˚C), melting as they pass down through the furnace. This 'cold top' forms an insulating layer which reduces thermal losses from the glass melt. Electric furnaces are more efficient than air/fuel furnaces because they do not produce large volumes of hot waste gases. The 'cold-top' traps many of the pollutants produced by the melting process (e.g. SO_x, generated by refining agents) and has no associated NO_x emissions as long as nitrates are not used in the batch. Although the furnace has a shorter working life (6-8 years) compared to gas-powered furnaces (12-15 years), it is significantly cheaper to build and more efficient. It could be argued that, if economically comparable, a shorter life is an advantage, enabling manufacturers to exploit new furnace technology developments.

Larger-scale electric furnaces are expected to need a 'semi-cold-top', with efficiencies lower than a 'cold top' but still more efficient than combustion equivalents (natural gas, biofuels, hydrogen), and with minimal emissions. It has been determined that large all-electric furnaces will probably need a small amount of top heat in addition to in glass heating in order to melt some coloured glasses and especially to achieve comparable glass quality due to the mechanics and chemistry of glass melting.

The following table provides a summary of the main considerations that need to be considered by a glass manufacturer looking to switch to a 100% electric furnace.

Electric Melting		
Factor	**Impact of alternative energy source**	**Scalability potential & mitigation measures**
Impact on H&S	Electric melting should be safer than natural gas as it has a cold top, with no hot waste gases and uses no combustible fuels. Even if a semi-hot-top design is used, reduced volumes of hot gases will mean that H&S risks are lower than for conventional natural gas-powered furnaces.	Current use of some electrical boosting in industry gives all-electric melting a low risk in application across the UK. All sites currently have good H&S systems in place to properly deploy all-electric melting across the UK
Impact on regulatory measures/ Environment	Electric furnaces are well established within the glass sector internationally at small scale. Cold or semi-cold top has near zero emissions of NO_x or SO_x and so is capable of meeting all regulatory requirements. A semi-hot top furnace may lead to additional emissions (e.g. SO_x not be captured in cold-top) if natural gas is used to provide the heat, however much lower than a gas-powered equivalent and this heat could be provided by electrical heaters.	There is near zero risk of unseen regulatory issues arising upon upscaling this technology.

	There are currently limitations on amount of recycled glass that can be used in electric furnaces (reducing environmental benefits).	
Fuel Delivery Logistics	When installed, fuel delivery is simple and effective. However, the GF-P2 study has shown installation of significantly greater HV electricity distribution is required and take up across the UK glass sector likely requires major energy infrastructure upgrades at a large capex cost.	
Production Disruption	Some glass types and colours are technically more difficult to melt with all-electric furnaces, however electric melting is currently used on all common glass colours, only requiring some minor changes in some cases (e.g. Amber glass is typically handled in semi-hot top melting configuration). There are a number of concerns around stability of supply and the impact of potential blackouts if furnaces run all-electric; could be mitigated through use of on-site battery packs and/or generators.	
Relation to state of the art	Large scale all-electric melting is currently seen as technically unfeasible due to the melting mechanics of large (>600) ton per day furnaces. Smaller scale is possible (up to 300 tpd) so there is some work to do in the field of all-electric melting for large furnaces (which account for around 6/32 UK furnaces). More fundamental research followed by demonstration is required to ensure advancement in this area.	
Barriers to implementation	The fuel cost, as well as the cost to upgrade supply to site (grid and on-site), are likely to prevent the industry switching to all-electric melting in the near future. The requirement for significant infrastructure changes and running costs in the region of 3x mean this fuel source is not seriously considered in the current UK market, even where it is clearly technically feasible.	
Driving factors for adoption	The decarbonisation potential, reduction of waste gases and widespread use globally as a technically recognised alternative fuel option mean all-electric melting will always be considered for a large majority of the market but the decision is driven by fuel economics. The smaller footprint offered by the lack of abatement systems is seen as a distinct advantage for plants where space is at a premium. Moreover, the all-electric horizontal melter utilizes an almost identical footprint to existing natural gas furnaces.	
Commercial	The main concern raised across the glass sector was fuel costs and potential costs associated with upgrading site infrastructure.	

***Table 15** Overview of All electric fuel suitability for the glass industry*

5.4 Flexible-Hybrid fuel scenarios

Beyond a small amount of electric boost to complement natural gas combustion, there is little experience of hybrid scenarios.

The main benefits of the flexible-hybrid scenarios are to (a) provide ability to increase glass pull-rate quickly, (b) enable significant demand side response on electricity use, (c) reduce risk of fuel supply disruption.

Although it is likely that a hybrid-fuel furnace will have higher CAPEX costs, it is likely that the above benefits will off-set such costs, particularly if significant costs are required to upgrade fuel delivery infrastructure (e.g. the local electric grid).

A hybrid furnace scenario would also offer the capability to respond to fluctuations in the price of electricity. For example a furnace with the potential to use excess electrical energy at night is of particular interest (as the industry already participates in demand side response schemes in some areas), although there is uncertainty as to whether this scenario would materialise e.g. electric vehicles may 'mop up' any spare electricity generated overnight. It should be noted that there are existing predictive control systems currently on the market that can optimise fuel usage based on price on a real time.

There are also likely to be optimum fuel-mixes whereby the fuels complement one another to give improved melting behaviour, efficiency, or emissions, or adapt to regulatory changes. A hybrid furnace should also increase operational flexibility to make it easier to control glass colour through redox atmosphere in the furnace as/when required.

The following table provides a summary of the main considerations that need to be considered by a glass manufacturer looking to switch to a flexible hybrid furnace design.

Hybrid Furnace technologies		
Factor	**Impact of alternative energy source**	**Scalability potential & mitigation measures**
Impact on H&S and Environmental issues	Operational costs, H&S and environmental regulations will vary significantly depending upon fuel mix used (also glass subsector and region) but the main considerations have already been covered above.	Potentially easier to scale than other fuel-scenarios, as allows for sites to use existing infrastructure as much as possible and reduce volumes of any one new fuel.
Fuel Delivery Logistics & Production Disruption	The way in which fuel is delivered to site depends on the specific hybrid solution, with different ratios of hybrids also having different implications for production processes but, in general, hybrid systems should reduce fuel/energy supply risks due to the flexibility to switch when required.	
Relation to state of the art	Current precedent exists for electrical boosting of natural gas furnaces, additional use of more electricity is TRL8 at the moment. New novel hybrids highlighted in our feasibility study show good potential but are low TRL (4)	
Barriers to implementation	Economic drivers around existing hybrid models are a key barrier (e.g. increased CAPEX, fuels need to be close in price to encourage variability). Novel hybrid concepts will need to show economic parity with current models to be considered.	
Driving factors for adoption	The ability to change fuel sources based on fuel cost, carbon pricing and availability is attractive to the glass sector. Significant ability to offer large scale load balancing for the national grid frequency is of particular interest.	
Commercial	Depending on the type of hybrid furnace there are a number of scenarios where a commercial advantage could be gained through the use of intelligent demand side load balancing for the grid. There is also a number of scenarios available where fuels could be switched seasonally if this results in a more economically sustainable process	

Table 16 *Overview of hybrid fuel suitability for the glass industry*

6 Economic assessment

To provide a provisional indication of how each fuel scenario might compare to natural gas, a high-level cost-modelling exercise was undertaken by Element Energy, supported by Glass Technology Services and furnace designers TECOGLAS and FIC.

The model compared the lifetime furnace costs of different fuel technologies – natural gas, hydrogen, electric, biodiesel and flexible hybrid scenarios – including CAPEX, OPEX, fuel cost, carbon cost, rebuild and repair cycles and high/low controls. It should be noted that, due to limited time and budget available within the Phase 2 study, there are several additional costs which are not currently included in the model and so all figures should be treated as indicative estimates. It should also be noted that the model only considered biodiesel and not any other forms of biofuels.

6.1 Methodology

The model uses input parameters such as the capacity of the furnace, the rebuild schedule, and the type of glass produced (currently limited to container or float). These are then combined with detailed information on operational parameters of different glass furnaces (furnace efficiency, repair cycles, etc.) and informed assumptions around costs of components and fuels to output the CAPEX and OPEX cost of each fuel switching option in annually[19]. As each glass making site operates differently, producing different products and with different operational parameters, the parameters used in modelling can be tuned. Further controls are available to adjust some of the inputs and assumptions, and these will be expanded within future studies to allow increased customisation on a site by site basis.

6.2 Results

The costs of the different fuel switching options were calculated. Illustrative costs over a 30 year time period are shown below for a 300 t/day container furnace built in 2035 operating on 100% hydrogen, 100% electric and 100% biofuel, as well as the cost difference to a 100% natural gas furnace.

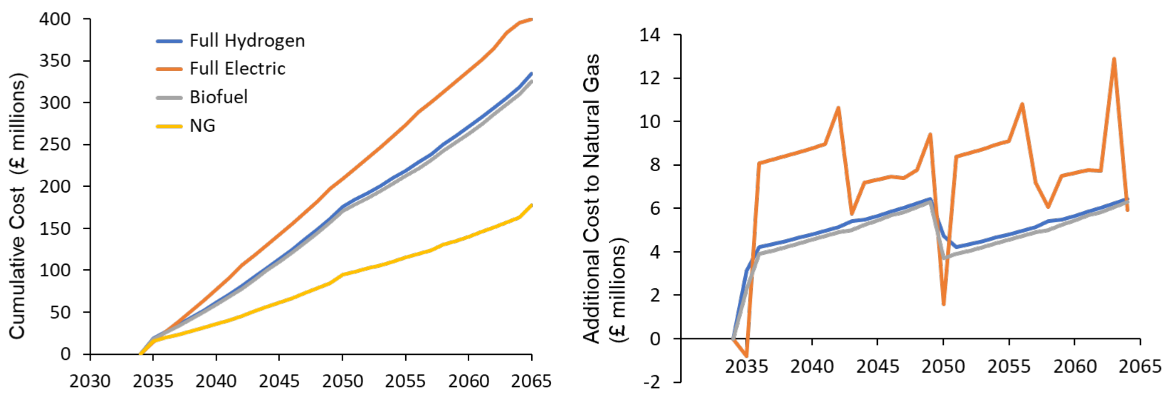


Figure 17 *Illustrative costs of fuel switching options for a glass furnace deployed in 2035 compared to natural gas (price of carbon omitted).*

[19] Energy cost predictions based on BEIS data, 2019

6.3 Carbon Pricing

The base case cost comparison is without the carbon price applied due to the uncertainty over future carbon pricing and free allowances granted to the industry (due to the strong international competition). As such, none of the fuels are cost competitive with natural gas and are very unlikely to become so in the future. However, if incentives such as carbon pricing were applied this could make it economically viable to convert to these fuels, and the model has functionality to include carbon price trajectories in calculations and outputs. Whether these incentives will be provided through fuel subsidies, allowing the sale of free carbon emissions permits or by removing free carbon emissions allowances is unknown, however any solution must ensure the competitiveness of UK industry is maintained and the risk of carbon leakage is mitigated. Figure 18 below illustrates the effect of carbon pricing being applied but omits and reference to CCUS costs as they are currently uncertain.

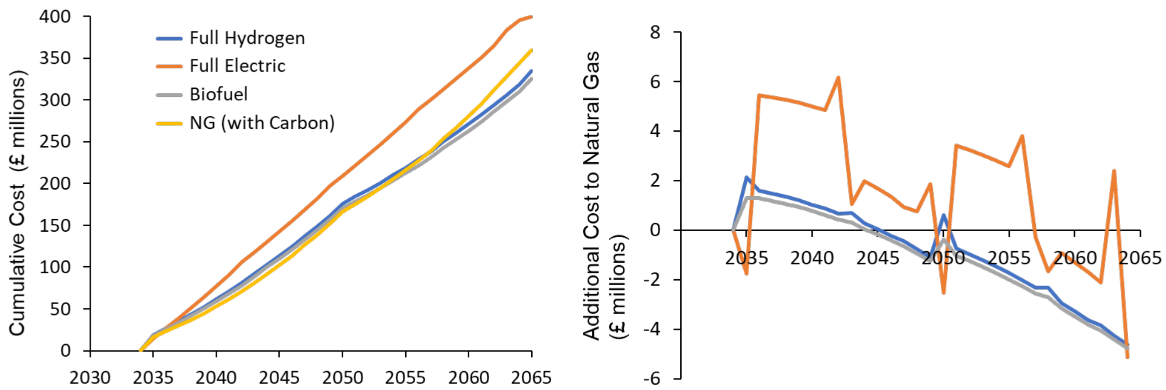


Figure 18 *Illustrative costs of fuel switching options for a glass furnace deployed in 2035 compared to natural gas (including price of carbon).*

6.4 Lifetime costs

Figure 19 below shows the discounted total lifetime costs of the different options broken down into CAPEX, fuel costs, carbon cost and other OPEX, and figure 20 shows the undiscounted annualized cost.

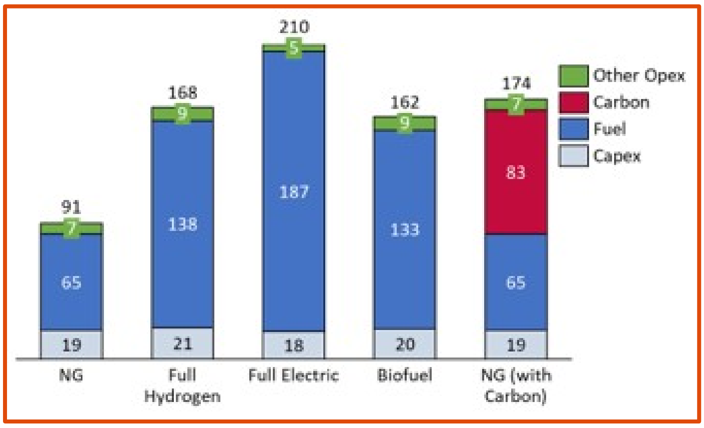


Figure 19 *Illustrative lifetime costs (300 t/day container furnace deployed in 2035, discounted at 5%)*[20]

[20] When discounted the carbon cost has a lower impact, due to a strong increase with time over the project's course. Annualised costs are undiscounted.

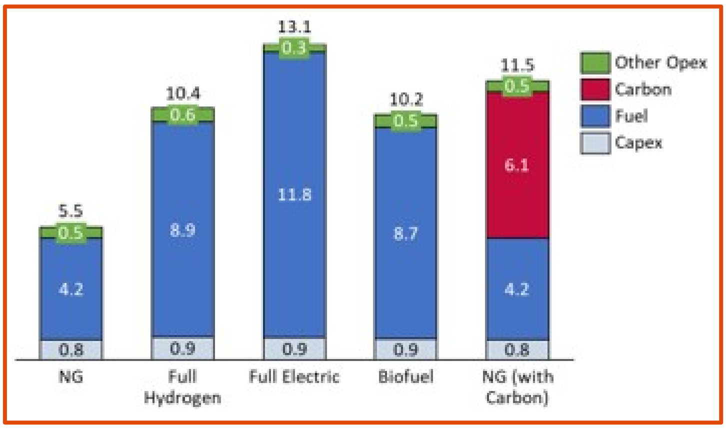


***Figure 20** Annualised cost (undiscounted) for 300 tpd container furnace deployed in 2035*

Due to the increased fuel costs for alternative fuels, none of the fuel switching scenarios investigated is cost competitive with the natural gas case (when the cost of carbon or similar incentives is not included). When carbon pricing is included, the biofuel and hydrogen scenarios become cost competitive with natural gas for furnaces constructed in approx. 2035. However, this is sensitive to a number of factors, including discount rate, fuel and carbon price, and furnace efficiency for the different options, and could range from 2030 to 2045. It should also be noted that lower-grade bio-oils may well prove more cost-effective and so should be included in future studies.

The dominance of fuel (and carbon) costs in the lifetime costs means residual uncertainty in the costs of fuel (and carbon) has a significant impact on the economically preferred fuel switching option. Due to the high level of uncertainty in fuel costs, any of the options could be the most economically feasible option, and Table 21 shows lifetime costs in 2025, 2035, and 2045 together with the range between the low and high sensitivities. As well as the technical unknowns, this economic uncertainty is an important reason why all fuel options need to be explored in future work.

Estimated Lifetime Costs (£ millions)[21]. (Low – High Sensitivities)			
Fuel Option	**2025**	**2035**	**2045**
Natural Gas	90 (68 – 103)	91 (68 – 103)	91 (68 – 103)
Natural Gas + CO_2 cost	143 (81 – 263)	174 (88 – 355)	201 (93 – 444)
Biodiesel	165 (138 – 291)	163 (136 – 338)	162 (136 – 384)
Hydrogen	169 (155 – 228)	168 (154 – 236)	167 (153 – 245)
Electric	211 (196 – 246)	210 (196 – 248)	210 (196 – 253)

***Table 21:** Estimated Lifetime Costs including Low and High Sensitivities for Fuel Options*

[21] 30 year lifetime cost for 300 T/day container (end fired) furnace, 5% discount rate.

6.5 Proposed Further Development to economic model

It should be noted that the current model has omitted several cost categories. As such it is recommended that the economic fuel switching model should be further developed and enhanced to provide a comprehensive tool for the glass industry (including use by individual glass manufacturing sites) to assess the likely fuel switching solutions. This should include:

- **Feedback from technical demonstrations –** further technical demonstrations and technical modelling are required to enhance the understanding of the different fuel switching options. This will enhance the modelling of the different CAPEX and OPEX components and fuel costs on an operational furnace.

- **Inclusion of lower-grade bio-fuels** – Such as oils from pyrolysis of carbon-based wastes, which may offer a fuel that has a closer life-time cost to that of natural gas.

- **Impact of fuel switching on site infrastructure –** Site infrastructure audits should be undertaken to allow enhanced analysis of existing infrastructure on glass sites. This will help understand requirements for each of the different fuel switching options and will evaluate cost and necessity of subcomponent repair/replacement at stages in furnace lifetime, site wide infrastructure changes (e.g. ATEX compliance), and the potential for and benefits of ancillary infrastructure (e.g. fuel storage, batteries) which could be installed on site. When incorporated into the model, this will enhance the comparative assessment process.

- **Customisation –** once developed, it is anticipated that the model will be used to inform glass sites about their fuel switching options and scenarios. This will require significant additional functionality to customize model runs and outputs, accounting for subsector specific (glass type/colour) requirements, possible impacts on and requirements to achieve glass quality, and site specific requirements (e.g. size of electricity connection, space constraints, pipework components). As well as these, it is recommended to include additional parameters with impact on the lifetime cost assessments (e.g. cullet % - high % difficult with all electric melting) and additional fuel switching scenarios (a range of hybrid scenarios and custom scenarios) within the model.

- **Completion of Model** – to achieve usability for glass sites, the model must be informative, usable, and updatable. Usability and usefulness of the model will be iterated upon accounting for feedback from glass sites (the future users). To ensure the model can be used for as long as possible, it needs to be future proofed with appropriate customisation and functionality to allow updating as projections change (fuel costs) or as further technical requirements of the fuel scenarios come to light.

7 Timeframes and implementation

7.1 Biofuels

Adhering to the same standard as conventional diesel-fuel, biodiesel fuels should be compatible with existing glass furnace infrastructure with minimum additional CAPEX investment required to adopt this fuel technology. As operators have experience of diesel firing, there will lower risk and associated costs in up-skilling the work force compared to 100% electric or hydrogen (both of which would be new technologies to much of industry and its workforce) and this process would not take long (in-house training would probably be sufficient).

The only significant technical barrier to implementation is a lack of data to demonstrate that 100% biodiesel will not adversely impact furnace infrastructure, nor glass melting. Therefore, with a suitable R&D programme of work to investigate and trial biofuels, it is estimated that within 3-5 years the industry will have a proven low-carbon technology that can be implemented at all sites and will have had time to up-grade facilities, accordingly, should the market conditions make the use biodiesel economically viable. Given that the UK has potential to create biodiesel capacity to supply the entire glass sector, this could provide a route to decarbonise all glass furnaces within the UK by 2030, although detailed studies into the sustainability aspects of these fuels would be needed. Although very unlikely to ever be cost competitive with natural gas without a different approach to carbon pricing, if carbon pricing is considered then they are estimated to be cost competitive over a 30 year lifetime for a furnace constructed in the early 2030s.

Lower-grade bio-oils, or carbon-based fuels from waste-streams (e.g. cooking oils, pyrolysis of plastics or tyres, or other bio-wastes) have been identified that may offer a more cost-effective source of low-carbon fuels. It is likely that specific glass plants will need to work with the supply chain to develop reliable, consistent supplies of biofuels from specific sources of wastes, most likely to be determined by geography. The Phase 2 study also identified that there might be opportunities to utilise waste heat from the glass furnace to drive the pyrolysis processes that convert waste-streams into bio-oils, thus further reducing the net CO_2 emissions of these fuels.

There are many unknowns surrounding the technical and economic viability of such bio-oils, such as levels of contaminants, variations in calorific and moisture content. Many of the methods for processing such wastes are also still unproven at scale. Therefore, although plants may begin to bleed in such bio-oils into existing furnaces in the short term (e.g. firing through only 1-2 of the multiple burner ports on the furnace) to give a partial decarbonisation, it is expected to take 7-10 years (probably with support from further grant-funded projects) to establish a stable supply chain such that these fuels provide a full decarbonisation solution. However, if a route could be identified to produce suitable bio-oils such fuels such that the price is comparable (or lower) to that of natural gas, then favourable economics may drive this technology forwards more rapidly.

One key risk identified in this Phase 2 study was a reliance of road-transport on fuel and the seasonal variation/availability of some biofuels; such issues will need to be investigated in future to provide a clearer picture of such risks and mitigation strategies.

7.2 Hydrogen

Numerous gaps have been identified in the technical understanding of how hydrogen fuels can be integrated into a glass furnace. One of the greatest risks surrounds uncertainty over required health and safety measures specific to the glass sector. Significant further work is required to identify key technical challenges that need to be addressed if hydrogen is to be widely adopted as a fuel within the glass sector. A portfolio of evidence will also need to be developed, along with engineering designs, furnace simulations and a study outlining costs to integrate an hydrogen supply from the mains into the furnace, with the objective to provide glass manufacturers with a detailed (technical and economic) business case to make a decision as to whether to proceed with a trial on their furnace. Training programmes for operators will also need to be considered, and these are likely to be extensive, requiring significant investment and a number of years to properly establish across the glass sector.

Discussions with BOC indicated that current hydrogen supply could only meet 5% furnace fuel requirements for a plant based in NW England (due to production and transport limitations). However, it is estimated that within 5-10 years there could be sufficient supply to meet the needs of a full furnace (based upon HyNet and H21 timescales). As such it is likely that the grid will begin bleeding hydrogen into the existing natural gas supply before then and so urgent R&D work is required to provide some groundwork as to the impact of this on the glass manufacturing process so that the industry is well positioned and informed as to actions that may need to be taken to reduce the risks associated with this.

Despite all of the challenges, this study has identified several research groups equipped with suitable equipment and expertise to tackle the challenges and unknowns surrounding use of hydrogen to melt glass. As such, with a suitably intense R&D test programme, the glass industry could be in a position to technically switch to 100% hydrogen melting within 5-10 years. Although very unlikely to ever be cost competitive with natural gas without carbon pricing, if carbon pricing is considered then they are estimated to be cost competitive over a 30 year lifetime for a furnace constructed in the early 2030s, similar to the biofuels fuel scenario.

7.3 Large-scale electric melting

The 2015 glass industry decarbonisation roadmap highlights this route as the preferred option for decarbonising the industry. Furnace designers are confident that they already have technically viable 100% electric furnace designs capable of melting upwards of 600 t/day, and they just need a manufacturer willing to take the risk of making such an investment. As such, large-scale 100% electric furnaces could be realised within 2-3 years (although it may require a number of years of operation before other sites would be willing to follow).

However this study has identified that this will be challenging to implement primarily due to the high cost of electricity, as well as the significant requirement to upgrade the electricity grid and supply of electricity to sites, combined with the need for new designs of large-scale furnaces and trials at scale before industry will adopt.

There are also questions as to whether suitable volumes of economically attractive ‘green’ electricity will be available by 2050. Currently a 100% electric furnace would only offer the ability to off-set some carbon considering the grid is in the region of 30% decarbonised[22], this would lead to a net increase in total CO2 emissions. As such this would be an effective method to move carbon emissions but not to reduce them when looking at the overall decarbonisation of glass melting in the short term. As such, it is unlikely that 100% electric furnaces will be a reality before 2040, primarily due to economic factors and availability of supply.

There is a need to address some of the unknowns surrounding the practicalities and costs for upgrading UK glass sites to all electric, partly so that this can be benchmarked against the other fuel options, but also to cover the eventuality that there may be local supplies of green electricity

[22] Energy and emissions projections 2018, BEIS, 2019

that make this scenario viable (e.g. if located near a windfarm). Further modelling of large-scale electric-furnace designs is also required such that there are designs 'on-the-table' should a manufacturer wish to choose this option.

As an example of scale, typical furnaces in the 200tpd range have in the region of 1 MWh of electrical boosting installed and would consume a total site demand of 3-4MWh for all other site processes. If this furnace were to be 100% electric it would likely need an additional 6MWh, which represent a huge sit increase in electrical distribution infrastructure.

Electric melting also has limitations in terms of the ability to use 100% recycled glass (if this were ever an option), as such other raw materials will need to be used. Although electric melting does not produce any emissions from the fuel at the point of use, some emissions are likely to be produced from the decomposition of carbonate-based raw materials, such that small-scale CCUS might be required.

7.4 Flexible Hybrid fuel scenarios

Due to the challenges, costs and risks associated with each individual fuel scenario, it is most likely that glass plants will adopt a flexible hybrid furnace approach, which will vary across sectors and from region to region. Such scenarios will enable manufacturers to take advantage of fluctuations in fuel costs (e.g. could overheat furnace at night with cheap green electricity then switch to combustion fuels during the day, at a reduced rate due to the residual heat stored in the glass tank).

Such scenarios would also bridge the transition from natural gas to new fuels, a likely necessity to allow the industry to build the required knowledge and operator experience of these new fuels and associated technologies in a more manageable manner than a 100% switch in one go. Although hybrid furnaces may have a higher CAPEX, the reduced risk to fuel supply disruptions, coupled with the cost-savings potential from controlled fuel-switching will potentially more than off-set these costs.

It is recommended that the remit of future studies should initially focus on the following combinations of fuels, each with significant scope for combining with electric boost (whereby up to 80% furnace could be powered with electricity): (1) Biofuel + natural gas, (2) hydrogen + natural gas, (3) Biofuels + hydrogen.

As well as aiding the transition to low-carbon fuels, this creates a route to begin off-setting CO_2 emissions in the short-term whilst the respective supply chain is established. Hybrid furnaces combining either natural gas or biofuels with hydrogen also addresses issues with the low emissivity and high temperatures associated with a hydrogen flame, offering a route to achieve a 'yellower' flame, burning at a lower temperature, thus aiding heat transfer and reducing NO_x.

Given the uncertainty in the future availability and prices of fuels and the fact that most glass furnaces are designed to operate for between 15-20 years, it is likely that furnaces with hybrid-capability will be built within the next 3-5 years, or at least furnaces that can be easily up-graded to a hybrid design. Even though the CAPEX might be higher, such furnaces will offer a route to respond to future energy scenarios and avoid the need for an early rebuild.

7.5 Compatibility with CCUS

In parallel to the above developments, developers of CCUS technologies (e.g. Apache, C-Capture) need to be engaged to identify the most suitable technologies for capturing CO_2 produced by the glass furnace in order to direct future research towards finding a CCUS solution for the glass sector. It is expected that it may take up to 20 years for such solutions to be realised. It is recommended that future R&D studies undertake detailed characterisation of the emissions. This will reduce this time-frame and potentially identify routes to optimise fuels and/or combustion parameters and/or glass composition in order to make it easier and quicker to employ CCUS technologies in future, thus reducing the development timeframe, which could enable the glass sector to become carbon negative by 2050. It will also provide inputs into future furnace designs so that even if the CCUS technology is not available at the time of the build, the potential for retro-fitting CCUS technologies can be included in the design.

Given some glass container plants are located near carbonated drinks filling lines some of this CO_2 could be utilised in down-stream processes; even if not, 80% glass plants are based along M62 corridor and close to planned future CO_2 pipelines for carbon storage projects.

7.6 Summary of possible implementation timeframe with sufficient R&D investment

In summary this study indicates that, with suitable R&D investment, biodiesel could enable the glass industry to eliminate up to 90% of the CO_2 emissions associated with heating glass furnaces by 2030. If combined with CCUS, this could offer a route to net-carbon negative emissions.

However in the longer term, it is likely that the industry would want to move towards a hydrogen-electric hybrid (once such fuel sources are available), possibly with a small amount of bio-oils (e.g. either to optimise the hydrogen flame or as a back-up when electricity is in high demand), such that the fuels can be delivered to site without the need of a road-based haulage network. This also reduces the reliance on the biofuel network, freeing it up for other sectors.

Figure 22 below provides an outline of the implementation timescales that might be achievable if the industry fully backs R&D activities proposed in this report.

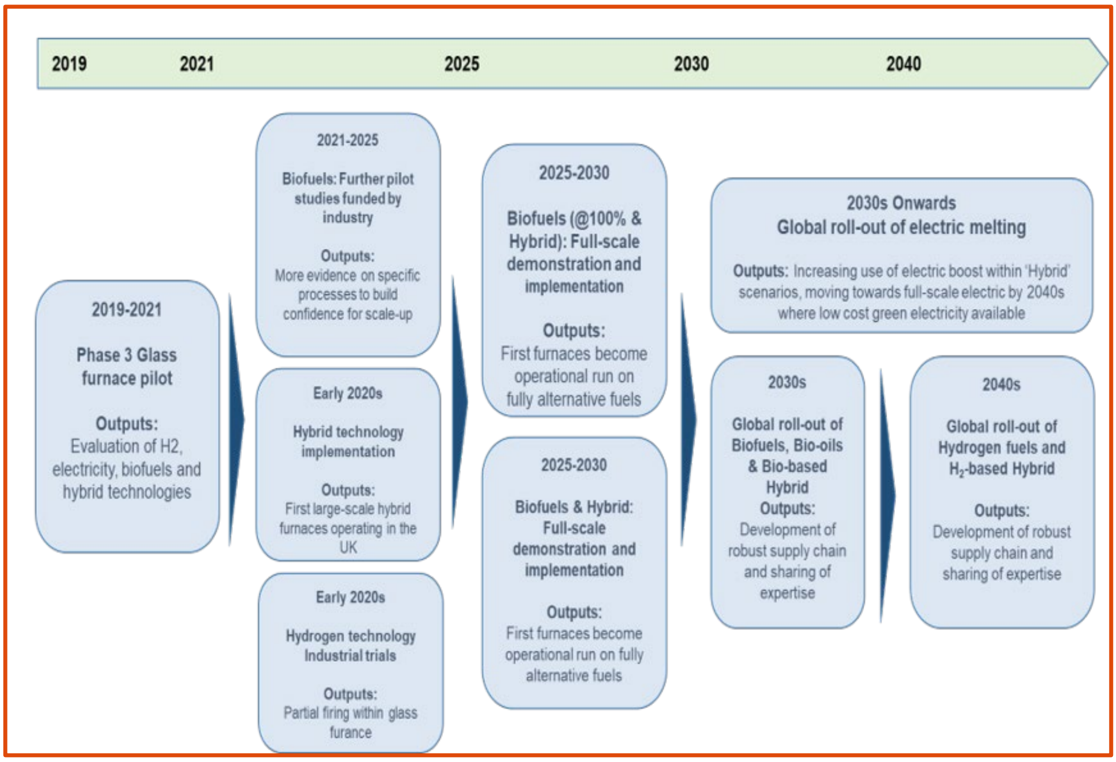


Figure 22: *Estimated implementation timelines for the various fuel switching Options*

8 Conclusions and Recommendations

Due to uncertainties and differences between subsectors and predicted future variations in availability and affordability of different fuels across the UK (e.g. hydrogen supply may be localised; local grid capacity for electricity supply limited), no single low-carbon fuel scenario is likely to be suitable for all 17 of the largest glass manufacturing sites which account for the large majority the UK's glass manufacturing output (and associated CO_2 emissions from glass melting).

Of the four potential fuel-scenarios investigated (biofuels, hydrogen, large-scale electricity, flexible-hybrid) this study has found that each has potential to be technically feasible, with the potential to fully decarbonise the glass furnace heating process whilst meeting regulatory requirements, if the fuel could be supplied at an economic price.

8.1 Biofuels

Biofuels (i.e. fuels derived directly or from wastes from 100% renewable bio-sources, so not including blends with standard diesel) could be a good option for fuel switching, given the similarities of some biofuels to gas oil, the industry's preferred fuel before natural gas, and that there is further potential to use lower cost bio-oils. The UK has biofuel capacity to upgrade 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. However, it was identified that there is no understanding of how biofuels will perform in a glass furnace compared to natural gas and standard diesel, in particular in terms of their effect on glass melting behaviour and on emissions as there are no recorded cases globally of firing a glass furnace with bio-oils. As such, further R&D is required into these areas.

8.2 Hydrogen

There is little understanding of how hydrogen will perform in a glass furnace. Key concerns include the heat transfer mechanism, the volumes of airflow through the furnace, H&S implications such as ATEX rated equipment, effects on glass melting and furnace refractories, whether furnace geometry is suitable, effects on emissions, e.g. higher NOx due to hotter flame. A significant R&D programme is required to build sufficient understanding of these and other technical challenges.

Significant effort also needs to be invested into training programmes and into building a proper understanding of the requirements for a site to implement hydrogen fuels.

The study suggested that it would currently only be possible to commercially source suitable volumes of hydrogen to provide 3-5% fuel for a typical glass furnace (from conversations with BOC), so it would be challenging to undertake a meaningful large-scale trial now, but suitable volumes may be available in future. Larger supplies of hydrogen would be required to enable the glass sector to undertake meaningful large-scale trials.

8.3 Large-scale 100 % Electric melting

The study identified that furnace designers are reasonably confident they can design larger-scale (>300 t/day) electric furnaces, despite technical unknowns, such as how efficient a semi-hot top furnace might be.

Due to lack of interest from the industry little, if any, modelling of such designs has been undertaken and so this should be the focus of short-term R&D efforts.

The greatest barrier to implementation surrounds the economics of electric melting (i.e. the higher cost of electricity compared to natural gas). There are also uncertainties around the scope/cost of upgrading the supply to each site in the UK to facilitate full-electric melting and the size of CAPEX investment required in new furnace designs and potential changes to plant layout. Significant engagement with government would be required to provide suitable incentives and investment into national supply infrastructure if 100% electric melting were to become viable across the UK.

8.4 Flexible Hybrid-fuel scenarios

Beyond the widely employed natural gas-electric furnaces, little work has been done into hybrid scenarios, nor into dynamic fuel-switching systems nor the impact that such a system might have e.g. emissions or CCUS.

The following three hybrid scenarios have been identified as having the greatest potential: (1) biofuels + natural gas + electric, (2) hydrogen + natural gas + electric, (3) biofuels + hydrogen + electric.

Further R&D studies and furnace modelling is recommended to identify the most suitable hybrid furnace designs, which should then be worked up into pilot furnaces for larger-scale trials.

The longer-term impact of a UK industry that has specialist knowledge in advanced furnace control could be highly advantageous to both the economics of UK-based glass manufacture as well as UK based specialist knowledge that can be exported globally.

8.5 Bio-methane

Although bio-methane was not covered within this study (due to it being out of the competition scope), it does offer a potential route to decarbonise the glass manufacturing process and so should be considered in future studies.

8.6 CO_2 reduction potential

If successful, our study has concluded that these low-carbon fuel technologies have the potential to remove up to 1.2 million tonnes of CO_2 emissions per year by 2030, totalling more than 20 million tonnes by 2050. Without continued funding in this area the industry is unlikely to explore these fuel scenarios until after 2030 and these new technologies are unlikely to be implemented widely until after 2040.

This study also identified the need to develop a research infrastructure and expertise within the UK that can support and drive rapid implementation of these low-carbon fuel technologies. This would have a knock-on benefit to the UK economy of creating new, high-skilled, jobs and leveraging significant international R&D investment.

It has been identified that the glass industry needs to review the 2014 British Glass decarbonisation roadmap, to update plans in accordance with findings from this project to ensure that the industry is not only aware but signed up to implementing the most promising decarbonised fuel technologies.